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TECHNICAL ARTICLE

Is Treatment of Mine Dewatering Water Necessary Prior to Rapid Infiltration Basin Recharge? A Case Study

Andy Davis[1] · Guosheng Zhan[2] · N. Sims[1] · M. Metheny[1] · C. Whitehead[1]

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Abstract
In Nevada, USA, the return of mine dewatering water (MDW) to the subsurface through rapid infiltration basins (RIBs) requires treatment if the quality exceeds the state's Division of Environmental Protection (NDEP) Profile I reference values. However, a 2019 change to the Nevada Administrative Code allows discharge without treatment if the natural background groundwater solute concentrations are not exceeded. We developed a novel approach to demonstrate that groundwater will not be adversely affected by the untreated discharge of MDW. At the Cortez Gold Mine, dewatering will discharge water to the Grass Valley RIBs with 0.045 mg/L of As, exceeding the NV Profile I reference value (0.010 mg/L) and natural background (0.015 mg/L). A MODFLOW-SURFACT groundwater model incorporated empirical hydraulic conductivities to evaluate the extent to which changes in mound water depth and quality would occur. Modeling inputs were determined using column tests to assess SO_4 leaching from the alluvium and batch tests to quantify As partition coefficients ($Kd_{As} = 8.9$ L/kg) to the alluvium. The results indicated that Profile I will be met at all compliance wells due to dispersion and attenuation. The Kd_{As} was also used to calculate the attenuation capacity of the alluvial mound water by adsorption (100-years), well beyond the 13-year operational span of the RIBs. Based on this analysis, and in conjunction with a similar analysis in the adjacent Crescent Valley, where 25 years infiltration of 0.045 mg/L As had not affected groundwater quality, the NDEP concurred that a dewatering water treatment plant was unnecessary. Overall, our analysis obviated construction of four treatment plants in the area and permitted direct discharge of mine dewatering water to the subsurface.

Keyword Infiltration attenuation capacity

Introduction

Nevada Gold Mines LLC—Cortez District (Cortez) operates the Cortez gold mine in the southern part of Crescent Valley in north-central Nevada. The return of mine dewatering water (MDW) to the subsurface through rapid infiltration basins (RIBs) is both an environmentally and economically preferred method to re-infiltrate excess water (Fig. 1) to locally raise the ambient groundwater table (at t_0) to form a mounded water surface (at t_1).

Previously, the Nevada Div. of Environmental Protection (NDEP) required treatment of MDW to manage solute concentrations above Profile I reference values (Profile I) prior to infiltration (e.g., at the Turquoise Ridge mine; RPA 2018). However, a recent (2019) change to the Nevada Administrative Code (NAC) states, "a facility may not degrade the waters of the State to the extent that (for groundwater) the quality is above state or federal regulation for drinking water, or the natural background concentration of the regulated drinking water constituent" (NAC 445A.424).

Cortez proposed to NDEP that the treatment requirement for MDW prior to infiltration in RIBs would be unnecessary if: (1) MDW solutes were below a background concentration that was naturally elevated above their respective Profile I values, (2) percolating solutes could be demonstrated to attenuate to background levels, or Profile I (whichever is higher) within the vadose zone (including the ephemeral mound water (Fig. 1), or (3) that the ambient receiving groundwater concentration exceeded both Profile I and the infiltrated MDW RIB water (mound water). NDEP concurred with these interpretations (NDEP 2018). Therefore,

✉ Andy Davis
andy@geomega.com

[1] Geomega, 2585 Central Ave, Boulder, CO 80301, USA

[2] Barrick Gold, 310 South Main Str, Suite 1150, Salt Lake City, UT 84101, USA

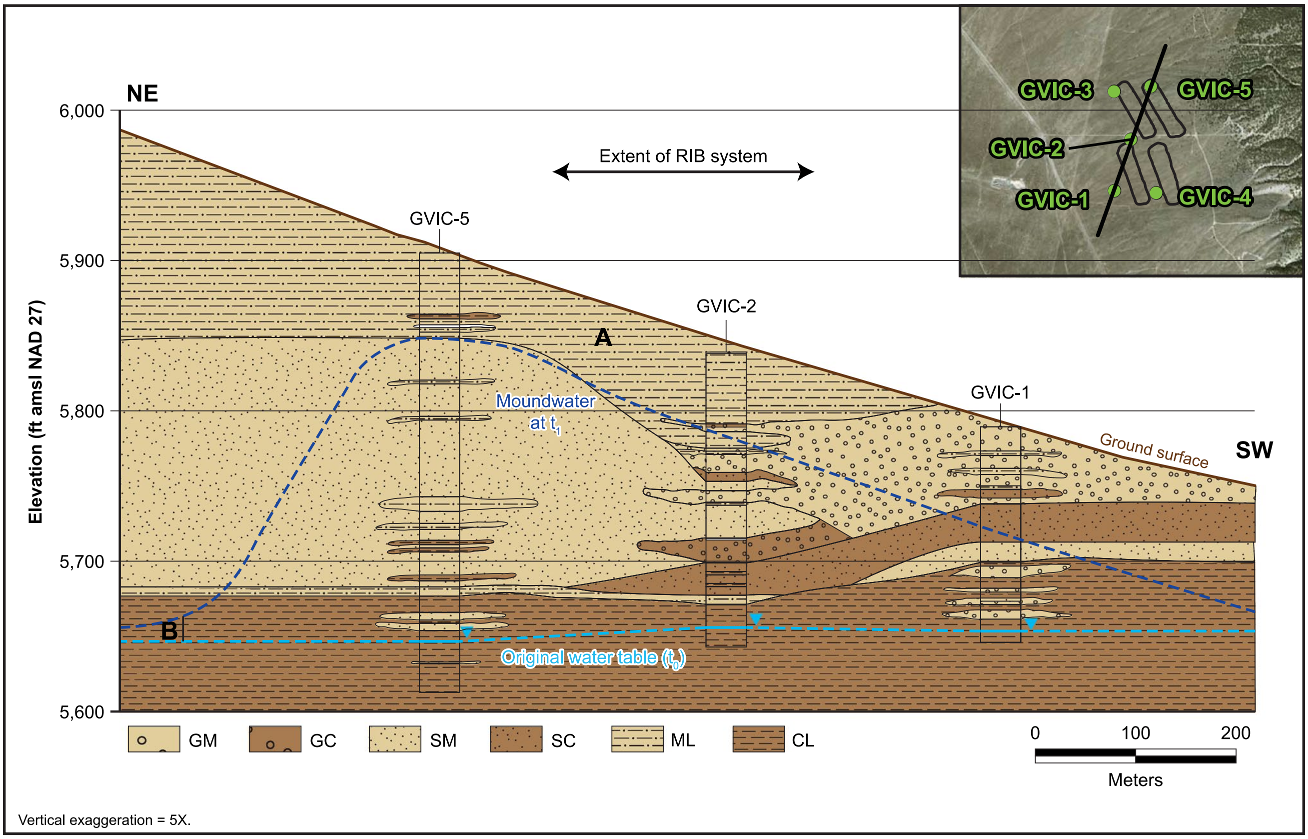


Fig. 1 Alluvial lithology underlying the Grass Valley RIB area showing mound water development

if it could be demonstrated that infiltrating MDW into the Grass Valley RIBs would not cause groundwater to exceed natural background concentrations, there would be no degradation, negating the need for a treatment plant.

This paper describes the testing, analyses, and solute transport simulations that led to the decision regarding the need for a treatment plant for the Grass Valley RIBs. Our approach hinged on a change in the regulatory language that had far-reaching consequences on requirements for treating MDW. This appears to be the first contribution that resulted in an integrated field, hydrogeological, modeling, and geochemical framework to analyze this issue in the closely watched and highly-challenged mining environment.

The RIBs site conceptual model (SCM) was based on the solute concentrations in MDW sent to the RIBs that may evolve by leaching or adsorption during contact with alluvium in the vadose zone (Fig. 1). The SCM initially focused on solutes that exceeded Profile I in either the: (1) MDW, (2) alluvial leachate after interaction between MDW and alluvium, or (3) the receiving groundwater chemistry, which are all important components required to assess the potential for groundwater degradation.

The process developed was to compare the MDW and ambient (pre-RIB) groundwater chemistry (Fig. 2). Next, column tests using MDW determined which solutes (e.g., Cl, F, NO_3, SO_4) might naturally leach from the alluvium, and to what extent. If solutes were sorbed to the alluvium but still exceeded Profile I (e.g., As), batch tests were used to quantify the attenuation coefficients (Kds). A groundwater flow and solute transport model was run using the MDW volumes to compute the extent and elevation of the mound water over time and the transport distance of the solutes of interest. The solute concentrations were compared to Profile I at compliance locations just beyond the mound water extent, defined as 3 m above ambient groundwater elevations (t_0 on Fig. 1). Finally, the empirical Kd was used in conjunction with the mound water volume to compute the available attenuation capacity (in years) that was compared with the life-of-mine to ascertain the potential for impacts to groundwater.

Hydrogeological Framework

The Grass Valley (State of Nevada Hydrographic Area #138) is a topographically closed ≈ 1530 km^2 basin that is ≈ 64 km long and 29 km wide. The Grass Valley RIBs are located ≈ 3 km south of the Cortez Hills Complex (Fig. 3) on the western edge of the Cortez Mountains at an elevation of

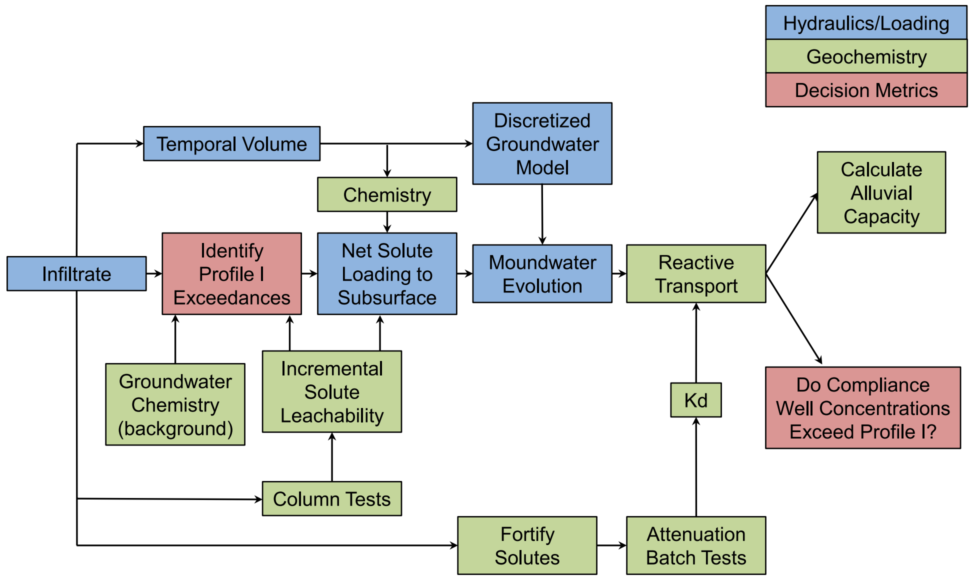


Fig. 2 RIB permitting technical elements

≈ 1760 m amsl. The 600 × 300 m RIBs gallery will comprise four 270 × 24 m (base dimension) basins that will infiltrate up to 3220 L/min total dewatering water. Each basin will be excavated at > 6 m below ground surface (bgs) prior to use to minimize dissolution of shallow soluble playa salts.

In Grass Valley, the Quaternary-age alluvium consists of material derived from the Hamburg dolomite, Eureka quartzite, Hanson Creek Formation, and Roberts Mountains limestone. It is a heterogeneous mix of gravels, sands, silts, and clays in lenses with little lateral continuity. The facies include alluvial fans along the base of the mountain ranges that consist of unsorted to poorly sorted clay, silt, sand, gravel, and boulders, sorted to well-sorted fine-grained material (clay and silt), and interbedded coarse-grained material (sand and gravel) lacustrine and stream-channel deposits (Fig. 1). Large areas of playa with elevated salt content occupy the north-central parts of the basin. The RIBs will be constructed at the head of the alluvial fan deposits where the drainage and depth to groundwater (> 30 m) are favorable and playa salts are less abundant.

Materials and Methods

Hydrogeologic Tests

Five rotosonic bores drilled to characterize the RIBs site (Fig. 3) intercepted groundwater from ≈ 41–79 m below ground surface (bgs). Cores from the boreholes were logged for material type, including the gravel/sand/silt/clay distribution, by site geologists and sampled for column testing.

Constant head tests were completed in the upper 30 m of the five Grass Valley RIBs bores to assess the potential for water infiltration and to estimate field-saturated hydraulic conductivity K_{fs} values. Each hole was drilled to 12 m bgs, then a 12 m long, 9 cm diameter slotted PVC casing and vibrating wire piezometer (VWP) were installed to run a constant-head infiltration test, after which the PVC screen was retracted, and drilling resumed to 30 m bgs. At that depth, 30 m of slotted PVC and a VWP installed and another constant-head infiltration test run. Subsequently, the PVC casing was retracted, and drilling resumed to groundwater, where a water sample was collected, field filtered (0.45 µm), and preserved for dissolved metals (to determine the baseline groundwater quality). The borehole was then abandoned following Nevada regulations.

The hydraulic conductivity (K) of the Grass Valley infiltration complex (GVIC) was estimated using constant-head borehole permeability tests by filling the casing with clean, sediment-free water to the ground surface and maintaining a constant ground-surface water level, while measuring the inflow rate. Subsequently, field-saturated hydraulic conductivity (K_{fs}) values from the constant-head tests were computed using the closely related and widely studied solutions of Glover (1953), Philip (1985), the Reynolds half-source (Reynolds et al. 1983), Stephens and Neuman (1982), and Zangar (1953). These methods assume a wetting area adjacent to the borehole, allowing calculation of a "free surface" solution.

Twenty-six samples from different depths in bores GVIC-1 (5), GVIC-2 (5), GVIC-3 (6), GVIC-4 (5), and GVIC-5 (5) were analyzed for particle size distribution (Supporting Information Appendix S-1) using sieve screen sizes of 5 cm, 4 cm, 2.5 cm, 2 cm, 1.3 cm, 4.76 mm (#4), 2.38 mm (#8), 2.00 mm (#10), 1.19 mm (#16), 0.595 mm (#30), 0.420 mm (#40), 0.297 mm (#50), 0.149 mm (#100), and 0.074 mm (#200), and hydrometer delineations of 0.0265 mm, 0.0183 mm, 0.0114 mm, 0.0084 mm,

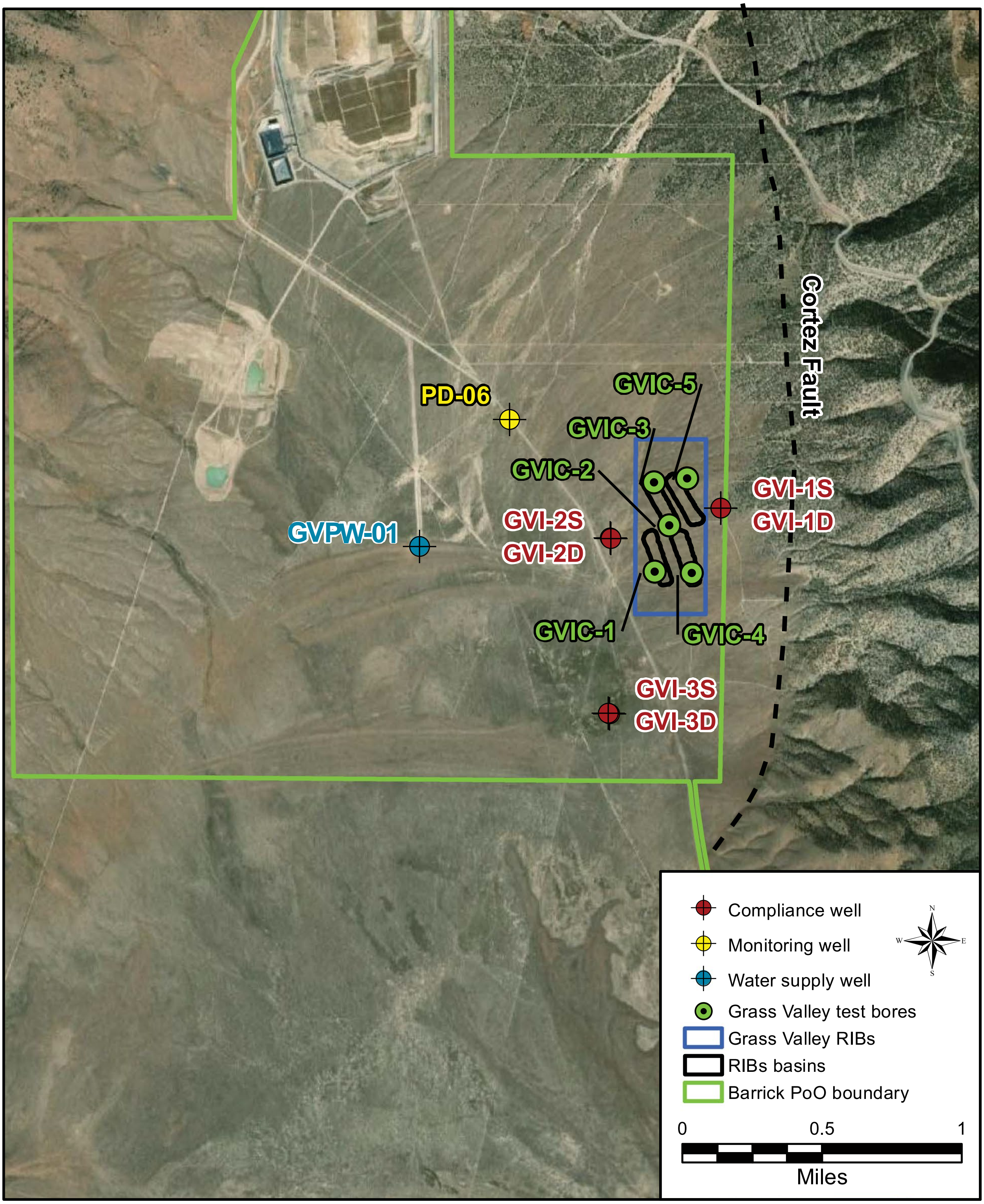


Fig. 3 Location of RIBs, boreholes and monitoring wells in Grass Valley

0.0062 mm, 0.0032 mm, 0.0014 mm, and 0.0010 mm. The mechanical or sieve analysis (ASTM D422-63 2007) determined the distribution of the coarser, larger-sized particles, while a hydrometer was used to determine the distribution of the finer particles.

In addition to the existing PD-06, 6 compliance wells (GVI-1S, GVI-2S, GVI-3S, GVI-1D, GVI-2D, and GVI-3D) were constructed in 2018 within the predicted > 3 m mounding area of the Grass Valley RIBs (Fig. 3). The well pairs were screened 12 m across the future predicted shallow mound water elevation and 9–30 m across the current groundwater elevation to facilitate monitoring of the evolving mound water level and quality (Fig. 3).

Geochemical Tests

The MDW scheduled for infiltration in the Grass Valley RIBs will come from dewatering of the Cortez Hills mine complex. Water from the dewatering manifold was used as the lixiviant to, 1) assess the potential for leaching of major ions (e.g., Ca, NO_3, and SO_4) from the alluvium, and 2) test the hypothesis that attenuation of trace metals will occur in the alluvium exposed to the dewatering water. It was used in both column and batch tests (Table 1).

Column tests were run following ASTM method D4874-95 (ASTM 2014) to evaluate the potential for As to leach from and/or adsorb to the alluvium and to qualitatively determine if adsorption occurred; if so, batch tests (EPA 1992) were used to quantify the partition coefficients (Kd_{As}).

Column Tests

The alluvium below the Grass Valley RIBs was evaluated at three intervals, a shallow layer of alluvium directly below the base of the RIBs (6–12 m bgs), mid-level (18–30 m bgs), and a deep interval (12 m) above the groundwater, recognizing that the groundwater depth is variable (36–80 m bgs) with respect to the ground surface in the boreholes. Each sample (≈ 4 kg) was packed in a 0.3 × 0.1 m diameter column and flushed with Cortez Hills Complex dewatering water (Table 1) at a rate analogous to that anticipated during RIBs operation (≈ 1.4 mL/min based on historical RIBs use in Crescent Valley; Geomega 2007). Samples were collected for Profile I analyses at ≈ 0.4, 2, 4, and 8 pore volumes (PVs), with subsequent PVs analyzed only for As because all other solutes had decreased to their influent concentrations.

Batch Tests

The alluvium was contacted with groundwater containing seven different As concentrations in separate containers to generate a curve demonstrating the extent to which As will partition to the alluvial matrix. The linear regression describing As lost from solution defined the partition coefficients that were subsequently used in solute transport modeling and attenuation capacity calculations.

Batch reactors (polypropylene bottles) were assembled with 200 g (dry weight) of alluvium and leached with 200 mL of dewatering water containing 0.004–0.28 mg/L As. Splits of alluvium used in the column tests, from the shallow, intermediate and deep intervals, were mixed with the As-spiked dewatering water and rotated for 72 h. (Roy et al. 1992). The aqueous supernatant was filtered through a 0.45 µm in-line filter and analyzed for As. The adsorbed concentration was calculated as the difference between the initial and final solute concentration. Temperature, pH, Eh, and specific conductance were measured at the bench.

Table 1 Groundwater chemistry (mg/L) from the dewatering manifold used in the column and batch experiments

Parameter	Column blank	Profile I	Influent
Aluminum	< 0.08	0.2	< 0.08
Antimony	< 0.003	0.006	**0.0063**
Arsenic	< 0.003	0.01	**0.045**
Barium	< 0.002	2.0	0.12
Beryllium	< 0.002	0.004	< 0.002
Bicarbonate	< 1	–	179
Boron	< 0.04	–	0.14
Cadmium	< 0.002	0.005	< 0.002
Calcium	0.1	–	39
Carbonate	< 1	–	< 1.0
Chloride	< 0.2	400	23.6
Chromium	< 0.006	0.1	< 0.006
Copper	< 0.01	1.0	0.0102
Fluoride	< 0.01	4.0	0.72
Iron	< 0.01	0.6	< 0.1
Lead	< 0.003	0.015	< 0.003
Magnesium	< 0.50	150	17
Manganese	< 0.008	0.10	0.0155
Mercury	< 0.0002	0.002	< 0.0002
Nickel	< 0.01	0.1	< 0.01
Nitrate/Nitrite as N	< 0.05	10	0.30
Nitrogen, Total as N	< 0.55	10	< 0.55
pH[a]	5.1	6.5–8.5	7.9
Potassium	< 0.05	–	6.82
Selenium	< 0.003	0.05	< 0.003
Silver	< 0.005	0.1	< 0.005
Sodium	< 0.5	–	36.2
Sulfate as SO_4	< 0.3	500	52.7
Thallium	< 0.001	0.002	< 0.001
TKN	< 0.5	–	< 0.5
Total Alkalinity	< 1.0	–	179
Total Diss. Solids	< 10	1000	309
Uranium	< 0.001	–	0.0013
Zinc	< 0.01	5	< 0.01

Results above Profile I in bold

NA not analyzed

[a]Standard units

Results

Ambient Groundwater Quality

Under pre-mounding conditions, the deep monitoring wells (GVI-1D, GVI-2D, GVI-3D, and PD-06) intersect the water table while the shallow wells (GVI-1S, GVI-2S, GVI-3S) were dry. Groundwater in the compliance wells was sampled for three quarters (Appendix S-2), generally meeting Profile I, with the pH consistently between 8.3–8.7 and 280–340 mg/L of total dissolved solids (TDS), dominated by alkalinity (164–209 mg/L), Ca (35–54 mg/L) and SO_4 (55–59 mg/L). Water quality in the compliance wells was consistent with that of PD-06 (Fig. 3). Arsenic was occasionally detected in GVPW-01 at 0.015 mg/L (above Profile I) in 2014.

The groundwater used in the experiments (Table 1) was collected from the system that will provide the future RIBS discharge and was alkaline (179 mg/L $CaCO_3$) with a circumneutral pH (7.9) and low TDS (309 mg/L). Sulfate was also low (52.7 mg/L), while As (0.045 mg/L) exceeded Profile I (0.01 mg/L) in the dewatering water from this portion of the site, with all other solutes meeting Profile I.

Column Tests

The full suite of Profile I solutes was measured in the effluent for the first 8 or 9 pore volumes (Appendix S-3), beyond which analyses were limited to As. Several solutes were flushed from the shallow alluvial column at concentrations above Profile I. The first PV contained SO_4 (2320 mg/L; Fig. 4a), Cl (1610 mg/L), Mg (272 mg/L), and NO_3 (11.1 mg/L; Fig. 4b). These rapidly decreased in PV 2 (128, 31, 4, and < 0.55 mg/L respectively), reaching steady state at the influent concentration by PV 4.

Every effluent sample collected contained less As (Fig. 5a) than the influent, demonstrating that As was consistently attenuated by the alluvium. Arsenic was the only solute in the effluent that was above Profile I for the two lower depth intervals (mid- and deep intervals). The sample of Grass Valley alluvium from the mid-interval was analyzed for 51 PVs before As increased to 0.011 mg/L, while the deep interval sample was analyzed for 20 PVs before As increased to 0.011 mg/L (Fig. 5a) in the shallow interval. Nevertheless, 75% of the influent As mass was retained in the column. Arsenic declined to < 0.01 mg/L by PV 12 through 22 (Fig. 5a). The column tests demonstrated that the alluvium below the RIBs and in the mound water zone have a strong affinity for adsorption of As.

Batch Tests

There was a strong correlation between adsorbed and soluble As (Fig. 5b) for the Grass Valley 10–20 m bgs ($r = 0.97$), 20–40 m bgs ($r = 0.95$), and 12 m above the groundwater ($r = 0.77$) materials. Linear regressions (Deutsch 1997) fit to these data sets resulted in a Kd_{As} of 8.9–11.8 L/kg (Table 2), consistent with Baes and Sharp (1983) who reported 1.9–18 L/kg for As attenuation by 37 clay or agricultural soil samples over the pH range of 4.5–9.0, and proposed an aggregate value of 6.7 L/kg.

Discussion

Numerical Modeling

The Four-Basin groundwater flow and solute transport model (SRK 2018) is a *MODFLOW-SURFACT,* version 4 (HGL 2011) three-dimensional (3-D) finite-difference groundwater flow model used to predict and manage groundwater in the Cortez Mine Complex area. The model area includes four hydrographic basins (the Grass, Crescent, Carico, and Pine Valleys). The graphical user interface Groundwater Vistas, version 7 (ESI 2011), was used to develop input files and process model results. The model was used to predict both the extent of the groundwater mound from the RIBs to a perimeter where the incremental mounding height was ≈ 3 m, and the evolving As and SO_4 concentrations downgradient from the RIBs.

Grid Refinement for RIBs Infiltration

The 138 row, 189 column, 28-layer model was re-discretized in the Grass Valley RIBs area by adding 21 rows and 112 columns to represent the groundwater mound height more precisely and to eliminate numerical dispersion in the solute transport simulations. The refined mesh ranged from 57 × 61 m in the vicinity of the RIBs basins to 122 × 190 m downgradient of the RIBs. The monthly input and output flows were modeled over the 13-year RIB operational period.

Model Hydraulic Conductivity

Changes to the distribution of hydraulic parameters in the area of the Grass Valley RIBs were partly based on the bore constant head test results (Appendix S-4), and partly on the ability to refine parameter distribution within the refined grid. The lateral hydraulic conductivity ($K_{x,y}$) of the younger basin-fill was set at 15 m/day and the vertical hydraulic conductivity ($K_{v)}$) to 7.6 m/day. The older basin-fill was assigned a lower hydraulic conductivity ($K_{x,y}$ of 0.76 m/day and K_v of 0.076 m/day). Younger basin-fill,

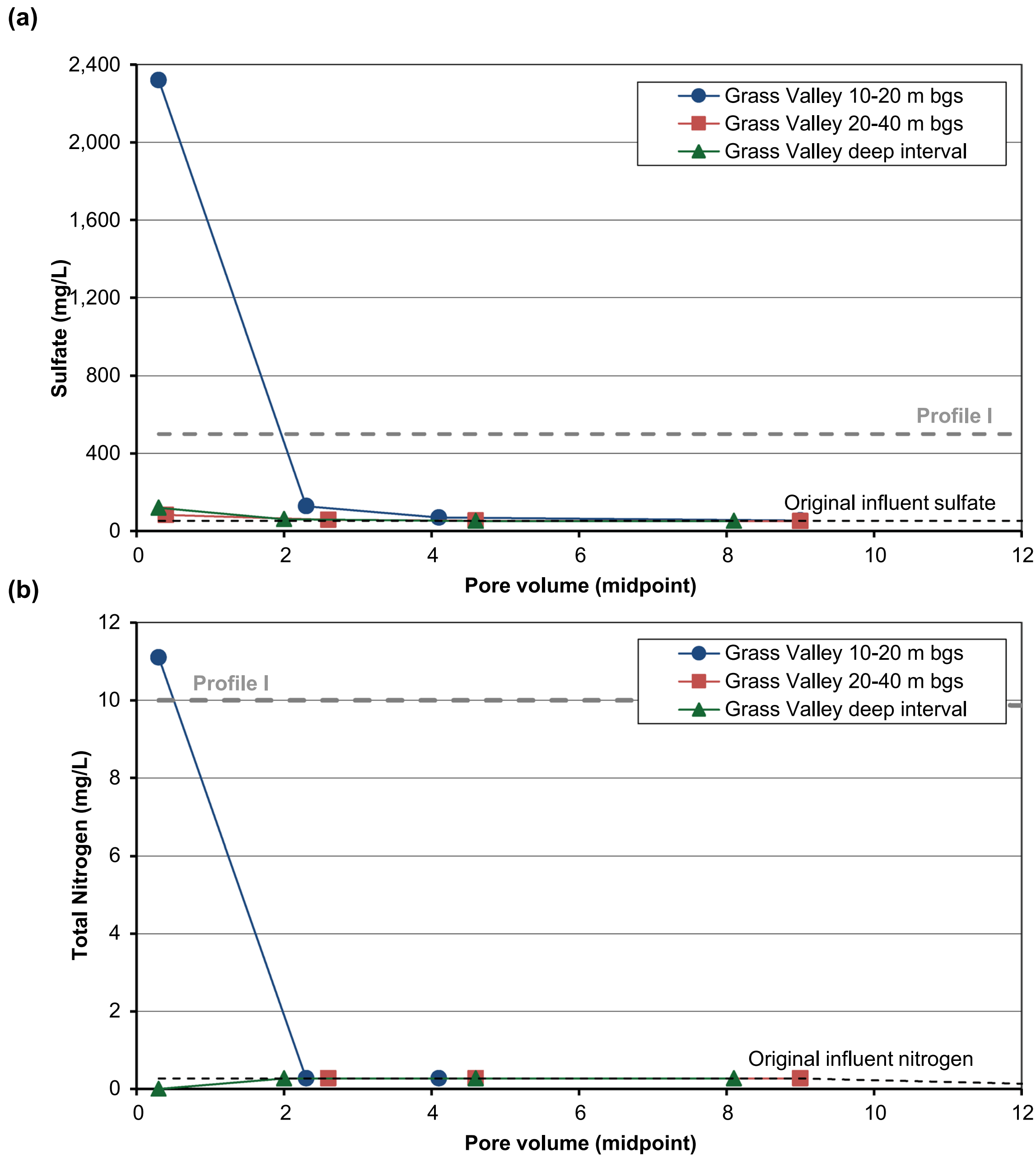


Fig. 4 **a** Sulfate and **b** nitrogen released from Grass Valley alluvial columns

where infiltration will occur, overlies the older basin-fill in the RIBs area and increases in thickness toward the central region of Grass Valley.

The changes were extensive enough to encompass the Grass Valley RIBs mounding, but sufficiently local to not require model recalibration. The flows and water levels between the Four-Basin calibrated model (1996–2017) and the Grass Valley RIBs model compared well with flows in and out of the refined model (within 0.2% of the original model). The overall RMSE of the refined Four-Basin model was within 1 m of the transient calibrated model (1996–2017) and the overall scaled RMSE of the refined model was within 0.044% of the transient calibrated model (1996–2017), indicating that the simulated water levels in the two models were similar. Observed versus calculated water levels ($r = 0.99$) in the revised Four-Basin model for the calibration period October 2014 through 2016 (Fig. 6) demonstrated that the refined model was accurate.

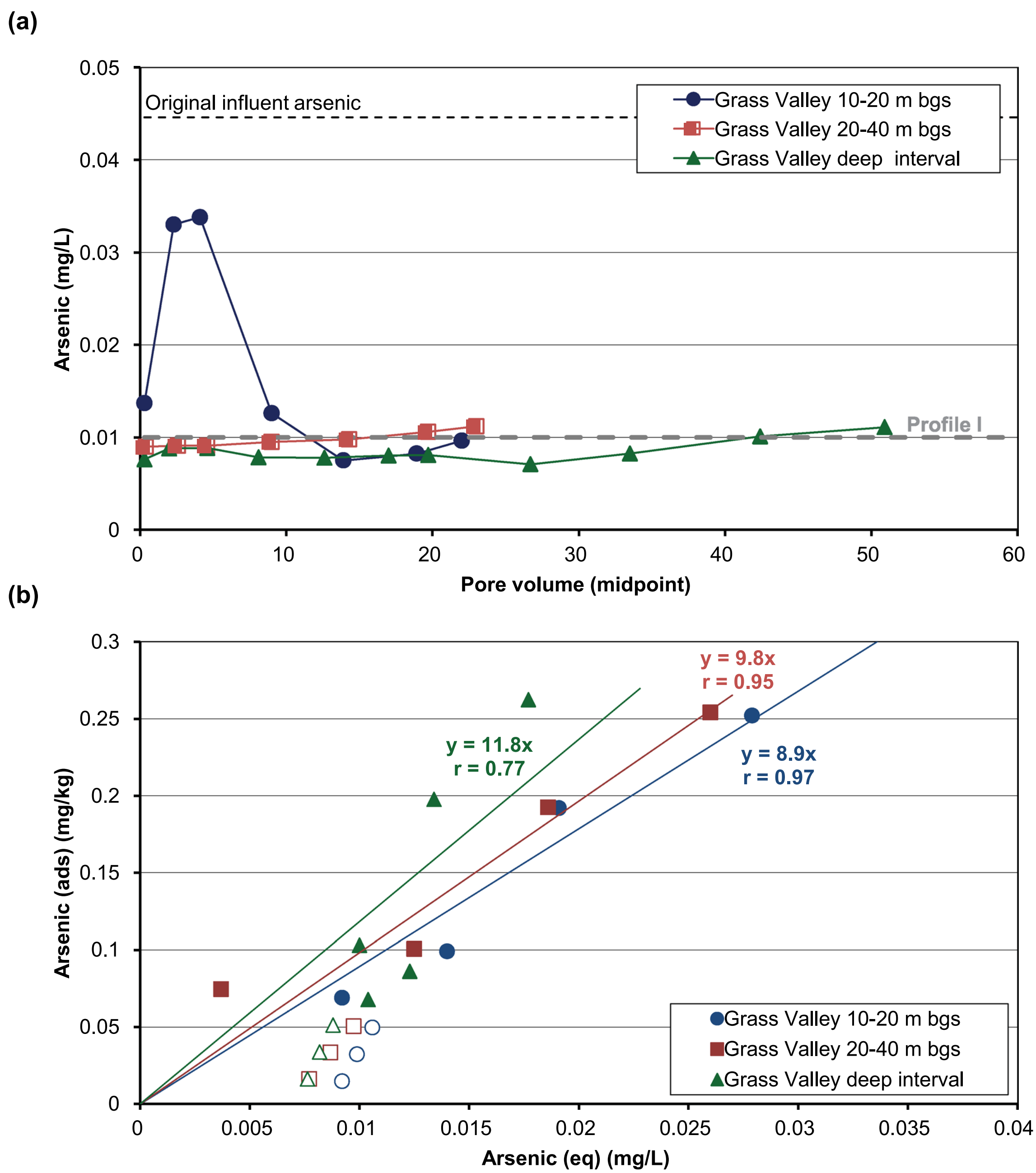


Fig. 5 **a** Arsenic retention by Grass Valley alluvial columns (open symbols are non-detect values), and **b** linear regression of arsenic batch attenuation (open symbols represent desorption from storage)

Transport Modeling

A solute loading term was applied in the refined Four-Basin model to evaluate the impacts of RIBs on natural groundwater. Each 1-month stress period (equivalent to ≈ 6 PVs in the column testing), was assigned concentrations based on the column leachate concentrations. The As partition coefficient (Kd_{As}) was used to simulate attenuation, while SO_4 was assumed to be non-reactive with alluvium and a proxy for Cl and NO_3 that also leached from alluvium columns in PV #1 at lower concentrations.

The transport solver total variation diminishing (TVD) scheme (HGL 2011) is a numerical solution that conserves mass, eliminating the effect of numerical dispersion. The TVD scheme requires longer run-times but was selected because a sharp solute front was preferred over a faster solution because the transport domain is dominated by advective flow. The adaptive time-stepping (ATO)

Table 2 Arsenic and antimony concentrations in the batch testing experiments

Sample	As influent (mg/L)	As final (mg/L)	As adsorbed (mg/kg)	% As adsorbed	Sb influent (mg/L)	Sb final (mg/L)	Sb adsorbed (mg/kg)	% Sb adsorbed	pH
Grass valley 20–40'	0.28	0.0279	0.25	90	0.0586	0.0206	0.038	65	8.30
	0.211	0.0191	0.19	91	0.0373	0.0132	0.024	65	8.39
	0.113	0.014	0.10	88	0.021	0.00801	0.013	62	8.38
	0.0985	Not analyzed (sample mass limitation)			0.0174	Not analyzed (sample mass limitation)			
	0.0782	0.00921	0.07	88	0.0141	< 0.00300	Non-detect value	79	8.42
	0.0601	0.0106	0.05	82	0.0107	0.00488	0.006	54	8.33
	0.042	0.00989	0.03	76	0.00738	0.00399	0.003	46	8.40
	0.0239	0.00922	0.01	61	0.00398	0.00306	0.001	23	8.30
	0.00438	0.00861	No attenuation		< 0.0030	< 0.00300	Non-detect values		8.29
Grass valley 60–100'	0.28	0.026	0.25	91	0.0586	0.02	0.039	66	8.25
	0.211	0.0186	0.19	91	0.0373	0.0124	0.025	67	8.37
	0.113	0.0125	0.10	89	0.021	0.00749	0.014	64	8.38
	0.0985	Not analyzed (sample mass limitation)			0.0174	Not analyzed (sample mass limitation)			
	0.0782	0.0037	0.07	95	0.0141	< 0.00300	Non-detect value	79	8.32
	0.0601	0.00975	0.05	84	0.0107	0.00473	0.006	56	8.44
	0.042	0.00869	0.03	79	0.00738	0.00378	0.004	49	8.35
	0.0239	0.00772	0.02	68	0.00398	< 0.00300	Non-detect value	25	8.29
	0.00438	0.00759	No attenuation		< 0.0030	< 0.00300	Non-detect values		8.34
Grass valley 40' above GW	0.28	0.0177	0.26	94	0.0586	0.0155	0.043	74	8.25
	0.211	0.0134	0.20	94	0.0373	0.0103	0.027	72	8.26
	0.113	0.01	0.10	91	0.021	0.00693	0.014	67	8.35
	0.0985	0.0123	0.09	88	0.0174	0.00615	0.011	65	8.35
	0.0782	0.0104	0.07	87	0.0141	< 0.00300	Non-detect value	79	8.33
	0.0601	0.0088	0.05	85	0.0107	0.00522	0.005	51	8.40
	0.042	0.00819	0.03	81	0.00738	0.00465	0.003	37	8.28
	0.0239	0.00763	0.02	68	0.00398	0.00396	0.000	1	8.26
	0.00438	0.00769	No attenuation		< 0.0030	0.00372	Non-detect value		8.31

package (HGL 2011), used in conjunction with the TVD scheme to control time-step size, was set at a maximum equal to the stress period length.

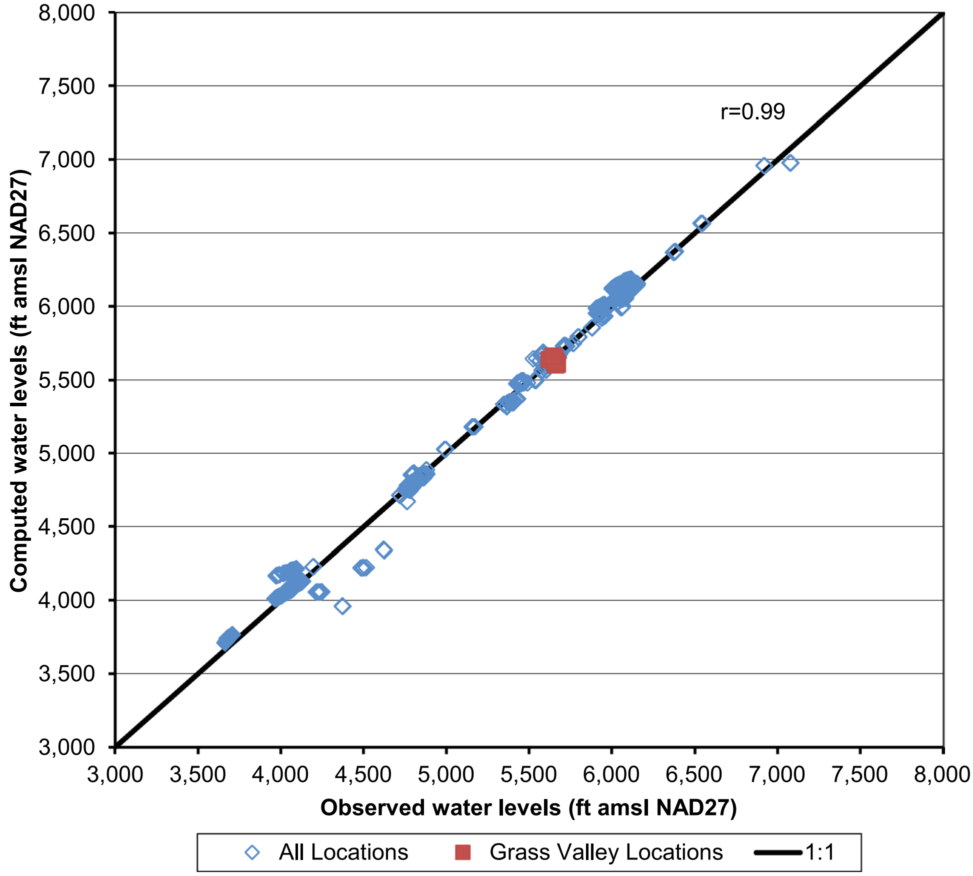
The specific yield (20%) was adopted in both young and old basin-fill material transport calculations. The longitudinal (α_x), transverse (α_t), and vertical (α_v) dispersivity transport parameters used to model the advancing solute front ahead of the advective front were set at 50, 5, and 0.5, respectively. The longitudinal dispersivity was estimated using the method of Xu and Eckstein (1995), whereas the transverse and vertical values were assigned typical values of 0.1 and 0.01 of the longitudinal value (Zheng and Bennett 2002). The Courant criterion and Peclet number for the area of transport were within acceptable values (Appendix S-5).

Vadose Zone Leachate Draindown

The initial column effluent 2320 mg/L SO_4 (Fig. 4a) from the uppermost alluvium (10–20 m bgs) was conservatively applied in the transport model, although the average SO_4 through the first stress period of 30 days in the model (equivalent to 6.2 PVs) was 437 mg/L. The column and batch tests demonstrated that no incremental As would be flushed from the alluvium into the RIBs infiltrate. Therefore, vadose zone flushing of As was excluded.

To determine the volume of leached alluvium, it was assumed that the alluvium immediately beneath the RIBs (the 6–12 m interval that leached 2320 mg/L SO_4) within the entire 60 × 30 m RIBs basin footprint would contribute SO_4 to the mound water (the mid- and deep intervals

Fig. 6 Comparison of observed and simulated water levels at the end of the transient calibration period



were <≈ 100 mg/L; Fig. 4a). This meant that the volume of wetted alluvium corresponding to the Grass Valley (6–12 mbgs) column will be:

$$\text{Wetted volume} = 6\ \text{m} \times 600\,\text{m} \times 300\,\text{m} = 1.13 \times 10^7\ \text{m}^3 \tag{1}$$

One PV is equivalent to the amount of pore space (assuming ≈ 20% porosity) in the wetted volume; therefore, the vadose zone prism pore volume will be:

$$\text{Pore volume} = 1.13 \times 10^7\ \text{m}^3 \times 20\% = 2.26 \times 10^8\ \text{L} \tag{2}$$

The flow rate entering the alluvium is:

$$\text{Flow rate (L/day)} = 3220\ \text{Lpm} \times 1440\ \text{min}/\text{day} = 4.64 \times 10^7\ \text{L/day} \tag{3}$$

The number of PVs flowing through the wetted volume within the first model stress period of 30 days will be:

$$\text{Pore volumes per stress period} = 30\ \text{days} \times \frac{4.64 \times 10^7\ \text{L/day}}{2.26 \times 10^8\ \text{L/PV}} = 6.2\ \text{PVs} \tag{4}$$

After ≈ 6.2 PVs, the column test effluent SO_4 approximated the influent SO_4, so subsequent stress periods were assigned the influent water quality (≈ 55 mg/L SO_4).

Modeling RIB Operations

The model was run under two scenarios, a no-action simulation assuming no infiltration at the RIBs, while the second had an applied RIBs infiltration rate of 3220 L/min with infiltration beginning in 2020 and continuing at a constant rate until the end of 2032.

RIBS Mounding

The height and extent of the mound water was determined by subtracting the “no infiltration” water table from the Grass Valley RIBs infiltration water table at the end of infiltration in 2032 (Fig. 7). The highest mound elevation (≈ 37 m above baseline) will be directly beneath the RIBs (Fig. 8). The mound will extend to the northwest, west, and south, but will be limited to the east by bedrock and the southeast trending, porous Cortez Fault zone, resulting in an extension of the 3 m contour to the north and southeast of the main mound. To the north and east of the

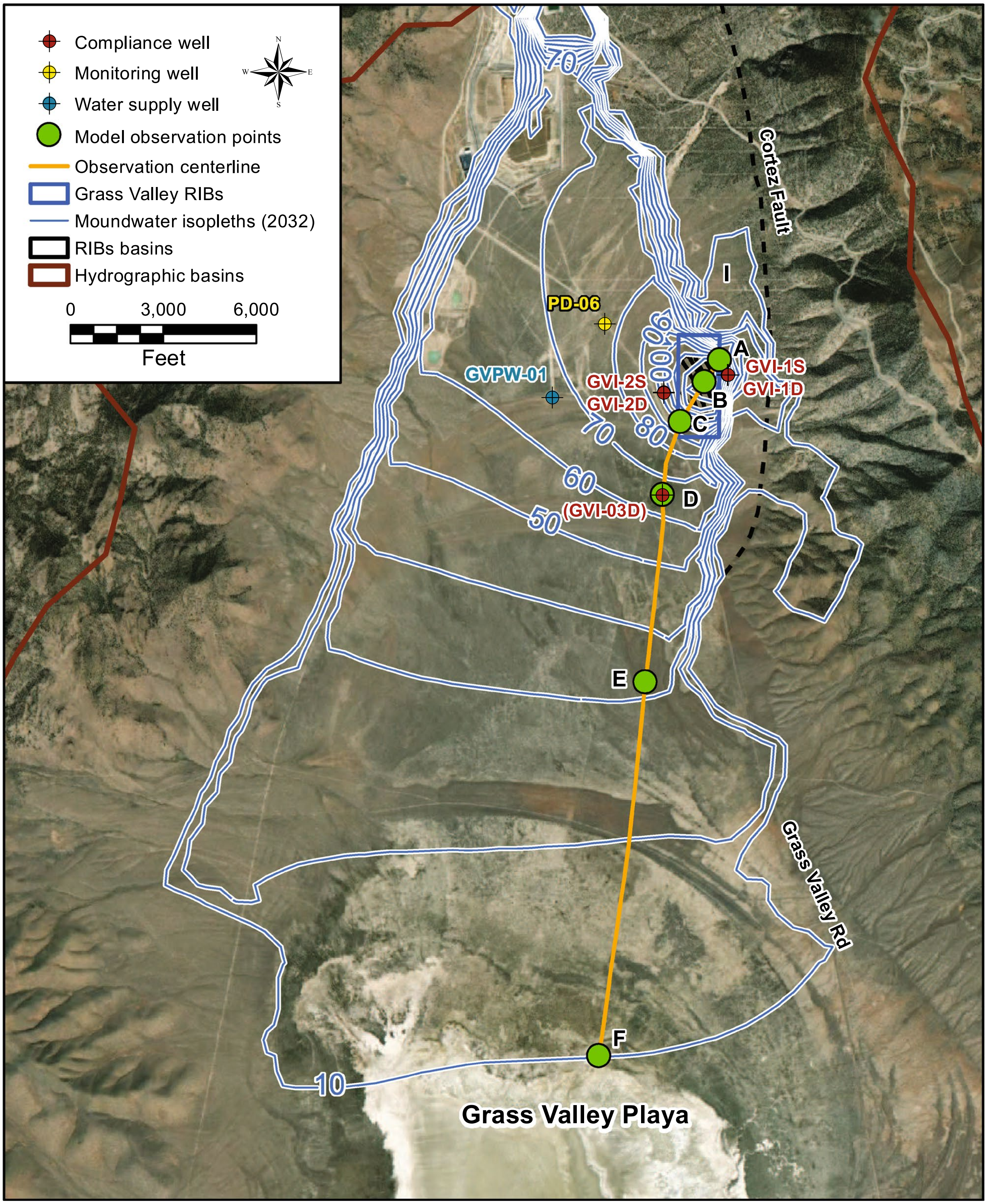


Fig. 7 Predicted extent of the RIBs-derived 10 ft mound water extent at the end of 2032. The transect A–F is shown on Fig. 8

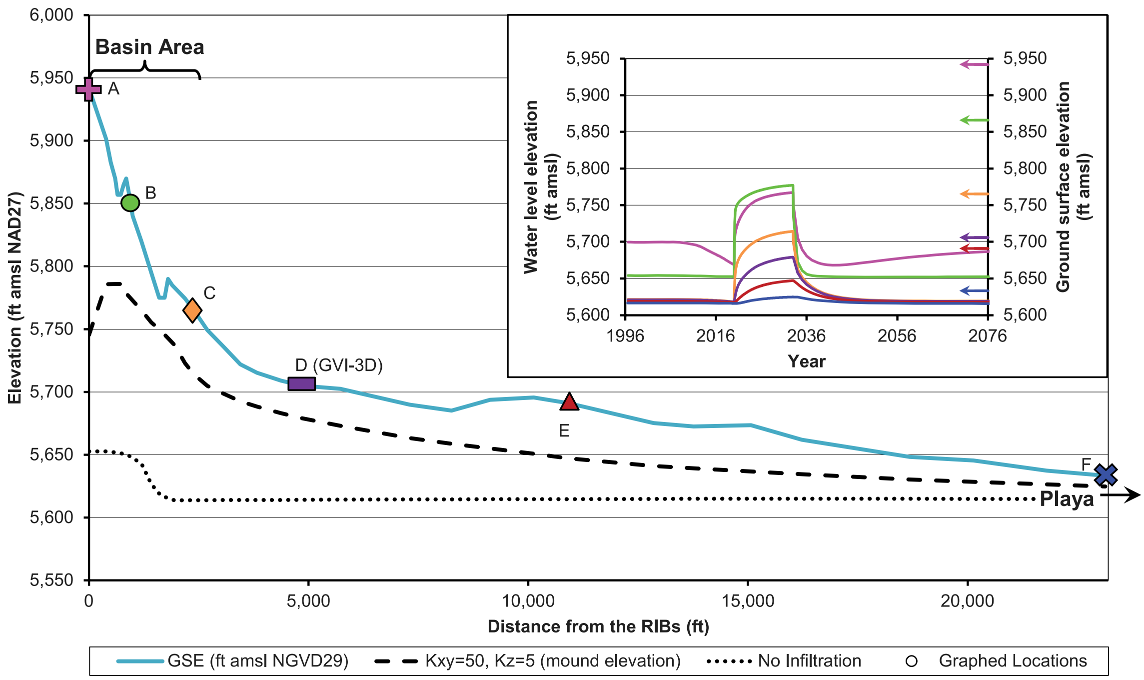


Fig. 8 Profile of water levels along the centerline A–F of Fig. 7 at the end of 2032. The inset (color coordinated by location and symbol shows the evolving mound water elevations at locations downgradient from the RIBs

RIBs, the water levels will not rise during RIB infiltration because there will be continued drawdown from dewatering at the adjacent Cortez Hills Complex, resulting in an aggregate decreased rate of drawdown.

The mound profile from the RIBS through compliance well GVI-3D and beyond (Fig. 8) represents the water levels at the end of 2032. It extends topographically upslope from the RIBs basins (A) to the Grass Valley playa where the mound height will be ≈ 3 m. The mound is highest at the RIBs (≈ 1770 m amsl), declining downgradient and approaching (within 3 m) the ground surface in the downslope direction. The water-table profile for the "no infiltration" simulation at the RIBs is also shown for comparison and remains relatively flat (≈ 1700 m) in the central portion of Grass Valley.

The mound will develop over time but remain ≈ 9 m below the base of the RIBs (Fig. 9 inset). Water levels continuously rise over the entire infiltration period, although the rate of mounding diminishes over time as steady state is approached, demonstrated by the declining elevations with distance downgradient from the RIBs. After RIBs use ceases, the mound declines rapidly within the first four to five years, then decreases gradually for ≈ 12 years as the groundwater elevations stabilize. The long-term trend, after 2050 will be a rise in water levels as the Cortez Hills Complex cone of depression recovers.

Solute Loading and Transport

Sulfate

Sulfate was imposed at 2320 mg/L for the first 30-day stress period and 55 mg/L thereafter. The initial leached SO_4 (2320 mg/L) migrates directly beneath the RIBs basins after the first 30-day stress period, decreasing substantially by the end of the next stress period (60 days after infiltration begins) to 63 mg/L. Because the infiltrate will always contain ≈ 55 mg/L SO_4 that leached from the alluvium in the first month will increase the concentration to 2320 mg/L, but will be diluted to < 250 mg/L within the first year, as the mound water reaches location F (Fig. 8), the anticipated mound water boundary defined by a 3 m elevation increase. The continued infiltration of ≈ 55 mg/L SO_4 through 2033 will further dilute SO_4, which will remain below Profile I at location F.

To the east of the RIBs at A, SO_4 reached a maximum of 917 mg/L at the end of the first 30-day stress period, but subsequently decreased to < 500 mg/L. In the center of the RIB area at B, the initial 30-day maximum SO_4 (≈ 2266 mg/L) is similar to that directly beneath the RIBs, with SO_4 decreasing below Profile I after the first 60 days. Further downgradient, at D through F, SO_4 is not anticipated to exceed Profile I.

Fig. 9 Calculations of alluvial arsenic attenuation capacity clour coordinated for ease of interpretation

$$Local\ Capacity = \frac{mg/kg}{mg/L} = Kd_{As} * dissolved\ As\ = 8.9\,\frac{L}{kg} * 0.01\,\frac{mg}{L} = \mathbf{0.089}\,\frac{mg}{kg}$$

$$Alluvial\ bulk\ density, \rho_b = s.g.\,2.41\,\frac{g}{cm^3}\,(1 - 0.326) = 1.62\,\frac{g}{cm^3} = \mathbf{45.9}\,\frac{kg}{ft^3}$$

4.13×10^8 m^3 of alluvium (model) x $\mathbf{1.62 \times 10^8}\,\frac{kg}{m^3}$ = $\mathbf{6.7 \times 10^{11}}$ kg in the moundwater

$$Field\ As\ capacity = \mathbf{6.7x10^{11}}kg \times \mathbf{0.089}\,\frac{mg}{kg} = \mathbf{5.96x10^4}\ kg\ As$$

$$As\ requiring\ adsorption = \left(0.045\,\frac{mg}{L}\ As\right) - \left(0.010\,\frac{mg}{L}\ Profile\ I\right) = \mathbf{0.035}\,\frac{mg}{L}$$

The annual infiltrate rate is 3,220 Lpm = $\mathbf{1.7x10^{10}}$ L infiltrate per year:

$$Annual\ As\ retention = \mathbf{1.7x10^{10}}\,\frac{L}{yr} \times \mathbf{0.035}\,\frac{mg}{L}\ As = \mathbf{594}\,\frac{kg}{yr}\ As$$

$$As\ Retention\ Lifespan\ (years) = \frac{\mathbf{5.96x10^4}\ kg}{\mathbf{594}\,\frac{kg}{yr}}\,As = 100\ years$$

Arsenic

Arsenic mass loading was applied at four infiltration locations using the fracture well (FWL4) package in *MODFLOW-SURFACT* over 13 years. Each location received 25% of the RIBs discharge (a total of 3220 L/min). Infiltration and solute loading began Jan. 1, 2020, and continued at a constant 3220 L/min through 2032.

Arsenic was imposed at 0.045 mg/L throughout the infiltration period (13 years). Retardation was calculated within *MODFLOW-SURFACT* based on the lowest partitioning coefficients, i.e. $Kd_{As} = 8.9 \times 10^{-6}$ L/kg, an aquifer dry bulk density of 1.71×10^6 mg/L, and model effective porosity of 0.2 (Appendix S-5). The retardation factors (R) were calculated from (Fetter 1999):

$$R = 1 + [K_d * (\rho_b/\theta_m)] \tag{5}$$

resulting in a R_{As} of 78. Since As will migrate 78 times more slowly than the average groundwater flow due to attenuation, most of the mass will remain within the RIBs footprint during infiltration and through the end of the simulation (542 years). Arsenic below the RIBs will reach a maximum of ≈ 0.045 mg/L (the influent concentration); however, beyond the immediate RIBs area, As will not exceed Profile I (0.01 mg/L).

Groundwater As evolution at locations A, B, C, and D along the transect line demonstrate that the incremental As in the mound water east of the RIBs at A will remain below 0.002 mg/L due to alluvial attenuation of As in the infiltrate. Between the RIBs basins (location B), As will reach 0.025 mg/L while south of the RIBs (location C), the top of the mound water cone will be 0.013 mg/L As in the first 15 years before the mound water dissipates below 1720 m (to the next model layer), where Profile I is never exceeded. All other locations (D, E, and F) remain below Profile I.

Alluvial Attenuation Capacity

This analysis determines the amount of adsorption sites in the vadose zone that can attenuate As and the time required to exhaust the alluvial attenuation capacity. The logic is portrayed in Fig. 9 to facilitate clarity of the ensuing construct. The As attenuation capacity that is attainable in steady state resulting in groundwater As of 0.010 mg/L was derived from:

$$\begin{aligned} &\text{Capacity} = \text{Kd}_{\text{As}} * \text{Dissolved As} \\ &\text{L/kg} * 0.01\ \text{mg/L} = 0.089\ \text{mg/kg} = 8.9 \end{aligned} \tag{6}$$

Therefore, 0.089 mg/kg was used as an appropriate empirical data point to calculate the available adsorption capacity in the RIB mound water.

Determining the specific attenuation capacity to the field-available attenuation capacity depends on the volume of alluvium that will be wetted by the infiltrating dewatering water, and the bulk density of the alluvium that is wetted. The alluvium wetted in the mound water is the volume between the simulated "*no action water table surface*" and the "*maximum RIBs mound at the end of 2032*" using the elevation of the mound water within the 3 m mound water extent (Fig. 8), resulting in 4.13×10^8 m^3 of alluvium.

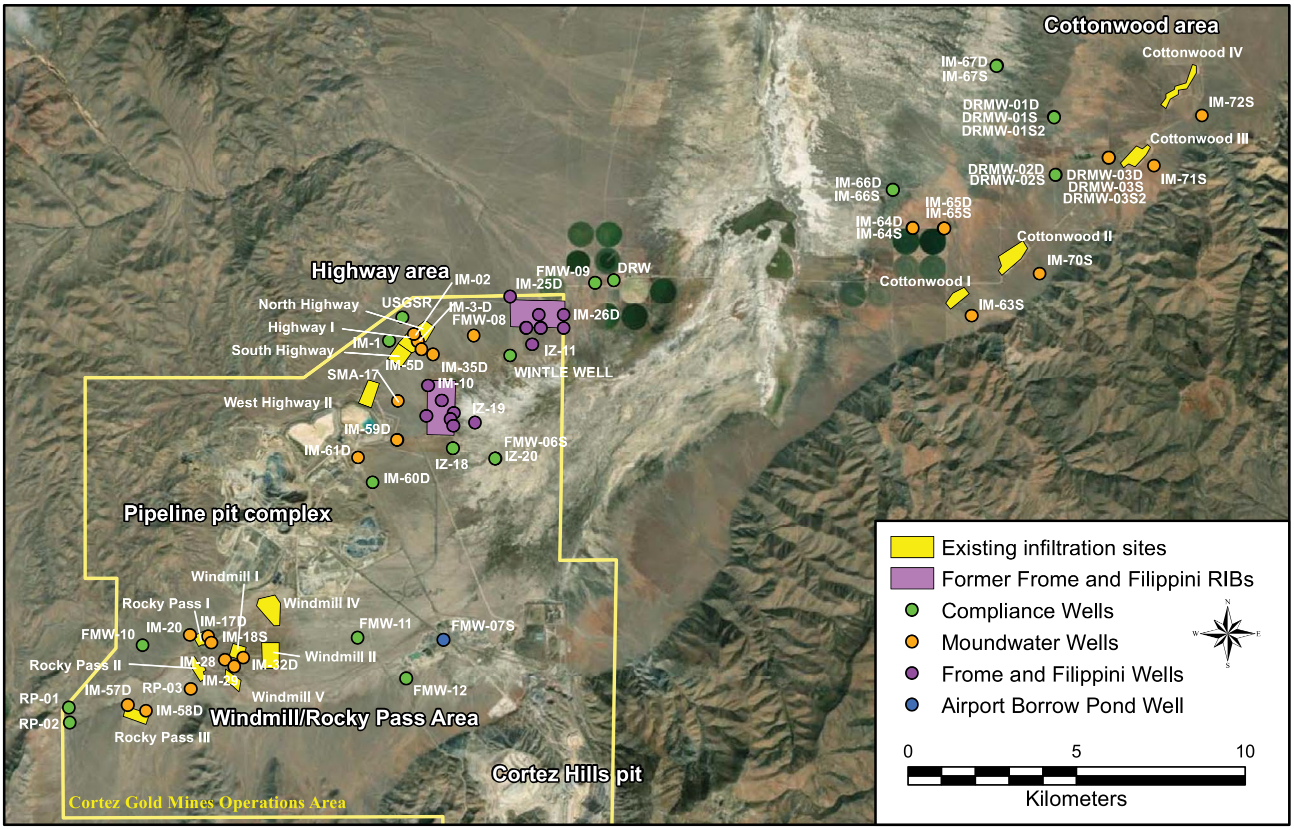


Fig. 10 Infiltration basins and associated mound water and compliance monitoring wells in Crescent Valley

Applying the alluvial density to the volume wetted by mound water establishes a mass of accessible alluvium and enables application of the quantified As adsorption capacities. During column testing, the alluvial porosity was determined to be ≈ 33%, making calculation of the mound water alluvial mass more conservative (i.e., less solid mass per m^3) than in the model. The dry bulk density (ρ_b) of the alluvium was estimated assuming a specific gravity (ρ_s) of 2.4 g/cm^3:

$$\rho_b = 2.41\ \text{g/cm}^3(1 - 0.326) = 1.62\ \text{g/cm}^3 = 1.62 \times 10^3\ \text{kg/cm}^3 \tag{7}$$

Therefore, 4.13×10^8 m^3 of alluvium is equivalent to a mass of 6.7×10^{11} kg in the mound water available to attenuate solutes. The 6.7×10^{11} kg of alluvium that is wetted by the Grass Valley RIBs will have an attenuation capacity of at least 0.089 mg/kg As (Eq. 6). Therefore, the mass of As retained on the wetted alluvium will be:

$$\text{Field As capacity} = 6.7 \times 10^{11}\ \text{kg} \times 0.089\ \text{mg/kg} = 5.96 \times 10^4\ \text{kg As} \tag{8}$$

The lifespan over which the RIBs in Grass Valley can operate without impacting waters of the State (i.e. dissolved As will remain < 0.010 mg/L) was calculated assuming that the infiltrate will consistently contain 0.045 mg/L As and will enter the mound water volume at a flow rate of ≈ 32,000 L/min.

Consequently:

$$\text{As adsorbed} = (0.045\ \text{mg/L As [infiltrate]}) - (0.010\ \text{mg/L As [Profile I]}) = 0.035\ \text{mg/L} \tag{9}$$

and, based on the flow rate of 3220 L/min or 1.7×10^{10} L infiltrated per year, the annual As retained on the alluvium will be:

$$\text{As retention} = 1.7 \times 10^{10}\ \text{L/year} \times 0.035\ \text{mg/L As} = 594\ \text{kg/year As} \tag{10}$$

The lifespan calculation for the alluvial As capacity, with infiltration at 3220 Lpm containing 0.045 mg/L As is:

$$\text{As Retention Lifespan (years)} = \frac{5.96 \times 10^4 \ \text{kg}}{594 \ \ \text{kg/year}} \text{As} = 100 \text{ years} \tag{11}$$

Crescent Valley Field Validation

Dewatering in Crescent Valley began in 1996 with approval of the Pipeline Project, followed by subsequent expansion and development of the Pipeline and Cortez Hills Projects. There are 11 RIB galleries in the adjacent Crescent Valley, consisting of 56 basins that have operated for 24 years (Fig. 10). An analysis of ≈ 12,300 water level elevations and ≈ 60,600 water quality analyses provided field validation of the Grass Valley RIB predictions. The operations include dewatering (which regulatory agencies approved at an annualized rate of up to 137,000 L/min). A typical year sent 15,500 L/min to irrigation and 11,700 L/min for consumptive use, with the remainder (≈ 76,000 L/min) averaging 0.045 As mg/L sent to the RIBs.

The Crescent Valley RIBs are located on younger basin-fill consisting of unconsolidated alluvial fans, landslides, stream flood plains, and playa deposits resulting from the erosion of bedrock in the adjacent mountain ranges. Groundwater chemistry is monitored by a network of 58 wells that are sampled for water elevation and Profile I analytes, either quarterly or monthly.

At the Windmill/Rocky Pass area the background upgradient As was naturally elevated (0.025 mg/L; n = 19) exceeding Profile I, while Highway (0.005 mg/L; n = 4) and Cottonwood (0.009 mg/L; n = 15) did not. Regardless, there have been no As exceedances above Profile I in any compliance well beyond the mound water boundary (Geomega 2018), providing cogent evidence for natural As alluvial attenuation.

Conclusions

Based on As attenuation, the Grass Valley RIBs could be run for a minimum of 100 years before the alluvial capacity is exhausted. However, this estimate is extremely conservative because: (1) the modeled Kd_{As} was assigned the lowest value of the three measurements for Grass Valley alluvium; (2) while this calculation accounts for all of the As infiltrated over the life of the RIBs, it does not include the adsorptive matrix beyond the ≈ 3 m mounding contour that will also retard As (zone A on Fig. 1). In addition, (3) the calculation excluded the vadose zone that will be wetted between the RIBs and the saturated zone (mound water surface) i.e. the volume beyond the 10 ft mound water extent, and the wetted vadose zone (zone B on Fig. 1), and (4) a conservative value for porosity (32.6%) was chosen to calculate the alluvial density, consistent with the uncompressed column tests, but higher than the Four-Basin model alluvium (20–24%). This means that the calculations of field attenuation capacity, which are based on the volume of wetted alluvium, assume less alluvium mass, and therefore fewer sorption sites. Based on the results of this analysis, Cortez proposed, in conjunction with the historical Crescent Valley data, that construction of a treatment plant to treat dewatering water prior to infiltration in the Grass Valley RIBs would be unnecessary, and NDEP (2020) concurred.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10230-021-00839-2.

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