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A Case Study of Rapid Water Flow through Full-Scale Waste-Rock Piles

by K.A. Morin

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who encouraged me to pursue this case study.

TABLE OF CONTENTS

Abstract

For decades, full-scale waste-rock piles have been recognized as complex minesite components in all three spatial dimensions and through time. While many waste-rock investigators recognize this complexity of coarser and finer material, many ignore its reality and oversimplify water movement in the coarser material. It appears the primary reasons for this are: (1) the lack of high-frequency monitoring data (hourly and more frequently) to characterize the rapid flow of water through full-scale waste rock, (2) detailed studies of smaller "test piles" and laboratory columns that are unavoidably unrepresentative of full-scale waste rock, and (3) the desire to model water flow through waste rock despite a lack of realistic equations to simulate turbulent, non-Darcian, non-capillary flow in coarse rock.

For full-scale waste-rock piles at minesites, the way to resolve the many current misconceptions is by (1) frequent (at least hourly) monitoring of full-scale waste-rock piles, and (2) abandoning the notions of laminar flow and capillarity in coarse waste rock. This MDAG Case Study contributes by reviewing one previous case study of rapid flow through a full-scale pile. Then the subsequent sections present a new case study, based on new interpretations of an existing high-frequency monitoring database of waste rock.

The previous case study included monitoring of internal waste-rock temperatures and basal water-table levels in a run-of-mine, full-scale, waste-rock pile approximately 40 meters high. The monitoring showed that some infiltration could pass downward through tens of meters of waste rock within 12 hours. Moreover, a substantial mass of infiltration could pass through 40 m of waste rock in 36-42 hours.

The primary focus of this new study is derived from Case Study 1 in Morin (2016). At this minesite, approximately 10^8 metric tonnes of waste rock, mostly in one pile, were stacked up to tens of meters high. Each year the uncovered run-of-mine waste rock was exposed to about 1.8-1.9 m of precipitation. In this cool coastal climate, there was relatively little evaporation and no long-term winter snowpacks. In other words, precipitation, which was measured daily, was a reasonably reliable estimate of infiltration into the waste rock.

Recent studies of this site using least-squares spectral analysis in the frequency-wavelength domain led to two important conclusions. First, precipitation, and thus infiltration, was generally random ("white noise"), but in an annually repeating cycle. Second, in outflow close to the toe of waste rock, no signal filtering of white-noise precipitation occurred at wavelengths less than 9-26 hours. Thus, unattenuated rapid flow ("plug flow") passed through the full-scale waste rock in less than 9-26 hours. This timing is similar to the previous case study discussed above, and is now supported by the findings below.

If a substantial amount of infiltration passed rapidly through the full-scale waste-rock piles at this site, then strong temporal correlations should be seen between peak values of precipitation and peak values of effluent flow. Peaks of precipitation should match peaks in measured flows, even when the peaks are offset by lag times representing the transit time through the waste rock.

Such correlations were seen, at both upstream Station EMO at the toe of waste rock and downstream Station WME representing a composite of upstream flows. Moreover, the daily peaks of outflow

lagged behind their corresponding daily peaks of precipitation by only 0-2 days at both stations. Because time discretization was one day for precipitation, refining these lag times to hours was not possible, although additional data (discussed below), showed the shortest lag times are likely roughly a few hours. In any case, these peaks represent the fastest flows, but not necessarily a significant mass (or volume) of flow, which requires further analysis of the data.

Histograms of daily flows showed that flow at Station WME displayed a lognormal distribution based on 2.5 years of high-frequency monitoring, and flows at EMO were also expected to do so if a full year of monitoring were conducted. In turn, their lognormal probability density functions provided estimates of the mass of water that flows rapidly through the full-scale waste rock. Close in at the toe of the rock, Station EMO revealed roughly 50% of the water mass was due to highly variable rapid flow. Downstream at WME, roughly 25% of the water mass was due to highly variable rapid flow. This highlighted the downstream location of WME at a confluence, resulting in smoothing of flows, which was consistent with spectral analyses (Morin, 2016).

A further examination of the daily masses of water involved converting flow into units of mm/day, for direct comparison to precipitation in mm/day. For WME, this showed that the daily peak of flow following a daily peak of precipitation rarely represented more than two-thirds of the mass of precipitation. In other words, at downstream Station WME where flows were smoothed and composited, less than two-thirds of the volume of a daily peak of precipitation passed through all waste rock in less than a day or two. In contrast, EMO at the waste-rock toe showed that daily peak flow could represent around 75% of a preceding peak of precipitation. Thus, 75% or less of the volume of a daily peak of precipitation passed through the local waste rock in less than a day or two.

In both cases, flows after a peak value of precipitation remained elevated, and thus additional drainage of the infiltration occurred over subsequent days not addressed above by peak flows. This became the focus of the next evaluation of the data.

For this site, the "hydrologic year" began in October of a calendar year, when precipitation but necessarily flow typically increased sharply. The hydrologic year ended September 30 of the next calendar year, when drier summer months provided less precipitation and infiltration. Running mass balances of water retention and outflow were calculated for the hydrologic years with high frequency monitoring. This led to the following observations.

When precipitation and infiltration began increasing sharply in a hydrologic year, outflow did not immediately respond. Instead, flow reached peak values, confirming the onset of rapid movement, only during later precipitation events.

This is sometimes called "wetting up" of a waste-rock pile after a dry period, in this case after spring and summer. For downstream Station WME that monitors all the on-land waste rock at this site, and for upstream Station EMO at the toe of local waste rock, approximately 0.085-0.188 m of precipitation occurred before rapid flow began. Because the waste rock at this site is up to several tens of meters high, this means less than 1% of the waste rock had to be wetted and/or saturated before rapid flow began.

After this initial retention of water, 100% mass of water equivalent to precipitation from a storm event typically drained from the waste rock within days to weeks, during the wet portion of the hydrologic year. During the drier portion, 100% drainage of a peak rainstorm required weeks to months. It is important to note that 100% equal masses, or volumes, of precipitation and outflow do not confirm identical masses of water. That is an issue that cannot be assessed here based purely on precipitation and outflow. Here, only the short-term peaks within a day or two of a peak in precipitation can be confirmed as identical, based on spectral analysis.

After the initial water retention, there was generally little additional retention through the wet portion of a hydrologic year. During the subsequent drier portion, there was a gradual net loss of retained water. Thus, any net retention of water during a hydrologic year was virtually drained by the end of that year. This led to the repeat of wetting as the next hydrologic year began.

To this point, the high-frequency measurements of flow had been summed to daily values, for comparison with daily-measured precipitation. However, the comparison of high-frequency flows, to daily precipitation and to daily flow, led to additional observations and corrected information. This included the following.

- Some daily values indicated peak outflow occurred the day after peak precipitation. In contrast, high-frequency flows showed that some peak flow occurred the same day.
- Daily sums masked significant short-term temporal variability. Flows could increase and decrease sharply within a few hours, by a factor of two or more, with peak flows lasting only 15-60 minutes.

Thus, high-frequency monitoring confirmed the rapid and highly variable flow of water through this full-scale waste rock within hours, more than was apparent from daily flows.

With high-frequency flow measurements, short periods of about two weeks were identified during which flow rates significantly oscillated daily. Where consistent, hourly flows reached minimum values around or just after midnight and peaked around noon or just after each day. The cause of these brief periods of oscillation is not known.

All the preceding findings highlight the importance of high-frequency monitoring of full-scale waste-rock piles. This would lead to the more reliable understanding, characterization, and modelling of water flow through full-scale waste-rock piles.

1. Introduction

For decades, full-scale waste-rock piles have been recognized as complex minesite components in all three spatial dimensions and through time (e.g., the critical literature review of Morin et al., 1991; Morin and Hutt, 1997, 2000, 2001a and 2001b; Morin et al., 1997; Morin, 2016). As a minimum, full-scale rock piles can be thought of as two components or compartments (e.g., Kirchner, 2016a and 2016b). The higher-conductivity coarser rock, and the lower-conductivity finer rock, can create sequential lateral to vertical layers that can be relatively small to nearly the size of an entire rock pile. More likely, these layers represent a continuum of particle size and hydraulic conductivity (Smith et al., 1995).

While many waste-rock investigators recognize this complexity of coarser and finer material, many ignore its reality and oversimplify water movement in the coarser material. It appears the primary reasons for this include the following.

- The lack of high-frequency monitoring data (hourly and more frequently) to characterize rapid flow in full-scale waste-rock piles.
- Detailed studies of smaller on-site "test piles" and laboratory-based columns that are unavoidably unrepresentative of full-scale waste rock.
- The desire to model water flow through waste rock despite a lack of realistic equations to simulate turbulent, non-Darcian, non-capillary flow in coarse rock.

These are explained in more detail in the following subsections.

1.1 Rapid Hydrogeologic Responses Cannot Be Reliably Characterized by Daily, Weekly, or Monthly Monitoring

The following sections of this MDAG Case Study show that substantial amounts of water can pass through full-scale waste-rock piles within hours and days. To characterize this reliably, drainage flows from waste rock must be measured hourly or more frequently.

Kirchner et al. (2004) used an analogy to explain this point.

> "Imagine trying to understand a Beethoven symphony if one could only hear one note every minute or two! That is what we are trying to do when we infer the hydrochemical functioning of a catchment [or a minesite component] from weekly or monthly grab samples. . . . Continuous high-frequency monitoring of catchment hydrochemistry will require significant resources and tenacity. In our view, however, what we stand to learn is well worth the effort. If we want to understand the full symphony of catchment hydrochemical behaviour, then we need to be able to hear every note."

Such high-frequency monitoring is rare. Therefore, most waste-rock investigators have missed the "full symphony" and are working with an occasional "musical note" that tells them flow through finer rock is often more important.

1.2 Most Waste-Rock Models Cannot Reliably Simulate Turbulent, Non-Darcian, Non-Capillary Flow in Coarse Rock

At the Diavik diamond minesite in northern Canada, university studies of smaller-scale "test piles" started with the recognition of full-scale flow complexity.

> "Preferential flow, such as through large macropore pathways or as non-capillary film flow, may occur in both the coarser waste rock fraction and open voids (matrix free zones). With little capillarity, this coarser fraction can result in rapid movement of water through waste rock piles, and is difficult to monitor in situ with current hydrological instruments." (Fretz et al., 2011)

Despite the monitoring difficulties, three years later the conclusion became:

> "Once infiltrated, water flow through the matrix [finer rock] was observed to be the dominate transport mechanism under average rainfall conditions despite a grain size distribution with less than 18% of the waste rock composed of the finer than 5-mm fraction.
>
> "Only in response to large storm events was water flow through preferential flow paths observed. Continuous monitoring of water discharge at the base of the test piles indicated the rate of initial wetting front advancement under average precipitation was about 7.5 m•yr-1 and under drier conditions was about 6 m•yr-1." (Momeyer, 2014)

Although finer rock less than 5 mm comprised less than 18% of this test pile, what caused this bias towards the dominance of finer rock on flow? Some explanations can be:

- the difficulty in high-frequency monitoring of coarse-rock rapid flow (see Section 1.1 above), leading to averages reflecting the scarcer finer rock that is not likely hydraulically continuous at such low percentages (<18%).
- the fact that the smaller-scale test piles could not contain the extensive coarser-rock channels seen in full-scale piles.

Momeyer (2014) explained that rapid flow occurred only "in response to large storm events". Perhaps the large storm events created much of the annually infiltrated mass of water. Perhaps infiltration then passed rapidly through the coarser channels, but this apparently was not monitored and characterized. This missing information could account for the remaining conclusion that flow through finer rock was dominant.

As another example, Kempton (2012) explained,

> "Unsaturated-flow models and column studies of waste rock structures demonstrate that unsaturated flow is conveyed preferentially through fine materials at low water flux typical of capped waste rock facilities".

Kempton (2012) does not explain that such models are Darcian-capillary-based and thus by definition have to inevitably show preferential unsaturated flow in finer particles. Also, full-scale "capped waste rock facilities" have found the integrities of caps degrade with time (e.g., Taylor et al., 2003; Morin et al., 2003 and 2010) so that "typical" water flux increases through time. As a result, Kempton's typical "low water flux" to maintain flow only through finer rock is undefined, and is likely variable spatially and temporally for any particular full-scale "capped" pile.

Where full-scale rock piles are modelled, the spatial complexity, and the coarser vs. finer layers, are often recognized (e.g., Fala et al., 2003; Dawood et al., 2011; Dawood and Aubertin, 2012; Franklin et al., 2006). However, the piles are then often modelled using finite-element or finite-difference codes that include capillarity, unsaturated hydraulic conductivities, Richard's equation, van Genuchten model parameters, etc.

These modelling results must, by definition, show that coarser-rock channels carry little if any water under unsaturated conditions. For example, Herasymuik (1996) concluded,

> "The soil water characteristic curves and the hydraulic conductivity function curves therefore demonstrate that the fine grained waste rock layers will . . . provide the pathways for the liquid water flow in the waste pile under unsaturated conditions."

This limitation of current models does not mean that nature is "shoe-horned" into obeying them, especially when high-frequency monitoring is not conducted to characterize rapid flow.

Finally, some models are manipulated to artificially show the channelling or "fingering" of coarse-rock flow within waste rock. For example, undulating the base of the surficial model layer can create water channeling in underlying layers that resembles real coarse-rock channeling (e.g., Dawood and Aubertin, 2014), but that is just an artifact of the input grid.

1.3 A Realistic Way Out of These Problems and Misconceptions

For full-scale waste-rock piles, the way to resolve the problems discussed above in Sections 1.1 and 1.2 is by:

- frequent (at least hourly) monitoring of full-scale waste-rock piles, and
- abandoning the notions of laminar flow and capillarity in coarse waste rock.

For example, monitoring every hour for both precipitation and drainage would show the rapid response of the coarser rock and the slower "recession curve" of the finer rock. However, this frequent and intensive monitoring of waste-rock drainage is rare (e.g., Hawkins and Aljoe, 1990 and 1991; Morin et al., 1994), This allows the much more abundant, inappropriate modelling discussed in Section 1.2 to become "believable".

This MDAG Case Study contributes by reviewing one previous case study of rapid flow through a full-scale pile in Section 2. Then the subsequent sections present a new case study, based on new interpretations of an existing high-frequency monitoring database of waste rock.

2. A Previous Full-Scale Example of Rapid Hydrogeologic Response to Rainfall

Morin et al. (1994) and Morin and Hutt (1997 and 2001a) discussed thermal monitoring within a full-scale waste-rock pile, and corresponding water-table monitoring at the base of that pile. This pile is located at a polymetallic minesite on Vancouver Island, Canada, and has a cool, marine-influenced rainforest climate.

The waste-rock pile contained approximately 10^7 metric tonnes of pyritic, heat-generating waste rock. It was built against a sloping valley wall, and was approximately 800 m in length parallel to the wall, approximately 300 m wide at the base, and reached a maximum measured height of 42 m.

Thermistor strings were installed in four boreholes in this pile for a total of 20 thermistors, and temperatures were transmitted to dataloggers every 12 hours. The temperature data at Thermistor T4 produced a maximum value of 51.6°C at an intermediate depth of 10 meters. This was consistent with an acidic zone identified in this zone using acid-base accounting to a depth of 26 m.

Also, four two-inch-diameter wells contained pressure transducers transmitting basal groundwater levels to dataloggers every 12 hours. Water-table fluctuations exceeding 1 m were recorded during some storm events consisting of roughly 7 cm of rain in 12 hours. Because daily precipitation was less than 15 cm/day (0.15 m/day), such storms would likely not have saturated more than 1% of the 40-m-high waste rock. As a result, the coarser rock was not responding to saturated flow during this time.

Infiltration events from major storms were tracked downward through the waste rock by their effects on internal temperature. Since precipitation was cold in winter, the chilling effect of infiltration could be seen to depths of 10 m. After passing through this hottest zone, infiltration then produced a heating effect at greater depths.

This behavior can be seen by focussing on one storm event (Figure 2-1). During the 12-hour period centered around 00:00 on January 31, precipitation began falling and increased to approximately 7 cm in 12 hr by 00:00 on February 1. Within the next 12 hours (to 12:00 on February 1), this storm caused rapid changes in temperature at T4, with temperatures to depths of 10 m decreasing and temperatures below 10 m increasing. There was no temperature response at 30 m depth.

Although temperatures responded within 12 hours to peak rainfall, the water table, at a depth of approximately 45 m, did not begin responding substantially until about 24 hours later. The midpoint of the water-table response occurred at 36-42 hours (shaded area in Figure 2-1), representing a rise of approximately 0.5-0.75 m. The difference between this hydrogeologic response of 36-42 hours, and the temperature response within 12 hours to depths of 20 m, likely indicated either:

(1) there is a perched water zone between 20 and 45 m that slowed infiltration, or
(2) the temperature responded to an initial, minimal amount of initial infiltration whereas the water table reflected the response to mass volume.

In summary, this example showed that infiltration could pass downward through tens of meters of full-scale, run-of-mine waste rock within 12 hours. Moreover, a substantial mass of infiltration could pass through 40 m of waste rock in 36-42 hours.

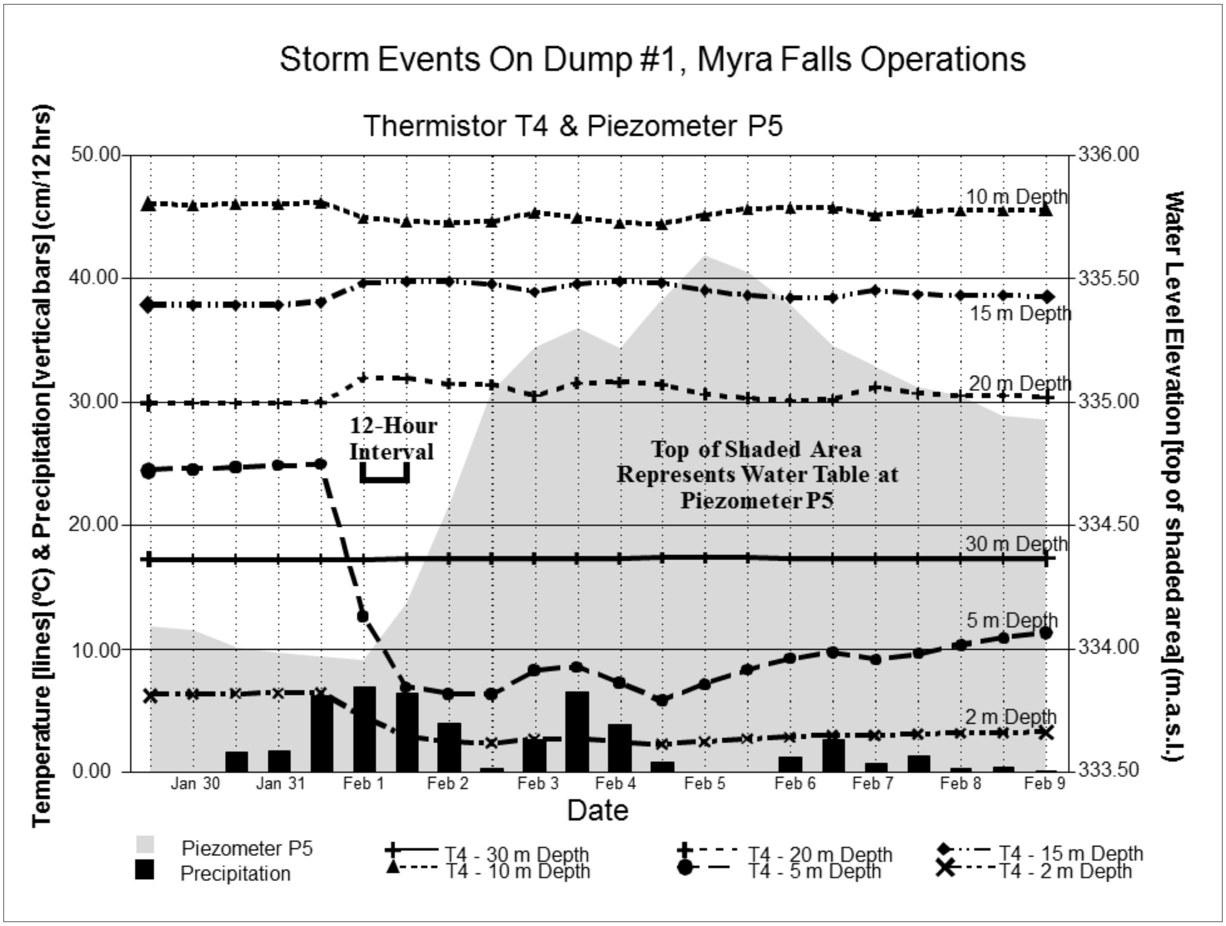


Figure 2-1. Responses of internal temperatures and the basal water table in a full-scale pyritic waste-rock pile about 40 m high (adapted from Morin et al., 1994).

3. General Description of the Minesite in This Case Study, Its Precipitation, Relevant Monitoring Stations, and Spectral Evidence for Rapid Flow

Case Study 1 (Chapter 6) of Morin (2016) discussed waste-rock drainage at a relatively large minesite near the northern end of Vancouver Island, Canada (Figure 3-1). Roughly 1x10^9 tonnes of ore and waste rock were mined from a single open pit. Most waste rock was placed in the adjacent marine inlet with tailings. However, more than 10^8 metric tonnes were placed on land around the pit perimeter, at heights of up to several tens of meters.

The climatic conditions at this site reflect a cool, marine-influenced rainforest. Annual precipitation is typically around 1.8-1.9 m/yr. Daily rainfall exceeded 40 mm/day (0.04 m/day) at least once each winter (Figure 3-2), but such storm events could only saturate less than 1% of the waste rock standing up to tens of meters high. Winter snowpack is not persistent, typically melting relatively quickly, and evaporation is relatively minor. Thus, daily precipitation can be used as an estimate of daily infiltration into waste rock. Least-squares spectral analysis of precipitation (Figure 3-3) showed infiltration was generally random (“white noise”). The exception was a prominent peak at a wavelength of one year, representing an annually repeating cycle of precipitation (Morin 2016).

Morin (2016) used least-squares spectral analysis of flow data, typically collected hourly or every 15 minutes, to identify rapid flow through the on-land waste rock. Close in to the waste-rock toe, at Station EMO (Figure 3-1), the power spectrum of flow showed no signal filtering of white-noise precipitation at wavelengths less than 9-26 hours (Figure 3-4). Thus, water passed rapidly and unfiltered through the waste rock upstream of Station EMO in less than 9-26 hours. This is confirmed in Section 5 of this case study.

Farther downstream, Station WME (Figure 3-1) monitored the merged flows from two major drainage ditches and from several waste-rock areas. This created a complex, superimposed power spectrum of flow at this location, which smoothed and masked signs of rapid flow through upstream waste rock (Figure 3-5).

This case study looks closely at the time series of precipitation and of flow at Stations EMO and WME. This reveals more details of the rapid flow occurring through the waste-rock piles at this site.

The primary difficulty here is that precipitation was typically measured only as a single daily value, with only a short period of hourly precipitation spanning a few months. As a result, the comparison of daily rainfall, to flows measured every hour or every 15 minutes, requires some compromise.

Here, to assist the comparison to daily precipitation, instantaneous measurements of flow in L/s were converted to m^3 for the applicable time interval of every 15 minutes or every hour. Flows over these intervals were then summed to obtain flows as m^3/day. In some cases, these daily sums were divided by the catchment areas to obtain the same units as precipitation, in mm/day.

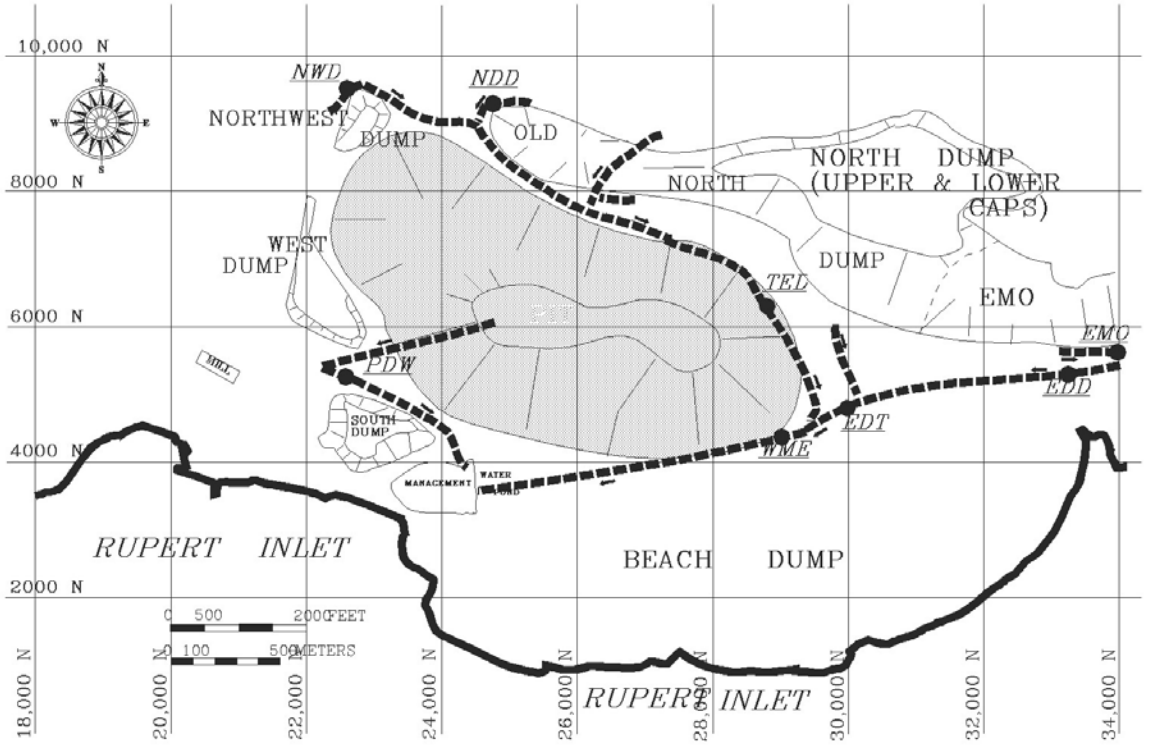


Figure 3-1. Map of the Island Copper Minesite during operation, including drainage ditches and major drainage-sampling stations.

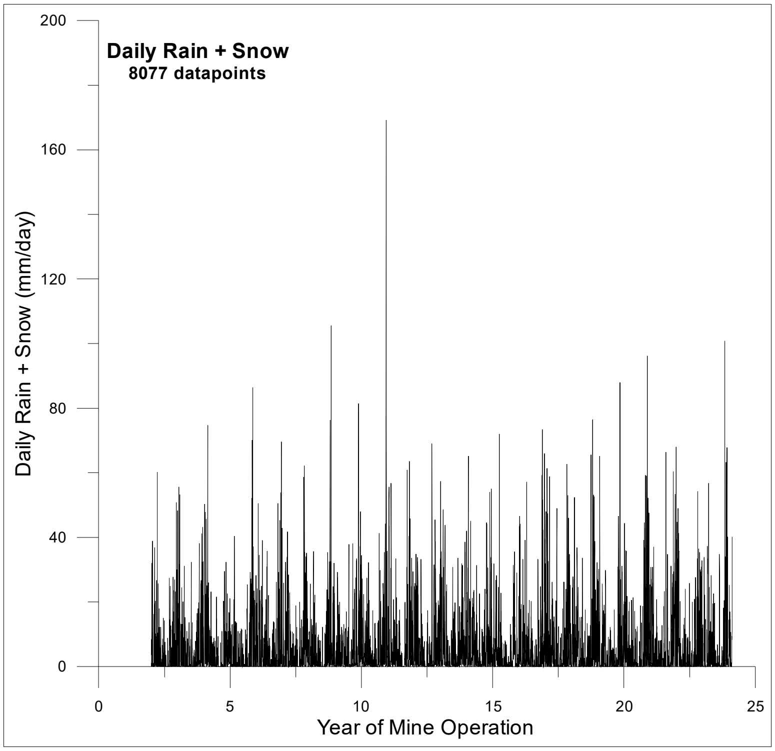


Figure 3-2. Time series of daily values of rain plus snow (precipitation) at the minesite (from Morin, 2016).

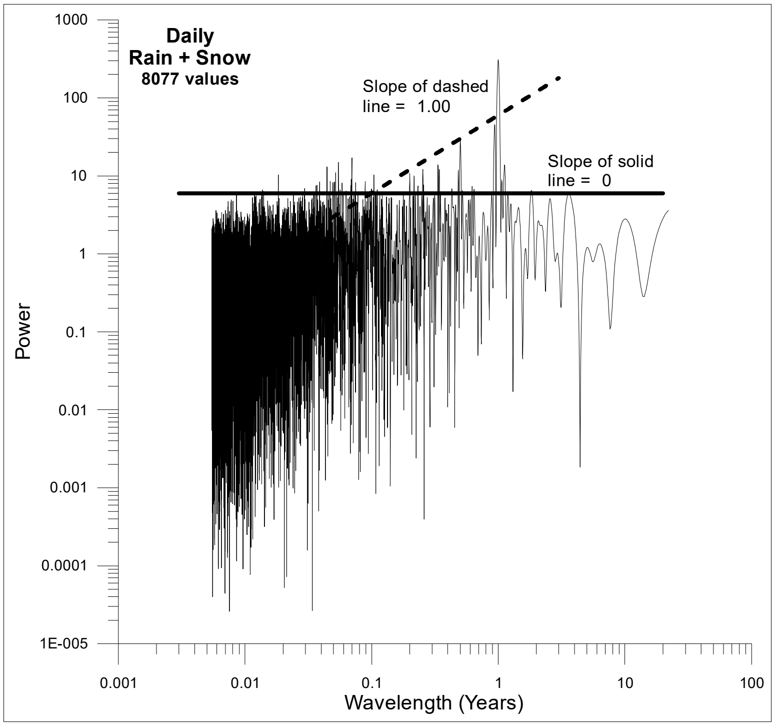


Figure 3-3. Power spectrum, from least-squares spectral analysis, of daily values of rain plus snow (precipitation), showing a random "signal input" into the waste rock (from Morin, 2016).

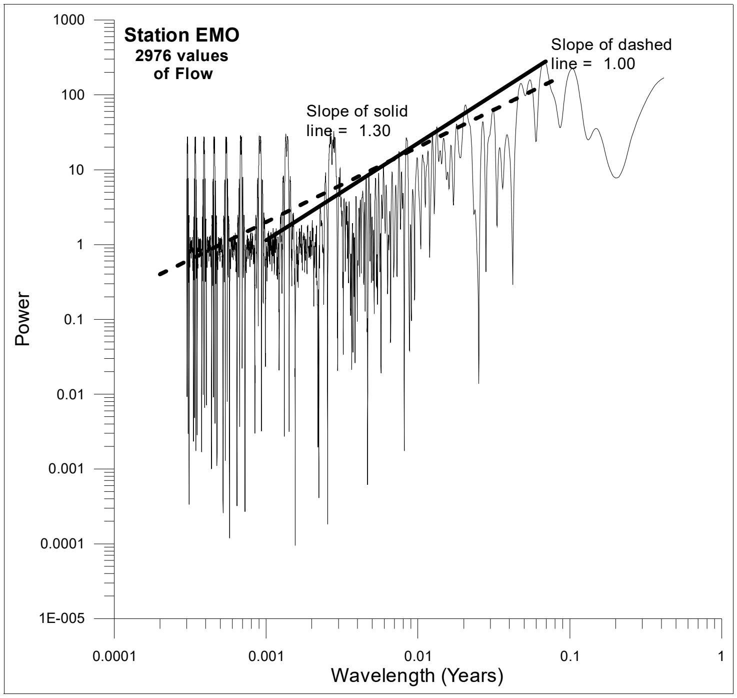


Figure 3-4. Power spectrum of drainage flow at Station EMO, located at the toe of the North waste-rock pile, showing no signal filtering, and thus rapid unattenuated flow, at wavelengths less than 9-26 hours (from Morin, 2016).

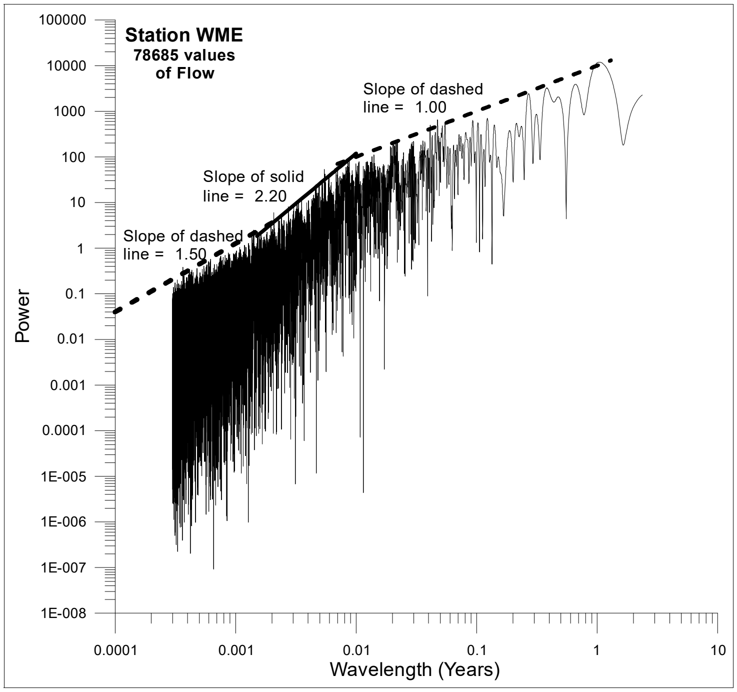


Figure 3-5. Power spectrum of drainage flow at Station WME, far downstream at the convergence of two main drainage ditches, showing the resulting complex superimposed spectrum and no short-wavelength signs of rapid flow (from Morin, 2016).

4. Comparisons and Correlations of Precipitation and Flow at Waste-Rock Stations EMO and WME

If a substantial amount of infiltration passed rapidly through the full-scale waste-rock piles at this site, then strong temporal correlations should be seen between peak values of precipitation and peak values of outflow. Peaks of precipitation should match peaks in flows, even when the peaks are offset by times representing the transit time through the waste rock.

For downstream Station WME, superimposed time series of (1) precipitation as mm/day and (2) daily sums of flows as m^3/day (Figure 4-1) generally showed the temporal correlation described in the previous paragraph over years of high-frequency monitoring. Thus, outflow from the waste rock was “flashy” and highly variable like precipitation. This also showed the “hydrologic year” at this minesite extended from October, when precipitation and flow typically increased sharply, through September of the subsequent year.

Upstream Station EMO had less than one hydrologic year of high-frequency monitoring. Nevertheless, the monitoring also generally showed the correlation expected from significant, highly rapid and variable flow driven by rapid infiltration and outflow (Figure 4-2).

It is important and informative to take more detailed, quantitative looks at these general correlations.

Where distinct, relatively isolated peaks of daily precipitation occurred, the time difference (“lag time”) between peak precipitation and peak flow could be defined. For Station WME, the nearly 90 lag times were predominantly between 0 and 1 day (due to the discretization time of one day), with substantially fewer between 1 and 2 days, and none longer (Figure 4-3). Station EMO had significantly fewer values of lag time, and these values were between 0 and 2 days (Figure 4-4) like WME. For both stations, the lag times did not correlate well with the amount of precipitation, except the highest precipitation values consistently produced lag times of only 0 to 1 day.

Therefore, rapid infiltration and outflow within 0 to 2 days was found across a large range of precipitation at both stations in this full-scale waste rock. Limited by time discretization of days for precipitation, this range of 0-2 days based on peak flows was consistent with the preceding spectral results of 9-26 hours (Chapter 3). This is refined further, to hours, in Section 5 of this case study.

However, a peak value of flow for a day or two after precipitation does not mean that most of the mass of infiltrating water passed through that quickly. This requires a different evaluation, for mass balance, which begins here and carries into Section 4 of this case study.

A histogram of all daily sums of 15-minute flows at WME showed a general lognormal distribution (Figure 4-5). However, daily sums of hourly flows at EMO were only collected over the wetter portion of the hydrologic year (Figure 4-2), and thus many lower flows were not measured and included. If additional lower flows had been measured, a general lognormal distribution for EMO flows could be expected (Figure 4-6).

Based on the statistical values describing these lognormal distributions, the lognormal probability density function tells how often a particular daily flow would be expected annually. For example, any flow at and above the lognormal mean would be expected 50% of the time and those flows account for 50% of the annual flow.

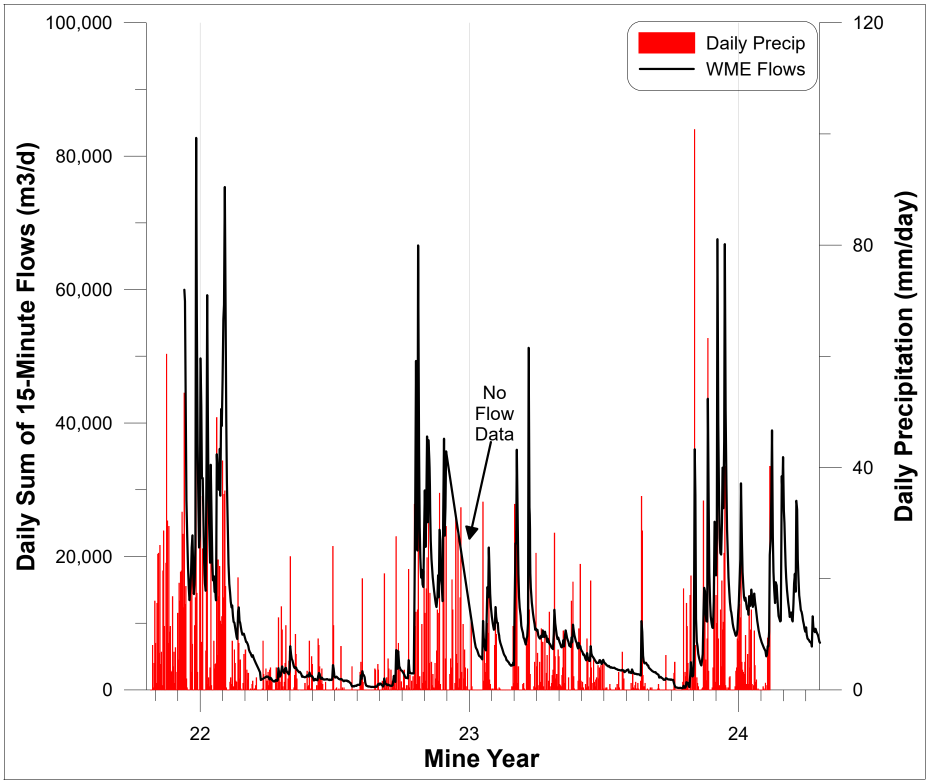


Figure 4-1. Time series of daily precipitation in mm/day and daily sums of flow in m^3/day at downstream Station WME.

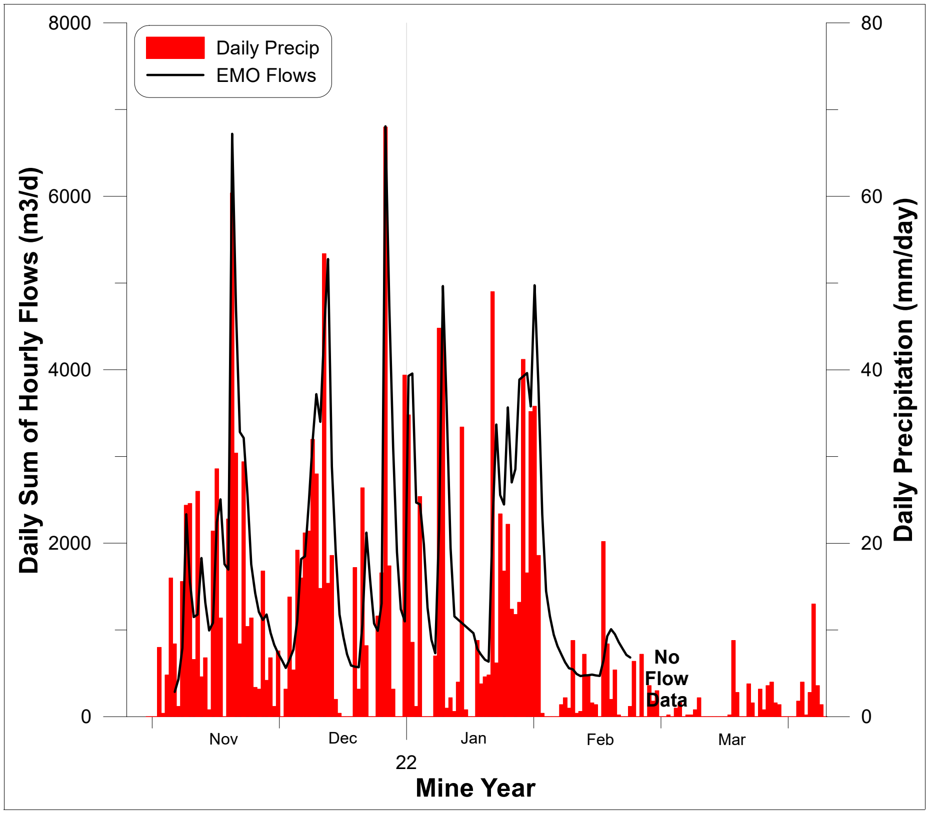


Figure 4-2. Time series of daily precipitation in mm/day and daily sums of flow in m^3/day at upstream Station EMO.

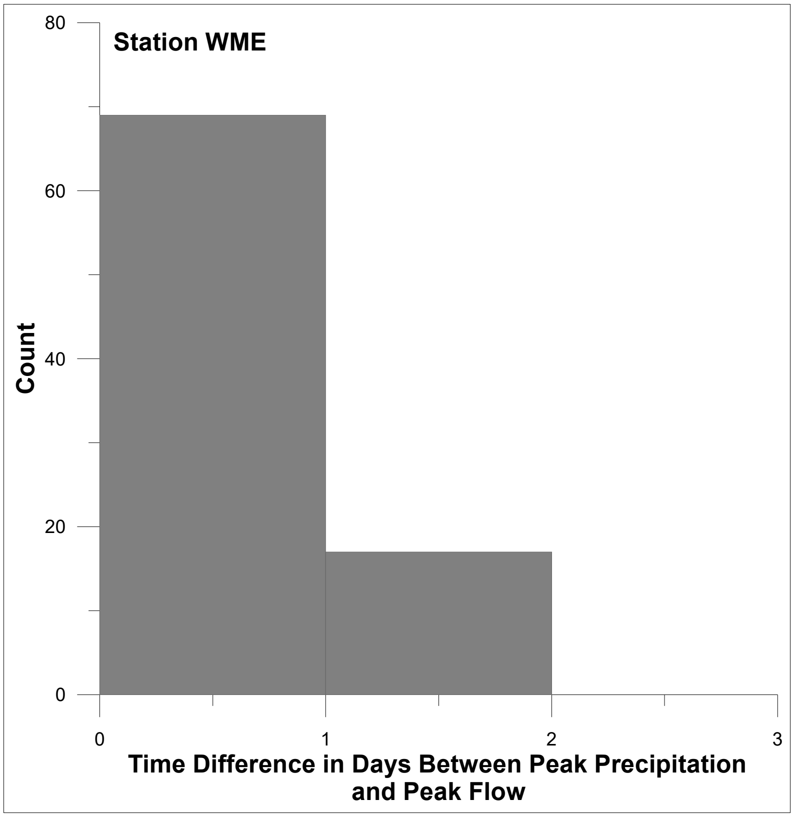


Figure 4-3. Histogram of lag times in days between peak precipitation and peak flow at Station WME.

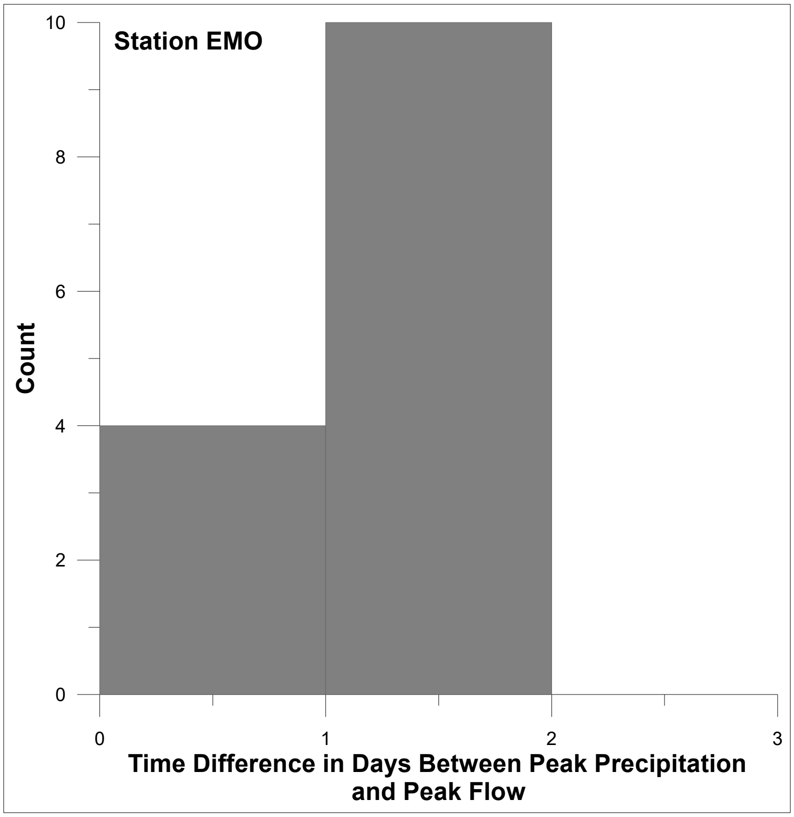
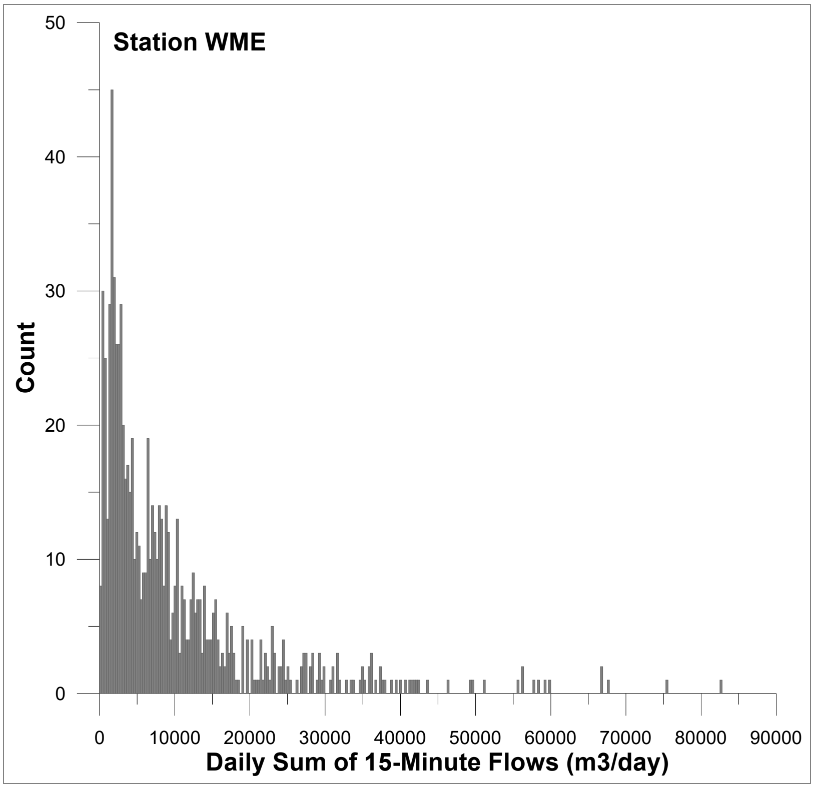


Figure 4-4. Histogram of lag times in days between peak precipitation and peak flow at Station EMO.



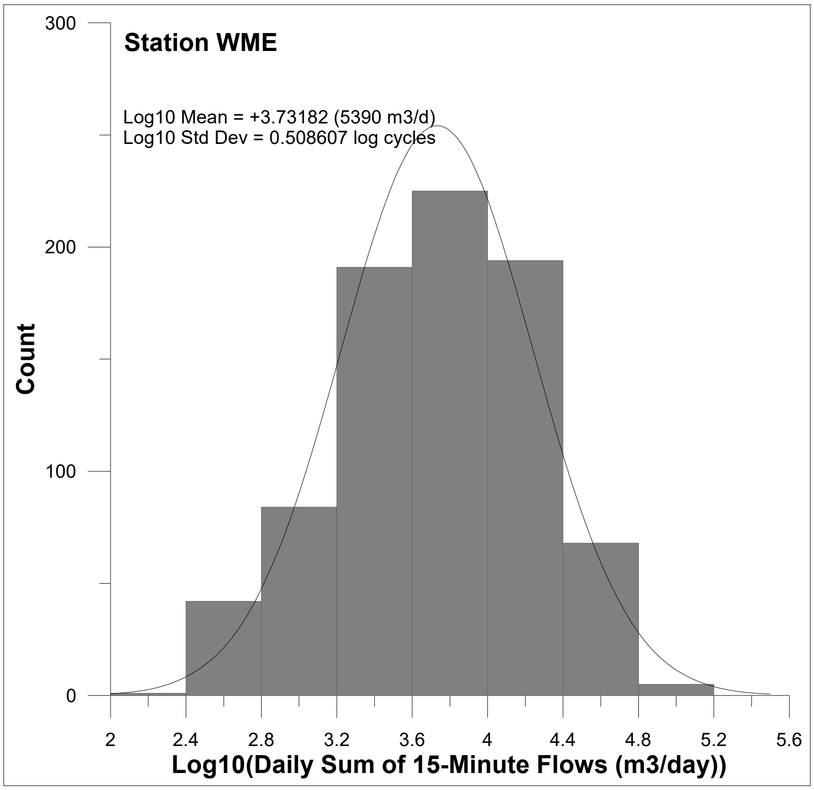


Figure 4-5. Histograms of daily sums of flow in m^3/day at Station WME; top (a) = arithmetic scale, bottom (b) = logarithmic scale.

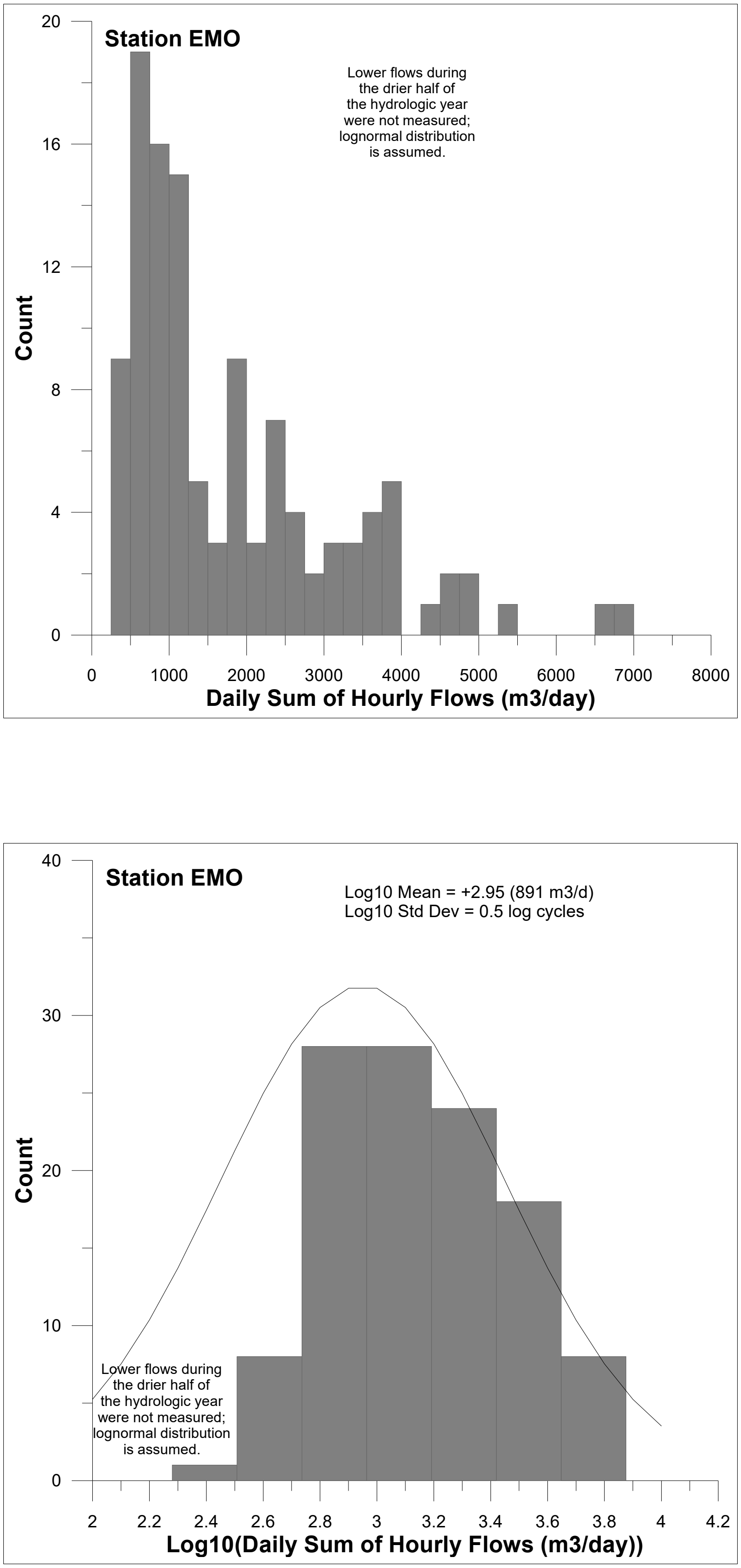


Figure 4-6. Histograms of daily sums of flow in m^3/day at Station WME; top (a) = arithmetic scale, bottom (b) = logarithmic scale.

For WME (Figure 4-7), 50% of annual flows were at and above 5390 m^3/day. Similarly, 25% of annual flows were at and above 11,900 m^3/day, and 10% of annual flows were at and above 24,200 m^3/day. As a result, the highest and most variable flows at WME represented roughly 25% of annual flows. Nevertheless, even during the drier portion of the hydrologic year, minor yet relatively significant peaks of flow can be seen after a summer rainstorm. Therefore, a significant portion of precipitation and infiltration passed quickly through the waste rock throughout the year.

For EMO(Figure 4-8), 50% of annual flows were at and above 891 m^3/day. Similarly, 25% of annual flows were at and above 1940 m^3/day, and 10% of annual flows were at and above 3900 m^3/day. Therefore, in contrast to WME, the highest and most variable flows at the toe of the waste rock represented roughly 50% of annual flows instead of only 25%. This is consistent with the downstream location of WME resulting in the attenuation and smoothing of peak flows, which is also consistent with spectral analyses (Chapter 3).

The next step in the mass balance is to compare precipitation in mm/day to the daily sums of flows as mm/day. This requires estimates of the "catchment areas" above Stations EMO and WME, based on maps like Figure 3-1. The map-estimated geographic catchment area for WME is approximately 2,000,000 m^2. The catchment area for EMO is less clear, because this station is located on a sloping drainage ditch that would not likely collect all waste-rock drainage from the EMO area (Figure 3-1). Geographically, the EMO catchment area should be around 400,000 m^2. As explained in the next paragraphs, EMO likely had a catchment area around 150,000 m^2. However, nearby downstream Station EDT (Figure 3-1) was better located to capture all shallow drainage from the EMO area, and does have an estimated area close to the geographic value of 400,000 m^2.

In a way, catchment area can be a calibration parameter. If the geographic areas from the last paragraph provide a summation of daily flows in mm/day that roughly equal the summation of precipitation, then little precipitation and infiltration is apparently (1) held indefinitely within fine grained waste rock (whose indefinite holding capacity in any case would have been full by operational Mine Year 22) and/or (2) lost to the deeper groundwater system flowing into the deep open pit. This was the case for WME whose catchment area was estimated at 1,800,000 m^2.

On the other hand, using the full geographic catchment area of 400,000 m^2 for EMO resulted in the summation of daily flows in mm/day being much lower than the summation of precipitation (as catchment area increases, the flow in mm/day calculated from measured flow in m^3/day decreases). In other words, most infiltration was being spontaneously lost in the catchment. Thus, the catchment area for EMO was reduced until summed flow in mm/day equaled summed precipitation in mm/day, as found downstream at WME, resulting in a catchment area of 150,000 m^2, within 0-2 days for peak values. Interestingly, this same approach was applied to Station EDT that was better located to capture all EMO drainage (Figure 3-1), and its calibrated catchment area of 400,000 m^2 was close to the geographic area.

With these catchment areas, daily sums of flow and daily precipitation were plotted together using the same units of mm/day (Figures 4-9 and 4-10). For WME, this showed that the daily peak of flow following a daily peak of precipitation rarely represented more than two-thirds of the mass of preceding peak precipitation. In other words, at downstream Station WME where flows are smoothed and composited, less than two-thirds of the volume of a daily peak of precipitation passed through the waste rock in less than a day or two.

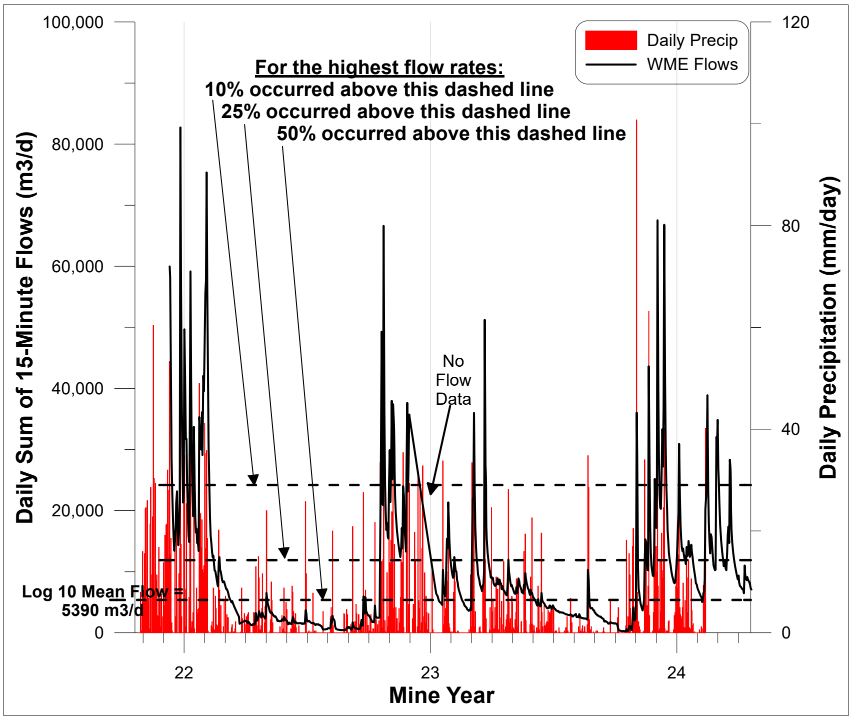


Figure 4-7. Time series of daily precipitation in mm/day and daily sums of flow in m^3/day at Station WME, showing days representing the maximum 10%, 25%, and 50% of flow rates based on lognormal statistics.

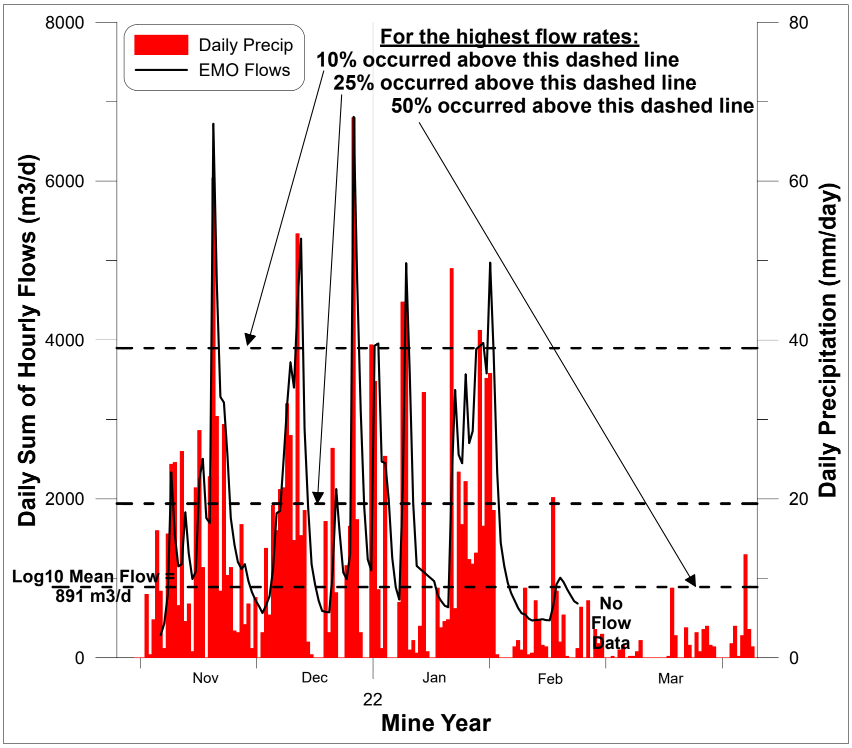


Figure 4-8. Time series of daily precipitation in mm/day and daily sums of flow in m^3/day at Station EMO, showing days representing the maximum 10%, 25%, and 50% of flow rates based on lognormal statistics.

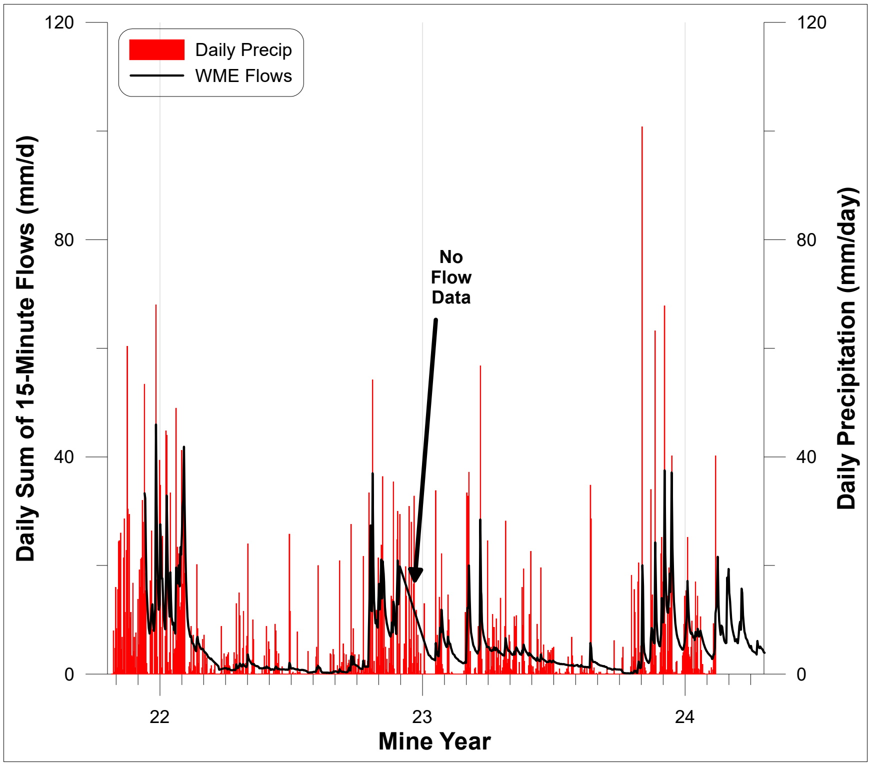


Figure 4-9. Time series of daily precipitation and daily sums of flow, both in mm/day and with the same vertical scale, at Station WME.

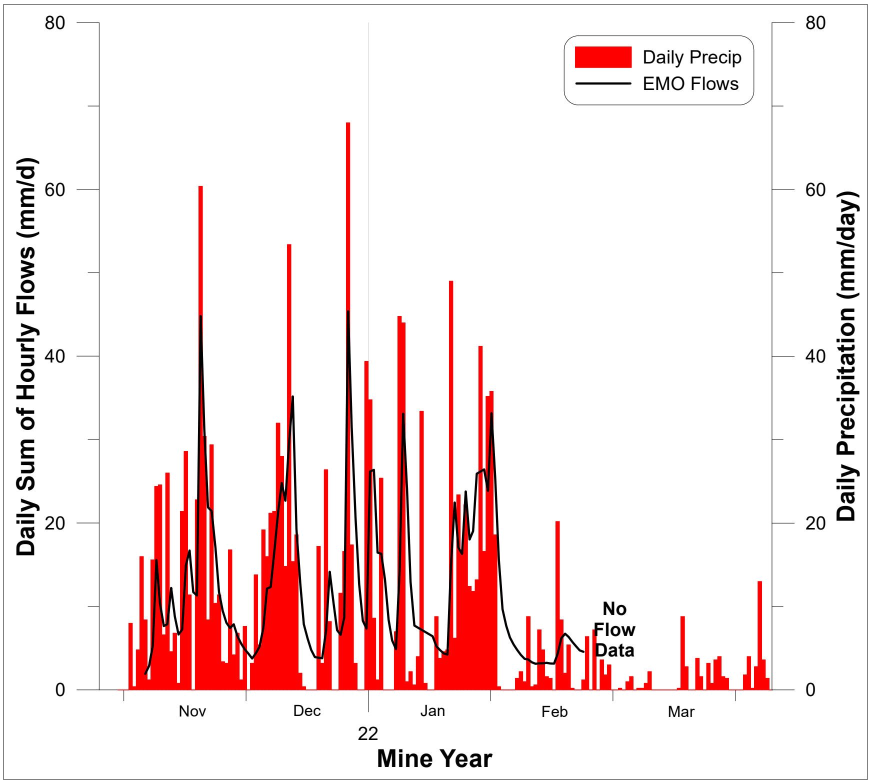


Figure 4-10. Time series of daily precipitation and daily sums of flow, both in mm/day and with the same vertical scale, at Station EMO.

In contrast, EMO showed that daily peak flow could represent around 75% of preceding peak precipitation. Thus, 75% or less of the volume of a daily peak of precipitation passed through the local EMO waste rock in less than a day or two.

This again highlighted the smoothing of flow at downstream Station WME receiving many inputs (Figure 3-1). Nevertheless, at both stations, peak daily flows could represent a substantial portion, but not all, of a preceding peak of daily precipitation.

This approach only considered individual peak daily values, which can be misleading. For example, perhaps two consecutive days of flow (one being a peak flow value) could account for 100% of a preceding peak of precipitation. Or perhaps two consecutive days of precipitation (one being a peak value) could create a later peak in flow. To evaluate these possibilities, we next have to look closely at day-to-day and cumulative water mass balances and at individual precipitation events.

5. Mass Balances of Inflowing Precipitation and Outflow during Individual Hydrologic Years and Individual Storm Events

As explained in Chapter 4, the hydrologic year can be defined as starting on October 1 of one calendar year, when precipitation typically increased sharply. It ended on September 30 of the following calendar year, after a relatively dry summer. Because high-frequency sampling started in Mine Year 21, Hydrologic Year 21-22 is the first examined in detail here.

To assist comparison of daily precipitation and flow, both are typically shown for this chapter in units of mm/day. This required estimated catchment areas, as discussed above in Chapter 4. This also required 15-minute flows at WME, 96 per day, to be summed for daily flows, and hourly flows at EMO, 24 per day, to be summed for daily flows.

5.1 Downstream Station WME

Station WME was located at the confluence of two primary drainage ditches from waste rock (Figure 3-1). It represented the composite drainage from most on-land waste-rock piles at this minesite.

5.1.1 Hydrologic Year 21-22

Because flow monitoring started at Station WME on December 10 of Mine Year 21, mass balances of water retention within the waste rock cannot be calculated reliably for the entire hydrologic year. However, these balances are calculated for the other hydrologic years, as discussed in the following subsections.

For this partial hydrologic year (Figure 5-1), one focus was on the series of wet days from January 23 to February 4, when cumulative precipitation was 302 mm. The interest here is how much time was required to drain an amount of water equivalent to 302 mm. Notably, the cumulative amount of outflow over this same period was 315 mm, with the highest daily flow on February 3. Thus, the volume of rainfall entering the waste rock over roughly 1.5 wet weeks flowed out of the waste rock over the same period, but not exactly equivalent each day. As a result, little if any coarser rock would have been saturated.

This indicated there was little long-term net retention of water within the waste rock during this wet period, which is confirmed below by the subsequent hydrologic years. This also indicated a large volume (mass) of precipitation could pass rapidly through the waste rock within a few weeks during wet times, which is also confirmed below by the subsequent wet years. However, there could be some net retention from one month to the next, as discussed later, so equivalent cumulative amounts of precipitation and flow do not mean they are entirely the same mass of water.

As mentioned before, flows at WME were measured every 15 minutes. A closeup of January 23 to February 5 of Mine Year 22 revealed interesting observations (Figure 5-2).

- First, sums of daily flows indicated peak outflow in mm/day occurred on February 3. In contrast, 15-minute flows showed that nearly equal peak flows in mm/15 minutes (multiplied by 96 in Figure 5-2 to match vertical scale) occurred on January 29 and 31 and February 2 and 3.

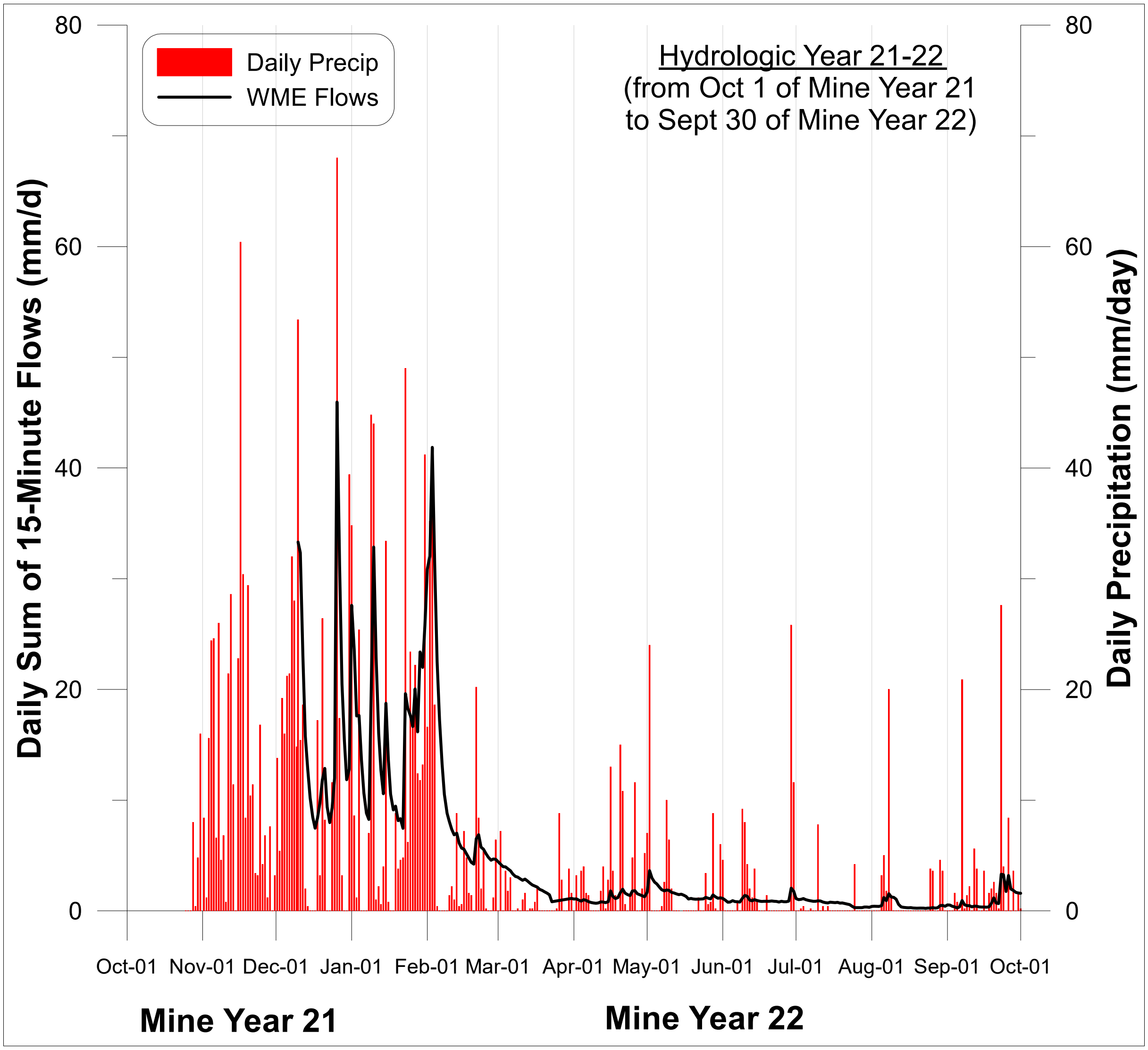


Figure 5-1. For Hydrologic Year 21-22, time series of daily precipitation, daily sums of flow, and 15-minute flows, both in mm/day and with the same vertical scale, at Station WME (see also Figure 4-9).

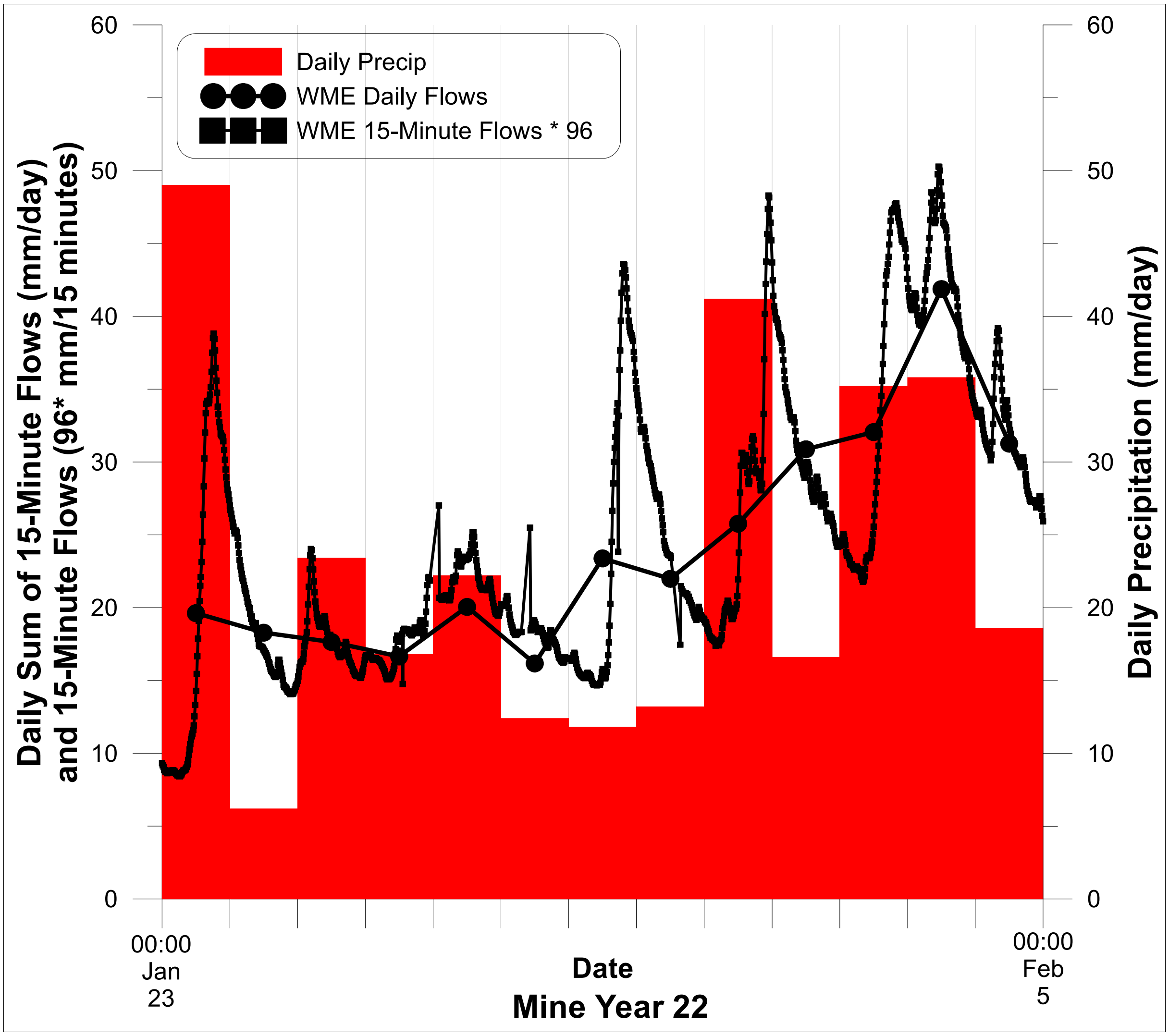


Figure 5-2. Closeup of January 23 to February 4 of Mine Year 22 showing time series of daily precipitation daily sums of flow, and 15-minute flows, all in mm/day and with the same vertical scale, at Station WME.

- Second, the 15-minute peaks showed daily oscillations in flows. This is discussed further at the end of this chapter (Section 5.3).
- Third, daily sums masked significant short-term (15 minute) temporal variability. This reflects the concerns of Kirchner et al. (2004), as expressed in the quotation in Section 1.1 above.
- Fourth, flows decreased sharply within a few hours of peak values, reflecting the fast response and rapid flow of water through this full-scale waste rock.

After February 4, values of cumulative precipitation and cumulative equivalent flow were calculated for each month. Daily peaks of precipitation did occur in these months. Some created minor peaks in flow that did not rival the amount of precipitation, but flow was more consistent from day to day than precipitation.

From February 5 to February 29, cumulative precipitation was 74 mm, whereas flow was 176 mm. This deficit of 102 mm is not possible, unless some water had been retained by the waste rock during earlier months before monitoring and was now released. This behavior is confirmed in subsequent subsections for later hydrologic years.

It is not clear what portion of this excess outflow by the end of February was drawn from earlier retention (October through December) and what portion was from the high rainfall of January 23 to February 4. In other words, what portion originated from “plug flow” or “piston flow” of immediately recent infiltration and what portion from slower, mixed matrix flow? The spectral results in Chapter 3 indicated flows that occur, from top to bottom of the waste rock, within 9-26 hours would be immediately recent, unfiltered infiltration. In contrast, water draining later than 9-26 hours would be matrix flow. Because the excess flow of February 5-29 mostly took place days to weeks later than the last storm, much of this flow was probably previously retained matrix flow.

For the month of March, cumulative precipitation (39 mm) was less than cumulative equivalent flow (56 mm). Thus, some previously retained water was presumably still draining.

For the warmer months of April through September, monthly precipitation typically exceeded monthly equivalent flow by tens of mm. This may reflect ongoing evaporation at the top of the waste rock during rainfall. However, this evaporative effect does not appear in the water balance of the next hydrologic year (Section 5.1.2).

Precipitation in September of Mine Year 22 was substantial at 93 mm, with relatively little outflow. This monthly amount of 93 mm was about 70 mm higher than the average of the three previous Septembers. Therefore, although not officially part of Hydrologic Year 22-23, September is included next in that year’s mass balance, in the next subsection.

5.1.2 Hydrologic Year 22-23

Two significant rainfall events occurred in September of Mine Year 22 (Figure 5-3), before the start of the next hydrologic year. Cumulative precipitation that September was 93 mm and cumulative equivalent flow was 30 mm. Thus, 63 mm of water was retained within the waste rock that September.

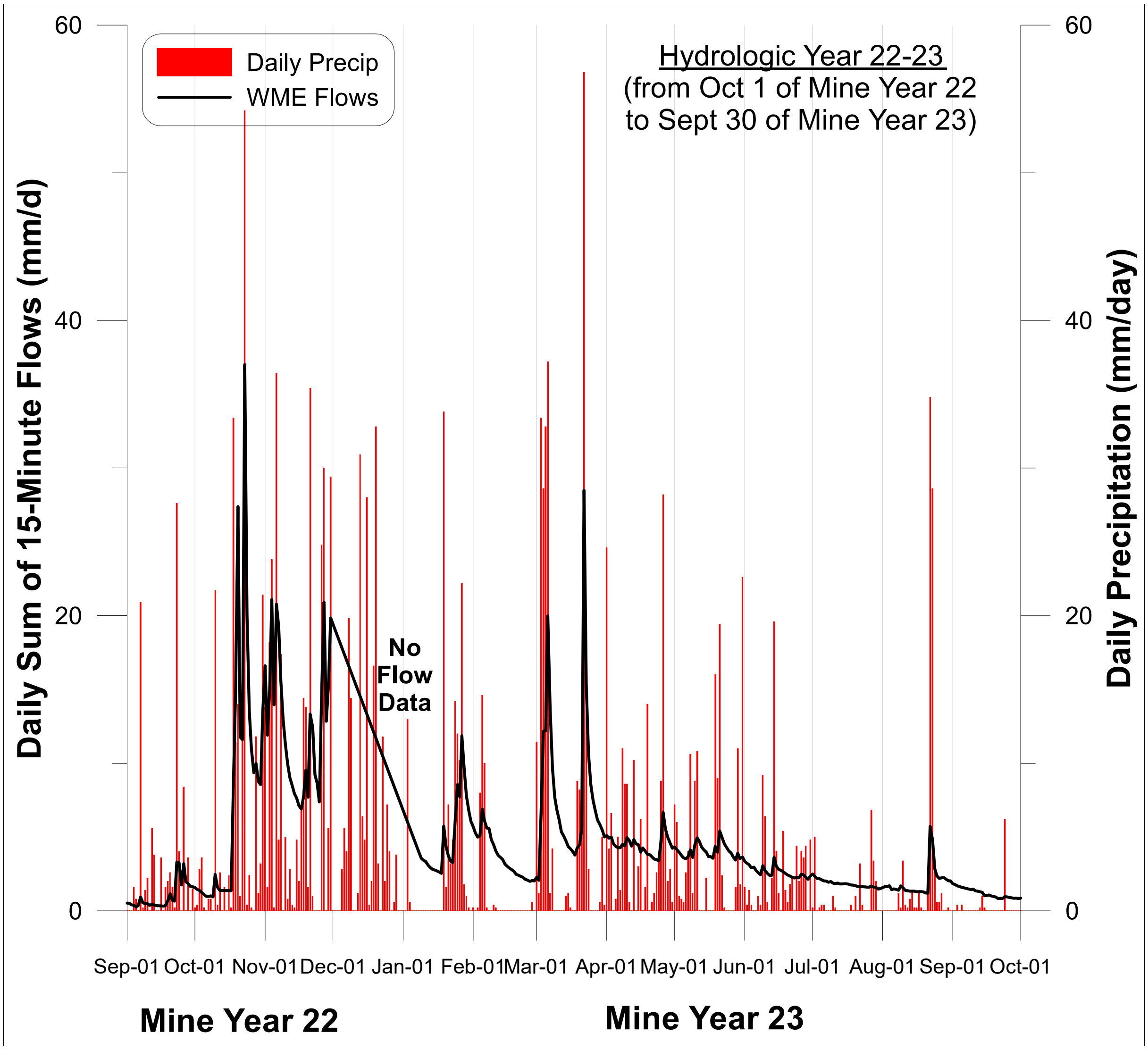


Figure 5-3. For Hydrologic Year 22-23, time series of daily precipitation, daily sums of flow, and 15-minute flows, both in mm/day and with the same vertical scale, at Station WME (see also Figure 4-9).

In October, peak flow rivalled peak precipitation with minor time lags starting October 18. From October 1 through October 17, cumulative precipitation was 38 mm. No flow data were available October 13-17, but cumulative equivalent flow was 16 mm to October 12. Thus, water retention was less than 22 mm, for a total retention of less than 85 mm since September 1. Therefore, on average, all waste rock at this site (upstream of WME) retained less than 0.085 m of water before rapid flow began. Because the waste rock is tens of meters high, this means less than 1% of the waste rock had to be wetted and/or saturated before rapid flow began.

Starting October 18, a series of wet days provided cumulative precipitation of 148 mm through October 30. The corresponding cumulative equivalent flow was 193 mm, with daily flow gradually decreasing in the last week. This deficit of 45 mm reduces the cumulative retention since September 1 to less than 40 mm.

During this period of October 18 through October 30, daily flow showed some response to the initial precipitation. However, peak daily flow occurred on October 23, the last day of substantial precipitation. On the other hand, 15-minute flows during this period tell another story (Figure 5-4). The peak 15-minute flow occurred around midnight on October 20, followed by another, nearly equal peak on October 23, with flows falling sharply within hours of the peaks. As with Figure 5-2, high-frequency flows every 15 minutes showed the rapid and highly variable flow of water through this full-scale waste rock within hours.

Two relatively wet periods starting October 31 through November 21 of Mine Year 22 produced a cumulative precipitation of 226 mm. At the same time, cumulative equivalent flow was 276 mm. This deficit of 50 mm offset the remaining net cumulative retention of less than 40 mm, so at this time there was net water retained within the waste rock.

No flows were measured in December through January 7 (Figure 5-3), so no water balance can be calculated. The relatively low daily flows from January 8 to January 18, lower than those in late October and November, suggested no major retention or deficit occurred during this unmonitored period. However, this cannot be confirmed, and later mass imbalances might be artifacts of this.

Starting January 19, some significant daily peaks in precipitation occurred until February 6. During this period, cumulative precipitation was 145 mm. Though flow showed some high daily peaks, the cumulative equivalent flow was 119 mm. So the retention of water within waste rock during this period was 26 mm.

From February 7 to February 28, there was relatively little rainfall, allowing the waste rock to drain down. This drained a net 69 mm from retained water, leaving an unreasonable deficit 43 mm within the waste rock that may reflect the missing mass balance from December.

Two major storm events in March, about two weeks apart, produced two major peaks in flow, but peak flows were less than peak precipitation. For the month of March, cumulative precipitation was 260 mm, and cumulative equivalent flow was 245 mm. Because there was little net retention (15 mm) during these two events, two weeks was sufficient to drain most infiltration into the waste rock.

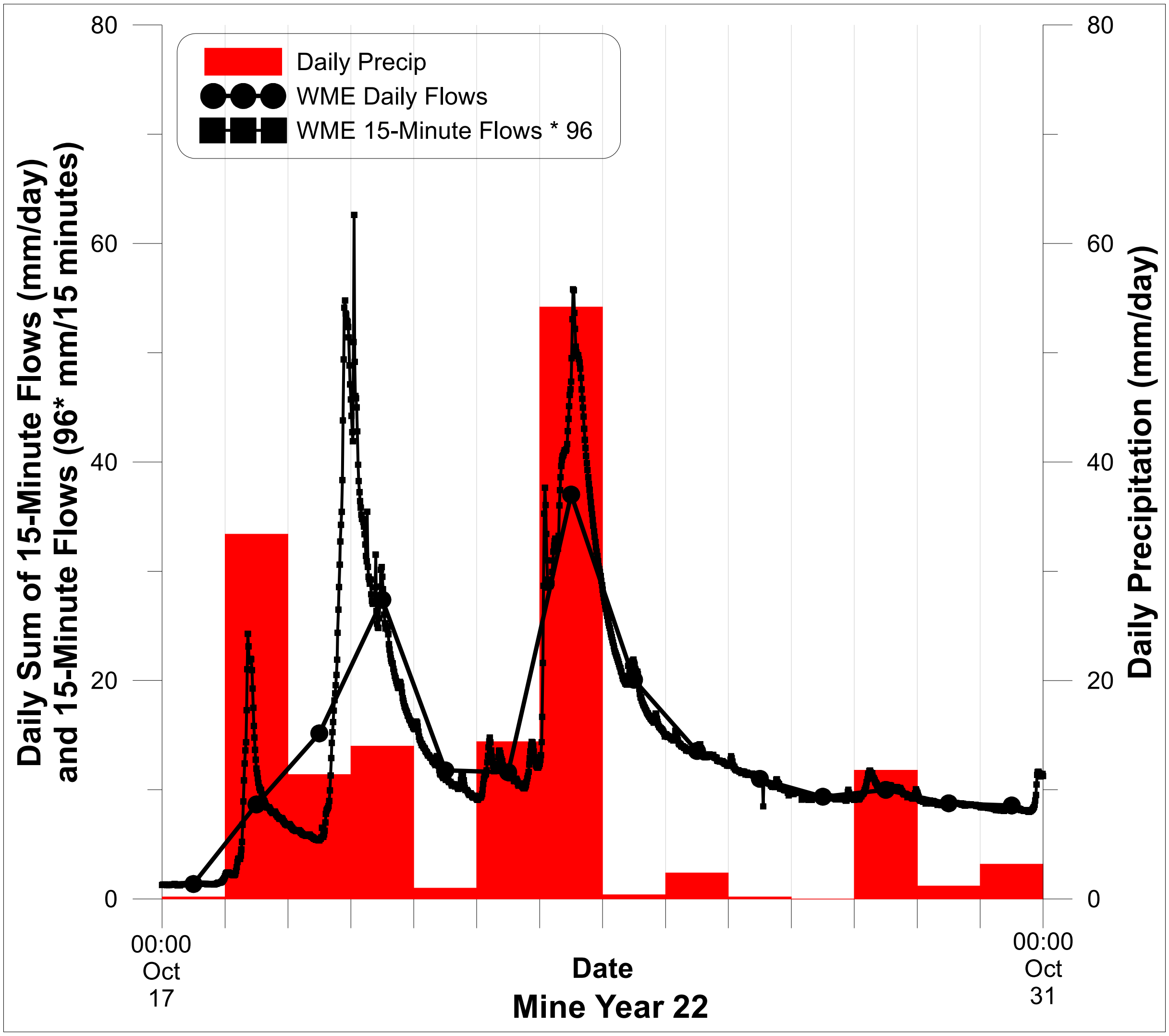


Figure 5-4. Closeup of October 17 to October 30 of Mine Year 22 showing time series of daily precipitation daily sums of flow, and 15-minute flows, all in mm/day and with the same vertical scale, at Station WME.

The drier portion of the hydrologic year started in April of Mine Year 23 (Figure 5-3). Through April, May, June, and July, there were several storm events with daily peaks of precipitation. Flow showed some response to these peak rainfalls, but the peaks were relatively subdued and did not rival the values of precipitation. The cumulative precipitation over these four months was 410 mm, and cumulative equivalent flow was 392 mm. Thus, there was little net retention (18 mm) across these four months, as was also noted for the previous, wet month of March. Unlike the previous hydrologic year (Section 5.1.1), evaporation did not appear to play a significant role in the water balance. By individual month, the cumulative values of precipitation and flow were equivalent in May and June, with April having a net surplus of water and July having an offsetting net deficit of water.

In August rainfall was relatively minor until August 22. From August 1 to August 21, cumulative precipitation was 11 mm, and cumulative equivalent flow was 30 mm. This minor deficit of 19 mm would erase the minor retention over the previous four months.

On August 22 and 23, 63 mm of rain fell on the waste rock. Peak flows were relatively minor compared with precipitation, but the recession curve over the following weeks showed this rainfall had drained out.

From August 22 through the end of September and of the hydrologic year, cumulative precipitation was 77 mm, with 82% occurring on August 22 and 23. Over the same period, cumulative equivalent flow was 65 mm. Thus, an amount equivalent to rainfall on August 22 and 23 had drained by September 30. This suggests waste-rock drainage during drier summer months required up to a month, whereas up to a few weeks were typical during wetter months.

5.1.3 Hydrologic Year 23-24

Flow was minimal through most of October of Mine Year 23 (Figure 5-5), but precipitation increased in mid month. The first sharp peak of flow occurred on November 2, when daily precipitation was 100.8 mm, and flow was an equivalent of 20 mm. From October 1 through November 2, cumulative precipitation was 227 mm and cumulative equivalent flow was 39 mm, for a difference of 188 mm (0.188 m). Thus, within the large WME catchment, 0.188 m of water was the amount of water retained in autumn within the waste rock before significant rapid outflow began.

No peak flow rivalling that of precipitation occurred until December 13. From October 1 through December 13, cumulative precipitation was 671 mm and cumulative flow was 476 mm. The difference representing net water retention in the waste rock was 195 mm. This closely matched the 188 mm of retention already noted through November 2, and thus no significant additional retention took place from November 2 through December 13. In turn, this meant that the lack of prominent peaks of flow rivalling precipitation between these dates was not due to retention of water within the waste rock, but downstream smoothing of flows over periods of days.

Higher-frequency flow data showed that flow did, in fact, respond rapidly to precipitation before December 13 (Figure 5-6). The peak of daily precipitation on December 3 caused two 15-minute peaks the same day, presumably reflecting two episodes of strong rainfall within the 24-hour period of December 3. As with Figures 5-2 and 5-4, high-frequency flows every 15 minutes showed the rapid and highly variable flow of water through this full-scale waste rock within hours.

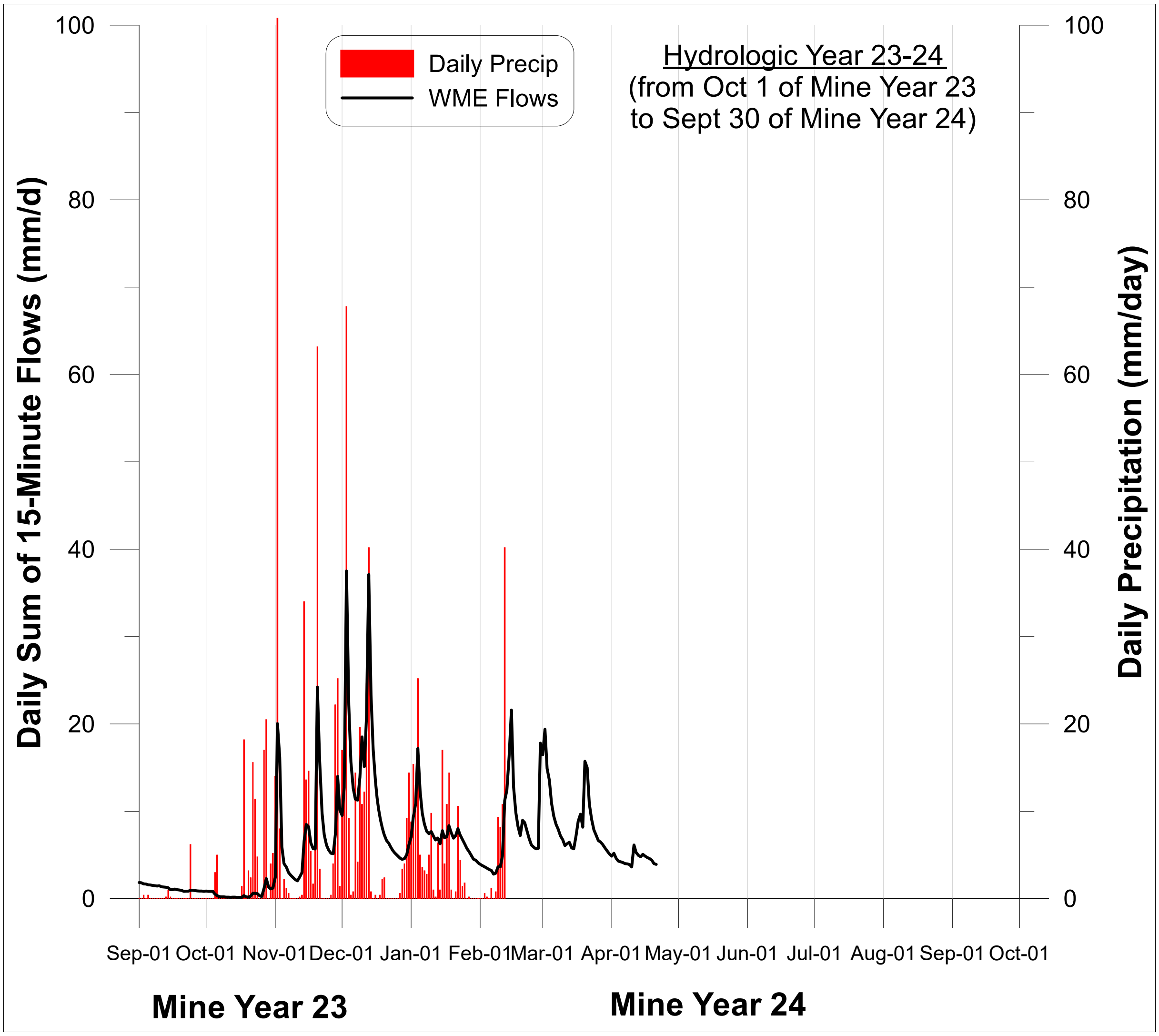


Figure 5-5. For Hydrologic Year 23-24, time series of daily precipitation, daily sums of flow, and 15-minute flows, both in mm/day and with the same vertical scale, at Station WME (see also Figure 4-9).

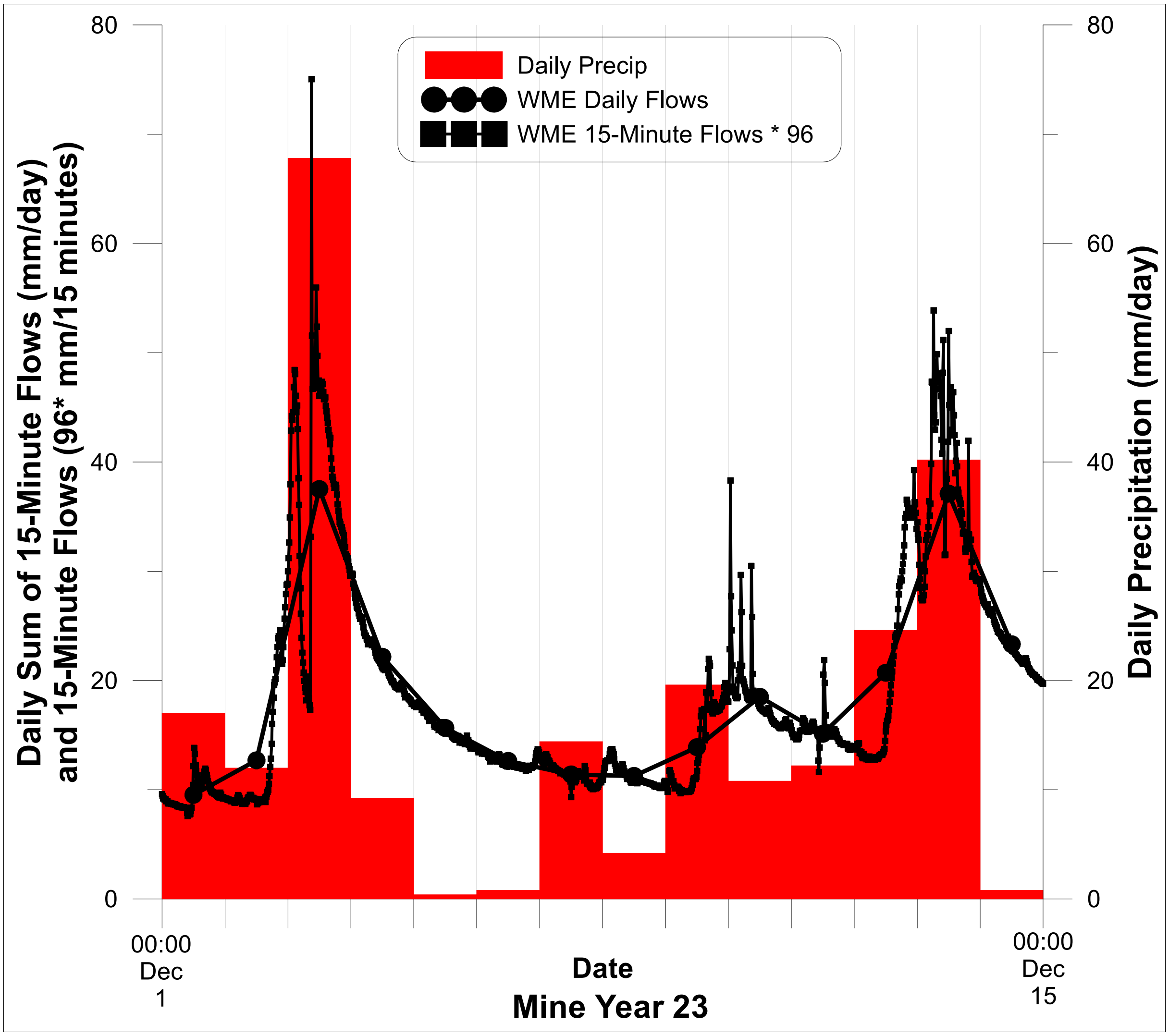


Figure 5-6. Closeup of December 1 to December 15 of Mine Year 23 showing time series of daily precipitation, daily sums of flow, and 15-minute flows, all in mm/day and with the same vertical scale, at Station WME.

Precipitation was relatively low in late December (Figure 5-5), and flow was higher than precipitation through December 30. From December 14 through December 29, cumulative precipitation was 14 mm and cumulative equivalent flow was 138 mm, for a net deficit of 124 mm. This means the roughly 195 mm of retained water decreased to about 71 mm by December 29.

Precipitation increased from December 30 through early January of Mine Year 24, then decreased through January 8. This span of precipitation produced only a single peak of daily flow, on January 4, the same day as highest daily precipitation. In fact, peak flow persisted only for about an hour on this day, based on 15-minute flows. The cumulative precipitation and flow from December 30 through January 8 was 101 mm and 94 mm, respectively. Thus, this 10-day span resulted in a negligible increase of 7 mm in retained water, for a retained cumulative total of 78 mm for this portion of the hydrologic year.

Occasional moderate peaks of precipitation through the remainder of January of Mine Year 24 created a relatively smooth rate of flow with only minor peaks. After precipitation decreased sharply on January 23, flow showed a gradually decreasing trend. From January 9 through February 8, cumulative precipitation was 93 mm and cumulative equivalent flow was 179 mm. This deficit of 86 mm offset the retained total of 78 mm for this hydrologic year, so at this point there was no net retained water.

On February 9 through 12, cumulative precipitation was 69 mm with the peak value of 40.2 mm on February 12, with no additional precipitation data after February 13. Flow also increased at this time, with a cumulative equivalent flow of 23 mm. Without subsequent precipitation data, addressing water retention any further at Station WME was not possible.

5.2 Upstream Station EMO, Hydrologic Year 21-22

Because the hydrologic year starts in October at this site, and frequent flow monitoring started on November 1 of Mine Year 21, flow data for that October were not available. Nevertheless, precipitation was relatively low (about half the long-term average for October, at 114 mm), and, on November 1, flow was relatively low. This suggests October was a minor contributor to the mass balance of water through the hydrologic year and relatively little of October precipitation drained from the waste rock.

After November 1, the first peak of flow that rivalled precipitation was on November 4 of Mine Year 21 (Figure 5-7). Through October to November 3, cumulative precipitation was 154 mm. Thus, an estimated 0.154 m of water was retained within the local portion of EMO waste rock in autumn before significant rapid outflow began. This localized value of 0.154 m is similar to 0.085-0.188 m above for the entire WME catchment. Because waste rock is up to tens of meters high, about 1% or less had to be “wetted” and/or saturated before rapid flow began.

From November 4 to November 15, cumulative precipitation was 178 mm and cumulative equivalent flow was 131 mm. Thus, another 47 mm was retained during this period, for a total of 210 mm during this hydrologic year through November 15.

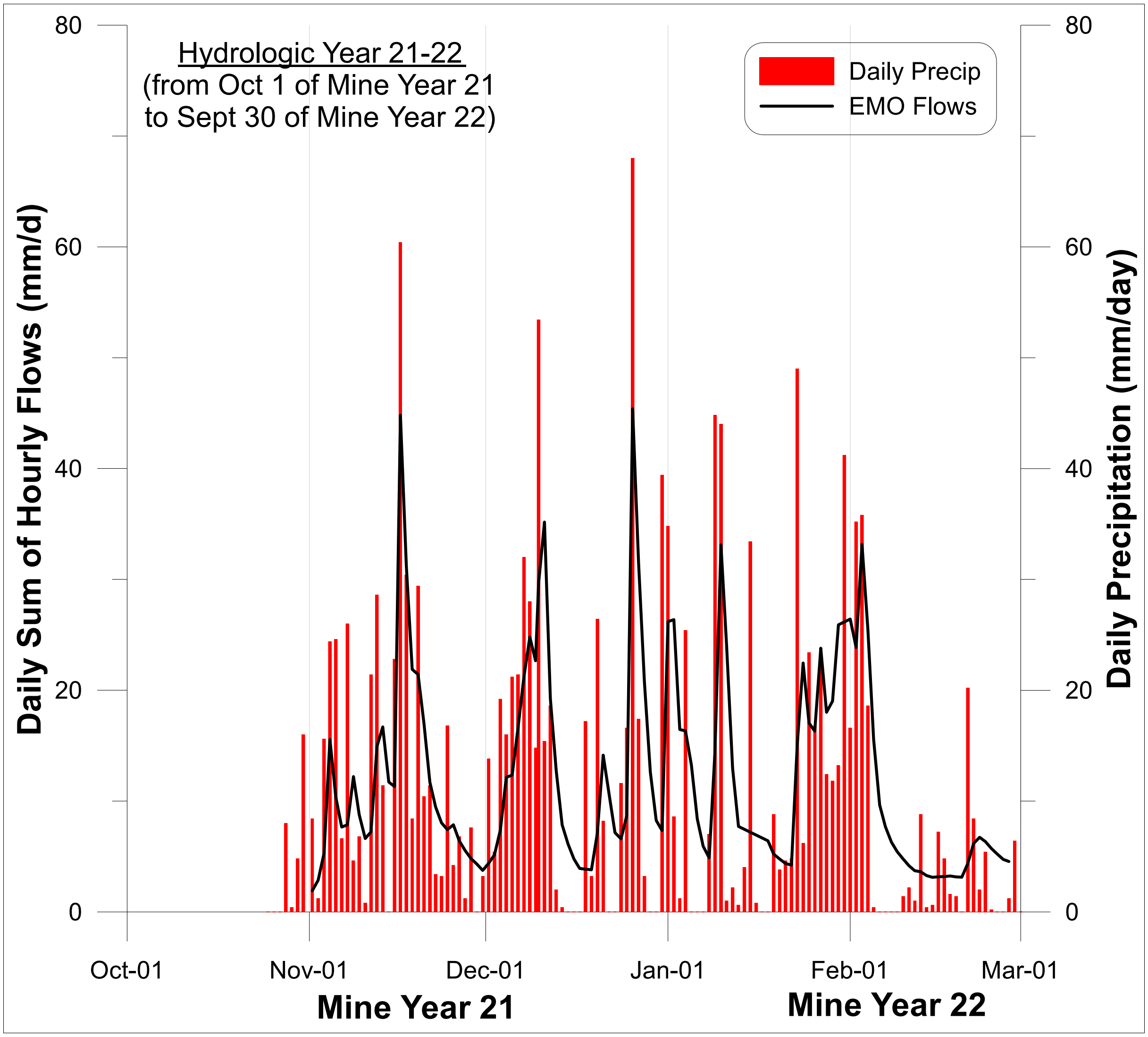


Figure 5-7. For Hydrologic Year 21-22, time series of daily precipitation and daily sums of flow, both in mm/day and with the same vertical scale, at Station EMO (see also Figure 4-10).

Prominent peaks in precipitation and flow occurred on November 16. Higher-frequency, hourly flow data (Figure 5-8) revealed that the dynamic variability of flow was much greater than indicated by a single daily value (Figure 5-7). On that day, hourly flow rose rapidly, doubled up to a maximum persisting for only about one hour, and then rapidly decreased by half. As also noted in Section 5.1 for WME, high-frequency flows every hour at EMO showed the rapid and highly variable flow of water through this full-scale waste rock within hours.

Precipitation and flow at EMO gradually decreased from November 16 through the end of November, but flow was typically higher each day (Figure 5-7). For the mass balance, November 16 through November 30 produced cumulative precipitation of 197 mm and cumulative equivalent flow of 206 mm. As a result, there was about the same outflow as infiltration during this time. The net retention of water within the waste rock decreased slightly by 9 mm for a running total of 201 mm.

Significant daily precipitation occurred through the first 12 days of December of Mine Year 21, causing daily flow to increase gradually and then peak on December 11. Flow then sharply decreased after the rainfall stopped on December 12, and continued to decrease until the next peak precipitation on December 18. From December 1 through December 17, cumulative precipitation was 262 mm and cumulative equivalent flow was 246 mm. Thus, infiltration was only about 7% higher during this period. Nevertheless, there was net retention of 16 mm of water, for a running total of 217 mm so far for the hydrologic year.

From December 18 through January 18, there were several peaks of daily precipitation, with some rivalled by near-simultaneous peaks of flow. An interruption in flow monitoring on January 14-17 means flow data was lost during a peak precipitation event of 33 mm on January 15. Based on flow measurements on January 13 and 18, average flow might have been 6-8 mm/day, with a four-day total of about 28 mm. The four-day total may have been even higher due to the precipitation on January 15. Overall, from December 18 through January 18, cumulative precipitation was 419 mm and cumulative equivalent flow was at least 432 mm. Thus, there was likely a net loss from retention of perhaps 13 mm or more, for a running total of roughly 220 mm so far for this hydrologic year.

Starting January 19 of Mine Year 22, an extended period of significant precipitation occurred daily until February 5. The first major peak of precipitation during this period occurred on January 23, which resulted in the first major peak of daily flow about a day later (Figure 5-7). However, hourly flow data indicated peak hourly flow occurred late the same day (Figure 5-9), with the flow rate increasing by more than a factor of four through the afternoon of January 23.

From January 19 through February 5, cumulative precipitation was 325 mm and cumulative equivalent flow was at least 301 mm, for a deficit of 24 mm. However, one day of flow monitoring on January 31 was missing, and flows on January 30 and February 1 were 26 mm/day, suggesting the flow on January 31 was around 26 mm. If correct, this cancelled the aforementioned deficit, and the running total of water retention remained around 220 mm for the hydrologic year. As above, high-frequency flows every hour at EMO tell a different story than the daily sums, and show the rapid and highly variable flow of water through this full-scale waste rock within hours.

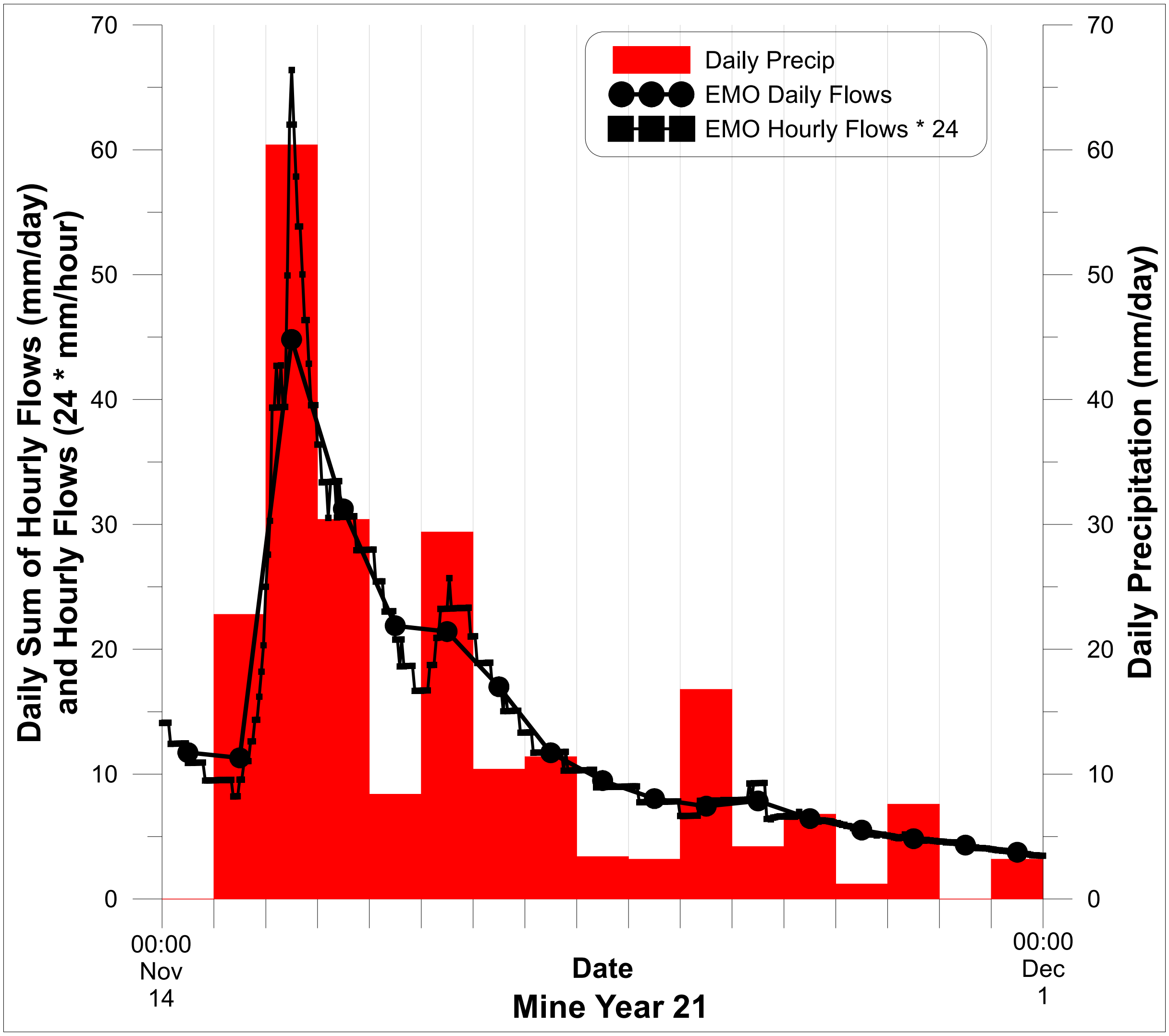


Figure 5-8. Closeup of November 14 to December 1 of Mine Year 21 showing time series of daily precipitation, daily sums of flow, and hourly flows, all in mm/day and with the same vertical scale, at Station EMO.

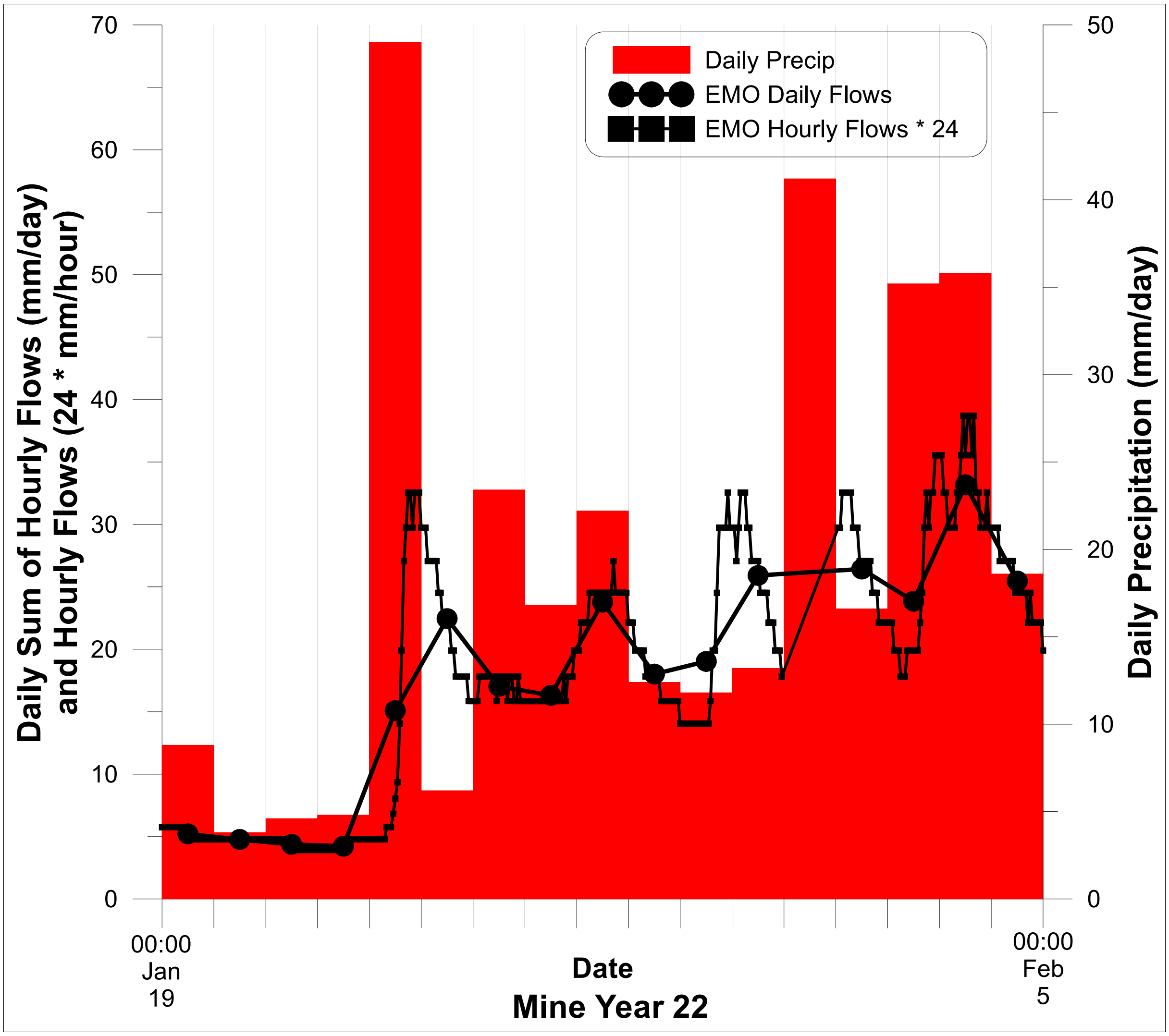


Figure 5-9. Closeup of January 19 to February 5 of Mine Year 22 showing time series of daily precipitation, daily sums of flow, and hourly flows, all in mm/day and with the same vertical scale, at Station EMO.

After February 5 of Mine Year 22, rainfall was mostly negligible with a few peaks in late March until high-frequency flow monitoring at EMO stopped on February 28. From February 6 through February 28, cumulative precipitation was 67 mm and cumulative equivalent flow was 111 mm. Thus, as the drier part of the hydrologic year was beginning, there was a net deficit of 44 mm, so the amount of water retained in the waste rock fell to 176 mm by the end of February. This locally determined retention is significantly higher than that for the whole WME catchment by the end of February of Mine Year 22.

During the later, drier portion of the hydrologic year, the outflow was likely greater than infiltration, as seen for WME (Section 5.1). This would have reduced the net retention until the next hydrologic year.

5.3 Brief Diurnal Oscillation in Flow

The measurements of hourly or 15-minute flows at this minesite provided important information not obtained by monthly, weekly, and even daily measurements. Preceding Sections 5.1 and 5.2 explained how the higher-frequency monitoring showed additional information, or more accurate information, than daily values (e.g., Figures 5-2, 5-4, 5-6, 5-8, and 5-9). This high frequency monitoring also showed how flow through full-scale waste rock could change substantially within hours. This is all in agreement with the quotation from Kirchner et al. (2004) in Section 1.1 of this MDAG case study.

This high frequency monitoring also revealed short periods of daily oscillations in flow from the waste rock. In late March of Mine Year 22, Station EDT located between Stations EMO and WME (Figure 3-1), showed these oscillations clearly (Figure 5-10). Hourly flows reached minimum values around midnight and peaked around noon each day.

Downstream at WME, which is a composite of waste-rock flows, these oscillations were superimposed on the recession curve of decreasing flows (Figure 5-11). At WME, the daily minimum and peak flows were typically delayed a few hours after EDT. Oscillations at WME were also noted about a month earlier (Figure 5-2), but these oscillations were not as regular and consistent.

The cause of these brief periods of significant daily oscillation in flow is not known. No other periods of significant oscillation were noted in the monitoring data.

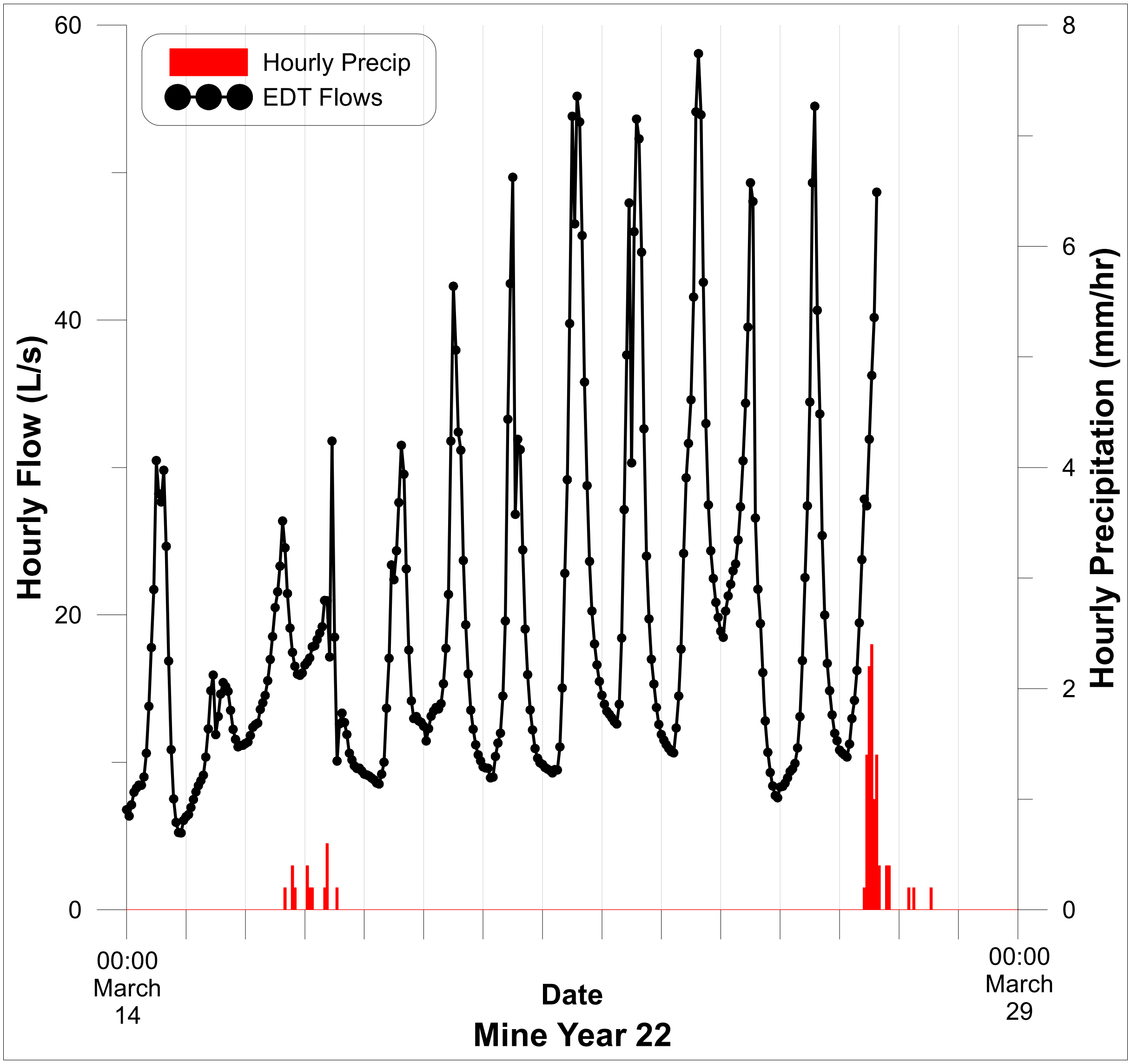


Figure 5-10. Closeup of March 14 to March 29 of Mine Year 22 showing diurnal oscillations in hourly flows, at Station EDT.

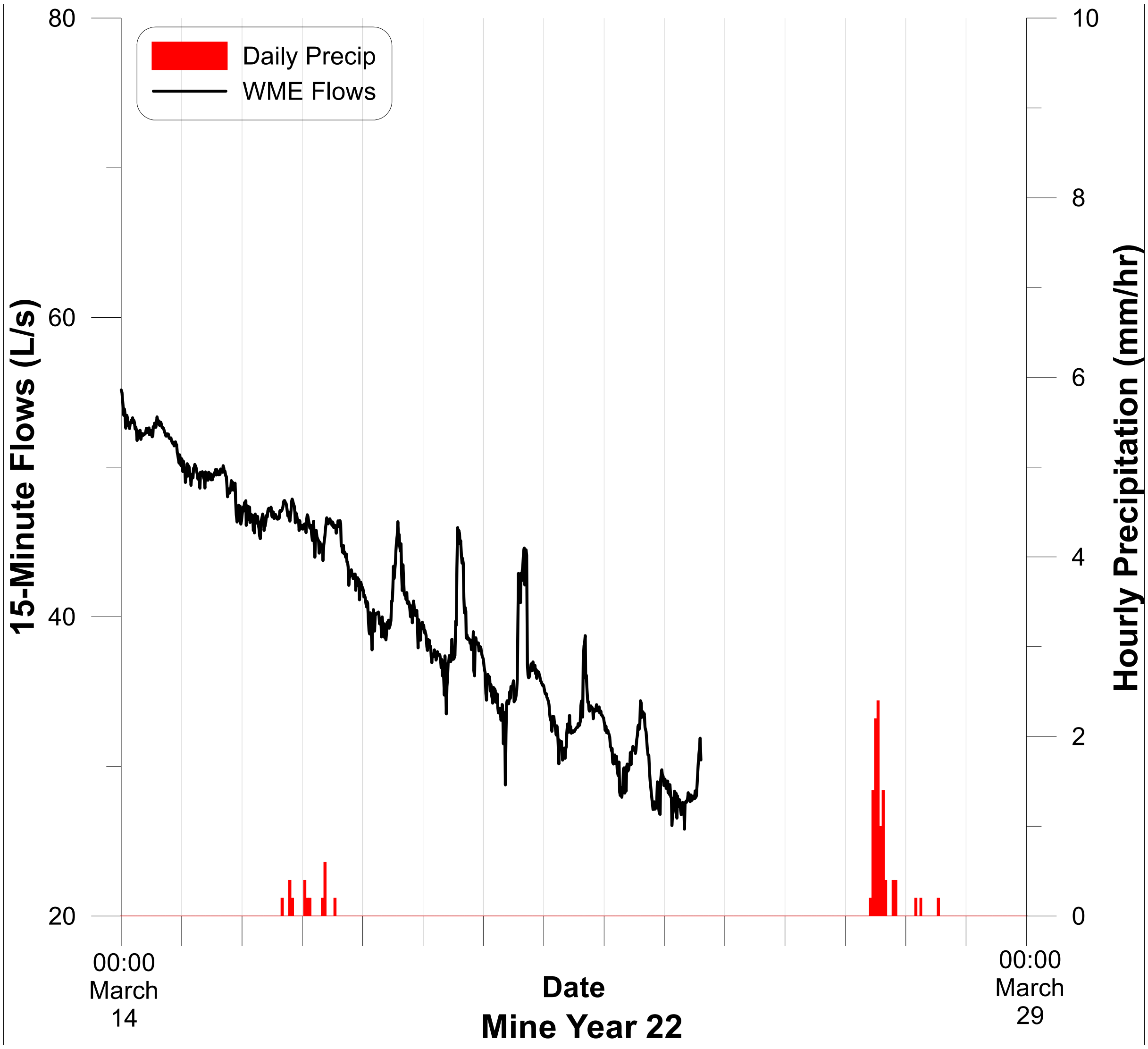


Figure 5-11. Closeup of March 14 to March 29 of Mine Year 22 showing diurnal oscillations in hourly flows, at Station WME.

6. Conclusion

For decades, full-scale waste-rock piles have been recognized as complex minesite components in all three spatial dimensions and through time. While many waste-rock investigators recognize this complexity of coarser and finer material, many ignore its reality and oversimplify water movement in the coarser material. It appears the primary reasons for this include: (1) the lack of high-frequency monitoring data (hourly and more frequently) to characterize the rapid flow of water through full-scale waste rock, (2) detailed studies of smaller "test piles" and laboratory columns that are unavoidably unrepresentative of full-scale waste rock, and (3) the desire to model water flow through waste rock despite a lack of realistic equations to simulate turbulent, non-Darcian, non-capillary flow in coarse rock.

For full-scale waste-rock piles at minesites, the way to resolve the many current misconceptions is by (1) frequent (at least hourly) monitoring of full-scale waste-rock piles, and (2) abandoning the notions of laminar flow and capillarity in coarse waste rock. This MDAG Case Study contributed by reviewing one previous case study and a new case study of rapid flow through a full-scale pile.

The previous case study included monitoring of internal waste-rock temperatures and basal water-table levels in a run-of-mine, full-scale, waste-rock pile approximately 40 m high. The monitoring showed that some infiltration could pass downward through tens of meters of waste rock within 12 hours. Moreover, a substantial mass of infiltration could pass through 40 m of waste rock in 36-42 hours.

In this new case study, approximately 10^8 metric tonnes of waste rock, mostly in one pile, were stacked up to tens of meters high. Each year the uncovered run-of-mine waste rock was exposed to about 1.8-1.9 m of precipitation. In this cool coastal climate, there was relatively little evaporation and no long-term winter snowpacks. In other words, precipitation, which was measured daily, was a reasonably reliable estimate of infiltration into the waste rock.

Recent studies of this site using least-squares spectral analysis in the frequency-wavelength domain led to two important conclusions. First, precipitation, and thus infiltration, was generally random ("white noise"), but in an annually repeating cycle. Second, in outflow close to the toe of waste rock, no signal filtering of white-noise precipitation occurred at wavelengths less than 9-26 hours. Thus, unattenuated rapid flow ("plug flow") passed through the full-scale waste rock in less than 9-26 hours. This timing is similar to the previous case study discussed above, and is now supported by the findings of this new case study.

If a substantial amount of infiltration passed rapidly through the full-scale waste-rock piles at this site, then strong temporal correlations should be seen between peak values of precipitation and peak values of effluent flow. Peaks of precipitation should match peaks in measured flows, even when the peaks are offset by lag times representing the transit time through the waste rock.

Such correlations were seen, at both upstream Station EMO at the toe of waste rock and downstream Station WME representing a composite of upstream flows. Moreover, the daily peaks of outflow lagged behind their corresponding daily peaks of precipitation by only 0-2 days at both stations. Because time discretization was one day for precipitation, refining these lag times to hours was not possible, although additional data (discussed below), showed the shortest lag times are likely roughly a few hours. In any case, these peaks represent the fastest flows, but not necessarily a significant mass (or volume) of flow, which required further analysis of the data.

Histograms of daily flows showed that flow at Station WME displayed a lognormal distribution based on 2.5 years of high-frequency monitoring, and flows at EMO were also expected to do so if a full year of monitoring were conducted. In turn, their lognormal probability density functions provided estimates of the mass of water that flows rapidly through the full-scale waste rock. Close in at the toe of the rock, Station EMO indicated roughly 50% of the water mass was due to highly variable rapid flow. Downstream at WME, roughly 25% of the water mass was due to highly variable rapid flow. This highlights the downstream location of WME at a confluence, resulting in smoothing of flows, which was consistent with spectral analyses (Morin, 2016).

A further examination of the daily masses of water involved converting flow into units of mm/day, for direct comparison to precipitation in mm/day. For WME, this showed that the daily peak of flow following a daily peak of precipitation rarely represented more than two-thirds of the mass of precipitation. In other words, at downstream Station WME where flows were smoothed and composited, less than two-thirds of the volume of a daily peak of precipitation passed through all waste rock in less than a day or two. In contrast, EMO at the waste-rock toe showed that daily peak flow could represent around 75% of a preceding peak of precipitation. Thus, 75% or less of the volume of a daily peak of precipitation passed through the local waste rock in less than a day or two.

In both cases, flows after a peak value of precipitation remained elevated, and thus additional drainage of the infiltration occurred over subsequent days not addressed above by peak flows. This became the focus of the next evaluation of the data.

Running mass balances of water retention and outflow were calculated for the hydrologic years (October through September) with high frequency monitoring. This led to the following observations.

When precipitation and infiltration began increasing sharply in a hydrologic year, outflow did not immediately respond. Instead, flow reached peak values, confirming the onset of rapid movement, only during later precipitation events.

This is sometimes called “wetting up” of a waste-rock pile after a dry period, in this case after spring and summer. For downstream Station WME that monitors all the on-land waste rock at this site, and for upstream Station EMO at the toe of local waste rock, approximately 0.085-0.188 m of precipitation occurred before rapid flow began. Because the waste rock at this site is up to several tens of meters high, this means less than 1% of the waste rock had to be wetted and/or saturated before rapid flow began.

After this initial retention of water, 100% mass of water equivalent to precipitation from a storm event typically drained from the waste rock within days to weeks, during the wet portion of the hydrologic year. During the drier portion, 100% drainage of a peak rainstorm required weeks to months. It is important to note that 100% equal masses, or volumes, of precipitation and outflow do not confirm identical masses of water. That is an issue that cannot be assessed here based purely on precipitation and outflow. Here, only the short-term peaks within a day or two of a peak in precipitation can be confirmed as identical, based on spectral analysis.

After the initial water retention, there was generally little additional retention through the wet portion of a hydrologic year. During the subsequent drier portion, there was a gradual net loss of retained water. Thus, any net retention of water during a hydrologic year was virtually drained by the end of that year. This led to the repeat of wetting as the next hydrologic year began.

To that point, the high-frequency measurements of flow had been summed to daily values, for comparison with daily-measured precipitation. However, the comparison of high-frequency flows, to daily precipitation and to daily flow, led to additional observations and corrected information. This included the following.

- Some daily values indicated peak outflow occurred the day after peak precipitation. In contrast, high-frequency flows showed that some peak flows occurred the same day.
- Daily sums masked significant short-term temporal variability. Flows could increase and decrease sharply within a few hours, by a factor of two or more, with peak flows lasting only 15-60 minutes.

Thus, high-frequency monitoring confirmed the rapid and highly variable flow of water through this full-scale waste rock within hours, more than was apparent from daily flows.

With high-frequency flow measurements, short periods of about two weeks were identified during which flow rates significantly oscillated daily. Where consistent, hourly flows reached minimum values around or just after midnight and peaked around noon or just after each day. The cause of these brief periods of oscillation is not known.

All the preceding findings highlight the importance of high-frequency monitoring of full-scale waste-rock piles. This would lead to the more reliable understanding, characterization, and modelling of water flow through full-scale waste-rock piles.

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