Groundwater Remediation in a Floodplain Aquifer at Shiprock, New Mexico - 16097

Dave Peterson*, David Miller*, Mark Kautsky**, David Dander*, Joni Nofchissey***
*Navarro Research and Engineering, Inc.
**US DOE, Office of Legacy Management
***Navajo Abandoned Mine Lands Reclamation Program, UMTRA Department,
Navajo Nation Division of Natural Resources

ABSTRACT

The Shiprock, New Mexico, Disposal Site is the location of a former uranium and vanadium ore-processing mill that operated from 1954 to 1968. During milling years, tailings leachate and other mill-related liquids migrated into underlying sediments, resulting in the contamination of groundwater beneath the river terrace containing the mill and a nearby floodplain alluvial aquifer adjacent to the San Juan River. The US DOE Office of Legacy Management manages the site and is implementing the current groundwater remedy for the floodplain area, consisting of natural flushing supplemented by extraction of alluvial groundwater to accelerate reduction in contaminant concentrations. The alluvial aquifer contains elevated concentrations of sulfate, uranium, and nitrate derived largely from the historical eastward migration of groundwater through terrace alluvium and underlying bedrock to the floodplain. The bedrock formation beneath the entire Shiprock site is Mancos shale, which forms an escarpment that separates the terrace from the floodplain.

Contamination in the floodplain alluvial aquifer is influenced by a dynamic flow system that changes seasonally and from year to year. Simulations with a floodplain flow model based on monitored groundwater levels and coincident river-surface elevations show that background groundwater flow, unaffected by remediation pumping, is characterized by distinct hydraulic conditions for three separate periods each year. During months of low river flow in winter and early spring, river losses to the aquifer create a large hyporheic zone in the south half of the floodplain. Simultaneously, recharge of continually flowing surface water emptying onto the north half of the floodplain from Bob Lee Wash creates divergent, radial flow from the wash outlet and diverts northwestward-migrating contaminant plumes to the northeast where they discharge to the river. Subsequent bank storage processes in May and June from high snowmelt runoff change background flow directions, increasing the spread of contamination in the alluvium. From mid-summer through fall, river flows are typically similar in value to those observed prior to the onset of snowmelt, but groundwater elevations in the aquifer are noticeably lower than water levels observed in winter and early spring and may induce river losses to the aquifer.

Several different contaminant sources have impacted the alluvial aquifer. Much of the contamination originated as tailings leachate and raffinate wastewater that infiltrated the terrace subsurface and eventually reached the floodplain at the escarpment. Additional sources of contamination in the aquifer included discharge of mill effluent to Bob Lee Wash and a pond at the base of the escarpment, and aqueous mobilization of solid-phase contamination in the form of windblown deposits and contaminants adsorbed to alluvial sediments. The degree to which remnant, secondary-source processes, such as leaching of solid-phase deposits and discharge of terrace groundwater across the escarpment, contribute to existing contaminant plumes is uncertain.

The floodplain remediation system consists of two groundwater extraction wells, pumping from two horizontal wells placed in trenches near the base of the escarpment, a sump collecting discharges from seeps in the escarpment wall, and discharge of collected water to an evaporation pond on the terrace. Flow-model simulations indicate that most contaminated areas are captured by remediation pumping, resulting in several zones of freshwater between the river and the escarpment.

Despite the highly transient nature of groundwater flow beneath the floodplain and the varied contaminant sources, initiation of remediation pumping in 2003 and coordinated operation of the system's various components have successfully removed large amounts of contaminant mass and helped prevent discharge of contaminated groundwater to the river. The percentage reductions of dissolved sulfate, uranium, and nitrate mass in the aquifer estimated for the first 9 years of remediation range from 40% to 72%.

INTRODUCTION

A uranium- and vanadium-ore-processing mill operated from 1954 to 1968 within the Navajo Nation near Shiprock, New Mexico. By September 1986, all tailings and structures on the former mill property were encapsulated in a disposal cell built on top of two existing tailings piles on the Shiprock site (the site) [1]. Local groundwater was contaminated by multiple inorganic constituents as a result of the milling operations. The U.S. Department of Energy (DOE) took over management of the site in 1978 as part of the Uranium Mill Tailings Remedial Action (UMTRA) Project. The DOE Office of Legacy Management currently manages ongoing activities at the former mill facility, including groundwater remediation. Remediation activities are designed primarily to reduce the concentrations and total plume mass of the mill-related contaminants sulfate, uranium, and nitrate.

In addition to contaminating groundwater in alluvial and bedrock sediments directly below the mill site, ore processing led to contamination of a nearby floodplain bordering the San Juan River. Groundwater in a shallow alluvial aquifer beneath the floodplain is strongly influenced by the morphology of the river channel as well as changing flows in the river, which provides drainage for regional runoff from the San Juan Mountains of Colorado. As part of a recent study of the floodplain hydrology, a revised conceptual model was developed for the alluvial aquifer along with an updated status of contaminant plumes that have been impacted by more than 10 years of groundwater pumping for site remediation purposes. Several findings from the recent study will be discussed here.

SHIPROCK SITE

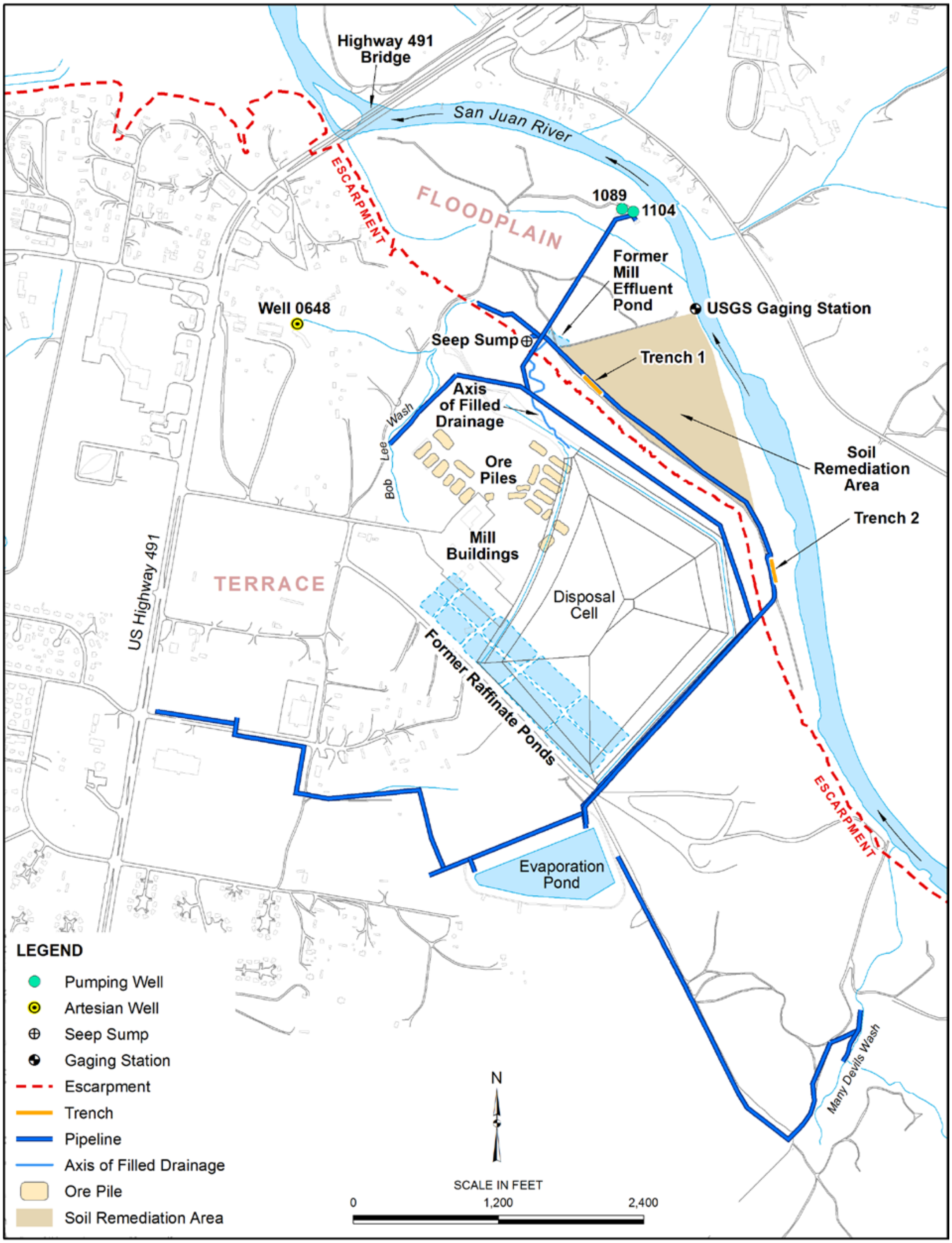
The Shiprock site is located in the northwest corner of New Mexico, on the west bank of the San Juan River (Fig.1). The site is divided physiographically into two regions, an elevated terrace and the river floodplain, separated by a 15 m escarpment. The former mill and appurtenant features were located on the terrace to the west and south of the escarpment. The escarpment is an erosion surface of the Mancos Shale, the bedrock formation for the entire site and surrounding areas. Groundwater beneath the terrace flows within both weathered and competent portions of the bedrock and about a meter of alluvium overlying the shale. Groundwater in the floodplain area flows primarily within the alluvial aquifer, but some subsurface flow also has the potential to occur in weathered shale and fractured parts of competent shale underlying the aquifer.

The current groundwater remedy for the floodplain alluvial aquifer consists of natural flushing of groundwater to the San Juan River supplemented by groundwater extraction from the aquifer to accelerate reduction in contaminant concentrations [2]. Natural flushing was selected on the basis of groundwater flow and transport modeling for the entire Shiprock site [1, 2] indicating that pumping of contaminated terrace groundwater would reduce terrace water levels and contaminant discharges to the floodplain to the extent that cleanup of the alluvial aquifer was feasible.

Historical and Current Features

The site disposal cell encompasses 31 ha on the terrace just south and west of the bedrock escarpment (Fig. 1). During milling years, 10 unlined raffinate ponds were located on the southwest edge of the tailings piles [1], in an area that today is partially covered by the southwest end of the disposal cell. Buildings and ore storage areas used in the milling operations were just northwest of the current footprint for the disposal cell (Fig. 1).

Two surface drainage features other than the San Juan River are capable of conveying surface-water flows at the site. Under natural conditions, Many Devils Wash (Fig. 1) carries limited quantities of surface water year-round directly to the river [1], thereby bypassing the floodplain. Under natural conditions, Bob Lee Wash, located approximately 460 m northwest of the disposal cell, is an ephemeral drainage that conveys storm runoff on the terrace to the north end of the floodplain. However, since the late-1970s, a flowing artesian well (well 0648) at the head of a small tributary to Bob Lee Wash has continuously fed surface water at a relatively constant rate to the lower parts of the wash and, subsequently, to the floodplain (Fig. 1).



\\LM\ess\EnvProjects\EBM\LTS\111\0020\20\000\S13427\S1342700.mxd smithw 10/26/2015 11:09:09 AM

Fig.1. Shiprock, New Mexico, Legacy Management Site

The floodplain is about 1.8 km long and 0.5 km wide at its widest point. Much of the floodplain area bordering the river is considered a riparian zone. Vegetation increased dramatically on the floodplain north and east of the mill site during the ore-processing due to increased availability of water, for both milling and other uses. As a result of mill operations, mill effluent was delivered to a small pond (Fig. 1) located near the escarpment at the outlet of a northwest-trending drainage that extended from the northwest corner of the tailings piles (Fig. 1) and was subsequently filled as part of the site's surface remediation. Since the milling years, vegetation in the area has expanded to cover virtually the entire floodplain. Delivery of surface water to the floodplain via ditches connected to the river and conveyance of artesian-well water to the outlet of Bob Lee Wash have induced much of the vegetative growth. Transpiration of moisture from trees on the floodplain is potentially an important process because it can affect groundwater flow in the alluvial aquifer.

Flow data for the local San Juan River are available dating back to 1931, when the U.S. Geological Survey (USGS) began gaging its flows. A USGS gaging station was installed in 1994 at a site about 150 m upstream of a highway bridge spanning the river near the north end of the floodplain (Fig. 1). The station location was moved upriver in June 2006 to its current location shown in Fig. 1, on the Shiprock site and approximately 1 km upstream of the bridge. Measured river stages and flows at the USGS gage help explain many of the groundwater flow patterns observed in the alluvial aquifer.

In the mill operation period and years thereafter, occasional strong winds dislodged contaminated materials from the tailings piles and deposited the airborne dust at lower onsite elevations, mostly on the south half of the floodplain. Shallow soil excavation on a large triangular section of the floodplain (Fig. 1) during surface remediation activities removed much of the windblown contamination to levels below applicable cleanup requirements.

Remediation System

Subsurface remediation at the Shiprock site began in 2003, using a combination of several pumping wells tapping the terrace groundwater system and two pumping wells in the floodplain alluvium near the San Juan River. The primary purpose of the two alluvial-aquifer wells was to reduce contaminant levels in an area that had contained some of the highest concentrations observed for the Shiprock site. Several months of groundwater extraction at the near-river location revealed that both wells were inefficient, suggesting that alternative pumping wells would be needed in this part of the floodplain. A decision was also subsequently made to expand the alluvial aquifer system by installing additional means of extracting groundwater in other parts of the floodplain.

The current floodplain remediation system, finalized in spring 2006, consists of groundwater extraction at two vertical wells near the San Juan River and two horizontal wells near the base of the escarpment [3], and pumping from a sump collecting perched terrace groundwater discharging at the escarpment. The near-river locations, consisting of wells 1089 and 1104 (Fig. 1), pump groundwater from an area (1089/1104 area) that continues to show some of the highest concentrations of sulfate and uranium. Pumping from the horizontal wells at Trench 1 and Trench 2 (Fig. 1), each 30.5 m long, greatly increases the total mass of contamination removed from the floodplain and prevents contamination at the base of the escarpment from discharging to the river. The sump, near the former location of the mill effluent pond at the base of the escarpment, captures contaminated water emanating from two seeps in the escarpment wall between Trench 1 and Bob Lee Wash, as well as minor amounts of local alluvial groundwater. Water collected at each of these system features is pumped via a pipeline to an evaporation pond on the terrace immediately south of the disposal cell (Fig. 1). The floodplain pipeline is part of a larger pipe network that also collects contaminated groundwater from several parts of the terrace groundwater system for delivery to the evaporation pond.

GROUNDWATER FLOW SYSTEM

Floodplain Aquifer

The alluvial aquifer, consisting largely of unconsolidated sand, gravel, and cobbles (basal gravels) that were deposited by the San Juan River on Mancos Shale bedrock, is unconfined under most of the floodplain. In most areas, finer-grained alluvial sediments consisting of fine- to coarse-grained sand, silt, and some clay overlie the basal gravels. The combined thickness of basal gravels and fine-grained surficial materials varies across the floodplain and can be as much as 8 m on the floodplain’s north end. The saturated thickness of the alluvial groundwater under low-flow conditions in the river ranges from about 1 m on the south end of the floodplain to 6 m on the north end. Depth to groundwater when not affected by a high river stage generally ranges from 1 to 2 m [1].

The uppermost meter of Mancos Shale below the alluvium is typically soft and weathered, and the upper surface of the shale is irregular. Prehistoric flows in the river incised the bedrock surface, creating paleochannels that were subsequently filled with high-energy, coarse-grained sediments. In general, bedrock elevations decrease about 7 m from south to north. In contrast, the land surface is relatively flat, with an elevation range of about 2 m and no visually apparent trends from south to north [1].

The hydraulic conductivity of the floodplain alluvium can vary by more than an order of magnitude (e.g., 2–100 m/day), with the coarse basal materials generally showing the largest conductivities. The relatively thin saturated thickness of the alluvial aquifer makes it difficult to identify vertical groundwater movement between the shallowest and deepest alluvial sediments; groundwater flow has typically been described as two-dimensional and horizontal. However, vertical groundwater flow, particularly in response to water-density gradients, is likely. Such spatial variations in density are attributed to high water salinity in the more contaminated portions of the aquifer. Historically, total dissolved solids (TDS) concentrations as high as 45,000 mg/L were common in near-escarpment locations and the 1089/1104 area, and TDS levels as high as 20,000 mg/L remain today [4]. Density-dependent groundwater flow has also likely influenced the orientation of contaminant plumes and enhanced transverse spreading of contamination [5].

Modeling Variable-Flow Systems

Previous studies of the Shiprock site [1, 6, 7] describe the dynamic nature of the floodplain groundwater system, with groundwater levels in the alluvial aquifer changing in response to variable river flows. Given that the magnitude of changes in river elevation varies with location in the river, it is likely that groundwater flow directions also change. Dynamic behavior of floodplain groundwater flow paths in turn impacts the spatial distribution of dissolved contamination in the aquifer.

Though the dynamic nature of floodplain groundwater has been acknowledged, previous evaluations of flow and transport in the alluvial aquifer have assumed that the flow fluctuates around an average steady-state configuration. To better understand transient flow paths in the aquifer and how they potentially affect the remediation system, the recent study of the floodplain included development of a groundwater flow model capable of representing spatial and temporal changes in groundwater levels. The modeling was conducted with the USGS code MODFLOW [8]. Model input and simulation results were handled with the graphical user interface GWVistas [9].

The influence of the San Juan River on groundwater flow in the alluvial aquifer was included in the model by treating the west and south edges of the river as a prescribed head boundary. This was accomplished with a method for estimating profiles of estimated surface-water elevation along the entire reach of the river bordering the floodplain for specific time periods. With the use of a combination of water-elevation surveys conducted on the river at two different times in 2011 and corresponding stage data at the USGS gaging station, river-elevation profiles were computed for both low-flow and bank-full conditions in the river. The low-flow profile revealed the locations and dimensions of sequential pools and riffles on the river that appear to exert control on river-aquifer interactions along the entire river reach adjacent to the floodplain. In contrast, the riffles observed in the low-flow profile between the Highway 491 bridge (Fig. 1) and about 450 m upstream of the USGS gage were not present in the bank-full profile. An interpolation algorithm was employed to estimate intermediate river profiles between the low-flow and bank-full cases.

The model was calibrated with simulations of both steady- and transient-flow states in the aquifer corresponding to specific groundwater monitoring events at the site. This resulted in a final set of model parameters that performed well in representing the flow system under a variety of hydrologic conditions. Calibrated parameters included a single, representative value of hydraulic conductivity and a single, uniform value of specific yield for approximating temporal changes in hydraulic head in response to system stresses. Each simulation included the effects of prescribed river heads and accounted for constant boundary inflows from terrace groundwater discharging across the escarpment and recharge at the outlet of Bob

Lee Wash. With the use of particle tracking software [10] in GWVistas, the flow patterns typical of three different seasons were identified. The simulations accounted for flow paths caused by remediation pumping as well as the flow directions associated with background, nonpumping conditions.

Flow Patterns in Winter and Early Spring

A simulation of flow during a groundwater monitoring event in March 2011 resulted in a potentiometric surface that was considered representative of background (nonpumping), steady-state flow conditions during winter and early spring (November–April) of each year, when river flows are generally stable and low. Model-generated flow paths for this simulation (Fig. 2a) indicate that baseline groundwater flow in the south third of the floodplain is largely parallel to the escarpment, with seepage losses from the river and inflow of terrace groundwater sourcing subsurface water in this area. Though much of the surface water lost to the alluvial aquifer remains in the subsurface, inflowing river water from some sections of the river returns to the river in other sections tens to hundreds of meters downstream (Fig. 2a). Areas of the aquifer exhibiting this type of exchange flow with the river are referred to as hyporheic zones. A particularly large hyporheic zone, spanning a 400 m long area southeast of the gaging station (Fig. 2a), is created by a large drop in river elevation of about 1.2 m over 400 m of river length. At the upstream end of the hyporheic zone, mixing of fresh water from the river with local groundwater can lead to chemical reactions that affect the concentrations of site contaminants. Constituent concentrations within the hyporheic zone are relatively low because of the freshwater influx from the river.

In winter and early spring (November–April), recharge of continuous surface-water flow from Bob Lee Wash dominates groundwater flows in the north half of the floodplain. The recharged water, which is relatively fresh, is centered on the outlet of the wash at the floodplain, causing local groundwater mounding and concomitant spreading of water in a radial pattern (Fig. 2a). Some of the recharged water diverts contaminated groundwater in the vicinity of the Trench 1 footprint toward the northeast, to a section of the river containing the gaging station.

Another steady-state simulation, based on measured groundwater levels during a site monitoring event in March 2010, provided an illustration of flow paths occurring in the aquifer in response to remediation pumping during the low river-flow season in winter and early spring. Fig. 2b shows the particle tracks associated with this simulation, including the capture zones created by pumping in the 1089/1104 area as well as groundwater extractions from Trench 1 and Trench 2. As indicated by the mapped flow paths, simultaneous pumping from Trench 1 and the 1089/1104 area produces a flow divide between the two pumping locations and a stagnation zone about 150 m northeast of Trench 1.

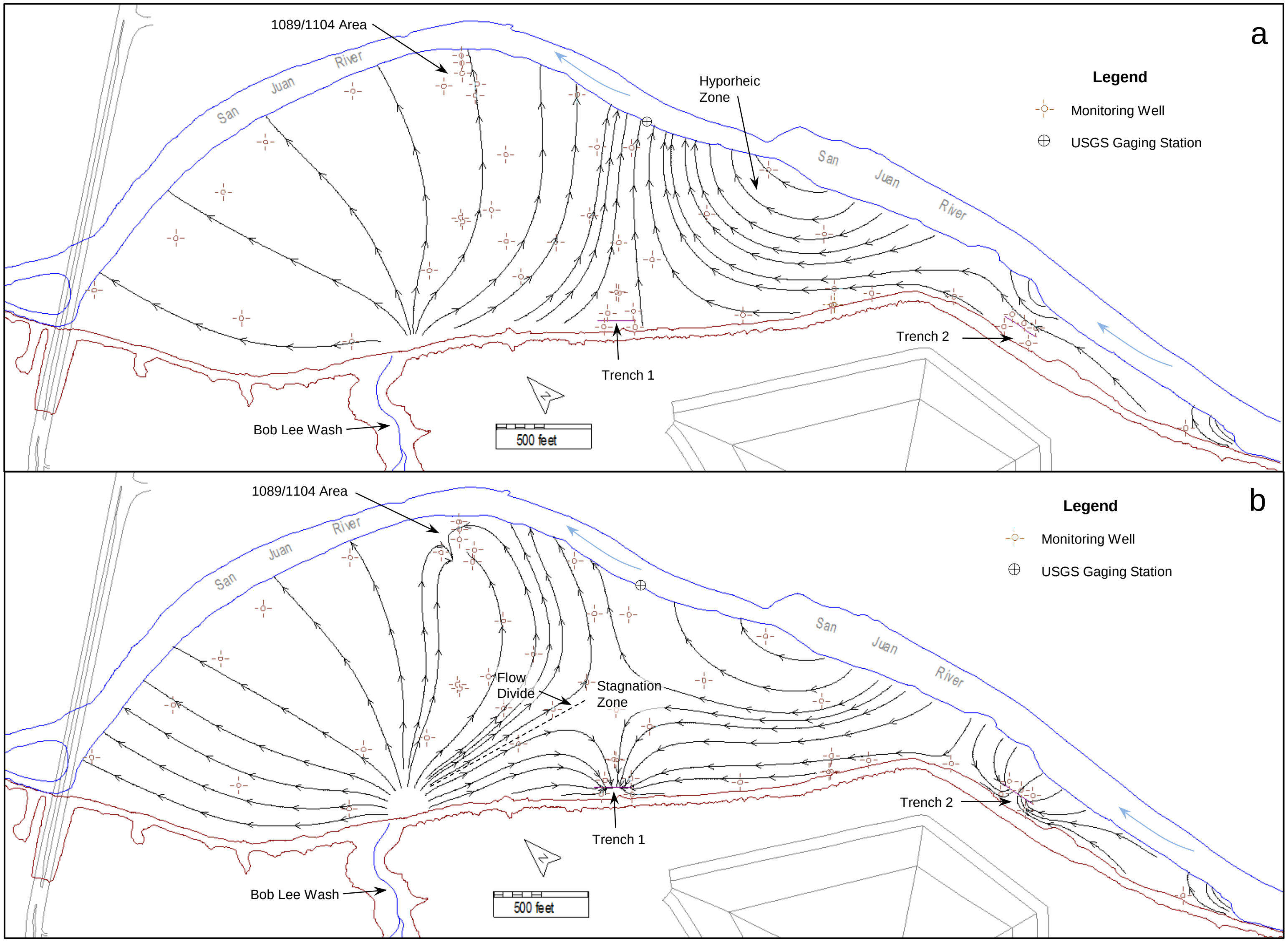


Fig. 2. Computed Flow Paths for Winter and Early Spring Under (a) Background Conditions and (b) Remediation Pumping

Fig. 2b indicates that pumping from Trench 1 induces inflow of relatively clean water from a section of the river to the southeast as well as from the groundwater mounding area to the northwest. The particle tracks in Fig. 2b also portray river losses to the aquifer in the Trench 2 area in response to pumping from the trench [7]. In addition, remediation pumping in the 1089/1104 area appears to induce northeastward flow of fresh water from the recharge area at the Bob Lee Wash outlet. Collectively, groundwater extraction from the three main pumping areas appears capable of creating multiple zones of relatively clean groundwater between the river and the escarpment.

Additional Flow Modeling

A simulation of flow conditions in the alluvial aquifer between late March 2011 and August of the same year illustrated the flow patterns that tend to dominate the aquifer during heavy snowmelt runoff from the San Juan Mountains. In 2011, the runoff began increasing in May and peak river flow was recorded in early June. Groundwater elevation data from three monitoring events during the simulation period were available for ground-truthing the modeling results. The transient simulation showed that elevated surface-water levels accompanying the high river runoff cause groundwater levels in the aquifer to rise, and surface water losses to the aquifer in the form of bank storage appear to take place along the entire length of the river adjacent to the floodplain prior to peak river discharge. Though most of the influent fresh water eventually returns to the river after passage of peak runoff, the simulation suggests that the influent river water radically changes flow patterns in the aquifer from those occurring during preceding months. Within portions of the aquifer containing high levels of contaminants, the altered subsurface flows likely divert groundwater in directions not seen in preceding months and, in the process, help spread contamination [11].

A final simulation of steady flow conditions in the October 2011, during a semiannual monitoring event, illustrated how the relationship between the river and groundwater during mid-summer through fall (July–October) tends to differ from the relationship during early spring. Specifically, groundwater elevations in wells near the river in mid-summer, late-summer, and fall are frequently lower than local river elevations, whereas groundwater levels during winter and early spring are typically higher than corresponding groundwater levels. This change occurs even though mean flows and elevations in the river during late summer and fall are close in value to those in winter and early spring. Evapotranspiration (ET) tied to floodplain vegetation appears to be the cause of the lower groundwater levels in summer through fall. On some days, decreased groundwater elevations near the river simply reduce the discharge of groundwater to the river, whereas ET-induced losses of river water to the aquifer become possible at other times.

CONTAMINANT SOURCES

The sources of contaminated groundwater in the floodplain aquifer are varied. Much of the contamination resulted from infiltration of contaminated liquids on the terrace in the vicinity of former mill operations and subsequent transport toward the floodplain via the terrace groundwater system [1, 2]. During the milling era, the origins of contaminated terrace groundwater included leakage from the unlined raffinate ponds, leaching by rainfall of materials piled in the ore storage area (Fig. 1), and downward seepage of liquids delivered to the tailings piles, now contained within the disposal cell.

Other historical sources of contamination in the alluvial aquifer consist of mill-related liquids deposited on the floodplain surface either through intended or accidental means. In summer 1960, a large volume of acidic waste effluent spilled from the northwest end of the raffinate ponds and flowed down Bob Lee Wash to the north half of the floodplain [1, 12]. Historically, mill-generated liquids were also delivered to the north half of the floodplain via mill discharges to Bob Lee Wash and by delivery of liquids to the small effluent pond at the base of the escarpment (Fig. 1). Leaching of contamination left in solid form in floodplain soils and deeper alluvium is a secondary source of contaminants in floodplain groundwater, both historically and currently. This includes dissolution of windblown tailings that deposited on the floodplain surface and subsequently escaped remedial excavation.

Hydraulic and water chemistry data collected during recent years at several terrace and floodplain wells indicate that discharge of contaminated terrace groundwater to the floodplain under current conditions is uncertain. Continued discharge is possible, but it is equally possible that, at some point, the discharge decreased to an insignificant level. Continued leaching of solid-phase contamination in floodplain sediments is also possible, but unknown at this time.

REMEDIATION PERFORMANCE

The dynamic nature of floodplain groundwater and the potential presence of multiple secondary sources for contaminant plumes in the alluvial aquifer represent challenges to the performance of the floodplain remediation system. Measures of remediation progress are derived from annual reports on groundwater remedy performance for the Shiprock site. The most recent report [3], for monitoring events in 2014 and 2015, indicates that large masses of sulfate, uranium, and nitrate have been removed from the alluvial aquifer (Table I) since remediation began in 2003, and that the rate of mass reduction remains high. Accordingly, temporal plots of contaminant concentrations at most monitoring wells in the floodplain show decreasing trends from 2003 to 2015 [3].

The color-flood plots in Figs. 3a and 3b show, respectively, the spatial distribution of maximum uranium concentrations in alluvial groundwater in the 4 years that immediately preceded the start of remediation (2000–2003) and, most recently, in years 2014–2015. Comparison of the two plots illustrates the large impact of uranium mass removal over 12 years of remediation. The flow patterns in response to remediation pumping during low-flow conditions on the San Juan River (Fig. 2b), as well as seasonal patterns under background conditions (Fig. 2a), help explain the mapped uranium concentrations for 2014–2015 (Fig. 3b).

TABLE I. Mass Removals of Contaminants from the Shiprock Site Floodplain Aquifer

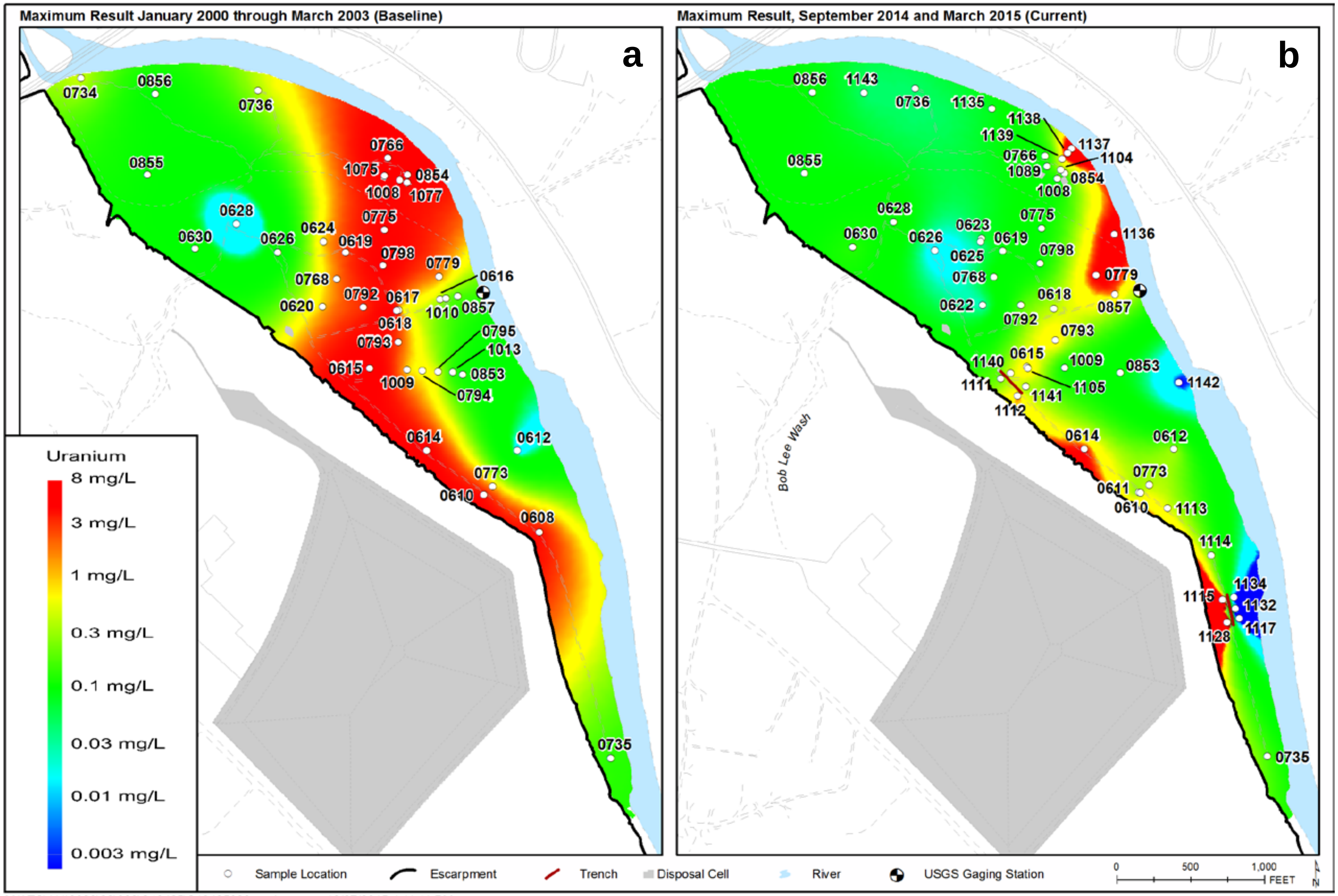
Constituent	**Sulfate**		**Uranium**		**Nitrate (as nitrogen)**	
Location	**Removed in 2014–2015**	**Cumulative Removal**	**Removed in 2014–2015**	**Cumulative Removal**	**Removed in 2014–2015**	**Cumulative Removal**
	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
1089/1104 Area	50,444	1,207,390	2.8	96	28	3,765
Trench 1	47,814	989,725	4.7	118	970	15,874
Trench 2	15,592	208,018	1.9	30	823	9,170
Seep Sump	7,082	56,676	0.5	5	65	476
Total Mass	*120,932*	*2,461,809*	*9.9*	*249*	*1,886*	*29,285*

With the use of the contour plots of contaminant concentrations in the alluvial aquifer during the 3 years 1999–2001 and 2011 and computational tools in GWVistas [9], calculated percentage reductions in the total dissolved mass of sulfate, uranium, and nitrate (as nitrate) during the initial 9 years of groundwater extraction were 40%, 64%, and 72%, respectively. This information, when combined with the previously discussed results of the most recent annual performance monitoring at the Shiprock site (e.g., Table I), indicates that highly transient flow conditions in alluvial groundwater and the uncertain nature of contaminant sources at the Shiprock site do not represent an impediment to remediation progress in the floodplain aquifer. Continued monitoring of contaminant levels at wells in the alluvial aquifer, particularly in areas near the base of the escarpment, is expected to shed light on the persistence of remnant, secondary sources for the floodplain plumes.

CONCLUSIONS

A recent assessment of the hydrology of the floodplain at the Shiprock site illustrated the dynamic nature of groundwater flow in the floodplain alluvial aquifer, which is largely driven by variable surface-water flows in the adjacent San Juan River. Transient river discharge induces changes in groundwater levels and flows, with notable changes occurring between seasons and from year to year. The transient groundwater flows in turn affect the distributions of sulfate, uranium, and nitrate contamination in the aquifer, as spatial and temporal variations in groundwater–surface water exchange cause changes in plume orientation and plume spreading.

When groundwater pumping is not occurring, background flow is characterized according to distinct hydrologic conditions observed during each of three general seasons: winter and early spring (November–April), early summer with high snowmelt runoff in the San Juan River (May–June), and mid-summer through fall (July–October). In winter and early spring, when river flows are typically stable and low, losses to the aquifer in the south half of the floodplain and subsequent return flows to the river in downstream areas create a large hyporheic zone that is



M:\LTS\111\0020\20\000\S13425\S13425000.mxd coatesc 10/27/2015 4:11:11 PM

Fig. 3. Color Flood Plot of Maximum Uranium Concentrations in the Floodplain Aquifer in (a) Preremediation Years and (b) 2014–2015.

characterized by relatively low contaminant concentrations. Simultaneously, recharge of continually flowing surface water emptying onto the north half of the floodplain from Bob Lee Wash produces divergent, radial flow from the wash outlet and diverts northwestward-migrating contaminant plumes to the northeast where they discharge to the river. In May and June and prior to the peak snowmelt runoff from the San Juan Mountains, the river appears to lose water to the aquifer in the form of bank storage along the entire floodplain length, and much of the lost surface water returns to the river for weeks following peak river discharge. Changing groundwater flow patterns during this period push plumes in directions not observed in preceding months and enhance transverse plume spreading. From mid-summer through fall, surface-water flows are typically similar in value to those observed prior to the onset of snowmelt, but groundwater elevations in the aquifer are notably lower than water levels during the preceding winter and early spring. The apparent cause of the lower groundwater levels is ET from shallow water-table areas and trees on the floodplain. Transpiration from near-river vegetation probably reduces groundwater discharge to the river at times, and river losses to the aquifer appear possible at other times.

Application of particle tracking software to simulations with a calibrated numerical model of groundwater flow in the alluvial aquifer shows the flow paths associated with background and remediation pumping conditions during winter and early spring months. The pumping-induced flow paths suggest that the remediation system creates several zones of relatively fresh water between the river and an escarpment of Mancos Shale bedrock that forms the west and south borders of the floodplain.

A variety of contaminant sources have contributed to contaminant plumes in the alluvial aquifer, and it is possible that remnant, secondary sources may continue to influence plume persistence beneath the floodplain. Historical and current mass loading rates from the secondary sources are uncertain. Monitoring of the aquifer near the escarpment will assist in determining whether secondary sources continue to be significant contributors to contaminant plumes.

Despite the highly transient groundwater flow in the alluvial aquifer and uncertain contaminant sources, the remediation system has been successful in removing contaminant mass, reducing the size of plumes in the floodplain, and preventing discharge of contamination to the river. Percentage mass removals estimated for sulfate, uranium, and nitrate contamination in floodplain groundwater during the first 9 years of remediation pumping range from 40% to 72%.

ACKNOWLEDGMENT

This work was performed under DOE contract number DE-LM0000421 for the U.S. Department of Energy Office of Legacy Management.

REFERENCES

1. U.S. Department of Energy, 2000. *Final Site Observational Work Plan for the Shiprock, New Mexico, UMTRA Project Site*, GJO-2000-169-TAR, Rev. 2, Grand Junction Office, Grand Junction, Colorado, November.
2. U.S. Department of Energy, 2002. *Final Ground Water Compliance Action Plan for Remediation at the Shiprock, New Mexico, UMTRA Site*, GJO-2001-297-TAR, Grand Junction Office, Grand Junction, Colorado, September.
3. U.S. Department of Energy, 2015. *Annual Performance Report, April 2014 Through March 2015, for the Shiprock, New Mexico, Site,* LMS/SHP/S13080, Office of Legacy Management, Grand Junction, Colorado, October.
4. U.S. Department of Energy, Environmental Sciences Laboratory, 2015*. Variation in Groundwater Aquifers: Results of 2013–2014 Phase I Field Investigations*, Final Draft, LMS/ESL/S12811, ESL-RPT-2015-02, Office of Legacy Management, Grand Junction, Colorado, September.
5. Zhang, H., and F.W. Schwartz, 1995. “Multispecies contaminant plumes in variable density flow systems,” *Water Resources Research* 31(4), pp. 837–847.
6. U.S. Department of Energy, 2005. *Refinement of Conceptual Model and Recommendations for Improving Remediation Efficiency at the Shiprock, New Mexico, Site,* GJO-2004-579-TAC, Office of Legacy Management, Grand Junction, Colorado, July.
7. U.S. Department of Energy, 2009. *Evaluation of the Trench 2 Groundwater Remediation System at the Shiprock, New Mexico, Legacy Management Site,* LMS/SHP/S05037, Office of Legacy Management, Grand Junction, Colorado, March.
8. Harbaugh, A.W., and M.G. McDonald, 1996. *User’s Documentation for MODFLOW-96, an Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model*, U.S. Geological Survey Open-File Report 96-485.
9. Rumbaugh, J.O., and D.B. Rumbaugh, 2001. *Guide to Using Groundwater Vistas,* Version 4, Environmental Simulations, Inc., Herndon, Virginia.
10. Pollock, D.W., 1989. *Documentation of Computer Programs to Compute and Display Pathlines Using Results from the U.S. Geological Survey Modular Three-Dimensional Finite-Difference Ground-Water Flow Model,* U.S. Geological Survey Open File Report 89-391.
11. Cirpka, O.A., and S. Attinger, 2003. “Effective dispersion in heterogeneous media under random transient flow conditions,” *Water Resources Research,* 39(9): SBH 9-1–9-19.
12. U.S. Public Health Service, 1963. *Shiprock, New Mexico Uranium Mill Accident of August 22, 1960.* U.S. Department of Health, Education, and Welfare, Denver, January.