Tracing Hydraulic Connections between the Undisclosed River and the Undisclosed Mine

State/Province, Country

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EXECUTIVE SUMMARY

The DHI Group of City, State, Country and GeoHydros, LLC of Reno, Nevada, USA (DHI Team) were contracted by Mining Company (VM) to conduct a groundwater tracing experiment between the Undisclosed River and VM's underground zinc mine in Undisclosed, State, Country. The fundamental objectives of the study were to: identify sources of river water infiltration to the mine workings; identify the section or sections of the river from which the infiltrated water is derived; quantify the amount of river water entering the mine; and quantify the amount of river water being lost to karstic features.

The DHI team designed a multiple tracer experiment that leveraged insitu fluorometers, an onsite analytical laboratory fluorometer, and regular water sampling to achieve the four objectives. The experiment was carried out between November 11 and December 7, 2013.

Two sets of tracer injections were performed in the Undisclosed River using three fluorescent dyes. In each test, the three dyes were injected at different locations in the river such that the pattern of detection in the mine would reveal the source areas in the river. The three dyes were: Uranine, Rhodamine-WT, and PTSA salt. The 2nd set of injections was the most successful. They were performed using 9.25 kg of each tracer where the PTSA was injected directly into a flowing swallet.

All three of the dyes were detected in the mine at the stations in the southern section of the mine. Uranine was detected at stations 1-11. Rhodamine-WT was detected at stations 1-3, 5-7, and 10-11. PTSA was detected only at stations 10 and 11. The pattern of detections in the mine indicate the presence of three discrete flow paths connecting the river the underground mine tunnels. One is from the upper part of the river (upstream of the Rhodamine-WT injection and the southernmost stations: 4, 5, and 8 at levels 420 and 388. One is from some point downstream of the Rhodamine-WT injections to mine stations 1, 2, 3, and 6 at levels 484 and 455. The last pathway is from the swallet located upstream of the river sampling station and the lowest levels of the mine at stations 10 and 11.

Mass recoveries were calculated for all three dyes at the river sampling station and for Uranine and PTSA in the mine discharge channel. Mass recoveries ion the river had to be based on estimated hydrographs at the Rochedo gauging station because the station was not functioning during the tracer testing period. The estimated hydrographs were created through statistical comparison of river flows at the Bertoldo and Rochedo stations during four different periods in 2013 where the magnitude and trend of flows at the Bertoldo station was similar to that recorded during the tracer test as well as for a 10-month period of record during which both stations were active prior to the tracer test.

The most significant recoveries were those after the 2nd set of injections: Uranine and Rhodamine-WT at the river sampling station, and Uranine and PTSA in the mine discharge channel. The recovered mass of Uranine at the river sampling station ranged between 1,567 and 2,705 grams using estimated flows at the sampling stations derived from the maximum of the four hydrographs and the period of record hydrograph. The recovered mass of Rhodamine-WT was between 368 and 489 grams.

Approximately 25% of the PTSA that was injected directly into the swallet in the river was recovered from the mine discharge channel where late-time detections recorded by the C3 fluorometer could raise the recovered mass to as much as 35%. The missing mass of PTSA (~65%) was attributed to adsorption to organic matter and rock substrate in the aquifer flow path. Given the possible loss due to adsorption, between 16% and 18% of the injected Uranine dye was accounted for by the recovery curve plotted for Uranine in the mine discharge channel. The substantially smaller recovery of Uranine is likely due to larger adsorption to organic matter in the river to which the PTSA was not exposed due to the injection method and location.

Comparison of the hydrograph from the Bertoldo gauging station to the estimated hydrographs for the Rochedo station during the tracer test reveal that as much as 37% of the mine discharge is river water lost to the aquifer between the Bertoldo and Rochedo gauging stations. The fractional recovery of Uranine in the mine discharge channel indicates that the fraction of river water in the mine discharge could be less than 10% though the inability to fully account for adsorption in the river channel renders this lower estimate less likely.

The pattern and timing of tracer detections relative to the karstic characteristics of the aquifer indicate that flow from the river to the mine occurs along discrete dissolutionally widened fractures but that there is not a perfect hydraulic connection between the river and the mine. Instead, flow from the river to the mine must first traverse substantial aquifer storage, most likely within the epikarst that is situated between the dolomite and the river. The magnitude and timing of the flow through the epikarst and into the mine is substantially affected by the hydraulic gradients created by fluctuating river stage and the presence of the phyllite that separates the river from the mine. Understanding the relationships between river stage, volume of water in the epikarst storage, and discharge in the mine will therefore be significant to the identification, design, and implementation of mitigation strategies designed to reduce river water infiltration to the aquifer and the mine.

Additional groundwater tracing experiments and modeling could be leveraged to gain a better understanding of the hydraulic relationship between the river and the mine; to better understand the hydraulic significance of the phyllite and the degree to which it impedes flow from the river to the mine; and to characterize the pattern and rate of groundwater flow into the northern part of the mine. The following list provides recommendations for specific tests and actions that, we believe, would achieve these objectives.

1. Identify and trace flow paths and groundwater velocities between other active swallets and the mine, and record the long term pattern of tracer responses in the mine. These could include swallets such as those observed during this experiment that have formed in the river channel as well as sinkholes in the river flood plain that receive water during floods. The objectives would be to identify the locations of connections and, more importantly, to define the pattern of tracer response in the mine relative to fluctuations in river stage occurring over the period of hours to days after the injections. Given the results of the tracer tests performed in this study, particularly the low detectability of Rhodamine-WT and PTSA in the mine and Undisclosed River waters, we recommend that future tracers be limited to Uranine where staggered injections at different locations and regular water sampling at all stations would be used to isolate pathways and quantify tracer mass recoveries at the specific discharge locations in the mine. Such injections would be performed sequentially leveraging the observation that more than 90% of the recovered dye was recorded in the mine discharge channel within 3.5 days of the river injection during these experiments.

2. Trace the path and velocity of groundwater flow from the north into the mine and compare the signal response in terms of concentration and mass recovery to the results obtained from the river experiments to define the relative contributions of each source in the mine discharge. Once again, we recommend that such traces use Uranine, staggered injection times, and water sampling at all major sampling stations to establish tracer mass recovery curves.

3. Better delineate the location of river flow losses in the Undisclosed River by repeating the river experiments but focusing the injections on locations immediately upstream of the probable loss points identified during the multiple filed reconnaissance surveys performed during this study. Regular water sampling at the mine discharge locations would permit the development of multiple tracer recovery curves, which could be used to quantify dilution between the specific discharge locations and the mine discharge channel and thereby better constrain the amount of river water in the total mine discharge.

4. Revise the existing FEFLOW model to include the discrete flow paths and groundwater velocities identified by the tracing experiments where calibration to heads would be used as the basis to evaluate multiple networks of discrete flow paths and identify the most probable pathways. Those pathways would then constitute targets for mitigation efforts intended to reduce river water infiltration to the aquifer and mine.

1 INTRODUCTION

The DHI Group of City, State, Country and GeoHydros, LLC of Reno, Nevada, USA (DHI Team) were contracted by Votorantim Metais (VM) to conduct a groundwater tracing experiment between the Undisclosed River and VM's underground zinc mine in Undisclosed, State, Country. The fundamental objectives of the study were to:

1. identify sources of river water infiltration to the mine workings;
2. identify the section or sections of the river from which the infiltrated water is derived;
3. quantify the amount of river water entering the mine; and
4. quantify the amount of river water being lost to karstic features.

The DHI team designed a multiple tracer experiment that leveraged insitu fluorometers, an onsite analytical laboratory fluorometer, and regular water sampling to achieve the four objectives. The experiment was carried out between November 11 and December 7, 2013. This report describes the methodology and results of that experiment.

1.1 Problem & Purpose

The Undisclosed zinc mine consists of multiple levels of underground mine workings that are below the local water table surface. Removal of groundwater discharge into the mine workings has created a cone-of-depression in the piezometric surface of greater than or equal to 180 meters. The cone-of-depression creates a large hydraulic gradient between the Undisclosed River, which flows west to east approximately 0.5 to 1.5 km south of the mine, and the underground mine workings. Groundwater discharge into the mine workings flows to the lowest level where it is lifted and discharged to the land surface via multiple pumps operating at a median rate of more than 11,500 m^3/hour.

The geology of the mine and river area consists predominantly of NE-SW trending fault-bounded dolomite that is bounded on the NW and SE sides by low permeability clastic rocks, where the zinc ore has formed as a result of hydro-thermal circulation through the dolomite. Faults and fractures in the dolomite have been dissolutionally widened creating rapid groundwater flow into the mine workings where the tunnels intersect the dissolved conduits. Numerous sinkholes have developed that extend to the land surface in the vicinity of the mine, some of which have resulted in significant damage to structures (Bittencourt et al., 2008). The rate of groundwater discharge into the mine workings and of sinkhole development at the land surface have increased through time as the mine workings have been extended along the NE-SW trend of the ore body (Bittencourt et al., 2008).

The Undisclosed River flows from west to east approximately 1 km south of the mine across the dolomite and across the aerial extent of the cone-of-depression in the water table surface created by the mine dewatering (Figure 1). Sinkhole formation has been most active in the region between the river and the mine (Bittencourt et al., 2008). Some sinkholes have formed in or adjacent to the river such that part of the river flow was diverted underground through the features. Since the sinkhole problem was recognized in 1999, VM has actively worked to mitigate sinkhole formation, particularly in and adjacent to the Undisclosed River through filling the features with rock and clay. Despite those efforts, losses from the river to the groundwater system of hundreds to thousands of m^3/hour occur along the reach of the river south of the mine and across the dolomite.

The purpose of this study was to identify the location of the river losses and quantify the contribution of the river losses to the groundwater discharge in the underground mine workings.

1.2 Proposed Approach

The proposed approach focused on:

1. staged injection of three tracers in the Undisclosed River between approximately the Bertoldo gauging station and the stage gauging station located on the mine property upstream of where the river crosses out of the dolomite;
2. quantitative analysis of tracer concentrations in the river measured at the downstream stage gauging station;
3. quantitative measurement of tracer concentrations at the discharge channel that carries all of the water pumped out from the underground mine workings; and
4. qualitative measurement of tracer concentrations measured at 15 sampling points in the mine.

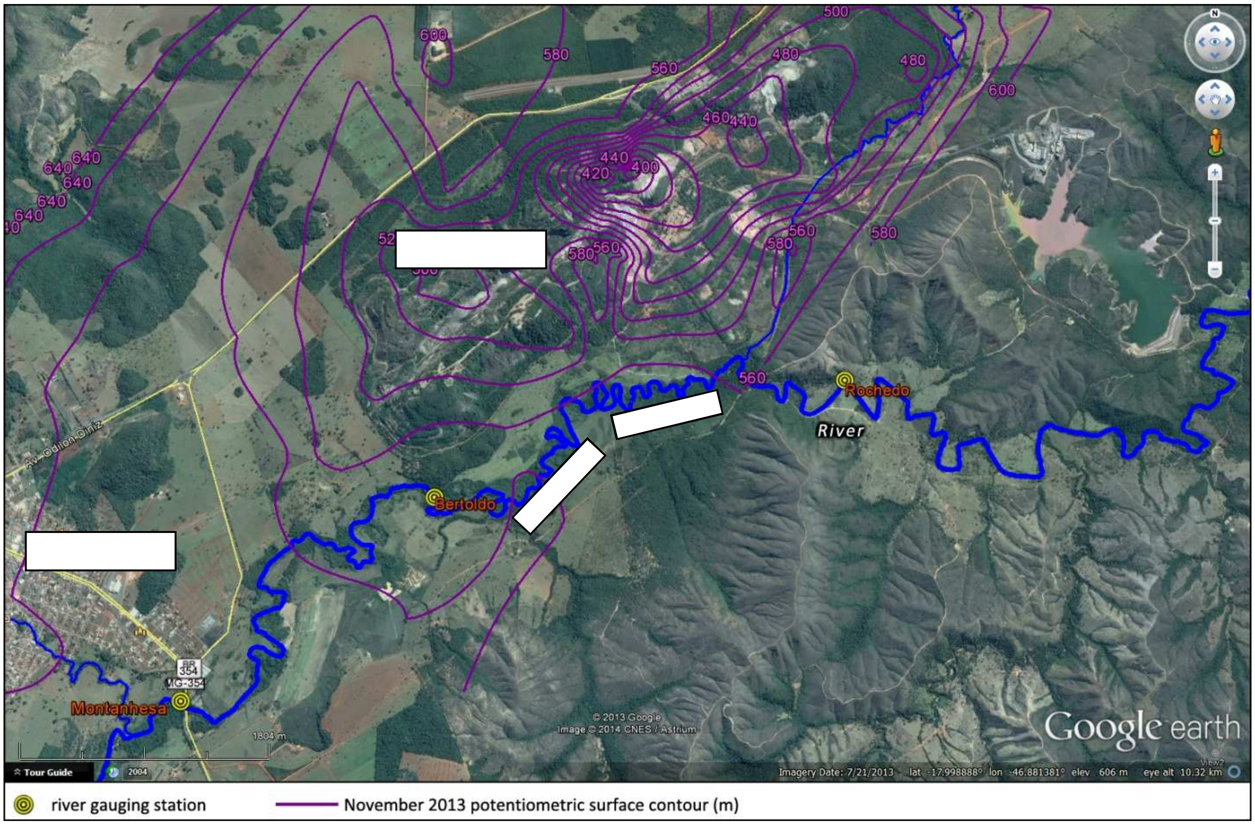


Figure 1 – Location of Undisclosed Underground Mine Relative to the Undisclosed River and Gauging Stations

The three tracers were: Uranine, Rhodamine-WT, and PTSA salt. All three dyes are environmentally harmless, non-reactive and therefore conservative tracers, readily detectable through optical fluorescence measurement, and have been successfully used elsewhere as groundwater tracers. Material Safety Data Sheets (MSDS) are provided as Appendix I. These three specific dyes were chosen because they fluoresce as sufficiently different wavelengths to allow each one to be independently identifiable with insitu optical fluorometers. Excitation and emission wavelengths as reported by Turner Designs (2013) are provided in Table 1 below. Based on this data, we determined that these three dyes could be successfully measured and distinguished from each other via onsite analyses.

Table 1. Tracer excitation & emission wavelengths in clear water.

Tracer	Excitation (nm)	Emission (nm)
Fluorescein (Uranine)	490	525
Rhodamine WT	530	555
PTSA salt	365	400

Quantitative analyses at the river and discharge channel sampling stations were performed with C3™ insitu submersible optical fluorometers manufactured by Turner Designs (Appendix II). Qualitative analyses at the mine sampling stations were performed on water samples collected at pseudo-regular intervals with a RF-5301-PC scanning spectrofluorophotometer manufactured by Schimadzu Scientific Instruments (Appendix II) set up onsite.

Required tracer injection quantities were estimated using a set of four published equations derived from empirical fits to 203 published historical artificial traces between swallets and springs in karstic aquifers using fluorescent dyes (Worthington and Smart, 2003) as well as two equations developed for this study designed to account for dilution and dispersion in the river. The four empirically derived equations describe the amount of injected dye required to produce a visible response at the sampled spring or discharge feature. The equations developed for this study estimate the amount of tracer required to be injected in the river to produce a desired peak tracer concentration at the discharge locations in the mine. The equations, the assumed variable values, and the resulting estimated values for required tracer mass and peak concentration in the mine are presented in Table 2.

Projected tracer mass values were balanced against a desire to minimize the length of river impacted by visible concentrations of injected dyes and by the functional range in detection limits prescribed by the manufacturer for the insitu fluorometers to be deployed in the river and the discharge channel. Those values essentially ranged from ~1-5 ppb at the low end to about 250-300 ppb at the high end in turbid water characteristic of the site conditions where the upper limit defined the upper extent to which concentrations measured by the fluorometers could be expected to vary linearly. As a result of that concern, the largest of the estimated values was ignored, and the proposed plan budgeted for ten kilograms of each tracer with the expectation that less might be used depending on observed flow conditions at the time of the experiment.

The injection plan is summarized in Figure 2. The plan called for the three dyes to be injected at three progressively downstream locations in the Undisclosed River such that detection of combinations of the dyes in the mine would indicate the portion of the river connected to the respective sampling stations.

The proposed sampling plan called for the collection of background samples at the mine sampling stations for a period of three weeks prior to the tracer injections. Active sampling was scheduled to last for ten days followed by up to three weeks of post-experiment sampling if the tracers were not detected during the active sampling period or if a reasonable approximation of the full tracer recovery curves were not recorded at the mine discharge channel. Charcoal and cotton aggregate samplers were to be installed at the mine sampling stations immediately prior to and after the active sampling period and collected at the end of the active sampling and post-experiment sampling periods. The aggregate samples were to be analyzed only if no dyes were detected in the water samples collected from the mine sampling stations.

Table 2. Equations used to estimate required mass of injected tracers.

#	Equation	a	b	R^2	Reference	Result
1	$M=a(LQC)^b$	19	0.95	0.93	Martel, 1913	4.6 kg
2	$M=a(TQC)^b$	0.73	0.97	0.97	Dole, 1906	15.0 kg
3	$M=a(LC)^b$	5.1	1.08	0.67	Parriaux et al., 1988	0.7 kg
4	$M=a(QC)^b$	40000	1.09	0.72	Haas, 1959	5.5 kg
5	$M_{Riv}=C_{Riv}*Q_{Riv}*(Dur_{Inj}+(D_{lon}/V_{Riv}))$				This Study	0.9 – 2.4 kg
6	$C=C_{Riv}/Q/Q_{Loss}$				This Study	50 – 135 ppb

where:		Assumed or
	equation units are: gram, meter, second	Desired Value
	M = mass of tracer injected at the swallet	Unknown
	L = distance between input and output	2000 m
	Q = discharge at spring *(equated to mine discharge tunnel)*	11,678 m^3/hr
	C = peak concentration at spring *(equated to mine discharge tunnel)*	50 ppb
	T = travel time	48 hours
	a and b are empirical values derived by authors	listed above
	R^2 = coefficient of determination derived from fit to 203 values	listed above
	M_{Riv} = mass of tracer injected in the river	unknown
	C_{Riv} = maximum tracer concentration in the river	250 ppb
	Q_{Riv} = river flow	20,000 m^3/hr
	Dur_{Inj} = duration of the injection	60 sec
	D_{lon} = longitudinal dispersivity	500 – 1,500 m
	V_{Riv} = river flow velocity (estimated based on Bertoldo/Rochedo analysis)	0.89 m/s
	Q_{Loss} = flow lost from river to aquifer	7,200 m^3/hr

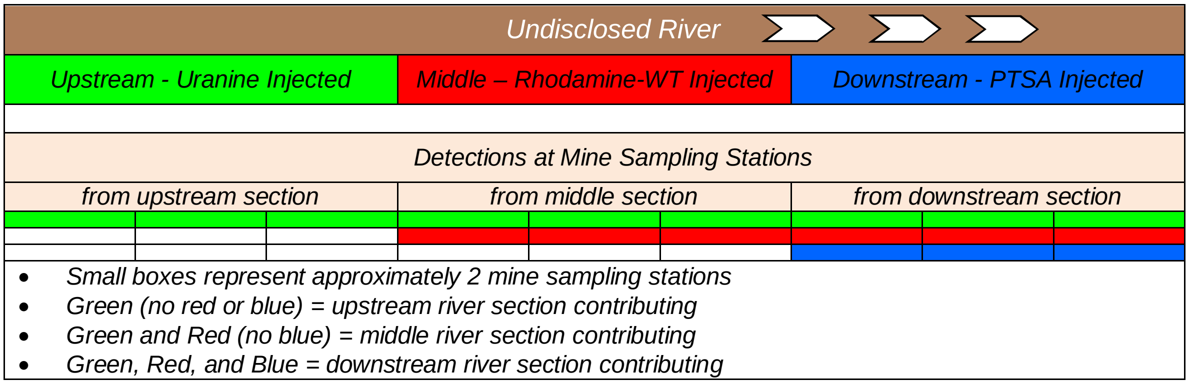


Figure 2 – Schematic representation of the proposed tracer injection strategy and implications of subsequent patterns of detections at the mine sampling stations.

1.3 Scope of Work

The scope of work included the following tasks.

1. Participation in a 1-week mine safety training course for 1 member of the DHI Team.
2. Weekly sampling at 15 stations in the underground mine over the course of 3 weeks prior to the tracer injections for the purpose of background sampling.
3. Observation of conditions at the mine sampling stations, discharge channel, and along the reach of the river between the Montanhesa and Rochedo river gauging stations over a 2-day period prior to the tracer injections.
4. Identification of three suitable tracer injection locations in the river and design of appropriate tracer injection methodologies.
5. Instrumentation of a single river sampling station and a single sampling station at the mine discharge channel with insitu fluorometers.
6. Establishment of an onsite laboratory for the analysis of water samples for the three fluorescent tracers with a scanning spectrofluorophotometer.
7. A single injection of three tracers at the locations identified in the river.
8. Twice-daily regular water sampling for a period of 10 days following the tracer injections at the 15 mine sampling stations.
9. Maintenance of the two deployed insitu fluorometers during the 10-day sampling period.
10. Analysis of approximately 400 water samples for the presence and concentration of the three injected tracers, which accounted for 1 sample per week from each of the 15 mine sampling station for the 3-week background sampling period, and 2 samples per day from 15 stations during the active sampling period.
11. Interpretation of the results of the tracer analyses and the fluorescence records measured by the two insitu fluorometers.
12. Preparation of this report.

2 WORK PERFORMED

2.1 Background Sampling

Five rounds of background samples were collected, which included one sample from each of the 15 mine sampling stations and one sample from the discharge channel. The first round was collected on November 5, 2013. The last round was collected on November 25, 2013. Only the samples from rounds 1 and 5 were analyzed. No dye was detected in any of the background samples analyzed.

2.2 Field Characterization & Instrumentation

Site conditions were observed over the course of two days (November 24 and November 25, 2013) prior to an intended injection date of November 26, 2013. The DHI Team accompanied VM staff to each of the 15 mine sampling stations and by boat and by truck on separate occasions along a section of the Undisclosed River between a point approximately 2.7 km downstream of the Montanhesa gauging station and the Rochedo gauging station (Figure 3).

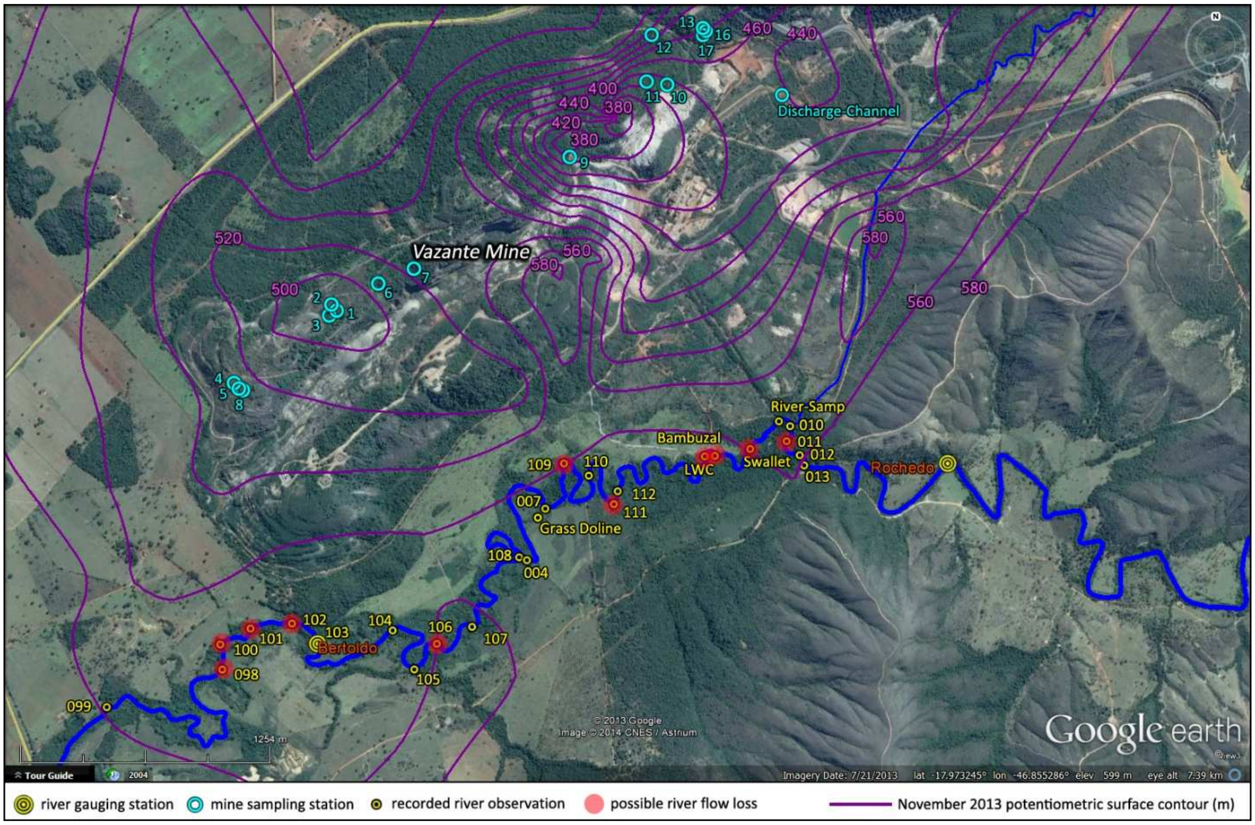


Figure 3 – Location of mine sampling stations, river observation points, and potential locations of river loss to the aquifer.

Observations at mine sampling station #13 (Cebola Falls) led to the establishment of two additional stations intended to capture flow crossing the falls: one upstream of the falls, and one downstream. These stations were identified as stations #16 and #17. Twelve of the stations including #16 and #17 were configured with charcoal and cotton aggregate samplers (Figure 4). The samplers were deployed beneath the water surface in the active flow of water past the respective sampling locations. Location coordinates, photographs, brief descriptions, and records of tracer detections at the mine sampling stations are provided as Appendix III.

Figure 4. Aggregate charcoal and cotton samplers deployed at 12 of the 17 mine sampling stations.

Observations were recorded at 26 points along the Undisclosed River over the course of two days prior to the tracer injections, the two days of the tracer injections, and one day after the tracer injections. Ten of those locations were identified as sites of where a substantial portion of the river flow could be lost to the aquifer via karst structures, two of which were observed to be actively receiving substantial river flow, and three of which were reported by VM staff to be locations of former sinkholes that have been filled in with rock and clay. Table 3 provides a list of the features along with a brief description of the mechanism for the possible loss of river flow. Location coordinates, photographs, and brief descriptions are provided as Appendix IV. The station names/numbers used here equate to the names that were assigned in the handheld VM GPS units that were used in the field during the characterization effort.

Table 3. Sites where observations revealed that river flow could be lost to the aquifer.

Observation Point	Description
98	filled former swallet
100	rock outcrop where flow could be lost to epikarst via fractures
101	rock outcrop where flow could be lost to epikarst via fractures
102	filled former swallet
106	possible collapse feature
109	rock outcrop where flow could be lost to epikarst via fractures – strong eddy at rock wall
111	enlarged horizontal parting in surficial sediments above epikarst
Bambuzal	filled former swallet
Swallet	swallet observed to be actively receiving substantial river flow
011	swallet observed to be actively receiving substantial river flow

Notes: location of observation points depicted on Figure 3
Location coordinates and photographs provided in Appendix IV

An onsite laboratory was established at the VM offices where the Schimadzu spectrofluorophotometer was set up and used for water sample analysis. After unpacking the shipped equipment, one of the Turner Designs C3 fluorometers was discovered to be inoperative. Several attempts to communicate with the device were made to no avail including an effort in conjunction with Turner Designs technical support staff via conference call. Consequently, the sampling plan was adjusted to conform to the use of only one insitu fluorometer. The C3 was dedicated to the long-term monitoring of the mine discharge and a plan was developed to monitor tracer concentrations in the river for a shorter period after the injections using high-frequency manual water sampling at the river stage gauging station (labeled “River Samp” on Figure 3).

The C3 was deployed four separate times prior to the tracer injections. It was initially deployed at mine sampling station #10, which is an aggregate of water flowing into the mine from the southern sampling points (stations 1-9 as identified on Figure 3). This placement was chosen to prevent the subsequent tracer recovery curves from being impacted by changes in the pumping schedules. After further consideration, evaluation of the pumping schedules, and considering the inability of that deployment to record contributions from the northern sampling points however, the C3 was redeployed to the mine discharge channel approximately 400 meters downstream of the point at which the water enters the open channel at the land surface (Figure 3). The fluorometer was initially deployed at that location by hanging it below a steel grate that covers the channel where it enters pipes that convey the water to a reservoir. It was subsequently learned however that when the pumping is reduced, the water level at that location dropped so far as to leave the fluorometer out of the water. It was then lowered but ultimately moved to a forth location located slightly upstream of the grate and offset from the middle of the flow. Pictures of the discharge channel and the C3 fluorometer deployments there are provided in Appendix V.

2.3 Tracer Injection

The tracer injections were initially planned to occur immediately following the two-day field characterization effort, after which time the injection locations were to have been identified, the injection methodologies defined, and the sampling stations appropriately instrumented. According to the planned schedule, the tracer injections were scheduled to occur on November 26, 2013. That schedule was delayed however due to substantial rain that raised river water flows and levels beyond those in which we deemed that the available tracer quantities would be sufficient to produce measurable recoveries in the mine.

Figure 5 provides hydrographs for the Undisclosed River as measured at the Montanhesa, Bertoldo, and Rochedo gauging stations. Flow levels observed on the first day of the site characterization (November 24) were regarded as acceptable and within the range that had been anticipated and prepared for. Though the Rochedo gauging station (downstream of the anticipated points of loss from the river to the aquifer) was offline, the flow measured at the Bertoldo station was less than the 20,000 m^3/day rate that had been anticipated. The water has highly turbid (muddy), which was expected to raise the lower end of the sensitivity range in the C3 fluorometer but we expected the available quantity of dye to be more than sufficient to execute a successful trace.

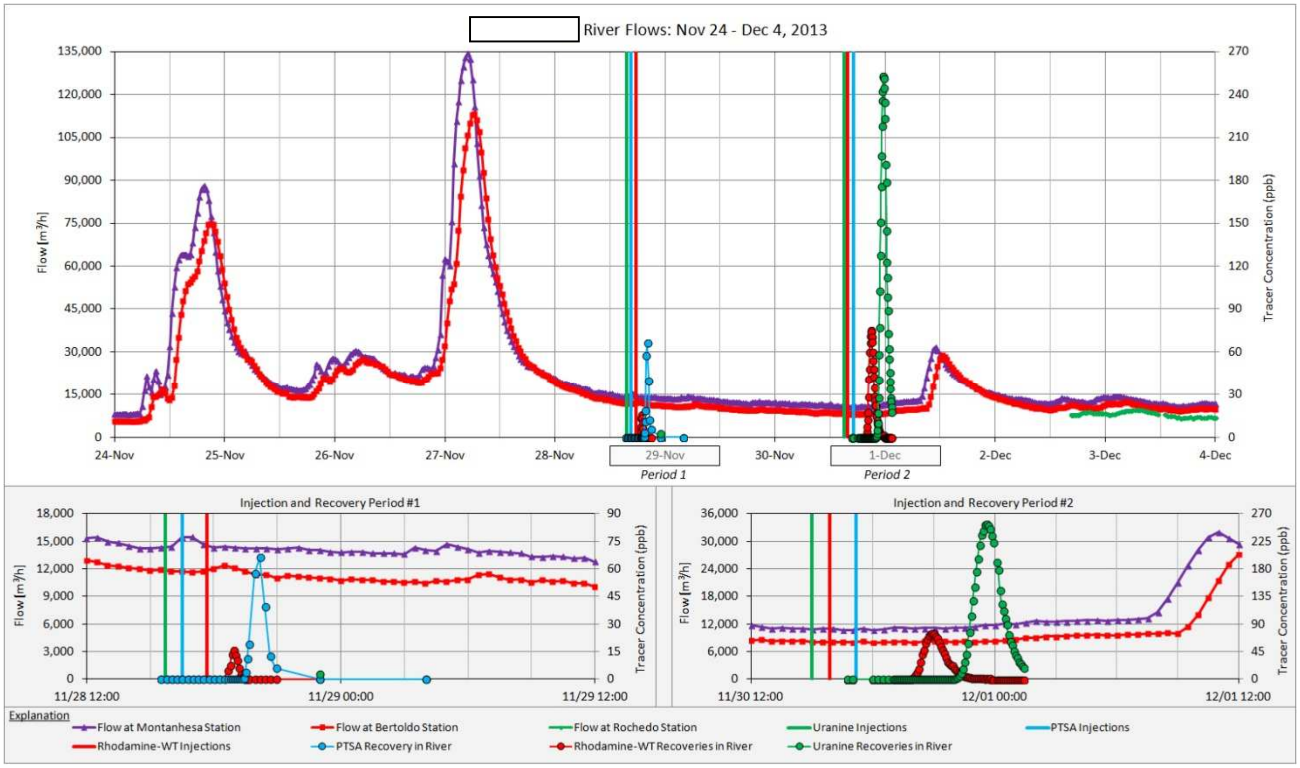


Figure 5 – Hydrographs for the Undisclosed River as measured at the Montanhesa, Bertoldo, and Rochedo, gauging stations relative to the dates of tracer injections in the river and the subsequent tracer recoveries measured at the river sampling station.

Rain during the afternoon and night of November 24th caused the river flow to rise to approximately 75,000 m^3/hr and remain substantially above the 20,000 m^3/hr for which the tracing experiment had been designed for approximately four days (Figure 5). During that time period, the DHI Team focused on setting up the onsite laboratory, running background samples and machine standards, and developing contingency plans in the event that the flows did not recede before the scheduled end of the project.

Flows did recede to less than 15,000 m^3/hr on November 28th and the weather forecast indicated that those conditions would continue for the ensuing several days. Given those conditions, the forecast, and the reduced sensitivity in the C3 fluorometer caused by the muddy water conditions, the DHI Team recommended and VM staff approved an adaptation to the plan in which two sequential tracer injections would be performed: an initial injection using a very small amount of the dyes, followed by a second injection using the remainder of the available dyes. The smaller injection was performed to guard against the possibility that tracer concentrations in the mine would exceed the upper limit of detection in the C3 fluorometer thereby precluding the delineation of tracer mass recoveries at the mine discharge channel.

2.3.1 Tracer Injection 1

The first set of three tracer injections was performed on November 28, 2013 using 0.75 kg of each of the three fluorescent dyes. The injection methodology followed the proposed plan described in Figure 2. Uranine was injected into the river flow at the upstream-most location (observation station 099) at 15:42. PTSA was injected into the river flow at a point approximately 1/3 of the way from the Uranine injection to the river sampling station (observation station 107) at 16:32. Rhodamine-WT was injected at a point another approximately 1/3 of the way down river (observation station 112) at 17:41. The injection locations are depicted relative to the river observation stations and the mine sampling stations on Figure 6.

All injections were performed by mixing 0.75 kg of the respective dyes into a 19 liter water bottle in an isolated room at the VM offices. The bottles were then sealed and transported to the respective injection locations. The water-dye mixtures in the water bottles was then diluted with river water onsite and transferred into two smaller water bottles. The water dye mixtures in those bottles were then poured into the river at approximately 1/3 and 2/3 of the river width by DHI Team and VM staff members. Pictures of the injections are provided in Appendix VI. Digital movies are provided as accompanying electronic files.

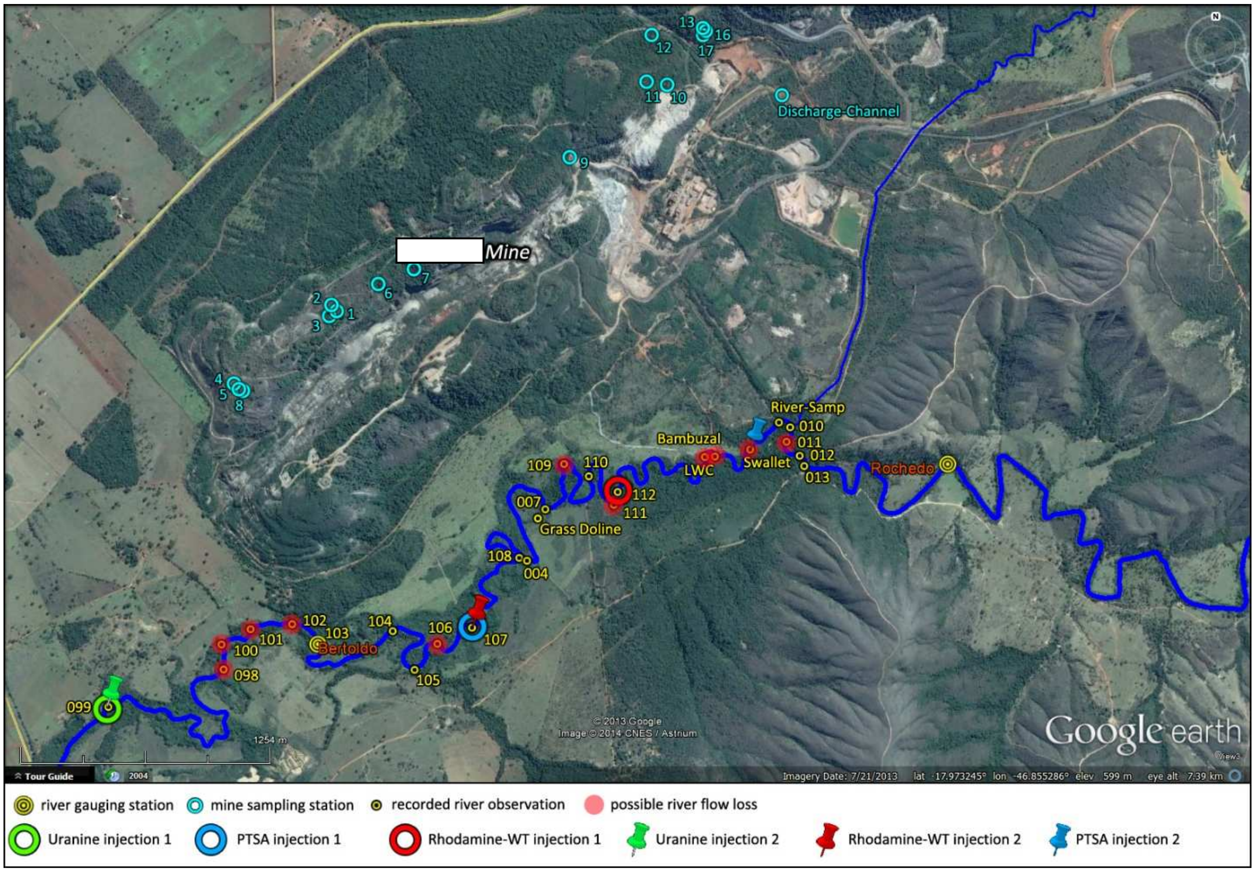


Figure 6 – Locations of fluorescent tracer injections into the Undisclosed River relative to river observation points and the mine sampling stations.

2.3.2 Tracer Injection 2

The second set of injections was performed on November 30, 2013 using 9.25 kg of each of the three dyes. The injection methodology was essentially the same as that used for the first set of injections with one important deviation being the location of the 3rd tracer injection, which was performed directly into the active swallet that was identified during the river characterization study. For the second set of injections, the Uranine was released into the river flow at the same location (observation station 099) at 15:00. Rhodamine-WT was released into the river flow at the same downstream location as was used for the PTSA injection from the first set (observation station 107) at 15:45. The PTSA was poured directly into the swallet (observation station swallet) at 17:10. The injection locations are depicted relative to the river observation stations and the mine sampling stations on Figure 6.

All injections were performed by mixing 9.25 kg of the respective dyes approximately equally into three 19 liter water bottles in an outdoor mechanical bay located at the VM offices. The bottles were then sealed and transported to the respective injection locations. The water-dye mixtures in the water bottles were then diluted with river water onsite and vigorously stirred until no evidence of the powdered dye could be observed. The water dye mixtures in those bottles were then poured into the river at approximately 1/4, 1/2, and 3/4 of the river width by DHI Team and VM staff members. Pictures of the injections are provided in Appendix VI. Digital movies are provided as accompanying electronic files.

2.4 Sampling & Analysis

2.4.1 River Water

Flow in the Undisclosed River was regularly sampled at the river stage gauging station (observation station River-Samp identified on Figure 3 and Figure 6) for a period of several hours following each of the two sets of tracer injections. Sampling following the November 28 injections began at 15:30 (approximately 10 minutes before the upstream-most injection). Sampling at 15-minute intervals was performed until 18:30 after which time the interval was decreased to 5-minutes and sampling at that rate continued until 19:40.

Fifteen-minute interval sampling was then resumed and continued until 20:55 after which two more grab samples were collected at 23:00 and 04:00 the following day.

All three dyes were detected but recovery curves for only the Rhodamine-WT and the PTSA were captured because Uranine was detected in only one sample (Figure 7). The pattern of tracer detections followed the general expectations. The first tracer observed was the last to be injected and closest to the sampling station, followed by the second tracer injected, and then by the first, which was farthest from the sampling station (Figure 6). Analysis of the recovery curves revealed an approximate river velocity of 1.3 km/hr based on peak concentration arrivals and that the majority of the Uranine recovery curve was likely missed due to premature cessation of regular sampling leaving only one detection of what was likely the leading edge of the curve. Recovered tracer concentrations are provided in Appendix VII.

Sampling following the November 30 injections began at 16:45 (approximately 1 hour 45 minutes after the upstream-most injection and 52 minutes after the downstream-most river injection). Sampling at 15-minute intervals was performed until 19:00 after which time the interval was decreased to 5-minutes and sampling at that rate continued until 01:25 the following day. No further samples were collected after that point.

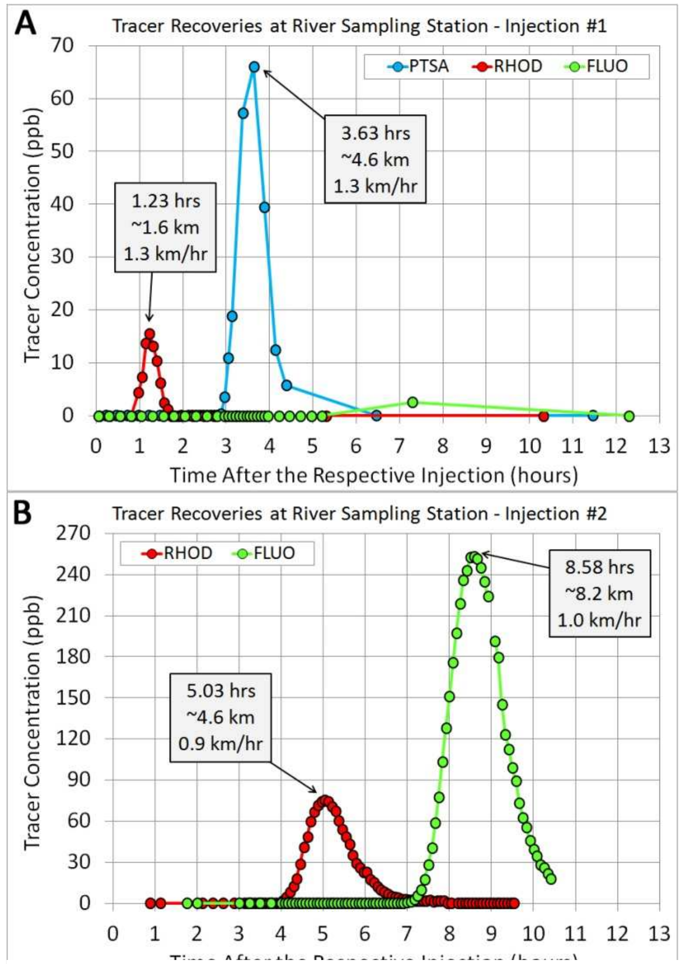


Figure 7 - Tracer recoveries at the river sampling station following (A) injection set #1 on Nov. 28, 2013 and (B) injection set #2 on Nov. 30, 2013.

Both the Uranine and Rhodamine-WT dyes were detected. A sufficient number of samples were collected to define a complete recovery curve for Rhodamine-WT (the downstream-most injected tracer) and a nearly complete recovery curve for Uranine (the upstream-most injected tracer). Figure 7 depicts the two recovery curves and shows the peak concentration arrival time and resulting estimated river velocities. The estimated river water velocity was approximately 30% slower than was observed after the first set of tracer injections though the river flow was smaller by approximately 4,000 m^3/hr (Figure 5). PTSA was not detected in the river but that was expected because 100% of the tracer was released directly into the swallet. Recovered tracer concentrations are provided in Appendix VII.

2.4.2 Mine Stations

Post-background grab sampling in the underground mine began on November 28 approximately coincident with the PTSA injection in the river and continued at a frequency of approximately 1-5 samples per day per station until December 2. Sampling was conducted by a team of two people, one from the DHI Team and a driver provided by VM. Samples were collected in shifts and rounds where a shift described all samples collected by a team in one working period. Rounds described the number of sample sets collected by the team. For each round, the team drove through the mine following the most direct N-S route that passed each station. Water samples were collected at each station in 30 ml glass vials that were labeled with the shift, round, and station numbers. Sample collection times and any comments about flow conditions were recorded in a field book and subsequently transcribed into a data table containing the analytical results (Appendix VIII). A summary of the results showing the number of positive detections for each tracer at each mine sampling station that were subsequently confirmed through analysis of the spectra measured in the samples is provided in Table 4.

Table 4. Record of tracer detections in water samples collected from the 17 mine sampling stations.

Injection Set #1 / November 28, 2013

S-R	Date Time	#	1			2			3			4			5			6			7			8			9			10			11			12			13			14			15			16			17		
			U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P
1-1	11/28 16:21	0																																																			
1-2	11/28 18:43	0																																																			
2-1	11/28 23:15	1										X																																								
2-2	11/29 01:40	0																																																		
3-1	11/29 08:46	9	X			X			X			X						X			X						X			X			X																				
3-2	11/29 11:06	9	X			X			X			X						X			X						X			X			X																				
4-1	11/29 15:08	9	X			X			X			X						X			X						X			X			X																				
4-2	11/29 17:10	9	X			X			X			X						X			X						X			X			X																				
5-1	11/29 23:30	9	X			X			X			X						X			X						X			X			X																				
5-2	11/30 01:35	9	X			X			X			X						X			X						X			X			X																				
6-1	11/30 07:19	5	X			X			X									X															X																				
Total # Detections		*60*	*7*	*0*	*0*	*7*	*0*	*0*	*7*	*0*	*0*	*7*	*0*	*0*	*0*	*0*	*0*	*7*	*0*	*0*	*6*	*0*	*0*	*0*	*0*	*0*	*6*	*0*	*0*	*6*	*0*	*0*	*7*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

Injection Set #2 / November 30, 2013

S-R	Date Time	#	1			2			3			4			5			6			7			8			9			10			11			12			13			14			15			16			17		
			U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P	U	R	P
7-1	12/01 08:21	7	X			X			X			X												X									X		X																		
8-1	12/01 14:55	20	X	X		X	X		X	X		X			X			X	X		X	X		X			X			X	X	X	X	X	X																		
8-2	12/01 16:45	19	X	X		X	X		X	X		X			X			X	X		X			X			X			X	X	X	X	X	X																		
8-3	12/02 11:05	3	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	X	X	X	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
9-1	12/02 15:35	14	X			X			X	X		X			X			X			X			X			X			X		X	X		X																		
Total # Detections		*63*	*4*	*2*	*0*	*4*	*2*	*0*	*4*	*3*	*0*	*4*	*0*	*0*	*3*	*0*	*0*	*3*	*2*	*0*	*3*	*1*	*0*	*4*	*0*	*0*	*3*	*0*	*0*	*3*	*2*	*3*	*5*	*3*	*5*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

Notes: *S-R = Shift & Round of the mine sample collection program*
 # = total # of positive detections for the respective Shift and Round
U R P = columns where "X" marks denote positive detections for Uranine "U", Rhodamine-WT "R", and/or PTSA "P" / cells also colored to denote respective tracer detections: green = Uranine, red = Rhodamine-WT, and blue = PTSA
Blank cell = no tracers detected
N = no sample collected
Total # Detections = total # of positive detections recorded for all stations after each injection set and for each station over all Shifts and Rounds after each injection set

Confirmation of tracer detections was performed by evaluating the wavelength and height of the peaks in the emission spectra preliminarily recorded by the spectrofluorophotometer relative to: 1) the wavelength of the emission peaks measured in calibration standards that were prepared on site immediately prior to the injections; 2) the background fluorescence measured in each sample; and 3) the intensity of the emission peaks relative to the perceived detection limit.

These criteria were adapted from tracer analysis procedures published by Aley and Kirkland (2011) to conform to site-specific conditions. Table 5 shows the emission wavelengths recorded by the spectrofluorophotometer in the calibration standards relative to the values defined by Turner Designs (2012) for the C3 fluorometer. The specific confirmation criteria for Uranine were: 1) an observable peak in the emission spectra at 511 +/- 2 nanometers; 2) an intensity at least 3X the observed background fluorescence level in the sample; and 3) a calculated concentration >= 0.01 ppb.

The specific confirmation criteria for Rhodamine-WT were: 1) an observable peak in the emission spectra at 575 +/- 3 nanometers; 2) an intensity at least 3X the observed background fluorescence level in the sample; and 3) a calculated concentration >= 0.05 ppb.

PTSA criteria are less well established. The emission spectra for the calibration standards developed for the PTSA dye consistently revealed two peaks, one at 385 nanometers, which was considered to be the most relevant peak, and one at 406 nanometers, which was considered to be a secondary peak more characteristic of background fluorescence. Based on those observations, a single criterion was used for the confirmation of PTSA detections, which was that the peak intensity at 385 nanometers exceed that at 406 nanometers.

Table 5. Reported and observed emission peaks.

Tracer	Rep. Emission Peak[1]	Rep. Emission Peak[2]	Obs. Emission Peak
Uranine	525	506.8-510.6	511
Rhodamine-WT	555	572.4-577.7	575
PTSA	400	not provided	385

Notes: Rep Peak[1]: provided by Turner Designs (2013)
Rep Peak[2]: provided by Aley and Kirkland (2011)
Obs. Peaks: established from calibration standards

Graphical representations of the emission spectra recorded in all samples across the range relevant to each of the tracers relevant to the emission spectra recorded in the relevant calibration standards identifying the samples that contained confirmed tracer concentrations are provided in Appendix IX.

A total of 122 confirmed positive tracer detections were recorded in the grab samples collected from the mine sampling stations of a total of 777 analyses performed (Appendix VIII). Following the first set of tracer injections but prior to the second set of injections, Uranine was detected and confirmed in 60 samples (Table 4). The stations where the positive Uranine concentrations were detected are in the southern section of the mine (stations 1, 2, 3, 4, 6, 7, 9, 10, and 11). The maximum Uranine concentration recorded during this period was 0.1 ppb, which occurred at multiple stations (stations 1-4 and 11). No confirmed positive detections of Rhodamine-WT or PTSA were recorded at any of the mine sampling stations during that period.

Following the second set of injections, Uranine was detected and confirmed in 40 samples (Table 4). The stations where the positive Uranine concentrations were detected were again limited to those in the southern section of the mine (stations 1-11). The maximum Uranine concentration recorded during this period was 2.7 ppb, which occurred at stations 1-3. This time, Rhodamine-WT was detected and confirmed in 14 samples and PTSA in 8 samples (Table 4). The Rhodamine-WT detections also occurred at the southern sampling stations (stations 1-3, 6-7, and 10-11). The PTSA detections were only recorded at the aggregate southern stations (stations 10-11). The maximum Rhodamine-WT concentration recorded during this period was 0.5 ppb, which occurred at stations 1-3. The maximum PTSA concentration recorded during this period was 18.2 ppb, which occurred only at station 11. By comparison, the highest concentration recorded at station 10 was 3.8 ppb.

2.4.3 Discharge Channel

Regular monitoring at the discharge with the C3 fluorometer channel began on November 26, two days prior to the first set of tracer injections. The fluorometer was configured to measure fluorescence in the water at the three wavelengths determined by turner Designs to be characteristic of Uranine, Rhodamine-WT and PTSA (Table 5) at 5 minute intervals. Monitoring at that interval was continued with the C3 through the duration of the tracing experiment and then for more than 30 days afterward. The device was calibrated to dye standards onsite prior to the start of monitoring such that the output was in form of tracer concentration rather than raw fluorescence units. This was done to facilitate an onsite comparison between the C3 data and the spectrofluorophotometer data. Figure 8 shows the fluorescence curves produced by the C3 fluorometer during the monitored time period. Figure 9 shows the fluorescence curves relative to river flow measured at the Bertoldo gauging station. All of the fluorescence data collected during the approximately 40 day period is provided in Appendix X.

Despite the calibration, the fluorescence curves track anything in the water that fluoresces near the respective emission wavelengths. Green fluorescence (525 nm) includes Uranine. Red fluorescence (555 nm), includes Rhodamine-WT. Blue fluorescence (400 nm), includes PTSA. Variance in the green and red curves was more than 3 ppb making it difficult to identify tracer recovery curves. The most apparent trend was that red fluorescence (Rhodamine-WT signature) was higher than green fluorescence (Uranine signature) over most of the record. The most substantial deviation occurred approximately 24 hours after the 2nd set of injections and is attributed to the Uranine tracer from that injection. The blue fluorescence curve (PTSA signature) is considerably cleaner showing only one obvious deviation from the 0-trend, which we attribute to PTSA from the November 30 injection.

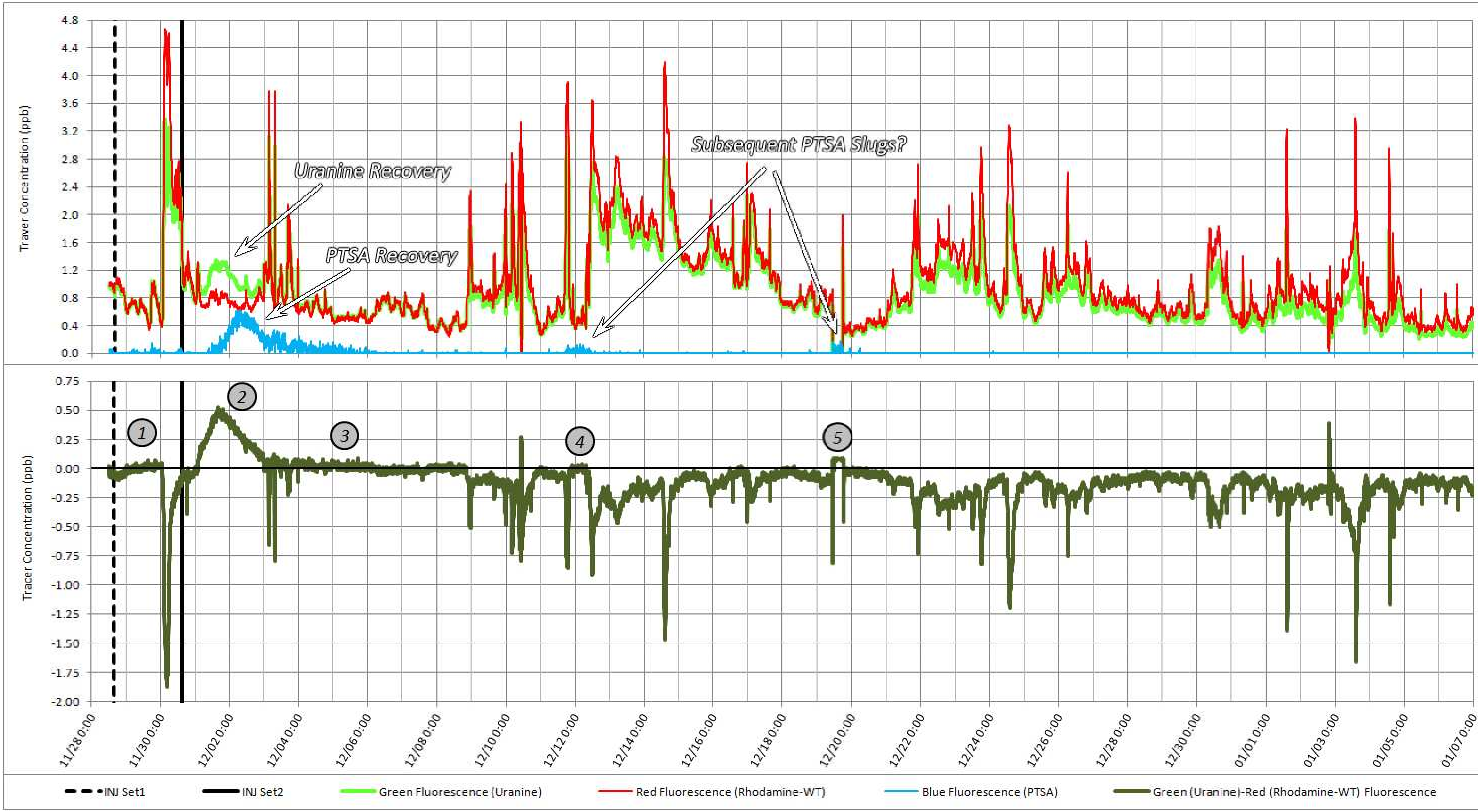


Figure 8 – Fluorescence in the mine discharge water measured by the insitu C3 fluorometer at the discharge channel between November 28, 2013 (slightly before the 1st set of tracer injections) and January 7, 2014 (30 days after the termination of the tracing experiment).

The fluorescence curves track anything in the water that fluoresces near the respective emission wavelengths. Green fluorescence (525 nm) includes Uranine. Red fluorescence (555 nm), includes Rhodamine-WT. Blue fluorescence (400 nm), includes PTSA. Each fluorescence response was calibrated to dye standards prior to the start of monitoring. Variance in the green and red curves is more than 3 ppb making it difficult to identify tracer recoveries. The most apparent trend is that red was higher than green over most of the record. The most substantial deviation occurred approximately 24 hours after the 2nd set of injections and is attributed to the Uranine tracer from that injection. The blue fluorescence curve is considerably cleaner showing only one obvious deviation from the 0-trend, which we attribute to PTSA from the Nov. 30 injection. The lower plot shows green minus red fluorescence. Aside from two spikes, the resulting signal deviates into positive space only 5 times during the 40-day time period, all of which correspond to bumps in the blue fluorescence. We attribute numbers 2 and 3 to Uranine from the Nov. 30 injection. Number 1 could be a very faint response to Uranine from the Nov. 28 injection and numbers 4 and 5, along with the associated PTSA bumps could be associated with delayed slugs of tracer from slower flow paths.

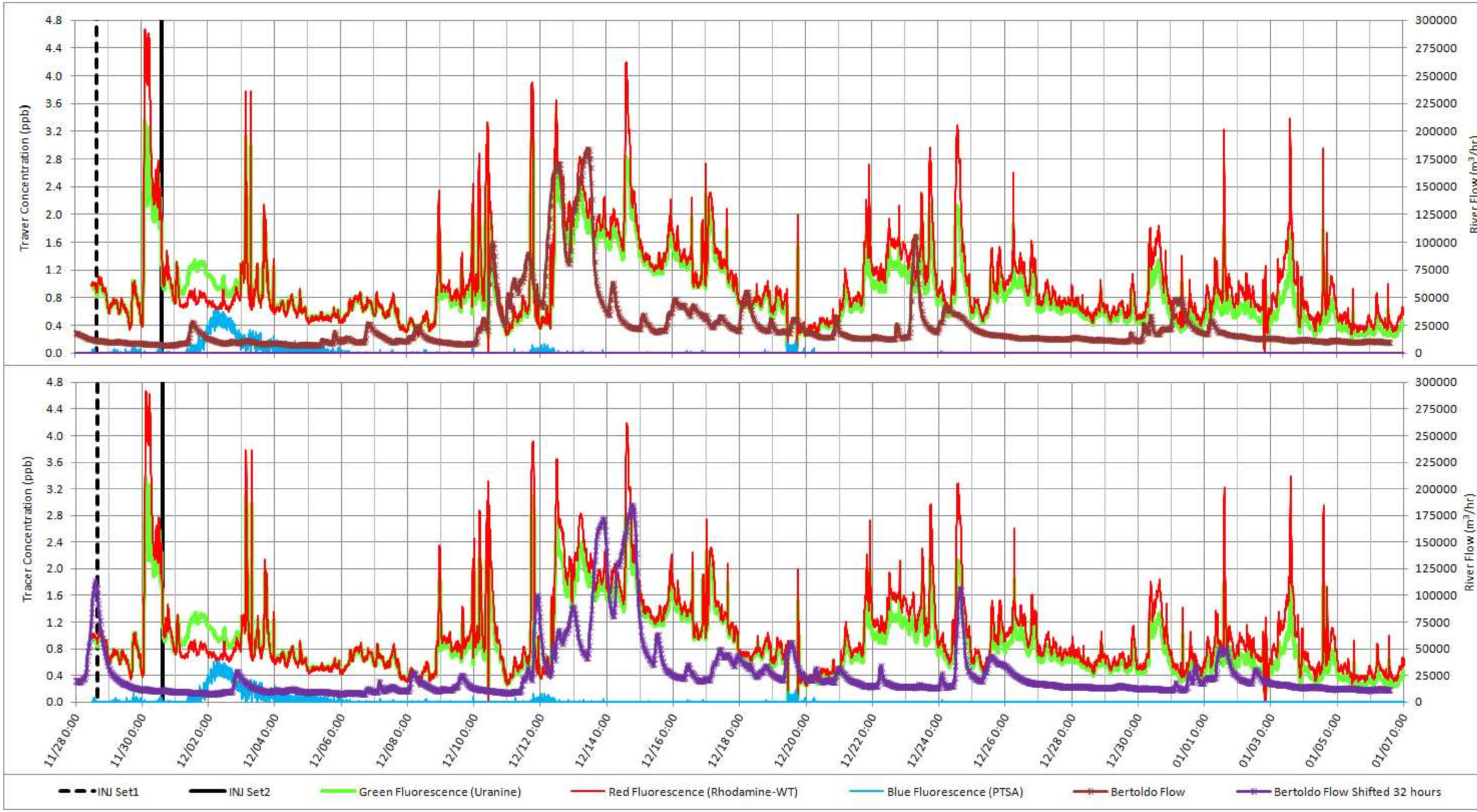


Figure 9 – Fluorescence in the mine discharge water measured by the insitu C3 fluorometer at the discharge channel between November 28, 2013and January 7, 2014 relative to flow in the Undisclosed River measured at the Bertoldo gauging station.

(TOP) River flow depicted at the time of measurement at the Bertoldo station. (Bottom) Timing of depicted river flow shifted forward by 32 hours to account for the probable travel time of the river water between the Bertoldo station and the mine discharge channel. The relationship between the peaks in river flow and the variation in the green and red fluorescence signals indicates that the observed variance is, at least in part due to fluctuations in river flow that likely affect the turbidity and background fluorescence of the water entering and flowing through the mine.

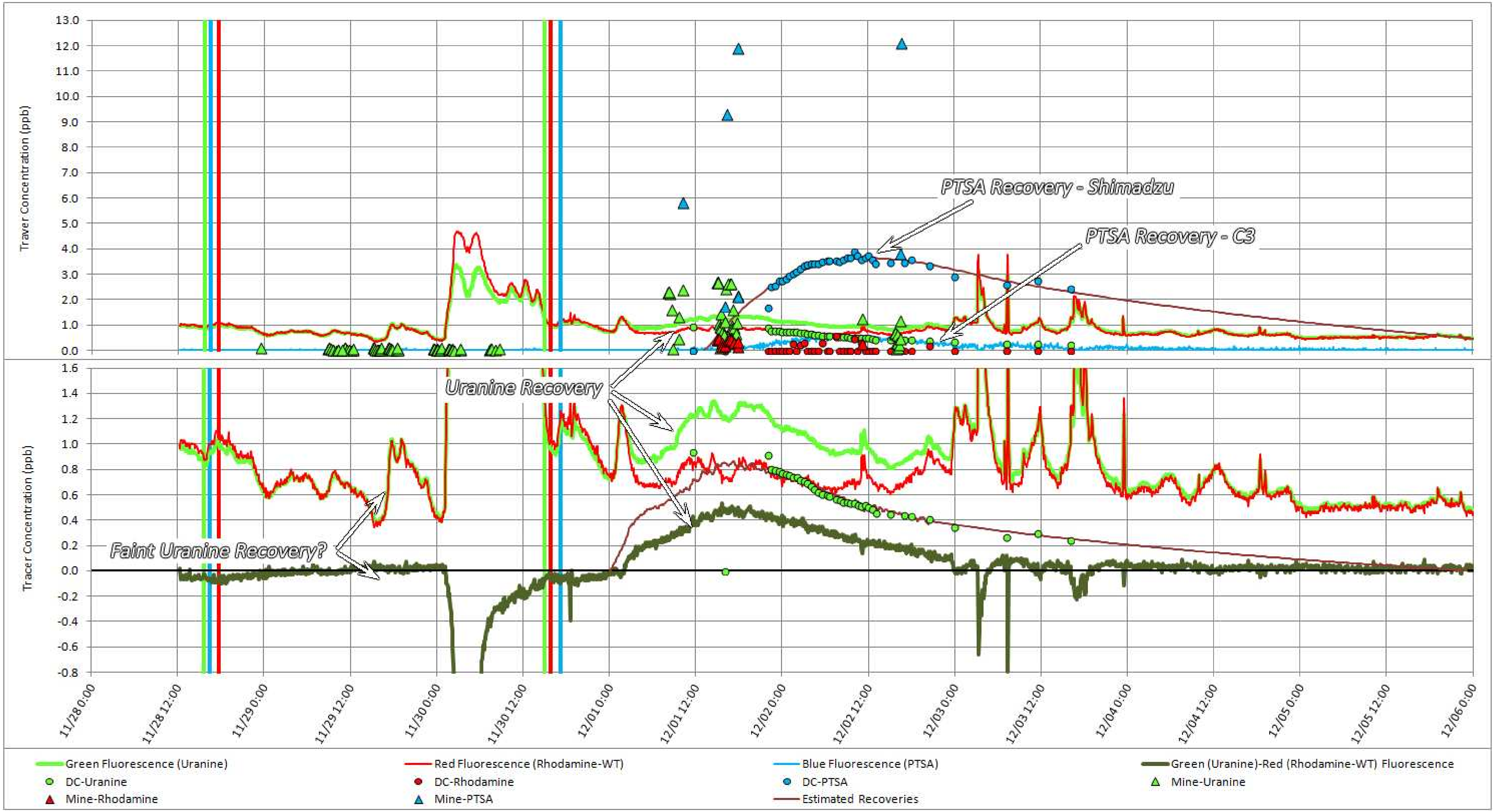


Figure 10 - Fluorescence in the discharge channel measured by the insitu C3 fluorometer relative to Uranine, Rhodamine-WT, and PTSA concentrations measured at the discharge channel and at the mine sampling stations by the Schimadzu spectrofluorophotometer.

(Top) All data plotted on the same scale along with an estimated complete recovery curve for PTSA. The PTSA recovery in the discharge channel was definitively recorded by both the C3 and the spectrofluorophotometer and corresponded in timing to PTSA detected at mine stations #10 and #11. Differences between the mine station and discharge channel concentrations are attributed to dilution in the reservoir. The difference between the C3 and spectrofluorophotometer concentrations are likely due to the different calibration methods (the C3 relied on a single-point method whereas the spectrofluorophotometer used a 3-point method) where the spectrofluorophotometer values were considered to be more accurate. (BOTTOM) Uranine data from the discharge channel plotted relative to the red and green fluorescence records, a green-red curve, and an estimated full recovery curve for Uranine that follows the shape of the green-red curve translated to the values recorded by the spectrofluorophotometer for the tailing edge of the curve.

The lower plot in Figure 8 shows green minus red fluorescence, which was calculated to more readily identify portions of the record where green fluorescence deviated substantially from the trend. Aside from two spikes, the resulting signal deviates into positive space only 5 times during the 40-day record. All of those deviations correspond to bumps in the blue fluorescence. We attribute the two largest deviations to Uranine from the November 30 injection. An earlier small deviation could be a very faint response to Uranine from the November 28 injection. The two remaining deviations occurred approximately 11 and 20 days after the November 30 injection respectively. Though the responses are not definitive, they, along with the associated PTSA bumps could be associated with delayed slugs of tracer from slower groundwater flow paths.

The nearly-direct correlation between the green (Uranine) and red (Rhodamine-WT) fluorescence signals and the magnitude of the corresponding concentrations deviated from the expected response associated with the spectrofluorophotometer results from the mine station samples collected after the 1st set of tracer injections. Those results, which are presented in Table 4, Appendix VIII, and described in Section 2.4.2 revealed very low Uranine detections (maximum 0.1 ppb) and no Rhodamine-WT or PTSA detections. The initial data from the C3 that corresponded to the time period immediately before and then shortly after the 1st set of tracer injections indicated that the background fluorescence for both the red and green fluorescence signals was between 0.4 and about 1 ppb. The subsequent sharp rise to 3.2 ppb green and 4.6 ppb red was therefore suspicious because it represented 2-3 ppb change in both red and green fluorescence that corresponded to the expected timing of tracer recoveries but not to the concentrations that had been recorded in the mine.

In order to verify subsequent C3 response signals, a grab sampling strategy was developed and executed after the 2nd set of tracer injections in which water samples were collected from December 1st at 11:39 (approximately 20 hours after the 2nd Uranine injection) to December 3rd at 16:00 (approximately 73 hours after the 2nd Uranine injection). The sampling interval was initially 4-6 hours for the 1st 10 hours of the period but was decreased to a 30-minute interval thereafter. The results are presented relative to the fluorescence signals recorded by the C3 on Figure 10 and are provided numerically in Appendix XI.

A total of 40 samples were collected and analyzed with the spectrofluorophotometer for all three dyes. Uranine was detected and confirmed in 39 of the samples. The only non-detect occurred in the second sample after an earlier positive detection and is therefore regarded as suspicious. The maximum Uranine concentration was 0.9 ppb, which occurred in the 1st and 3rd samples. Those were followed by a steady decline in concentrations indicating that we likely missed the peak due to the large sampling interval between the first 3 samples.

Rhodamine-WT was detected and confirmed in 8 samples where the maximum recorded concentration was 0.6 ppb. The distribution of the detections was, however, sporadic and interspersed with repeated non-detects making it impossible to equate the detections to a recovery curve.

PTSA was detected and confirmed in 38 samples. The maximum recorded concentration was 3.9 ppb. The distribution of the detections and the trend in values corresponded to the shape and timing of the definitive rise in the blue fluorescence signal that was attributed to the PTSA recovery as well as to the general timing of the PTSA detections recorded at mine sampling stations #10 and #11. The magnitude of the detections in the mine discharge channel was lower than the magnitude of the detections at the mine sampling stations and higher than the concentrations indicated by the C3 fluorescence signal. The differences between the mine station and discharge channel concentrations were attributed to dilution in the reservoir. The difference between the C3 and spectrofluorophotometer concentrations are likely due to the different calibration methods wherein the C3 relied on a single-point method whereas the spectrofluorophotometer used a 3-point method and was therefore considered to be more accurate.

3 INTERPRETATIONS AND DISCUSSION

3.1 Mass Recoveries

The total mass of tracer recovered was calculated, where possible, at the river and mine discharge sampling stations. The purpose of the mass recovery calculations was to compare the amount of dye recovered in the river to the amount recovered from the mine and thereby estimate how much of the river loss flows to the mine. In order to make this estimate, it must be assumed that the tracer or tracers used for the mass recovery calculations are conservative, meaning that there are no losses due to adsorption or decay along the tracer flow paths. In order to calculate the total mass of tracer recovered, a full recovery curve for the tracer in question must be either measured or estimated, and the water flow past the sampling station must be known for each sampling timestep. The calculation is performed according to:

$$Mass_{Total} = \sum(Conc_i \times Flow_i \times Timestep_i)$$

where: $Mass_{Total}$ = total mass of tracer recovered as defined by the full tracer recovery curve;
$Conc_i$ = tracer concentration at timestep i;
$Flow_i$ = flow of water past the sampling station at timestep i;
$Timestep_i$ = the time between consecutively collected samples; and
it is assumed that the tracer is well mixed in the water flow at the sampling station.

3.1.1 Undisclosed River

All three dyes were definitively detected in sufficient detail at the river sampling station to estimate mass recovery after at least one of the set of tracer injections. Regular high-frequency sampling was terminated after the first set of injections before a sufficient number of Uranine detections were recorded but full recovery curves were plotted for both PTSA and Rhodamine-WT. PTSA was not injected into the river during the second set of injections resulting in no PTSA detections at the river sampling station. The sampling duration and frequency after the 2nd set of injections was sufficient, however, to record complete or nearly complete recovery curves for Rhodamine-WT and Uranine.

Unfortunately, the river gauging station at Rochedo (downstream of the river sampling station) was off line during the tracing experiment leaving no direct flow measurements for the downstream portion of the river. The Rochedo station was online nearly continuously for periods immediately prior to and after the tracer testing period: 3/11/2013 to 11/21/13 and 12/2/13 to 12/9/13. Four segments of those periods were identified through hydrograph analyses to be similar to the tracer testing period based on the trend of measured flows at the Bertoldo station and the relationship between flows at the Bertoldo and Montanhesa stations. The hydrographs for those periods as well as for the full period of record prior to the tracer tests were used to estimate a hydrograph at the Rochedo Station during the tracer testing period. The analysis and estimation was performed as follows.

1. All available flow data from the Montanhesa, Bertoldo, and Rochedo gauging stations for the period between March 2013 and January 2014 was obtained from VM staff.
2. Four periods of relatively steady flow similar to the conditions observed during and immediately after the two tracer injections were identified in the record.
3. A linear regression was calculated for the relationship between flow at the Bertoldo and Rochedo gauging stations for each time period as well as for the entire period of record.
4. The linear equation resulting from those regressions was used to estimate flow at the Rochedo station during the time period spanning the tracer recoveries after both sets of injections: 11/28/2013 at 15:30 to 12/1/2013 at 15:30.
5. The resulting river hydrographs for that period were plotted and evaluated visually.
6. The period of record (POR) and maximum records were used as the basis for estimating the mass of tracers recovered at the river sampling station.

Figure 11 shows the estimated hydrographs at the Rochedo station during the tracer sampling period relative to the tracer recovery curves and tracer injection times. Figure 12 shows the river gains and losses between the Montanhesa and Rochedo stations during each of the 5 periods. Table 6 lists the regression statistics and the linear equation parameters derived for the 4 time periods relative to the same statistics derived for a longer period of record in which all three gauging stations were operative (3/15/2013 – 11/21/2013). The statistical regressions for all five time periods as well as the estimated river flows at the Rochedo station during the tracer sampling period are provided in Appendix XII.

PTSA was the larger of the two recovery curves plotted after the first set of injections, which was surprising because Rhodamine-WT was the downstream-most injected tracer. The total mass of PTSA recovered was between 368 and 489 grams based on the POR and maximum estimated river flows at the Rochedo station respectively. These values represent between approximately 49% and 65% of the 750 grams of tracer injected. By comparison, the total mass of Rhodamine-WT recovered was only between 56 and 72 grams, which represents only 7% to 10% of the 750 grams injected. Based on these mass recoveries, between 35% and 51% of the injected PTSA (261 – 382 grams) and between 90% and 93% of the injected Rhodamine-WT (678 - 694 grams) was lost either to the aquifer or adsorption to organic material in the river and/or the river substrate.

Table 6. Linear regression statistics and equation parameters for the correlation between river flows measured at the Bertoldo and Rochedo gauging stations during five different periods in 2013.

Begin Date	3/17	4/2	11/20	12/3	3/15
End Date	3/20	4/5	11/21	12/5	11/21
Duration (days)	3.0	3.0	0.8	1.9	251.0
Bertoldo-Montanhesa (m3/hr)	-857	927	-3,245	-2,140	-296
Rochedo-Bertoldo (m3/hr)	-1,594	-1,951	-2,842	-2,918	-3,352
Slope	0.96	1.08	0.57	1.24	1.08
Intercept	-895	-3,512	-676	-5056	-4872
RSQ	0.79	0.90	0.84	0.88	0.97

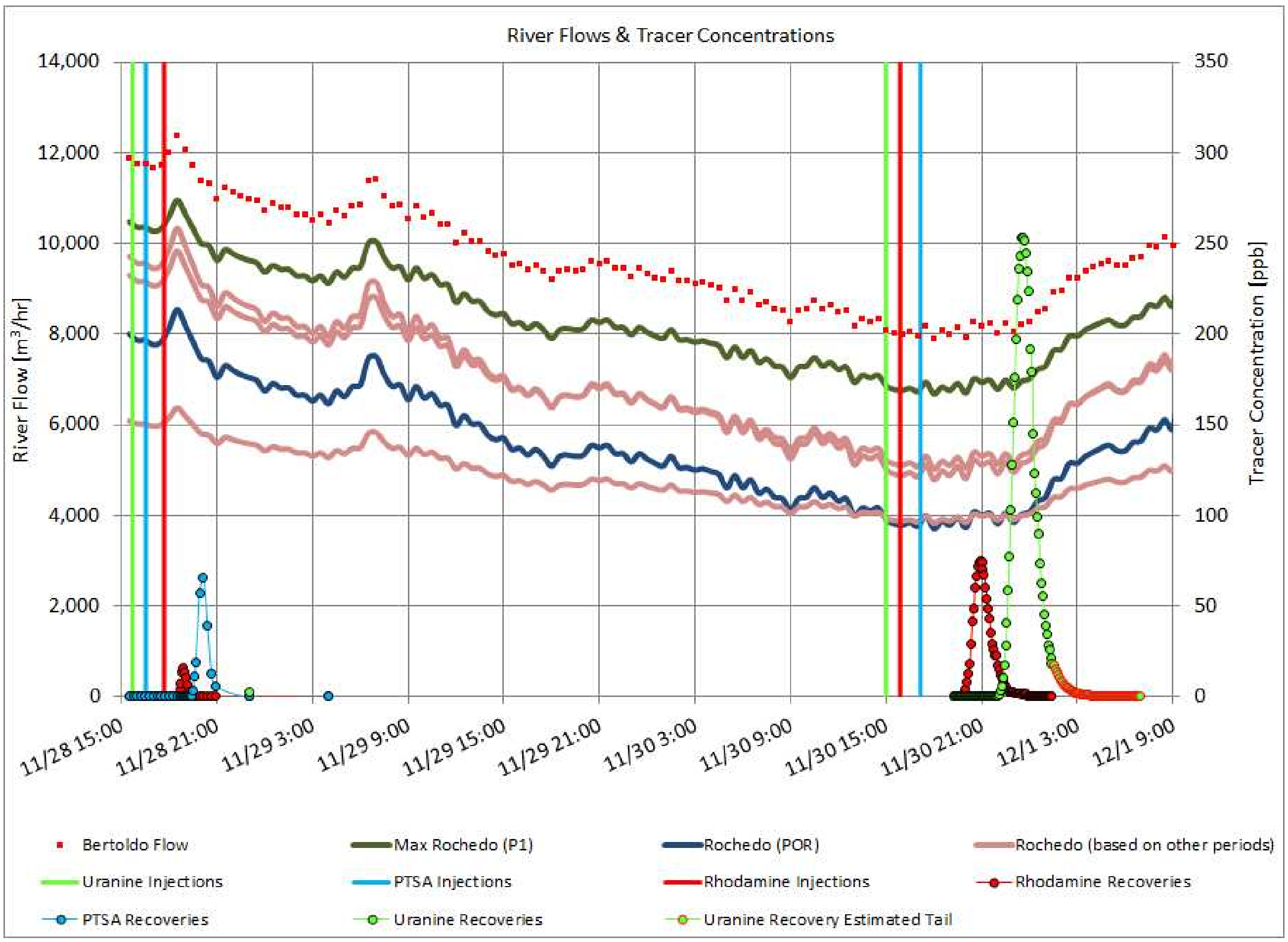


Figure 11 – Estimated flow at the Rochedo gauging station during the tracer sampling period.

Estimates were based on linear regression parameters derived for the relationship between flow at the Bertoldo and Rochedo gauging stations during 5 periods in 2013. The period of record (POR) and maximum hydrographs were used as in the calculation of tracer mass recoveries in the river. Estimated hydrographs are shown relative to the tracer recovery curves. Sampling at the river was terminated after the 2nd set of injections before the entire recovery curve for Uranine could be plotted. The final section of the declining limb of that curve was estimated based on an exponential fit to the plotted concentrations (shown above).

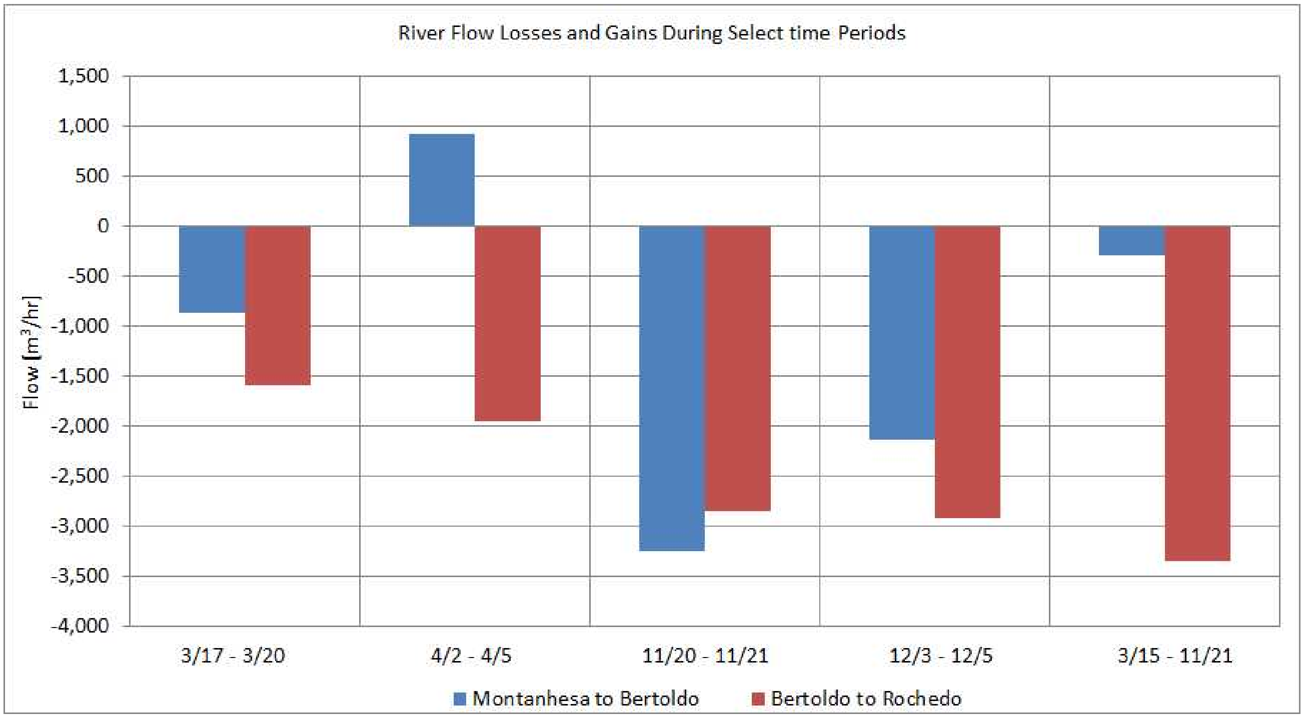


Figure 12 – River gains and losses between the Montanhesa and Rochedo gauging stations during 5 periods in 2013.

Uranine was the larger of the two recovery curves after the second set of injections, which was not surprising despite the fact that it was the upstream-most of the injected tracers. This is because Uranine is known to be the most fluorescent and therefore detectable of the three dyes used in the tracer study. Sampling at the river was terminated however before the entire recovery curve for Uranine could be plotted. The final section of the declining limb of that curve was therefore estimated based on an exponential fit to the measured concentrations representing the tailing edge of the curve.

The total mass of Uranine recovered after the second set of tracer injections in the river was between 1,567 and 2,705 grams based on the POR and maximum estimated river flows at the Rochedo station respectively. These values represent between approximately 17% and 29% of the 9.25 kg of tracer injected. By comparison, the total mass of Rhodamine-WT recovered was only between 389 and 677 grams, which represents only between 4% and 7% of the 9.25 kg injected. Based on these mass recoveries, between 71% and 83% of the injected Uranine (6,545 - 7,683 grams) and between 93% and 96% of the injected Rhodamine-WT (8,573 – 8,861 grams) was lost either to the aquifer or adsorption to organic material in the river and/or the river substrate. The percentage of Rhodamine-WT recovered was slightly less than what was recovered from the 1st injection but the distance traveled by the dye between the injection and sampling points was farther indicating that a similar degree of river loss and/or adsorption and degradation was active. The data and equations used to calculate the recovered mass of tracers in the river are provided in Appendix XIII.

3.1.2 Mine Discharge Channel

Uranine and PTSA were both definitively detected in the mine discharge channel after the second set of tracer injections in sufficient detail to enable the calculation of mass recovery though estimation methods had to be used for both tracers to approximate complete recovery curves. For Uranine, concentrations in 37 of the 40 collected water samples tracked the declining limb of a recovery curve but sampling was terminated before the complete tail could be established. Three steps were taken in order to estimate a full recovery curve.

1. The Uranine concentrations measured by the spectrofluorophotometer were correlated to the green (Uranine) minus red (Rhodamine-WT) fluorescence signal recorded by the C3 to create a curve that mimics the shape of the green minus red curve but approximates the spectrofluorophotometer-defined values.

2. A logarithmic fit was established to the last seven spectrofluorophotometer-defined values plus a zero-value set at a time that approximates the return of the Uranine minus Rhodamine-WT fluorescence signal to negative space.
3. And, a linear equation was used to approximate the rise from a zero-value set at a time that approximates the shift in Uranine minus Rhodamine-WT fluorescence from negative to positive space, to the first point used to correlate the tracer concentrations to the fluorescence signal.

Figure 13 shows the estimated recovery curve for Uranine at the mine discharge channel relative to the C3 and spectrofluorophotometer data and the analytical models used to define the estimated tracer recovery curve, as well as a plot of Uranine minus Rhodamine-WT fluorescence as recorded by the C3 fluorometer versus spectrofluorophotometer-defined concentrations and the resulting linear regression fit. The total mass of Uranine recovered at the discharge channel after the 2nd injection based on this approximation was 419 grams, which is approximately 5% of the 9.25 kg of Uranine that was injected in the river and between 5.5 and 6.4% of the 6,545 - 7,683 grams of Uranine that either traveled with the lost river flow into the aquifer or was lost due to adsorption. The data and equations used to calculate the recovered mass of Uranine in the mine discharge channel are provided in Appendix XIV.

For PTSA, 38 of the 40 collected water samples tracked the rising limb, peak, and first part of the declining limb of a recovery curve but sampling was terminated before the complete tail could be established. Two steps were taken in order to estimate a full recovery curve.

1. A polynomial equation was fit to the rising limb, peak, and small portion of the declining limb of the concentration data.
2. And, a logarithmic fit was established to the last seven spectrofluorophotometer-defined concentrations plus a zero-value set at a time that approximates the return of blue fluorescence recorded by the C3 to a zero baseline level.

Figure 14 shows the estimated recovery curve for PTSA at the mine discharge channel relative to the C3 and spectrofluorophotometer data and the two analytical models used to define the estimated tracer recovery curve.

The total mass of PTSA recovered at the discharge channel after the 2nd injection based on this approximation was 2,314 grams, which is 25% of the 9.25 kg of PTSA that was injected in the swallet adjacent to the river and therefore 25% of the PTSA that could have traveled with the lost river flow into the aquifer. The data and equations used to calculate the recovered mass of PTSA in the mine discharge channel are provided in Appendix XV. Cumulative tracer recoveries in the river and in the mine discharge channel are provided on Figure 15.

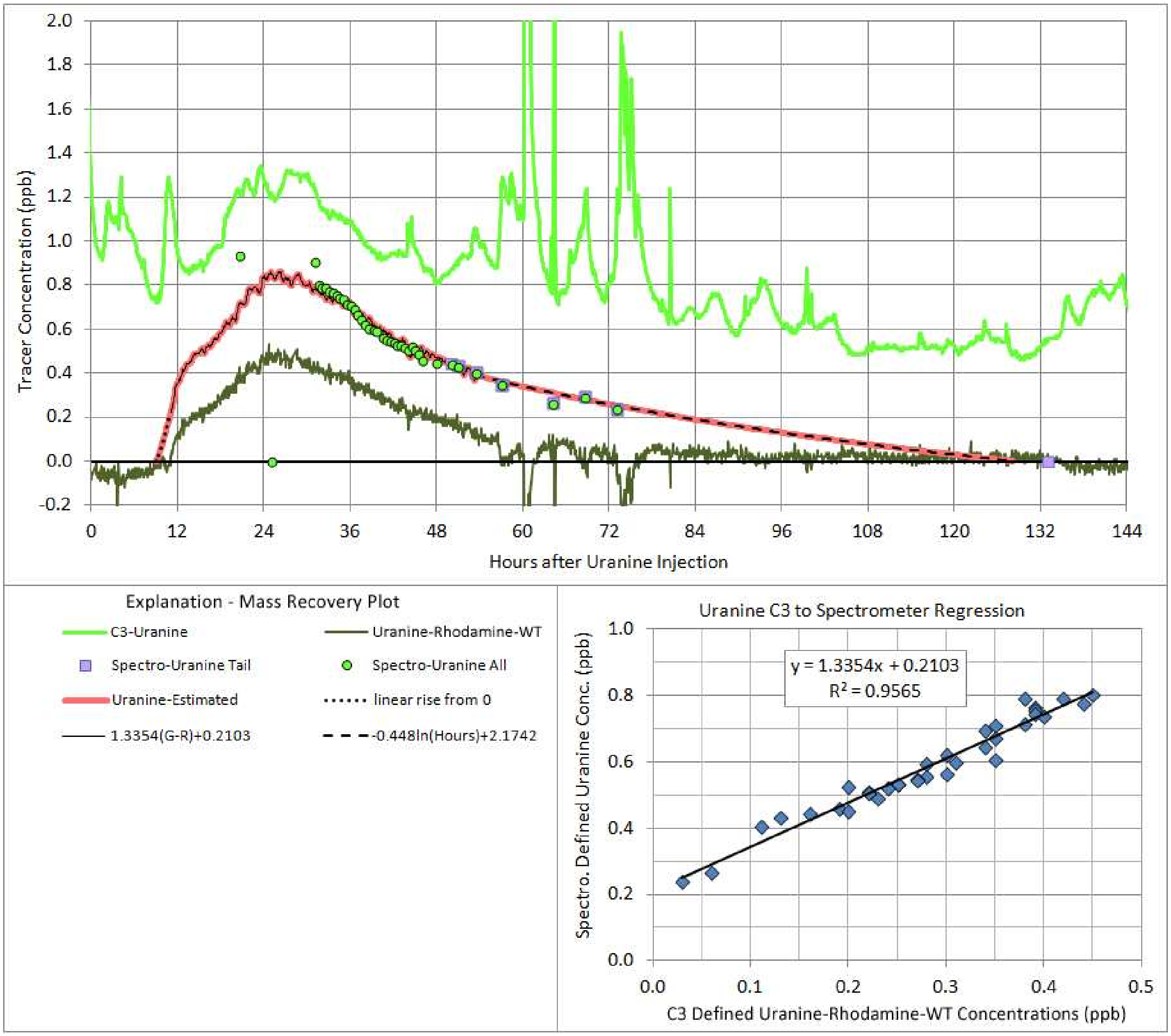


Figure 13 – Estimated recovery curve for Uranine at the mine discharge channel after the 2nd injection.

The estimated curve is shown relative to the spectrofluorophotometer and C3 data. The recovery curve was estimated using three equations: a linear fit between zero and the 1st estimated concentration on the rising limb; a linear equation relating Uranine concentration to Uranine minus Rhodamine-WT fluorescence (bottom right) for the remainder of the rising limb, peak and beginning part of the falling limb; and a logarithmic fit to the last seven concentrations measured on the falling limb of the curve plus a zero set at a time that approximates the return of Uranine minus Rhodamine-WT fluorescence to negative space.

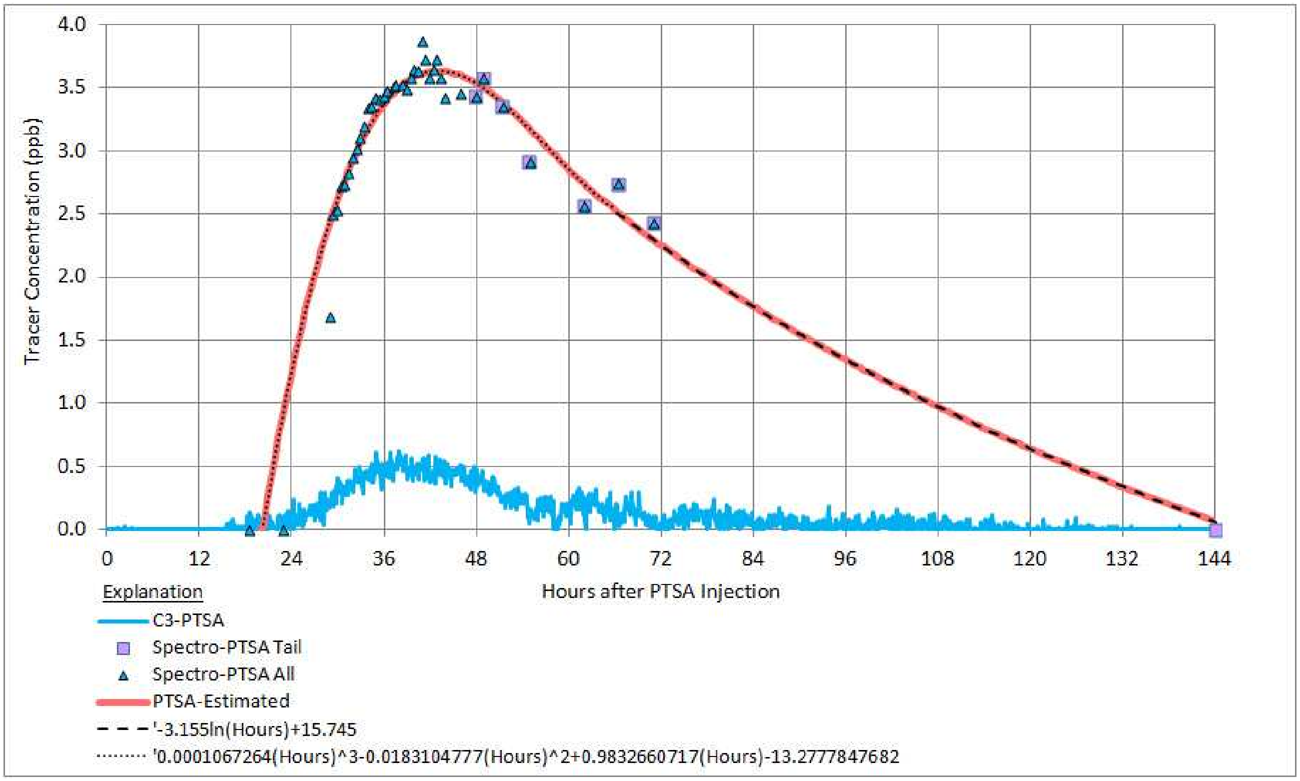


Figure 14 - Estimated recovery curve for PTSA at the mine discharge channel after the 2nd injection.

The estimated curve is shown relative to the spectrofluorophotometer and C3 data. The recovery curve was estimated using two different equations relating only to the distribution and value of the concentrations measured by the spectrofluorophotometer: a polynomial fit to the data marking the rising limb, peak, and beginning of the falling limb; and a logarithmic fit to the last seven concentrations measured on the falling limb of the curve plus a zero set at a time that approximates the return of blue fluorescence recorded by the C3 to a zero baseline level.

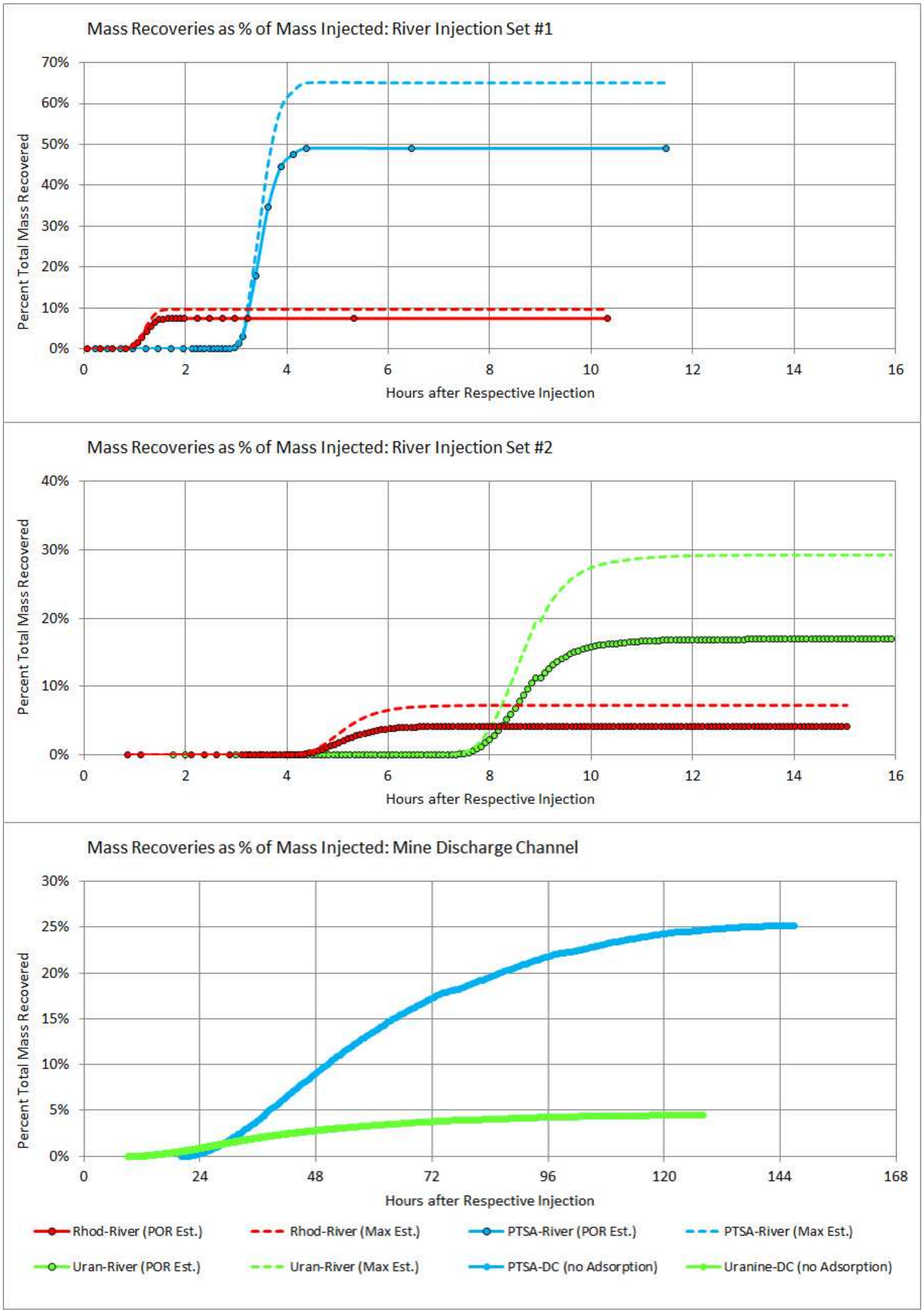


Figure 15 – Cumulative tracer recovery plots showing the patterns of tracer recovery in the river and mine discharge channel after the 1st and 2nd sets of injections.

The timing of the recoveries in the river was controlled by the distance between the respective tracer injections and the river sampling station and the velocity of the river flow. Tracer recoveries in the mine discharge channel reached their full extent between approximately 96 and 120 hours after the injections.

3.1.3 Percent River Loss in Mine Discharge

Table 7 presents a summary of the tracer mass recoveries in the river and in the mine discharge channel. The calculated recovery of Uranine provides the only measure of the possible percentage of river loss to the aquifer along the traced section that flowed to the mine because the PTSA was injected directly into a swallet and therefore does not track river loss along a broader reach. Using the Uranine recovery calculations from the river and the discharge channel, an estimate for the possible percentage of river loss that flowed to the mine was derived by:

$$\%River_{Loss} = [DyeRec_{DC}/(DyeInj - DyeRec_{Riv})] \times 100$$

where: $\%River_{Loss}$ = percentage of flow lost from river in mine discharge channel;
$DyeRec_{DC}$ = mass of tracer dye recovered in mine discharge channel;
$DyeInj$ = mass of tracer dye injected in river; and
$DyeRec_{Riv}$ = mass of tracer dye recovered at river sampling station.

From this approach, the mass of Uranine recovered at the discharge channel represents only about 6% of the mass of dye not recovered in the river after the second injection. This estimation approach does not however account for the following processes that are likely important factors, to different degrees, that must be considered:

1. loss of dye in the river prior to recharge due to adsorption of the dye onto rock and sediment substrate and organic matter in the river;
2. sequestration of parts of the dye cloud in eddies in the river;
3. loss of dye in the river due to decay in sunlight;
4. loss of dye in the aquifer due to adsorption of the dye onto rock and sediment substrate and organic matter in the dissolved void spaces within the aquifer; and
5. sequestration of part of the dye cloud in aquifer storage.

The fact that less than 100% of the PTSA was recovered despite the fact that 100% of the injected tracer traveled quickly and directly into the aquifer via a swallet indicates that, at a minimum, factors 4 and 5 were active and significant to the results. The long-term fluorescence record provided by the C3 (Figure 8) revealed two smaller rises in blue fluorescence occurring at approximately 11.5 and 19 days after the injection. Though these responses were not confirmed with the spectrofluorophotometer, they likely mark the passage of discrete small slugs of PTSA well after the main dye cloud had passed.

The dye cloud therefore likely entered some form of aquifer storage after entering the swallet and then fractionated. The available record indicates that a large portion of the fractionated cloud traveled into the mine rapidly via dissolutionally enhanced flow paths and that smaller portions of the remainder of the cloud moved episodically thereafter into the mine. A comparison of the timing of the late-time events to the river flow data (Figure 9) reveals that the subsequent responses in the discharge channel correlate to spikes in the river flow, especially if the flow record is shifted forward to account for the probable travel time between the gauging station and the discharge channel through the aquifer.

It is reasonable to conclude therefore that water flow from the river to the mine is substantially affected by the stage in the river. River losses occurring under low (or relatively steady stage) fill aquifer storage between the river and the mine and then diminish. Sharp rises in river stage likely drive water from storage into the mine along with a larger portion of the river flow into the aquifer. As the stage returns to low and steady conditions, both losses to the aquifer and flow from aquifer storage to the mine diminish.

Even accounting for episodic flow and the later arrival of the dye, it is likely that adsorption to aquifer and sediment substrate accounted for a significant portion of the amount of PTSA dye that was not recovered (~75% of the injected mass). Visual comparison of the late-time PTSA responses recorded by the C3 to the primary response shortly after the injection indicates that the smaller late-time rises might account for another 10% recovery. Even accounting for them, the total amount of dye that entered the discharge channel within approximately 40 days of the injection is likely not more than 35% of the injected mass. Adsorption could therefore account for as much as 65% of the injected mass.

If we use that estimate of adsorption and reconsider the Uranine recovery data presented in Table 7, a reasonable expectation for the amount of Uranine that should have been recoverable in the discharge channel could be less than or equal to 35% of the mass that did not pass the river sampling station. When accounting for loss due to adsorption in this way, a reasonable estimate for the total mass of Uranine that could have been recovered in the discharge channel falls to between 2,291 and 2,689 grams based on the maximum and POR estimated flows at the Rochedo station respectively. The 419 grams of Uranine recovered in the mine discharge channel is then between about 16% and 18% of the mass of tracer that could expected to enter the mine discharge channel after accounting for the estimated adsorption. The equation used to arrive at that estimate is defined below.

$$Dye_{Recoverable} = \left(Dye_{Injected} - Dye_{RecoveredRiver}\right) \times \left(1 - Loss_{Absorption}\right)$$

where: $Dye_{Recoverable}$ = potential mass of dye recoverable in the discharge channel;
$Dye_{Injected}$ = mass of dye injected into the river;
$Dye_{RecoveredRiver}$ = mass of dye recovered in the river; and
$Loss_{Absorption}$ = percentage of mass that could have been lost to adsorption.

The expected quantity of Uranine in the mine discharge channel is likely even less than that because adsorption of the dye to substrate and organic materials in the river would have likely reduced the amount of dye entering the aquifer and those processes were not relevant to the PTSA because it was injected directly into the aquifer via the swallet. Using this estimate for minimum adsorptive losses however, the calculation of the percentage of lost river flow in the aggregate mine discharge can be amended according to the equation listed below where the estimate percentages are provided in Table 7.

$$\%River_{Loss-Adj} = [DyeRec_{DC}/(Dye_{Recoverable})] \times 100$$

where: $\%River_{Loss-Adj}$ = percentage of flow lost from river in mine discharge channel adjusted to account for the potential loss of dye due to adsorption;
$DyeRec_{DC}$ = mass of tracer dye recovered in mine discharge channel; and
$Dye_{Recoverable}$ = potential mass of dye recoverable in the discharge channel after accounting for potential loss due to adsorption.

Table 7. Summary of tracer mass recoveries and percent recoveries in mine.

		River			Mine Discharge Channel		
		Uran	Rhod	PTSA	Uran	Rhod	PTSA
Injection Set #1	Mass injected	750	750	750	-	-	-
	Mass recovered	-	56-72	448	-	-	-
	% Recovered	-	7-10	49-65	-	-	-
	Max mass lost to aquifer	-	678-694	261-382	-	-	-
	% Lost flow in mine	-	-	-	-	-	-
Injection Set #2	Mass injected	9,250	9,250	9,250	9,250	?	9,250
	Mass recovered	1,567-2,705	389-677	-	419	-	2,314
	% Recovered	17-29	4-7	-	5.5-6.4	-	25
	Max mass lost to aquifer	6,545-7,683	8,573-8,861	-	6,545-7,683	-	9,250
	Possible loss to adsorption	-	-	-	4,254-4,994	-	6,013
	Expected recoverable mass				2,291-2,689	-	3,237
	% Lost flow in mine (no adsorption)	-	-	-	5.5-6.4	-	35
	% Lost flow in mine (with adsorption)	-	-	-	15.6-18.3	-	100

Notes: Max mass lost to aquifer = mass of injected dye tracer that was not recovered at the river sampling station
Possible loss to adsorption = minimum mass of PTSA not recovered or represented by the tracer recovery plot in the mine discharge channel
Expected recoverable mass = mass of tracer dye that could have been recovered in the mine discharge channel after adjusting for the possible loss of PTSA due to adsorption
% Lost flow in mine (no adsorption) = mass of dye recovered / (mass injected – mass recovered in river)
% Lost flow in mine (with adsorption) = % lost flow in mine adjusted to account for possible loss of tracer due to adsorption *(values for PTSA inflated to account for probable late-time peaks recorded by C3)*
- = not applicable due to lack of adequate tracer detection

3.2 Volume of River Water in Mine Discharge

The volume of river water in the water discharging into the underground mine workings and subsequently pumped to the land surface at the mine discharge channel can be estimated in two ways. One is to estimate the total loss of river flow occurring along the stretch of river thought to be contributing flow to the mine and then to assume that 100% of that loss ultimately flows to the mine. Another way is to use the mass recovery of tracer at the mine discharge channel to estimate the amount of river water in the channel and, by extension, the amount of river water that might be flowing to another location, presumably some lower point of discharge in the river. This was done by multiplying the total river loss calculated from the gauging station data by the percent tracer recovery after adjusting for possible adsorption.

Both of these methods were used to develop the percentages presented in Table 8 where the estimates are based on the measured or estimated total volume of water that passed through the mine discharge channel and the Bertoldo and Rochedo river gauging stations during the period of the tracer test that was used for mass recovery calculations (11/28/13 @ 15:30 to 12/1/13 @ 15:00). The results indicate that lost river flow between the Bertoldo and Rochedo stations could account for as much as about 37% of the total mine discharge assuming that 100% of the lost river flow travels to the mine. The fractional recovery of Uranine in the mine discharge channel indicates that the fraction of river water in the mine discharge could be less than 10% though the inability to fully account for adsorption in the river channel renders this lower estimate less likely.

Table 8. Estimated % river water in the mine discharge.

Estimation Period				
Beginning of Estimation Period	11/28/2013 15:30			
End of Estimation Period	12/1/2013 15:00			
Duration of Estimation Period (hrs)	71.5			
			Rochedo	
Station Flows	*Mine*	*Bertoldo*	*Max*	*POR*
Total Volume of Water Passing Station (m3)	756,192	778,299	685,641	496,279
Average Discharge at Station (m3/hr)	10,576	10,885	9,589	6,941
Measured River Loss	*Max Flow*		*POR Flow*	
Total River Loss (m3)	92,659		282,020	
Average River Loss (m3/hr)	1,296		3,944	
Total River Loss as % of Mine Discharge	12.3%		37.3%	
Tracer Lost from River	*Max Flow*		*POR Flow*	
Mass of Uranine Lost to Aquifer or Adsorption (grams)	6,545		7,683	
Mass of Uranine Recovered in Discharge Channel	419		419	
Mass of Uranine in Discharge Channel as % of River Loss	6.4%		5.5%	
Accounting for Adsorption	*Max Flow*		*POR Flow*	
Possible Loss to Adsorption (65% based on PTSA Recovery)	4,254		4,994	
Expected Loss to Aquifer (accounting for Adsorption)	2,291		2,689	
Mass of Uranine in Discharge Channel as % of Expected Loss	18.3%		15.6%	
Recovered Flow During Trace in Mine Discharge	*Max Flow*		*POR Flow*	
Recovered Flow in Discharge Channel (m3/hr)	237		615	
Recovered Flow as % of Mine Discharge	2.2%		5.8%	

3.3 Pattern of Hydraulic Connections

Figure 16 depicts the pattern of positive tracer detections at the mine sampling stations. No dye was detected at any of the northern sampling stations. There are three likely discrete flow paths that connect the river to the mine at three different elevations. There is an apparent pathway that connects the upstream portion of the river to the far southern end of the mine at levels 420 and 388. This is indicated by the singular detection of Uranine at stations 4, 5, and 8.

The pathway between the swallet, located in the lower portion of the river, and the mine must be singular and is to level 345 at or upstream of station 11. This is indicated by the detection of PTSA at only stations 10 and 11 and the pattern of water flow and tracer concentrations where the water from station 11 flows past station 10 and the PTSA concentrations at station 11 were higher than those recorded at station 10.

A third, shallower discrete flow path likely connects the river to the southern section of the mine in the levels 484 and 455. This is indicated by the detection of Uranine and Rhodamine-WT at stations 1, 2, 3, and 6. The pathway most likely connects from the middle section of the river, upstream of the swallet but it is possible that this connection is from a point farther downriver because PTSA was not injected into the river during the 2nd round of injections and therefore the connection could be from any point downstream of the Rhodamine-WT injection. The pathway must be different than the one connecting from the swallet because no PTSA was detected. Figure 17 shows potential conduit flow pathways that follow local and regional structures mapped by VM that would explain the pattern of tracer detections in the mine.

Figure 18 provides a cross-section showing the hydrogeologic relationship between the river and the mine tunnels that was developed by VM and copied from Pessoa and others (2012). The river is shown to be separated from the mine tunnels by a black phyllite and from the dolomite by an epikarst. Rapid water flow from the river to the mine is therefore predicated on faults and/or fractures that cross the phyllite and provide hydraulic continuity. The epikarst would likely create substantial storage and a vehicle for lateral flow away from the river to faults and/or fractures in the dolomite. The results of the tracer test indicate that flow is from the river into the epikarst. From there it travels rapidly via faults and/or fractures in the dolomite that provide hydraulic continuity through the phyllite to station 11, which we equate to the lowest level and to stations 1-6 and 8 along other discrete flow paths. The piezometric surface depicted on Figure 18 indicates that hydraulic continuity through the phyllite is sufficient to allow heads to equilibrate to the lowest tunnel elevation. The sporadic nature of the PTSA response at the mine discharge channel, however, indicates that heads may not be in equilibrium but that elevated river stage causes heads on the river side of the phyllite to rise relative to those on the mine side resulting in episodic flows across the phyllite into the mine.

3.4 Implications for Groundwater Flow Modeling

Numerical groundwater modeling can be and has been used to simulate this flow system. If adequately adapted to simulate the conduit flow characteristics identified by this tracing experiment, the model could be used as a platform for evaluating the benefit of various hypothesized strategies to reduce inflow from the river to the mine. The key features that should be explicitly added to the model are: 1) the strike, dip, and thickness of the black phyllite; 2) only a subset of the mapped faults/fractures that could contribute to the observed pattern of tracer detections; and 3) the probable extent and thickness of the epikarst.

The position and thickness of the phyllite is important because it likely establishes a hydraulic barrier between the mine tunnels and the river where rapid flow to the mine can only occur where the phyllite has been breached by faults and/or fractures. The epikarst is important because it likely provides aquifer storage that is responsible for the episodic flows that were inferred from the long-term distribution of PTSA response signals recorded by the C3.

Once the model is redesigned to accommodate these features, it should then be recalibrated to observed heads in the piezometers and shut-in value pressures in the mine; to the observed flux into the mine as recorded by the pumping rates; and to the approximate groundwater velocities along the dissolved conduit pathways as recorded by the tracer test. Once the model has been recalibrated, it will serve as an excellent platform for evaluating the effect of mitigation strategies such as moving or lining the river where the losses have been recorded or surmised; or sealing the dissolved conduit pathways. The model would also provide the ability to predict the effect of reducing river water losses on the aerial extent and depth of the existing cone-of-depression.

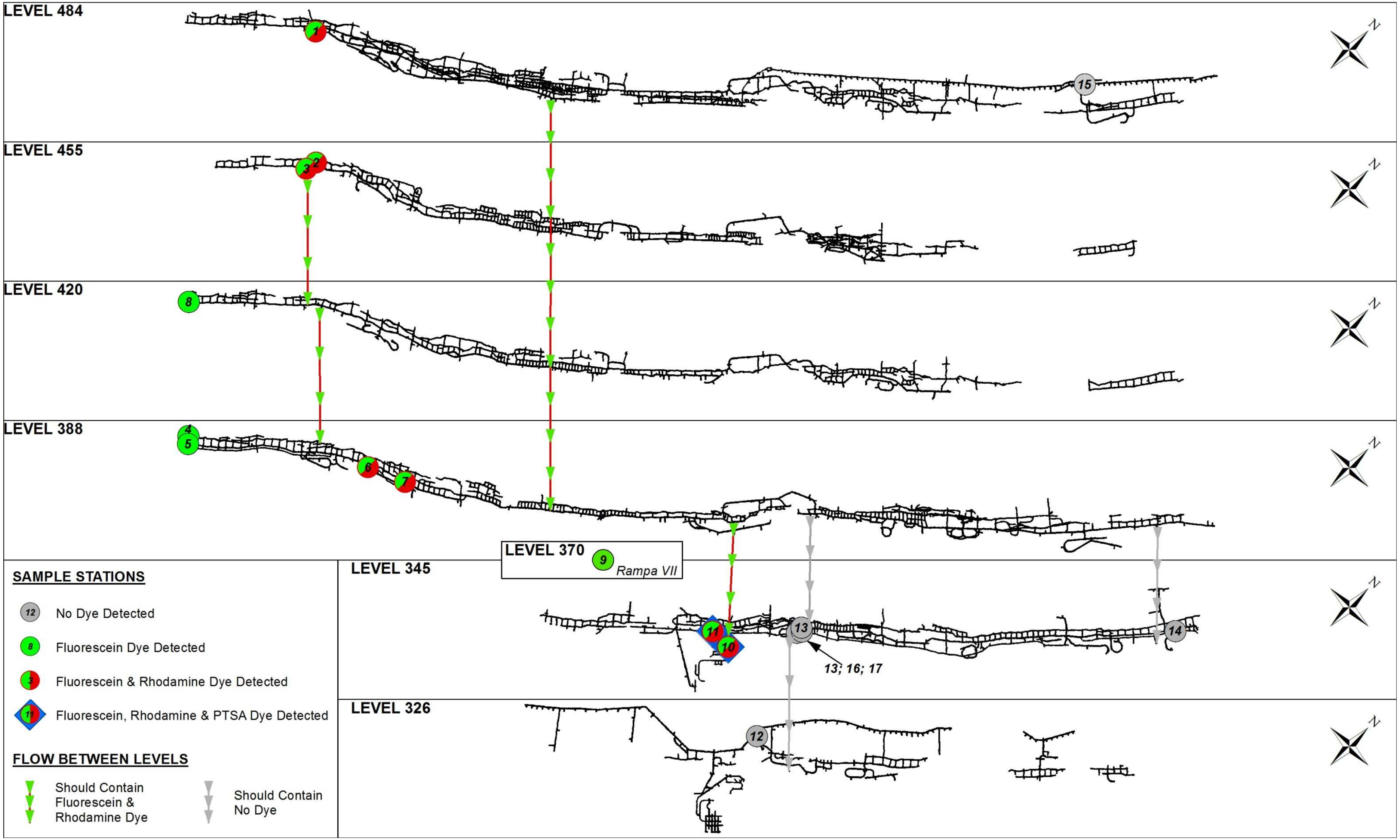


Figure 16 – Pattern of positive tracer detections in the mine.

No dye was detected at any of the northern sampling stations. The pattern of detections indicates three likely discrete flow paths: one that connects the upstream portion of the river to the far southern end of the mine at levels 420 and 388 (stations 4, 5, and 8); another that connects the middle section of the river to the southern section of the mine in the levels 484 and 455 (stations 1, 2, and 3); and one that connects the swallet located in the lower portion of the river to the deepest part of the mine at station 11 (level 345).

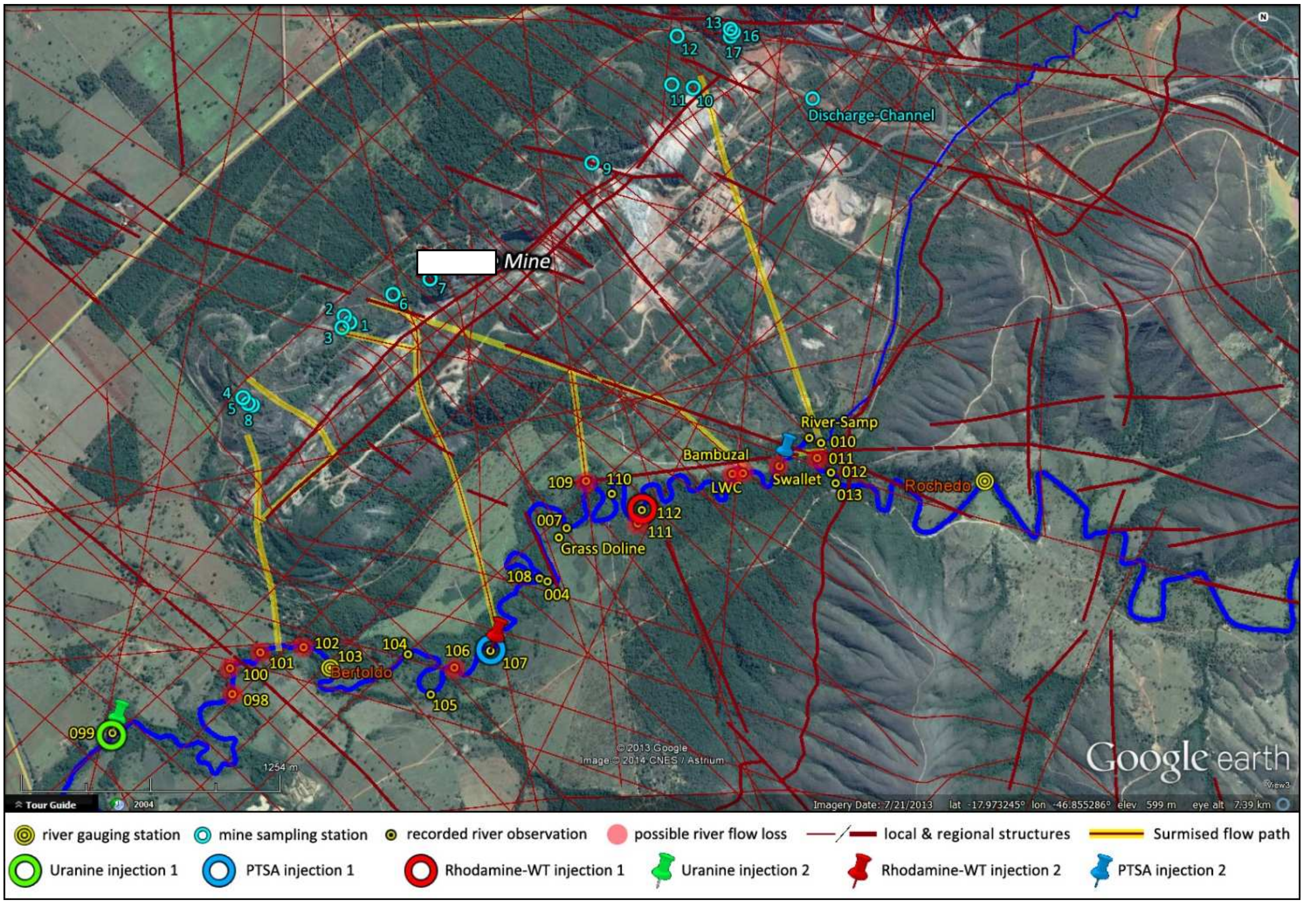
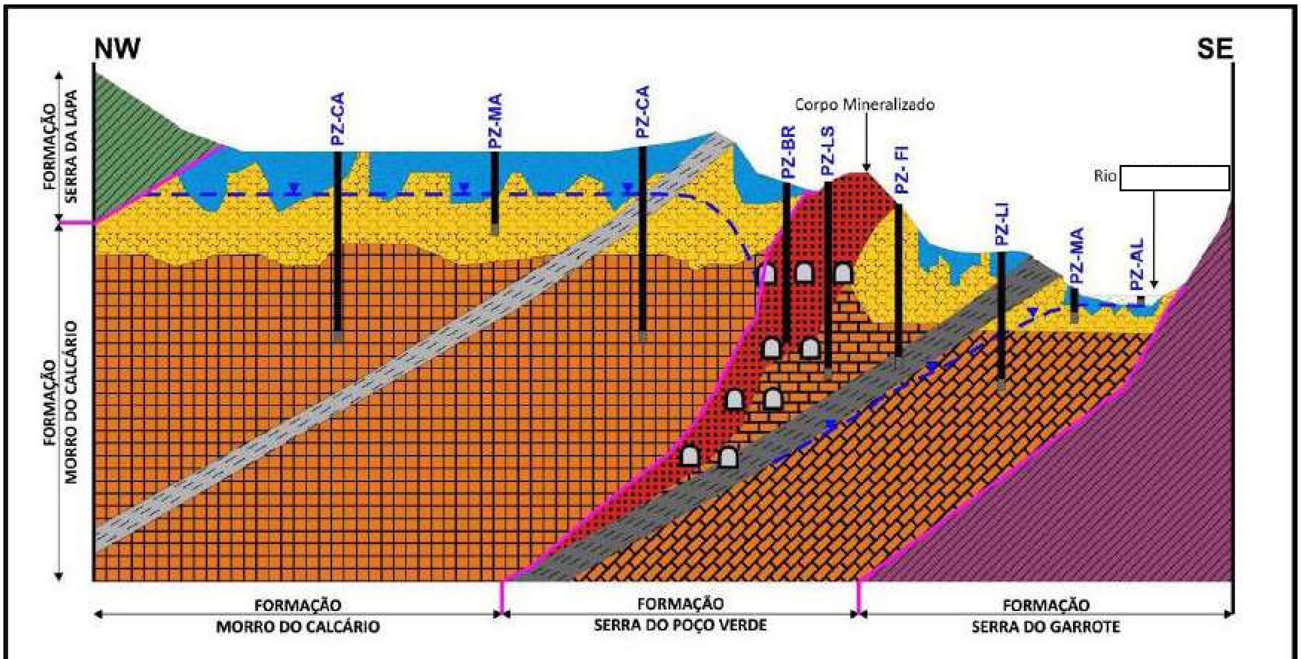


Figure 17 – Surmised conduit flow paths between the river and the mine based on mapped local and regional structures.

Thin and thick maroon lines are mapped local and regional structures provided by VM. The transparent yellow lines mark the closest structures that connect points downstream of the tracer injections with the sampling stations (or points close to the sampling stations) in the mine where the tracers were detected. There are three pathways depicted: one that connects the river at a point downstream of the Uranine injections but upstream of the Rhodamine-WT in injections to sampling stations 4, 5, and 8; one that connects the river from a point downstream of the 2nd Rhodamine-WT injection to sampling stations 1, 2, 3, and 6; and another that connects the swallet where the PTSA was injected to the mine close to station 11.



LEGENDA	UNIDADE HIDROGEOLÓGICA	TIPOLOGIA	LITOTIPO
	Aluvião	Aquífero Intergranular	Argilas e areias
	Colúvio	Aquífero Intergranular	Siltitos e argilitos
	Formação Serra da Lapa	Aquiclude/Aquitardo	Filitos com lentes de quartzitos finos
	Epicarste	Aquífero Cárstico	Carte superficial
	Capa	Aquífero Cárstico/Fissural	Metadolomito rosa
	Filito dolomítico	Aquiclude	Filito dolomítico
	Brecha mineralizada	Aquífero Cárstico/Fissural	Metadolomito rosa brechado e mineralizado
	Lapa Superior	Aquífero Cárstico/Fissural	Metadolomito cinza com intercalações de marga
	Filito Preto	Aquiclude	Filito preto (carbonoso)
	Lapa Inferior	Aquífero Cárstico/Fissural	Metadolomito cinza
	Formação Serra do Garrote	Aquiclude	Metapelito com intercalação de filito carbonoso
	Nível d'água	Galerias de mina	

Figure 18 – Cross-section showing the hydrogeologic relationship between the mine and the Undisclosed River

From Pessoa and others (2012). The river is shown to be separated from the mine tunnels by a black phyllite and from the dolomite by an epikarst. Rapid water flow from the river to the mine is therefore predicated on faults and/or fractures that cross the phyllite and provide hydraulic continuity. The epikarst would likely create substantial storage and a vehicle for lateral flow away from the river to faults and/or fractures in the dolomite. The results of the tracer test indicate that flow is from the river into the epikarst. From there it travels rapidly via faults and/or fractures in the dolomite that provide hydraulic continuity through the phyllite to station 11, which we equate to the lowest level and to stations 1-6 and 8.The piezometric surface depicted above indicates that hydraulic continuity through the phyllite is sufficient to allow heads to equilibrate to the lowest tunnel elevation. The sporadic nature of the PTSA response at the mine discharge channel indicates that heads may not be in equilibrium but that elevated river stage causes heads on the river side of the phyllite to rise relative to those on the mine side resulting in episodic flows across the phyllite into the mine.

4 SUMMARY & RECOMMENDATIONS

4.1 Summary

Two sets of tracer injections were performed in the Undisclosed River near the Undisclosed Mine using three fluorescent dyes. In each test, the three dyes were injected at different locations in the river such that the pattern of detection in the mine would reveal the source areas in the river. The three dyes were: Uranine, Rhodamine-WT, and PTSA salt. The 1st set of injections was performed using 0.75 kg of each dye. The 2nd set of injections was performed using 9.25 kg of each tracer where the PTSA was injected directly into a flowing swallet.

Uranine dye from the 1st set of injections was detected at very low levels in 9 stations in the southern section of the mine: stations 1-4, 6-7, and 9-11. No dye was detected at the stations in the northern part of the mine. All three of the dyes from the 2nd set of injections were detected in the mine, again at the stations in the southern section. Uranine was detected at stations 1-11. Rhodamine-WT was detected at stations 1-3, 5-7, and 10-11. PTSA was detected only at stations 10 and 11.

The pattern of detections in the mine indicates the presence of three discrete flow paths connecting the river the underground mine tunnels. One is from the upper part of the river (upstream of the Rhodamine-WT injection and the southernmost stations: 4, 5, and 8 at levels 420 and 388. One is from some point downstream of the Rhodamine-WT injections to mine stations 1, 2, 3, and 6 at levels 484 and 455. The last pathway is from the swallet located upstream of the river sampling station and the lowest levels of the mine at stations 10 and 11.

Mass recoveries were calculated for all three dyes at the river sampling station and for Uranine and PTSA in the mine discharge channel. Mass recoveries ion the river had to be based on estimated hydrographs at the Rochedo gauging station because the station was not functioning during the tracer testing period. The estimated hydrographs were created through statistical comparison of river flows at the Bertoldo and Rochedo stations during four different periods in 2013 where the magnitude and trend of flows at the Bertoldo station was similar to that recorded during the tracer test as well as for a 10-month period of record during which both stations were active prior to the tracer test.

The most significant recoveries were those after the 2nd set of injections: Uranine and Rhodamine-WT at the river sampling station, and Uranine and PTSA in the mine discharge channel. The recovered mass of Uranine at the river sampling station ranged between 1,567 and 2,705 grams using estimated flows at the sampling stations derived from the maximum of the four hydrographs and the period of record hydrograph. The recovered mass of Rhodamine-WT was between 368 and 489 grams.

Approximately 25% of the PTSA that was injected directly into the swallet in the river was recovered from the mine discharge channel where late-time detections recorded by the C3 fluorometer could raise the recovered mass to as much as 35%. The missing mass of PTSA (~65%) was attributed to adsorption to organic matter and rock substrate in the aquifer flow path. Given the possible loss due to adsorption, between 16% and 18% of the injected Uranine dye was accounted for by the recovery curve plotted for Uranine in the mine discharge channel. The substantially smaller recovery of Uranine is likely due to larger adsorption to organic matter in the river to which the PTSA was not exposed due to the injection method and location.

Comparison of the hydrograph from the Bertoldo gauging station to the estimated hydrographs for the Rochedo station during the tracer test reveal that as much as 37% of the mine discharge is river water lost to the aquifer between the Bertoldo and Rochedo gauging stations. The fractional recovery of Uranine in the mine discharge channel indicates that the fraction of river water in the mine discharge could be less than 10% though the inability to fully account for adsorption in the river channel renders this lower estimate less likely.

The pattern and timing of tracer detections relative to the karstic characteristics of the aquifer indicate that flow from the river to the mine occurs along discrete dissolutionally widened fractures but that there is not a perfect hydraulic connection between the river and the mine. Instead, flow from the river to the mine must first traverse substantial aquifer storage, most likely within the epikarst that is situated between the dolomite and the river. The magnitude and timing of the flow through the epikarst and into the mine is substantially affected by the hydraulic gradients created by fluctuating river stage and the presence of the phyllite that separates the river from the mine. Understanding the relationships between river stage, volume of water in the epikarst storage, and discharge in the mine will therefore be significant to the identification, design, and implementation of mitigation strategies designed to reduce river water infiltration to the aquifer and the mine.

4.2 Recommendations

Additional groundwater tracing experiments and modeling could be leveraged to gain a better understanding of these hydraulic relationships; to better understand the hydraulic significance of the phyllite and the degree to which it impedes flow from the river to the mine; and to characterize the pattern and rate of groundwater flow into the northern part of the mine. The following list provides recommendations for specific tests and actions that, we believe, would achieve these objectives.

1. Identify and trace flow paths and groundwater velocities between other active swallets and the mine, and record the long term pattern of tracer responses in the mine. These could include swallets such as those observed during this experiment that have formed in the river channel as well as sinkholes in the river flood plain that receive water during floods. The objectives would be to identify the locations of connections and, more importantly, to define the pattern of tracer response in the mine relative to fluctuations in river stage occurring over the period of hours to days after the injections. Given the results of the tracer tests performed in this study, particularly the low detectability of Rhodamine-WT and PTSA in the mine and Undisclosed River waters, we recommend that future tracers be limited to Uranine where staggered injections at different locations and regular water sampling at all stations would be used to isolate pathways and quantify tracer mass recoveries at the specific discharge locations in the mine. Such injections would be performed sequentially leveraging the observation that more than 90% of the recovered dye was recorded in the mine discharge channel within 3.5 days of the river injection during these experiments.

2. Trace the path and velocity of groundwater flow from the north into the mine and compare the signal response in terms of concentration and mass recovery to the results obtained from the river experiments to define the relative contributions of each source in the mine discharge. Once again, we recommend that such traces use Uranine, staggered injection times, and water sampling at all major sampling stations to establish tracer mass recovery curves. Figure 19 shows a suggested injection location based solely on the locations of prominent fractures that have been mapped by VM staff.

3. Better delineate the location of river flow losses in the Undisclosed River by repeating the river experiments but focusing the injections on locations immediately upstream of the probable loss points identified during the multiple filed reconnaissance surveys performed during this study. Regular water sampling at the mine discharge locations would permit the development of multiple tracer recovery curves, which could be used to quantify dilution between the specific discharge locations and the mine discharge channel and thereby better constrain the amount of river water in the total mine discharge. Figure 19 shows suggested injection locations.

4. Revise the existing FEFLOW model to include the discrete flow paths and groundwater velocities identified by the tracing experiments where calibration to heads would be used as the basis to evaluate multiple networks of discrete flow paths and identify the most probable pathways. Those pathways would then constitute targets for mitigation efforts intended to reduce river water infiltration to the aquifer and mine.

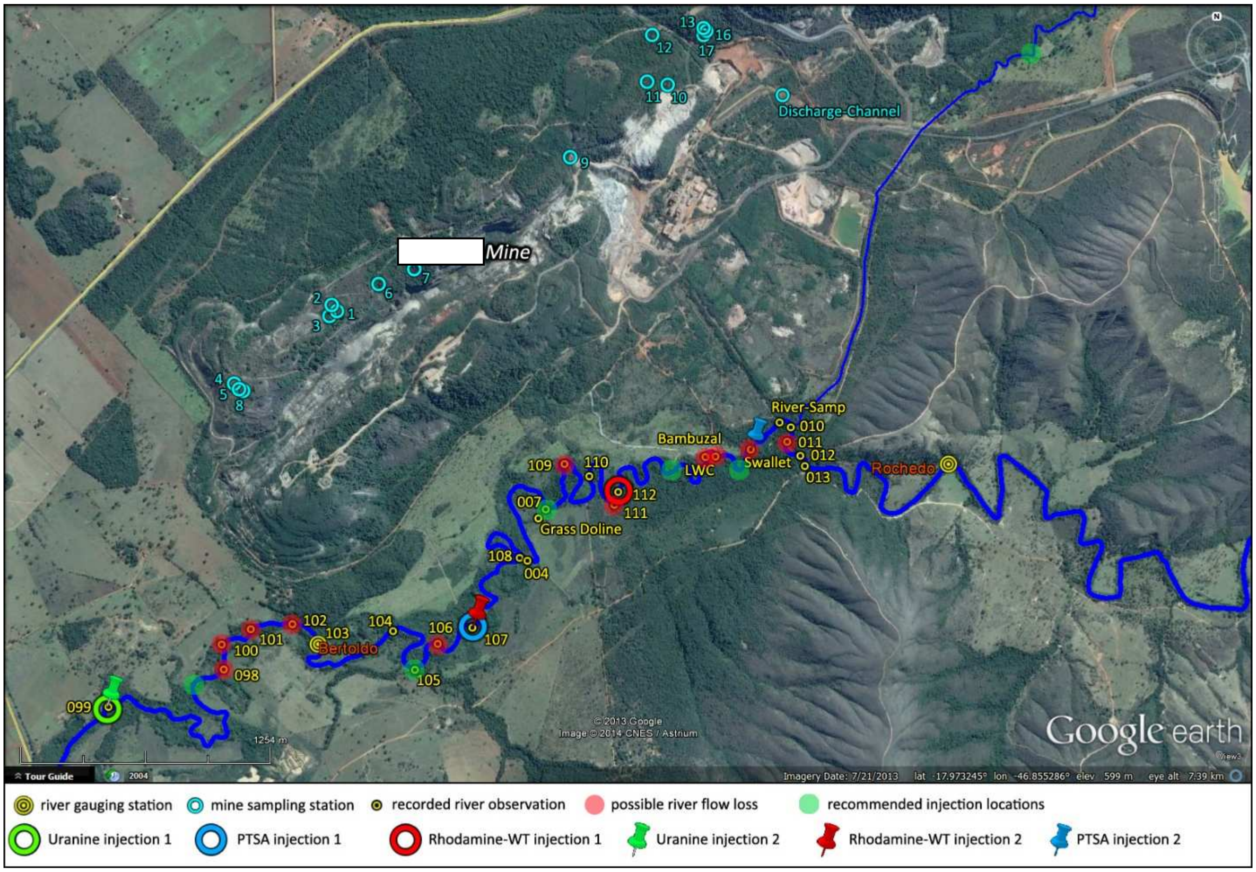


Figure 19. Location of recommended tracer injections for subsequent groundwater tracing investigations.

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APPENDIX I
FLUORESCENT TRACER MATERIAL SAFETY DATA SHEETS

APPENDIX II
FLUOROMETER DESCRIPTION AND SPECIFICATION SHEETS

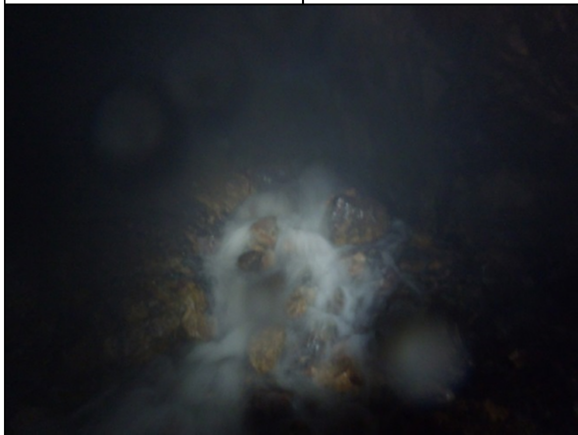
APPENDIX III
PHOTOGRAPHS AND DESCRIPTIONS OF THE MINE SAMPLING STATIONS

Station Map ID	Mine - 01			
NO PHOTOGRAPHS				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 7,0,0 / INJ2: 4,0,2
Level	**Elevation (m)**	**Charcoal**		
484	502	No		
Description	At wall in mine. Brown water flow.			

Station Map ID	Mine - 02			
				
Mine02_PB290179.JPG		Mine02_PB290181.JPG		Mine02_PB290182.JPG
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 7,0,0 / INJ2: 4,0,2
Level	**Elevation (m)**	**Charcoal**		
455	475	Yes		
Description	Two water falls from karst conduits. Brown water flow.			

<table>
<tr><td>Station Map ID</td><td colspan="4">Mine - 03</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Mine03_PB290183.JPG</td><td colspan="2">Mine03_PB290184.JPG</td><td>Mine03_PB290185.JPG</td></tr>
<tr><td>Latitude</td><td>Longitude</td><td>Easting (m)</td><td>Northing (m)</td><td># Tracer Detections (U,P,R)</td></tr>
<tr><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>INJ1: 7,0,0 / INJ2: 4,0,3</td></tr>
<tr><td>Level</td><td>Elevation (m)</td><td>Charcoal</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>455</td><td>475</td><td>No</td></tr>
<tr><td>Description</td><td colspan="4">Large waterfall from karst solution pipe ~1 meter in diameter. Brown water flow.</td></tr>
</table>

<table>
<tr><td>Station Map ID</td><td colspan="4">Mine - 04</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Mine04_PB290186.JPG</td><td colspan="2">Mine04_PB290189.JPG</td><td>Mine04_PB290190.JPG</td></tr>
<tr><td>Latitude</td><td>Longitude</td><td>Easting (m)</td><td>Northing (m)</td><td># Tracer Detections (U,P,R)</td></tr>
<tr><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>INJ1: 7,0,0 / INJ2: 4,0,0</td></tr>
<tr><td>Level</td><td>Elevation (m)</td><td>Charcoal</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>388</td><td>420</td><td>Yes</td></tr>
<tr><td>Description</td><td colspan="4">Confluence of two chambers where flow is out of drill holes in walls and ceiling. Pressure gauge read 8.3 kg/cm^2.
Light brown water flow.</td></tr>
</table>

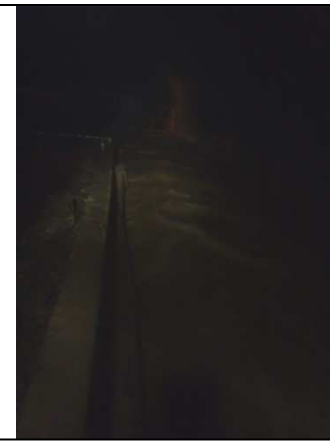
<table>
<tr><td>Station Map ID</td><td colspan="5">Mine - 05</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Mine05_PB290192.JPG</td><td colspan="2">Mine05_PB290193.JPG</td><td colspan="2">Mine05_PB290195.JPG</td></tr>
<tr><td>Latitude</td><td>Longitude</td><td>Easting (m)</td><td>Northing (m)</td><td colspan="2"># Tracer Detections (U,P,R)</td></tr>
<tr><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>XXXX</td><td colspan="2">INJ1: 0,0,0 / INJ2: 3,0,0</td></tr>
<tr><td>Level</td><td>Elevation (m)</td><td>Charcoal</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>388</td><td>420</td><td>Yes</td></tr>
<tr><td>Description</td><td colspan="5">Flow is from three obvious karst features. One discharge is small and from floor where it is bubbling with gas.
Light brown water flow.</td></tr>
</table>

Station Map ID	Mine - 06			
				
Mine06_PB290197.JPG				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 7,0,0 / INJ2: 3,0,2
Level	**Elevation (m)**	**Charcoal**		
388	412	Yes		
Description	Flow in tunnel. Not as much as at #7. About 1/10 as much. Dark brown water flow.			

Station Map ID	Mine - 07			
				
Mine07_PB290196.JPG				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 6,0,0 / INJ2: 3,0,1
Level	**Elevation (m)**	**Charcoal**		
388	408	No		
Description	Strong brown flow in tunnel.			

<table>
<tr><td>Station Map ID</td><td colspan="4">Mine - 08</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Mine08_PB290198.JPG</td><td colspan="2">Mine08_PB290199.JPG</td><td>Mine08_PB290200.JPG</td></tr>
<tr><td>Latitude</td><td>Longitude</td><td>Easting (m)</td><td>Northing (m)</td><td># Tracer Detections (U,P,R)</td></tr>
<tr><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>INJ1: 0,0,0 / INJ2: 4,0,0</td></tr>
<tr><td>Level</td><td>Elevation (m)</td><td>Charcoal</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>420</td><td>447</td><td>Yes</td></tr>
<tr><td>Description</td><td colspan="4">Flow is from drill holes in wall and flow from a side tunnel. Strong brown water flow.</td></tr>
</table>

Station Map ID	Mine - 09			
				
Mine09_PB290201.JPG		Mine09_PB290202.JPG		
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 6,0,0 / INJ2: 3,0,0
Level	**Elevation (m)**	**Charcoal**		
370	382	No		
Description	Low flow from tunnel and drips from ceiling where rock bolts installed plus flow from karst feature in wall, 708 cm in diameter. Brown water flow – probably from tunnel water.			

Station Map ID	Mine - 10			
				
Mine10_PB250123.JPG		Mine10_PB250126.JPG		Mine10_PB250128.JPG
				
Mine10_PB250129.JPG		Mine10_PB250133.JPG		Mine10_PB290208.JPG
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 6,0,0 / INJ2: 3,3,2
Level	**Elevation (m)**	**Charcoal**		
345	345	Yes		
Description	Movie: Rapidly flowing water in concrete channel that is collection of flow from multiple points including large pipe flow water fall depicted above. Pouring concrete during sample collection. Muddy brown water flow. Mine10_PB290207.MP4			

Station Map ID	Mine - 11


Mine11_PB250134.JPG


Mine11_PB250136.JPG


Mine11_PB250137.JPG


Mine11_PB250139.JPG


Mine11_PB290204.JPG


Mine11_PB290205.JPG

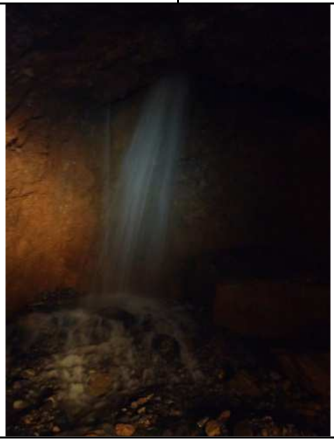
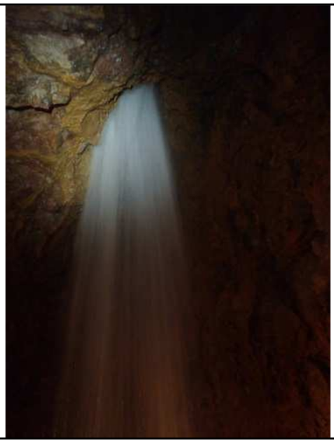
Latitude	Longitude	Easting (m)	Northing (m)	# Tracer Detections (U,P,R)
XXXX	XXXX	XXXX	XXXX	INJ1: 7,0,0 / INJ2: 5,5,3
Level	**Elevation (m)**	**Charcoal**		
345	348	Yes		

Description	Very muddy and rapid flow from pipes through wall. Flow fluctuated significantly during sampling. Charcoal was above water when flow dropped the first time. Flow is from and into abandoned tunnel due to collapse.

Station Map ID	Mine - 12

		
Mine12_PB290210.JPG	Mine12_PB290211.JPG	Mine12_PB290212.JPG

Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 0,0,0 / INJ2: 0,0,0
Level	**Elevation (m)**	**Charcoal**		
326	332	No		
Description	Brown water flow through tunnel.			

Station Map ID	Mine – 13 (Cebola Falls)			
				
Mine13_PB250108.JPG		Mine13_PB250110.JPG		Mine13_PB250113.JPG
				
Mine13_PB250115.JPG				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 0,0,0 / INJ2: 0,0,0
Level	**Elevation (m)**	**Charcoal**		
345	350	Yes		
Description	High flow from solution pipe in ceiling that creates water fall into mine tunnel. Appears that water fall has conveyed substantial rock and sediment creating apron at base of falls. Water flows across tunnel to join flow through adjacent tunnel.			

Station Map ID	Mine – 14			
NO PHOTOGRAPHS				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 0,0,0 / INJ2: 0,0,0
Level	**Elevation (m)**	**Charcoal**		
345	373	Yes		
Description	Brown water flow through tunnel.			

Station Map ID	Mine - 15			
				
Mine15_PB290217.JPG				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 0,0,0 / INJ2: 0,0,0
Level	**Elevation (m)**	**Charcoal**		
484	499	Yes		
Description	Very clear water flow out from base of wall.			

Station Map ID	Mine - 16			
				
Mine16_PB290213.JPG				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 0,0,0 / INJ2: 0,0,0
Level	**Elevation (m)**	**Charcoal**		
345	349	Yes		
Description	Tunnel flow upstream of junction with water from Cebola Falls (#13).			

APPENDIX IV
PHOTOGRAPHS AND DESCRIPTIONS OF THE RIVER OBSERVATION POINTS

Station Map ID	099			
				
Riv099_PB240059.JPG (Upstream)		Riv099_PB240060.JPG (Downstream)		Riv099_PB240062.JPG (Downstream)
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Sand bar on river left. Site of Uranine injections for injection sets #1 and #2. Movie: Riv099_PB240063.MP4			

Station Map ID	098			
				
Riv098_PB230026.JPG (Upstream)		Riv098_PB230027.JPG (Downstream)		
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	River bank on river right that has been filled in with clay and rock.			

Station Map ID	100

		
Riv100_PB240067.JPG (Downstream)	Riv100_PB240068.JPG (Downstream)	Riv100_PB240069.JPG (Downstream)

Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Outcrop of breccia on river left. Strong eddy at rock outcrop. Fractured rocks could be source of river loss. Almost on top of mapped fracture at this point in the river.			

Station Map ID	101

		
Riv101_PB240072.JPG	Riv101_PB240073.JPG	

Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Outcrop of breccia on river left. Fractured rocks could be source of river loss.			

Station Map ID	102			

Riv101_Riv103_PB240077.JPG

Riv101-Riv103_PB240076.JPG

Riv101-Riv103_PB240078.JPG

Latitude	Longitude	Easting (m)	Northing (m)	# Tracer Detections
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Possible collapse features on river right between station 101 and station 103 near former sinks that have been filled in with clay. Movie: Riv102_PB240082.MP4			

Station Map ID	103			

Riv103_Bertoldo_PB240079.JPG (Downstream)

Riv103_Bertoldo_PB240080.JPG (Downstream)

Riv103_Bertoldo_PB230041.JPG

Latitude	Longitude	Easting (m)	Northing (m)	# Tracer Detections
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	River gauging station at Bertoldo – depicted on river right.			

Station Map ID	103			
				
Riv103_Bertoldo_PB240081.JPG		Riv103-Bertoldo_PB230042.JPG		
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	River gauging station at Bertoldo.			

Station Map ID	104			
				
Riv104_PB240083.JPG (Downstream)				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Example of possible doline collapse features seen along river where part of clay bank has been removed in a semicircular pattern revealing exposed roots. Could also be due to mechanical erosion in river.			

Station Map ID	105			
No Photographs				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	No Notes. Movie: Riv105_PB240084.MP4			

Station Map ID	106			
				
Riv106_PB240085.JPG (Upstream)				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Possible collapse features on river right.			

Station Map ID	107			
				
Riv107_PB240088.JPG (Upstream)		Riv107_PB240089.JPG (Upstream)		Riv107DS_PB240090.JPG (Downstream)
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Strung rope across river at top of bend but narrow channel.			

Station Map ID	108 - *005 from previous day*			
				
Riv108_PB230028.JPG		Riv108_PB230029.JPG (Upstream Side)		Riv108_PB230031.JPG (Downstream Side)
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Hairpin turn in river. Water overflowing bank 1st day (pictured), not on second day. Will create an oxbow at some point.			

Station Map ID	108 - *005 from previous day*


Riv108_PB240092.JPG (lower water)


Riv108DS_PB230032.JPG (Downstream)

Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled

Description	Hairpin turn in river. Water overflowing bank on 1st day, not on second day (pictured) Will create an oxbow at some point.

Station Map ID	004


Riv004_PB230033.JPG

Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled

Description	Looking upstream from bank on river right. At end of access road.

Station Map ID	Grass Doline			
				
Grass_Doline_PB230037.JPG		Grass_Doline_PB230035.JPG		Grass_Doline_PB230036.JPG
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Doline expressed as small circular collapse in sediment in tall grassy area near river.			

Station Map ID	007			
				
Riv007_PB230040.JPG				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Looking downstream from bank on river right near the doline observed in grass field.			

Station Map ID	109			
				
Riv109_PB240093.JPG		Riv109_PB240094.JPG		Riv109_PB240095.JPG
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Conglomerate bank and eddy pool at top of curve. Feature is on river left.			

Station Map ID	110			
				
Riv110_PB240096.JPG				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Drainage feature on river right.			

Station Map ID	111			
				
Riv111_PB240097.JPG		Riv111_PB240098.JPG		
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Horizontal crack in clay bank.			
Station Map ID	112			
				
Riv112_PB240100.JPG (Upstream)		Riv112_PB240101.JPG (Downstream)		Riv112DS_PB240105.JPG (Downstream)
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Sand bar on river right. Site for river injection set 1-3. Movie: Riv112DS_PB240103.MP4			

Station Map ID	LWC			
				
LWC_PB230052.JPG		LWC_PB230053.JPG		
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Low water crossing accessed from mine property roads.			

Station Map ID	Bambuzal			
				
Bambuzal_PB230046.JPG		Bambuzal_PB270166.JPG		Bambuzal_PB270167.JPG
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Stand of bamboo trees on river right. Site of former sinkhole/swallet that was filled in with rock and clay. Strong eddy located at the rock bank created by the fill.			

Station Map ID	Swallet			
				
Swallet_PB270168.JPG		Swallet_PB270171.JPG		Swallet_PB270173.JPG
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Collapse feature taking significant river flow. Located on river left. Site for 2nd PTSA injection.			

Station Map ID	River-Samp			
				
River-Samp_NCM_0369.JPG		River-Samp_NCM_0372.JPG		
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections (U,P,R)**
XXXX	XXXX	XXXX	XXXX	INJ1: 1,9,9 / INJ2: 44,0,47
Description	Stage gauge station with remote real-time camera. Sampling station for river sampling.			

Station Map ID	110			
No Photographs				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Confluence with stream on river left (Barroquinha). Some flow – could not progress upstream for >50 meters.			

Station Map ID	011			
				
Riv011_PC010018.JPG		Riv011_PC010020.JPG		Riv011_PC010026.JPG
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Small sinkhole/swallet on river right. Bank creates dam between river and swallet. River water was lower than top of bank. Substantial flow coming through bank into swallet.			

Station Map ID	012			
				
Riv012_PC010028.JPG		Riv012_PC010030.JPG		
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Rock exposure on river left. Appears to be contact between dolomite and phyllite.			

Station Map ID	013			
				
Riv013_PC010031.JPG		Riv013_PC010032.JPG (Upstream)		Riv013_PC010033.JPG (Axs at eddy)
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**# Tracer Detections**
XXXX	XXXX	XXXX	XXXX	Not Sampled
Description	Rock exposure and strong eddy. Noticeably lees flow in river by this point.			

APPENDIX V
PHOTOGRAPHS AND DESCRIPTIONS OF THE DISCHARGE CHANNEL INSTRUMENTATION

Station Map ID	Discharge Channel	
		
DC01_PB260148.JPG (1st deployment)	DC02_NCM_0316.JPG (exposed at low water)	DC03_NCM_0320.JPG (2nd deployment)
		
DC04_PB270154.JPG (3rd deployment)	DC05_PB270155.JPG (3rd deployment–high water)	DC06_NCM_0376.JPG (3rd deployment-low water)

<table>
<tr><td>Station Map ID</td><td colspan="4">Discharge Channel</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">DC07_PC010009.JPG (Downstream at deployment)</td><td colspan="2">DC08_PC010010.JPG (Downstream at deployment)</td><td>DC09_PB260147.JPG (Downstream from deploy.)</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">DCUS01_PB260151.JPG (discharge from mine)</td><td colspan="2">DCUS02_PC010005.JPG (Upstream at discharge)</td><td>DCUS03_PC010004.JPG (Upstream at discharge)</td></tr>
<tr><td>Latitude</td><td>Longitude</td><td>Easting (m)</td><td>Northing (m)</td><td># Tracer Detections</td></tr>
<tr><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>Not Sampled</td></tr>
<tr><td>Description</td><td colspan="4">Channel conveys all discharge from mine into pipes that go to reservoir downstream of study area in river.
Movie 1: DCUS_PB260149.MP4, Movie 2: DCUS_PB260150.MP4, Movie 3: DCUS_PC010008.MP4</td></tr>
</table>

APPENDIX VI
PHOTOGRAPHS AND DESCRIPTIONS OF THE FLUORESCENT TRACER INJECTIONS IN THE UNDISCLOSED RIVER

Station Map ID	Injection 1-1	
		
INJ1-1_NCM_0331.JPG	INJ1-1_NCM_0333.JPG	INJ1-1_NCM_0334.JPG
		
INJ1-1_NCM_0343.JPG	INJ1-1_NCM_0344.JPG	INJ1-1_NCM_0345.JPG

Station Map ID	Injection 1-1

INJ1-1_NCM_0346.JPG

INJ1-1_NCM_0347.JPG

INJ1-1_NCM_0348.JPG

INJ1-1_NCM_0349.JPG

INJ1-1_NCM_0350.JPG

INJ1-1_NCM_0352.JPG

Station Map ID	Injection 1-1			
				
INJ1-1_NCM_0353.JPG		INJ1-1_NCM_0357.JPG		INJ1-1_NCM_0363.JPG
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**Injection Time**
XXXX	XXXX	XXXX	XXXX	11/28/2013 15:42
Description	Movie 1: INJ1-1_PB270158.MP4 , Movie 2: INJ1-1_PB270159.MP4			

Station Map ID	Injection 1-2			
NO PHOTOGRAPHS				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**Injection Time**
XXXX	XXXX	XXXX	XXXX	11/28/2013 16:32
Description				

Station Map ID	Injection 1-3			
NO PHOTOGRAPHS				
Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**Injection Time**
XXXX	XXXX	XXXX	XXXX	11/28/2013 17:41
Description	Movie1: INJ1-3_PB270163.MP4 / Movie2: INJ1-3_PB270164.MP4 / Movie3: INJ1-3_PB270165.MP4			

<table>
<tr><td>Station Map ID</td><td colspan="4">Injection 2-1</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">INJ2-1_PB290221.JPG</td><td colspan="2">INJ2-1_PB290224.JPG</td><td>INJ2-1_PB290226.JPG</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">INJ2-1_PB290227.JPG</td><td colspan="2">INJ2-1_PB290229.JPG</td><td>INJ2-1_PB290230.JPG</td></tr>
<tr><td>Latitude</td><td>Longitude</td><td>Easting (m)</td><td>Northing (m)</td><td>Injection Time</td></tr>
<tr><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>11/30/2013 15:00</td></tr>
<tr><td>Description</td><td colspan="4">Movie1: INJ2-1_PB290225.MP4 / Movie2: INJ2-1_PB290228.MP4</td></tr>
</table>

<table>
<tr><th>Station Map ID</th><td colspan="5">Injection 2-2</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">INJ2-2_PB290232.JPG</td><td colspan="2">INJ2-2_PB290235.JPG</td><td>INJ2-2_PB290236.JPG</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">INJ2-2_PB290238.JPG</td><td colspan="2">INJ2-2_PB290239.JPG</td><td>INJ2-2_PB290241.JPG</td></tr>
<tr><th>Latitude</th><th>Longitude</th><th>Easting (m)</th><th>Northing (m)</th><th>Injection Time</th></tr>
<tr><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>XXXX</td><td>11/30/2013 15:45</td></tr>
<tr><th>Description</th><td colspan="4">Movie 1: INJ2-2_PB290234.MP4, Movie 2: INJ2-2_PB290237.MP4, Movie 3: INJ2-2_PB290240.MP4</td></tr>
</table>

Station Map ID	Injection 2-3			

		
INJ2-3_PB290246.JPG	INJ2-3_PB290247.JPG	INJ2-3_PB290251.JPG
		
INJ2-3_PB290256.JPG		

Latitude	**Longitude**	**Easting (m)**	**Northing (m)**	**Injection Time**
XXXX	XXXX	XXXX	XXXX	11/30/2013 17:10

Description	PTSA poured directly into swallet flow. No dye escaped to river. Mostly gone <= 1 min. All gone <= 3 min. No movies.

APPENDIX VII
TRACER RECOVERIES IN THE UNDISCLOSED RIVER

APPENDIX VIII
TRACER CONCENTRATIONS MEASURED AT THE UNDERGROUND MINE SAMPLING STATIONS

APPENDIX IX
EMISSION SPECTRA MEASURED IN THE MINE SAMPLES

APPENDIX X
FLUORESCENCE DATA RECORDED BY THE C3 FLUOROMETER AT THE MINE DISCHARGE CHANNEL BETWEEN NOVEMBER 28, 2013 AND JANUARY 7, 2014

APPENDIX XI
TRACER CONCENTRATIONS MEASURED AT THE MINE DISCHARGE CHANNEL AFTER THE NOVEMBER 30 TRACER INJECTIONS

APPENDIX XII
STATISTICAL ANALYSIS OF RIVER FLOWS FOR THE ESTIMATION OF FLOW AT THE ROCHEDO STATION DURING THE NOVEMBER 2013 TRACER EXPERIMENT

APPENDIX XIII
DATA AND EQUATIONS USED FOR THE CALCULATION OF TRACER MASS IN THE UNDISCLOSED RIVER

APPENDIX XIV
DATA AND EQUATIONS USED FOR THE CALCULATION OF URANINE MASS IN THE MINE DISCHARGE CHANNEL

APPENDIX XV
DATA AND EQUATIONS USED FOR THE CALCULATION OF PTSA MASS IN THE MINE DISCHARGE CHANNEL