Technical Memorandum

To: Anthony Brown, BP

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Re: Development of the Rico Argentine Mine DR-3 Hydrologic Model

Amec Foster Wheeler, Inc. (Amec Foster Wheeler) and Pioneer Technical Services, Inc. (Pioneer) have prepared this memorandum to describe the hydrologic modeling of the St. Louis Tunnel discharge (DR-3) at the Rico-Argentine Mine (site). The modeling effort utilized data collected at DR-3 and near the outfall of the pond system (DR-6). While continuous flow measurements are preferable, data from DR-3, prior to 2011, was intermittent and prior to 2001, DR-3 measurements were inconsistently collected by various organizations via differing field flow measurement methodologies. Data collected post-2011 was sampled continuously and consistently collected via instrumented Parshall Flumes at both locations, but was collected during an overall drought. More consistent and continuous data over a longer time period can be found in the discharge measurements collected from the USGS Dolores River gauge (DR-G) and precipitation data from several weather stations nearby. This memo describes how calibration against this additional information was utilized to develop a predictive model of the hydrologic response for DR-3.

Background

To quantify the water balance and perform hydrological forecasting for the site at DR-3, a hydrologic model was constructed for the St. Louis Tunnel and the approximate 15 square mile watershed that is estimated to recharge it. The model was calibrated to raw data collected on site at DR-3 and DR-6, data from stream flow measurements of the Dolores River, estimates of

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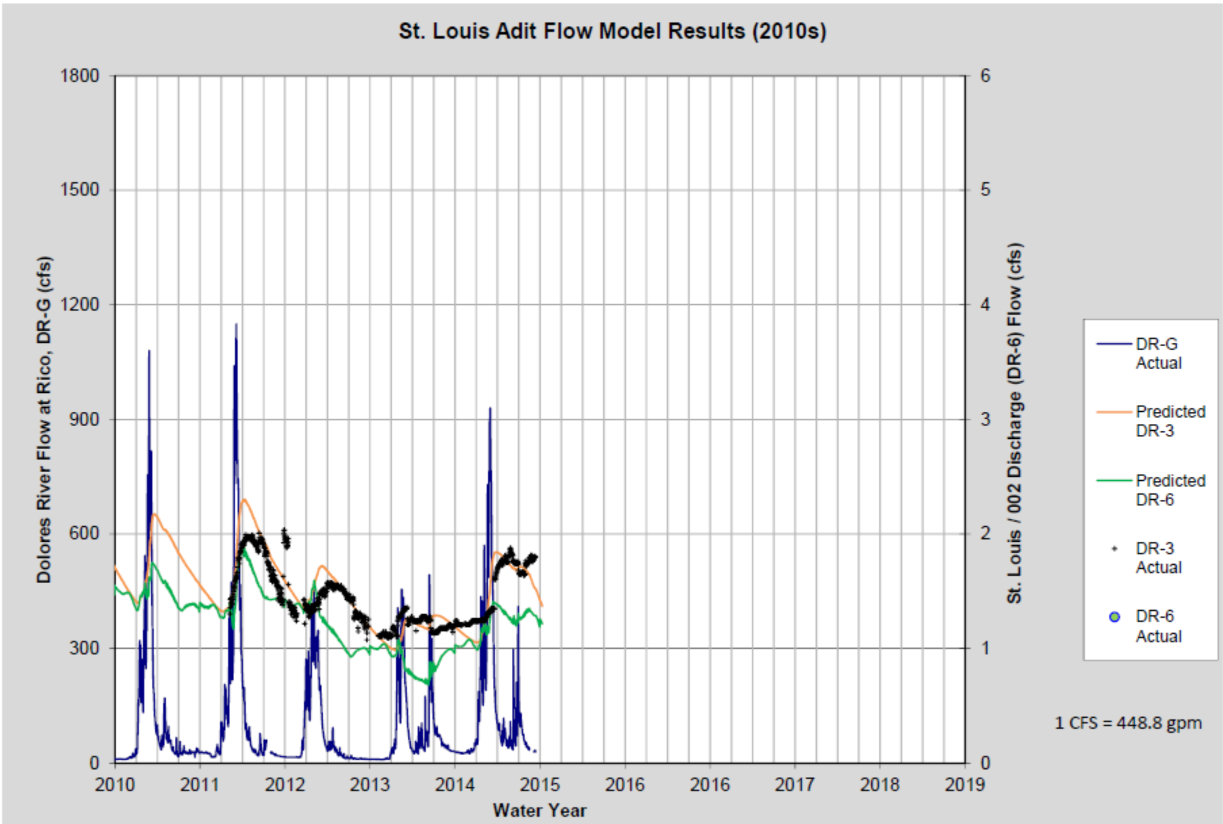
internal mine workings flow distribution, snow pack thickness, precipitation, and temperature. Data was compiled from many sources, including:

- U.S. Geological Survey's river gauge at the Dolores River below Rico (DR-G) (gauge number 09165000) (data from 10/1/51);
- St. Louis Tunnel Discharge (DR-3) (sparse data on irregular dates from 9/15/73, Parshall Flume installed 2001, data collector installed 2011 provides consistent, continuous data);
- St. Louis Ponds Outlet (DR-6) flow gauge (sparse data on irregular dates from 10/31/80);
- SNOTEL data from Scotch Creek (gauge# 739); and
- Weather stations in Rico (ID# E6434) and Telluride (data from 10/1/80).

Flow data at DR-3 prior to the installation of a Parshall flume in 2001 was collected utilizing various methods including the float method, Marsh McBirney meter, and similar field measurement methods. It is known that flow channels where measurements were collected have changed over time, and include pipes, constructed channels and distributed surface flows due to modifications by local property owners. Flow data at DR-6 is believed to have been consistently collected at a Parshall Flume installed sometime coincident with beginning of data collection in the late 1970s. Data since 2011 from DR-3 and DR-6 are collected every 15 minutes at the Parshall Flumes, recorded by a data logger, and calibrated via hand measurements. For this data, a daily average was computed and used in the model. When weather station data for the local Scotch Creek SNOTEL or Rico weather stations were unavailable, data from Telluride were used.

Several of the draft model parameters were determined iteratively by calibrating with the raw data. Soil infiltration and runoff rates were based on a vertical-wall storage tank water balance model. Several tank model studies were referenced in the development of this model, including Sugawara et al., 1976; Sugawara, 1979; Sugawara et al., 1984; and Sugawara, 1995. The soil infiltration rate model assumption was estimated by forward calculating from precipitation, and backward calculating from DR-G river flows. The inferred infiltration rate was a constant fraction of the Dolores River hydrograph (Figure 2). The model estimates sublimation, evaporation and snowmelt based on temperature. Surface runoff values were the result of the sum of the precipitation and snowmelt values, less the estimated infiltration and evaporation. Due to some of these assumptions and model parameters, the draft hydrologic model, based on a theoretical vertical-wall tank and constant fraction of infiltration, almost consistently over-predicted the actual DR-3, see Figure 1.

Figure 1. Modeled Data Showing Over Predictions



Refining the Model

The initial step in refining the draft hydrologic model involved reviewing the raw data from DR-3, DR-6, and DR-G. The correlation of data from these three monitoring locations were analyzed to determine statistically relevant outliers. ProUCL 5.0 statistical software was implemented for the use of Rosner's outlier test at 5% and 1% significance levels. This is a two tailed test which indicates whether selected data are in 5% and 1% probability of being outliers. Data with a 5% significance level was removed, except for one instance in which DR-3 (3.03 cubic feet per second [cfs] on May 12, 1983) and DR-6 (2.60 cfs on May 21, 1983) both had statistically outlying data, but the similar flow values, in combination with the dates of the events, corroborated the data, thus they were kept in the data set. See Table 1 for the list of data identified as statistical outliers. Outliers were removed from the model as described above.

Table 1. Rosner Test Statistically Significant Outliers (5% significance level)

DR-3		DR-6		DR-G		DR-G (cont'd)	
Date	Flow (cfs)	Date	Flow (cfs)	Date	Flow (cfs)	Date	Flow (cfs)
9/15/1973	3.12	9/7/1982	3.87	6/10/1952	1810	1/17/1958	42
7/15/1979	2.78	*5/21/1983*	*2.60*	1/5/1958	42	5/27/1958	1790
7/15/1980	2.79	6/12/1983	3.31	1/6/1958	42	9/6/1970	1210
11/11/1980	3.07	7/26/1983	4.32	1/7/1958	42	1/19/1971	42
3/15/1983	1.86	9/22/1983	2.84	1/8/1958	42	10/26/1972	126
5/12/1983	*3.03*	1/7/2004	0.26	1/9/1958	42	4/8/2004	442
8/15/1995	4.90			1/10/1958	42	10/7/2006	1020

The theoretical shape of the model storage tank was modified to better represent the hydraulic fluxes of the system. The vertical-walled storage tank was modified to a conical shape, which better represents the groundwater fluctuations and the mountain valley watershed in which the site is located. The conical tank shape allows for the relationship between runoff and storage to be more of an accelerative type, and the relationship between infiltration and storage to be more of a saturation type. To better quantify the relationship between surface water flow in DR-G and infiltration rate, a unit hydrograph was calculated using the average of the daily averages recorded at DR-G using the entire data set (10/1/1951 to 11/16/2014) minus the outliers. Infiltration versus runoff was estimated. A weekly average flow rate histogram was constructed using the DR-G data set (Figure 2, gray bars). The infiltration estimate was used to determine the base flow for the model (Figure 2, black bars), with excess flow considered surface runoff.

It was found that the infiltration estimate based on the unit hydrograph in Figure 2 improved the model when the basin was further subdivided into two basins: one using the infiltration estimate based on the unit hydrograph, and one using the constant infiltration of initial draft model. This blended model is considered to better fit the actual physical hydrologic conditions of the site, where the mountains above the mine are generally subject to surface infiltration via the estimate based on the unit hydrograph, and areas where infiltration enters the groundwater via faults and fracture sets. Most of the mineralization zone in the mine is along the Blackhawk Fault that crosses the Silver Creek drainage portion of the basin. Topography is preferentially eroded along the fault to provide valleys that likely concentrate runoff and snow melt along potential entrance pathways of the fault's surface expression. Various historic mine documents report seepage entering the mine via the Blackhawk Fault and spurs. Roughly 1/3 of the basin area provides the optimal fit for the fault-controlled infiltration portion and correlates with what would be expected. The updated hydrologic model results are shown in Figure 3.

Figure 2. DR-G Weekly Average Hydrograph with Projected Infiltration Rate

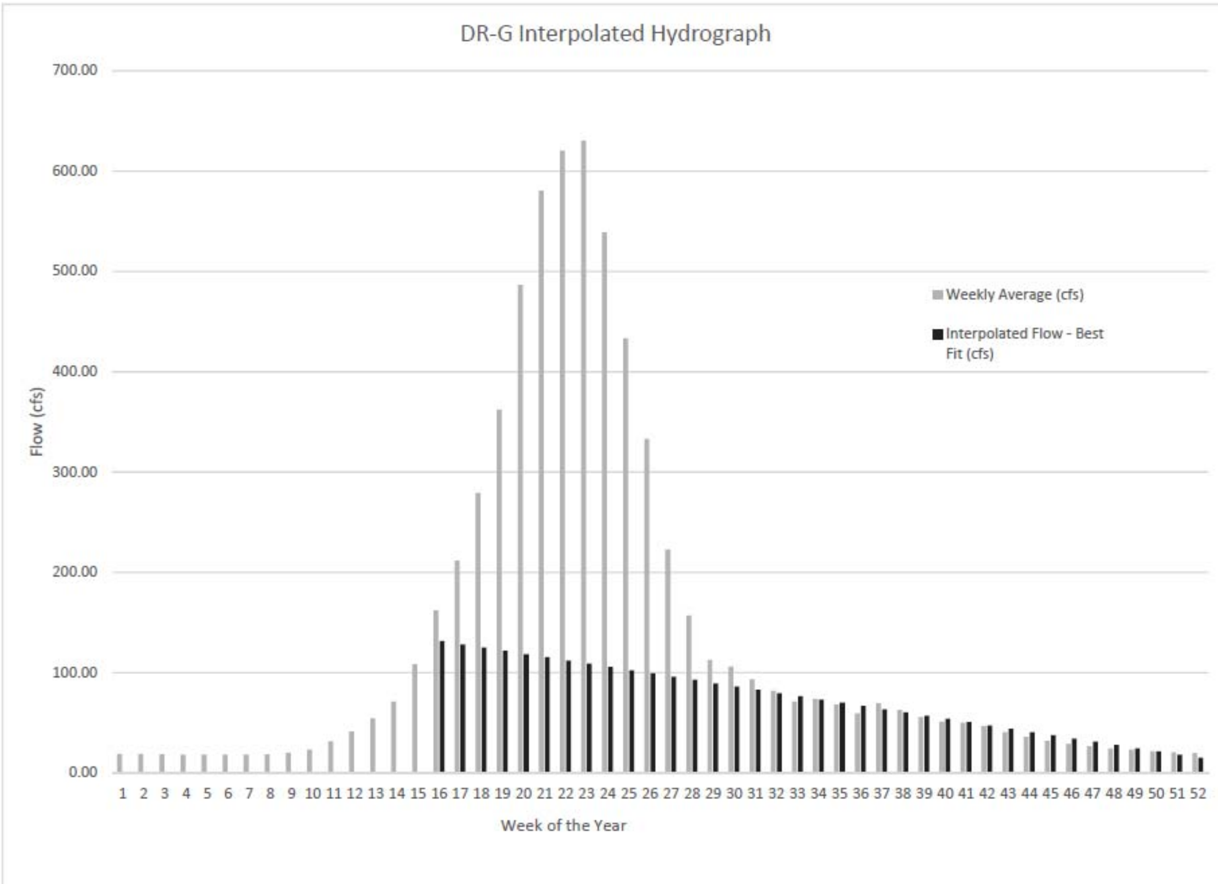
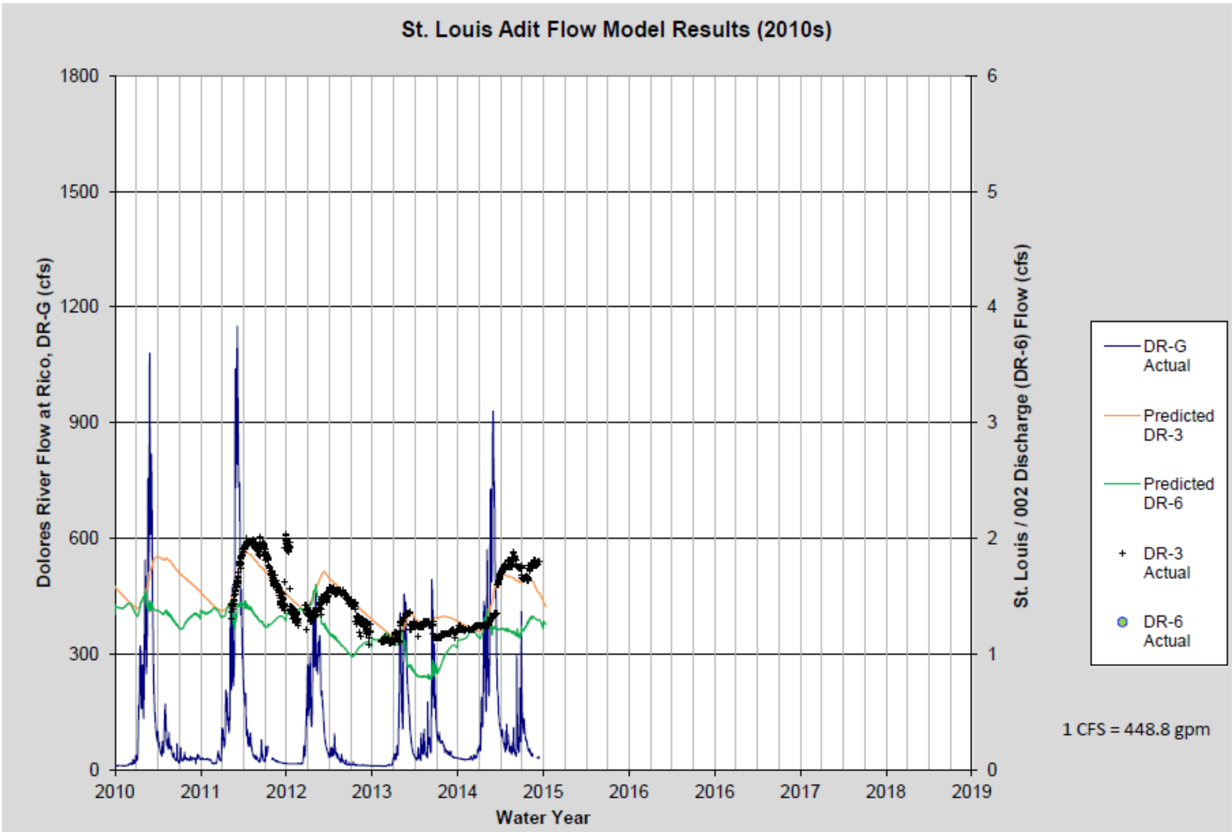


Figure 3. Updated Model Fit to Real Data



Return Interval Analysis at DR-3

Once the hydrologic model was configured to produce an accurate estimate of the flows at DR-3, the daily predicted flows from the model were tabulated and flood frequency analyses were performed to estimate expected return intervals (RI) at DR-3. Two methods, Log Pearson Type III and Weibull plotting position, were used to determine the RI. The techniques involve using the predicted annual peak discharges to calculate statistical information such as mean values, standard deviations, skewness, and recurrence intervals. Frequency distributions are constructed from these statistical data and values extrapolated for events with return periods well beyond the observed flood events. The Log Pearson Type III recurrence interval of a 50-year event predicted 2.75 cfs (1234 gallons per minute [gpm]), while a 100-year event predicted 2.87 cfs (1288 gpm). The Weibull plotting position provided data and a best fit curve fitted to the data. The curve, shown in Figure 4 has the form of a natural log function and for the given data, appears to over-predict the higher return interval flows. The R^2 of the fitted data is 0.9098. The predicted 50-year event using the Weibull plotting position is 2.98 cfs (1337 gpm), and the 100-year event is 3.20 cfs (1436 gpm). The 85th-percentile flow rate, which is based on the modeled annual peak flow data (1952-2014), is 2.39 cfs (1073gpm). The 85th-percentile flow rate provides a value of an event that is greater than 85% of the storms that occur. This value provides a reasonable value in which to address the vast majority of flows that will be encountered. This information is presented in Table 2.

Figure 4. Weibull Method Line of Best Fit Compared to Modeled Data

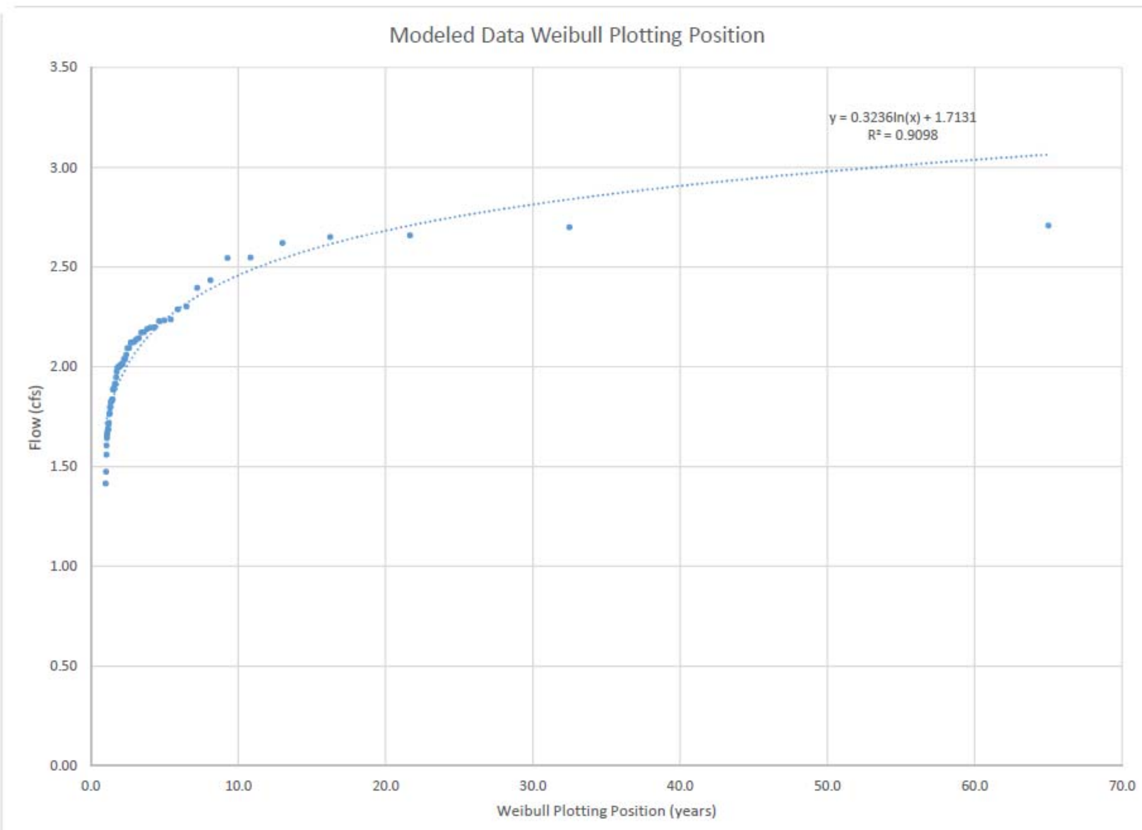


Table 2. DR-3 Return Intervals Compared With 85th Percentile Flows

Analysis Type	Flow (cfs)	Flow (gpm)
85th Percentile	2.39	1073
Log Pearson - 50 year	2.75	1234
Weibull - 50 year	3.20	1436
Log Pearson -100 year	2.87	1288
Weibull -100 year	2.98	1337

The return interval frequencies calculated for DR-3, shown above in Table 2, range from 2.75 – 2.98 cfs (1234 – 1337 gpm) for a 50-year event and 2.87 – 3.20 cfs (1288 – 1436 gpm) for a 100-year event. The 85th-percentile flow rate based on the refined hydrologic model is 2.39 cfs (1073 gpm).

Summary

Based on multiple enhancements to the draft hydrologic model including the removal of outlier data, refinement of the theoretical tank model shape, and the use of a blend of general surface and fault-model infiltration rates, the refined model fit to actual data was improved and very closely fits actual measurements (see Figure 3). Due to the variable collection methods of much of the historic data, the focus of the model fitting was based on the most recent data as it is considered to be the most reliable (even though it was calibrated during a dry period). The fit to annual peak runoff was improved relative to the draft model, which appears to overestimate peak flows. The refined model provides confidence in the validity of the DR-3 peak discharge recurrences.

References

Sugawara, M., Ozaki, E., Wantanabe, I., & Katsuyama, Y., 1976. Tank Model and its Application to Bird Creek, Wollombi Brook, Bihin River, Sanaga River, and Nam Mune. National Center for Disaster Prevention, Tokyo, Research Note, 11.

Sugawara, M., 1979. Automatic Calibration of the Tank Model, Hydrological Science Bulletin-des Hydrologiques, pp. 375-388.

Sugawara, M., Watanabe, E. Ozaki, E., and Katsuyama, Y., 1984. Tank Model with Snow Component. The National Research Center for Disaster Prevention, Science and Technology Agency, Japan.

Sugawara, M., 1995, "Tank model." Computer models of watershed hydrology: pp. 165-214.