APPLICATIONS OF PERMEABLE BARRIER TECHNOLOGY TO GROUND WATER CONTAMINATION AT THE SHIPROCK, NM, UMTRA SITE

B.M. Thomson, E.J. Henry, and M.S. Thombre, Department of Civil Engineering, The University of New Mexico, Albuquerque, NM, 87131, Phone: 505-277-4729, FAX: 505-277-1988*

ABSTRACT The Shiprock uranium mill tailings pile in far northwestern New Mexico consists of approximately 1.5 million tons of uranium mill tailings from an acid leach mill which operated from 1954 to 1968. Located on land owned by the Navajo Nation, it was one of the first tailings piles stabilized under the Uranium Mill Tailings Remedial Action (UMTRA) project. Stabilization activities were completed in 1986 and consisted principally of consolidating the tailings, contouring the pile to achieve good drainage, and covering the pile with a multi-layer cap to control infiltration of water, radon emanation, and surface erosion. No ground water protection or remediation measures were implemented other than limiting infiltration of water through the pile, although a significant ground water contamination plume exists in the flood plain adjacent to the San Juan River. The major contaminants at the Shiprock site include high concentrations of sulfate, nitrate, arsenic, and uranium. One alternative for remediation may be the use of a permeable barrier in the flood plain aquifer. As proposed for the Shiprock site, the permeable barrier would be a trench constructed in the flood plain that would be backfilled with a media that is permeable to ground water, but would intercept or degrade the pollutants. Work to date has focused on use of a mixed microbial population of sulfate and nitrate reducing organisms. These organisms would produce strongly reducing conditions which would result in precipitation of the metal contaminants (i.e., Se(IV) and U(IV)) in the barrier. One of the first considerations in designing a permeable barrier is developing an understanding of ground water flow at the site. Accordingly, a steady state numerical model of the ground water flow at the site was developed using the MODFLOW code developed by the U.S. Geological Survey. This model was calibrated using data collected at a suite of monitoring wells at the Shiprock site and then used to simulate a variety of hydraulic alternatives. These alternatives included use of permeable barriers, use of a combination of impermeable and permeable barriers to achieve a "funnel and gate" effect, and manipulation of the hydraulic gradient in the flood plain through use of infiltration trenches to increase contaminant migration rates. A preliminary ranking system was developed to allow comparison of these alternatives which included length of the barriers, ground water velocities (and therefore aquifer flushing rates), and hydraulic gradient manipulation considerations.

KEYWORDS: ground water remediation, permeable barriers, modeling

INTRODUCTION

In recognition of the environmental problems associated with uranium (U) mill tailings, Congress passed the Uranium Mill Tailings Radiation Control Act (UMTRCA) in 1978. This act resulted in initiation of the Uranium Mill Tailings Remedial Action (UMTRA) Project to clean up mill tailings and other contaminated materials at 24 inactive and abandoned U processing sites throughout the country [1]. To date this program has achieved stabilization of nearly all of the U mill tailings piles; however, remediation of contaminated ground water was deferred until the EPA established

*To whom all correspondence should be addressed (email: bthomson@unm.edu).

water quality standards for the UMTRA sites. The standards for ground water at U mill tailings sites were established in early 1995 resulting in a major effort to develop remediation technologies to meet these criteria [2]. A goal of the ground water remediation program is to achieve complete remediation in 100 years.

Shiprock, NM, is a community of about 10,000 people located on the Navajo Indian reservation in the far northwestern corner of New Mexico. A U mill was operated approximately 1 mile south of town from 1954 to 1968 by a succession of companies. The mill processed about 1.4 million metric tons of ore using the acid-leach process. Stabilization of the tailings and remediation of surface contamination in the surrounding area was completed in 1986. Stabilization consisted of consolidating tailings and contaminated soils into a single 31 ha pile which is covered with a 2 m thick compacted clay soil to serve as a radon barrier and a riprap cover for erosion protection. The tailings pile was constructed on a natural terrace above an alluvial floodplain. Ground water in the flood plain is highly contaminated with constituents from the U milling process including high concentrations of sulfate (SO_4^{2-}), nitrate (NO_3^-), selenium (Se), and U.

One of the ground water remediation alternatives which may be feasible at this site is use of a permeable barrier (also referred to as reactive walls by Blowes, *et al.*) to remove the contaminants from solution [3]. A permeable barrier is a zone in the subsurface environment which permits flow of water, but which contaminants from solution by either degradation or sorption/precipitation reactions. Thomson, *et al.*, summarized the permeable barrier concept and suggested that barriers may be constructed by trenching methods or, for some classes of contaminants, they may be created using combinations of injection and withdrawal wells to alter the subsurface geochemistry to achieve contaminant degradation or removal [4]. Most of the work to date at UNM has focused on trench-based barriers. Possible barrier materials which may be used in trench-based barriers are listed in Table 1.

This paper describes a ground water modeling investigation of the Shiprock UMTRA site leading to development of a remediation strategy based on the permeable barrier concept. The project consisted of a modeling study to consider the hydraulic aspects associated with the permeable barrier technology. Alternative barrier locations in the flood plain alluvium were evaluated. Several schemes were also considered in which the hydraulic gradient of the aquifer was altered to accelerate and direct the flow of ground water through the formation.

TABLE 1. POSSIBLE BARRIER MATERIALS FOR TRENCH-BASED BARRIERS (MODIFIED FROM [4]).

Degradable Contaminants	Non-Degradable Contaminants
1. Aeration/deaeration systems	1. Sorption/exchange media
2. Nutrient addition systems	2. pH modification agents
3. Oxidizing/reducing agents	3. Oxidizing/reducing agents
	4. Precipitating agents
	5. Microbial transformation systems

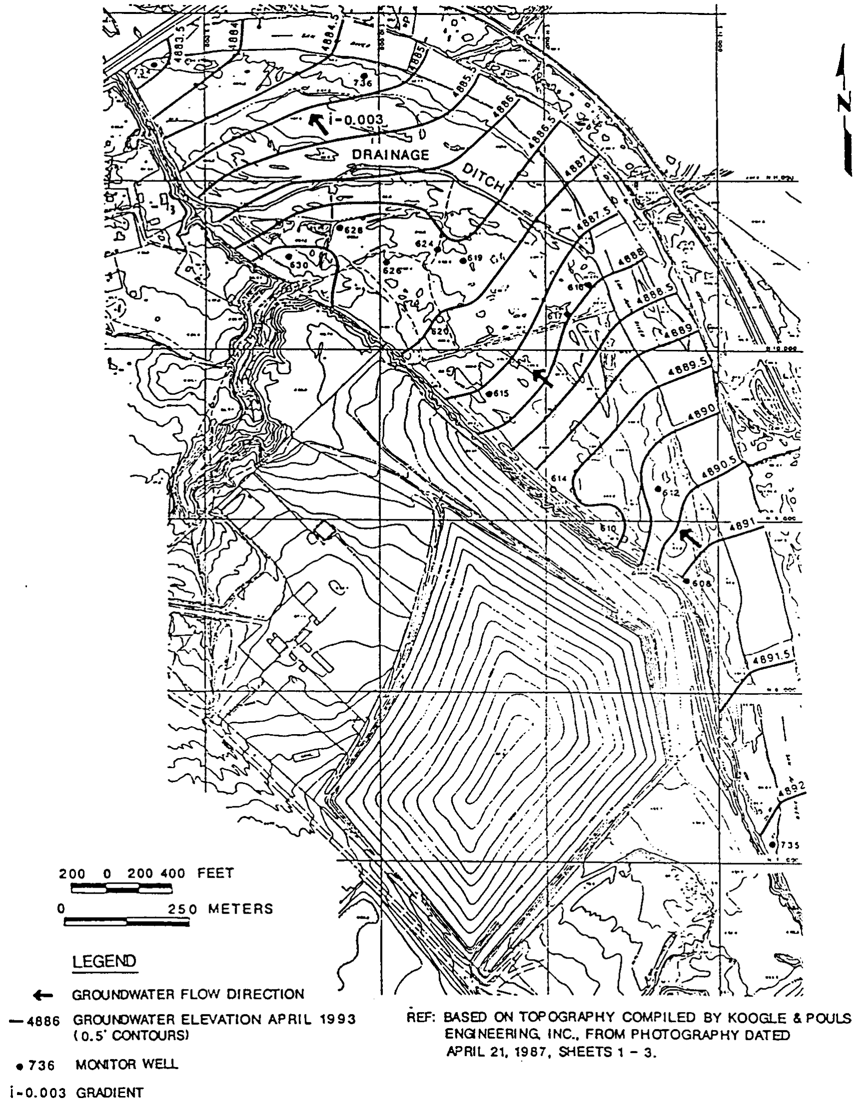

FIGURE 1. MAP OF THE SHIPROCK UMTRA SITE [5].

BACKGROUND INFORMATION

Hydrogeology & ground water contamination at the Shiprock UMTRA site

The Shiprock UMTRA site has been well characterized in a number of studies by the DOE and the results summarized in the "Baseline Risk Assessment of Groundwater Contamination at the Uranium Mill Tailings Site Near Shiprock, New Mexico" [5]. The Shiprock UMTRA site is located on an elevated river terrace approximately 15 m above the flood plain of the San Juan River (Figures 1 and 2). The underlying strata consists of coarse alluvial material underlain by Mancos Shale, a marine shale of very low permeability, although the top few meters is more permeable due to weathering. Material in the flood plain consists of unconsolidated silts, sands, gravels, and cobble-sized material and is highly permeable. Alluvial material in the flood plain is believed to be 5 to 10 m thick and is underlain by impermeable Mancos Shale. A near vertical

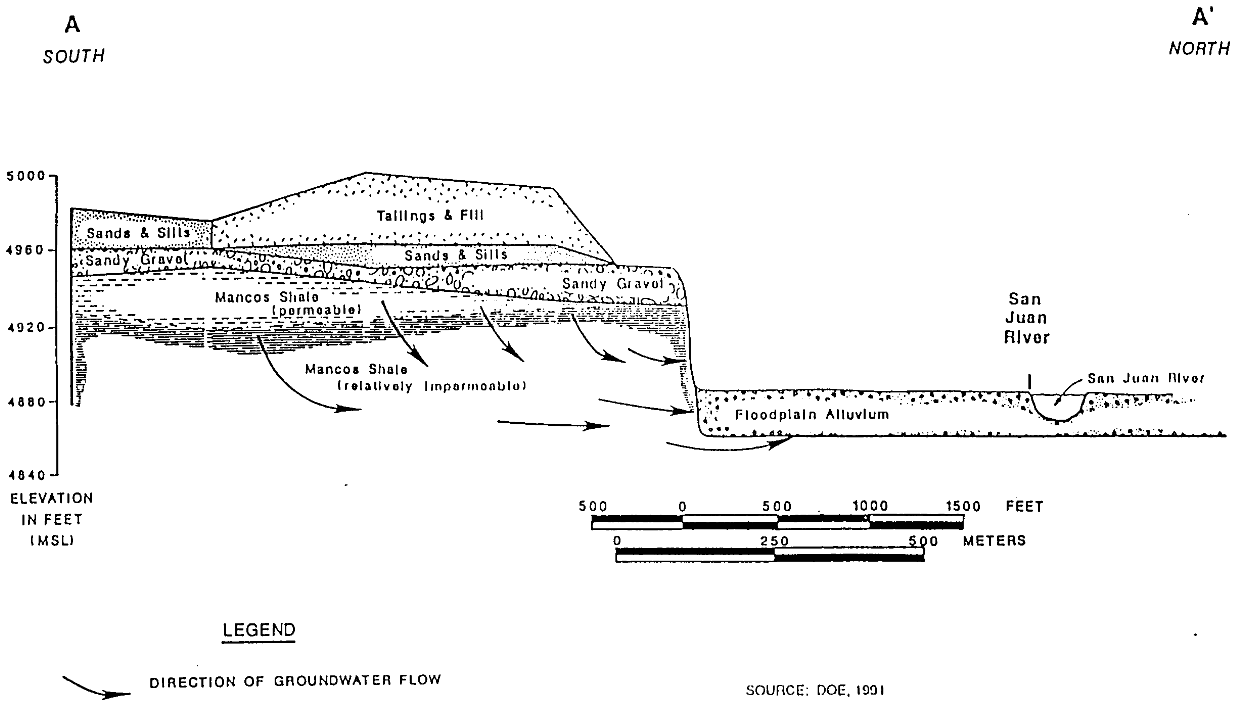

FIGURE 2. CROSS SECTION OF THE SHIPROCK UMTRA SITE [5].

escarpment separates the elevated terrace and the flood plain.

The principal contaminants at Shiprock are listed in Table 2. A map of the flood plain showing the sulfate distribution is presented in Figure 3. This concentration distribution is representative of other ground water constituents in the flood plain.

Prior ground water modeling of the flood plain alluvium suggests that flow is primarily from the southeast to the northwest, paralleling the San Juan River. The hydraulic gradient is strongly influenced by the river which borders the flood plain and a small continuous discharge of approximately 300 m^3/d (60 gpm) from the Bob Lee Wash [6].

TABLE 2. SUMMARY OF WATER QUALITY CHARACTERISTICS IN CONTAMINANT PLUME DOWN-GRADIENT FROM THE SHIPROCK URANIUM MILL TAILINGS PILE [5].

	Observed Concentrations (mg/l)		
Constituent	Minimum	Median	Maximum
SO_4^{2-}	6,230	13,000	15,600
NO_3^-	400	3,300	5,300
U	1.64	2.8	4.07
Se	.070	.122	.599
As	<.005	<.028	.05-.10
^{226}Ra (pCi/l)	0.0	0.1	3.0

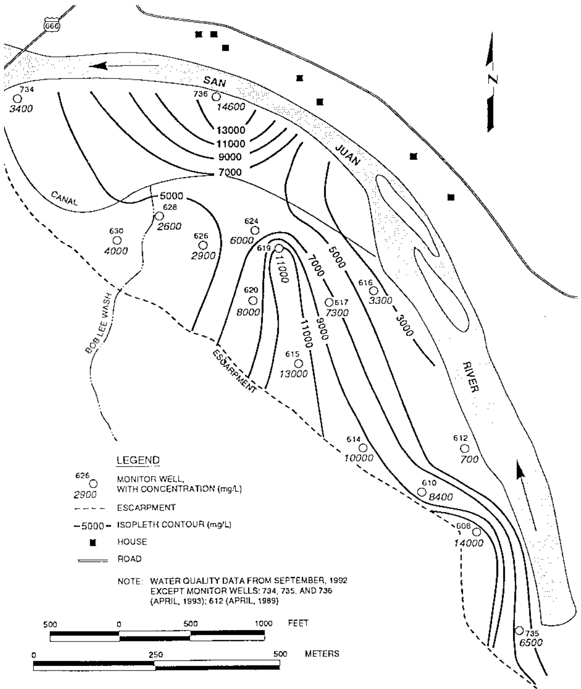

FIGURE 3. SULFATE CONTAMINANT PLUME, SHIPROCK UMTRA SITE [5].

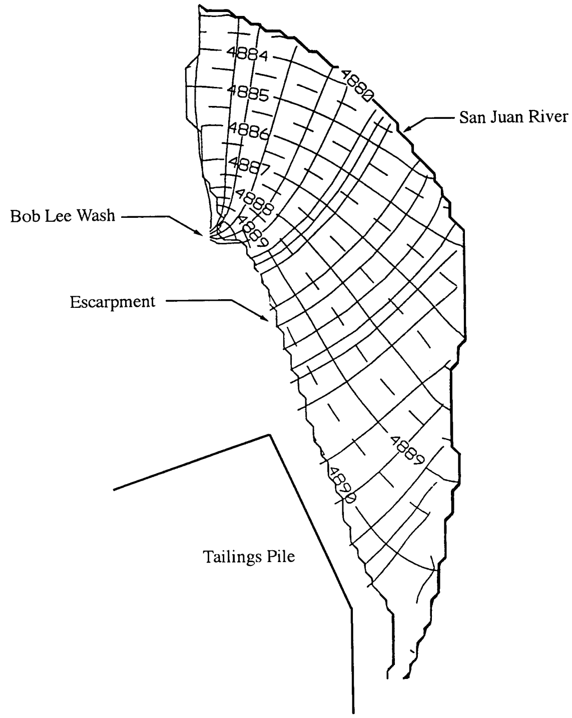

FIGURE 4. RESULTS OF THE NUMERICAL MODELING SHOWING GROUND WATER CONTOURS AND PATH LINES UNDER STEADY STATE CONDITIONS.

Model description

The USGS MODFLOW code was used to calculate heads in the alluvial soils in the flood plain, then the PATH3D code was used to calculate streamlines and ground water travel time [7]. The aquifer model was calibrated using water level data collected from a system of about 30 monitoring wells constructed in the flood plain. The alluvial aquifer was modeled as a single layer. The San Juan River was modeled as a constant head boundary, and the escarpment was modeled as an impermeable boundary. A uniform recharge rate of 0.5 in./yr was applied to the entire flood plain to simulate atmospheric precipitation. Infiltration from the Bob Lee Wash was simulated by adding injection wells at nodes where the channel enters the flood plain. Hydraulic conductivity of the alluvial sands has not been determined at the Shiprock UMTRA site. Literature values for similar materials range from less than 5 ft/d to greater than 300 ft/d [5]. The value used in this investigation was 35 ft/d. A more complete description of the model was provided by Henry [8].

The model was calibrated by comparison to water level measurements in a series of 15 monitoring wells maintained by the DOE. The numerical criteria used to evaluate model fit were the residual mean, residual standard deviation, and the residual sum of squares, where the residual represents the difference between the predicted ground water elevation and that in the monitoring wells. The results of the calibrated model are presented in Figure 4. Three important points were noted in developing the steady state model of ground water flow in the flood plain alluvium: 1) the aquifer is

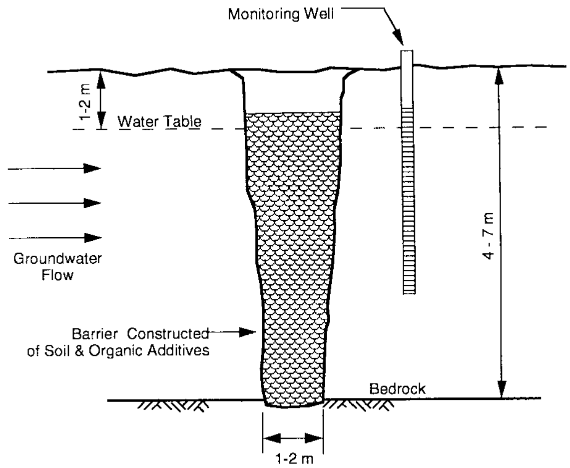

FIGURE 5. PROPOSED BARRIER DESIGN.

strongly influenced by the river, 2) ground water elevations in the northwest portion of the aquifer are influenced by the continuous discharge from the Bob Lee Wash, and 3) ground water velocities are slow resulting in very long travel times for some path lines (up to 40 years) due to the nearly flat hydraulic gradient.

Permeable barriers

Previous work on barrier technologies at UNM has determined that there are three major criteria which must be met for the approach to be successful:

1) The depth to ground water and to the bottom of the contaminant plume or an underlying impermeable layer must be sufficiently shallow that it can be reached with excavation equipment. While it may be possible to create a permeable barrier using injection and extraction wells, this technology does not appear to be practicable at present. Current barrier emplacement technologies appear to be limited to a maximum depth of about 20 m.

2) The contaminants must have reasonably rapid migration rates as determined by a combination of high ground water velocities and low retardation factors. This requirement reflects the fact that the permeable barrier concept relies upon ground water flow to transport the contaminants to the barrier for removal. Pollutants which are not mobile in ground water such as high molecular weight organics or cationic metals (e.g., Pb^{2+}, Cd^{2+}, Zn^{2+}) will remain bound in the soil matrix and no benefit will be derived from the barrier.

3) The barrier material must be capable of intercepting or degrading the contaminants. Current research is directed towards adapting conventional surface treatment technologies for application in barrier environments.

All of these criteria appear to be met at the Shiprock UMTRA site. The best information available shows that the depth to ground water ranges from 1 to 2 m, and that depth to the underlying impervious Mancos Shale is less than 7 m. This is within the reach of most conventional excavation equipment, so that a permeable barrier keyed into the impermeable shale is proposed (Figure 5). The contaminants of concern at Shiprock are all soluble anions and therefore amenable to transport by ground water. However, one potential limitation that must be recognized is the low ground water velocities due to the flat hydraulic gradient. Finally, there are a number of barrier options which may be utilized to remove the contaminants of concern (U, NO_3^-, SO_4^{2-}, and Se) including biological reduction, chemical reduction, and sorption. These will be discussed below.

BARRIER INVESTIGATION

Modeling barrier alternatives

Once the numerical model of steady state ground water flow in the flood plain aquifer was calibrated, it was used to explore alternative placements of barrier systems to achieve remediation of the aquifer. These alternatives included 1) natural flushing, 2) gradient manipulation through use of infiltration ditches and interceptor trenches, 3) gradient manipulation using impermeable barriers, and 4) combined gradient manipulation and incorporation of a permeable barrier. These alternatives were evaluated using a ranking system developed by Henry to include the following parameters: 1) ground water travel time, 2) barrier length, and 3) length of the infiltration or interceptor channel [8]. The basis for selection of these factors is that the first parameter, ground water travel time, is an indication of the length of time required to remediate the contaminated ground water. The other two parameters, length of prospective barrier and infiltration channels, correlate with the capital costs of a remediation alternative. Due to the preliminary nature of this study, no weighting factors were included in the scoring system. This semi-quantitative scoring system was applied to 17 alternatives developed in the modeling study. The top six remediation alternatives are summarized in Table 3. The results of the top ranked simulated system is shown in Figure 6. Although a barrier was not explicitly included in this simulation, it would have virtually no effect on the hydraulics of the system provided its hydraulic conductivity was greater than that of the surrounding soils. Note that the top ranked option has the same ranking as that for a "no action" alternative in which natural flushing is relied upon to remove the contaminants (Figure 5).

The results of the ranking study found that the options with the lowest total score, and therefore the highest ranking, were those which involved the least amount of construction of barriers and infiltration trenches. To a large extent this was due to the lack of weighting factors associated with cost of construction and length of the remediation process. It is believed that the "no action" option scored as well as it did because of the limited and somewhat arbitrary scoring system which did not take into account issues such as environmental

TABLE 3. SUMMARY OF TOP SIX GROUND WATER REMEDIATION ALTERNATIVES FOR THE SHIPROCK SITE AS DETERMINED BY HENRY [8] (BEST SCORE = 1.0, WORST SCORE = 3.0).

Rank	Description	Max. Flushing Time (yrs)	Score
1.	Induced flushing scheme incorporating an infiltration trench along base of escarpment, no barrier	9	1.14
1.	Natural flushing, no gradient manipulation, no barrier	41	1.14
3.	Natural flushing, short impermeable barrier, long permeable barrier across flood plain	41	1.18
4.	Natural flushing, short impermeable barrier, long permeable barrier across flood plain	41	1.23
5.	Natural flushing, medium impermeable barrier, medium permeable barrier across flood plain	53	1.31
5.	Natural flushing, short impermeable barrier, long permeable barrier across flood plain	42	1.31

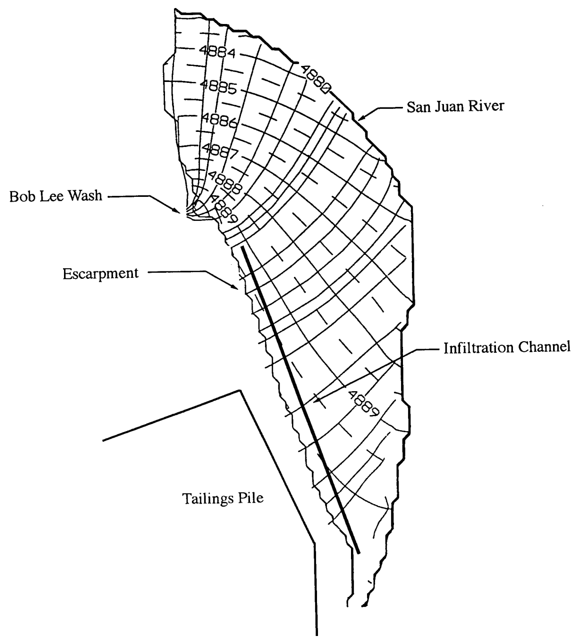

FIGURE 6. GROUND WATER FLOW SIMULATION FOR SYSTEM WITH INFILTRATION CHANNEL AT TOE OF ESCARPMENT.

risk. Nevertheless, it is clear from this preliminary study that the "no action" alternative merits further consideration at this site. If remediation must be accomplished in a time frame of less than many decades, a more aggressive and therefore more costly alternative may be needed.

In addition to the time and cost criteria, there is at least another important factor that must be considered in evaluating these remediation alternatives and that is the rate of contaminant migration through the alluvial aquifer. Both the flushing and the barriers alternatives are based on transport of pollutants through the formation, eventually reaching either the San Juan River or a permeable reactive barrier. Rapid transport of the principal contaminants of concern (SO_4^{2-}, NO_3^-, U(VI), and As(V)) has been assumed in this study based on the premise that they are relatively soluble and, therefore, are readily transported by ground water. If retardation mechanisms are present which limit contaminant migration rates, aquifer restoration will require much longer times than that predicted by the simple flushing calculations. Accordingly, laboratory studies are being developed which will determine these migration rates.

A significant limitation of nearly all of the ground water work at the Shiprock site reported to date is that it has focused entirely on the flood plain. It has been postulated that drainage from the stabilized tailings pile atop the terrace presents a continuing source of contaminants to the flood plain aquifer [9]. A recent geophysical survey of the site found high regions of high electrical conductivity on the terrace which are consistent with this scenario. Although the results are difficult to interpret definitively, these high electrical conductivity regions could constitute a plume of highly contaminated water that will slowly drain to the flood plain for many decades. Accordingly, the site remediation process should provide a method for intercepting this plume.

Thus it appears that there are actually two distinctly different ground water quality problems at the Shiprock UMTRA site. The first is the existing contaminant plume in the flood plain alluvium that is amenable to remediation through use of flushing, with possible incorporation of a permeable barrier system. The second problem is the slow drainage of highly contaminated water from the stabilized tailings. It is proposed here that a combined gradient manipulation and barrier system can be designed which will address both problems. The design will consist of an infiltration trench constructed along the toe of the escarpment to increase ground water velocities through the alluvial aquifer. A permeable barrier system would

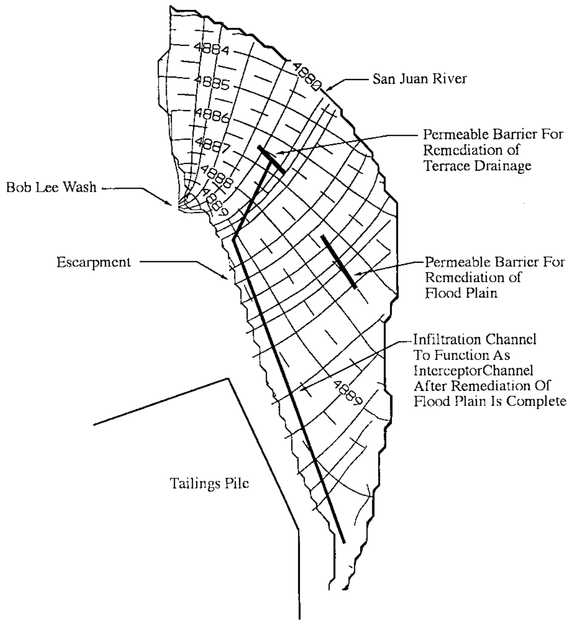

FIGURE 7. PROPOSED REMEDIATION SYSTEM.

be constructed to intercept the bulk of the contaminant plume. This system is shown in Figure 7. Water would be diverted from the river to the infiltration trench to raise the ground water level at the toe of the escarpment approximately .6 m (2 ft). This would accelerate remediation of the flood plain aquifer, so that ground water travel times through the contaminated zone would be less than 5 years. After contaminants in the flood plain had been reduced, the diversion from the river would be stopped and the infiltration gallery would function as a French Drain or interceptor trench. Water draining from the terrace would be collected in this trench and be directed to a small permeable barrier at its end where it would be treated prior to discharge to the river. Advantages of this approach include rapid remediation of the flood plain aquifer, provision of a simple low maintenance system, and easy monitoring of the system performance.

Barrier design

A cross section of a prospective permeable barrier was presented in Figure 5. Three different barrier approaches have been proposed for application at this site : 1) use of anaerobic microbial populations to achieve reduction of SO_4^{2-} and NO_3^-, and subsequent reduction and precipitation of metals, 2) use of zero valent iron to reduce and precipitate metals, and 3) use of surfactant modified zeolites (SMZ) to selectively remove anionic constituents [10]. These are briefly described in turn.

The ability of sulfate-reducing bacteria to facilitate reduction of a variety of metals is well known. Thomson demonstrated reduction and subsequent precipitation of Cr(VI) and Se(VI) in suspended culture chemostat and column systems using lactate as a substrate [11]. More recently Lovley and Phillips demonstrated reduction of and subsequent precipitation of U(VI) [12]. This work has been extended by a group at UNM led by Barton and Thomson [13]. A significant limitation of most of the previous work with microbial reducing systems is that it has been done with single component—well characterized substrates, most commonly low molecular weight organic acids. Recently Bechard, *et al.*, demonstrated use of cellulosic substrates for growth of sulfate-reducing organisms to treat acid mine drainage [14]. This work has been extended to leachates from U mill tailings by Thombre, *et al.* [15]. This study used a mixed culture of naturally-occurring organisms grown on sawdust, hay, and wheat straw to achieve immobilization of U(IV) in column studies. Formation of $UO_{2(s)}$ was documented through use of x-ray diffraction. The use of a cellulosic substrate for mixed culture microbial reduction has been proposed for the Shiprock site [10].

Bowman and coworkers were the first to demonstrate that addition of quaternary ammonium surfactant compounds to zeolite minerals would result in a strong affinity for inorganic anions such as CrO_4^{2-}, NO_3^-, and SeO_4^{2-} [16, 17]. Prior to this, his group and others demonstrated the affinity of SMZ for nonpolar organic compounds such as BTEX and chlorinated solvents dissolved in water. The work on sorption of organics developed from earlier work on surfactant-modified clays [18, 19]. Unlike clays, which occur only in micron- and submicron-size particles, zeolites occur in stable aggregates which may be sized to yield any desired permeability.

Bowman, *et al.*, demonstrated that the SMZ is stable under aggressive environmental conditions including pHs in the range 3-10 and ionic strengths up to 1 *M* [20]. Recent unpublished work has shown that the surfactant treatment is stable under alkaline conditions even to pH 13. The surfactant is retained on the zeolite surface by a combination of electrostatic and van der Waals forces [21]. Retention of anions such as CrO_4^{2-} and NO_3- by SMZ appears to be due to a combination of ion exchange and surface precipitation [17].

Many inorganic reactive materials have been proposed for use in removing U and associated metals from mill tailings fluids. A large amount of interest has focused on use of zero valent iron (elemental iron which is represented as Fe° here). Powell, *et al.*, reported on a recent investigation mechanism Fe° reduction of CrO_4^{2-} and possible use in subsurface remediation processes [22]. Steel wool, steel wool treated with a copper catalyst, and a metallic iron foam have been considered for use by Sandia National Laboratories, Albuquerque investigators [23]. Batch studies showed that steel wool decreased U concentrations in water from the Durango U mill tailings pile from 6 mg/l to < 1 mg/l after about 150 hours. Tests with Cu-catalyzed steel wool achieved the same results in less than 24 hours. Fe° foam has been considered because it provides increased surface area as well as improved hydraulic conductivity. Measured surface areas of the Fe° foam range from 0.1 to 5 m^2/g compared to an estimated surface area of 5.E-3 m^2/g for the steel wool. Batch experiments with the Fe° foam found U concentrations reduced to below detectable values in less than 10 hours.

Sandia National Laboratories (SNL), Albuquerque, is conducting a pilot scale research project on Fe° barriers at the Bodo Canyon UMTRA disposal dell near Durango, CO. Approximately 2.5 M cubic yards of tailings were relocated from a site near Durango in 1990. Fluids associated with the contaminated tailings currently draining from the cell are collected by a gravity drain and pipe at the toe of the pile. In late 1995 SNL built four subsurface Fe° treatment systems in the existing retention pond to simulate flow and treatment of leachate from the pile. The treatment zones consist of two drainfields and two flow-through baffled containers. Monitoring of this system is in progress.

Constructability of permeable and impermeable barriers in saturated soils is a very difficult and expensive undertaking in many geologic formations. The high unconsolidated alluvial sands and high water table at Shiprock present a near worst-case scenario. To date most research and development has focused on the treatment medium itself, not on construction and emplacement issues. In order to successfully implement permeable barrier technologies, the treatment medium has to be placed below the ground water table in an appropriate manner. There is little experience with methods for emplacing potential permeable barrier materials in unconsolidated saturated soils. Excavation of a trench below the water table in these conditions is a fairly common but highly empirical engineering practice. The purpose of this task is to consider available methods and identify those which are suitable for this project. It will begin by measuring the geotechnical properties of soils from the alluvial formations. The properties of interest include the particle size gradation, bulk density, and unconfined compressive strength. Four of the possible techniques for permeable barrier construction include: 1) dewatering the formation through use of shallow wells, 2) sloped excavations, 3) use of mud or grout to stabilize walls, and 4) use of sheet piles. While the first two options are almost certainly not feasible, the last two alternatives may be. Once the trenching method has been identified, methods will be needed to emplace the barrier materials. While this is not expected to be a problem with materials of density similar to sand, cellulosic materials such as wood chips may separate from the sand if not correctly installed.

CONCLUSIONS

The Shiprock UMTRA site has widespread contamination of ground water in a shallow alluvial aquifer that is the result of a U processing facility. Modeling of steady state ground water flow in the alluvial aquifer suggests that natural flushing will occur; however, it will be very slow due to the small hydraulic gradient. The modeling has shown that the ground water hydrology is dominated by the influence of the San Juan River on the northeast boundary and by the small but continuous flow from the Bob Lee Wash near the middle of the flood plain.

The nature and extent of the ground water contamination at the site suggests that remediation may be feasible through use of a permeable barrier system, possibly including hydraulic gradient manipulation to accelerate flow through the barrier. The proposed barrier would consist of a trench, keyed into the underlying Mancos Shale formation, in which reactive media would be placed to remove or immobilize the contaminants. Ground water flow modeling was used to evaluate the alternative barrier locations and gradient manipulation schemes. The parameters used in the evaluation process included length of the barrier, length of the infiltration or interceptor channel, and the ground water travel time to pass through the entire formation. Based on these very simplistic criteria, the best alternative appears to consist of either natural flushing or gradient manipulation achieved by installation of an infiltration channel along the toe of the escarpment and a permeable barrier system down-gradient from the contaminant plume. The latter alternative presents an interesting operational option in that after the remediation of the alluvial flood plain was completed, the infiltration channel could be quickly reconfigured and operated as an interceptor trench or French Drain. In this configuration, contaminants transported from the tailings pile would be conveyed to a small barrier. This option would have the dual benefit of quickly remediating the flood plain aquifer and preventing future contamination with a small, low maintenance system.

The permeable barrier systems which have been proposed for the Shiprock UMTRA site include microbial reduction barrier, zero valent iron barrier, and sorption barriers using surfactant modified zeolites. The microbial reduction barrier would consist of a trench backfilled with an inexpensive cellulosic compound such as wheat or hay straw. Naturally-occurring microbial consortia would produce anaerobic conditions through degradation of this material. These conditions would result in reduction of NO_3^- and SO_4^{2-} and metal pollutants (principally Se and U). The metals would be immobilized on the media and could be subsequently re-excavated and disposed of properly. A similar process would be achieved through use of zero iron; however, the reactions would principally be chemical reductions rather than biological reductions. Surfactant-modified zeolites would provide selective removal of anionic constituents through sorption processes.

The Shiprock UMTRA site presents unique challenges. There is diversity in the contaminants, they are present at high concentrations, ground water velocities are low, and water resources in the region are especially valuable. However, an increasing understanding of the site, its hydrogeology, and the geochemistry of the ground water and soils suggests that permeable barrier technologies may provide an effective remediation strategy.

ACKNOWLEDGMENTS

The technical assistance of Anchor Holm with Geraghty-Miller, Inc., and Russell Edge with the U.S. Department of Energy is greatly appreciated. This project was supported by the U.S. Department of Energy UMTRA Project Office under contract PR 04-94AL633805.507.

REFERENCES

1. R.S. Portillo, Mill tailings remediation: The UMTRA Project, In: C. Reith and B. Thomson (Eds.), Deserts As Dumps?, University of New Mexico Press, 1992, pp. 281-302.

2. USEPA, 40 CFR Part 192: Groundwater Standards for Remedial Actions at Inactive Uranium Processing Sites, Federal Register, vol. 60, no. 7, 1995, p. 2854.

3. D.W. Blowes, C.J. Ptacek, J.A. Cherry, R.W. Gillham, and W.D. Robertson, Passive remediation of groundwater using *in situ* treatment curtains, In: Y. Acar and D. Daniel (Eds.), Geoenvironment 2000, Geotech. Spec. Pub. No. 46, Am. Soc. of Civil Engrs., New York, NY, 1995, pp. 1588-1607.

4. B.M. Thomson, S.P. Shelton, and E. Smith, Permeable barriers: A new alternative for treatment of contaminated groundwater, 45th Purdue Industrial Waste Conference Proceedings, Lewis Pubs., Inc., Chelsea, MI, 1991, pp. 73-80.

5. Jacobs Engineering Group, Inc., Baseline Risk Assessment of Groundwater Contamination at the Uranium Mill Tailings Site Near Shiprock, New Mexico, DOE/AL/62350-48D, prepared for U.S. DOE UMTRA Project Office, Albuquerque, NM, 1994.

6. DOE (U.S. Dept. of Energy), Status of the Ground Water Flow Model for the UMTRA Project Shiprock, New Mexico, Site, DOE/AL/62350-166, Rev. 0, prepared by the USDOE UMTRA Project Office, Albuquerque, NM, 1995.

7. M. McDonald and A. Harbaugh, A modular three-dimensional finite-difference groundwater flow model, Techniques of Water-Resources Investigations, Chapter A1, Book 6, U.S. Geological Survey, Reston, Virginia, 1988.

8. E.J. Henry, Groundwater Modeling of Gradient Manipulation and Barrier Location for Remediation at a Uranium Mill Tailings Remedial Action (UMTRA) Site, M.S. Thesis, University of New Mexico, Albuquerque, NM, 1995.

9. D. Tarbox, Personal communication, Jacobs Engineering Group, Albuquerque, NM, 1996.

10. B.M. Thomson, J.C. Stormont, R.S. Bowman, and S. Semken, Pilot Scale Field Demonstration of Three Permeable Barrier Technologies for Ground Water Remediation, Proposal to Waste-management Education and Research Consortium, Las Cruces, NM, 1996.

11. B.M. Thomson, Microbially induced reduction and precipitation of aqueous metal contaminants, Proc. 60th Annual Conf., Water Poll. Control Fed., Philadelphia, PA, 1987.

12. D.R. Lovley and E.J. Phillips, Bioremediation of uranium contamination with uranium reduction, Envir. Sci. & Tech., 26 (1992) 2228-2234.

13. L.L. Barton, K. Choudhury, B.M. Thomson, K. Steenhoudt, and A.R. Groffman, Bacterial reduction of soluble uranium: The first step of in-situ immobilization of uranium, Radioactive Waste Management and Environmental Restoration, 1995, in press.

14. G. Bechard, H. Yamazaki, W.D. Gould, and P. Bedard, Use of cellulosic substrates for the microbial treatment of acid mine drainage, J. Environ. Qual., 23 (1994) 111-116.

15. M.S. Thombre, B.M. Thomson, and L.L. Barton, Microbial reduction of uranium using cellulosic substrates, In: L.E. Erickson, D.L. Tillison, S.C. Grant, and J.P. McDonald (Eds.), Proceedings of the HSRC/WERC Joint Conference on the Environment, Albuquerque, NM, May 21-23, 1996, Hazardous Substance Research Center/Waste-management Education & Research Consortium, Manhattan, KS/Las Cruces, NM, 1996.

16. R.S. Bowman, M. Flynn, G.M. Haggerty, R.G. Huddleston, and D. Neel, Organo-zeolites for sorption of nonpolar organics, inorganic cations, and inorganic anions, Proc. Joint CSCE-ASCE National Conference on Environmental Engineering, July 12-14, 1993, Montreal, Quebec, Canada, pp. 1103-1109.

17. G.M. Haggerty and R.S. Bowman, Sorption of inorganic anions by organo-zeolites, Environ. Sci. Technol., 28 (1994) 452-458.

18. F.J. Cadena, Use of tailored bentonite for selective removal of organic pollutants, Environ. Eng., 115 (1989) 756-767.

19. F. Cadena, and R.S Bowman, Treatment of waters contaminated with BTX and heavy metals using tailored zeolites, Proc. 4th Annual WERC Technology Development Conf., April 13-15, 1994, Las Cruces, NM, 1994, pp. 297-310.

20. J.-F. Lee, J.R. Crum, and S.A. Boyd, Advanced retention of organic contaminants by soils exchanged with organic cations, Environ. Sci. Technol., 23 (1989) 1365-1372.

21. R.S. Bowman, G.M Haggerty, R.G. Huddleston, D. Neel, and M. Flynn, Sorption of nonpolar organics, inorganic cations, and inorganic anions by surfactant-modified zeolites, In: D.A

Sabatini, R.C. Knox, and J.H. Harwell (Eds.), Surfactant-Enhanced Remediation of Subsurface Contamination, ACS Symposium Series 594, American Chemical Society, Washington, DC, 1995, pp. 54-64.

22. E.J. Sullivan, D.B. Hunter, and R.S. Bowman, Topological and thermal properties of surfactant-modified clinoptilolite studied by tapping-mode atomic force microscopy and high-resolution thermogravimetric analysis, Clays Clay Min., 44 (1996) in press.

23. R.M. Powell, R.W. Puls, S.K. Hightower, and D.A. Sabatini, Coupled iron corrosion and chromate reduction: Mechanisms for subsurface remediation, Environ. Sci. & Tech., 29 (1995) 1913-1922.

24. D. Marozas, Personal communication, Sandia National Laboratories, Albuquerque, NM, 1996.