PREDICTING LIFE-OF-MINE TAILINGS DISCHARGE WATER QUALITY[1]

by

Andy Davis[2], Amy Tisdale and Cindi Byrns[3]

Abstract. A model was developed for the mill circuit at the Robinson Operation, Ely, Nevada, to assess variables such as ore type and water source that are likely to lead to elevated total dissolved solids (TDS) concentrations at the tailings outfall. Mill process water is retained in a tailings impoundment and recycled through the mill process. Various sources of TDS to the mill process circuit have been identified including, 1) existing water in the circuit, 2) the ore being processed and changes in processing technology that increase recovery and reduce TDS, 3) the volume of fresh makeup water added to the circuit, and 4) disposal of historical mine waters (HMW) into the circuit. All these factors were incorporated in a predictive algorithm that allowed for determination of the probable future TDS levels at the tailings outfall.

Introduction

Total dissolved solids (TDS) levels at the tailings outfall at the Robinson Operation near Ely, Nevada have sporadically been elevated above normal operating levels. The excess TDS concentrations result from several sources. A major source results from milling oxide ore, which causes an increase of TDS in the tailings effluent (Figure 1). Therefore, a model was developed for the Robinson Operation mill circuit to assess variables such as ore type and water source that are likely to lead to elevated TDS concentrations at the tailings outfall. The model identified which processes are most significant in terms of contributing TDS to the tails, and which conditions will produce target TDS levels. By understanding the cause-and-effect relationship between TDS and mill circuit components, potential changes in the mill circuit can be identified which will achieve target TDS levels.

Due to the complexity of the mill circuit and the inherent variability in influent conditions, a deterministic approach that results in production of a single value in response to a series of input values is inappropriate to define cause-response relationships. Therefore a probabilistic approach which allows for a continuum in input variables and results in a probability distribution for the computed output was employed. The flow streams entering or leaving the mill circuit were identified and a probability distribution function was assigned for the TDS values of each stream. Numerical equations were then developed to represent the system and the risk analysis software program @Risk (Palisade Corporation) was used to calculate a probability distribution for TDS at the outfall.

Mill Circuit Components

Ten individual streams were identified as either inflows or outflows to the mill circuit between where the water enters the mill and exits the system at the tailings outfall as shown in Figure 2.

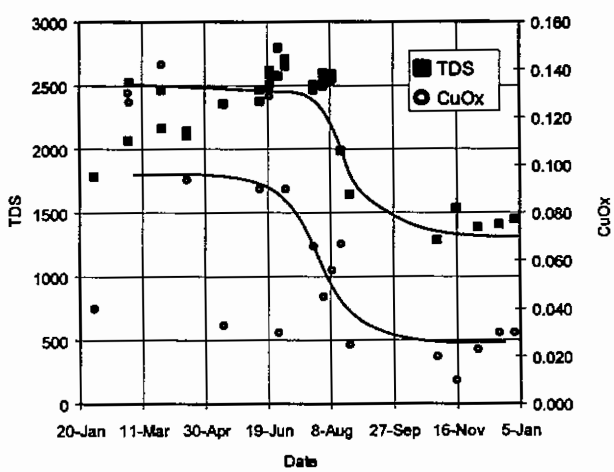

Figure 1. Relationship between run-of-mill ore and total dissolved solids.

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[2] Andy Davis is Vice President and Director of Geochemistry and Amy Tisdale is an Environmental Engineer, Geomega, 2995 Baseline Rd., Suite 202, Boulder, CO 80303.

[3] Cindi Byrns is the Environmental Manager, BHP Robinson, 7 miles West of Ely, NV 89319.

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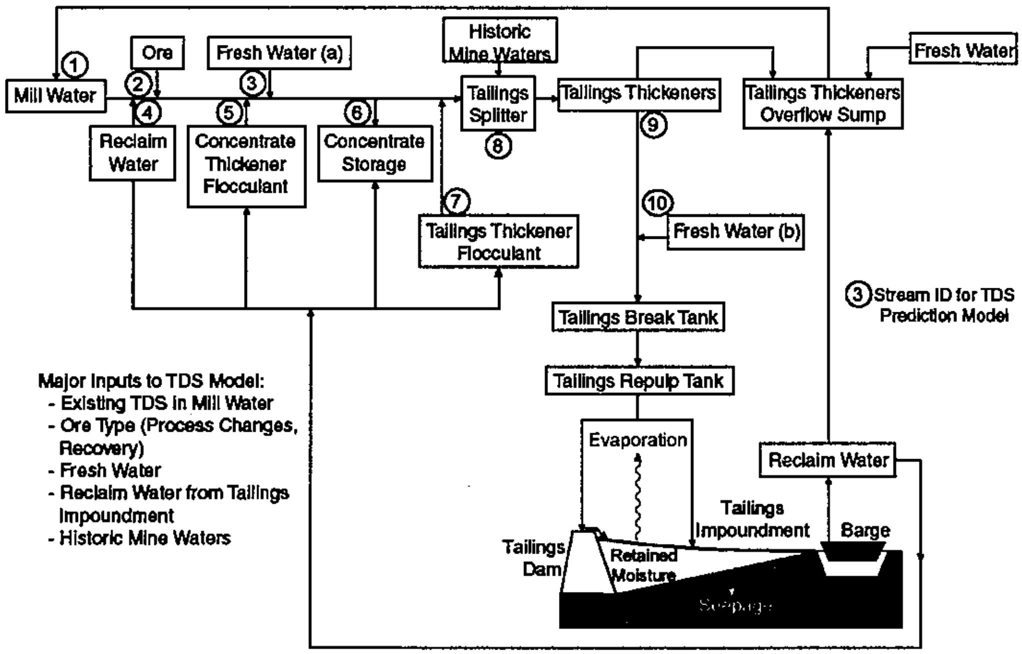

Figure 2. Dynamics of total dissolved solids in the mill circuit.

Mill water is the water from the process that leaves the tailings thickener overflow sump and is re-circulated back into the mill. This water includes tailings thickener overflow, fresh water, and reclaim water.

The ore processed through the mill contributes TDS to the process water. The ore also adds approximately 500 gpm of water to the mill circuit, due to the moisture content in the ore.

Fresh water (a) enters the mill in the form of seal water, cooling water, and water used in the crushing and coarse ore storage. Fresh water is pumped from various wells at the mine and stored in the fresh water mill ponds. It is then pumped from the ponds to the mill.

Reclaim water is recovered from the tailings impoundment barge operating channel and is recycled to the mill.

Water reclaimed from the tailings impoundment enters the concentrate thickener system, where flocculant is added. This water is then piped into the concentrate thickener tank where flocculant aids in settling the solids.

A small quantity of water leaves the mill circuit with the concentrate.

Reclaim water from the tailings impoundment enters the tailings thickener system, where flocculant is added. This water is then piped into the tailings thickener tank where flocculant aids in settling the solids.

Historic mine waters may include pit lake water, drainage water from waste rock dumps, and/or leach pad effluents. These waters enter the mill circuit prior to the tailings thickeners.

Tailings thickener underflow is sent to the tailings impoundment. The flow rate for the tailings thickener underflow was used to compute TDS values at the outfall.

A second component of fresh water (b) enters the mill circuit after the tailings thickeners as seal water for the tailings pumps. The fresh water comes from the mill ponds.

Numerical Model Formulation

Numerical equations were used to simulate the interaction of the flow streams described above in the mill circuit. The TDS model uses seven steps to describe the mill circuit process (P1 through P7).

Process 1 (P1)

The two flows considered in equation P1 include mill water (1) and ore (2).

$$P1_{flow} = (1)_{flow} + (2)_{flow} \quad (1)$$
$$P1_{TDS} = (1)_{TDS} + (2)_{TDS} \quad (2)$$

The flows in step P1 (as in every step) are additive (i.e. the flow in step P1 is the result of adding the mill water flow rate to the ore water flow rate). TDS contributed from ore is added to the mill water TDS because solutes from the ore are being dissolved in the mill water without any significant addition of water to the mill circuit.

Process 2 (P2)

The three flows considered in equation P2 include fresh water (a) (3), reclaim water (4), and the concentrate thickener flocculant system (5).

$$P2_{flow} = P1_{flow} + (3)_{flow} + (4)_{flow} + (5)_{flow} \quad (3)$$

$$P2_{TDS} = P1_{TDS}\,(P1_{flow}/P2_{flow}) + (3)_{TDS}\,((3)_{flow}/P2_{flow}) + (4)_{TDS}\,((4)_{flow}/P2_{flow}) + (5)_{TDS}\,((5)_{flow}/P2_{flow}) \quad (4)$$

Fresh water (a), reclaim water, and water from the concentrate thickener flocculant system are added to the mill circuit at P2. The TDS for P2 is determined by calculating the relative percentage of TDS from each of the four flows.

Process 3 (P3)

The flow considered in equation P3 is the flow to concentrate storage (6).

$$P3_{flow} = P2_{flow} - (6)_{flow} \quad (5)$$

$$P3_{TDS} = P2_{TDS} \quad (6)$$

Flow to the concentrate storage is subtracted from the mill circuit at P3. The TDS remains the same as it was in P2.

Process 4 (P4)

The flow considered in equation P4 is the flow from the tailings thickener flocculant system (7).

$$P4_{flow} = P3_{flow} + (7)_{flow} \quad (7)$$

$$P4_{TDS} = P3_{TDS}\,(P3_{flow}/P4_{flow}) + (7)_{TDS}\,((7)_{flow}/P4_{flow}) \quad (8)$$

Water from the tailings thickener flocculant system is added to the tailings thickeners. The TDS for P4 is determined by calculating the relative percentage of TDS from P3 and stream (7).

Process 5 (P5)

The flow considered in equation P5 is the flow from historic mine waters (8).

$$P5_{flow} = P4_{flow} + (8)_{flow} \quad (9)$$

$$P5_{TDS} = P4_{TDS}\,(P4_{flow}/P5_{flow}) + (8)_{TDS}\,((8)_{flow}/P5_{flow}) \quad (10)$$

Historic mine waters (HMW) from the pit lakes, waste rock dump drainages, and leach pad effluents are added to the mill circuit at the tailings splitter, which is located before the tailings thickeners. Two scenarios are considered to reflect the addition of various HMWs. The model randomly selects one of these scenarios, then uses the appropriate flow rate and TDS distribution for the waters being added. The TDS at the tailings splitter is then calculated by using the relative percentages of TDS from P4 and the appropriate HMW.

Process 6 (P6)

The flow considered in equation P6 is the tailings thickener underflow (9).

$$P6_{flow} = (9)_{flow} \quad (11)$$

$$P6_{TDS} = P5_{TDS} \quad (12)$$

Water from the tailings thickeners is split into two streams. Tailings thickener overflow is returned to the mill while tailings thickener underflow is sent to the tailings impoundment and therefore affects the TDS at the outfall. This step determines the tailings thickener underflow rate. The TDS remains the same as it was for the tailings splitter (i.e. P5).

Process 7 (P7)

The flow considered in equation P7 is fresh water (b) (10).

$$P7_{flow} = P6_{flow} + (10)_{flow} \quad (13)$$

$$P7_{TDS} = P6_{TDS}\,(P6_{flow}/P7_{flow}) + (10)_{TDS}\,((10)_{flow}/P7_{flow}) \quad (14)$$

In step P7, fresh water (b) is added to the process water. The TDS is calculated by determining the relative contributions from P6 and stream (10). The result of step P7 is the TDS and flow rate at the outfall.

Model Input Data

Flow rates for the model were derived from engineering flow diagrams of the BHP mill circuit. The flow rates for the HMWs were based on the maximum authorized flow rate for pumping these waters into the mill circuit.

Records of TDS measurements were compiled to generate a TDS distribution for each relevant flow stream. TDS values were available for: fresh water from the mill ponds, HMWs, tailings reclaim water, and tailings effluent as measured en route to the tailings impoundment.

TDS values were also available for the ore stream entering the mill. The BHP metallurgical laboratory conducted a test program to define average recoverability and concentrate grades for the major ore types in the three pits at the mine. Tests on samples for the Optimization Metallurgical Test Program provided information regarding mill throughput and copper, gold, and silver recoveries for the major ore types from each pit to be mined. Recovery curves for the various ore types, developed as a result of the optimization study, are incorporated into the mine planning block model for calculation of recoverable metal in each of the model blocks. Effluent from the tests for each ore type was collected and analyzed for TDS and the results were used to determine the amount of TDS each ore type would contribute to the mill circuit.

Model Implementation

Flow Rates

All of the flow rates used in the model were assumed to be constant because the mill water flow rate remains fairly constant so the mill can function properly. The same is true for any of the other flows entering the mill. The amounts of fresh water or reclaim water entering the tailings thickener overflow sump may vary, but only the total water flow rate leaving the tailings thickener overflow sump (and returning as mill water) was used in the model.

TDS Distributions

A normal distribution was assumed for each of the probability distribution functions. To verify this assumption, both graphical and analytical tests of normality were performed on the TDS concentrations from each source. Because much environmental data is log-normally distributed, both the normal and natural-log converted data were tested. The graphical tests consisted of plotting the histogram and normal probability plot of the normal and log-converted data.

The normal probability plot graphs each data point against the expected value from an ideal normal distribution. In this method, the data from a normal distribution would fall on a straight line. This graph allows a visual inspection of how close the data is to normal, and where the data departs from normality. The analytical method used was the Shapiro-Wilk test. The Shapiro-Wilk test is based on the normal probability plot and quantifies how linear (close to normal) the data distribution is. A Shapiro-Wilk value of one indicates an ideal normal distribution. The closer the value to one, the more normal the distribution. For each of the input flow streams, the Shapiro-Wilk value fell between .86 and .97. This test demonstrated that the raw data from all sources was normally distributed. The flow rates and TDS values used in the model are presented in Table 1.

Table 1. Flow rates and total dissolved solids values used in the TDS prediction model.

			TDS (mg/L)	
Stream ID	Stream Description	Flow Rate (gpm)	Mean	Standard Deviation
1	Mill Water	18,000	1,730	530
2	Ore	500	850	590
3	Fresh Water (a)	1,300	660	140
4	Reclaim Water	1,700	2,110	540
5	Concentrate Thickener Flocculant	5	2,110	540
6	Concentrate Storage	12	--	--
7	Tailings Thickener Flocculant	200	2,110	540
8	Historic Mine Waters			
	--Liberty Pit	1,000	4,660	1,620
	--Intera Drain	500	14,400	5,210
	--Ruth Pit	2,000	4,110	230
9	Tailings Thickener Underflow	7,000	--	--
10	Fresh Water (b)	150	660	140

Selected Source TDS Values

The TDS distribution for the mill water was based on the extensive set of tailings effluent measurements, which are representative of the water at the tailings thickener overflow sumps.

The TDS for the ore going into the mill was derived from the mill optimization tests conducted by the BHP metallurgical laboratory. Data from five ore types were available.

The TDS distribution for the fresh water (a) stream was derived from measurements taken from the fresh water mill ponds.

The TDS distribution for the reclaim water stream was taken from measurements of tailings impoundment reclaim water.

The TDS distribution for the concentrate thickener flocculant stream was taken from a series of actual TDS measurements of tailings reclaim water. Reclaim water from the tailings impoundment enters the concentrate thickener system, where flocculant is added. This water is piped into the concentrate thickener tank. Although flocculant settles suspended solids, it does not significantly affect TDS. Because flow from the concentrate thickener flocculant system is low and changes in TDS from the flocculant are minimal, the distribution for the reclaim water TDS was used.

There is no TDS value associated with the concentrate storage stream because water is leaving the system.

The TDS distribution generated for the reclaim water from the tailings impoundment was used for the tailings thickener flocculant stream.

TDS measurements were available for the HMWs and were used to generate distributions for that stream.

The TDS distribution at the tailings thickener underflow is the same as for the tailings splitter box where the HMWs enter the mill circuit.

The TDS distribution for the fresh water (b) stream was derived from measurements taken from the fresh water mill ponds.

Monte Carlo Simulation

A Monte Carlo simulation was performed to predict TDS levels at the tailings outfall. The @Risk program determined which input variables were significant in terms of meeting certain target TDS levels and calculated the median values for these variables by:

1) calculating the median and standard deviation for each input variable,
2) creating a subset of the data, using input values only for iterations where the target TDS level is achieved and,
3) calculating the medians for the subset of the input values.

The difference between the subset median and the median for the entire data set was then calculated, and compared to the standard deviation for the entire input data set. If the absolute value of the difference in medians was greater than half a standard deviation, then that input value was termed significant. The median was also given as a percentile in the entire input data set.

Model Results

The @Risk program was used to simulate TDS at the outfall. Ten thousand iterations were run in order to return a consistent mean and standard deviation for the model. The model predicted a mean TDS value of 2,590 mg/l at the outfall (Figure 3). A sensitivity analysis was performed to identify the input streams that most significantly affect TDS values at the tailings outfall (Figure 4). In the sensitivity analysis, each input variable was regressed against the output variable to determine the impact of each individual input parameter on the output. The value in Figure 4 represents a normalized regression coefficient associated with each input value. The most significant inputs to the model were the TDS added from ore and the TDS from the re-circulated mill water.

An analysis was performed to determine which conditions would cause the TDS to remain below 2,000, 2,500, and 3,000 mg/l at the outfall. A median TDS value for the mill water of 1,250 mg/l, and a median TDS value for ore of 220 mg/l were found to be important in maintaining a level of TDS below 2,000 mg/l. To maintain a TDS less than 2,500 mg/l at the outfall, a median TDS value for the mill water of 1,440 mg/l and a median TDS value for ore of 480 mg/l are necessary. The values derived from the TDS distributions used in the model (i.e. mean mill water TDS of 1,730 mg/l and mean ore TDS of 850 mg/l) were sufficient to maintain a TDS value below 3,000 mg/l for 75% of the time.

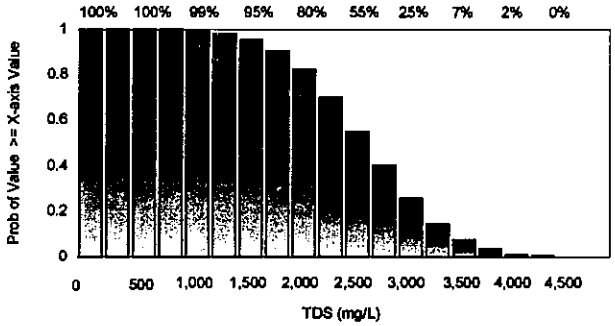

Figure 3. Probability distribution of total dissolved solids sent to the tailings impoundment.

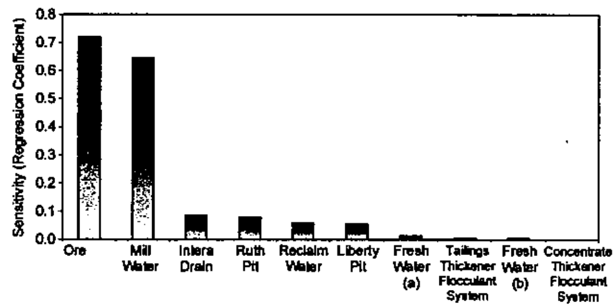

Figure 4. Simulation sensitivities for factors controlling total dissolved solids.

Conclusions

The TDS model described in this paper predicted that the mean TDS value will be 2,590 mg/l at the outfall. It also indicated that the TDS in ore and mill water will most significantly influence the TDS concentrations at the tailings outfall.

The model has been used to predict the range of conditions over the entire proposed mine life. As more data are accumulated, alternative scenarios can be modeled to predict cases such as milling of a particular ore type or addition of a certain HMW to further identify how changes in each stream could affect TDS at the outfall.

Literature Cited

Palisade Corporation. 1996. @Risk: Advanced Risk Analysis for Spreadsheets. Newfield, NY.