Preliminary Investigations of Effluent Drainage from Mining Heap Leach Facilities

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ABSTRACT

Long-term infiltration and drainage through unsaturated metal mining waste poses the potential to transport toxic contaminants, such as arsenic, cyanide, and mercury, to the underlying groundwater. However, an almost complete lack of analysis of the long-term infiltration rates through these wastes signficantly hampers quantitative assessment of the environmental impacts. This work synthesizes drainage data taken from regulatory reporting of gold and copper heap leach structures in the state of Nevada to investigate the magnitude of long-term infiltration and the factors controlling infiltration. Because heap leach structures are lined, infiltration and drainage rates can be directly measured at a downstream point. Drainage rates following rinsing showed an exponential decline, and in three of the eight sites examined in this study, drainage reached a steady state derived from precipitation. The remaining five sites continued to show a very slow decline in drainage after as much as 57 mo of drainage. Estimated precipitation-derived drainage ranged from 6 to 160 mm yr^{-1}, which constituted recharge ranging from 2 to 23% of annual precipitation. At low precipitation sites, estimated recharge through heaps was higher than predicted by models used to estimate recharge in semiarid regions, and the highest recharge rates were calculated for heaps containing coarse textured ore. At higher precipitation sites, estimated recharge was lower than model predictions. Many of these sites had engineered soil and vegetation covers that successfully limited infiltration of moisture through the heaps. Water infiltration and drainage may be greater where the ratio of potential evapotranspiration to precipitation is low and where a high proportion of slope surface area is exposed, but the relationship between these variables and drainage could not be clearly defined based on the data in this study.

RECENT ADVANCES in technologies for mining and minerals processing now rely upon unsaturated fluid flow and reactive chemical transport at large scales through heap leaching facilities. Following mine closure, large quantities of reactive rock, often containing toxic elements, such as As, Hg, and other metals, remain at the land surface where infiltration can continue to leach these contaminants through the vadose zone to the underlying groundwater. At this point in time, little quantitative study has been done on long-term infiltration rates and chemical transport from these mining processes. In this study, we assess the current state of data availability and, using these data, develop preliminary predictions of the rates of natural deep infiltration (or recharge) through typical mined areas of widely varying precipitation in Nevada. These results provide the most quantitative analysis to date, but also point out the limitations in currently available data and the need for much more attention in the future to assess more accurately the long-term transport of contaminants from these sites.

Heap leaching of ores mined from open pits is a technique that allows gold and copper to be extracted from low-grade ores at low capital and operating costs (Bartlett, 1992). Heap leaching for copper (using acid as the leach solution) has a long history, and now heap leaching of low-grade gold ores (~0.5 g gold Mg^{-1}) is also common. Such low-grade ores require large volumes of rock to be processed in a heap leach, and it is not uncommon to require 150 to 200 Mg of ore to produce 28.3 g (one ounce) of gold. Ores used in heap leaching are either taken directly from the mine pit (*run-of-mine* ores) or crushed to expose more surface area to the leaching solution. Ores containing fine soil or rock particles are often agglomerated with cement (*agglomerated* ores) to allow adequate solution flow (Burkhalter et al., 1999).

After crushing and possible agglomeration, ores are piled onto heap leach pads (Fig. 1) using haul trucks, front-end loaders, or mechanical conveyors. Successive ore layers are called *lifts* (Bartlett, 1992), each ranging in height from 7 to 16 m (Burkhalter et al., 1999). Some heaps, known as *expanding pads*, are gradually expanded both vertically and horizontally as more ore is added. In other heaps, known as *valley pads*, ore is piled up against an embankment in a valley. Pads examined in this study cover a surface area up to 32 ha and may be as high as 50 m. Heaps larger than this exist, but most have not yet reached the closure stage. Typically, heaps are lined on the bottom with 30 to 46 cm of low-permeability compacted clay and a 1- to 2-mm thickness (40–80 mil) high-density polyethylene (HDPE) liner, which is sloped to allow gravity drainage along the bottom and prevent loss of solution to the underlying vadose zone. Usually, a layer of coarse ore or gravel is placed above the liner to facilitate drainage, and perforated pipes above the liner serve to carry out effluent draining from the heap.

Once the ore has been placed in a heap, cyanide solution is sprinkled or dripped on top at rates generally between 2.5 and 5.0 × 10^{-3} L s^{-1} m^{-2}. Applied solution pHs are adjusted to well above neutral to prevent the production of HCN gas. Cyanide solutions will complex with and solubilize gold, which drains out the bottom of the heap as part of a “pregnant” solution (Bartlett, 1992). This solution drains into a pregnant pond and then to a recovery plant where the gold is extracted. Metals may be recovered through adsorption on hardshell activated carbon or through zinc precipitation using the Merrill Crowe process (Bartlett, 1992). Spent solution then moves to a “barren” pond and is recirculated back to the top of the heap.

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Abbreviations: gpd, gallons per day; NDEP, Nevada Division of Environmental Protection; PET, potential evapotranspiration; PET/P, ratio of annual potential evapotranspiration to annual precipitation.

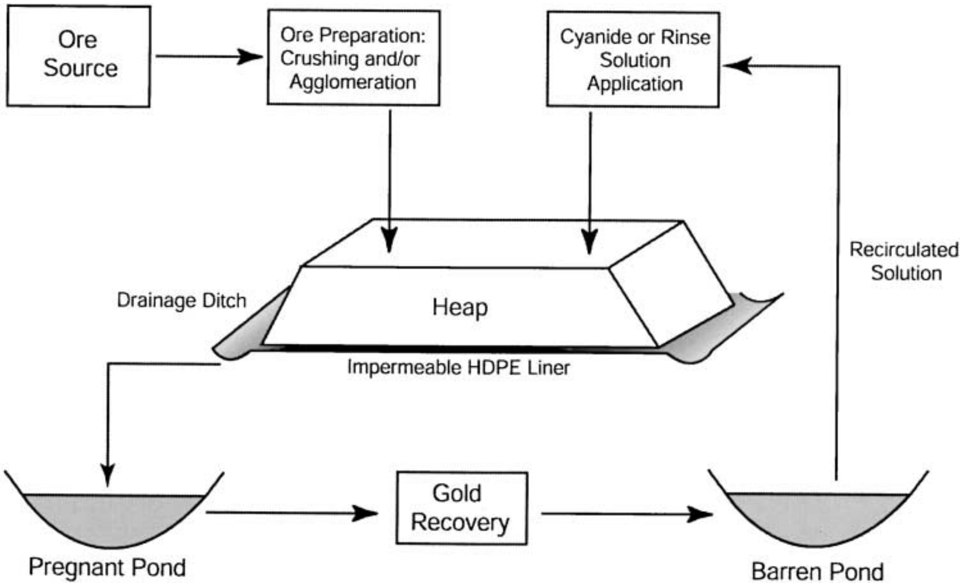

Fig. 1. Heap leach process diagram. Mined ore is crushed and/or agglomerated and placed onto an impermeable liner. During leaching, cyanide solution is applied to the top of the heap of ore with sprinklers or drippers. Solution passes through the heap and is collected in a drainage ditch at the bottom of the heap. This solution containing a gold–cyanide complex is piped to a "pregnant" pond, and gold is subsequently extracted from the pregnant solution. The remaining solution then flows into a barren pond and may be recycled back to the top of the heap for additional rinsing.

Heap leaching is terminated when the cost of operating the facility exceeds the value of the gold produced. In Nevada, regulations require final effluent concentrations to be below 0.2 mg L^{-1} weak acid dissociated cyanide (WAD) and to have pH less than 9. These levels are typically obtained by rinsing the heaps, initially with barren solution from which gold has already been extracted, and later with fresh water and/or detoxifying agents (Burkhalter et al., 1999). Usually, several pore volumes of solution must be replaced in the heap before cyanide reaches acceptable levels (Burkhalter et al., 1999), though at this point in the process heap effluent is often elevated in arsenic, sulfate, nitrate (from blasting agents and cyanide degradation), chloride, and other toxic solutes. Cyanide concentrations may also rise some time after acceptable values have been reached during the rinsing process due to the gradual diffusion of cyanide out of immobile regions of the heap (Decker and Tyler, 1999).

At the end of the rinsing process, heap leach facilities enter a final closure phase. Because of challenges in detoxifying heap effluent, it is important that long-term natural infiltration (recharge) through the heaps be limited, so heaps are generally covered with topsoil and vegetation that acts to limit infiltration of water through the heap. Regulations for heap leach closure in Nevada require that side slopes be stable, so pads will typically be recontoured such that the sides have a slope ratio of three horizontal to one vertical. Heaps will then be covered with a layer of soil and seeded with a mixture of native species (Ross, 1999) that facilitate appropriate reintegration of the heap with the surrounding environment. Unless an impermeable cover is placed over the top of the heap, all heaps will continue to produce effluent resulting from infiltration of precipitation.

Closed or abandoned heaps represent unique opportunities to characterize drainage rates due to precipitation forcing, as these heaps are essentially enormous lysimeters collecting deep infiltration and directing it to a measurable discharge point. They therefore provide direct, integrated measurement of what would normally constitute groundwater recharge. Swanson et al. (1998) and Swanson (2000) predicted deep infiltration through mining waste rock facilities in arid regions and showed that long-term infiltration is strongly a function of the presence of an engineered cover and, to a lesser degree, annual precipitation. Waste rock facilities are similar in geometry to heap leach piles; however the particle-size distribution and structure may not be similar. For uncovered waste rock facilities, deep infiltration ranged from 14% of annual precipitation (125 mm yr^{-1} precipitation) to 50% (500 mm yr^{-1} precipitation), whereas covered piles were predicted to have between 0.2 and 12% of the annual precipitation converted to deep infiltration. Land disturbance has also been shown to increase deep infiltration and recharge, and studies on mining materials may provide insights into the magnitude of this increase. Land disturbance has been shown to increase groundwater recharge in arid climates. In a study of recharge potential at three desert sites, Gee et al. (1994) showed significant recharge occurring in disturbed lands in spite of extreme aridity. Another study by Gee et al. (1992) summarized recharge rates through disturbed and bare soil lysimeters in the semiarid regions of eastern Washington. Under conditions of coarse soils or gravel at the land surface, recharge rates as high as 59% of the annual precipitation were reported in spite of the low rates of precipitation in the area (131–231 mm yr^{-1}). The presence of coarse gravels and lack of vegetation on the lysimeters allowed large percentages of annual precipitation to pass below the zone of active evaporation. Similarly, in spite of the arid or semiarid climate, the limited vegetation and coarse texture of the heap materials may allow significantly higher rates of recharge than would normally be predicted from climate data. Data from heap leach recharge may also be used to estimate recharge rates through the adjacent waste rock piles at most mine sites. Waste rock piles are generally unlined and may contain reactive rock capable of releasing metals, oxyanions, and nitrate to the recharging water and may ultimately pose a threat to groundwater quality.

The fluid flow through the surface and through the highly heterogeneous ore is extremely complex. In a numerical study on heap leach hydraulics, Orr (2002) has shown that ore conveyance, stacking, sorting, and agglomeration will have tremendous impacts on the fluid pathways through heap materials. Orr (2002) and Orr and Vesselinov (2002) clearly showed that during leaching, macropore flow, finger flow, and the presence of preferential flow paths dominate the transport process through the heap material. Orr and Vesselinov (2002) showed numerically that fluid pathways and the magnitude of preferential flow is a function of water application rate during heap leaching and the distribution of saturated conductivity within the heap. Orr and Vesselinov (2002) simulated infiltration rates representing active leaching. These rates are much higher than natural precipitation (except perhaps during intense precipitation); however, preferential flow mechanisms are likely to occur at all infiltration rates. In a study of transport through copper-bearing waste rock, Eriksson and Destouni (1997) conducted probabilistic reactive transport simulations to investigate the importance of both flow heterogeneity and reactive chemistry on long-term drainage water quality. They also concluded that flow heterogeneity, in the form of preferential pathways through the waste rock, is the dominant processes governing the time-dependent drainage water quality.

Because we have only measurements of input (precipitation) and integrated output (drainage from the bottom of the heap), we are forced to have limited concern for the internal fluid flow behavior. Although laboratory column testing is routinely performed on ores to be leached, the heterogeneities present at the field scale cannot be duplicated at the laboratory scale. In addition, these laboratory data are generally not public information. We must therefore treat the heap as a filter and attempt to assess how its response indicates the nature of filtering and fluid flow within the heap. It is probable that the fluid flow will be dominated by preferential pathways (due to ore placement by dumping) and may not even follow commonly held laws of fluid flow (e.g., Darcy's Law, Richards equation) because of the large fragments and voids formed during construction. Furthermore, infiltration processes at the surface may be highly variable due to localized compaction and the presence of large void spaces at or near the surface. Geochemical reactions, in particular the slow dissolution of carbonates formed during leaching, may also alter the hydraulic properties of the heap material. These and other processes are important factors influencing recharge and transport in heap material. Unfortunately, the field data reported are not sufficient to quantify these processes.

The heap leach method is relatively new in precious metal mining, and to date, only numerical modeling predictions of cover performance have been used to estimate the long-term rates of infiltration and effluent production (Swanson et al., 1998). This study represents a simplified vadose zone approach to determine effluent production rates after closure or abandonment using field data. At this stage, such data are neither readily available nor entirely reliable. Nevertheless, an understanding of drainage from heaps is fundamental in determining how the heap leach process may be affecting the quality of the environment and in defining closure design parameters. Such data, combined with predicted effluent water quality, can be used to begin to assess the long-term environmental impact of the effluent. The geographic scope of the study is limited to the semiarid state of Nevada because of the prominence of heap leaching in the state and the availability of records from heap leach facilities. The overall objective is to achieve a basic understanding of the long-term drainage processes associated with heap leach mining by reporting information on drainage amounts and the factors that influence drainage quantity in the state of Nevada. Although limited in scope, this information gives insight on the variables that influence drainage rates from heap leach pads and provides a basis for determining the amount of contaminants draining from these heaps as well as suggestions for improvements in monitoring practices.

MATERIALS AND METHODS

This study utilizes data on heap drainage rates after the end of the rinsing process, hereafter referred to as *draindown*. Draindown represents the quantity of fluid remaining in the heap following rinsing in addition to infiltration from precipitation. Since rinsing rates greatly exceed precipitation rates, draindown through the coarse-textured heap material rapidly declines following the cessation of rinsing. Data were obtained from the Bureau of Mining at the Nevada Division of Environmental Protection (NDEP), which maintains files on heap leach facilities in the state. These files include closure plans, reports from mining companies and consulting firms, and observations by state employees. Although mining companies are required to submit to the NDEP a closure plan that provides data on rinsing, stability analysis, cover design, and revegetation (Burkhalter et al., 1999), data on draindown are not required. Therefore, only limited draindown data of mixed quality were available for this study. Although mines often maintain more comprehensive records of draindown, this study is limited primarily to information on file at the NDEP.

Files for a total of 37 mines in or nearing closure were reviewed, but for most mines, no draindown data were available. Many of these mines are in bankruptcy, making further data investigations difficult. At other mines, only a few measurements had been recorded. Most of the mines highlighted in this paper are those for which comprehensive closure plans and reports had been filed. Numeric values of draindown at various times were available for several facilities, but for most of the mines used in this study, closure plans included only graphs of draindown over time. In order to obtain the most accurate estimation of this graphical data, the graphs were scanned, and draindown vs. time values were digitized. Addi-

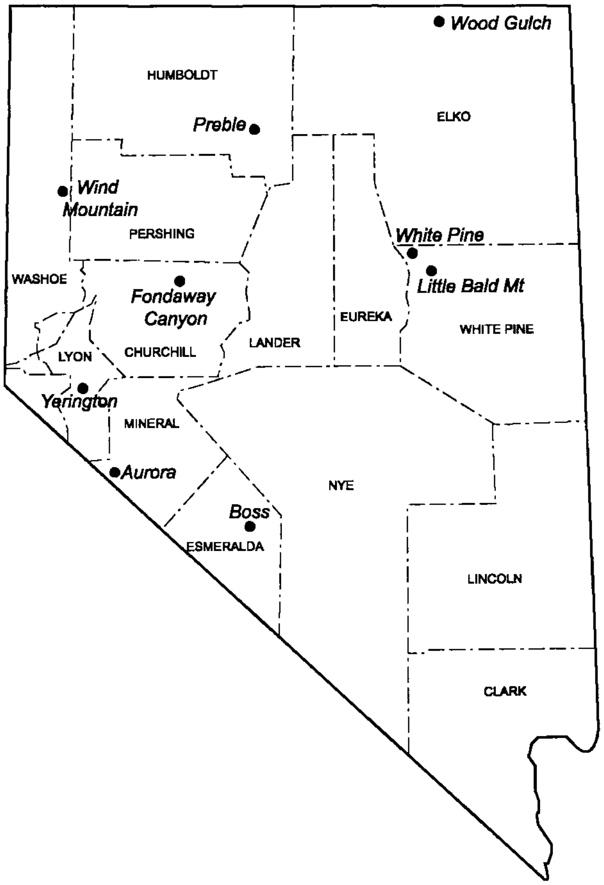

Fig. 2. Locations of Nevada mine sites examined in this study. Black dots mark mine sites, and dashed lines indicate county boundaries.

tional electronic draindown data for the Little Bald Mountain heaps were provided by Placer Dome and by Wind Mountain Mining, Inc. for the Wind Mountain heaps.

RESULTS

The mines examined in this study are located throughout the state of Nevada (Fig. 2). The type and quantity of data obtained as well as the frequency of data collection is quite variable for the heaps examined (Table 1), and the accuracy of the data is limited by several factors. In most cases, a continuous record of heap draindown is not available, giving an incomplete record of drainage rates over time. For many sites the precise date when rinsing terminated could not be found, so analyses rely on an estimated time of last rinsing. Draindown data for some mines represents the sum of drainage rates for more than one heap, thus giving an inaccurate representation of the drainage characteristics of individual heaps. Given these complications, complete data sets are not available for most of the chosen mine sites. Nevertheless, data used in this analysis represent the most complete set currently available and suggest important trends in draindown over time.

Table 1. Quantity and type of available draindown data.

Mine	Quantity and type of data†
Boss	1 N; Oct. 1999
Yerington 1	2 N; Mar.–Apr. 2000
Yerington 2	1 N; Apr. 2000
Yerington FX	1 N; Mar. 2000
Fondaway Canyon	8 N; May 1998 to May 2000
Wind Mountain 1	115 G,E; Jan. 1998 to Jan. 2001
Wind Mountain 2	115 G,E; Jan. 1998 to Jan. 2001
Preble W	66 G; Jan. 1998 to July 1999‡
Preble E	
Little Bald Mountain 1	6 E; 1st quarter, 1999 to 3rd quarter 2000‡
Little Bald Mountain 2	
Aurora	9 N, 11 G; Aug. 1999 to June 2000
White Pine	8 N; 34 G; July 1997 to May 2000
Wood Gulch	21 N; Apr. 1993 to Oct. 1998

† G = data digitized and extracted from paper graphs, N = data found in tables of numeric values, E = data obtained in electronic form. Numbers represent the quantity of draindown values recorded for each data type.

‡ Drainage data is composite of both pads.

Heap Characteristics

All of the mines examined are gold mines except Yerington, which is a copper mine, and each has different construction characteristics (Table 2). Most of the heaps examined contain sedimentary-hosted ores found in limestones, siltstones, or calcareous shales. Several heaps contain igneous or volcanic-hosted ores. Most ores had been crushed to approximately 1 to 8 cm in diameter, and many were agglomerated. At White Pine and Wind Mountain, some run-of-mine ore had been placed directly on the heaps. The sizes of the heaps examined are widely variable, with bottom surface areas ranging from 2.6 to 31.5 ha and heights ranging from 7 to 39 m.

Each of these heaps was in a different state of closure during the time of this study (Table 2). All information on vegetation cover came from photos and verbal or written reports. This information on closure status was incomplete and not always current. Most heaps for which information was available had been covered with clay, alluvium, and/or topsoil. Some of these heaps reportedly have a well-established vegetation cover, whereas others apparently have little to no vegetation. According to reports collected during the fall of 2000, Preble and Wood Gulch heaps have the most well-established vegetation; Aurora, Little Bald Mountain, and White Pine heaps have moderate vegetation coverage; and Fondaway Canyon has a poor cover of vegetation.

Climate characteristics at the heap sites are also somewhat variable, with average annual precipitation at the mines ranging from 127 to 810 mm, and average annual potential evapotranspiration (PET) from 720 to 1987 mm (Table 2). Much of this variability is related to the site elevations, with higher elevation sites such as Wood Gulch tending to have higher precipitation and lower PET.

Draindown Behavior

The time of last rinsing at the heaps ranged from 1992 to 1999, and the available draindown data sets ranged in duration from 3 mo to 7 yr. The widely varying characteristics of these heaps prohibit any comprehensive analysis of their relative drainage rates, but several attempts have been made to normalize the data and facilitate comparison of draindown characteristics. In order to

Table 2. General heap characteristics.

Mine	Elevation	Precipitation	PET	Ore type	Surface area	Average height	Date of last rinsing†	Closure status
	m	mm yr^{-1}	mm yr^{-1}		ha	m		
Boss	–	127	1473	crushed to 7.6 cm	4.6	9	3rd quarter 1996 *Aug. 1996*	Not available
Yerington 1	1210	140	1295	igneous	6.0	37	Nov. 1997	Bankrupt; no cover
Yerington 2	1265	140	1986		21.1	37	Nov. 1997	
Yerington FX	1265	140	1986		20.0	37	Dec. 1999	
Fondaway Canyon	1265	140	1986	crushed to 1.9 cm and agglomerated	2.8	4.5	Fall 1998 Oct. 1998	Covered with 30 cm compacted silt and clay + 30 cm topsoil. Seeded fall 1998. Vegetation cover reported to be poor in fall 2000.
Wind Mountain 1	1372	152	1512	30% crushed to 1.9 cm; 70% run-of-mine	31.5	37	June 1997	Covered Dec. 1999 with 15 cm topsoil over 30% of Pad 1 and 80% of Pad 2. Seeded winter 1999–2000.
Wind Mountain 2	1372	152	1512		26.3	37		
Preble W	1450	191	1656	Sedimentary; crushed to 3.8 and agglomerated	6.0	12	Aug. 1997	Well covered with vegetation in May 2000.
Preble E					6.4	12		
Little Bald Mountain 1	2302	343	937	sedimentary; crushed to 1.9 cm and agglomerated	1.7	7	1st quarter 1998 *Feb. 1998*	Covered 30 Aug. 1998 with 1 m topsoil. 42% vegetation cover estimated in fall 2000.
Little Bald Mountain 2					0.8	6		
Aurora	2210	356	1044	igneous; crushed to 0.6–0.8 cm and agglomerated	11.2	33.5	Oct. 1999	10–30% vegetation cover in Aug. 2000.
White Pine	1936	395	1083‡	sedimentary; crushed to 3.2 cm with some run-of-mine	8.9	14	Fall 1995 *Oct. 1995*	Covered Nov. 1997 with 30 cm alluvium + 15 cm topsoil. 23–30% vegetation cover in Aug. 1998.
Wood Gulch	2186	810	720	sedimentary; agglomerated	3.6	–	3rd quarter 1992 *Aug. 1992*	Seeded by end of 1992. Well vegetated by 1998.

† Dates in italics represent estimated date of last rinsing.

‡ Value generated by evapotranspiration model of Shevenell (1996); all other PET data obtained from mining permit files.

reduce variability in drainage caused by heap size, data are normalized by dividing the drainage rates at each heap by the total pad surface area. Draindown data from Little Bald Mountain and Preble heaps represent the composite of two pads at each site, so the total surface area is assumed to be the sum of the pad surface areas. The date of last rinsing at all heaps is set to zero time to allow comparison of all the draindown curves as a function of time since last rinsing.

After these normalizations, the draindown data show that during rinsing, drainage rates at heaps could be in excess of 2000 mm yr^{-1}. Just after rinsing stopped, drainage rates decayed rapidly over periods of days to weeks. This rapid decline in drainage rates is characteristic of gravity-dominated flow through the most conductive pathways in the ore. Rates then decreased more gradually for the next several months to several years. To give a better indication of fluctuations at individual heaps, normalized draindown curves from heaps with relatively low discharge are plotted (Fig. 3). After a year or less, most of these heaps had normalized draindown values averaging <10 mm yr^{-1}. The draindown data for Aurora show an expected exponential decline in drainage, representing slow drainage of rinse water. After approximately 7 mo, draindown appeared to stabilize, with fluctuations in the range of 20 to 70 mm yr^{-1}. The record is too short, however, to determine if draindown will continue to decline or if the pad has reached equilibrium with precipitation-derived moisture input. Draindown values at Fondaway Canyon remained consistently low at <30 mm yr^{-1} throughout the period of measurement, indicating that drainage is in equilibrium with infiltration. Drainage at the Preble heaps was more variable, with several large drainage spikes indicating probable response to climate forcing followed by an exponential decline after each of these events. These large drainage spikes occurred more frequently during the first year, and subsequently, drainage rates remained relatively stable at <40 mm yr^{-1}. At Little Bald Mountain, drainage rates were nearly 100 mm yr^{-1} during the first months of the second year after rinsing, but rates subsequently dropped and remained consistently low at <20 mm yr^{-1}.

At heaps with higher overall drainage rates, normalized draindown after 1 yr tended to be in the range of 50 to 100 mm yr^{-1} (Fig. 4). The draindown record at White Pine has one low outlying value at approximately 11 mo since the last rinse, but the complete record began 20 mo since rinsing when the heap was covered and revegetated. At this time, draindown decreased exponentially from >300 to <30 mm yr^{-1}. During the first year after coverage, drainage fluctuated somewhat, re-

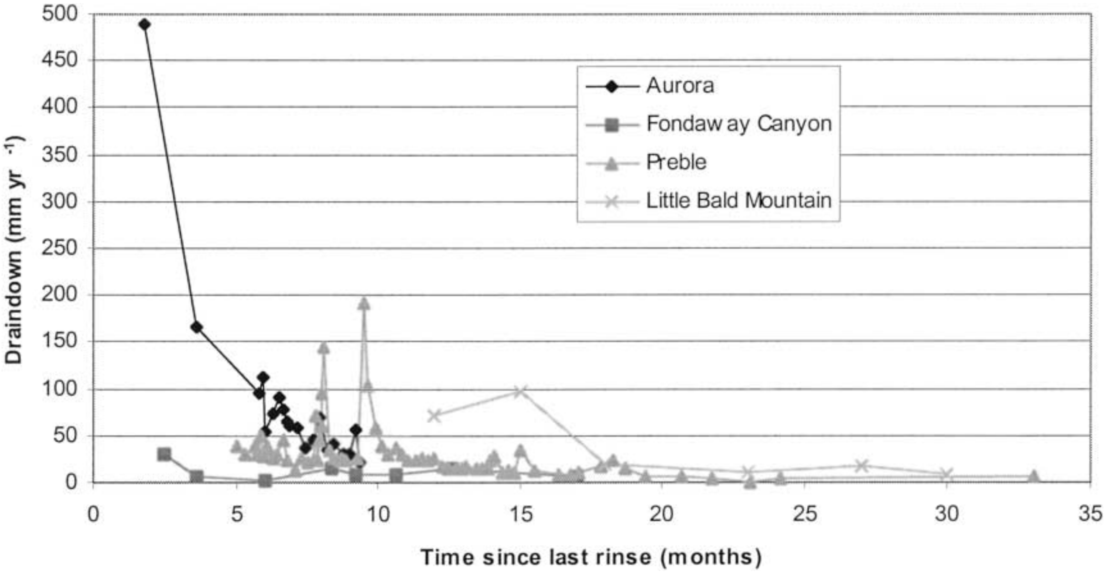

Fig. 3. Draindown as a function of time since the last rinse for low drainage heaps. Curves are somewhat variable, but generally, heap draindown decreases rapidly just after rinsing stops and drops to <1 m^3 ha^{-1} d^{-1} within a year after the last rinsing. Small spikes in draindown are apparent, particularly in the Preble curve, indicating probable response to climate forcing.

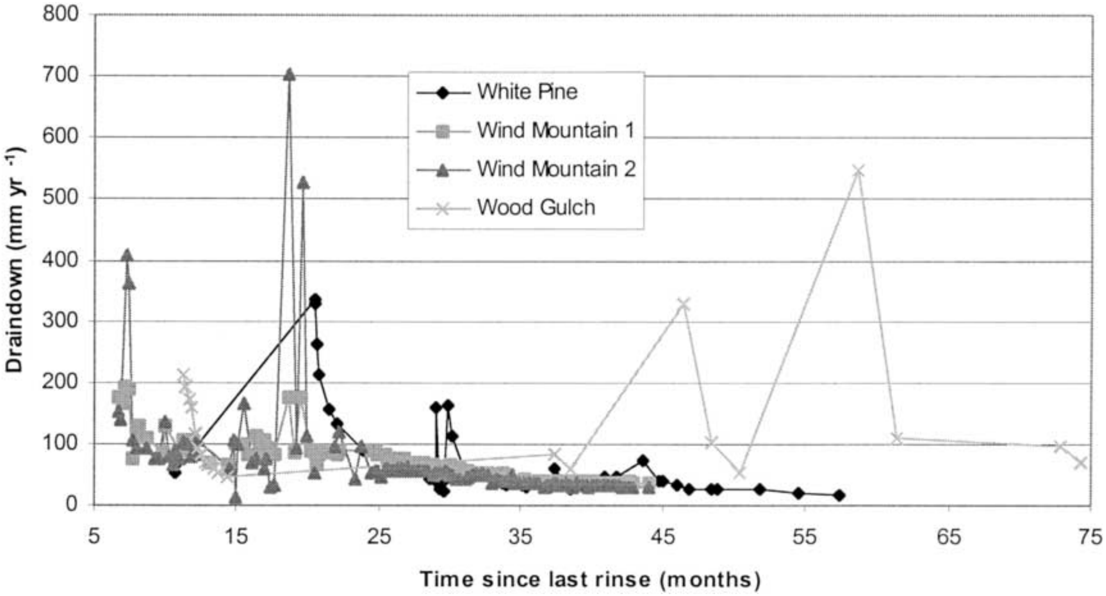

Fig. 4. Draindown as a function of time since the last rinse for higher drainage heaps. Curves are variable, but generally the sharpest decrease in draindown occurs soon after the last rinsing followed by a gradual decrease to steady-state drainage rates between 0 and 2 m^3 ha^{-1} d^{-1}. Spikes in curves indicate probable response to climate forcing, particularly in the Wood Gulch curve, which shows spikes in drainage more than 5 yr after the last rinsing. Note that the gradual increases in draindown suggested by parts of the White Pine and Wood Gulch curves represent discontinuities in the data set and should not be considered representative of overall drainage patterns during those time periods.

flecting probable response to climate forcing, but draindown then remained relatively stable at <30 mm yr^{-1}. Although a case could be made for a continued exponential decline strictly from drainage of rinse water at White Pine, the high frequency fluctuations do indicate that precipitation-derived drainage is being produced.

The two Wind Mountain heaps show significant and parallel response to climate forcing during the first 2 yr after the last rinsing, but peak drainage rates differed dramatically for the two heaps. The highest draindown on Heap 2 (only half covered with vegetation) reached >700 mm yr^{-1}, whereas draindown from Heap 1 (almost fully covered with vegetation) never reached as much as 200 mm yr^{-1}. Reports suggest that some of the large spikes in drainage at Wind Mountain reflect precipitation falling directly on open pad liners or drainage ditches adjacent to the leach pads. Rapid thawing of snow and ice in the ditches may also have contributed to drainage, rather than moisture infiltrating through the entire heap (Roach, 2001, personal communication). After the first 2 yr, however, draindown at both heaps steadily decreased to <40 mm yr^{-1}, and neither heap has since shown spikes in drainage.

Draindown at Wood Gulch decreased rapidly 1 yr after rinsing from >200 to <50 mm yr^{-1}, but during subsequent years draindown continued to fluctuate from <50 to >500 mm yr^{-1}. The Wood Gulch curve has fewer data points after the initial period of rapid draindown, so apparent gradual increases and decreases in drainage 36 and 50 mo since the last rinsing probably reflect discontinuities in the data. The drainage peaks probably reflect rapid responses to climate forcing, and baseline draindown most likely remained in the range of 50 to 100 mm yr^{-1} for most of the period of record.

Estimating Recharge from Heap Draindown Measurements

Few direct measurements of natural recharge in arid regions are available, but numerous studies have been conducted to estimate recharge via surrogate measurements. Maxey and Eakin (1949) and Eakin et al. (1951) developed an elevation–recharge relationship for the Great Basin that is still widely used to estimate basin-scale recharge in Nevada. This method, based on basin-scale groundwater discharge measurements, assumes no recharge will occur when annual average precipitation is <200 mm. Recharge is estimated to be 3% of the annual precipitation when precipitation ranges between 200 and 300 mm, 7% when precipitation is between 300 and 380 mm, 15% between 380 and 510 mm, and 25% for annual precipitation >510 mm. While this method is quite simplistic, few other methods have been developed.

Heap draindown data can be used to estimate recharge by dividing the draindown into two phases. During the first phase, effluent remaining in the heap from the rinsing process drains out. Although this phase is important in fluid management, the data used in this study are not sufficient to allow a thorough analysis of this draindown process. The second phase of heap draindown constitutes long-term drainage in which heap drainage responds only to natural precipitation. The drainage rate in this phase should be equivalent to the recharge predicted by the Maxey–Eakin model. However, recharge is difficult to estimate using the data in this study, as drainage rates at most heaps could be construed to continue to decrease throughout the period of measurement. As a closest approximation to the long-term drainage rate, the last available drainage measurement was used to estimate recharge at Fondaway Canyon, Wind Mountain, Aurora, and White Pine heaps (Table 3). Since the rate of decline in drainage rates is relatively small at all of these heaps, the calculated percentage recharge is likely to be a close but slightly overestimated approximation of long-term recharge rates. The only available drainage measurements are used to estimate long-term recharge at the Boss and Yerington heaps. For all other heaps, the long-term drainage rate is estimated using an average of all values subsequent to the point on the draindown curve when drainage rates show nearly constant values. The average drainage after 15 mo since rinsing is used at Wood Gulch; the average after 18 mo is used at Little Bald Mountain, and the average after 20 mo is used for the Preble heaps. Recharge rates at all sites were expressed as a percentage of site annual precipitation.

It is obvious that there is some subjectivity in assigning the time in which precipitation-derived input dominates the drainage (see Fig. 3 and 4). However, it is important to recognize that the heap structures are all engineered to *drain rapidly* so that cyanide solution can be quickly injected and recovered. The draindown data in some cases represents more than 6 yr of time since water was artificially applied to the heaps. Release of rinse water from the heap could be construed to continue to decay exponentially for an infinite time; however, unless the heap is covered with an impermeable cap (none of those examined in this work are), there must exist a component of drainage from precipitation infiltrating through the tops and sideslopes of the heap. Some of the heaps clearly show precipitation-derived drainage spikes (Wood Gulch, Wind Mountain, and Preble), but for most of the remainder of the sites with available data, Fig. 3 and 4 indicate a visible but perhaps not statistically significant stabilization of drainage rates. As will be seen below, the estimation of precipitation-derived infiltration from the data for each of these sites is consistent in magnitude with that predicted by simple recharge models. While it might be fortuitous that the drainage of rinsing water would be similar in magnitude to the

Table 3. Estimated recharge through heaps.

Mine	Time since last rinsing	Time to reach steady-state drainage	Estimated steady-state drainage rate†	Expected recharge‡	Calculated recharge	Calculated recharge including 10 mm yr^{-1} leakage
	months		mm yr^{-1}	%		
Boss	**36**	**Insufficient data**	**9**	**0**	**7**	**15**
Fondaway Canyon	**30**	**>30**	**6**	**0**	**5**	**14**
Yerington 1	**30**	**Insufficient data**	**25**	**0**	**18**	**25**
Yerington 2	**5**	**Insufficient data**	**15**	**0**	**11**	**18**
Wind Mountain 1	**44**	**>44**	**36**	**0**	**23**	**30**
Wind Mountain 2	**44**	**>44**	**30**	**0**	**20**	**26**
Preble	**33**	**20**	**4§**	**0**	**2**	**7**
Little Bald Mountain	**30**	**18**	**15§**	**7**	**4**	**7**
Aurora	**9**	**>9**	**21**	**7**	**6**	**9**
White Pine	**57**	**>57**	**18**	**15**	**5**	**7**
Wood Gulch	**74**	**15**	**160**	**25**	**20**	**21**

† Value represents best approximation of steady-state drainage. For heaps with insufficient data, the only drainage value available is used. For heaps where drainage rates were still declining, the last drainage value was used. For heaps that no longer showed a net decrease in drainage, the average of all drainage rates subsequent to achieving steady state conditions was used.

‡ Based on models of Maxey and Eaking (1949) and Eakin *et al.* (1951).

§ Composite draindown from two pads.

predicted recharge at one site, for it to occur at all sites suggests that the majority of drainage occurring 1 to 2 yr after rinsing is originating from precipitation at the surface. Recall, however, that the low flow drainage measurements were not made continuously and probably are of poor accuracy, having been made at best with a calibrated bucket and a stopwatch using an unknown number of replicates.

Overall, the approximated long-term recharge rates range from <1 to nearly 25% of average annual precipitation. Table 3 compares these calculated recharge rates with values predicted by the Maxey–Eakin model. At the low precipitation sites (<200 mm yr^{-1}), this model predicts that no recharge should occur, yet all heaps continue to drain at these sites. Probably the best estimate of long-term recharge at these low precipitation sites is that calculated for the Preble heaps, where drainage rates had apparently reached equilibrium with climate. These heaps have the lowest estimated recharge at 2% of annual precipitation, somewhat but not significantly higher than the Maxey–Eakin model prediction. Estimates for Boss and Fondaway Canyon indicate that these sites recharge approximately 4 to 7% of annual precipitation. The heaps at Yerington and Wind Mountain drain 10 to 25% of annual precipitation, although again the model predicts they should not drain at all. The factors causing these high percentages may include thin and incomplete cover, coarse heap material, or, in the case of Wind Mountain, precipitation falling directly on the pad liners or drainage ditches adjacent to the leach pads. These factors will be discussed in more detail in the following section.

At the higher elevation and higher precipitation mine sites (White Pine, Aurora, Wood Gulch, and Little Bald Mountain), recharge rates estimated from draindown data are actually lower than predicted rates. At Aurora and Little Bald Mountain, estimated recharge rates are 4 to 6%, less than the predicted 7%. The estimated recharge at White Pine is only 5%, much less than the predicted 15%, and the 22% recharge estimated for Wood Gulch is somewhat lower than the predicted 25%. Recharge at these high elevation sites may be more consistent with model predictions due to a variety of factors, including greater ease in establishing vegetation on the heap surface and different climatic characteristics.

We emphasize that the recharge percentages listed in Table 3 represent merely best estimates based on limited data and should not be considered absolute values. These recharge estimates also assume no leakage of water through the liners before the fluid discharges from the heap. In a study of liner leakage rates, Giroud and Bonparte (1989) showed that liners can leak at rates of 3 to 13 mm yr^{-1}, depending on their construction characteristics. Therefore, an additional recharge estimate assuming 10 mm yr^{-1} of liner leakage is included in Table 3, independent of ore type. It can be suggested that run-of-mine ores, with larger size fractions, may have more potential for liner puncture and leakage during operation, although data are not available. Most heaps examined in this study do have leak detection systems, but no estimates of leakage were obtained for any of the sites examined.

Factors Influencing Long-Term Drainage

The factors controlling long-term drainage rates from heaps should be identical to those factors controlling groundwater recharge in arid climates, that is, precipitation, potential evapotranspiration (PET), soil texture, and vegetation (Gee and Hillel, 1988). Isolating these variables is difficult, though, due both to previously discussed difficulties in estimating long-term drainage rates and to the large variability in heap characteristics. An initial attempt is made to separate these factors in the subsequent analysis, but the results obtained should be considered as a guide for future work rather than absolute conclusions, given the limitations of the available data.

Both precipitation and evapotranspiration should affect the long-term drainage from heaps, so the ratio of PET to annual precipitation (PET/P) is compared with long-term percentage recharge (Fig. 5). In theory, a small PET/P indicates greater potential for water to infiltrate past the root zone before evaporating, so small PET/P ratios should correlate with high percentage recharge. However, based on the data in this study, no such relationship appears to exist. Also, to emphasize the limited data quality in this analysis, bubble size in this and subsequent figures is inversely proportional to the number of data points used to calculate the long-term recharge percentage. The high frequency of large bubbles is therefore indicative of a large margin of error in recharge estimates.

Qualitative observations of draindown characteristics for the heaps examined suggest that heap size and shape may also affect drainage. As heap height increases, the proportional area of side slopes to upper surface increases, which may impact drainage rates due to the relative rates of water infiltration on the flat tops and

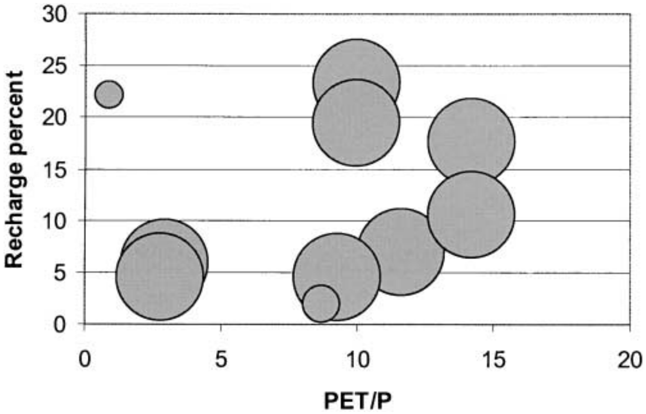

Fig. 5. Estimated recharge percentage as a function of available moisture. Recharge percentage represents the best estimate of long-term steady-state drainage as a percentage of annual precipitation. PET/P values represent estimated annual potential evapotranspiration divided by average annual precipitation. Bubble size is 1/*N*, with *N* being the number of data points used to calculate recharge percentage. Large bubbles represent fewer data points. No definitive relationship between recharge and available moisture is apparent, perhaps due to variations in vegetation cover.

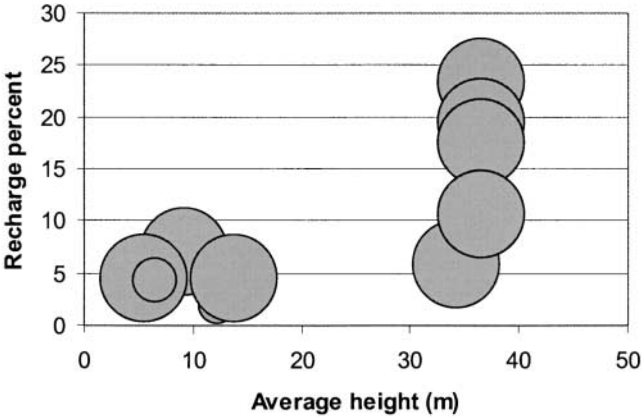

Fig. 6. Estimated recharge percentage as a function of average heap height. Recharge percentage represents the best estimate of long-term steady-state drainage as a percentage of annual precipitation. Bubble size is 1/*N*, with *N* being the number of data points used to calculate recharge percentage. Large bubbles represent fewer data points. The correlation is not definitive, but the data suggest that higher heaps may be more likely to have higher recharge rates.

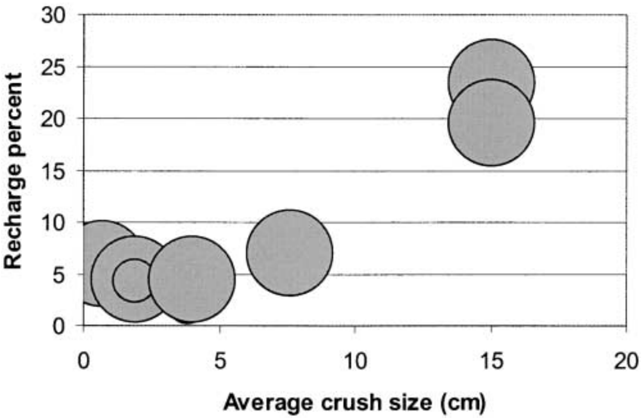

Fig. 7. Estimated recharge percentage as a function of ore texture. Recharge percentage represents the best estimate of long-term steady-state drainage as a percentage of annual precipitation. Crush size represents the estimated average particle size in the heaps. For heaps containing run-of-mine ore, this size was assumed to be 15 cm. Bubble size is 1/*N*, with *N* being the number of data points used to calculate recharge percentage. Large bubbles represent fewer data points. The plot suggests that heaps with coarser material allow greater moisture flow and a higher percentage recharge.

side slopes. Rain can pond and more readily evaporate from the flat tops of heaps, which tend to have been compacted by vehicular traffic and may be more exposed to solar radiation than the steep side slopes (except in cases where the slopes have a southern exposure). In contrast, side slopes tend to be more coarse textured, and it may be more difficult to establish vegetative covers on these areas than on the flat tops. Water is therefore more likely to infiltrate beyond the region of active evaporation through the side slope areas. Previous work on landfill covers by Fayer et al. (1999) would support that side slopes may be more efficient recharge areas than the top surfaces of the heaps. To examine these effects, the long-term recharge percentage is plotted against average heap height (Fig. 6). Again, no definitive relationship is apparent from this data, though it could be inferred that higher heaps are more likely to have a high percentage recharge than are shorter heaps.

The texture of heap material is certainly likely to influence drainage rates for moisture infiltrating past the heap cover. Coarse material can quickly remove water from the zone of evapotranspiration and can also provide preferential flow paths and/or unstable flow behavior, causing rapid fluid transmission. Recharge percentage is therefore plotted against average ore crush size (Fig. 7). For heaps containing run-of-mine ore, the average crush size is assumed to be 15 cm. Figure 7 does suggest an important relationship between heap texture and percentage recharge. As expected, more recharge occurs through coarser heap material than through finer-textured material due to the lower water holding capacity and the higher potential for preferential flow paths in the coarse ore. If the texture of heap material does exert a strong influence on long-term drainage rates, as this plot suggests, then moisture must have infiltrated past the heap covers, indicating that covers have not been entirely successful in impeding the flow of water through heaps. However, the limited data on soil and vegetation cover at the heaps prevents any quantitative analysis of the effectiveness of covers. Good soil and vegetation covers do effectively decrease draindown to some extent, even if they cannot entirely prevent moisture from infiltrating through the heaps. For example, the installment of a soil and vegetation cover at the White Pine heap resulted in a sharp decrease in draindown, while all the heaps that have reached steady-state drainage rates (Little Bald Mountain, Wood Gulch, and Preble) apparently have good soil and vegetation covers. Furthermore, with the exception of Preble, all of the heaps with good covers recharge less moisture than predicted by the Maxey–Eakin model, indicating that the covers are quite effective in mimicking natural conditions.

Overall, these analyses do not provide definitive conclusions as to how climatic and design characteristics influence drainage rates, but the results are nevertheless consistent with previous studies of recharge in natural settings. As more emphasis is placed on the long-term environmental impacts of heap leach facilities, lessons learned in natural recharge studies must be applied to these engineered vadose zones.

SUMMARY AND CONCLUSIONS

This analysis represents the first effort to characterize long-term heap leach drainage on a statewide basis. The data utilized provide information on the quantity of water that may be produced from closed heap leach piles. Such data are critical for the assessment of the long-term impacts of these sites on groundwater and will also help designers in developing long-term strategies for the disposal of these waters. However, significant uncertainties remain due to the limited data available.

Drainage apparently increases for heaps with coarse-textured material, such as run-of-mine ore, and for those with limited or nonexistent vegetation covers. Water infiltration and drainage may be greater where the ratio of potential evapotranspiration to precipitation is low and where a high proportion of slope surface area is exposed, but the relationship between these variables and draindown cannot be clearly defined based on the data in this study.

Management of heap effluent demands an understanding of both the time required for a heap to reach equilibrium with climate and of the long-term drainage that can be expected once steady-state conditions are reached. Three of the sites examined in this study appear to have reached steady-state drainage rates 15 to 20 mo after the last rinsing. All of these sites reportedly had good soil and vegetation covers. The remaining sites show some decline in drainage long after rinsing; however, without additional data collection including geochemical analysis of drainage water, it is difficult to deduce whether or not this represents continued draining of rinse water.

Because of this continued decline in drainage rates at many heaps, it is difficult to accurately determine long-term drainage rates at these sites. However, best estimates of long-term recharge suggest that in areas where annual precipitation is <200 mm, heaps with good vegetation cover will drain at a rate of 6 to 9 mm yr^{-1}, which constitutes a recharge rate of 4 to 7%. With coarser-textured heap material and/or inadequate cover design, however, drainage will increase substantially, such that nearly 25% of precipitation may drain out of the heaps. In areas with annual precipitation between 200 and 500 mm, heaps with good vegetation cover may drain at a rate of 14 to 21 mm yr^{-1}, which constitutes a recharge rate of 4 to 6%. These recharge rates are less than model predictions for natural recharge rates at those sites, indicating that with appropriate design and cover, it is possible to limit successfully the flow of water through coarse heap material.

Whether below or above expected recharge rates, the amount of effluent draining from these heaps constitutes a significant volume over time. As an example, for the most arid sites, assuming a recharge rate of 7%, annual precipitation of 200 mm, and a 10-ha heap, approximately 3.8 $\mathrm{m}^3\ \mathrm{d}^{-1}$ (1000 gallons per day [gpd]) can be expected to drain from the heap. A larger 30-ha heap would drain 12 $\mathrm{m}^3\ \mathrm{d}^{-1}$ (>3000 gpd). If recharge rates are higher at 25%, a 10-ha heap would drain 14 $\mathrm{m}^3\ \mathrm{d}^{-1}$ (>3600 gpd), and a 30-ha heap would drain 41 $\mathrm{m}^3\ \mathrm{d}^{-1}$ (>10 000 gpd). At higher elevation sites, assuming annual precipitation of 500 mm and a recharge rate of 15%, a 10-ha heap would drain 21 $\mathrm{m}^3\ \mathrm{d}^{-1}$ (5400 gpd), and a 30-ha heap would drain 66 $\mathrm{m}^3\ \mathrm{d}^{-1}$ (>17 000 gpd). This constitutes a volume of 24 000 m^3 per year, or more than 6 million gallons per year. These volumes are likely to be even higher for the much larger heaps that have not yet been closed.

High recharge rates and such substantial quantities of water could also cause problems in waste rock dumps at heap leach facilities. These dumps are similar in nature to the heaps, but may be unlined, which means that percolating can go directly to groundwater recharge. They therefore represent a possible source of groundwater pollution, as they can contain reactive rock. With improved data collection, long-term drainage rates from heap leach pads may be used to estimate recharge through these waste rock dumps and provide a basis for determining the quantity of contaminants that may be entering the groundwater at heap leach facilities. Drainage from heaps is affected by many factors, including the nature of the ore, operation procedures, climate, and fluid management. All of these factors lead to highly variable draindown characteristics, which are difficult to separate without a multi-varied analysis and a more comprehensive data set. At present, ongoing studies are directed at expanding the database of drainage values and verifying heap closure design and status in the field. However, the current state of data collection and reporting limits detailed analysis. It is recommended that the current spot measurement methods be replaced with continuous flow measurement systems to accurately record the total volume of drainage from a closed heap, and continuous fluid electrical conductivity–pH sensors. Such instrumentation is no longer costly and would provide a continuous record of drainage behavior and indicator parameters for changes in fluid chemistry. In addition, automated meteorological stations should be installed within close proximity of the mining sites to provide basic data for analysis of closure performance. An instrumented heap is also being constructed at an active heap so that invasive and noninvasive (surface geophysics) methods can be used to assess fluid flow. The present study, combined with increased interest in transport of fluids in highly heterogeneous unsaturated media, should lead to an improvement in the efficiency of mine closure and reclamation.

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REFERENCES

Bartlett, R.W. 1992. Solution mining: Leaching and fluid recovery of materials. Gordon & Breach Science Publishers, Taylor and Francis Group, London, UK.

Burkhalter, C.J., R.H. Allison, and B.F. Flint. 1999. Precious metals heap leach facilities: Design, closure and reclamation. p. 29–36. *In* D. Kosich and G. Miller (ed.) Closure, remediation and management of precious metals heap leach facilities. 14–15 Jan. 1999. Center for Environmental Sciences and Engineering Publication. Univ. of Nevada, Reno, NV.

Decker, D.L., and S.W. Tyler. 1999. Evaluation of flow and solute transport parameters for heap leach recovery materials. J. Environ. Qual. 28:543–555.

Eakin, T.E., G.B. Maxey, T.W. Robinson, J.C. Fredericks, and O.J. Loeltz. 1951. Contributions to the hydrology of eastern Nevada: Nevada State Engineer, Water Resources Bulletin 12. Nevada Div. of Water Resour., Carson City, NV.

Eriksson, N., and G. Destouni. 1997. Combined effects of dissolution kinetics, secondary mineral precipitation and preferential flow on copper leaching from mining waste rock. Water Resour. Res. 33:471–483.

Fayer, M.J., E.M. Murphy, J.L. Downs, F.O. Khan, C.W. Lindenmeier, and B.N. Bjornstad. 1999. Recharge data package for the immobilized low-activity waste 2001 performance assessment. p. A23–A25. *In* Contract Report DOE/PNNL-13033. U.S. Dept. of Energy, Richland, WA.

Gee, G.W., M.J. Fayer, M.L. Rockhold, and M.D. Campbell. 1992. Variations in recharge at the Hanford site. Northwest Sci. 66:237–250.

Gee, G.W., and D. Hillel, 1988. Groundwater recharge in arid regions: Review and critique of estimation methods. Hydrol. Processes 2:255–266.

Gee, G.W., P.J. Wierenga, B.J. Andraski, M.H. Young, M.J. Fayer, and M.L. Rockhold. 1994. Variations in water balance and recharge potential at three western desert sites. Soil Sci. Soc. Am. J. 58:63–72.

Giroud, J.P., and R. Bonparte. 1989. Leakage through liners constructed with geomembranes. Geotextiles Geomembranes 8:27–67.

Maxey, G.B., and T.E. Eakin. 1949. Ground water in White River Valley, White Pine, Nye and Lincoln Counties, Nevada. Nevada State Engineer Water Resources Bull. 8. Nevada Div. of Water Resour., Carson City, NV.

Orr, S. 2002. Enhanced heap leaching, I. Insights. Mining Engineering, Technical Papers, SME. (In press).

Orr, S., and V. Vesselinov. 2002. Enhanced heap leaching, II. Applications. Mining Engineering, Technical Papers, SME. (In press).

Ross, C. 1999. Mine revegetation in Nevada: The state of the art in the arid zone. p. 71–76. *In* D. Kosich and G. Miller (ed.) Closure, remediation and management of precious metals heap leach facilities. 14–15 Jan. 1999.

Shevenell, L.A. 1996. Statewide potential evapotranspiration maps for Nevada. Nevada Bureau of Mines and Geology, Report 48. University of Nevada, Mackay School of Mines, Reno, NV.

Swanson, D.A. 2000. Addressing policy and technology challenges for the environmental sustainability of waste rock facilities in dry climates. p. 1–10. *In* M. Sanchez et al. (ed.) Waste treatment and environmental impact in the mining industry. Proc. Int. Conf. on Clean Technologies for the Mining Industry, Fith. May 2000. University of Concepcion, Santiago, Chile.

Swanson, D.A., J.H. Kempton, C. Travers, and D.A. Atkins. 1998. Predicting long-term seepage for waste rock facilities in dry climates. Society for Mining, Metallurgy and Exploration, Inc. Annual Meeting. Orlando, FL. 9–11 Mar. 1998. SME, Littleton, CO.