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ORIGINAL ARTICLE

Hydrologic compartmentalization and analytic-element groundwater-flow simulations for a draining mine tunnel

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Abstract
Draining mine tunnels contribute contaminants to groundwater and surface water, but remediation strategies may be hindered as hydrogeologic characterization and modeling of these heterogeneous features generally relies on sparse data sets. The Captain Jack mine site in Colorado, USA, presents a unique data set allowing for temporal evaluation of groundwater connectivity in the vicinity of an abandoned mine, where a hydraulic bulkhead is impounding water within the mine workings. This study applied statistical analysis of system pressure responses to bulkheading and used an analytic-element modeling approach to characterize heterogeneity and groundwater flow. Groundwater-level elevation data collected over a period of 4 years, both prior to and after bulkheading, indicate that the mine workings act as a sink to the local groundwater system. Despite groundwater flow being generally oriented towards the mine workings, there are also large vertical and horizontal hydraulic gradients which persist through time. Although the groundwater system is highly compartmentalized, statistical analysis using Kendall's Tau indicates correlations between hydraulic head changes in the mine workings and several wells completed in crystalline bedrock, indicating the influence of fracture flow. An analytic-element model was parameterized to account for uncertainty in hydraulic conductivity, recharge, and discharge. Model results reproduced the range of observed hydraulic heads in the mine workings and adjacent igneous dikes but failed to closely simulate hydraulic heads in several wells located distal from the mine workings in granitic bedrock. The modeling approach shows potential promise, however, for conducting preliminary modeling to guide data collection at other similar mine sites.

Keywords Mine tunnels · Acid mine drainage · Analytic element · Statistical analysis · Colorado

Introduction

Draining mine tunnels and adits represent a substantial source of acid mine drainage (AMD) to waterways in the western United States, including in the mountainous state of Colorado (Byrne et al. 2017; von Guerard et al. 2007). Mine drainage may contain elevated concentrations of metals and acidity which cause ecological harm and may make water unusable for human activities (Kimball et al. 2010). Remediation of draining tunnels remains a challenge, because sources of groundwater inflow are difficult to constrain and control, and dangerous conditions within mine workings make direct hydrologic observations sparse. One remedial strategy for precluding AMD outflow from mine tunnels is the emplacement of hydraulic bulkheads which impound water within underground mine workings (Walton-Day et al. 2021). Remediation using bulkheads likely causes changes to groundwater discharge and storage at the watershed scale, which also affect the spatial distribution of solute discharge from watersheds affected by AMD (Petach et al. 2021; Walton-Day et al. 2021).

Despite observations of watershed-scale hydrologic changes following the use of hydraulic bulkheads (Petach et al. 2021; Walton-Day et al. 2021), few studies have focused on site-scale modifications to the local groundwater system that result from bulkhead use. Potential site-scale changes include changes in groundwater-flow direction and increased discharge from springs connected to mine tunnels by fractures. Lack of site-scale observations hinders remediation and is a source of uncertainty in long-term effects of bulkheading (Walton-Day et al. 2021). In this study a monthly observation data set (Newman 2022a) was used from the Captain Jack Superfund Site, located in

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north–central Colorado, to evaluate hydrologic changes resulting from bulkhead use and to develop a detailed conceptual model of the local groundwater system. Statistical and groundwater modeling methods were used to achieve these goals in a quantitative manner.

The Captain Jack Mill, mine waste, and associated mine workings are located near the town of Ward, Colorado, USA (Fig. 1) and comprise a Superfund site designated by the U.S. Environmental Protection Agency (EPA) in 2003. Active mining and mineral processing for gold and silver were carried out at the site from the 1860s through 1992 (U.S. Environmental Protection Agency 2017). The site is located near Lefthand Creek (Fig. 1) and has affected surface water within the Lefthand Creek watershed, where numerous other abandoned mines are present (Bautts et al. 2007). Ongoing remedial activities have removed most surface mine waste and the primary remaining source of AMD is Big Five adit, which releases approximately 1.3–10 L/s of acidic drainage. The adit tunnel extends westerly for more than 2100 m from the portal (Fig. 1) and intersects a tunnel (the Niwot Crosscut), connecting the Big Five mine workings with the Columbia Mine District to the north. The intersection of these tunnels is estimated to be 120–130 m below land surface. The selected remedial alternative for the site included the installation of a hydraulic bulkhead in the Big Five mine workings and the construction of an in-tunnel treatment system to inhibit the generation of AMD behind the bulkhead. Installation of the bulkhead was completed in November 2017 and water was impounded behind the bulkhead beginning in May 2018. During the several months following impoundment, groundwater-level monitoring indicated that the mine workings were filling more quickly than had been anticipated (Colorado Department of Public Health and Environment 2018). Rapid water-level increases raised concern that mine water might begin to flow out of boreholes

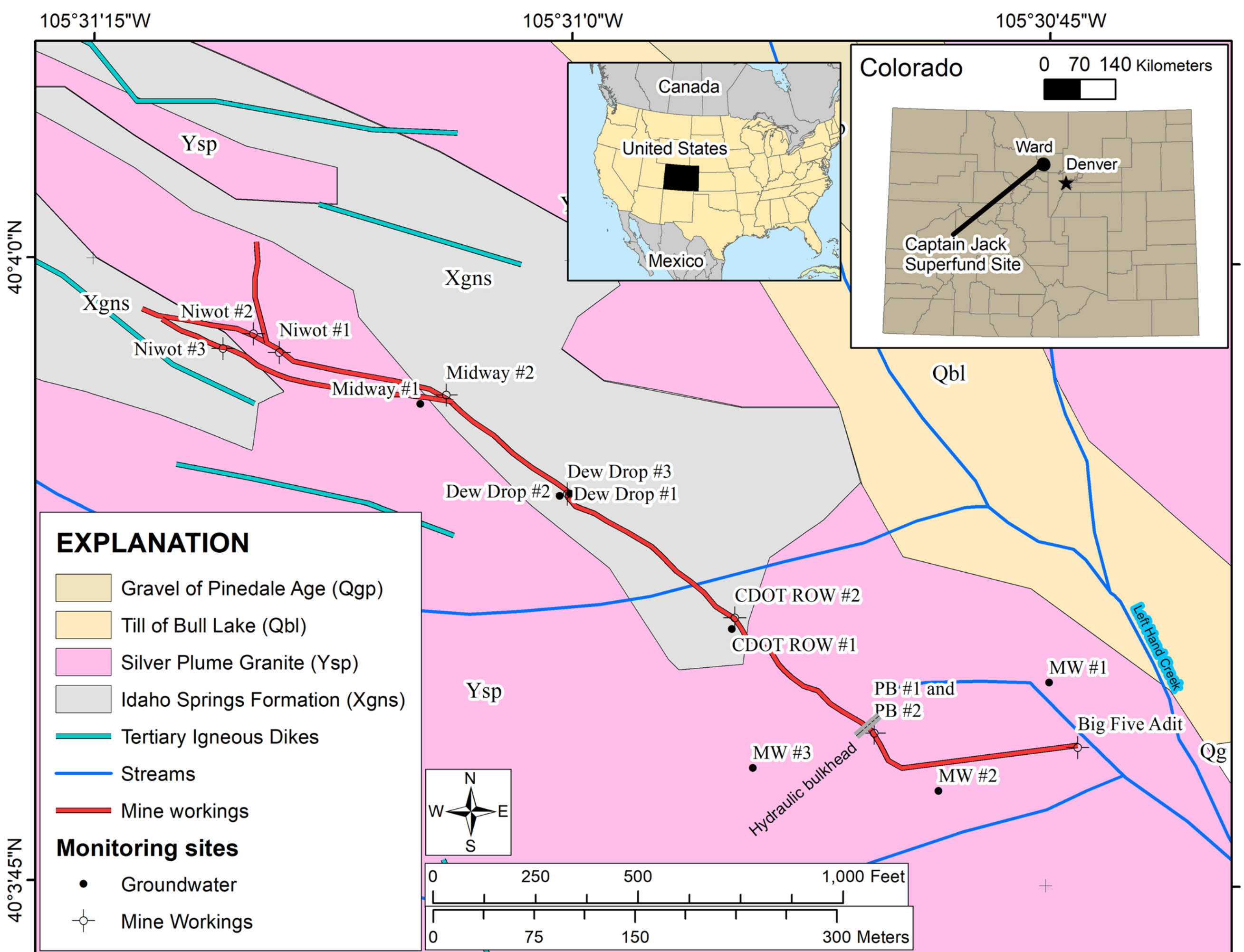

Fig. 1 Location, geology, and monitoring sites for the Captain Jack Superfund Site in Colorado. *Qgp* gravel of Pinedale age; *Qbl* till of Bull Lake; *Ysp* Silver Plume Granite; *Xgns* Idaho springs formation. Geologic map from Gable and Madole (1976)

drilled into the mine workings, which would result in an uncontrolled release of metal-laden water. To preclude an uncontrolled release, the valve on the bulkhead was partially opened, allowing mine water to flow past the bulkhead and reducing the level of the mine pool in September 2018. In September 2021 the bulkhead valve was closed again. This study focuses on hydrologic conditions during the bulkhead closure between May and September 2018.

The geology of the study area is comprised primarily of crystalline igneous and metamorphic rocks ranging in age from Precambrian to Tertiary. The oldest rocks in the study area are biotite gneiss and schist of Precambrian age (1.7–1.8 billion years before present; Ga) regionally known as the Idaho Springs Formation (Tweto 1977) and the Silver Plume Granite of middle Proterozoic age (1.4 Ga). The Idaho Springs Formation and Silver Plume Granite underlie most of the site (Fig. 1). Tertiary igneous dikes are also present including quartz latite porphyry, quartz monzonite, and monzo-granodiorite porphyry (Gable and Madole 1976). Intrusion of Tertiary igneous dikes into the Idaho Springs Formation and Silver Plume Granite were associated with regional igneous activity and ore-forming hydrothermal alteration and mineralization during the Laramide orogeny (Lovering and Goddard 1950). Igneous dikes generally strike in a northwest–southeast orientation, and because mining was developed along hydrothermal features coincident with dikes, the Big Five mine workings follow a similar trend as the igneous dikes and associated hydrothermal alteration (Fig. 1; Lovering and Goddard 1950). Quaternary glacial till and gravel outwash overlie the bedrock formations along Lefthand Creek (Fig. 1). Structural geologic features in the vicinity of the site strike primarily northwest–southeast and include igneous dikes and breccia zones. Dikes and breccia zones tend to dip steeply (with dips ranging from 45 to 80° dipping to the northeast; Lovering and Goddard 1950). There are no notable mapped fault systems in the vicinity of the site, but there are indications of faulting within the workings. Lovering and Goddard (1950) noted that both pre- and post-mineralization faulting was apparent along the strike of the vein system. Structural features such as faults and shear zones may influence groundwater movement near the site by focusing or impeding groundwater flow. Mineralization can also substantially alter hydraulic properties (Ingebritsen and Appold 2012), and thus groundwater-flow paths may be modified in the vicinity of the workings due to changes in permeability associated with the ore deposit.

The study purpose was to characterize the groundwater hydrology of the site to better understand groundwater connectivity in the area, to predict groundwater dynamics, and to evaluate the applicability and use of differing data sets and modeling techniques for informing remedial activities at mine sites in mountainous terrain. This analysis utilized an unprecedently large data set of groundwater-level elevations within and adjacent to the mine workings (Newman 2022a), allowing for a robust understanding of groundwater flow.

Materials and methods

The data set used in this analysis consists of groundwater-level elevations collected between May 2016 and December 2020. Discrete field measurement of depth to water was conducted according to standard methods of the U.S. Geological Survey (USGS) as described in Cunningham et al. (2011). Data from 2016 through May 2020 were collected by contractors to EPA and data from June through December 2020 were collected by USGS. Depth to water measurements were converted to groundwater-level elevation time-series data according to methods described by Cunningham et al. (2011). Groundwater-level elevation data were collected at sites denoted as groundwater (completed within crystalline bedrock) and mine water (completed within open mine workings) in Fig. 1 and in Table 1. All groundwater-level elevation data used in this analysis are available from Newman (2022a). In addition to groundwater wells there are also seeps and springs on the site which are monitored by the EPA. The aqueous geochemistry of these seeps and springs indicates they are not connected to the mine (Wood 2018), and thus the flow rates are unlikely to be affected by changes in the mine hydrologic system.

Using groundwater-level elevations from across the study area, the groundwater table was mapped. Maps of the groundwater table were created for each month between May 2016 and April 2020 with applicable observations by interpolating groundwater-level elevations spatially using the Python programming language (Van Rossum and Drake 2009). Monthly groundwater-level observations were also used to create hydrologic cross sections showing the elevation of groundwater within the mine void and surrounding bedrock aquifer.

In addition to spatiotemporal analysis of hydrologic gradients, statistical techniques were used to evaluate potential correlations between groundwater-level elevations within the mine workings and groundwater-level elevations in the surrounding bedrock. To facilitate statistical analysis the data set was differentiated into pre-impoundment (before 7 May 2018) and post-impoundment (after 7 May 2018) categories. The median groundwater-level elevation for the pre-impoundment data set was then calculated for each monitoring location. This median groundwater-level elevation represents the approximate static condition of the hydrologic system before any potential influences of water impoundment in the mine workings. The difference from the pre-impoundment median groundwater-level elevation was then calculated through time for each monitoring location. Difference from the pre-impoundment median is a useful estimate

Table 1 Naming conventions and site types of groundwater (wells completed in crystalline bedrock) and mine water (wells completed in mine workings) monitoring locations

USGS site ID	Short site name	Monitoring location type	Lithology
400348105304401	Big Five Adit	Mine water	Tertiary igneous dike
400351105305401	CDOT ROW #1	Groundwater	Tertiary igneous dike
400351105305402	CDOT ROW #2	Mine water	Tertiary igneous dike
400354105305901	Dew Drop #1	Groundwater	Tertiary igneous dike
400354105310001	Dew Drop #2	Groundwater	Idaho Springs Formation
400354105310002	Dew Drop #3	Mine water	Tertiary igneous dike
400356105310401	Midway #1	Groundwater	Tertiary igneous dike
400356105310301	Midway #2	Mine water	Tertiary igneous dike
400349105304401	MW #1	Groundwater	Silver Plume Granite
400347105304801	MW #2	Groundwater	Silver Plume Granite
400347105305401	MW #3	Groundwater	Silver Plume Granite
400357105310901	Niwot #1	Mine water	Tertiary igneous dike
400358105310901	Niwot #2	Mine water	Tertiary igneous dike
400357105311001	Niwot #3	Mine water	Tertiary igneous dike
400348105304402	PB#1	Mine Water	Tertiary igneous dike

Completion lithology was derived from surficial geologic maps and well logs provided by EPA. USGS station IDs are referenced to the USGS National Water Information System (NWIS) database (U.S. Geological Survey 2021). Well attributes including coordinates and depth are available from the NWIS database (U.S. Geological Survey 2021)

of the effect of the mine workings filling at any single location, because this procedure has a normalizing effect on the variation in groundwater-level elevations (i.e., the absolute value of the groundwater-level elevation is removed, while temporal variability is highlighted). Some seasonal groundwater-level elevation fluctuations occur in the data set likely due to recharge and evapotranspiration, typically on the order of 1–3 m. Seasonal fluctuations of this magnitude are minor when compared to observed fluctuations up to 30 m during impoundment. Seasonal fluctuations are, therefore, not anticipated to obscure statistical relationships.

Kendall's Tau was calculated for each location using the difference from pre-impoundment median groundwater-level elevation at the monitoring location compared to the difference from pre-impoundment groundwater-level elevation at site PB #1 (co-located with PB #2 in Fig. 1), which represents groundwater-level elevation changes within the mine void immediately upgradient from the hydraulic bulkhead. The null hypothesis of the calculation is that post-impoundment groundwater-level elevation changes in wells are not related to groundwater-level elevation changes in the mine workings (measured at PB #1). The alternative hypothesis is that groundwater-level elevations in wells are related to changes in the mine workings. The Kendall's Tau test is used here as a proxy to indicate hydrogeologic connectivity between the mine workings and adjacent crystalline bedrock. Results with p values < 0.05 were used to reject the null hypothesis and indicate statistically significant correlations. Although only results with p values < 0.05 were used to reject the null hypothesis, groundwater connectivity is likely a continuum. The full rang in p values may, therefore, be used to evaluate ranges in potential connectivity. The Kendall's Tau test is well suited to this data set, because this test requires no assumptions of normality, but is limited to monotonic trends between two variables (Helsel et al. 2020).

A groundwater-flow model was constructed for the study area using the analytic-element method (AEM). The AEM is a grid-less approach, wherein the principle of superposition is used to simulate interacting effects of various hydrologic stressors on the groundwater system (Strack 2003). The AEM has been successfully used at mine sites, where large gradient or other numerical issues would affect rigorous application of numerical models (Fitts 2018). The AEM was applied using the TimML package (Bakker 2006) implemented in the Python programming language. The AEM was used to simulate a steady-state condition prior to the first impoundment of water behind the bulkhead in May 2018.

Application of the AEM to simulate the physical groundwater-flow system requires estimates of the hydraulic properties of the aquifer and assignment of boundary conditions. The most pertinent hydraulic property required for the model is hydraulic conductivity (K), and important boundary conditions include recharge and discharge. Estimates of K for the bulk aquifer were estimated using the approach of Gagné et al. (2013). This approach estimates K based on analytical solutions to the Dupuit and Theim approximations for flow to a well combined with observed water inflow rates to the mine, differences in groundwater levels within the mine void and adjacent groundwater system, and dimensions of the mine void. The methods of Gagné et al. (2013) are only a first approximation but are based on site-specific data. Estimates of K by these methods range from 9.1×10^{-5} to 11 m/

day with a geometric mean of 1.5×10^{-3} m/day. This range of K over multiple orders of magnitude is similar to that reported by Freeze and Cherry (1979) for fractured igneous and metamorphic rock. Estimates also span multiple orders of magnitude, because the Dupuit and Theim approximations have different assumptions and use different inputs. It is useful to use the widest possible range in K value estimates for model calibration, because K values are inherently uncertain and using ranges of property values produces the most robust understanding of model uncertainty (White et al. 2020). The full range of estimated K values were assigned to the bedrock (K_{br}) and were used in model calibration and uncertainty analysis.

The methods summarized by Gagné et al. (2013) produce estimates of the bulk K for the bedrock aquifer, not K values within the open mine workings. Because the AEM simulates zones within an inhomogeneous system with variable K values (Bakker 2006), an estimate of the K for the mine tunnel is also required. Values of K for the mine void (K_v) ranged from 0.61 to 1097 m/day to promote rapid flow through the predominantly empty mine void system, based on K values used in other studies to simulate underground mine voids (Wolkersdorfer 2008) and to simulate lakes acting as open voids in regional aquifers (Anderson et al. 2002). The range in K_v conceptually captures the possibility of collapsed mine workings (leading to lower K_v) and that the workings may still be open voids in the subsurface (leading to higher K_v).

Primary boundary conditions to groundwater-flow models include groundwater recharge (both diffuse and focused) and groundwater discharge. Groundwater recharge in the study area may occur from infiltration of precipitation (diffuse recharge) or infiltration from losing streams (focused recharge), but the primary source of groundwater discharge is likely from the mine void via the Big Five Adit as potentiometric surface contours constructed from observations indicate that the interconnected mine tunnels act as a drain from the local groundwater system. In the AEM framework the steady-state diffuse recharge is implemented by applying a uniform flow field through a portion of the study area combined with Darcy's Law for steady-state flow (Bakker and Post 2022). Based on Darcy's Law, the discharge from an aquifer is calculated as the product of K, the hydraulic gradient between two points in the aquifer, and the area across which active flow occurs. Therefore, in the steady-state AEM, diffuse recharge is implemented by applying a known hydraulic gradient to a portion of the model. This applied gradient and the K value then are combined to induce a flux in the model domain. Because the model is in steady state, the flux calculated by Darcy's Law equals the recharge to the domain (in the absence of other boundaries). Because K values are uncertain, the recharge value is also uncertain and is inherently incorporated into the uncertainty analysis using different K values and different uniform flow fields. This approach robustly evaluates uncertainty in both K and diffuse recharge and directly addresses the non-uniqueness and covariability of K and recharge in groundwater-flow models (Moeck et al. 2020). Diffuse recharge to the system is the first boundary condition applied, so that the induced flux can be calculated.

Based on field investigation at the site, focused groundwater recharge to the mine void system may also be occurring from an unnamed tributary to Lefthand Creek that flows near the mine (immediately to the northwest of sites CDOT ROW #1 and CDOT ROW #2 in Fig. 1). In June 2020 a field visit to the site indicated that over a reach of approximately 100 m, the entirety of the flow within the unnamed tributary infiltrated into the ground. Streamflow measurements collected using an acoustic doppler velocimeter (ADV; Turnipseed and Sauer 2010), along the flowing reach upstream from the infiltration area, indicated that the stream had a flow of approximately 6 L/s, which was entirely lost to infiltration in the vicinity of the mine workings. Based on these field observations a focused groundwater recharge source was simulated along the observed losing reach of the creek (Q_{stream}), with recharge rates ranging from 2.8×10^{-3} to 14 L/s. The large range in possible input values allows the simulation to assess the effect of uncertainty in parameter values to the model outputs, because all of the stream loss may not flow directly to the mine workings. The losing stream was simulated as a line-sink in the AEM (Bakker 2007).

Simulation of groundwater discharge was based on observed outflow rates from the mine void, assuming that all water that has been observed to discharge from the adit is derived from groundwater inflow to the mine void, which is a discharge component from the local groundwater system. Observed discharge rates range from 1.3 to 10 L/s. Simulated groundwater discharge rates in the model (Q_{adit}) ranged from 2.2×10^{-2} to 16 L/s. Groundwater discharge was simulated using a line-sink in the AEM (Bakker 2007). Groundwater discharge from springs was not simulated, because the geochemistry of the springs indicates that they are not connected to the mine workings (Wood 2018).

A statistical uncertainty analysis was conducted to evaluate ranges of boundary conditions and hydraulic property values that produce the highest degree of corroboration with observations (i.e., error minimization). Uncertainty analysis was conducted in a probabilistic manner by varying K (K_{br}, K_v) and by focusing recharge from streamflow (Q_{stream}) and groundwater discharge from the mine system (Q_{adit}) within the bounds described above for each parameter. The minimum and maximum value of each quantity formed the limits of the distribution, and a right-skewed gamma distribution was assumed for each quantity between the upper and lower limits. A gamma distribution was used because property values were assumed to be non-normally distributed, and the gamma distribution is suitable for such distributions. The initial model run used to estimate the orientation of the steady-state flow field that best approximated groundwater flow at the Superfund site was run 1663 times, representing all possible combinations of wells to represent the steady-state flow field, plus the influence of two randomly distributed values each for the parameters K_{br}, K_v, Q_{adit}, Q_{stream}. This initial parameter estimation was used to identify the pair of wells that best represented steady-state flow in the system. Results indicate that steady-state flow between Midway #2 and MW#2 produce the best calibration to observed pre-closure groundwater levels. Next, a more complete exploration of parameter space was undertaken using Midway #2 and MW#2 but with nine randomly distributed values for each parameter (bounded by upper and lower limits). One simulation was run for each combination of the generated parameter sets, totaling 6560 model runs. This probabilistic analysis is expected to produce a robust estimate of the factors controlling the steady-state groundwater system. The AEM model used in this analysis is available in a USGS data release and model archive (Newman 2022b).

Results

Groundwater at the site is present within crystalline igneous and metamorphic rocks. Interpolated groundwater-level elevations indicate that the mine workings act as a drain on the local groundwater system, as groundwater-flow paths are generally towards the workings, regardless of whether the Big Five adit was flowing or water was impounded (Fig. 2). Generalized groundwater-flow lines plotted in Fig. 2 indicate that although the mine workings act as a drain on the local system, flow within the mine workings is not continuous. Specifically, a localized groundwater depression is present in the vicinity of the Midway wells, meaning that water does not necessarily flow from the Niwot workings to the Big Five workings.

Hydrologic cross sections through the Superfund site under drained and impounded conditions (Fig. 3) indicate that groundwater within different crystalline bedrock units and the mine void is highly compartmentalized. Groundwater-level elevations in bedrock monitoring wells completed adjacent to the mine void are commonly tens of m higher, despite being less than 5 m away from the workings in some instances (e.g., between Dew Drop #1 completed in crystalline bedrock and Dew Drop #3 completed in the mine workings, Table 1). Vertical gradients in the vicinity of the Dew Drop wells in March 2018 range from 9 to 13 m/m (crystalline bedrock groundwater level elevations are approximately 54 m higher with a horizontal distance of 4–6 m), whereas the vertical gradient in the CDOT ROW wells is 5.5 m/m.

Theoretically, the large hydraulic gradient over these short distances would drive groundwater flow from the crystalline bedrock into the mine void. The observed compartmentalization, therefore, indicates that strong hydraulic barriers must exist. Potential hydraulic barriers include faults, as noted by Lovering and Goddard (1950), shear zones and fractures described within the mine workings by the geotechnical examination of Deere and Ault (2006), or low-K zones of rock created during hydrothermal alteration and mineralization (Ingebritsen and Appold 2012). The only instance when groundwater-level elevations within the mine void were greater than in the adjacent crystalline bedrock was during September 2018 in the vicinity of sites MW #3 and PB #1 (Fig. 3b). Higher hydraulic head in the mine void, when compared to the adjacent groundwater system, has the potential to drive water from the mine pool out of the mine and into the surrounding groundwater system.

Groundwater-level elevations in some wells increased substantially when water was impounded within the mine void beginning in May 2018 (Fig. 4), including in wells CDOT ROW #1, Midway #1, and MW #3. Increasing groundwater-level elevations would be expected in the mine void itself, but increasing groundwater-level elevations in bedrock monitoring wells may indicate hydraulic connections that are not apparent from hydrologic cross sections shown in Fig. 3. Although the mine workings have lower hydraulic heads than throughout the crystalline bedrock, pressure changes within the mine could be transmitted to upgradient (higher head) bedrock wells if sufficient physical connectivity exists. Increasing groundwater levels in both the mine workings and the crystalline bedrock are also likely caused to some extent by spring snowmelt and recharge (e.g., CDOT ROW #1 in June 2019, Fig. 4). Several other wells completed in crystalline bedrock do not visually appear to respond directly to water impoundment within the mine void (e.g., MW #1 or Dew Drop #1; Fig. 4), indicating that these wells are not affected by changes in the mine and are likely not hydraulically connected to the mine workings.

Statistical analysis with Kendall's Tau (Helsel et al. 2020) was used to indicate locations, where statistically significant correlations existed between groundwater-level changes in monitoring wells and within the mine void (measured immediately upgradient from the bulkhead at site PB #1). In this manner statistical relations are used as a proxy for hydrologic connectivity. Statistical analysis is more diagnostic than the visual analysis presented in Fig. 4 as relations may be more distinctly quantified. Results of statistical analysis are summarized in Table 2 and indicate that eight wells have statistically significant correlations to groundwater-level changes within the mine void. Importantly, these wells are not limited to those that are completed within the mine. Wells CDOT ROW #1, Midway #1, and MW#3 are all completed in crystalline bedrock yet show statistically significant correlations to changes within the mine workings. CDOT ROW #1 and Midway #1 are both immediately

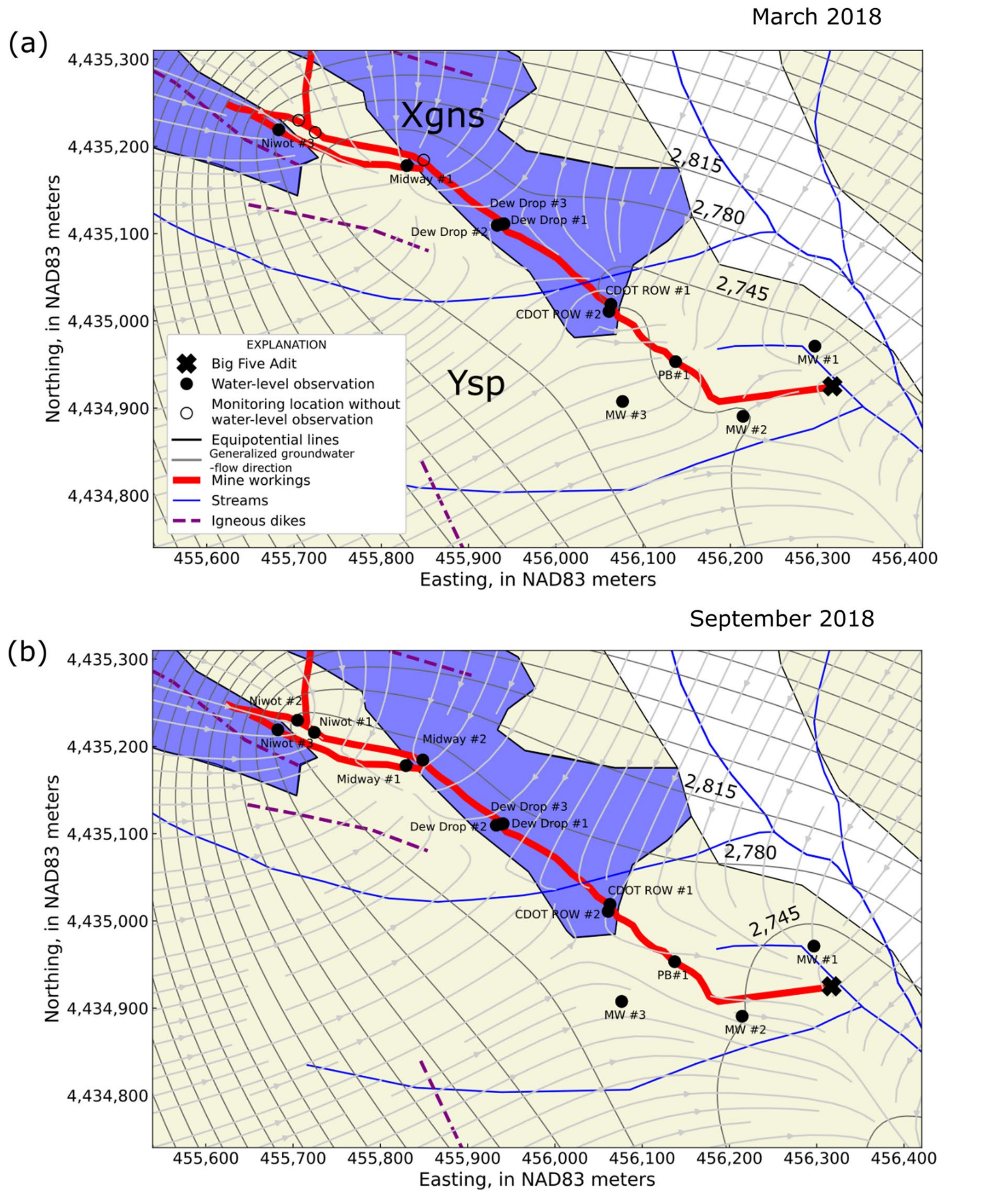

Fig. 2 Interpolated groundwater-contour maps and approximate flow paths for time periods when the Big Five adit was flowing (**a**) and when water was impounded (**b**). Bedrock geologic units are displayed and labeled (Xgns indicates Idaho Springs Formation, Ysp indicates Silver Plume Granite; Gable and Madole 1976). The spatial coordinate system is North American Datum of 1983 (NAD83) consistent with the projection of the AEM (Newman 2022b). Contour interval is 35 m and contours in the immediate vicinity of the site are labeled in meters above the North American Vertical Datum of 1988 (NAVD88)

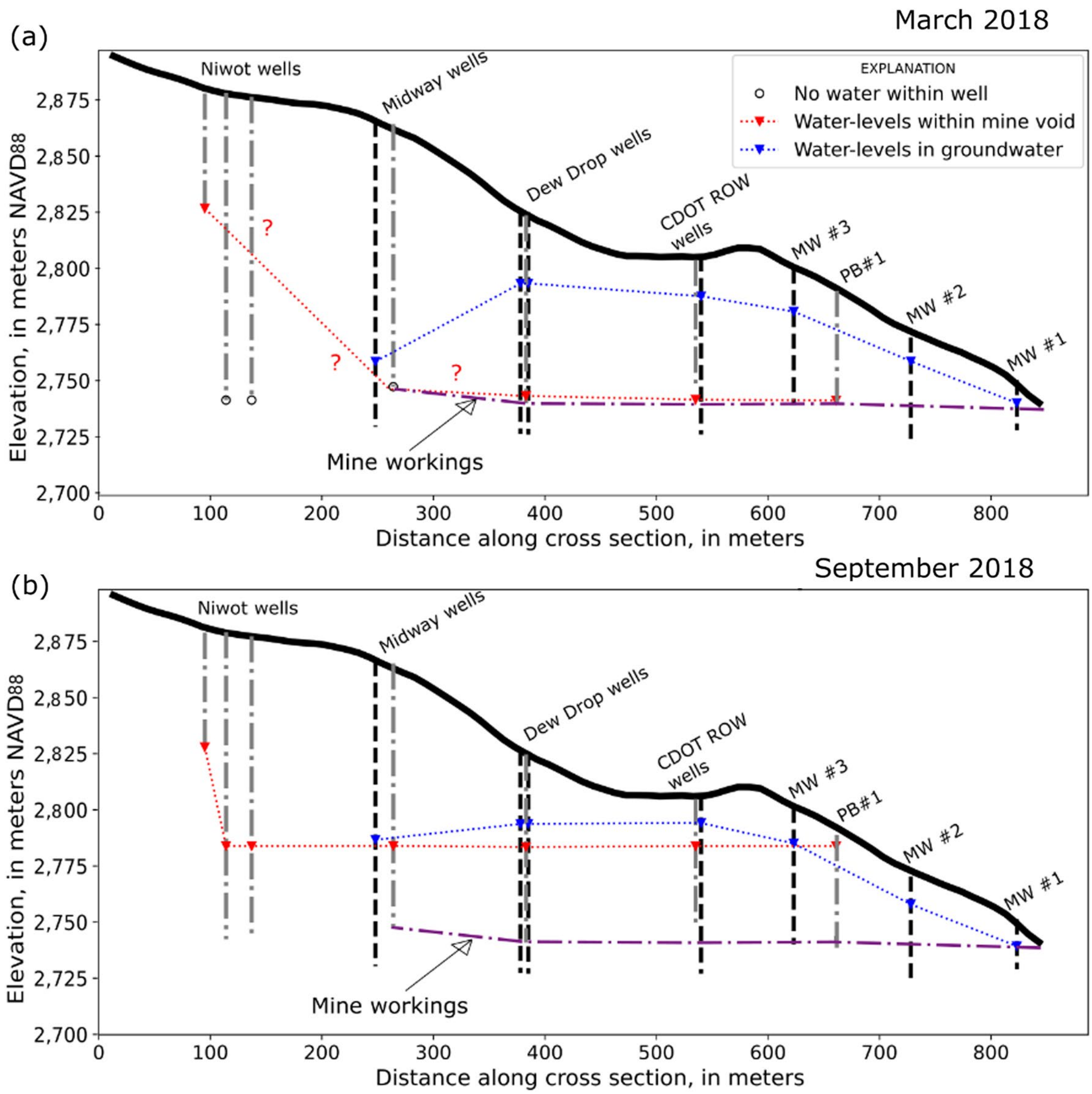

Fig. 3 Hydrologic cross sections (to scale, vertical exaggeration = 2.85) from northwest on the left (Niwot wells) to southeast on the right (MW #1) showing approximate elevation of the groundwater table for time periods when the Big Five adit was flowing (**a**) and when water was impounded (**b**). Well depths are shown to scale and are projected on to the cross section. Wells completed in mine workings are shown in gray dot–dash lines and wells completed in crystalline bedrock are shown in black dotted lines. Red dotted lines indicate the estimated groundwater-table elevation in the mine void (queried where uncertain). Blue dotted lines indicate the estimated groundwater-table elevation in the crystalline bedrock groundwater system. The purple dot–dash line indicates the approximate level of the base of the mine workings, which is not extended to the Niwot area because of unknown connectivity

adjacent to the mine workings, whereas MW #3 is located approximately 75 m laterally from the workings. Both CDOT ROW #1 and Midway #1 are likely completed in Tertiary igneous dikes based on surficial geologic maps (Gable and Madole 1976) and mapping of the workings (Lovering and Goddard 1950), while MW #3 is completed in the Silver Plume Granite. Monitoring wells are also screened within the vicinity of the mine workings depth, as screen intervals are typically approximately 15 m, and most groundwater wells are completed at a depth near the workings (see well depths in Fig. 4).

Use of Kendall's Tau as a proxy for hydrologic connectivity allows for quantitative analysis but does not account for continuums in groundwater connectivity, which likely exist at the Superfund site. The maximum groundwater-level difference from pre-closure median is also summarized in Table 2, and comparison of maximum differences between wells with and without statistically significant *p*

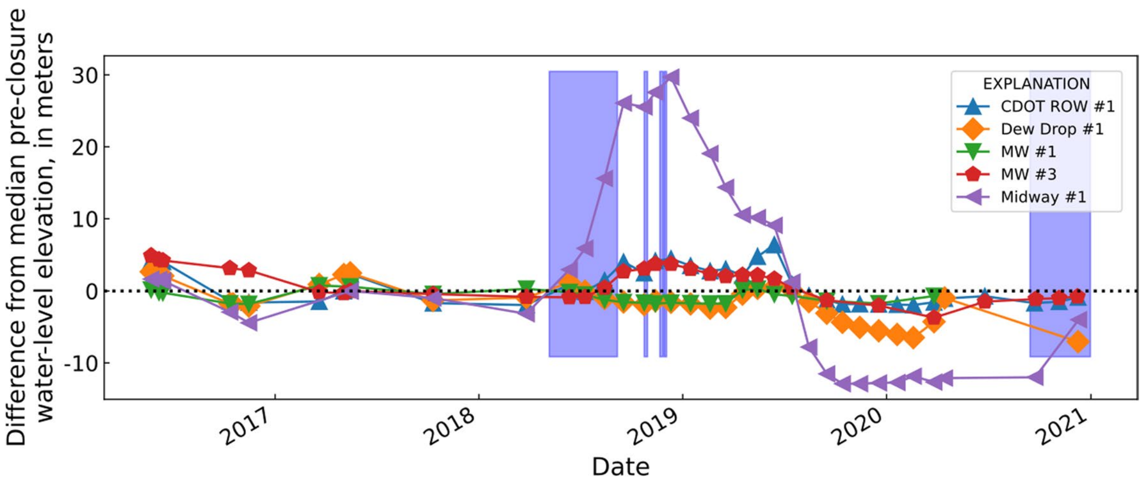

Fig. 4 Difference from median pre-closure (before May 2018) groundwater-level elevations for select wells at the Superfund site. Periods during which the bulkhead was closed are shaded in blue

Table 2 Results of Kendall's Tau statistical analysis comparing differences from median pre-closure (before May 2018) groundwater-level elevations in monitoring wells (completed either in the mine void [mine water] or in crystalline bedrock [groundwater]) to differences from median pre-closure (before May 2018) groundwater-level elevation in site PB #1 (representing the elevation of the groundwater table within the mine workings immediately behind the bulkhead)

Short site name	Monitoring location type	Kendall's tau	*p* value	Maximum groundwater-level elevation difference from pre-closure median (m)
CDOT ROW #1	Groundwater	0.67	**< 0.0001**	**2.77**
CDOT ROW #2	Mine Water	0.83	**< 0.0001**	**39.5**
Dew Drop #1	Groundwater	0.21	0.14	−1.54
Dew Drop #2	Groundwater	0.21	0.14	−2.43
Dew Drop #3	Mine Water	0.88	**< 0.0001**	**38.1**
Midway #1	Groundwater	0.81	**< 0.0001**	**19.1**
Midway #2	Mine Water	0.91	**< 0.0001**	**33.6**
MW #1	Groundwater	−0.33	0.06	−1.63
MW #2	Groundwater	−0.22	0.23	−0.23
MW #3	Groundwater	0.87	**< 0.0001**	**2.38**
Niwot #1	Mine Water	0.75	**< 0.0001**	**38.0**
Niwot #2	Mine Water	0.82	**< 0.0001**	**36.7**
Niwot #3	Mine Water	0.29	0.10	−0.50

Bolded *p* values less than 0.05 were interpreted to represent statistically significant correlations between groundwater-level elevation changes at the given location and site PB #1. Maximum difference from pre-closure median during water impoundment is included with positive numbers indicating groundwater-level increases and negative numbers indicating groundwater-level decreases

values indicates that wells with statistically significant correlations have greater maximum differences. Maximum differences are greater in all wells completed within the mine workings when compared to those completed in crystalline bedrock. As an example of potential ambiguity in statistical testing, MW #1 has a p value = 0.06, just above the selected alpha value for the test of 0.05, meaning that this well is interpreted as not having statistically significant hydrologic connectivity to the mine workings. Well MW #1 has one of the greatest maximum differences from pre-closure median groundwater-level elevation of any well with a non-statistically significant p value, but the maximum difference and Kendall's Tau are both negative, indicating that groundwater-level elevations in this well decreased when the workings were flooded. This is the opposite of the behavior observed in all wells with statistically significant p values. Groundwater-level fluctuations in this well may be complicated by processes other than water impoundment within the mine workings. This discussion is meant to explore some of the ambiguity inherent in the use of strict cutoff criteria in p

values. It is important, however, to not over-interpret p values close to the cutoff, a process known as p hacking (Helsel et al. 2020; Wasserstein and Lazar 2016).

Groundwater-flow modeling using the AEM approach was implemented to quantify groundwater dynamics at the Superfund site, and to test the AEM for application to other similar sites. Groundwater modeling utilized a probabilistic approach, wherein parameters were varied over statistically relevant distributions bounded by observations or assumptions (e.g., observations of streamflow loss, ranges in K values, etc.). The probabilistic approach incorporates uncertainty in model inputs to derive a best-fit model. One simulation was completed for each combination of the generated parameter sets, totaling 6,560 separate model calculations.

Selected results of probabilistic simulations are illustrated in Fig. 5. Histograms in panels (a) and (c) of Fig. 5 show ranges of simulated parameters (K_{br}, K_v, Q_{adit}, Q_{stream}) and the parameter value for the selected model in the vertical black line. Scatterplots in panels (b) and (d) of Fig. 5 show observed versus simulated groundwater-level elevations. Model #412 (Fig. 5a, b) simulates full range of hydraulic head values observed in the system but under-simulates the groundwater-level elevation at PB #1. Simulation of PB #1 is important for the model, because this is the location of the bulkhead and, therefore, represents the location of the groundwater discharge point simulated in the model. Model #3702 (Fig. 5c, d) produces a much better groundwater-level elevation fit to all sites in the mine workings, but did not well simulate the monitoring wells completed in the Silver Plume Granite, resulting in large over-estimations of groundwater-level elevations at MW #1, MW #2, and MW #3 (which plot off the top of Fig. 5d). Despite the large residuals in model fit, these models assist in conceptualizing the groundwater system at the Superfund site by corroborating basic analyses presented, above, that groundwater is highly compartmentalized and that inhomogeneities in hydraulic properties are required to fit observed hydraulic heads in the crystalline bedrock and mine workings.

The input parameter sets indicate the extent to which simulations are affected by variable K values and boundary conditions. Estimated parameter values tended to move to the edges of the probability distributions, indicating a distribution that may be too narrowly defined. Several attempts were made to widen the distribution but parameter values continued to move to the edges of the distribution. Parameter distributions could be continued to be widened arbitrarily,

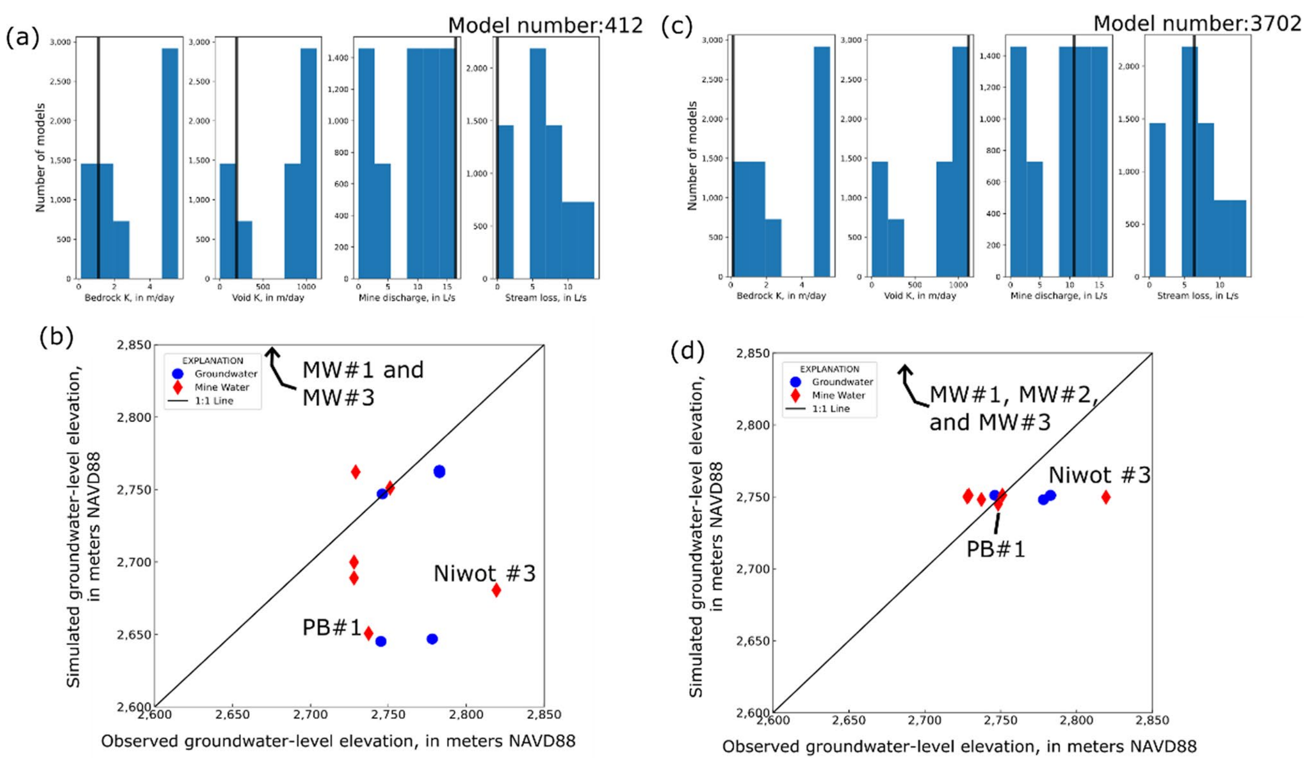

Fig. 5 Selected results of probabilistic groundwater-flow modeling, including **a** histogram of model input parameter distributions and parameter values used in model #412 (vertical black lines), **b** observed versus simulated groundwater-level elevations from model #412, **c** histogram of model input parameter distributions and parameter values used in model #3702 (vertical black lines), and **d** observed versus simulated groundwater-level elevations from model #3702

but if changes are not based on observations, this would tend to make the results less applicable to the site.

Discussion

The combination of observed groundwater compartmentalization in conjunction with statistical correlations between groundwater-level changes in the mine void and in groundwater wells indicates the prevalence of fracture-controlled groundwater flow at the site. At the scale of 10's to 100's of meters, strong hydraulic barriers appear to preclude interaction between groundwater in the Precambrian bedrock (Idaho Springs Formation/Silver Plume Granite) and the mine workings (Fig. 3). However, on the scale of single meters, water-bearing fractures with estimated connections to the mine workings occur in both Tertiary igneous dikes and Silver Plume Granite, based on statistically significant correlations at MW-3 (Table 2). Groundwater compartmentalization and connectivity play a key role in conceptualizing the physical hydrology of the Superfund site, which in turn could partially govern remediation strategies.

Steep vertical (5.5–13 m/m) and horizontal hydraulic gradients were maintained between the mine workings and surrounding crystalline bedrock before the bulkhead was closed (Fig. 3). Little temporal variability in these gradients indicates that groundwater flow is impeded by a physical barrier. Mine excavation typically produces fractures which may increase the permeability of host rocks (Gagné et al. 2013), and would tend to produce the opposite effect as that observed on the Superfund site. The most likely explanation for the maintenance of high vertical gradients is the loss of permeability due to hydrothermal mineralization which formed the deposit (Ingebritsen and Appold 2012). In addition to hydrothermal mineralization, the formation of secondary minerals in fractures due to natural weathering of the mineral deposit may have reduced permeability. Despite the high degree of compartmentalization and steep hydraulic gradients, fracture connectivity does provide spatially variable pathways for groundwater flow based on statistical analysis.

It is important to note the large quantity of groundwater-level data utilized in this analysis in comparison with other studies of flooded mine workings (Cravotta et al. 2014; Wellman et al. 2011; Wolkersdorfer 2008), and the manner in which these spatially and temporally distributed data sets allow for hydrologic conceptualization. It is common in assessment of flooded underground mines to utilize geochemistry to understand flow dynamics (Elliot and Younger 2007; Gammons et al. 2009; Walton-Day et al. 2021), but direct observation of hydraulic heads within and adjacent to mine workings is rare. For instance, in the Animas River watershed in southwest Colorado, where the Gold King mine release occurred in 2015 (Rodriguez-Freire et al. 2016), there were no observation wells drilled directly in the flooded workings as of 2022. This is compared with the density of observation wells drilled into and adjacent to the workings at the Captain Jack site, which allows for detailed interpretation of groundwater-flow directions (Fig. 2). In the few published investigations where hydraulic head data were collected within or adjacent to flooded workings (Cravotta et al. 2014; Wellman et al. 2011), these data sets were typically limited in spatial extent and temporal frequency. This analysis utilized a data set of 455 individual groundwater-level measurements made on up to monthly basis for a period of years. This high-frequency data set allowed for statistical relations to be recognized that would have been difficult to discern with fewer observations.

Results of AEM modeling for the Superfund site may have implications for groundwater-flow modeling at mine sites in similar mountainous terrain. The AEM was effective at simulating groundwater-level elevations within the central portion of the study area, specifically at wells CDOT ROW #1, CDOT ROW #2, Midway #1, Niwot #1, Niwot #2, and PB #1. These sites are completed in both crystalline bedrock and the mine workings, and each was simulated with a residual of less than 30 m, and important sites such as PB #1 was simulated with a residual of 3 m (Fig. 5d). The model was consistently unable to match observed groundwater-level elevations at MW #1 and MW #3. As indicated by statistical analysis, MW #3 likely has fracture-related connectivity to the mine workings, but no such connection was simulated by the model, because data on faults or fractures at the scale of the model are lacking despite the geotechnical assessment of Deere and Ault (2006), which did indicate shear zones and fractures intersecting the mine workings. Similarly, the model was unable to accurately simulate Niwot #3 despite correctly fitting other wells completed in the mine workings. Water-table maps (Fig. 2) and hydrologic cross sections (Fig. 3) indicate that Niwot #3 has somewhat variable behavior from Niwot #1 and Niwot #2. Niwot #3 remains saturated when other wells in the vicinity become dry. Those results combined with the modeling results indicate that the mine workings penetrated by Niwot #3 may not be in hydraulic connection with the remainder of the open workings, consistent with hydrologic cross sections (Fig. 3).

Overall, AEM results show that the method is useful for screening level analysis of groundwater flow at mine sites, but lack of detailed hydrogeologic data hinders the model fit. Creation of models supporting detailed decision making would require substantial field collection programs including methods, such as geophysics (Wellman et al. 2011) or discrete fracture aquifer testing (Manning et al. 2020). Results of such advanced field efforts could be included in AEM applications and would likely provide more robust tools for predictive modeling.

Although without collection of additional hydrogeologic data the AEM model is not sufficient for predictive modeling for mine remediation, it is helpful in conceptualizing the system and indicating where future data collection would be useful. Modeling of a highly heterogenous system is a primary benefit of using an AEM model. This conceptual understanding may be equally useful in remediation planning and focusing data collection activities. The AEM groundwater-flow model prepared for the study site illustrates that the model cannot be calibrated without including inhomogeneities in the groundwater system or by collection of additional hydrogeologic data. These inhomogeneities would have needed to be determined prior to bulkhead emplacement and would have most likely shown that the mine void has poor connectivity to the adjacent crystalline bedrock. This information would have been useful for predicting the rapid filling of the mine workings after the bulkhead was closed. Application of the AEM in similar screening-level analyses may be useful at other sites, because unlike numerical groundwater models, the AEM can be rapidly formulated to use statistically based sets of parameter values. Numerical groundwater-flow models have the ability to use large sets of unknown parameter distributions, but computational and cognitive burden to analysts may be substantial for numerical models due to their complex nature (White et al. 2020). The AEM may be rapidly parameterized and tested, potentially increasing efficiency in the early stages of a project when planning robust data collection is most useful.

Conclusions

The Captain Jack Superfund Site, near the town of Ward, in north-central Colorado contains a draining mine adit in which a hydraulic bulkhead has been installed to preclude discharge of contaminated water to local streams. Rapid filling of mine workings following closure of the bulkhead necessitated an investigation into the hydrology of the area, such that a better understanding could guide future remediation efforts. Patterns in groundwater flow were assessed using temporal variations in measured groundwater-level elevations. Statistical analysis of correlations (Kendall's Tau) between hydraulic head changes in the mine workings and in nearby monitoring wells were used to evaluate spatial patterns in groundwater connectivity. The groundwater system was also simulated using inhomogeneities in an AEM model to evaluate the applicability of the method to similar sites.

Mine workings act as a sink on the local groundwater system and most of the estimated groundwater-flow paths in the local watershed are deflected towards the workings. Prior to bulkheading, steep hydraulic vertical hydraulic gradients (5.5–13 m/m) are maintained between the workings and crystalline bedrock, likely due to decreased permeability from hydrothermal and secondary mineralization. After bulkheading, the gradients are reduced but flow reversals from the workings into bedrock groundwater were not indicated. Statistical analysis of groundwater connectivity indicates that a subset of wells completed in crystalline bedrock have statistically significant correlations to hydraulic head changes in the mine workings. Wells with correlations to the mine workings are completed both in Tertiary igneous dikes associated with mineralization and in Precambrian granite, illustrating that fractures controlling groundwater flow are present throughout the watershed.

The AEM was used to simulate groundwater flow and incorporated probability distributions of parameters controlling hydraulic conductivity, recharge, and discharge to understand uncertainty in the model and to guide future data collection. More than 6000 model simulations were completed; only two of which were discussed for conciseness. The AEM was able to reproduce high observed hydraulic gradients between the mine workings and crystalline bedrock, and was able to match observed groundwater-level elevations at the simulated point of groundwater discharge (the bulkhead). The model was unable to match observed groundwater-level elevations in several bedrock monitoring wells, however, indicating the need for additional model complexity based on additional data collection.

The combination of approaches used at the Captain Jack Superfund Site provide examples of infrequently used methods of characterizing groundwater flow at mine sites. Despite the regulatory mandate for data collection at mine sites undergoing remediation these data are rarely analyzed using statistical techniques well suited to trend or correlation analysis. Increased application of these low-cost data analysis techniques may lead to enhanced understanding of groundwater flow and transport at these sites. In addition, this study indicates that the AEM approach may be useful at sites with few parameterization data with which to accurately simulate groundwater levels within a groundwater model, because the AEM model may be rapidly parameterized and tested.

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Author contributions CN completed field work, conducted statistical and modeling analyses, prepared figures, text, and tables. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The author has no conflicts of interest to report.

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