Integrating Surface Water Load Modelling into Mine Closure Performance Evaluation

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Abstract

Predictive water quality models are often used to support mine permitting but too often are not used later in mine life to re-evaluate mine performance. Models have equal or greater value during mine operation and closure as a means of comparing actual mine performance to expected performance. Integrated use of models and water quality monitoring throughout the mining life cycle may provide important early warning signs of potential compliance issues and can serve to pinpoint facilities that may be contributing off-site loading. Mass load models also provide a means of predicting the response in a receiving water from chemical loading from the mine. This paper describes the development and use of a surface water mass loading model for assessing closure success at El Sauzal Mine in Chihuahua State in southwest Mexico. In December 2015, El Sauzal (Goldcorp) became the first mine in the world to be decommissioned in accordance with the International Cyanide Management.

Key words: Mine water, water quality compliance, surface water hydrology, mass load model, Goldsim, modeling

Introduction

El Sauzal Mine (Figure 1) is located in the southern Sierra Madre Occidental Mountains in southwestern Chihuahua, Mexico. Ore was mined from four open pits from late 2004 to late 2014. Mining waste was placed in several waste rock storage facilities and a dry-stack Tailings facility. Large surface water diversions were constructed during mine closure to manage water from steep headwater basins upgradient of the mine. Additionally, waste rock and tailings facilities were re-shaped and covered to reduce seepage contributions from mine facilities. The purpose of this presentation is to describe the framework developed to measure closure performance.

Background

Geology

El Sauzal (Charest et al. 2005, Weiss and Espinoa 2007) is a volcanic hosted high sulfidation epithermal gold deposit (Arribas 1995). Mineralization was caused by circulation of strongly oxidized and acidic water that caused pervasive weathering of feldspars, creating concentric zones of vuggy quartz, quartz-alunite enrichment, argillic alteration, and sulfide enrichment. The entire deposit may be surrounded by zones of propyllitic alteration (enrichment in chlorite with or without carbonates). Numerous surficial red-stained areas are located on strike with the deposit, and are evidence of district scale intensive hydrothermal alteration.

At El Sauzal, gold is hosted in a series of volcanic units with highest gold grades found in vuggy quartz and in quartz-alunite alteration zones. Intensive silica enrichment is found in the center of the deposit, which is dominantly within a “megabreccia” unit. The megabreccia and associated volcanic units consists of a suite of depositional events that includes lithic tuffs (often pyritic), andesite flows, and dacitic to rhyolitic pyroclastic units (breccias). In places, the pit highwalls expose zones with sulfide enrichment. Volcanic rocks are likely of Oligocene age (30 million years before present), typical of the Sierra Madre province (Weiss and Espinosa 2007). The volcanic host rocks are underlain and overlain by andesitic rocks that are generally devoid of sulfides and contain low levels of carbonates.

Climate

The climate in the Sierra Madre Occidental region is dominated by a summer monsoon season that occurs from July through September. Annual rainfall averages 809 mm and nearly 80 % of the annual rainfall at El Sauzal occurrs in July through September. The climate for the remainder of the year is typical of an arid subtropical regime with monthly rainfall averaging only 15 mm per month for October through June (Figure 2).

Hydrology

El Sauzal is located in steep dissected terrain adjacent to Rio Urique, which is a major tributary to the Rio Fuertes an important source of irrigation water for Sinaloa State. Streamflow in Rio Urique exhibits wide seasonal swings in discharge rate with the majority of surface water discharging in July through September. Gochis et al. (2006) found that an average of 13 % of annual precipitation contributes to streamflow in the Urique basin.

Most stream courses are ephemeral at El Sauzal with streamflow occurring for a few hours after larger monsoonal storm events. Perennial flows occur in three drainages that transect the site. Flow and water quality are monitored at these locations (PS-02, PS-04 and PS-05, Figure 3) that are located below the Tailings facility, mine pits and waste rock piles. Flow rates in these small drainages average 50 to 260 L/min, with peak flows from 400 to 1,200 L/min and minimum flows near zero. No regional groundwater has been detected at Sauzal (Jones 2014) so water that exits the mine is believed to travel as surface runoff or via localized subsurface pathways within perched systems in the layered volcanic rocks.

Water Quality

Rio Urique was has low TDS, neutral pH and slightly alkaline water quality that varies little through the year (Table 1). Water quality monitoring stations located upgradient of the mine or at off-site locations show a wide range of background water quality conditions. While many local ephemeral drainages had water that was similar to Rio Urique (low TDS background stations, Table 1), many local background monitoring sites stations had much higher TDS and elevated sulfate. Some higher TDS sites had neutrall pH (moderate DS background stations, Table 1) and many had low pH and high TDS (acidic background stations, Table 1). Acidic water quality stations were located in mineralized areas that exhibited sparse vegetation and prominent iron-staining, which is representative of El Sauzal prior to mine development. The naturally occurring acidic areas were similar to natural hydrothermal scars that occur near the Questa Mine in New Mexico (Meyer and Leonardson 1990 and Logsdon 2011), which can have pH levels of 3 or less. Average water quality downgradient of El Sauzal is similar to the Moderate TDS background water in Table 1.

While water quality in Rio Urique is relatively constant through the year, historic water quality in small basins near El Sauzal showed strong seasonal variations. For most of the year water in small arroyos is neutral in pH and is alkaline with low metal levels. For short durations (e.g., generally days to weeks) after larger rain events, flow rates increase sharply and water tends to become more acidic and higher in dissolved aluminum, copper and zinc. As streamflow decreases, water quality returns to neutral pH-alkaline conditions (Figure 2).

This seasonal pattern in water quality is attributed to interaction of water with localized mineralized rock exposed in mine pits and in natural outcrops near the mine. The seasonal variations in both flow and quality were attributed at least in part to natural background conditions. The hydrological conceptual model developed to explain the short duration pulses of poorer quality water presumes that there are two differing subsurface flow paths that water may follow at El Sauzal. During low flow periods, water is thought to follow a deep subsurface pathway, which encounters carbonates in deeper volcanic rocks. After intense storms, the abundant water tends to follow a shallow flow path where water interacts with quartz-alunite altered rocks that are acidic and devoid of carbonate. Water in springs downgradient of the mine has a very different signature than standing water in the mine pits. Mine contact water has low pH and elevated iron. Water in springs, though still low in pH is high in aluminum and low in iron. The high aluminum water is attributed to interaction with abundant alunite within the mineralized zones where aluminum may swap for iron through solid solution of iron for aluminum in alunite ($KAl_3(SO_4)_2(OH)_6$). A dynamic mixture of slower moving alkaline water and short duration pulses of more acidic water best explains the flow and water quality variation observed at El Sauzal. Water quality in Rio Urique downstream of the mine meets all applicable water quality standards even during the monsoon season when loading from the site is highest.

Mine Reclamation

The goal of site closure completed during 2015 and 2016 is to maintain or reduce loading from the mine site so that water quality in the Rio Urique continues to be protected. An extensive system of surface water diversions was constructed to maintain stability of waste rock facilities and to minimize surface run-on into acidic areas in the mine pits. Facilities were regraded and covered with suitable material to promote vegetation establishment.

Basin Hydrology and Mass Load Model

A GOLDSIM surface water basin model was developed to predict the response of mine facilities to annual and seasonal variations in rainfall. The surface water mass load model has been integrated into post-closure water quality monitoring program at Sauzal to insure that chemical loading is consistent with the expected performance of the closure actions.

The model computes a hydrograph for each hydrologic basin upgradient of key monitoring stations (PS-02, PS-04 and PS-05, Figure 3) by determining the abundance of water from shallow and deep pathways. Water in the shallow pathway has a median travel time of 7 days (e.g. 50 % of cumulative hydrograph discharges within 7 days) versus 70 days for the deeper flow path. The hydrograph recession curve was modeled assuming a fixed proportion of water in storage (B) would discharge (Q) to the stream each day ($Q_n = \alpha B_{(n-1)}$). Shallow water is assumed to contain high metals while deeper water is low in metals. Measured and predicted zinc at monitoring point PS-04 (Figure 4) illustrates how the mass load model replicates the seasonal changes in streamflow and dissolved zinc in response to seasonal precipitation events. The model replicates the erratic shifts in dissolved zinc at high streamflow and the low zinc during low streamflow periods.

Integrating Performance Model with Post-Closure Monitoring

The calibrated Goldsim model was used to predict how reclamation would affect future loading from the mine site. Reclamation will change surface runoff routing and will reduce net infiltration into waste rock and mine pits. Reductions in net infiltration are assumed to phase in over ten years as the vegetation slowly establishes in the desert environment.

One problem with modeling a monsoon-driven system is that annual loading is highly dependent on annual rainfall and the number of large storms (over about 30 mm) that occur during a year. To illustrate this variability, future mass loading was simulated in Goldsim using a stochastic precipitation data set after January 1, 2016. A series of five random model realizations with varying climate (Figure 5) show that year-to-year variations in rainfall cause such large variations in predicted loading that long-term trends are completely masked. However, when 100 model realizations are conducted, the median and quartile results (Figure 6) show that median zinc loading at PS-04 is expected to decline from about 0.3 kg/d to 0.15 kg/d in the 10 years following mine reclamation. For the same simulation, predicted zinc in Rio Urique downstream of the mine (P3) remains close to background levels (P1) and zinc levels would not be measurably different below the mine than above the mine.

The El Sauzal basin hydrograph mass load model will be used in conjunction with water quality monitoring to determine the success of reclamation. The primary success criterion for the site will be water quality compliance with NOM-001 criteria at downstream station P3 at Rio Urique (Figure 3). A secondary success criterion would be for water quality at P3 to be the same as at P1 (upstream). A final success criterion is for internal monitoring locations on arroyos (PS-02, PS-04 and PS-05) to remain within a reasonable margin of error of the flows and chemical loads predicted by the mass load model. Inclusion of modeled basin behavior into the monitoring plan provides a tool for identifying whether mine reclamation is performing as expected and supports the objective of protecting water quality in Rio Urique.

Figures

Figure 1: *Location of El Sauzal mine site in Chihuahua, Mexico.*

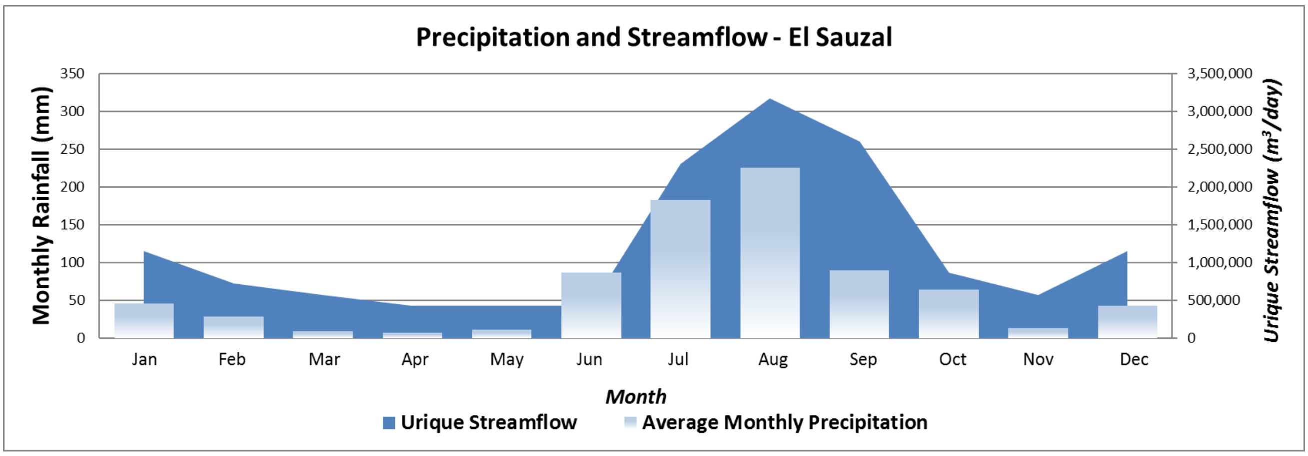

Figure 2. *Monthly rainfall and Urique streamflow at El Sauzal.*

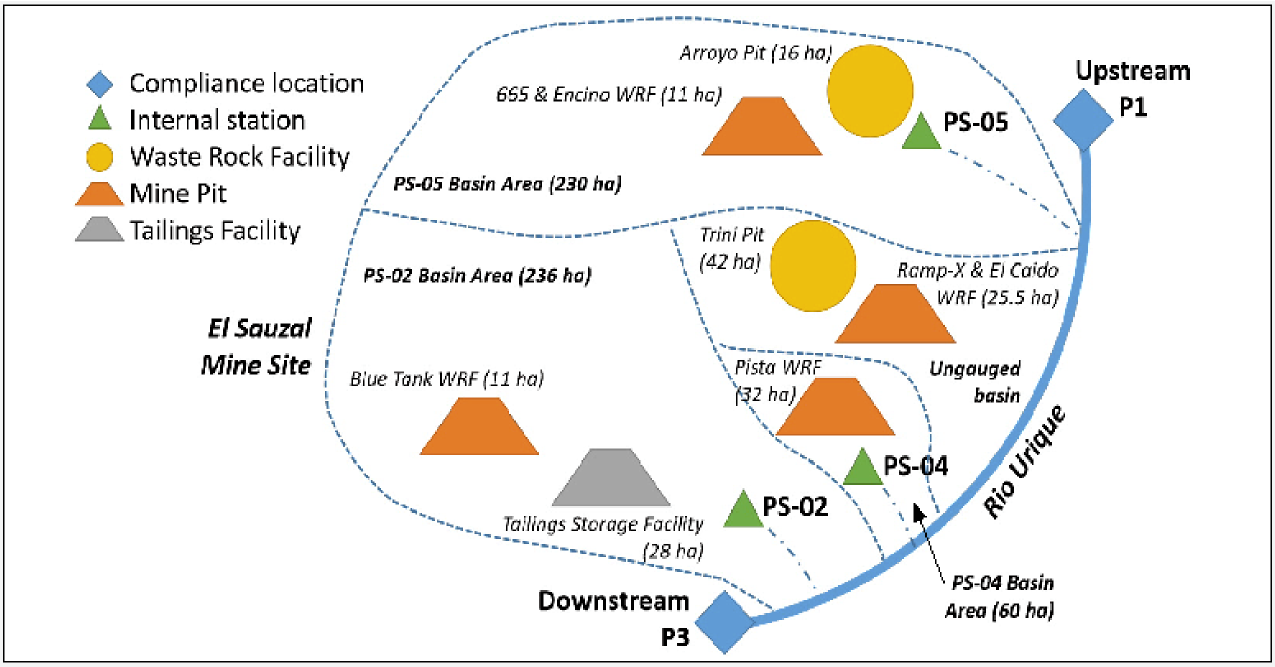

Figure 3: *Schematic of El Sauzal mine site.*

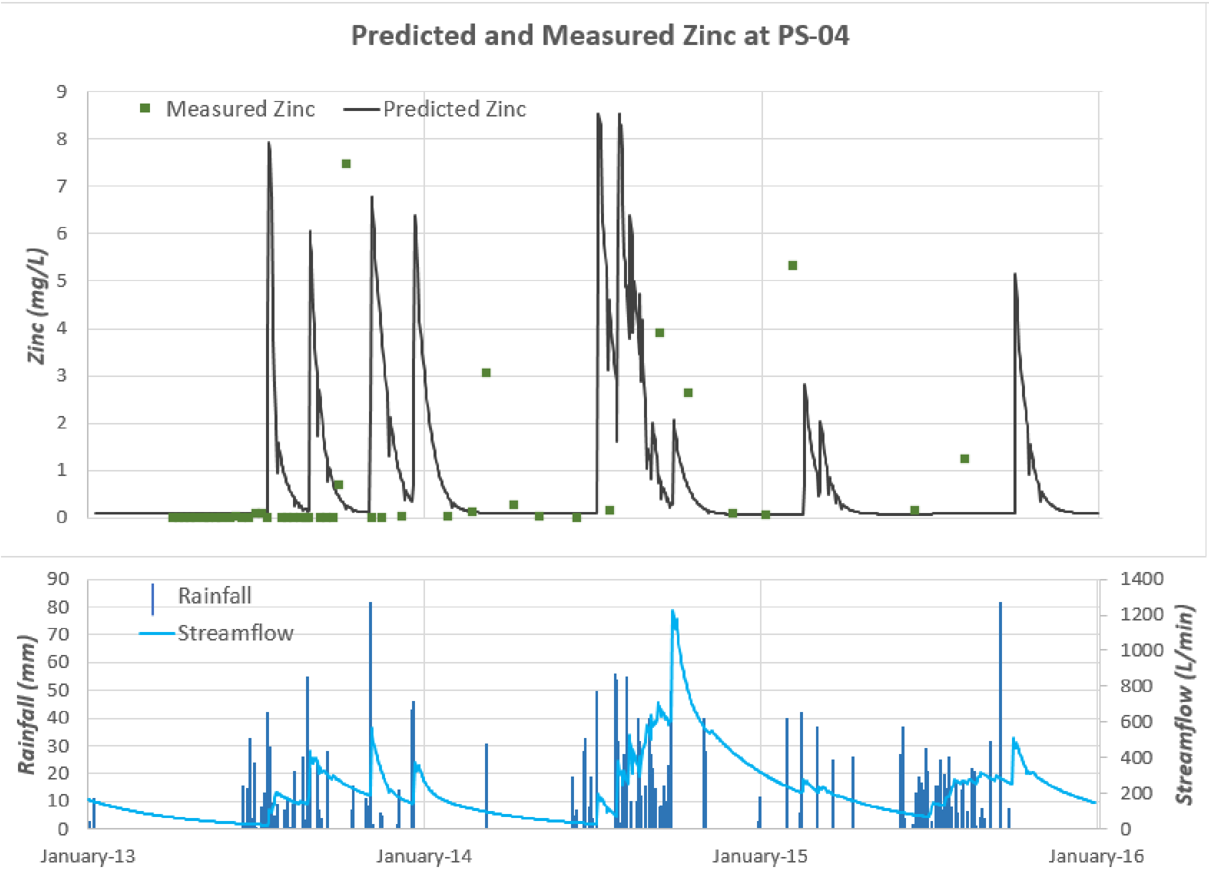

Figure 4: *Seasonal variations in zinc at a downstream monitoring location at Sauzal.*

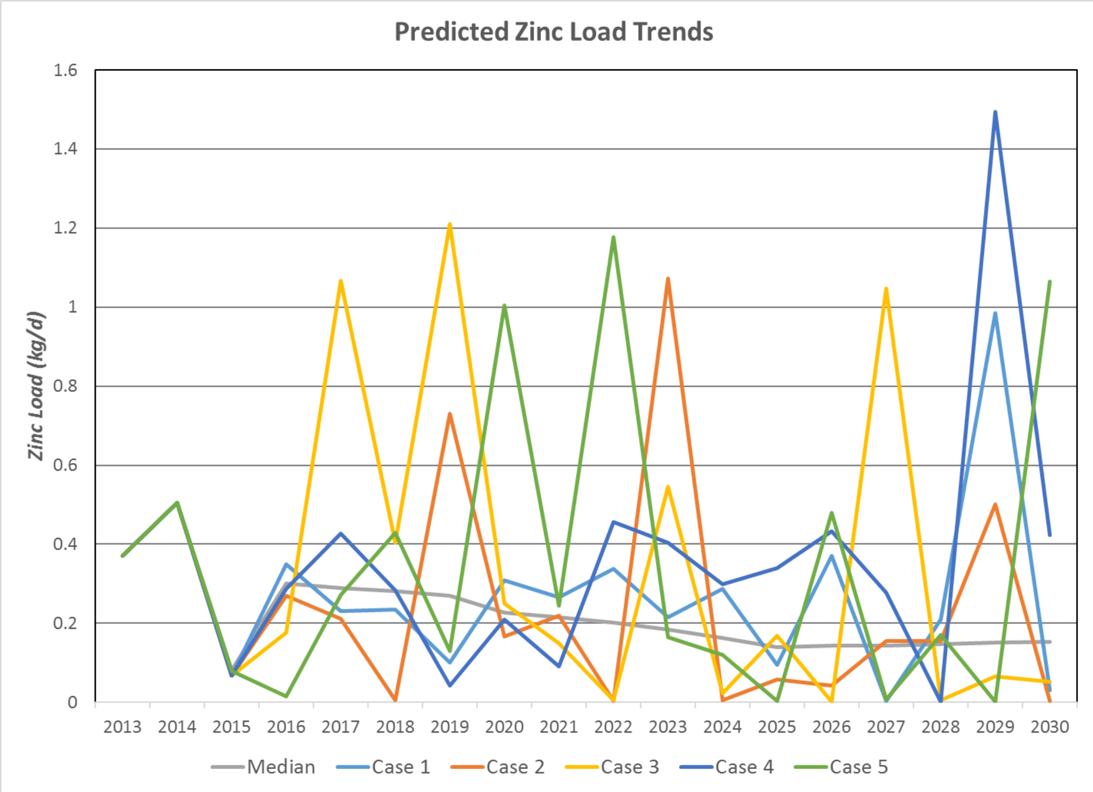

Figure 5: *Predicted trends in zinc loading for five model realizations.*

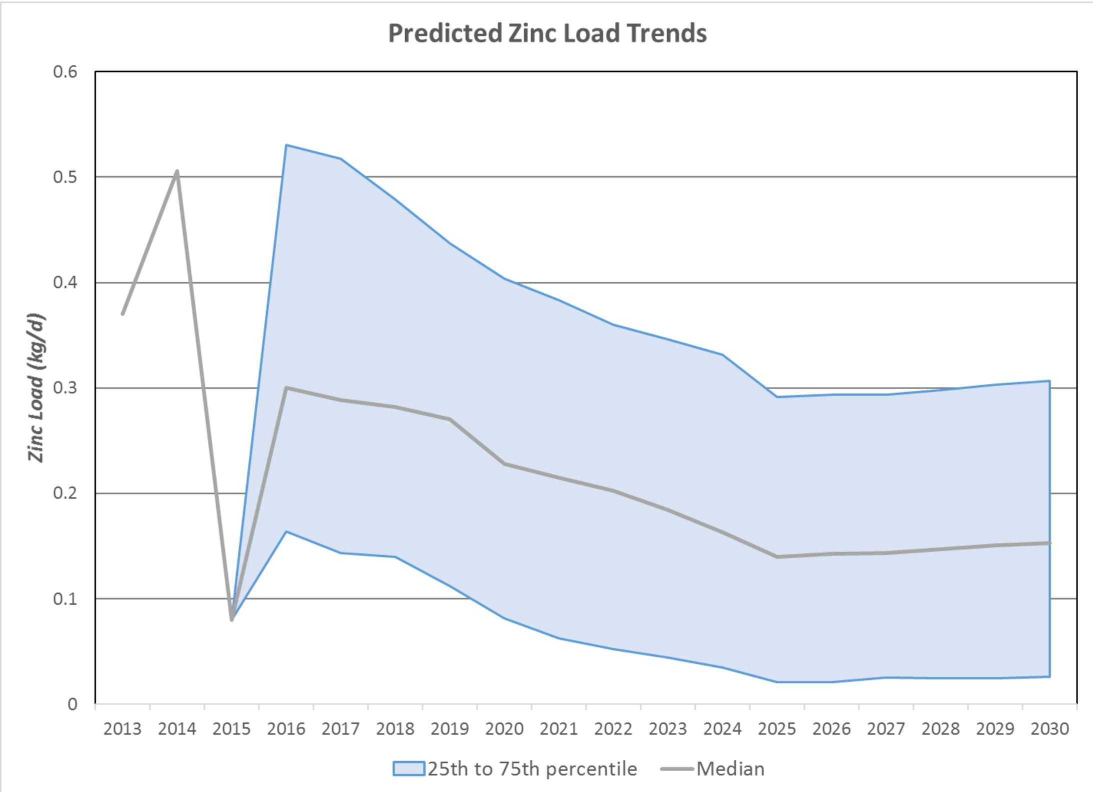

Figure 6: *Probabilistic forecast for trends in zinc load at PS-04 based on 100 realizations.*

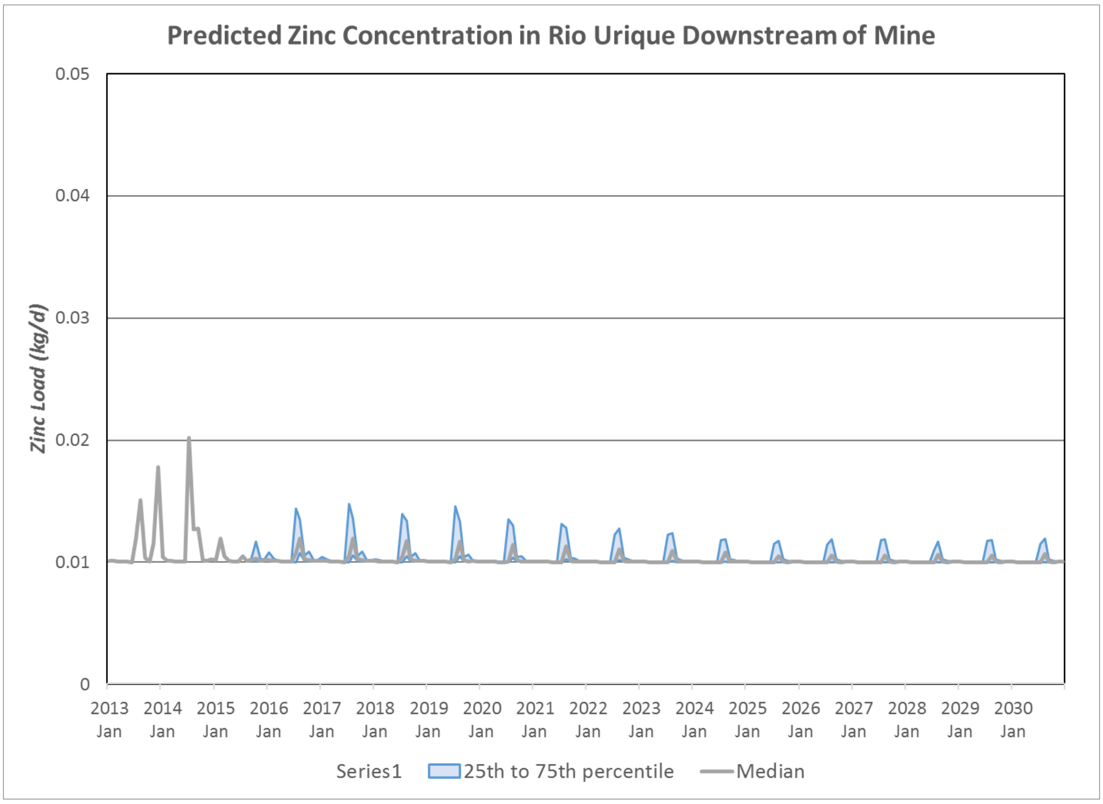

Figure 7: *Probabilistic forecast for trends in zinc concentration in Rio Urique downstream of mine based on 100 realizations.*

Tables

Table 1. *Average water quality conditions for background waters, Rio Urique and monitoring stations downgradient of El Sauzal. Mexican water quality criteria applicable to Rio Urique are also shown.*

Constituent	Rio Urique (P1)	Background Water Quality: Low TDS Stations	Background Water Quality: Moderate TDS Stations	Background Water Quality: Acidic Stations	Average of Site Monitoring Stations [1]	NOM-001 [2]
pH	7.7	7.9	7.4	3.1	6.9	<5
Specific Conductance (uS/cm)	127	494	2022	3070		
Acidity as ($CaCO_3$) (mg/L)	4.8	<1	<1	1171	51.0	
Alkalinity as ($CaCO_3$)	39	237	141	<1	128	
Sulfate	15	37	1184	2653	1671	
NO3 as N	0.2	0.4	0.1	<0.1	14.4	>15
Total Aluminum	9.4	0.9	1.0	131.6	7.6	
Total Iron	4.4	0.9	0.8	121.5	3.0	
Total Zinc	0.07	0.02	0.02	6.13	0.8	>10

1 – average acidity estimated from average iron and aluminum at PS-02, PS-04 and PS-05

2- Mexican water quality criteria for Rio Urique, Nitrogen standard is for total N. Semarnat 1996

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