Appendix B
Mine Water Balance Analysis

CDM

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Memorandum

To: *Emily Corsi, Herb Rolfes, DEQ*

From: *Bill Bucher, Kim Chase - CDM*

Date: *April 12, 2010*

Subject: *Mine Water Balance Analysis - Troy Mine*

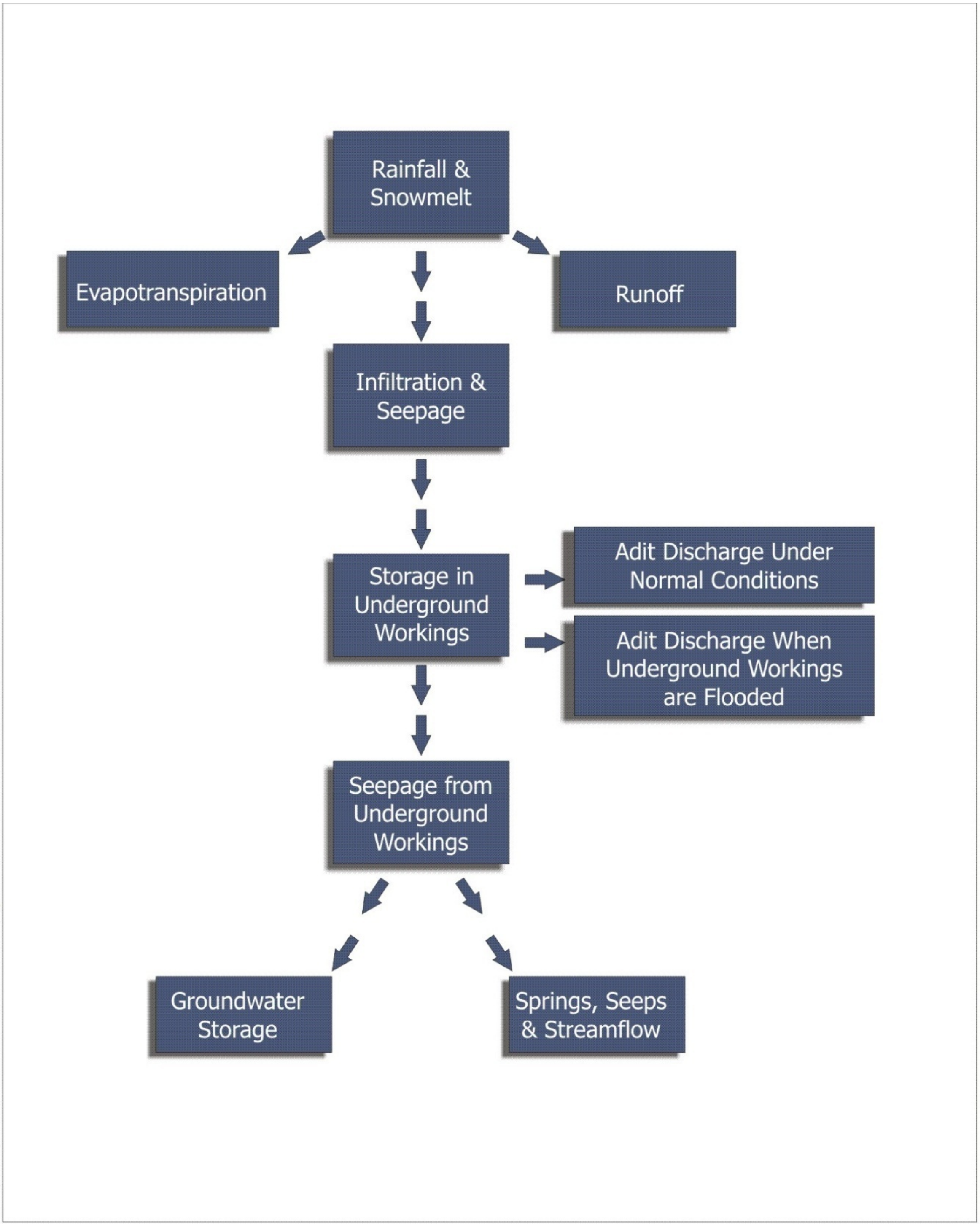
CDM has been retained by the Montana Department of Environmental Quality (DEQ) to develop a water balance model for the Troy Mine to predict expected discharge from the mine workings, if any, after mine closure. The purpose of this memorandum is to present the results of our analysis of existing data that we used to predict whether the Troy Mine will fill with water after pumping ceases to a level that will allow discharge of mine water to the surface. If the mine workings are predicted to discharge, how long it will take to do so and how much discharge may be expected will also be predicted. A review of the existing data and the conceptual water balance are available in a Technical Memorandum prepared by CDM dated January 16, 2009.

The Troy Mine is an underground copper and silver mine located south of the town of Troy in Lincoln County, MT. ASARCO began operating the mine in 1982 and halted production in 1993 due to low metals prices. The mine was sold to Revett Silver Company and production resumed under Genesis, a subsidiary of Revett, in 2005. In 2006, Genesis submitted a Revised Reclamation Plan, for which an Environmental Assessment (EA) must be completed. In support of the EA, this Memorandum assesses the possibility of mine flooding discharging to the surface.

Conceptual Water Balance Model

The conceptual water balance is shown in Figure 1 and is discussed in detail in the January 16, 2009 Technical Memorandum. The water that enters the mine all originates as rainfall or snowmelt above or near the underground workings. This precipitation, minus the portion lost to evapotranspiration, overland or subsurface runoff, enters the groundwater system adjacent to the mine workings and potentially seeps through the mine walls or enters fractures that connect to the mine. The water received by the underground workings may be held as storage or it may seep out through fractures or porous formations. If the underground workings are flooded, water may discharge from the service adit, the lowest

Figure 1. Conceptual Model of Mine Water Balance



P: Troy Mine|7.0 Reports\WaterBalance TechMemo|Figure1.cdr potential connection to the surface. Under normal conditions, there is some discharge from the service adit due to water entering from the adit walls and back. It is only the water entering or leaving the mine workings that is of concern in this analysis of whether the or not the mine workings will flood to an elevation which will result in discharge from the mine workings via the service adit.

The conceptual model of mine flooding developed in this study is based on the following assumptions about groundwater in the vicinity of the mine:

- The geology of the rock around the mine workings is fractured metamorphic rock, which allows significant flow through the fractures.
- The aquifers adjacent to the mine workings are local, unconfined aquifers which have the potential to fluctuate rapidly in response to precipitation and runoff patterns as well as mine dewatering activities.
- If pumping ceases and water levels recover, there is a potential for water to discharge through the service adit at a known elevation (4225 ft.).

Figure 2 is a conceptual drawing of a flooded mine that will discharge through an adit. In this scenario, water levels have recovered to an elevation sufficiently high to permit overflow through a discharge point, in this case the service adit of the Troy Mine. Figure 3 shows an alternate scenario in which the recovered water level remains below the overflow point and the mine does not discharge. Determining which scenario occurs in the future after pumping has ceased depends on the recovered elevation of the local aquifer. This is essentially a groundwater analysis problem, which requires an understanding of the local geology and aquifers that we do not have. Therefore, the ability to analyze this problem completely is compromised, and we are limited to the storage data collected by the mine operators to interpret the potential behavior of the local systems under future conditions.

Methods

Because no quantitative information is available about the groundwater conditions surrounding the underground workings, it is not possible to directly calculate the mine water's effect on the surrounding water table. Additionally, there is no way to calculate the magnitude of flows into the underground workings or natural seepage out of the workings. However, it is possible to calculate the difference between inflow and outflow from the change in storage over a given time period. The basic method employed here is the analysis of mine inflow volumes as determined from the pumping rates and storage changes measured by the mine operators through the years. The inflow to the mine workings can be defined as the pumping rate plus the change in storage:

Figure 2. Conceptual Model of Mine Discharging through Adit

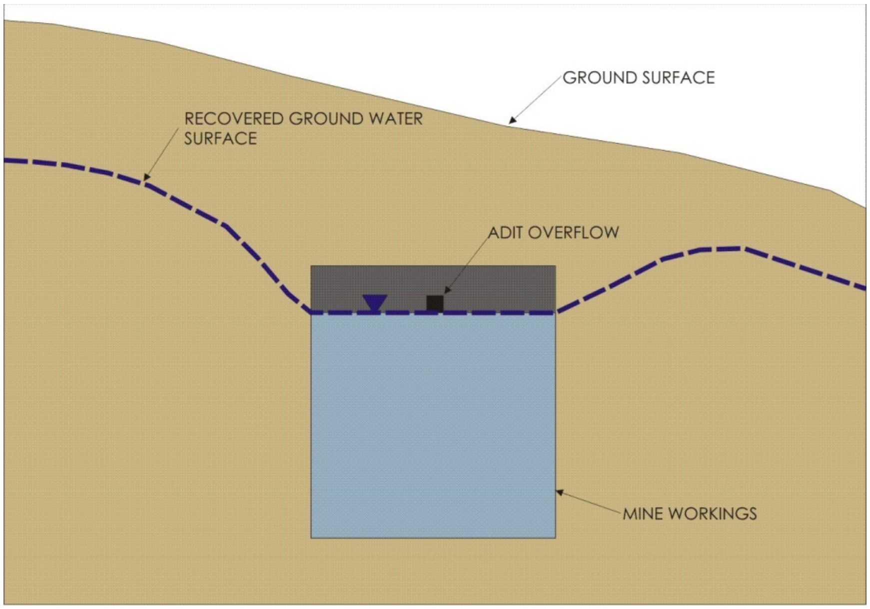
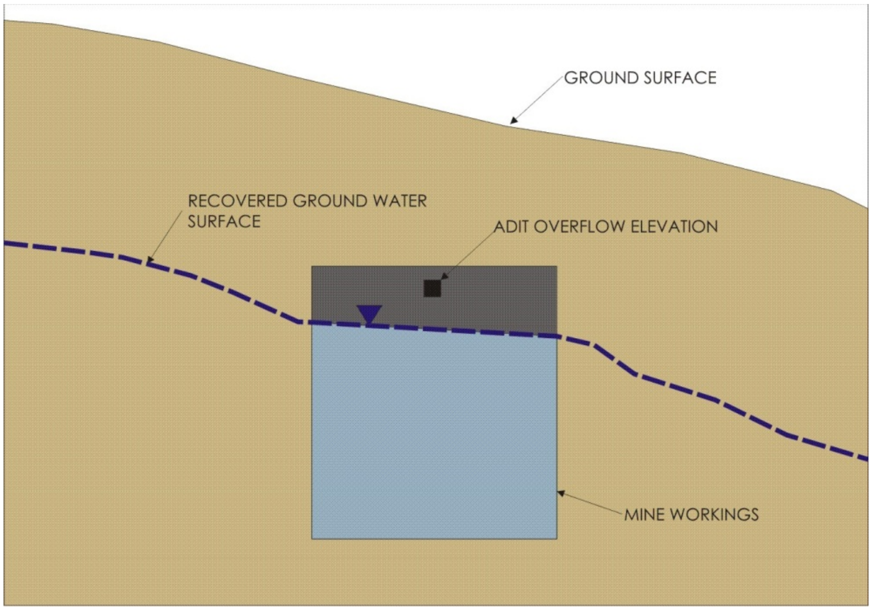


Figure 3. Conceptual Model of Mine without Discharge to Surface



$$I = Q_p + \Delta S$$

Where:

I is the mine inflow for the period
Q_p is the pumping rate for the period
ΔS is the change in mine storage for the period.

It is possible that portions of the mine discharge to the surrounding formations where the local water table is below the mine water elevation. This potential is highest when the mine pool is at a high elevation and the local aquifers are depressed after a dry period such as normally occurs in late summer. However, records indicate that this mine generally receives inflow in excess of any outflow, and in this analysis we will use the term mine inflow to mean the net difference between inflow and outflow from the mine workings.

Relationships for inflow were established based on the hypothesis that inflow to the underground workings would be dependent on rain and snowmelt amounts and on water levels in the underground workings. Rain and snowmelt, acting through the groundwater pathway, are believed to be the primary source of water input to the underground workings. When groundwater levels are higher, it follows that the head difference between water in the underground workings and the surrounding groundwater is greater and, therefore, inflow to the underground workings will be greater. Therefore, inflow is proposed to be a function of both recent rain and snowmelt and the elevation of the local groundwater surface:

$$I = f(R, H)$$

Where R is a rainfall and snowmelt and H is a measure of head difference between the mine pool and the local aquifer. The sum of rainfall plus snowmelt is a logical measure of water that has potential to enter the mine. To show that the inflow to the underground workings is related to rainfall and snowmelt, inflow was plotted for each year alongside rainfall and snowmelt.

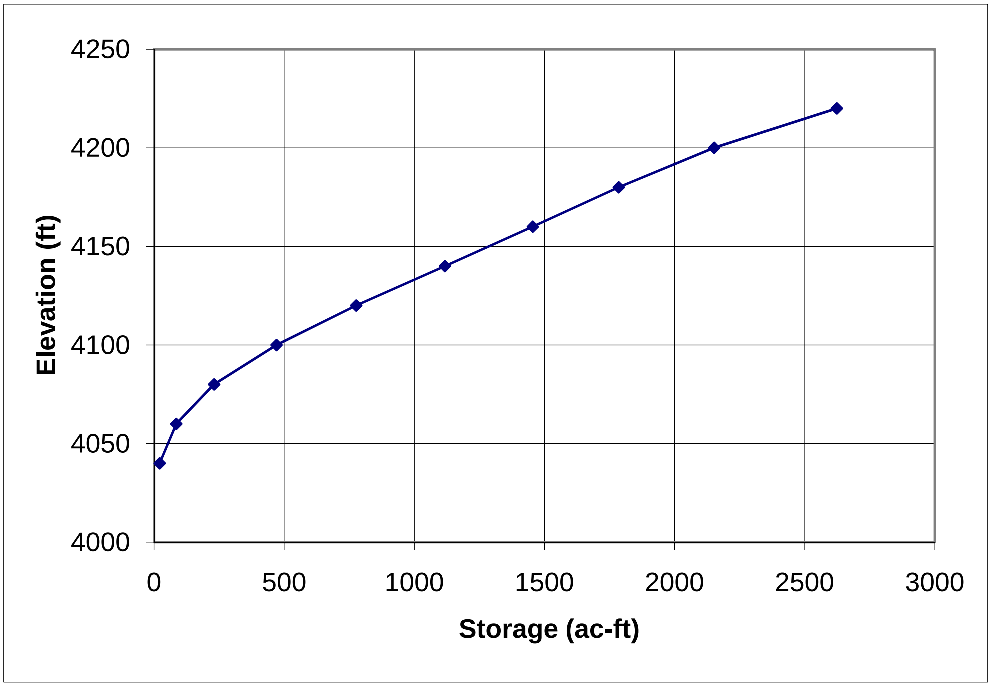
Rain and snowmelt was plotted against inflow over several different time-scales to determine the most appropriate time scale for analysis. This resulted in a method for predicting the inflow to the mine for any precipitation/runoff condition. For the annual time scale, an average value of total rain plus snowmelt was used as the input variable for the years 2004 through 2008 giving a set of four different inflows for these years. Then the actual value of inflow for each year was compared to the value predicted by the linear correlation. This predicted inflow was then plotted against the average water elevation in the underground workings during each year. A second linear correlation was then calculated for inflow as a function of water elevation and was used to predict the expected effect of water level on the change in storage.

With this information, it is possible to estimate the potential for surface discharge from the underground workings and the expected outflow. Further calculations can predict the time until discharge with an assumed initial mine pool elevation and typical precipitation conditions.

Analysis and Results

Our analysis of mine water levels relies on the elevation-storage curve developed by Genesis, Inc. (2004) which is shown in Figure 4 after conversion to acre-feet (ac-ft). This relationship is based on mine surveys of the extent of workings at sequential elevations in the mine with allowance for remaining pillars.

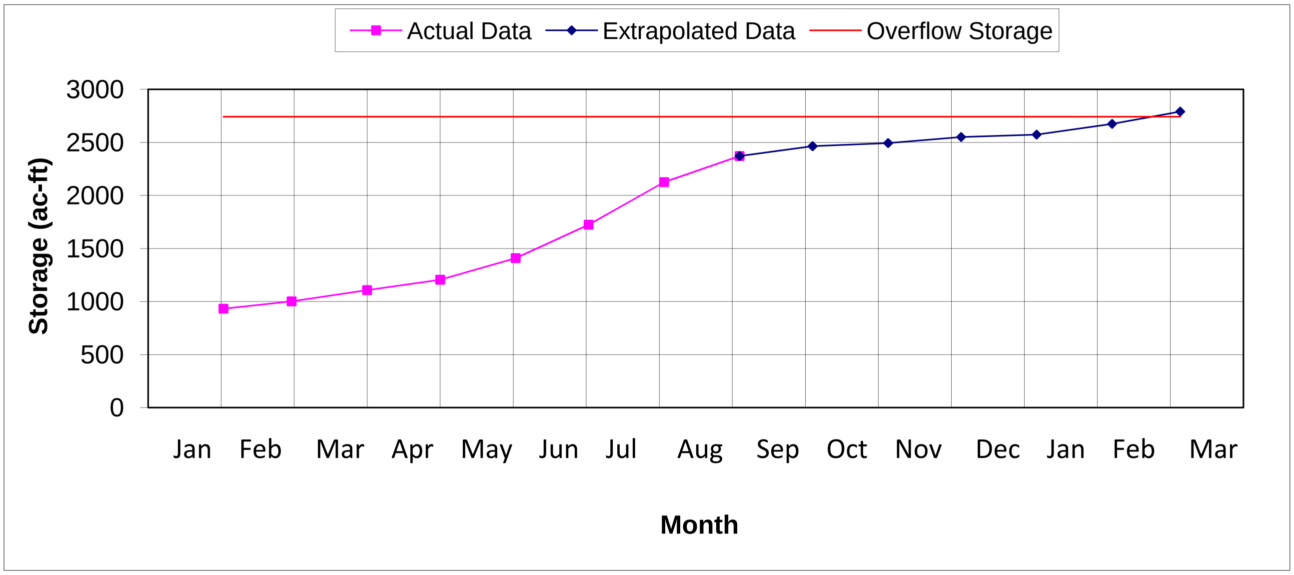
Figure 4. Water Elevation vs. Storage Relation for Troy Mine



Potential for Mine Flooding

The discharge of mine water from a flooded mine appears to be a real possibility based on data collected in water year 2003 when mine pumping did not occur. Figure 5 plots cumulative mine water storage from January 2003 through August 2003 (end of month values). At the end of August 2003, the storage volume was 2371 ac-ft, which corresponds to an elevation of 4209 ft, the highest recorded water level in this portion of the mine. This level is just 16 feet short of the adit overflow elevation of 4225 ft. In September pumping resumed, the storage volume did not exceed 2371 ac-ft, and pumping continued at a higher rate into 2004, decreasing the storage volume. If the pumping volumes are added to the cumulative volume at the end of August 2003, it is seen that the storage volume could have continued to increase, potentially exceeding the storage volume of 2,742 ac-ft (corresponding to a discharge elevation of 4225 feet) in February 2004. Thus, if pumping had not resumed, the mine may have started discharging in a relatively short period of time. On the other hand, it is expected that inflow rates decrease with higher water elevations. Therefore, it is also possible that the inflows would have decreased with increasing water elevation sufficiently that the mine would not have discharged. In the following analysis, an attempt is made to determine which of these scenarios is most likely based on analysis of available data.

Figure 5. Measured and Extrapolated Cumulative Mine Water Storage, 2003 – 2004.



Relationship between Inflow and Precipitation Events

As described in the methods section, the relationship for inflow was separated into a function dependent on rain and snowmelt history and a function dependent on water elevation. The first step was to develop the relationship between inflow and precipitation and runoff. This was initiated by examining the temporal sequence of rain and snowmelt at a local SNOTEL site with the inflow to the mine.

Daily precipitation and snow-water equivalent data were gathered from Natural Resources Conservation Service SNOwpack TELemetry (SNOTEL) site 932, Poorman Creek (Natural Resources Conservation Service, 2008). The SNOTEL site is located approximately 14.7 miles to the southeast of Troy Mine. It is located at an elevation of 5100 feet, near the middle of the range of surface elevations directly overlying the mine (4600 feet to 5580 feet). Data for accumulated precipitation are available for water years 1999 to 2008 and snow-water equivalent data are available from water year 1969 to 2008. Because of its relative proximity to the mine and its similar elevation, the Poorman Creek SNOTEL site should adequately represent precipitation conditions in the mine area.

The analysis was conducted on monthly, seasonal and annual time scales with special attention paid to lag between surface events and the inflow. The graphs located in Appendix A (Rain+Snow, Storage vs Time) show that the monthly change in storage within the underground workings follows the amount of rainfall and snowmelt very well. However, the lag time between the peak of rainfall plus snowmelt to the peak change in storage is inconsistent. The amount of time that the change in storage peak follows the rainfall plus snowmelt peak varies from zero to two months. In attempting to correlate rainfall and snowmelt with change in storage plus pumped volume during periods of pumping, several time scales were used. The correlation on a monthly basis was weak, with an r-squared of 0.3. When the change in storage was lagged one month behind the rainfall and snowmelt, the correlation weakened even further. The data was then reorganized by season: winter being January, February, March; spring being April, May, June and so on. This improved the correlation to an r-squared of 0.61. On an annual basis, the r-squared improved to 0.73. After removing 2007 from the data, the correlation improved further to an r-squared of 0.87. Because of the poorer correlations for the shorter time scales, the annual time scale was adopted for this analysis.

Figure 6 shows the relationship between mine inflow and rain plus snowmelt on an annual basis for water years 2004 through 2006 and 2008. The data for 2007 is excluded from this analysis because it is suspect for reasons explained later in this memorandum.

Based on the period of record from 1999 to 2008, the average annual rain plus snowmelt for the Poorman Creek SNOTEL site was 79.5 inches. Using the correlation relation established above, this amount of precipitation predicts an average annual inflow into the mine of 1418 ac-ft. To eliminate the effects of rainfall and snowmelt from the inflow relation, predicted inflows were calculated using the relationship in Figure 6 and then subtracted from the actual inflows measured in the corresponding years. These residual amounts were then added to the average annual inflow of 1418 ac-ft resulting in a set of adjusted inflows that are independent of rainfall and precipitation effects to the extent that the data allow. Table 1 summarizes this calculation.

Figure 6. Correlation between Mine Inflow and Rain plus Snowmelt for Water Years 2004 – 2006 and 2008

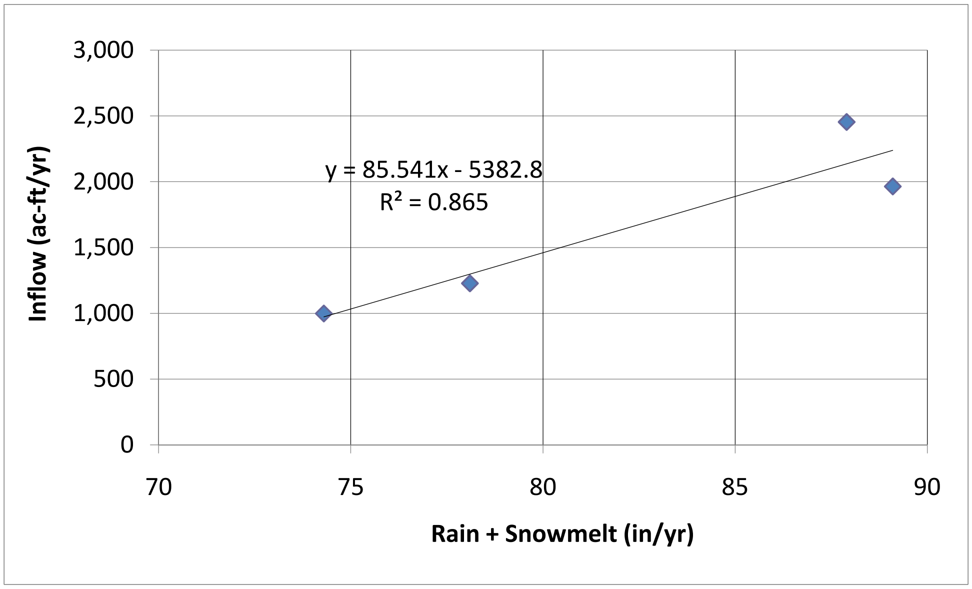


Table 1. Variables and Results of Adjusted Inflow Calculation.

Year	Average Elev (ft)	Measured Inflow (ac-ft)	Rain+snow (in/yr)	Predicted Inflow (ac-ft)	Residual (ac-ft)	Adjusted Inflow (ac-ft)	Q (cfs)
2008	4082.8	2454	87.9	2130	324.2	1736.4	2.4
2006	4169.9	1228	78.1	1291	-63.5	1348.8	1.9
2005	4189.8	999	74.3	966	32.6	1444.9	2.0
2004	4189.9	1965	89.1	2233	-267.5	1144.7	1.6

Relationship between Inflow and Water Elevation

Cumulative mine inflows for the years that the pool elevation was being controlled by pumping are plotted in Figure 7. These curves show that mine flow is generally relatively small and consistent through the fall and winter months and increases greatly, but by varying amounts, in the spring before tapering to lower rates in the summer. As shown in Figure 8, which shows storage levels in the mine throughout this period, stored water was rather high in 2004 through 2006, averaging 1854 ac-ft. In 2007, the water level was drawn down and remained relatively low through 2008. Figure 7 shows clearly the effects of maintaining a low storage level in 2008: the annual inflow for this year was the highest in the pumping period although annual rain plus snowmelt was higher in 2004.

Figure 7 also shows that mine inflow was negative during the winter in 2007. This suggests that water was flowing out of the mine for this period by means other than pumping. Inspection of Figure 8 shows that the mine was being rapidly drawn down through this period. That water would not be flowing into the mine during a period of rapid drawdown is physically difficult to explain and it is suspected that either the storage data or the pumping rates are in error during this period. Therefore, data from water year 2007 have not been used in this analysis.

With a relation between rainfall plus snowmelt and inflow established on an annual basis, the residual information can be used to develop information on the relation between water elevation and inflow. Conceptually the mine workings can be thought of as a large diameter well

Figure 7. Cumulative Inflow for Water Years 2004 through 2008

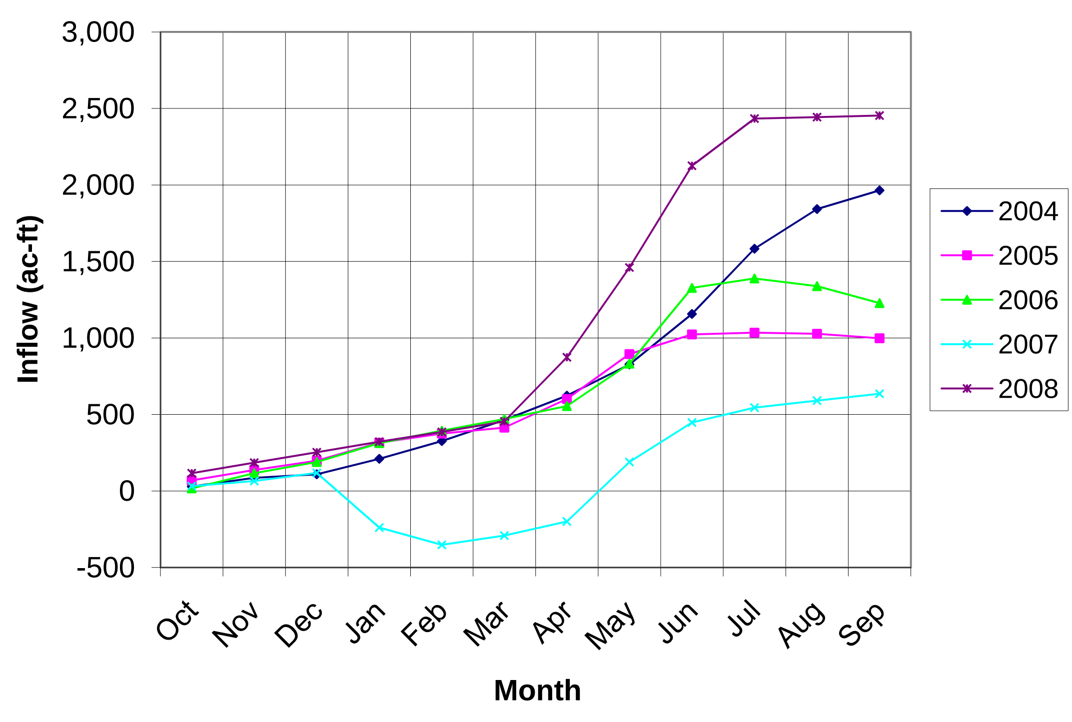
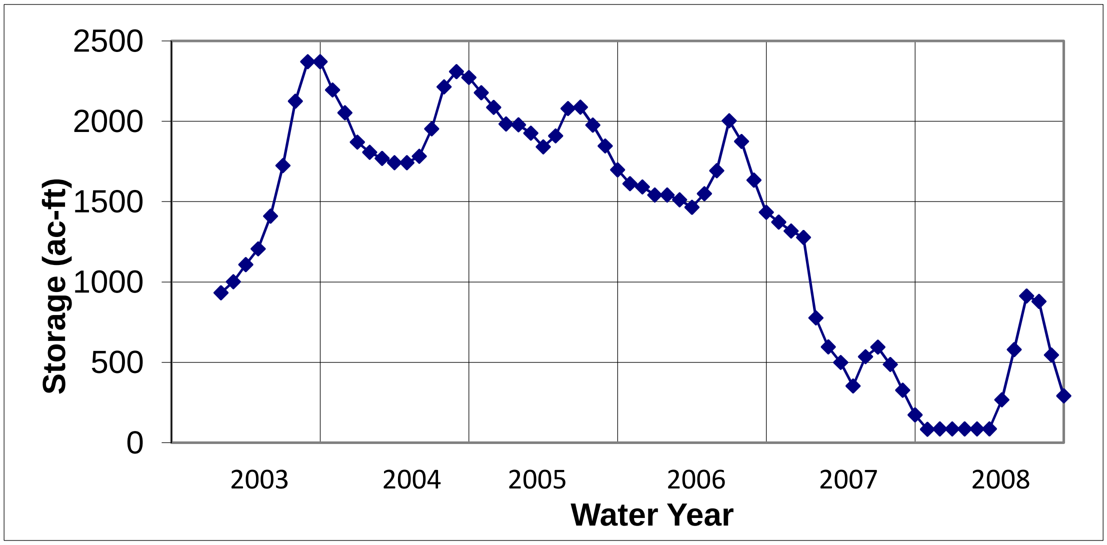


Figure 8. Mine Water Storage 2003 through 2008.



located within an unconfined aquifer. Because the time period for pumping in this analysis is a year, which is relatively long in most pumping applications, the relation of inflow and water elevation should approximate a Theis curve (Freeze and Cherry, 1979). The equation for the Theis curve is:

$$h_0 - h = \frac{Q}{4\pi T} W(u)$$

where $W(u)$ is the well function

$u = \frac{r^2 s_y}{4Tt}$

h_0 is the initial height of the water table

h is the height of the water table at distance r and time t

Q is the flow into the well

r is the radial distance from the well

S_y is the specific yield for an unconfined aquifer

T is the transmissivity of the aquifer

t is time since initiation of pumping

This linear equation relates water elevation (*h*) and inflow (*Q*). Plotting water elevation versus inflow for the four years of data presented in Table 1 and fitting a linear regression line through the points results in the graph shown in Figure 9. The r-squared for this correlation is 0.75. Extrapolating the line to the point where $h = h_0$ results in a predicted initial value (or recovered value) for h_0 of 4413 ft., well above the adit overflow elevation of 4225 ft. This suggests the water level in the mine will rise to the adit discharge level when pumping ceases.

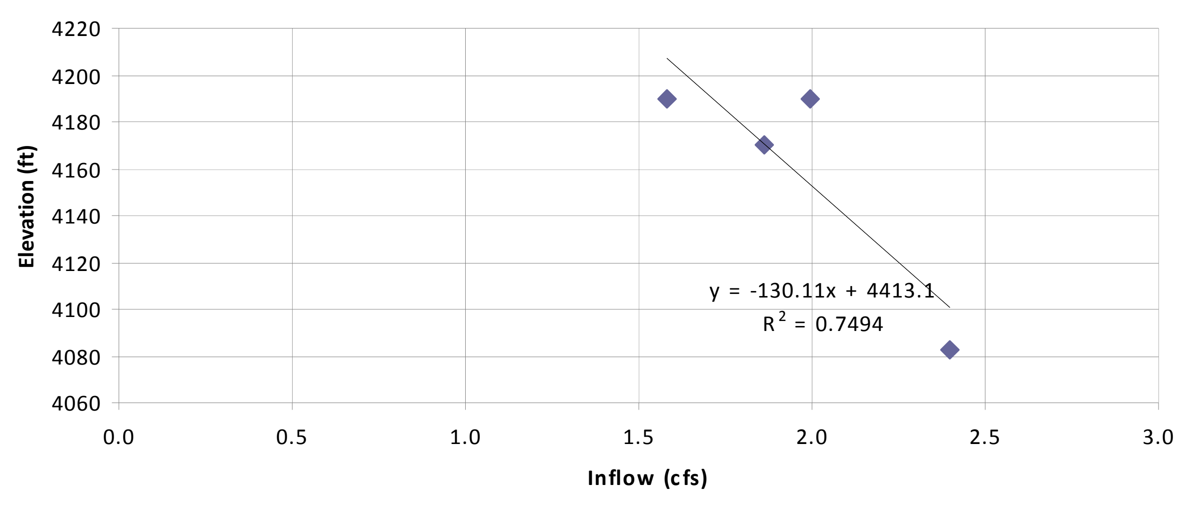
As a check on the validity of the Theis equation in this application, it is shown that a consistent set of aquifer parameters can be derived from the slope of the linear regression (negative 130). If we assume that the typical radius at the edge of the mine workings is related to the area of workings at elevation 4220 ft, the radius for computational purposes is about 800 ft. We can also use a specific yield of 0.05 for fractured crystalline rock (the range is typically zero to 0.10, Freeze and Cherry, 1979), we can calculate from the Theis equation that the formation transmissivity is about 4×10^{-4} ft^2/s. If we assume that the thickness of the affected aquifer is about 400 ft., this corresponds to a hydraulic conductivity of about 3×10^{-5} cm/s, which is mid-range in the expected hydraulic conductivities of fractured metamorphic rocks (Freeze and Cherry, 1979). Thus, a reasonable set of hydraulic parameters appears to be consistent with the slope calculated from the data. Note that this is not an attempt to derive actual hydraulic parameters; this calculation is merely a check that it is physically probable that the calculated slope can occur.

Timing and Quantity of Overflow

The relations derived in the previous sections can be used to estimate the time frame in which the mine workings will fill to the overflow point as well as the potential discharge volume. The average precipitation/runoff condition of 79.5 inches per year is assumed and the water elevation versus inflow relation is applied to calculate when the mine will fill to the overflow point. Then the average inflow at that elevation is used to calculate the average annual discharge from the adit due to the mine workings overflow. An additional assumption is that the inflow is distributed through the year approximately as it was in 2006, a year with close to average rain plus snowmelt.

If the mine starts completely pumped down to elevation 4020 in October and then the pumps are shut down, the calculations indicate that the mine will fill under average rain plus snowmelt conditions sometime in June of the following water year, 21 months later. Thereafter, the average rate of discharge to the service adit is anticipated to be about 1.5 cfs or 1,050 ac-ft per

Figure 9. Relation of Water Elevation to Adjusted Mine Inflow.



year. It is possible that the discharge will cease in August and September because of the lowered local water table in these months.

Annual and Seasonal Variations in Adit Discharge

Given the great variations from year to year and within any year in inflow to the mine, it is expected that discharges from the overflowing adit will vary both annually and seasonally. Given, the limited available data, estimates of natural variation in mine discharge rates cannot be made precisely and cannot accurately assess discharge rates during years in which precipitation is substantially higher or lower than during the years for which mine outflow data are available. The additional data necessary to refine this analysis can only be collected during unusually high or low precipitation years, and it cannot reasonably be expected that such opportunities will occur during the time frame in which this environmental analysis must be completed. Other methods of mine discharge estimation would require that data (ground water elevations, spring locations and flow rates, etc) have been collected prior to mining. Such data do not exist and cannot be obtained.

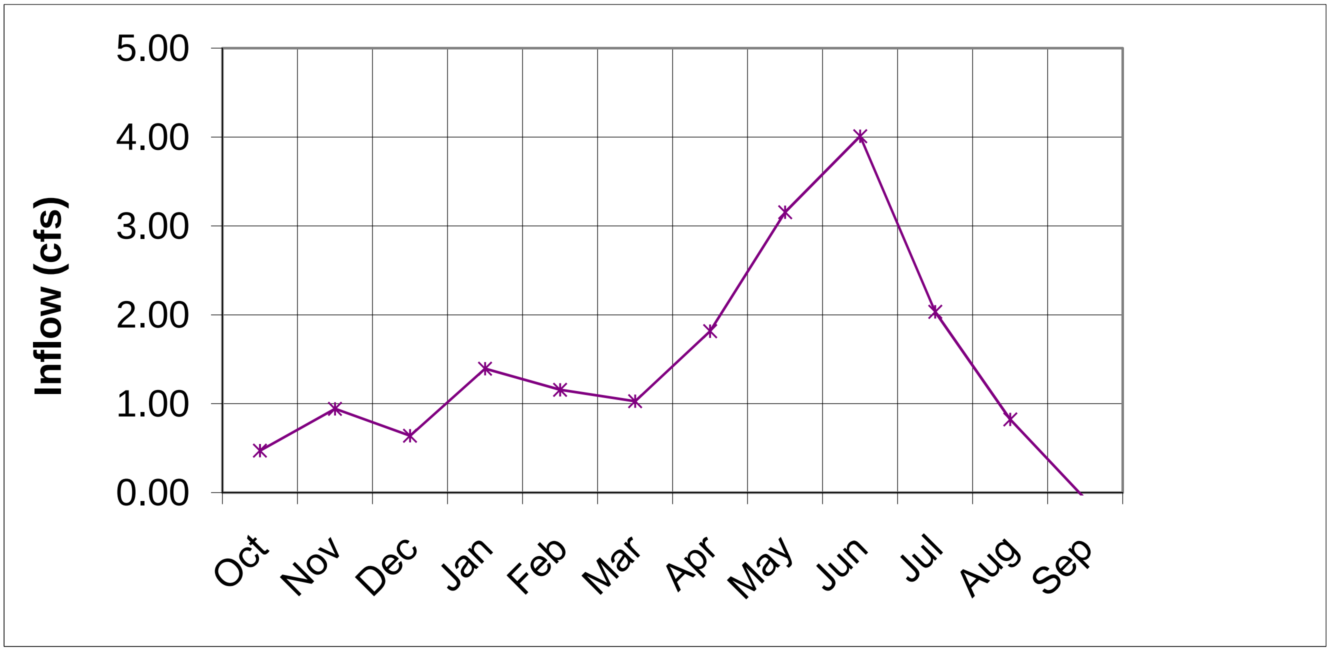
The relationship of water elevation to mine inflow (with no mine discharge) was determined based on four years of storage records. Within these years, 2004 was the wettest year (89.1 inches rain plus snowmelt) and 2005 was the driest (74.3 inches of rain plus snowmelt).

Comparing the calculated annual inflow for these years compared to the mean annual inflow shows that inflows were 39% higher than average in 2004 and 30% lower than average in 2005. If these ratios are assumed to apply to the inflow that would occur at the discharge elevation, the range of annual discharges varies from 1.0 to 2.0 cfs.

These two years, however, are not extreme precipitation years at the Poorman Creek SNOTEL site. In 2002 rain plus snow was about 104.1 inches and 2001 had 45.4 inches at this site, much greater and lesser amounts than were observed in 2004 and 2005. If we attempt to convert these more extreme amounts to inflows using the relationship derived for years 2004 through 2006 plus 2008, considerable extrapolation of the relation is required. In fact, the inflow predicted for 2001 is negative, indicating the inapplicability of this relation during drier years. Without storage-elevation data for more extreme years, it is not possible to predict with any certainty the behavior of adit discharge in extreme precipitation years. However, using the maximum rain plus snow value in 2002 (104.1 inches) from the ten-year period of record at Poorman Creek, an estimated annual adit discharge of 3.6 cfs is calculated. For lack of better data, this figure may approximate a 10-year return interval annual discharge.

Determining seasonal variations in predicted adit discharge is also problematic. As discussed previously, the attempts to develop robust, predictive models of monthly or seasonal flow were not successful. However, an estimation of the seasonal variation in predicted discharge for average conditions can be developed from the high storage level records of 2004 to 2006. Using the mean monthly values for these three years, and proportioning them by the ratio of the predicted annual average flow (1.45 cfs) to the annual flows for this period (1.93 cfs), the monthly flows presented in Figure 10 were calculated. The peak monthly flow is 4.0 cfs in June and the minimum is zero in September, when no discharge is expected. Inspection of the mine inflow data for individual months from 2004 to 2006 and correcting to average annual discharge from the mine adit indicates that a maximum discharge of 6.25 cfs could occur at the adit. In this 36 month period of record, four months would have had no discharge (always the August-September period). However, 2006, when the peak monthly discharge is predicted, was not an extremely high precipitation year so larger discharges than 6.25 cfs are possible.

Figure 10. Average expected monthly mine discharges based on 2004 to 2006 mine inflow data.



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