THE WATER BALANCE AND CHEMICAL MASS LOADS AT THE ZORTMAN AND LANDUSKY MINES, MONTANA[1]

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Abstract. How well have generalized hydrologic models predicted infiltration and water quality impacts at hardrock mine sites? The mine water balances developed with site-specific data in this study gave greatly different results than ones based on regional data and general methods. The lined leach pads and seepage capture systems at the Zortman and Landusky mines allowed entire rock dumps and small drainage basins to be evaluated as huge lysimeters, enabling direct estimates of groundwater recharge and evapotranspiration. The average steady-state water balances, based on data from years 1997-1999, were calculated for 22 facilities/ basins on the 210-hectares Zortman Mine, and 36 facilities/ basins on the 580-hectares Landusky mine. Infiltration rates (as % of precipitation) calculated for, a) unreclaimed leach pads, b) pits, and c) reclaimed pads and rock dumps were 70.5 %, 56 %, and 45 %, respectively for the Zortman mine, and were 69%, 62% and 48.6%, respectively for the Landusky mine. The annual water budget for the two mines averaged: evapotranspiration 51.4%, infiltration 43.8 %, and surface runoff 4.8 %. The results of previous water budget estimates using more general methods gave results of approximately 81%, 5.0% and 14%, respectively. Based on the facility-specific water budgets, chemical mass loading models of both mines were developed to estimate the total loads of contaminants generated by all mine facilities, and evaluate the ultimate fate of the contaminants. Average annual loads of total dissolved solids, acidity, sulfate, nitrate, arsenic, selenium and seven cationic metals were calculated. Site-specific water balances are valuable tools for analysis of hydraulic and contaminant loading rates from various mine facilities and cover types. A check of the models with independent data showed that they should not be applied outside the period of record or hydrologic conditions for which they were developed, without further verification and calibration.

Additional Key Words: Mine Hydrology, Infiltration, Water quality

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Background and Purpose

The Zortman and Landusky Mines are located two miles apart, in the Little Rocky Mountains of north-central Montana (Figure 1). Both mines are near the southern boundary of the Fort Belknap Indian Reservation in the southwest corner of Phillips County on a mixture of private land and public land managed by the BLM. The Little Rocky Mountains are within the Northern Great Plains geographic region, and are one of the "Island Mountain Ranges", so named because they rise up out of the relatively flat plains like islands in an ocean. Emplacement of these intrusive rocks mobilized and deposited elements such as gold in sufficient concentrations as to make mining economically viable. The gold is hosted in the Cenozoic era igneous intrusive syenite porphyry rock that lies in the core of the mountains (AMI, 1996). Sulfide mineralization is associated with the gold deposits, and is the source of much of the water quality problems at the mines.

The mines lie at the headwaters of a number of drainages that are tributaries to the Milk and Missouri Rivers. Some drainage, such as Ruby Gulch and Montana Gulch are fed by perennial or intermittent discharges from mine water treatment plants. Groundwater systems at the mines occur in the syenite porphyry, with the flow system highly controlled by northeast trending shear zones and associated fracture systems, and abandoned underground mine workings. Groundwater also occurs in alluvial aquifers along drainages, and in Paleozoic era rocks flanking the uplift, including limestones and sandstones.

From 1979 through 1998, Pegasus Gold Corporation and its wholly owned subsidiary, Zortman Mining, Inc. (ZMI), operated the Zortman and Landusky Mines. While historic mining activity has occurred in the area since the mid-1860s, the advent of cyanide heap leach technology, combined with the sharp rise in gold prices, prompted the development of these large-scale, open pit mining operations beginning in the late 1970s. Following preparation of an Environmental Impact Statement (EIS), the Zortman and Landusky Mines were approved in 1979.

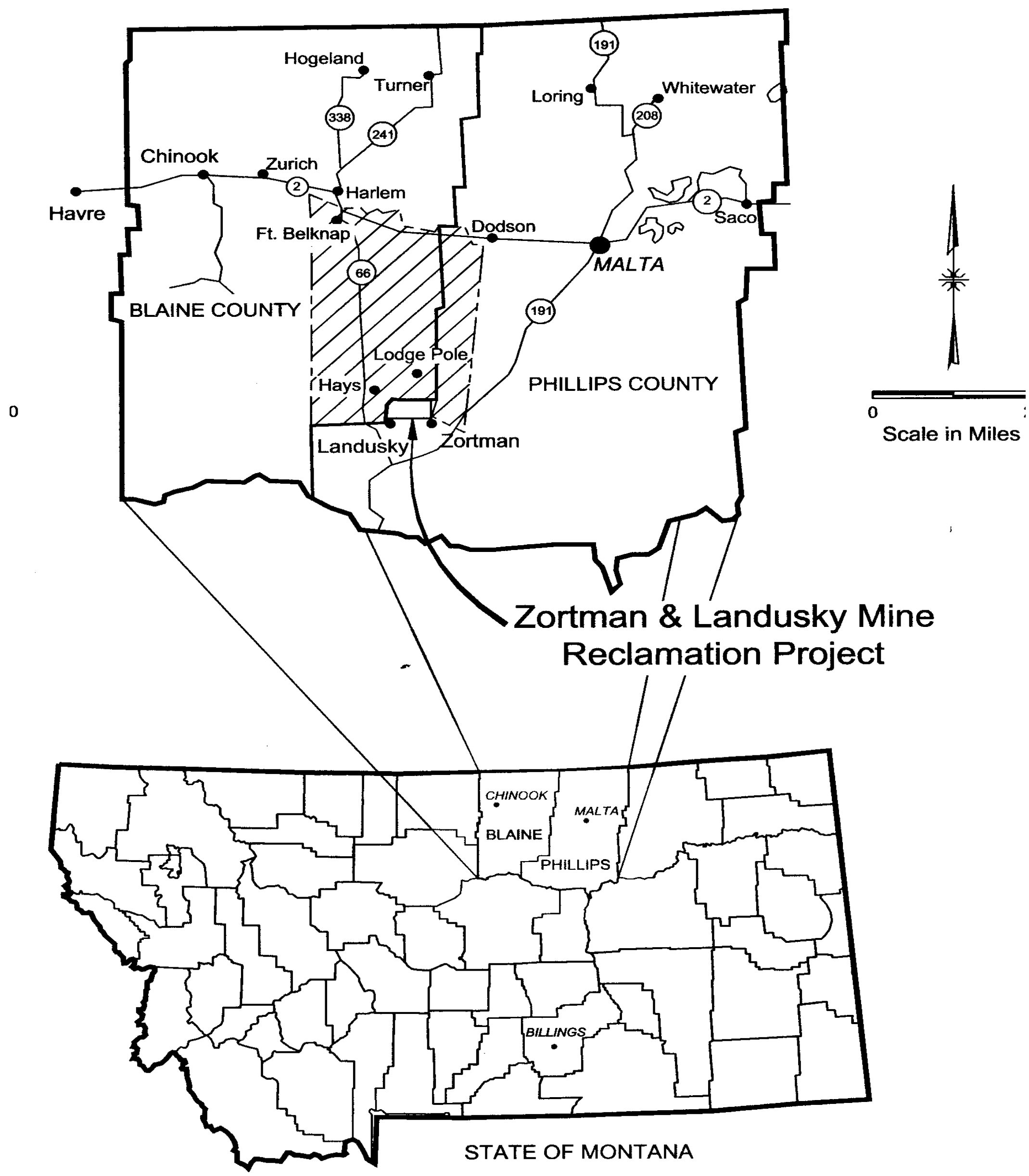


Figure 1. Location of Zortman and Landusky Mines.

In 1992, during review of water resources information submitted as part of ZMI expansion plans, it became apparent that acid rock drainage (ARD) was a widespread occurrence at both mines. In response to public comment, and due to the technical complexity of the ARD issue coupled with the mine expansion proposal, the agencies decided to require a new EIS (DSL/BLM 1994). After the completion of the Final EIS (FEIS) and signing of the water quality Consent Decree, a Record of Decision (ROD) was issued on October 25, 1996. A series of administrative orders, appeals, and lawsuits by the EPA and environmental groups over alleged Clean Water Act violations ensued. In January 1998, Pegasus Gold Corporation and ZMI filed for bankruptcy protection, and shortly thereafter announced they were going to reclaim and close the mines. At the conclusion of the bankruptcy proceedings in January 1999, there were seven surety bonds covering the Zortman and Landusky Mines totaling more than $67 million. A Supplemental EIS completed in 2001 (BLM and MDEQ, 2001) examined six reclamation alternatives for each of the mines, which ranged in cost from the existing bond amount up to $170 million. The cost of the selected alternatives greatly exceed the available bonds, placing great importance on evaluating the hydrologic and water quality implications of the reclamation strategies.

A water balance is a quantitative accounting of all of the principal components of the water cycle for a defined volume of earth materials or water body. A water balance accounts for precipitation (P), evapotranspiration (ET), surface runoff (RO), infiltration to groundwater (IT), and changes in storage. A chemical mass-loading model was developed that uses the results of the water balance, along with water quality data, to produce estimates of the quantity of chemicals or contaminants being transported or stored in various components of the water balance. The water balances and chemical mass loading models for the Zortman (Spectrum et al., 2000a) and Landusky (Spectrum et al., 2000b) mines were an important component of the reclamation decision-making process, and produced some surprising results that contrasted sharply with previous hydrology studies.

The water balances and contaminant loads at the Zortman and Landusky mines have been evaluated in several previous studies. The FEIS (BLM, 1996) used HELP modeling to estimate then current water and contaminant loads from mine facilities, and predict future loads under various reclamation scenarios. Another hydrologic consultant (WMC, 1998) made estimates of ET, RO and IT for mine facilities using generalized methods or the results of the FEIS. They provided a water balance of the area on a drainage-by-drainage basis for existing conditions. Most of these previous studies used precipitation data collected at the mines; however, estimates of ET and IT were obtained from regional meteorological and hydrologic statistics, published sources and the HELP modeling.

Since active mining ceased in 1996, and water capture systems were installed at seven locations, an opportunity to collect and evaluate site-specific hydrologic information arose. The

Water Balance and Chemical Mass Loading Worksheets developed for the mines were used to evaluate and prioritize reclamation plans designed to optimize hydrologic controls and water quality outcomes. Simulations of changes in the water balance and chemical mass loading were performed by adjustment of water balance components as predicted by specific reclamation proposals. This paper summarizes the results of the mine water balance evaluations, and compares these results to earlier studies that could only rely on regional data or generalized hydrologic models.

Limitations

There are many limitations to the water balance and mass loading estimates presented here. All the data available at the time were used to develop these estimates, and the models are strictly applicable only to the period of record utilized. Calibration to independent data was not performed, thus limiting the predictive value of the models. As more monitoring data from the capture systems and leach pads become available, it may be feasible to test and calibrate more general versions of the models.

Surface water runoff was indirectly calculated using the Curve Number Method. This method was developed for undisturbed land and not directly applicable to mining disturbed land. However, the calculated values were checked against actual runoff estimated from mine capture systems, and were checked against measured stream runoff records from the mine.

The water balance was based on observations from the calendar years 1997, 1998, and 1999. The average precipitation for these years was 56.8 cm, while the average precipitation over the past thirty years was about 48.2 cm. Maximum and minimum annual precipitation for the past thirty years was 74.5 cm and 27.3 cm, respectively. Thus, the period modeled is somewhat wetter than average, but is within a standard deviation. In addition, the terrain is rugged and precipitation could vary significantly within the mine sites. The water balance was designed so that any value for annual precipitation can be input and the outputs would all be scaled accordingly. As with any model, the validity can be stretched beyond its usefulness if the inputs far exceed the development criteria.

The chemical loads were developed from monitoring locations that best represented each of the sub-basins or mining facilities; however, ideal locations were not always available. Average concentrations at each monitoring station were converted to contaminant loads by application of the water balance results; however, average concentrations may not adequately represent actual loading processes. The chemical mass-loading model includes the total input of contaminants. The portion of the total loads from precipitation and the “natural background” are not isolated. The loading model assumes that, once in the groundwater, sulfate and metals behave conservatively within each modeled mine facility. Other assumptions are discussed below.

Methodology

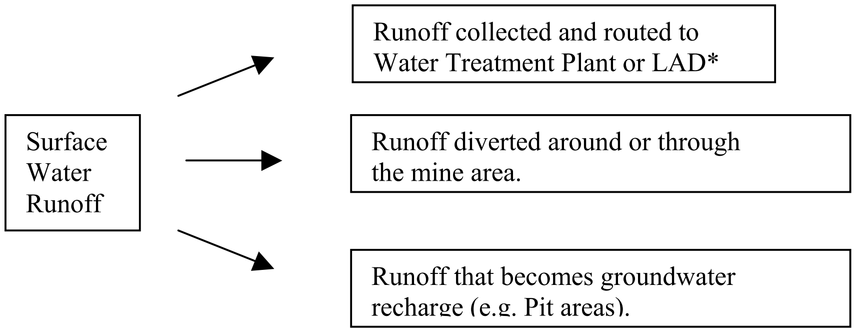
Basic Water Balance Equation

The basic water balance equation for the mines is:

$$P = RO+ET+IT \tag{1}$$

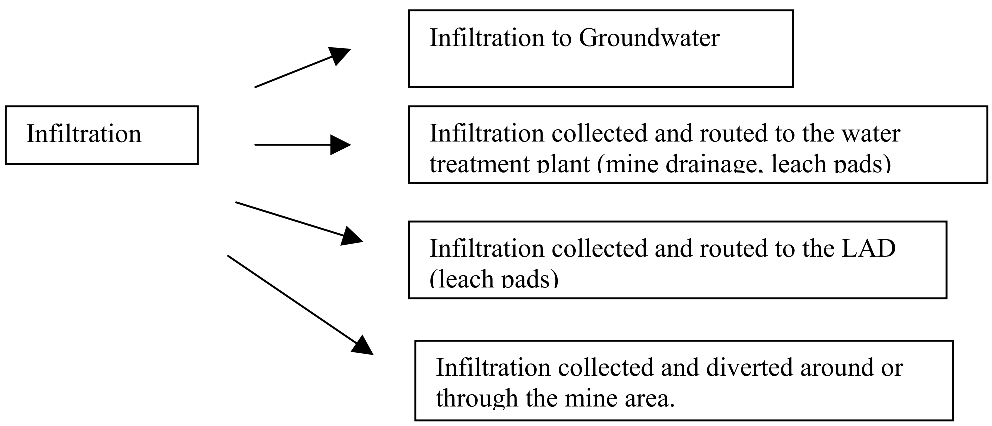
where, P = Precipitation, RO = Surface Water Runoff, ET = Actual Evapotranspiration, and IT = Infiltration beyond the root zone, all expressed on an annual basis. It was assumed that the annual change in groundwater and soil water storage was negligible, that all infiltration becomes groundwater (except for lined leach pads), and that other groundwater or surface water inflows are negligible. Additional study subsequent to this work demonstrated that groundwater storage was accruing in the syenite aquifer during the period of the water balance. This suggests that infiltration to groundwater was greater than indicated by the steady state water balance.

Based on the facilities at the mine, surface water runoff was allocated as follows:



* LAD- Land Application and Disposal Area

Infiltration was allocated as follows:



Methods to Estimate Water Balance Components

Surface Water Runoff

Total annual runoff was estimated by first computing daily runoff using the daily precipitation records from the mine stations and Curve Number Method, and summing the daily runoff values. The Curve Number Method was developed by the Soil Conservation Service (SCS), now Natural Resource Conservation Service (NRCS), and uses the three variables: precipitation, antecedent moisture condition, and hydrologic soil-cover complex. The runoff equation is presented in many texts along with graphical solutions. In this case, the equation was solved analytically. Runoff as a percentage of the total precipitation was computed for six basic cover and slope descriptions. In all situations, antecedent moisture condition II was assumed (USDA, 1972). For each of these six situations, a representative curve number was chosen. Complete tables showing the daily precipitation and runoff (from January 1, 1997 through

December 31, 1999) are provided in Spectum et al. (2000a and 2000b). A summary is provided in Table 1. The initial abstraction is an indication of the amount of precipitation that must fall before there is runoff. Thus, for the Zortman site, runoff occurrence depends on the occurrence of precipitation of at least 1.04 cm for hard surfaces, a significant event. Direct runoff was also estimated from the seven capture systems located in drainages on the mine perimeter. Runoff was based on net increases in the captured daily flows on the day of, and day following precipitation events exceeding 0.25 cm. Runoff computed from Curve Numbers was always somewhat greater than captured runoff, because not all runoff could be captured by the system.

Table 1. Surface Water Runoff Summary Table.

Description	Cover Soil Hydro Type	Slope	CN*	Initial Abstraction cm	Runoff As <u>% of Precip</u>. Zortman, Landusky
Rocky Slopes	A	Steep	68	2.39	4.49, 1.20
Rocky Flat Areas	A	Mild	49	5.28	2.08, 0.03
Covered Slopes, Some Veg	B	Steep	74	1.78	6.99, 2.68
Covered Flat Slopes Some Veg	B	Mild	69	2.29	4.83, 1.38
Undisturbed	B	Varies	58	3.68	2.05, 0.29
Hard Surfaces, Roads Highwalls	B	Varies	83	1.04	14.0, 7.56

CN- Curve Number

<u>Evapotranspiration and Infiltration on Reclaimed Surfaces</u>

There are three water capture systems at the Zortman mine: Carter Gulch, Alder Spur and Ruby Gulch, and four at the Landusky mine: Mill Gulch, Sullivan Gulch, Upper Montana Gulch and Lower Montana Gulch. These systems were built below reclaimed waste rock dumps and leach pad dikes, and engineered to intercept nearly all surface water runoff and groundwater moving through the unconsolidated sediments and upper syenite porphyry aquifers. Collection trenches are cut across drainage basins and keyed into bedrock below the mine area. Studies have shown (WMC, 1998) that most shallow groundwater in the syenite aquifer tends to emerge as surface water on the lower flanks of the Little Rocky Mountains, where it is captured by these systems.

Daily records of precipitation were available for each mine site. Daily records were also available for the volume of water pumped from each of the capture systems. This enabled estimates of infiltration, and that portion of direct runoff collected by the capture system, to be made directly. The evapotranspiration rate was calculated by difference. One system, Alder Spur, had indications that there is an "irreducible baseflow" component to the annual hydrographs of the capture system pumpage. The source of this baseflow could not be determined, but may have been related to flow from old underground mine workings or the shear zone and associated fracture system. The baseflow was subtracted from the IT component prior to estimating the evapotranspiration.

Evapotranspiration and Infiltration on Unreclaimed Surfaces

Gold was extracted from the ore through the cyanide heap leach process. The leach pads are large piles of coarse rock, enveloped in a PVC liner. At the time of this study, most leach pads were unreclaimed and devoid of vegetation. Essentially all infiltration is trapped and moves downward to the saturated zone. Large diameter wells (sumps) are fitted with pumps for extracting leach pad solution, which (in the absence of gold recovery) is pumped to the water treatment plant or the land application area. A running inventory of leach pad solution levels and volumes is kept. The difference in volume from time to time, in the absence of pumping, can be taken as the amount of infiltration reaching the saturated zone in the pad. Given the precipitation and infiltration, an estimate can be made of the evapotranspiration plus runoff, or:

$$P\text{-}IT = ET+RO \qquad (2).$$

Total runoff was estimated by the Curve Number Method discussed above, after which evapotranspiration was determined by difference.

Evapotranspiration and Infiltration on Undisturbed Areas

Actual evapotranspiration as a percentage of the total precipitation for undisturbed areas was estimated based on data from the reclaimed areas discussed above, particularly from capture systems with a greater proportion of undisturbed area. It was reasoned that since the slopes were similar, but the undisturbed areas have more mature vegetation and ground cover, that ET would be somewhat greater for undisturbed areas than for reclaimed areas. Runoff was calculated via the Curve Number method, as above, with IT being estimated by difference.

Evapotranspiration and Infiltration on Roads, Shop and Other Hard Surfaces

Actual evapotranspiration as a percentage of the total precipitation for these areas was estimated based on likely differences between these hard areas and the other areas already estimated. Runoff was estimated as above, with IT being determined by difference.

The water balance components were computed as percentages of the average precipitation for the period of study, and aggregated into a "Water Allocation Criteria" table for each mine. These criteria were spatially varied over the mine, consistent with the status of land cover at that time. The criteria were assumed to be time-invariate, and thus steady state. The Water Allocation Criteria for the two mines is provided in Table 2.

Mine Surface Drainage and Basin Areas

Building on previous mine studies (Harvey and Gallagher, 1996), 22 facilities/sub-basin areas were mapped on the 210-hectares (ha) Zortman Mine, and 36 facilities/ sub-basins on the 580-ha Landusky mine. Drainage divides, surface water runoff channels, and other drainage and erosion structures were field checked in detail. Principal mine facilities, such as leach pad liners, pits, dikes, topsoil piles, and waste rock dumps were also meticulously defined in order to partition the drainage basins into relatively homogeneous sub-areas. Maps of drainage basins and principal facilities for the Zortman and Landusky Mines are provided in Figures 2 and 3, respectively.

Surface water drainage basins and mine facility boundaries were used to subdivide the Zortman mine. Groundwater basins were believed to be reasonably congruent with surface water basins. The basin areas were delineated and named based on the facility or dominant land cover type, and lowest order, named receiving stream. The pit areas, which have no external surface water runoff, are internal basins. Nearly all surface water captured within the pit areas infiltrates to groundwater. All leach pads are also internally drained, and designated as: L- (year constructed).

Table 2. Water Allocation Criteria for the Zortman and Landusky Mines.

	Percentages of Annual Precipitation Zortman, Landusky			
Mine Facility or Land Cover Type	Liner Leakage	Runoff	Evapo-Transpiration	Infiltration
Unreclaimed Leach Pads		2.5, 1.0	27, 30	
Runoff Conducive Areas	0, 0	4.5, 1.2	25, 29.8	70.5, 69
Runoff Prohibitive Areas		0.8, 0.1	28.7, 30.9	
Reclaimed Leach Pads		6.3, 2.4	49, 49	
Runoff Conducive Areas	0, 0	7, 2.7	48.3, 48.7	44.7, 48.6
Runoff Prohibitive Areas		4.8, 1.4	50.5, 50	
Reclaimed Rock Dumps/ Other Areas		6.3, 2.4	49, 49	
Runoff Conducive Areas		7, 2.7	48.3, 48.7	44.7, 48.6
Runoff Prohibitive Areas		4.8, 1.4	50.5, 50	
Mill Gulch Reclamation Cover (Landusky only)		2.4	66.5	31.3
Undisturbed Areas		2.1, 0.5	65, 75	32.9, 24.5
Regraded/Topsoiled - Little Veg		9, 4.5	46.3, 46.9	
Runoff Conducive Areas		10.5, 5.3	44.8, 46.1	44.7, 48.6
Runoff Prohibitive Areas		7.2, 3.6	48.1, 47.8	
Pits		14, 8	30, 30	56, 62
Roads, Shop, Other Hard Surfaces		14, 8	56, 55	30, 37

A more complicated groundwater flow system exists at the Landusky Mine site. Unlike at the Zortman Mine, surface water basins could not be used as the basic watershed unit. Groundwater basins were defined for each capture system, based on factors including site geology, pre-mining topography, the potentiometric surface map, and annual volume of water reporting to each discharge point. A requirement was that the sum of the discharges from the groundwater basins

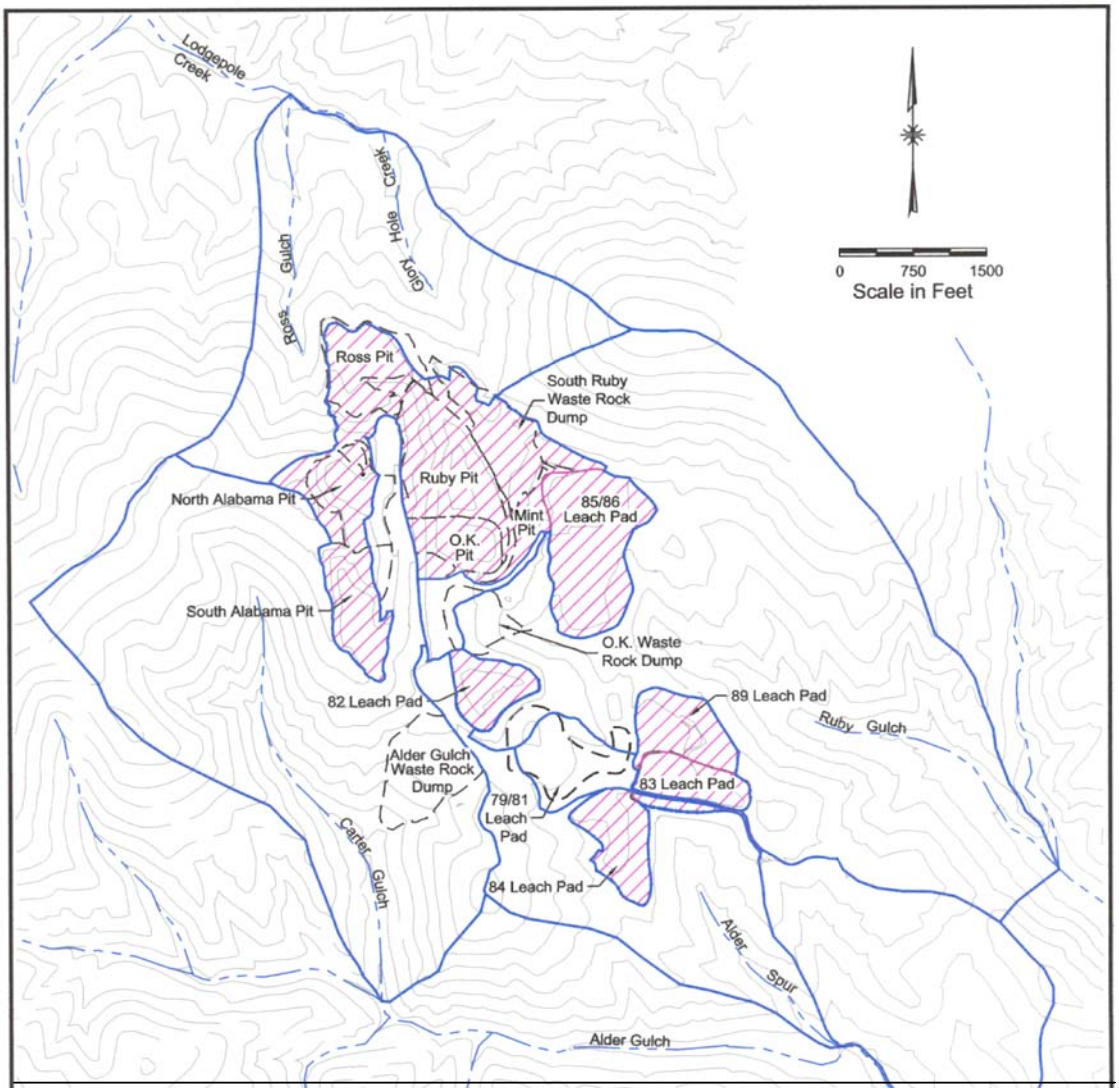


Figure 2. Zortman Mine Facilities and Drainage Basins.

had to equal the net recharge predicted over all the mine facilities. Landusky water treatment plant flow records were used to estimate the amount of captured and uncaptured water leaving the mine site (HSI and Gallagher, 2001).

Water Origination and Disposition Estimate

Once the sub-basins were mapped and water allocation criteria evaluated for the principal mine facilities and cover types, a detailed accounting of the origins and final dispositions of water on the mine was performed utilizing a large spreadsheet (Spectrum 2000a and 2000b, and HSI and

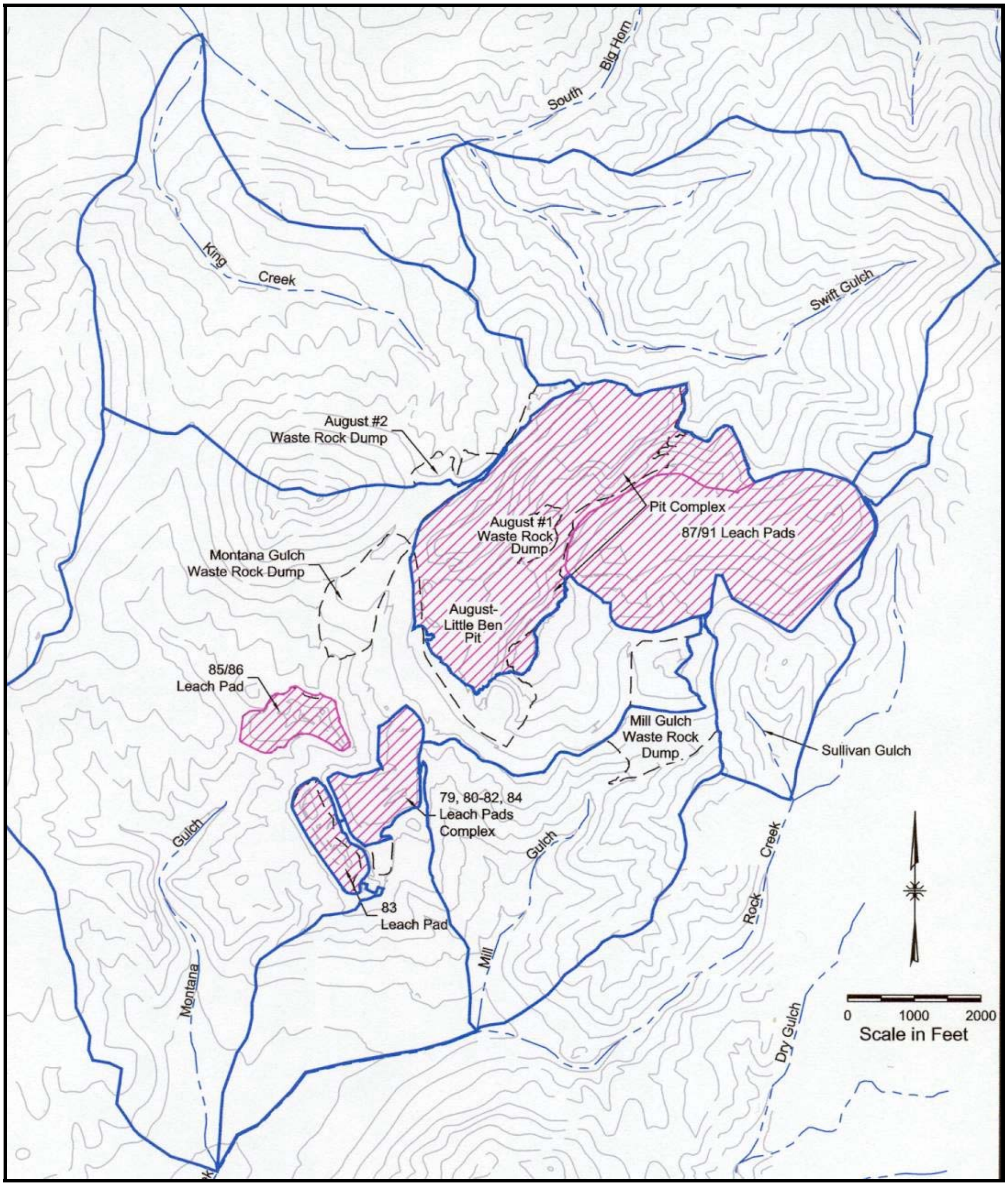


Figure 3. Landusky Mine Facilities and Drainage Basins.

Gallagher, 2001). Each sub-basin of the mine was partitioned into the appropriate facilities and land cover types. These components were then distributed into the following four EPA mine classification zones: Unclassified Zones, Storm Water Zones, Mine Drainage Zones and Process Water Zones. Finally, the appropriate water allocation criteria were multiplied by each sub-basin component to give the distribution of average annual precipitation for ET, RO and IT, by sub-basin facility or land cover type. Where several sub-basins contained multiple facilities or cover types, an area- weighted average was computed for the entire sub-basin.

Depending on the facility design or water controls, IT was allocated either to the groundwater (GW), to the water treatment plant (WTP), or to the land application disposal area (LAD). RO was allocated either to GW, the WTP, or to the surface water flow off the mine area. The various allocations of RO were estimated for each basin by observation and in consultation with mine personnel and other knowledgeable persons.

Results of Water Balance Study

A summary of the principal water balance components for each mine are provided in Figure 4. A chart depicting a more detailed disposition of the infiltration and runoff components as recruited by the mine facilities, or uncaptured, is shown in Figure 5.

Zortman Mine Water Balance

The water balance model of the Zortman Mine indicated that, of the total precipitation input (56.8 cm):

- ET = 47.9%
- RO = 8.1%, and
- IT = 44.0%.

Of the infiltration component:

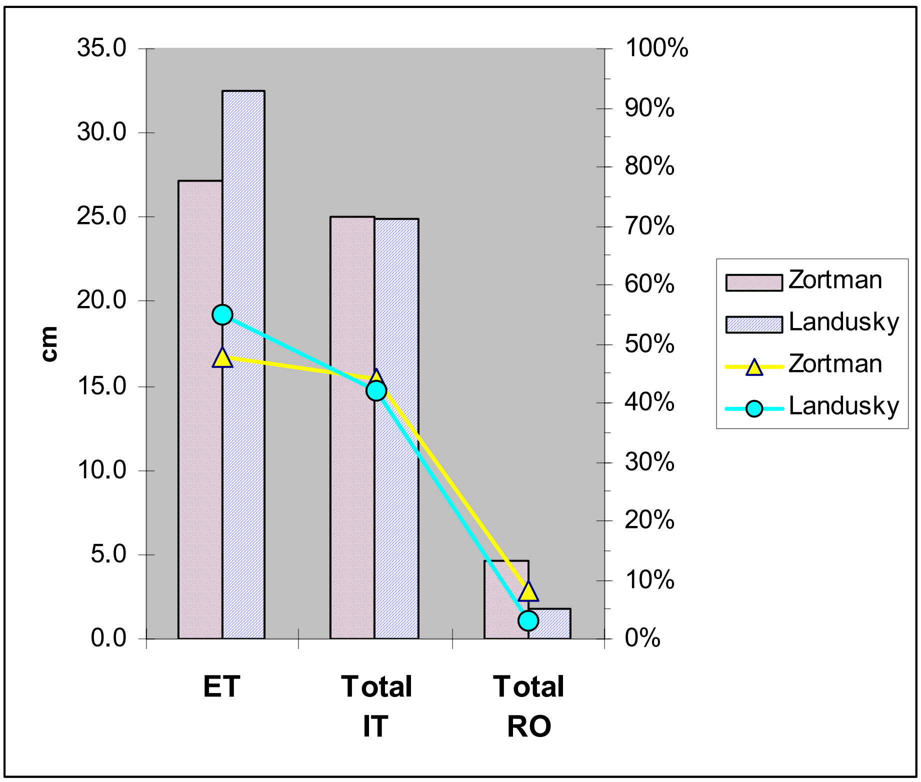
- 10.0% was recharge to leach pads, which was routed to the Goslin Flats LAD,
- 27.2% was recruited by the capture systems and sent to the Zortman water treatment plant,
- 3.8% was off-site groundwater flow, and
- 3.3% was increased groundwater in storage and/or residual error of the method.

Of the surface runoff:

- 5.2% was recruited by the capture systems,

- 2.6% runs off-site, and
- 0.3% is a residual of the method.

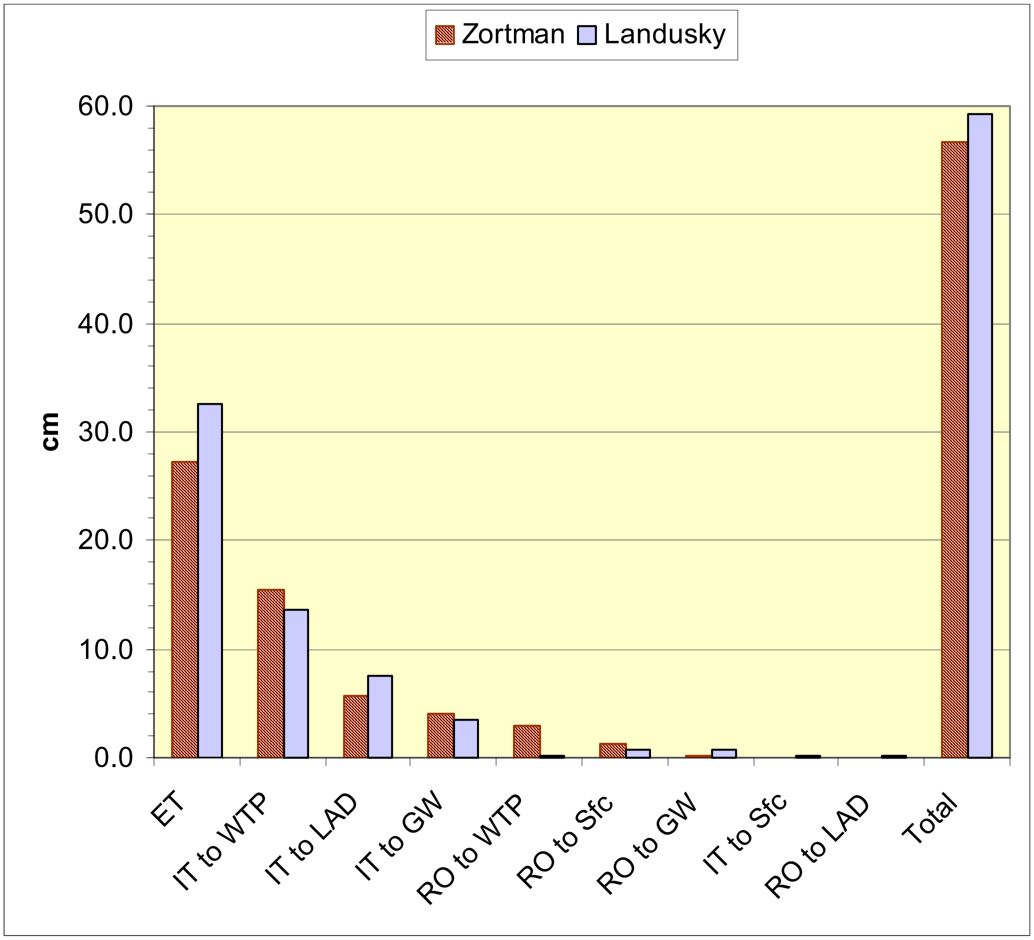
The capture systems and leach pads combined, collected 84% of the total groundwater discharge and about 67% of the total surface runoff from the mine site. Groundwater monitoring from the early-1990's through the present has shown a net increase in the groundwater level within the Zortman Mine shear zone of about eight feet per year, leveling off in 2000. This suggests that with unreclaimed conditions, average precipitation and recharge rates may be greater, and/or evapotranspiration rates lower than estimated in the steady state water balance.



Columns- Water Depth, cm
Lines & Points- Percentage of Total Annual Precipitation

Figure 4. Annual Water Balance for Zortman and Landusky Mines.

Infiltration rates (as % of precipitation) calculated for unreclaimed leach pads, pits, and reclaimed leach pads and rock dumps were 70.5 %, 56 % and 45 %, respectively. These rates are significantly greater than previous evaluations contained in the FEIS (1996) and WMCI (1998) reports. The estimated rates for regraded-topsoiled areas, undisturbed areas and hard surfaced area (e.g. roads), were 45 %, 33 % and 30 %, respectively.



ET - Evapotranspiration, RO - Runoff, GW- Groundwater, IT- Infiltration
LAD- Land Application Disposal Area, WTP- Water Treatment Plant
Sfc- Surface Water

Figure 5. Water Disposition For Zortman and Landusky Mines, Annual Average

Landusky Mine Water Balance

The water balance for the Landusky Mine was performed for 1998 due to the availability of consistent data and it being a more typical year for precipitation. The water balance model indicated that, of the total 1998 precipitation input (59.3 cm):

- ET = 54.9%

- RO = 2.1%, and
- IT = 43.0%.

Of the infiltration component:

- 12.6% was recharge to leach pads, which was routed to the Goslin Flats LAD,
- 23.1 % was recruited by the capture systems and sent to the Landusky water treatment plant, and
- 7.3 % was off-site groundwater discharge.

Of the surface runoff:

- 0.5 % was recruited by the capture systems or leach pads, and
- 1.6 % runs off-site.

The capture systems and leach pads combined, collected 84% of the total groundwater discharge and about 15.7% of the total surface runoff from the mine site. Infiltration rates (as % of precipitation) calculated for unreclaimed leach pads, pits, and reclaimed leach pads and rock dumps were 69%, 62% and 48.6%, respectively. These rates are significantly greater than previous evaluations contained in the previous water balance studies of these mines. A lower rate of 31.1% was obtained for the Mill Gulch Waste Rock Dump due to the use of a geosynthetic liner and thicker soil cover employed at this site. The estimated rates for regraded-topsoiled areas, undisturbed areas and hard surfaced areas, were 48.6%, 24.5% and 37%, respectively.

Water Balance Checks

Some components of the computed water balance were checked against the known outflows from the Zortman and Landusky water treatment plants for the period of the water balances. Although not an entirely independent check, it indicates how well the models reproduced one major output component. The check of the Zortman average water treatment plant flow produced a residual of 44,300 m^3, representing 11.4% of the actual WTP flow, and 3.7% of the average mine-wide precipitation volume. A similar check of the Landusky water balance gave a residual of –13,600 m^3, representing about 1.7% of the WTP flow, and 0.4% of average mine-wide precipitation volume.

An independent check of the water balance models using the flow in capture systems from 2000 was also performed. The total flow at each of the three capture systems at the Zortman mine for 2000 were compared to the respective flows predicted by the Zortman mine water balance model in Table 3.

Table 3. Actual and predicted capture system flows for the Zortman Mine, 2000.

	Alder Spur (m^3 x 1000)	Carter Spur (m^3 x 1000)	Ruby Gulch (m^3 x 1000)
Actual 2000	18.2	25.0	136.7
Predicted by Water Balance (m^3 x 1000)	15.1	27.6	261.2
Difference (m^3 x 1000)	-3.1	2.6	124.5
% Difference	-17%	10%	91%

The precipitation in 2000 was over 5 cm below normal. The predicted flows were too high for Carter and Ruby Gulches, and too low for Alder Spur. The flow was greatly over-predicted in Ruby Gulch for reasons not understood. Water balance data collected over a series of years would assist in the evaluation of the factors involved. However, it is likely that the flow to the capture systems is not a linear function of precipitation. As annual precipitation declines, evapotranspiration amounts to an ever-greater percentage of the total water balance. The pattern of precipitation has a significant influence as well. If a greater percentage of total precipitation falls during mid-summer months, more will be evapotranspired due to higher ambient temperatures and more mature vegetative development.

The total flow at two of the four capture systems at the Landusky mine for 2000 were compared to the respective flows predicted by the Landusky mine water balance model in Table 4. Water management at the other two capture systems changed greatly in 2000, and data were not comparable to pervious years.

Table 4. Actual and predicted capture system flows for the Landusky Mine, 2000.

	Mill Gulch (m^3 x 1000)	Sullivan Gulch (m^3 x 1000)
Actual 2000	69.3	10.6
Predicted by Water Balance (m^3 x 1000)	52.6	25.7
Difference (m^3 x 1000)	-16.7	14.7
% Difference	-24%	138%

The Landusky mine precipitation in 2000 was nearly 13 cm below the short-term average available for the site, and 17.3 cm less than that in 1998, the year used to develop the Landusky Water Balance Model. The predicted flow was low in Mill Gulch and much too great in Sullivan Gulch. Reasons for the discrepancies probably include those described above for the Zortman Mine. Sullivan Gulch is one of the smallest drainages at either mine, and model parameters are likely more sensitive

Based on the above application of the mine water balances to year 2000 data, it is apparent that the model criteria would have to be adjusted, and possibly additional criteria developed, to obtain an acceptable fit to observed data for generalized use. The models were developed using years of average to above-average precipitation, and are not likely to produce reliable results for drier than average years, as demonstrated by year 2000 data. Since, however, infiltration is disproportionately greater in wet years, and reclamation is designed for such periods, use of the existing model was appropriate for the reclamation cover assessment.

Comparison of Water Balance Methods

The results of the on-site water balance can be compared to that developed in a previous comprehensive hydrologic study of the Zortman and Landusky mines (WMC, 1998), before the capture system and leach pad monitoring data were available. The WMC report used precipitation data from the mines, and ET results from HELP modeling done for the FEIS (1996). These studies produced ET estimates for unreclaimed land, reclaimed land and native surfaces as, 42.1%, 65.4% and 84.2%, respectively. RO was estimated using area-discharge relationships developed from regional USGS stream gauging station data. IT was estimated by difference, based on the above parameters, and with distinctions among liner seepage, process water capture and net groundwater recharge. The study provided a water balance of the area on a drainage-by-drainage basis for average conditions. Since there were differences in basin areas and other details, the results from the WMC report were interpreted to obtain the best alignment with the framework of this study. The comparison of this study and the WMC report are summarized in Table 5.

Table 5. Comparison of Zortman and Landusky Mines Water Balance Using Site Data Versus Generalized Methods.

	Site Data Approach			**General Methods Approach ****
	Zortman Mine	Landusky Mine	**Average**	**Average**
Precipitation	100.0%	100.0%	100.0%	100.0%
ET	47.9%	54.9%	**51.4%**	**81.3%**
Runoff	7.8%	1.9%	**4.8%**	**13.6%**
Infiltration-Recharge	44.3%	43.3%	**43.8%**	**5.1%**
Totals	100.0%	100.1%	100.0%	100.0%
Net GW Recharge*	34.3%	30.7%	**32.5%**	**2.9%**

* *Excludes Leach Pads*

** WMC, 1998

A very significant difference is apparent between the methods. In fact, the generalized method produced net groundwater recharge rates an order of magnitude lower than this study. Correspondingly, the generalized method gave significantly higher estimates of evapotranspiration and surface water runoff. Although there are limitations to the comparison due to use of differing basin areas and time periods, the use of generalized methods and regional data do not provide a sufficiently accurate hydrologic model for making costly mine reclamation decisions.

Chemical Mass Loading Evaluation

The usefulness of a site-specific water balance model is demonstrated through its application to chemical mass loading calculations. Chemical mass loading models of both mines were developed to estimate the total loads of contaminants generated by all mine facilities, and evaluate the fate of the contaminants. Average concentration of chemical constituents monitored during a period similar to that of the water balance, along with the water balance flux rates, were used to compute loads. Based on the Zortman and Landusky mines sub-basins and the water balance, contaminant fate was allocated among that going to the water treatment plant, to the LAD, and to groundwater. Average annual loads of total dissolved solids, acidity, sulfate, nitrite plus nitrate, arsenic, selenium and seven cationic metals were calculated. The total metals load is the sum of aluminum, cadmium, chromium, copper, iron, lead, manganese, nickel and zinc. The loading rates are gross values that incorporate mining impacts, precipitation mass loading, and the "natural background contributions" for this site. The results are best interpreted by comparison of relative loading rates among the mine facilities. The procedures and limitations of the chemical mass loading evaluations are provided in Spectrum et al. (2000a and 2000b), and HSI and Gallagher (2001).

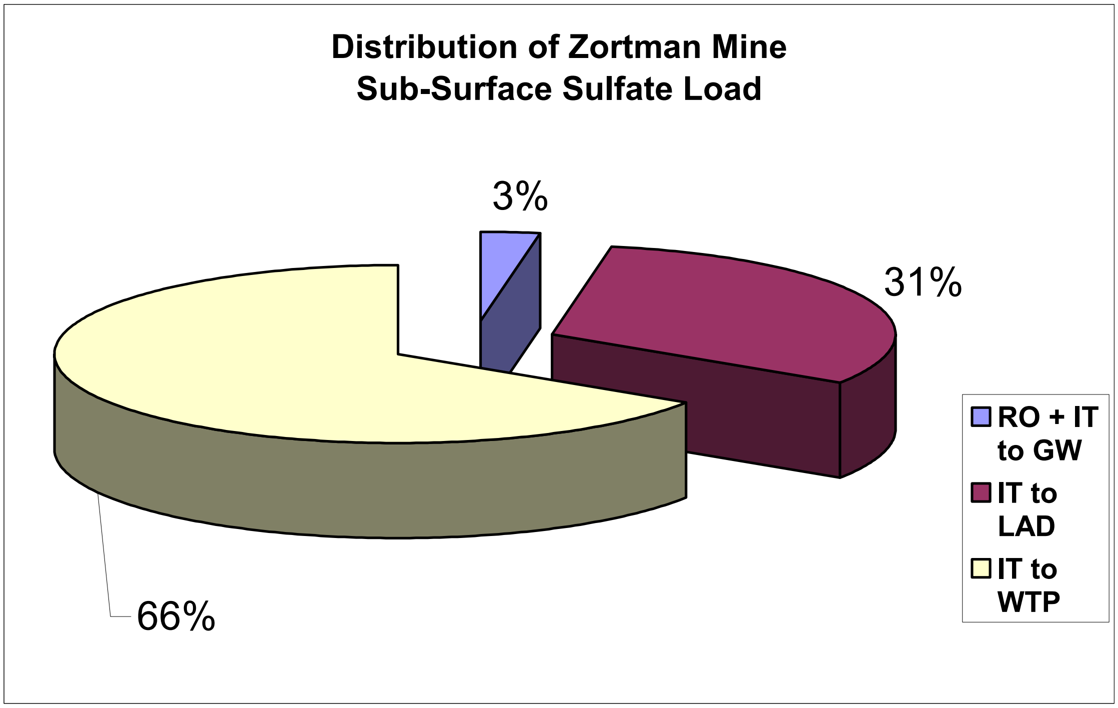
Zortman Mine Chemical Mass Loading

Sulfate loads in rank order, and corresponding total metal loads, by sub-basin are presented in Table 6. About 32 % of the total sulfate load was generated by the Z85/86 leach pad. The Alder Gulch waste rock dump (CG-02), OK waste rock dump (IN-01), plant process area (RG-03), and Ruby pit each generated from 5-10 % of the total sulfate load. As with sulfate, the total metal load was greatest from the Z85/86 leach pad, comprising nearly 22 % of the total metal load from the mine. The Alder Gulch waste rock dump and Ruby pit contributed about 11 % and 10 %, respectively, of the mine’s total metal load. Most of the facilities high in sulfate load were also high in metals load, not unexpected in a geochemical environment dominated by pyrite oxidation.

The distribution and fate of the Zortman Mine sulfate and metal loads are shown in Figure 6. It indicates that 78 % of the total metal load and 66 % of the sulfate load was captured and routed to the Zortman water treatment plant. The Goslin Flats LAD received 18 % and 31 % of the metals and sulfate loads, respectively. The total metal and sulfate loads to groundwater not captured, was estimated at 4 % and 3 %, respectively.

Table 6. Zortman Mine Sulfate and Total Metals Loads.

	Sulfate Load Rank Order		**Total Metals Load Rank Order**	
	kg/yr	%	kg/yr	%
1985-1986 Leach Pad	940,532	31.9%	73,360	21.8%
Carter Gulch Pump Back (Dump)	287,937	9.8%	35,833	10.6%
OK Rock Dump and Topsoil Pile	259,954	8.8%	32,674	9.7%
WTP, 85/86 and 89 Dikes	186,586	6.3%	30,297	9.0%
Ruby Pit	182,039	6.2%	34,754	10.3%
Ross Pit	138,951	4.7%	26,528	7.9%
1989 Leach Pad	119,580	4.1%	639	0.2%
1984 Leach Pad	119,449	4.1%	2,410	0.7%
South Alabama Pit	109,156	3.7%	20,840	6.2%
1982 Leach Pad	106,157	3.6%	21,840	6.5%
North Alabama Pit	99,528	3.4%	19,001	5.6%
1983 Leach Pad	92,941	3.2%	857	0.3%
79-81 Leach Pad	83,924	2.8%	4,851	1.4%
O.K. Pit	83,361	2.8%	15,915	4.7%
Mint Pit and S. Ruby Waste Dump	53,225	1.8%	7,313	2.2%
Area Around Alabama Pits	34,765	1.2%	8,320	2.5%
83 and 84 Dikes	33,584	1.1%	357	0.1%
Area Near SW Corner OK Pit	6,113	0.2%	1,463	0.4%
Upper Shell Butte Undisturbed	4,013	0.1%	9	0.0%
Alder Spur Non-Contributing Area	3,085	0.1%	3	0.0%
Generator Hill	2,148	0.1%	2	0.0%
East of 83 & 89 Leach Pads	556	0.0%	3	0.0%
Total	2,947,585	100%	337,271	100%



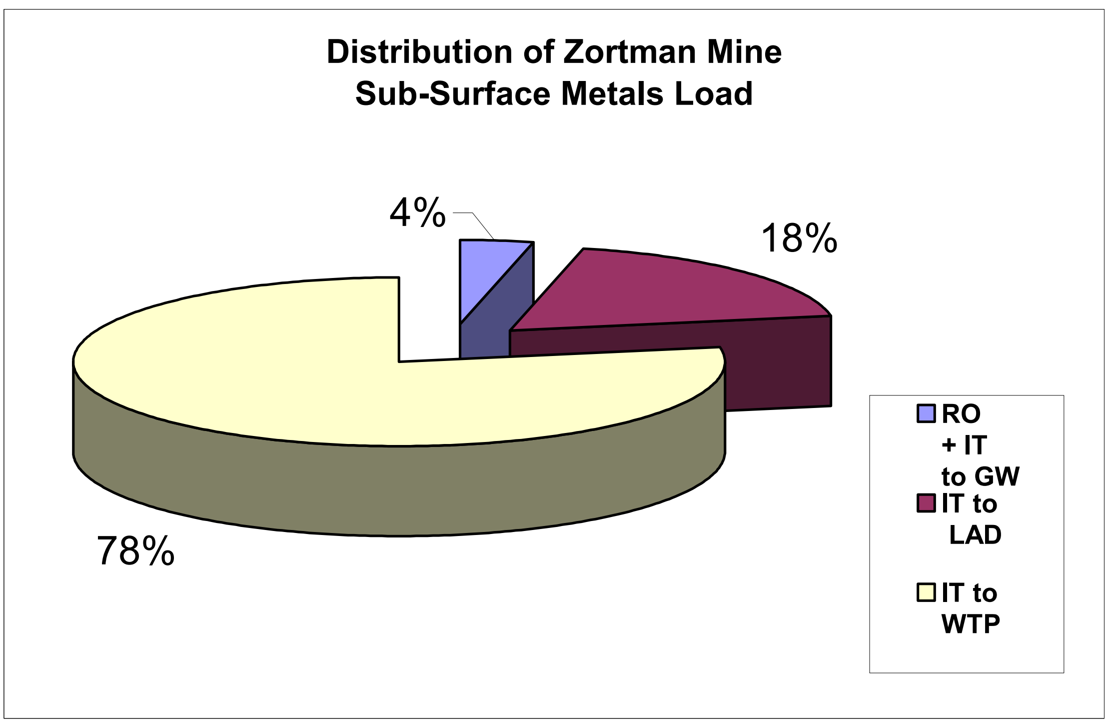


Figure 6. Distribution and Fate of Zortman Mine Sulfate and Total Metals Loads.

Landusky Mine Chemical Mass Loading

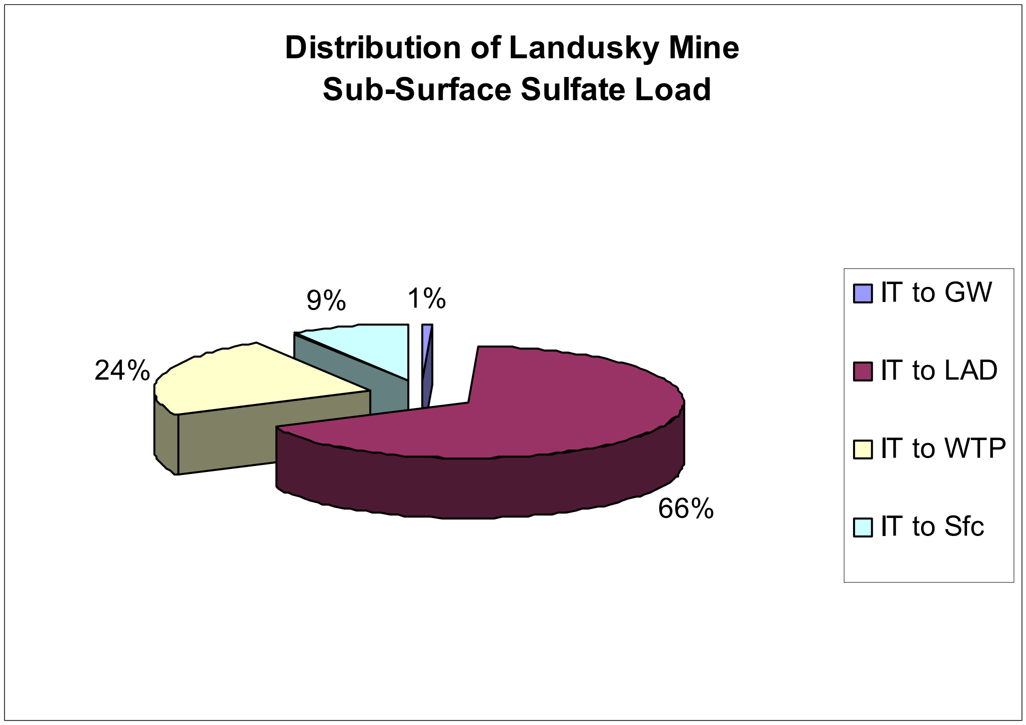
As done in the water balance, the 36 surface water basins at the Landusky Mine were replaced with 17 groundwater basins, which much improved the correspondence of the selected water quality stations and the accuracy of the contaminant load calculations.

Sulfate loads in rank order, and corresponding total metals loads, by sub-basin are presented in Table 7. The results indicate that the L-87 and L-91 leach pads produced the greatest loading rate of sulfate. The next largest total sulfate loads, in order, were derived from the Upper Montana Gulch capture system, Lower Montana Gulch capture system, the Gold Bug adit and the Sullivan Gulch capture system.

Table 7. Landusky Mine Sulfate and Total Metals Loads.

	Sulfate Load Rank Order		Total Metals Load Rank Order	
	kg/yr	%	kg/yr	%
L-91	735,018	37.9%	545	1.1%
L-87	710,752	36.6%	519	1.0%
UPPER MONTANA GULCH	222,826	11.5%	5,234	10.2%
LOWER MONTANA GULCH	206,405	10.6%	1,215	2.4%
GOLD BUG DISCHARGE	186,908	9.6%	25,018	48.5%
SULLIVAN GULCH	115,024	5.9%	8,179	15.9%
L-83	109,537	5.6%	3,891	7.6%
MILL GULCH	105,309	5.4%	2,717	5.3%
L-85-86	79,248	4.1%	41	0.1%
L-84	77,267	4.0%	3,752	7.3%
L-79,80,81,82	74,238	3.8%	823	1.6%
SWIFT GULCH (mine area only)	17,231	0.9%	62	0.1%
KING CREEK (mine area only)	16,411	0.8%	21	0.0%
X-03	15,238	0.8%	56	0.1%
X-02	1,753	0.1%	3	0.0%
MT-09 + MT-11	1,453	0.1%	1	0.0%
X-01	469	0.0%	0	0.0%
TOTALS	1,940,069	100.0%	51,532	100.0%

The sources and fate of the Landusky Mine sulfate and metal loads are shown in Figure 7. The Gold Bug adit discharge had the greatest overall loading rate of total metals, at 25,018 kg/yr.



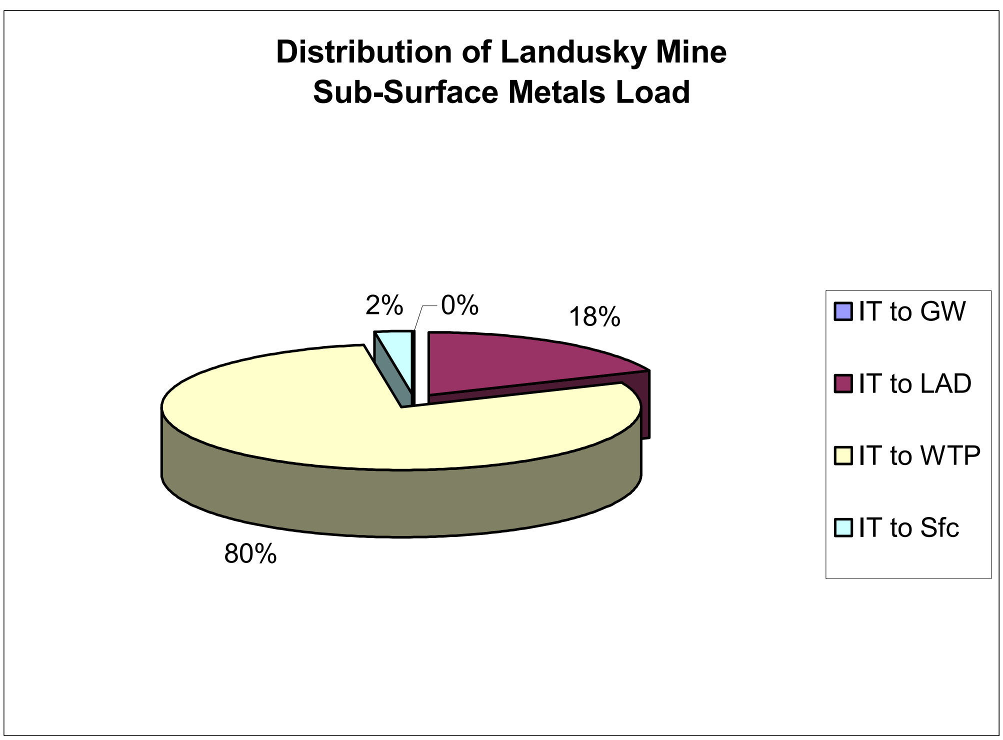


Figure 7. Distribution and Fate of Landusky Mine Sulfate and Total Metals Loads.

Sullivan Gulch and Upper Montana Gulch ranked second and third overall. The sulfate distribution indicates that 66% was collected from the leach pads and is routed to the LAD. 24% was recruited by the capture systems and went to the water treatment plant, 9% to surface water discharge (primarily Lower Montana Gulch), and 1% to uncaptured groundwater. Of the total sub-surface metals load, all but 2-3 % was recruited by the capture systems or leach pad drains.

Conclusions

This study demonstrates that site-specific steady state water balances can be developed for mines having "lysimeter-like" facilities and on-site precipitation data. Water balances developed with site-specific data can give greatly different results than ones based on regional data and general methods. Site-specific water balances are valuable tools for analysis of hydraulic and contaminant loading rates from various facilities and surface cover types, and for providing useful models in reclamation decision-making. Water balance models of this type should not be applied outside the period of record or hydrologic conditions for which they were developed, without further verification and calibration.

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