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BEFORE THE WATER QUALITY CONTROL COMMISSION

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EXHIBIT FINLEY - 6

CHAPTER 4

Hydrologic Characteristics and Classifications of Pit Lakes

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INTRODUCTION

The mining process—the act of extracting geologic materials from the earth's crust—always ends with a "hole in the ground." The nature of this hole can range from large, cavernous openings, kilometers in length beneath the ground surface, used to extract base and precious metals to a small pit outside of an urban area where gravel was once extracted. The latter technique, open pit mining, is likely the most common material extraction methodology utilized in mining today. Open pit mining techniques are used for extracting commodities such as sand and gravel, base metals (e.g., copper and zinc), and precious metals (e.g., silver and gold). Figures 4.1 and 4.2 provide typical examples of open pit mines. Open pit mining often intersects the groundwater table, such that when the extraction process is complete, the open pit will remain and, in many cases, may form a pit lake. The focus of this chapter is to discuss a handful of aspects related to the hydrology of open pits or pit lakes after mining ceases, such as

- How do "flow-through" pit lakes differ from "terminal" pit lakes?
- What is known about the water quality of these lakes from observations of existing pit lakes?
- What impact will climate change have on hydrology?
- How does artificial flooding of pit lakes with surface water affect groundwater input?
- What can be expected in future pit lakes?
- What are the current data gaps?

Woodhouse (2002) provides a grouping of articles that describe a wide range of topics associated with mine pit lakes.

HYDROLOGIC STATUS OF PIT LAKES

Two types of hydrologic conditions exist in pit lakes:

1. Flow-through conditions—surface and/or groundwater flows into and out of this type of lake (Figures 4.3 and 4.4).
2. Terminal conditions—groundwater flows into the pit and outflow occurs only as evaporation (Figure 4.5).

Flow-through pit lakes are common in areas where rainfall exceeds evaporation, in highly productive aquifers where groundwater inflows exceed evaporation rates (e.g., alluvial aquifers), and any time that the net water balance surrounding the pit is positive. Another type of a flow-through

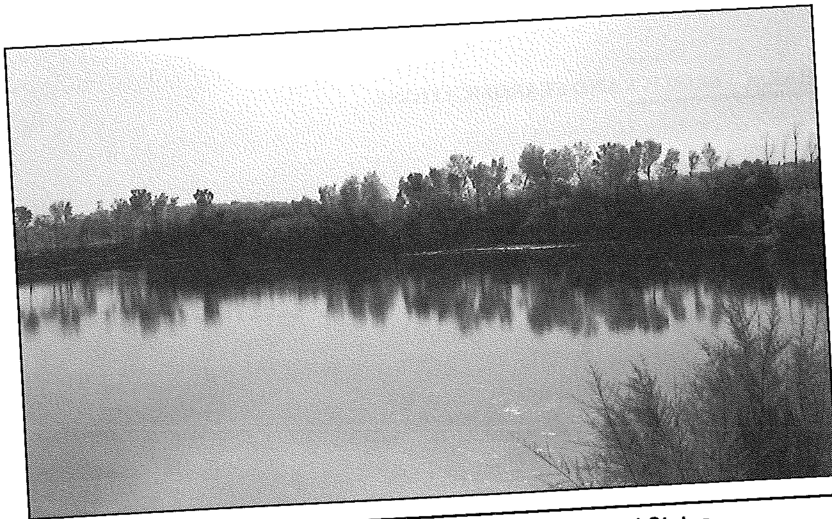

FIGURE 4.1 **Gravel quarry pit lake, Grand Junction, Colorado, United States**

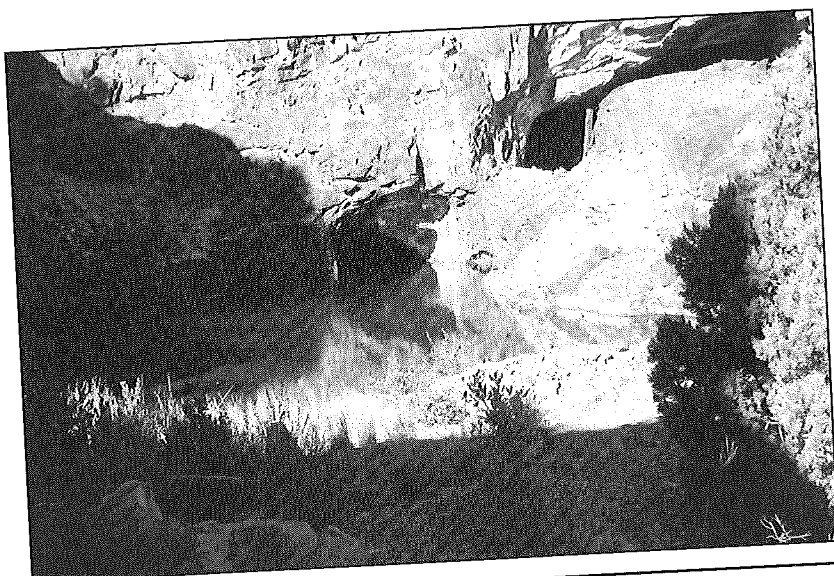

FIGURE 4.2 **Small mine pit lake with adits, arid region of southwestern United States**

pit lake is one that exists above the water table and is filled by surface water. Outflows consist of vertical leakage and evaporation.

Terminal pit lakes are common in the arid areas of the world where evaporation exceeds rainfall/precipitation or any time that the net water balance surrounding the pit is negative. With seasonal or long-term climatic changes, the hydrologic status of a pit lake may fluctuate between terminal and flow-through. The Martha mine in New Zealand (Ingle 2002) is an example of a uniquely engineered flow-through pit lake. After closure, the plan is to place a drainage pipe below the premining groundwater elevation that will fix the elevation of the postmining pit lake. Whereas all local groundwater will flow into the lake, the discharge of surface water will make the pit lake exhibit flow-through conditions. A terminal pit lake would have evaporation as the only discharge.

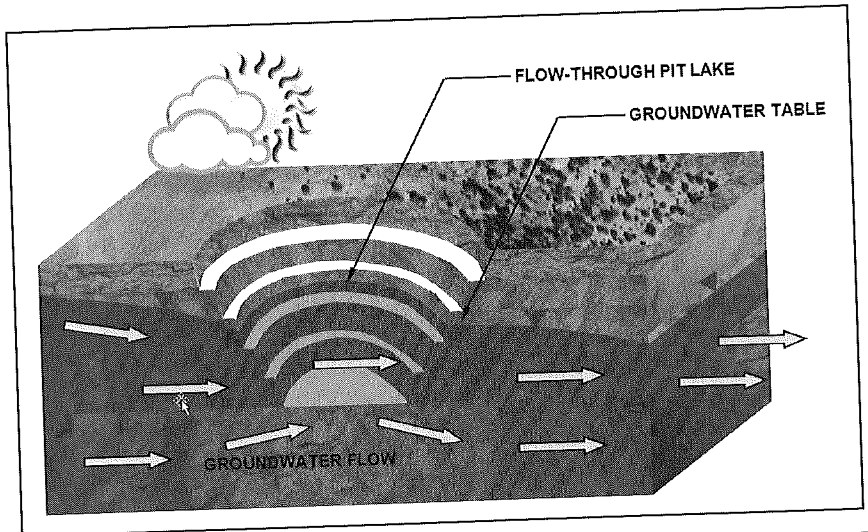

FIGURE 4.3 Flow-through pit lake below the groundwater table

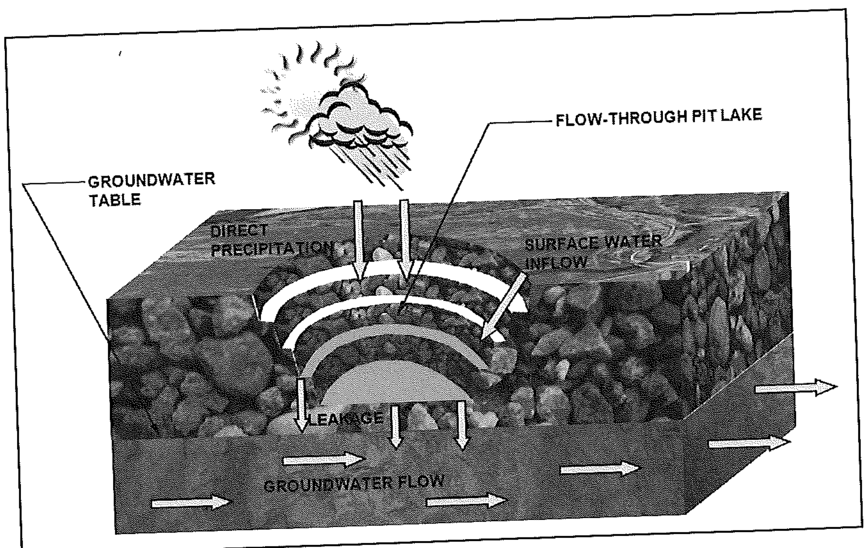

FIGURE 4.4 Flow-through pit lake above the groundwater table

In the United States, the Sweetwater pit in Wyoming is an example of a terminal pit lake, whereas the Berkley pit in Montana, if left unmanaged, is expected to become a flow-through pit lake.

To determine which condition exists for any particular pit lake, measurements and observations of the hydrologic components of the pit lake are key. Groundwater elevation data surrounding the pit lake, pit lake elevations, precipitation, and surface water inflows and outflows are parameters that should be measured. Maps of groundwater heads, expressed as groundwater elevations (i.e., potentiometric maps), and flow nets built from the collected groundwater head data can show the hydrologic status of a pit lake (Figure 4.6). Predicting the hydrologic condition of a pit prior to its filling and reaching steady state is a different endeavor and is covered

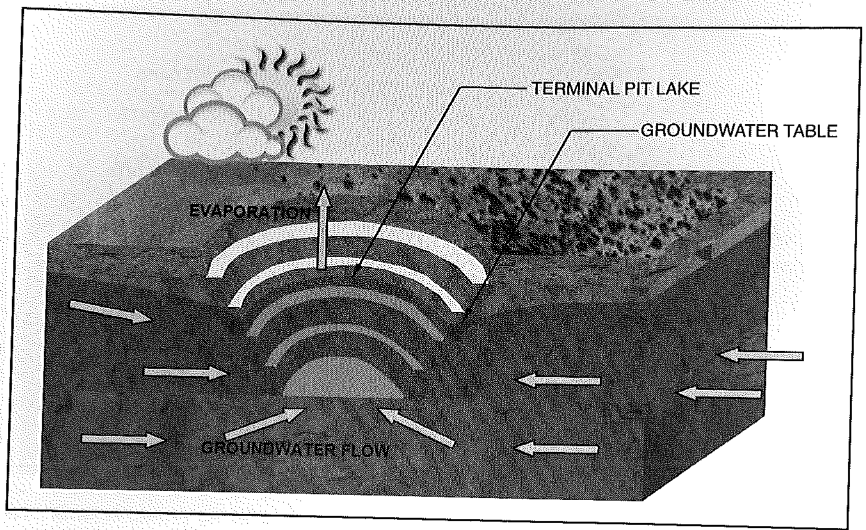

FIGURE 4.5 Terminal pit lake—all outflow is from evaporation

in Chapter 8. However, the same measurements required to determine the hydrologic status of a lake after filling are helpful in aiding predictions before filling.

Two possible scenarios are encountered when an evaluation to determine the hydrologic status of a pit lake is undertaken: (1) Information exists for the premining hydrologic conditions at the site and good records of dewatering rates at different mine elevations exist, and (2) little to no historic data are available. Scenario 1 provides the most robust method of evaluating the hydrologic status of a pit lake. Historical information can be used to quantify water balance components (Figure 4.7) and an estimate of the pit lake water balance (i.e., summing the inflows and comparing them to the outflows) completed. By evaluating available groundwater elevation data, comparing them to known pit lake water elevations, and examining the water balance, the hydrologic status of the pit lake can be estimated. For example, if the dewatering rate at a given elevation matches the net evaporation (i.e., the balance of direct precipitation, runoff, and lake evaporation) at the same elevation, the lake is likely at a steady state. If groundwater elevation data surrounding the pit lake are all higher than the lake surface elevation, the lake is terminal.

Scenario 2 presents a more difficult challenge; however, both a water balance and an estimate of the groundwater conditions must be made. Water balances without measurements require that estimates be made from available (or newly collected) data. It is beyond the scope of this chapter to describe all of the methods of estimating the various components of the hydrologic balance associated with a pit lake. The reader is therefore pointed to classic textbooks such as McWhorter and Sunada (1977), Freeze and Cherry (1979), Watson and Burnett (1993), and Schwab et al. (1981) to gain a fundamental understanding of these components. Provided herein is an example of evaluating the hydrologic status of a pit lake using a hypothetical pit lake.

Presuming that the owner of the hypothetical pit lake shown in Figure 4.6 purchased the property recently and that any hydrologic records from the previous owner had burned in a fire and were no longer available. The new owner wanted to estimate the amount of water flowing through the pit for regulatory purposes (e.g., to satisfy water rights regulations or meet discharge permit requirements). Given that there are wells in the area, he sent out a team from his

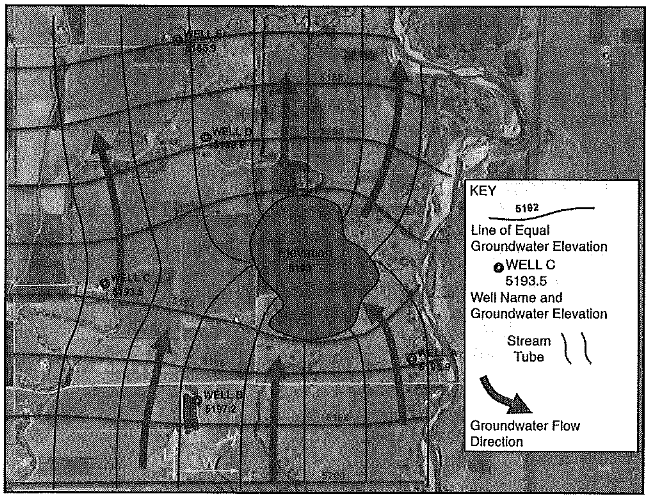

FIGURE 4.6 Potentiometric map and flow net associated with a flow-through pit lake. Water elevations are given in feet (1 foot = 0.3048 meters).

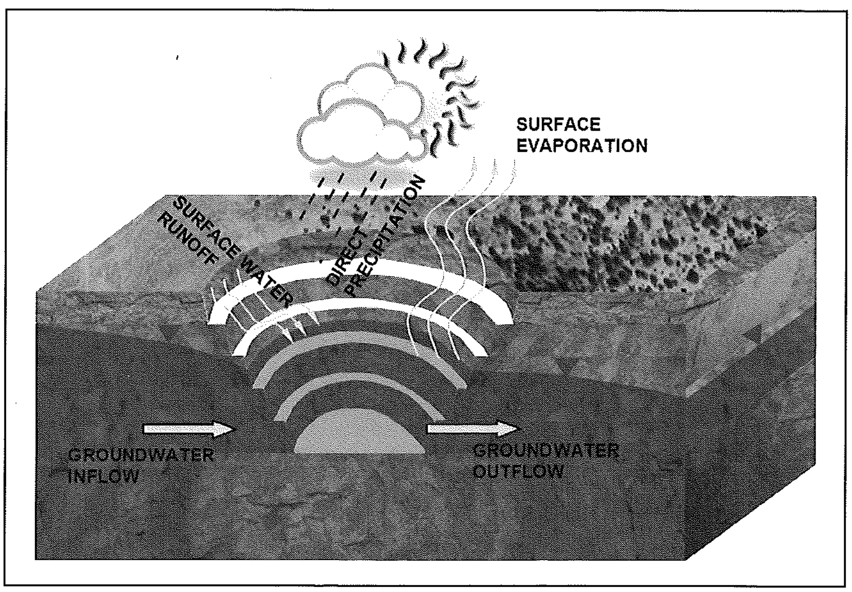

FIGURE 4.7 Hydrologic processes associated with a pit lake

environmental department to measure water elevations in the wells and the pit lake. He also had them perform aquifer tests in all the wells. Concurrently, the team searched the Internet and found the mean annual precipitation and pan evaporation rates from a nearby governmental weather station. Table 4.1 shows the data that were gathered during the investigation.

The team created the groundwater elevation and flow map shown in Figure 4.6, which shows that the pit is likely flow-through. To calculate the groundwater flow to the pit, they used Darcy's law and the flow net shown on Figure 4.6. These calculations are shown in Table 4.2. Table 4.2

TABLE 4.1 Example of field hydrologic investigation results

Well Name	Water Elevation, ft	Water Elevation, m	Hydraulic Conductivity, ft/d	Hydraulic Conductivity, m/d
Well A	5195.5	1583.5	375	114.3
Well B	5197.2	1584.0	700	213.3
Well C	5193.5	1582.9	350	106.7
Well D	5189.8	1581.8	600	182.9
Well E	5185.9	1580.6	150	45.7
Pit	5193.0	1582.7		
Geometric mean	—	—	383	116.7
Geometric mean, wells A–C	—	—	451	137.5
Mean annual precipitation	8 in./yr	20.3 cm/yr	—	—
Mean annual pan evaporation	72 in./yr	182.9 cm/yr	—	—

also shows that the outflow is approximately 85% of the groundwater inflow. This reduction in flow is represented by the narrower width of the stream tubes downgradient of the pit in Figure 4.6.

This straightforward approach is just an example of one method to estimate the hydrologic status of a pit lake, but it can be quite robust and provides a good idea of the magnitude of the flows associated with the pit lake. However, one should exercise diligence when performing any kind of analysis to make sure that other factors are not influencing the water balance associated with the pit. For example, unknown heterogeneity in the aquifer such as fractures, faults, and historic works may not be apparent in the investigation, yet they could have important effects on the actual flow. If these features are suspected to occur, further investigation is warranted.

HYDROLOGIC IMPACTS ON PIT LAKE WATER QUALITY

The water quality of a pit lake is a result of many contributing factors including but not limited to

- Geology and mineralogy of the host formations,
- Influent water quality,
- Concentrating effects of evaporation,
- Geochemical, biological, and limnologic processes within the lake, and
- Anthropogenic impacts.

The hydrology of a pit lake affects the water quality of the pit lake by changing the chemical mass balance associated with the lake.

To make a general statement that one type of hydrologic condition results in better water quality than another would be a misstatement on account of the influence of nonhydrologic processes. The ultimate disposition of pit lake water quality is a balance of all the effective processes. However, general statements regarding the impacts of individual hydrologic processes (Figure 4.7) on water quality can be made:

- Groundwater inflows carry dissolved constituents at background concentrations into the lake. Natural, upgradient groundwater will have a certain water quality and will contribute constituents to the pit lake. Inflowing groundwater can also pick up constituents from

TABLE 4.2 Calculation results

Darcy's Law

$$Q = \text{Area} \times K \times \frac{\Delta H}{L}$$

where
Q = groundwater flow
Area = cross-sectional area of flow
K = hydraulic conductivity
ΔH = change in hydraulic head over the flow length, L

Data	
L = 2,500 ft	Distance between hydraulic head contours on one stream tube (see Figure 4.6).
W = 2,500 ft	Width of an upgradient stream tube (see Figure 4.6).
D = 350 ft	Depth of pit and aquifer
K = 451 ft/d	Geometric mean of measured hydraulic conductivity in the area upgradient and near the pit lake. Note: The geometric mean typically yields that best estimate of the effective hydraulic conductivity that represents the overall aquifer.
ΔH = 2 ft	Change in hydraulic head over the calculation length L
A = 451 acres	Surface area of the pit lake
$evap_{rate}$ = 72 in./yr	Pan evaporation rate
$precip_{rate}$ = 8 in./yr	Mean annual precipitation
Calculations	
$q_{streamtube} = W \cdot D \cdot K \cdot \Delta H / L$ $q_{streamtube}$ = 1,640 gpm	Flow in upgradient stream tube using Darcy's law
$No_{streamtube}$ = 4	Number of stream tubes flowing to pit lake
$Q_{gw\_In} = No_{streamtube} \cdot q_{streamtube}$ Q_{gw_In} = 6,560 gpm	Groundwater inflow to the pit
Evap = $evap_{rate} \cdot A \cdot 0.7$ Evap = 1,173 gpm	Evaporation from the pit lake surface (0.7 is a typical factor to convert pan evaporation to lake evaporation rates)
Precip = $precip_{rate} \cdot A$ Precip = 186 gpm	Direct precipitation to the pit lake
$Q_{gw\_out} = Q_{gw\_In}$ + Precip − Evap Q_{gw_out} = 5,573 gpm	Groundwater outflow from the pit based on a water balance—assuming no surface water run-on
Conversions	
1 gpm = 3.7854 Lpm	U.S. gallons per minute converted to liters per minute
1 acre = 4,047 m^2	Acres converted to cubic meters
1 in. = 2.54 cm	Inches converted to centimeters
1 ft = 0.3048 m	Feet converted to meters

Source: Adapted from Marinelli and Niccoli 2000.

weathered rock immediately surrounding the pit lake or from recharging meteoric water passing through the dewatered zone.

- Surface water runoff from pit walls may transport constituents and sediments that will affect the chemistry of the lake.
- Direct precipitation generally is a diluting factor on pit lake quality.

- Because evaporation takes out the water and leaves behind any dissolved constituents, evaporation tends to have a concentrating effect on pit lake water quality.
- Ground- and surface water outflows from pit lakes typically have the effect of removing constituents from the lake. However, if the lake is stratified, these outflows may remove water of different quality, which may result in either improved or worsened water quality in the pit lake.

Generally, it can also be said that the hydrologic status of a pit lake can affect whether or not the lake water quality will reach a condition of hydrochemical steady state (i.e., dissolved constituent concentrations in the pit lake are relatively constant over time). For example, a flow-through lake has a better chance of reaching a hydrochemical steady-state condition because chemical inflows and outflows from the lake water column can eventually balance if no other processes are active. It is impossible for hydrologic processes alone to keep a terminal pit lake from reaching chemical equilibrium (i.e., chemicals flow into the pit lake water column but none flow out). These statements are by necessity generalities, and the impacts of hydrologic and other chemical processes are unique to each individual pit lake.

CLIMATE CHANGE AND PIT LAKE HYDROLOGY

Climate is the single most important factor on the hydrologic processes associated with a pit lake. Changes in climate (e.g., temperature, rainfall, wind, precipitation amount and distribution) will affect the individual hydrologic components differently. In general, surface hydrologic processes (e.g., direct precipitation, evaporation, surface water runoff) are impacted immediately upon a change in climate. Groundwater inflows are generally and ultimately generated from precipitation recharge. The groundwater system tends to buffer short-term climatic changes, but long-term climatic changes will be reflected in groundwater inflows over the long term.

The Intergovernmental Panel on Climate Change (IPCC 2007) indicated that there is a strong probability that temperatures will continue to increase into the future given that current conditions affecting atmospheric processes remain constant. This increase in temperatures will affect surface hydrologic processes differently in different parts of the world. Some areas will become wetter while other will become drier. For the western United States, Hoerling and Eischeid (2007) used climate models to predict the Palmer Drought Severity Index in the future. Their work indicates that drought conditions will be worse than at any time in the recent past and drier conditions will prevail. Thus, evaporation rates are anticipated to increase, resulting in an increased loss of surface water from rivers and lakes.

For pit lakes, a dryer climate will most certainly result in lower pit lake elevations. Contrarily, a wetter climate will most certainly result in higher pit lake elevations. However, it is difficult to make broad statements about how climate changes will affect the status of a pit lake (i.e., if it will change from a flow-through to a terminal pit lake or vice versa), because climate changes will affect all the components of the hydrologic system. Because each individual pit lake is different, the resulting water balance from climate change must be evaluated on a case-by-case basis to determine climate change effects on pit lake status. Assessing the effects of potential climate changes was described in Chapter 3.

ARTIFICIAL FLOODING EFFECTS ON GROUNDWATER INFLOW

One method for affecting pit lake water quality is to flood the empty pit at the end of mining with surface water, artificially raising the water elevation in the lake to long-term equilibrium levels over a relatively short time period. The idea being that if there are oxidizing conditions in the pit walls that release acidity and other constituents, a quick submersion reduces the time available (i.e., hydrologic steady-state conditions are reached more quickly) for oxidation to take place and thus reduces the ultimate chemical loading to the pit lake. Also, the water quality of waters used for flooding can be of high quality, resulting in an improvement of initial pit lake water chemistry over that which can result from natural inputs.

If a pit is below the water table and it is artificially inundated, then the hydraulic head in the pit lake will be immediately higher than all the surrounding groundwater elevations (Figure 4.8). Because groundwater *always* flows downgradient (not necessarily along geologic formations or features as is sometimes commonly thought), inflow to the pit will cease and flow will be out of the pit lake into the groundwater system, filling the void space in the surrounding wall rock. This process can push constituents released from the wall rock farther into the groundwater aquifer, effectively increasing the zone of impact surrounding the pit. As such, the potential environmental impacts of artificial filling on regional groundwater resources need to be considered prior to adopting this strategy. The size of the draw-down cone surrounding the pit, the time that the pit has been dewatered, the geology and mineralogy of the pit walls, and the ultimate hydrologic status of the pit lake will dictate the magnitude of impacts to the surrounding groundwater system.

Under artificial filling conditions, groundwater inflows to the pit will cease until the heads in the surrounding aquifer increase to elevations higher than the pit lake surface and the pore spaces surrounding the pit are filled. Groundwater inflows will then increase to the pit lake until a near-steady-state flow rate is achieved.

FUTURE OF PIT LAKES

The hydrologic status of future pit lakes will be dependent on a multitude of factors ranging from climate to regulatory policy changes. Short- and long-term climate changes will inevitably affect the hydrologic status of pit lakes. Continuing research in the prediction and monitoring of climate change will be important to understanding the future status of pit lakes, as climate will

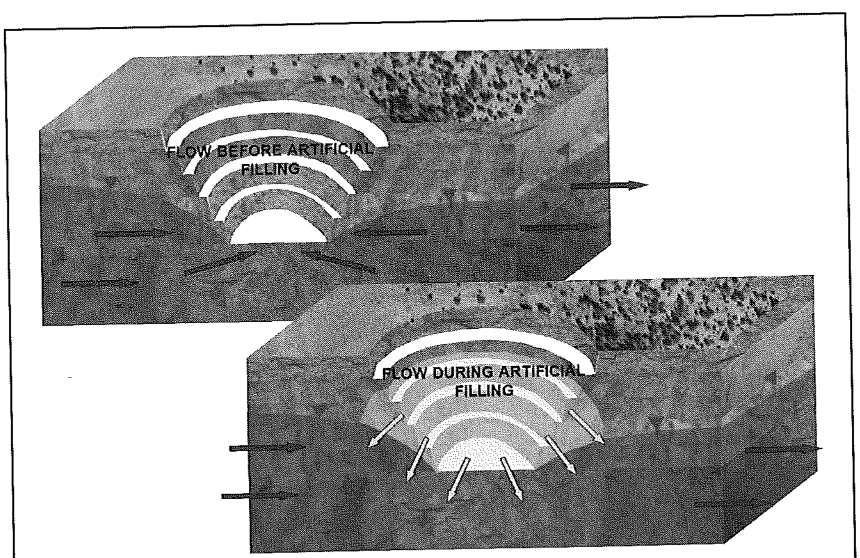

FIGURE 4.8 **Artificial filling impacts on groundwater inflow**

affect every component of the water balance associated with pit lakes. Future regulatory policies will likely be more protective of the environment. Regardless of climate or policy changes, each pit lake should be evaluated on its own individual merits and as a part of the entire hydrologic system. The advantages and disadvantages of allowing pit lakes to form should be evaluated and objectives developed (e.g., a pit lake may be allowed to form in order to treat water or to be a storage feature in a supply system) prior to pit lake formation. Then, if the lake is allowed to form, a robust monitoring and management program can be implemented to ensure that the pit lake is meeting its objectives.

HYDROLOGIC CHARACTERIZATION DATA GAPS

From a hydrologic standpoint, the inevitable question that is asked regarding an existing pit lake is, "What is the water balance associated with a pit lake?" Ancillary questions are also asked, such as when will it reach a steady water level, will it be terminal or flow-through, and what will its final depth be? By accurately defining the water balance associated with the pit lake, most associated hydrologic questions can be answered.

The most accurate method for determining a water balance would be a direct measure either at the time the question is asked or measurements taken during mining of the pit (e.g., groundwater inflow rates as a function of pit depth). Direct precipitation can be measured with a fair degree of accuracy, and lake surface evaporation can be estimated from pan evaporation measurements taken on-site near the pit lake in question. If complete and accurate dewatering flow rates and groundwater elevation records were taken during mining, groundwater inflow can be robustly estimated. The remaining components (high wall evaporation and groundwater outflow) are typically found through difference. Niccoli et al. (2004) describes a hydrologic balance approach to estimating hydrologic components with a mine pit in Montana. In arid regions, high wall evaporation (i.e., direct evaporation from groundwater exiting the high wall) can be a large component of the water balance, especially if groundwater elevations rebound such that a seepage face develops (Figure 4.9). Continuing research into high wall evaporation would be worthwhile.

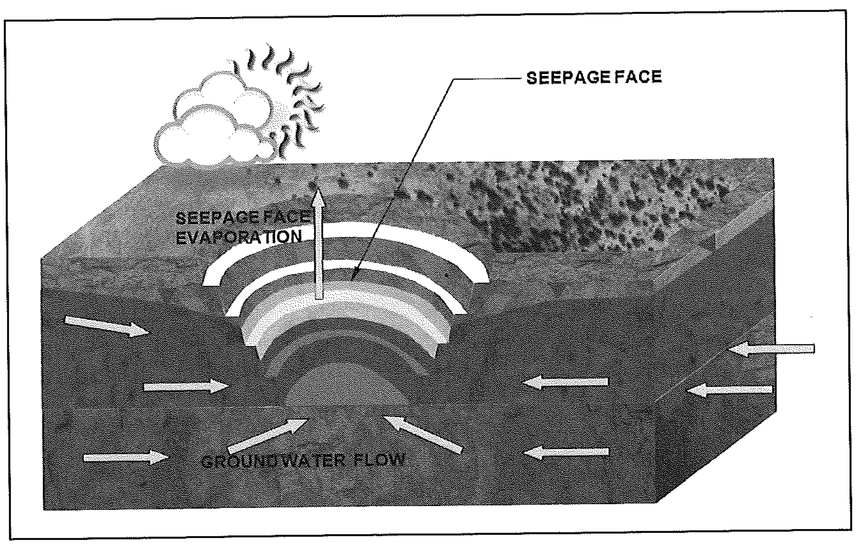

FIGURE 4.9 Seepage face evaporation—groundwater flows to the pit above the pit lake water level

Perhaps direct flux measurements along known seepage faces to verify previous estimates could further understanding of this component. A concerted effort in compiling a database of existing pit lakes and associated hydrologic predictions would be worthwhile. This database could then be used to understand how accurate predictions were, and whether they are close enough to answer the questions asked and to evaluate where weaknesses in predictions occur.

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