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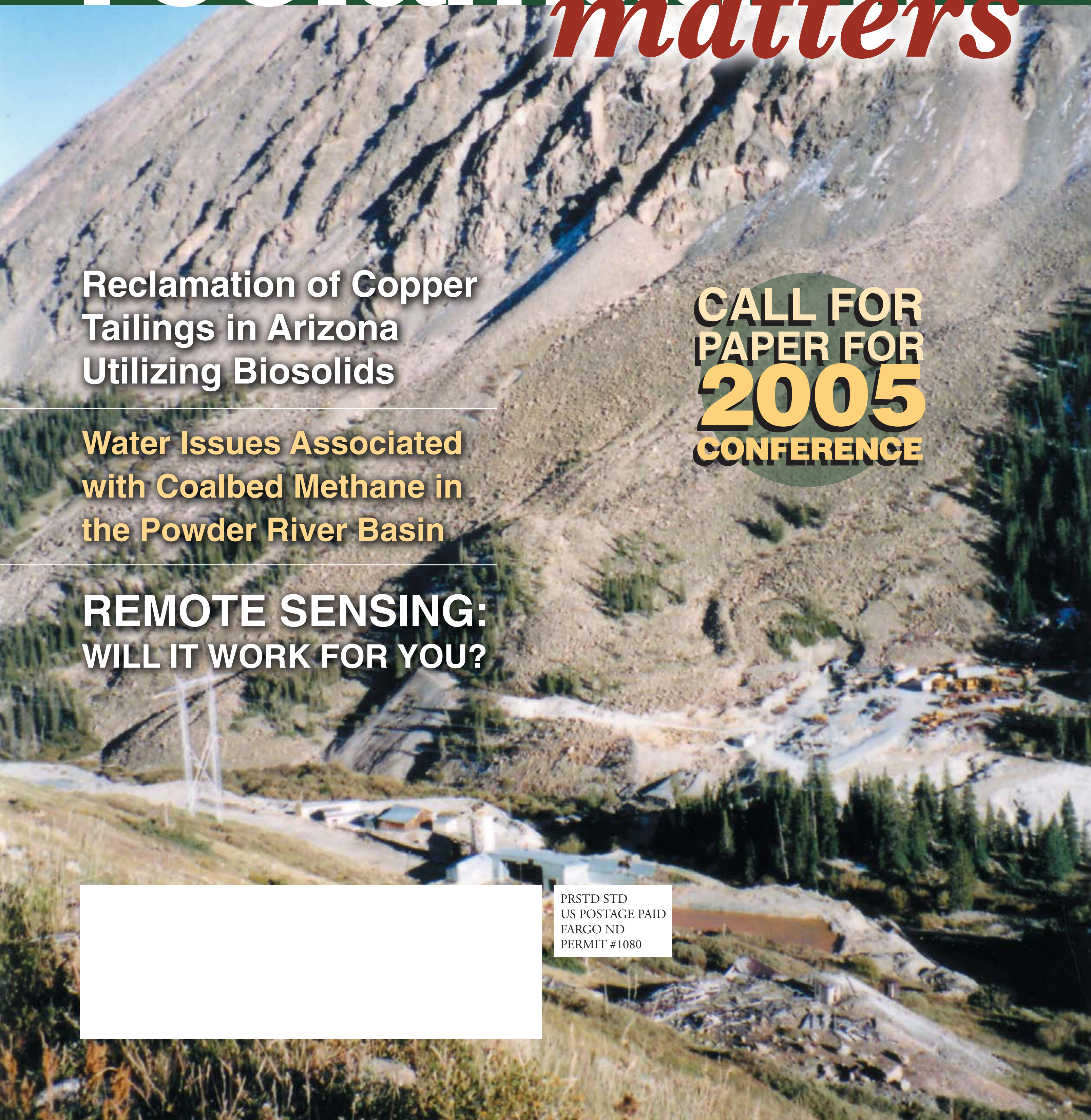

Reclamation of Copper Tailings in Arizona Utilizing Biosolids

Water Issues Associated with Coalbed Methane in the Powder River Basin

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Cover:
Lower portal of the London Extension Mine (gold, silver, lead) at an elevation of approximately 11,600 feet. The flank of the 13,006-ft. Pennsylvania Mountain is in the background. The site is also near several peaks with elevations exceeding 14,000 feet.
Photo by Jim Gusek.

contents

Fall 2004
Volume 1
Number 2

BY MARGARET DUNN, PG, 2004 ASMR PRESIDENT

MESSAGE FROM THE PRESIDENT

Making a Difference!

Members of ASMR have generously donated their time and talents to provide a wealth of knowledge relating to sustainable restoration of disturbed lands. This knowledge has been integrated into the modern mining process and has been responsible for the successful restoration of thousands of acres of abandoned mine lands and of hundreds of miles of streams. An understanding or awareness of this technology by elected officials, government regulators, watershed groups and the mining industry is imperative for economically and environmentally sound decisions relating to the utilization of our natural resources. ASMR members continually tackle and find solutions to our most difficult problems. Presentations, followed by energizing discussions at our annual conference, highlighted these breakthroughs, and resulted in the proceedings being a "must- have" reference for state-of-the-art restoration techniques. We have, however, the diversity, energy, resources and talent to contribute even more.

To spur advancements in technology and increase interest in and recognition of outstanding reclamation efforts, ASMR is focusing on the development of our Web site and our periodical, *Reclamation Matters.* The Web site can provide universal access to the body of knowledge available through ASMR. As the restoration of disturbed lands is a worldwide issue, the Web site will enable others to benefit from and encourage engagement in ASMR's efforts. It goes without saying, that the breakthroughs in reclamation, made by ASMR members, have worldwide application. The reader-friendly *Reclamation Matters* complements the Web site and provides the perfect venue to showcase our success stories and the abilities of our sponsors "to get the job done right." The response to the first issue was beyond expectations with the distribution and sponsorship growing much faster than projected.

Our accomplishments have made long-lasting positive impacts but our work is by no means complete. I appreciate being part of an organization that continues to make a difference! ■

BY DR. JEFF SKOUSEN

MESSAGE FROM THE EDITOR

A Big Thanks for a Great Meeting

Please accept my sincere thanks to all of you that attended the 2004 Task Force and ASMR joint meeting in Morgantown this past April. The final attendance figures were 440 people with about 152 presentations being made. I especially want to thank the presenters, moderators and reviewers of papers. We had several really great field trips and workshops and I express appreciation to those who led these activities. The exhibits were also excellent. All in all, I believe it was a wonderful meeting. We have included in this magazine a few pictures of exhibitors, field trips, and other highlights from the meeting. Thank you again. These annual meetings are one of our major purposes as a society.

This is the second issue of the *Reclamation Matters* magazine. We have changed our focus from reclamation issues in the eastern U.S., and the information needed for the 2004 Morgantown meeting, to reclamation issues in the western U.S. There is also a call for papers for the 2005 meeting in Breckenridge, Colorado. One of the great things about ASMR is the diversity of our organization and the wide ranging reclamation problems and opportunities we deal with. From acid mine drainage and steep slope mountaintop mining in the east to coal bed methane production, arid plant establishment and acid drainage from metal mines.

Please send me your ideas of articles for future editions of the magazine. We want to continue to cover a variety of issues in all facets of mining and reclamation. We accept papers from research institutions, mining companies, consulting firms, non-profit organizations and watershed groups, and companies supplying services and products to the industry. I can be reached at jskousen@wvu.edu. or give me a call at (304) 293-6256. ■

BY S.A. BENGSON[2]

RECLAMATION OF COPPER TAILINGS IN ARIZONA UTILIZING BIOSOLIDS[1]

There are many benefits to the utilization of biosolids (municipal sewage sludge) for reclamation. Biosolids offer a cost-effective source of organic matter and nutrients for successful reclamation; and the tailings sites offer an economical and environmentally sound solution for the management of biosolids. The main objective of using biosolids for reclamation is to incorporate enough organic matter into the reclamation site to produce a "growth medium" that can sustain plant growth without the need of "topsoil."

There is a tremendous need in today's environmentally conscious world for the mining industry to develop more effective methods for reclamation, especially in arid and semi-arid locales. Arizona is the leader in the nation in primary copper production, producing two-thirds of the nation's newly mined copper. One of our challenges is to produce the domestic minerals and commodities demanded by our society while protecting the environment. In this regard reclamation has become one of the cornerstones of modern mining.

Recognizing that copper tailings are essentially crushed rock, the parent material of soil, early tests to develop copper tailings into a "growth medium" by incorporation of organic matter began almost three decades ago. This early research indicated that if enough organic matter was incorporated into the tailings, vegetation could grow without the need of "topsoil." As this early work slowly progressed, it became evident that it would take substantial quantities of organic matter for successful reclamation. One of the major limiting factors that became evident was the economic availability of large quantities of organic matter. One obvious source of affordable organic matter was municipal biosolids or sewage sludge. The municipalities currently have a problem disposing of these wastes and the mining industry may be able to provide an outlet for large quantities of biosolids for use in reclamation. The utilization of biosolids for reclamation would eliminate the need for land filling or other less desirable means of disposal of the biosolids.

The idea of using municipal biosolids for reclamation of mining sites is not new. Biosolids have long been recognized as a beneficial amendment for mined land reclamation. The positive use of biosolids for successful reclamation goes back 25 years or more. Much of the early work involved coal-spoil reclamation in the Appalachian

Biosolids offer a cost-effective source of organic matter and nutrients for successful reclamation; and the tailings sites offer an economical and environmentally sound solution for the management of biosolids.

Figure 1. Revegetation potential of copper tailings material after biosolids application.

area. Sopper (1993) references 122 mined sites that have been successfully reclaimed with biosolids. More recently there has been some use of biosolids for reclamation of taconite tailing in Minnesota (Norland et al., 1992), copper tailings in British Columbia (Wilson et al., 1993), and metal tailings in Idaho and Utah (Brown, unpublished, 1997). Our work in Arizona is the first to look at biosolids for reclamation of copper tailings in the arid southwest.

Research involving biosolids for reclamation has concluded that many of the concerns over the use of biosolids are unsubstantiated (Sopper, 1993). The major concerns over the use of biosolids for mine reclamation include:

- leaching of nitrates
- heavy metal contamination from the biosolids
- acidic conditions mobilizing heavy metals

The major benefits of using biosolids for reclamation include:

- improvement of tailings fertility
- increasing tailings pH
- increasing vegetative establishment without topsoil

Biosolids provide residual fertilizing action that is superior to chemical fertilizers over time. Sopper (1993) cites little depletion of nutrients over a decade or more, and notes an increase in plant productivity. There have been no problems with heavy metals or pathogens. The research done to date indicates there is no evidence of nitrates leaching, or any threats to grazing animals or wildlife on the biosolids tests. Sopper (1993) also cites that biosolids can increase the pH of the mine wastes (in one instance from a pH of 4.2 to 7.2 with eight inches of biosolids incorporated into the top 12 inches of spoil). The biosolids chelate (bind or complex) the pyrites of the mine wastes and tie-up heavy metals. There is a marked increase in organic matter and an increase in microbial activity with a concurrent increase in nutrient cycling and decomposition of organics. High levels of biosolids will improve the physical characteristics of the mine wastes; such as decreasing bulk density, improving water holding capacity, and increasing infiltration. Biosolids also improve hydraulic conductivity and water saturation percentage, increase cation exchange capacity (CEC); and improve surface temperatures. The increased CEC helps to immobilize heavy metals.

Copper tailings are unique and unlike natural soils. The tailings are devoid of organic matter, have extremely low levels of nitrogen and other essential macronutrients and are sometimes acidic in nature. Tailings also have total heavy metals concentrations far in excess of any biosolids (especially those of “Class A or B” quality). There are no clay minerals in the tailings. Generally speaking, the tailings will “consume” large quantities of N, and if the pH can be raised to 5.0 or higher, most heavy metals are immobilized.

To achieve successful reclamation of copper tailings, enough organic matter must be incorporated into the tailings to produce a change in the physical texture and structure of the tailings. Earlier tests on tailings have shown that a mixture of 15 to 25 percent biosolids will yield an acceptable level of reclamation success.

In 1994, Chemical Lime Co. (Chem-Lime) conducted a column leach study on the leachate from lime-treated municipal biosolids mixed with acidic copper tailings. The results of this test indicated that a rate of 150 tons/acre of lime treated biosolids dramatically improved the tailings with no environmental impacts or leaching of metals. The pH of the tailing rose from 3.4 to 9.7, with a corresponding rapid drop in heavy metals in the leachate. Total Kjeldahl nitrogen was not analyzed, but nitrates were below detectable levels (Starr et al., 1994).

In 1995, a greenhouse pot study was conducted. The biosolids used in this study were not lime stabilized, but were Class B. The biosolids were mixed with acidic copper tailings at concentration rates of 10 percent, 15 percent and 25 percent. The 15 percent and 25 percent proved best. The pH rose from 3.5 to 5.2 at 15% biosolids and to 5.9 at 25%

biosolids. The biosolids also significantly improved the fertility of the tailings. The addition of biosolids significantly increased biomass production from less than 0.75 grams to over seven grams per pot of forage. Further, the addition of vesicular-arbuscular mycorrhizal fungi significantly increased biomass production in all biosolid treatments to as much as 10 grams per pot (Marx, 1996).

In 1996, a full-scale test was conducted on acidic tailings using four-different application rates of municipal biosolids. This test is designed to evaluate the incorporation of 20 percent to 30 percent solids Class “B” biosolids into the tailings. These biosolids are readily available from the wastewater treatment plant, can easily be transported and require no special handling. These acidic tailings were chosen as representative of a more challenging site and if successful this technique could be applied to many “abandoned” mine sites.

The biosolids were incorporated into the tailings at 5X the agronomic rate of N (approximately 20 dry tons/acre), 15 percent or two inches of biosolids (approximately 70 dry tons/acre), 25 percent or three inches (approximately 100 dry tons/acre), and 30 percent or four inches of biosolids (approximately 135 dry tons/acre). Because these were older tailings, the pH was in the 3-4 range. Due to the slightly acidic pH and concerns over the leaching of nitrates, some of the test plots were treated with lime (at 8.8 tons/acre) and others with greenwaste (at 0.5, 2, 3, and 4 inches for each of the application rates).

The results of this test indicated that there were no nitrates leaching below 12 to18 inches. Although there was an initial spike of ammonia and nitrate at the surface of the heaviest biosolids plots (135 tons/acre), this did not persist and there were no nitrates detected at depth (Bengson, 1999). After more than two years, there is still less than 20 ppm nitrate-N at depth under the heavier application rates of biosolids. The greenwaste apparently had some affect on promoting microbial-N immobilization and slowed the mineralization of organic-N, but did not make a significant difference in leaching. Sampling indicates little statistical difference in available metals with increasing biosolids application. According to research by Sopper (1993), plant metal concentrations generally increase with biosolids application, but remain below phytotoxic concentrations and decrease over time. Similar research on copper tailings elsewhere reported diluted levels of available copper with addition of biosolids (Wilson et al., 1993). The biosolids at all levels of application initially raised the pH to 6. After two years, the 70 and 100-dry tons/acre of biosolids alone still maintains a level near pH 5 & 6. The greenwaste did not appear to make any significant difference in pH. The lime-treated plots did show improved pH, but still did not maintain levels above pH 6.5.

As for reclamation success, biomass production showed a positive effect of additional biosolids. The “5X agronomic rate” did not provide sufficient plant growth no matter which additional amendment was used. The biggest contribution of the greenwaste to biomass production was the additional shrub and tree species that germinated from the greenwaste. This test indicates that reclamation success can be achieved at rates of 70 and 100 tons of biosolids/acre with no problems of nitrate leaching, heavy metal contamination or other environmental concerns (Bengson, 1999).

Another test was conducted on neutral copper tailings. This study tested the application of dried biosolids (70 percent solids) at rates of 30, 60 and 90 dry tons/acre (Thompson and White, 2000). Additionally, 100 tons of greenwaste were added to some of the plots. This provided a carbon to nitrogen ratio of 50:1. This latest test had similar results of the first test. The very best reclamation success came from the plots treated with 60 tons of biosolids and 100 tons of greenwaste/acre. However, the biosolids alone at 60 tons/acre was also successful in total biomass and groundcover (Thompson and White, 2000). The biggest contribution of the greenwaste in this test proved to be moisture retention.

Recognizing that copper tailings are essentially crushed rock, the parent material of soil, early tests to develop copper tailings into a “growth medium” by incorporation of organic matter began almost three decades ago.

These tests also included irrigation as a supplement to rainfall.

As with the previous test, this test proved there was little evidence of significant nitrate below 12 inches and none at 48 inches in depth (Thompson and White, 2000). There was also no evidence of heavy metals increasing significantly. Interestingly, there was some increase in nitrates with the greenwaste amendment in the surface 12 inches, but again none below 48 inches (Thompson and White, 2000).

A third test was recently conducted utilizing dried biosolids mixed with soil (from an evaporation pond) at a rate of approximately 100 tons/acre. This material was incorporated into the surface on approximately five acres of neutral tailings. Here the test was looking at microbial action. There was very little evidence of microbial activity in the tailing prior to treatment. The biosolids were of course extremely rich in organic matter that stimulated microbial growth and also contained microbes initially. The results indicated an approximate 10,000-fold increase in microbial activity. The tailings went from a MPN count of $5.4X10^3$ to $2.3X10^7$ with a very diverse microbial population (Pepper, 2000). This test showed no problems with pathogens such as Salmonella, Enterovirus or Microsporidia. As for reclamation success, the average ground cover was measured at 18 percent which is very good especially since this test was conducted without irrigation and during two of the worst droughts seen in southern Arizona.

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Footnotes

[1] Based on paper presented at the Mining, Forest and Land Restoration Symposium & Workshop, Golden, CO, July 17-19, 2000.

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Water Issues Associated with Coalbed Methane (Natural Gas) in the Powder River Basin of Wyoming and Montana

INTRODUCTION

Natural gas is an important energy source in the U.S. that is used to heat a majority of our homes and fuel most of our newer power plants. Coalbed methane (CBM) has only recently evolved as an important source of natural gas, currently accounting for about nine percent of U.S. natural gas production (Pinsker, 2002). Traditional natural gas exploration and production emphasizes deeper geologic formations that are separated from local aquifers (Figure 1). Unlike traditional natural gas, CBM is recovered by pumping water from coal seams, thus reducing water pressure and allowing the gas to desorb from the coal and migrate to the well bore.

Coalbed methane production has increased dramatically since the 1980s because of economic incentives, simplicity in developing CBM wells, and low costs associated with start-up expenses. Although extensive CBM production has occurred in many basins, CBM activities in the Powder River Basin in Wyoming and Montana are currently the most active in the U.S. The Powder River Basin contains extensive coal reserves, making CBM exploration and production very attractive; there are over 20,000 CBM gas wells currently permitted or drilled within the basin (Figure 2), with estimates ranging from 50,000 to 100,000 new wells to be drilled in the future (Wyoming Oil and Gas Conservation Commission, 2003).

A primary concern with the Powder River Basin development of CBM is related to the water that must be removed to access the natural gas. A single CBM well typically produces from one to 30 gallons per minute (gpm). Removal of CBM co-produced water (hereafter called CBM water) has been extremely controversial due to the potential for landowner well water and spring depletion and impacts from disposal of the

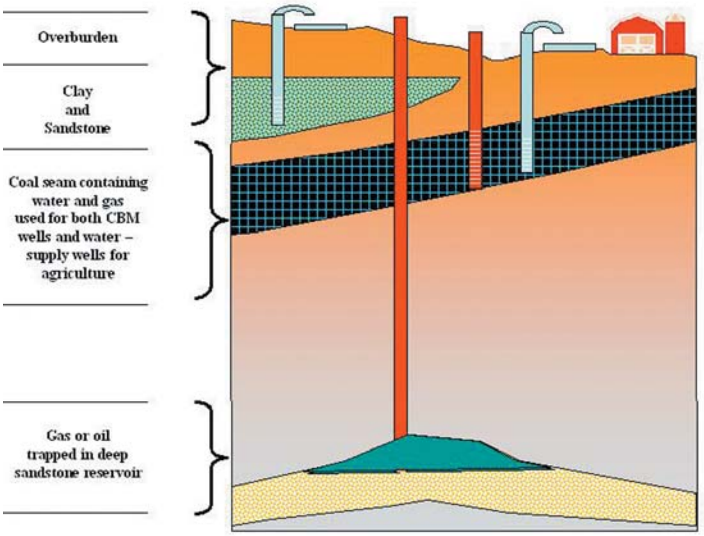


Figure 1. Traditional natural gas is separated from aquifers containing potable water, while in the PRB coalbed methane may be present in shallow aquifers used for domestic and agricultural water supplies.

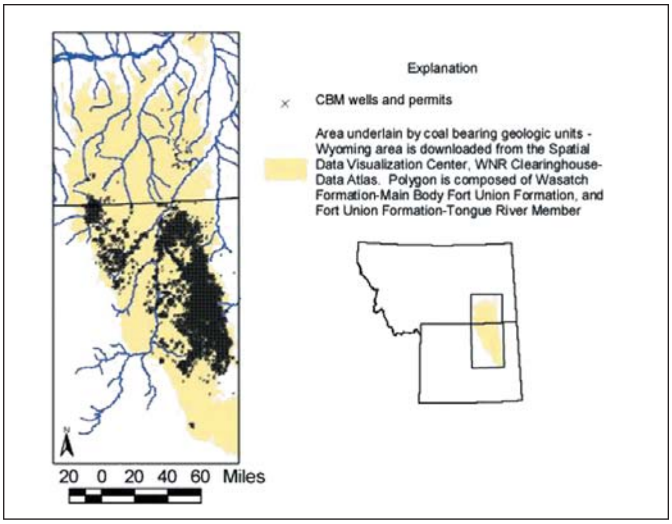


Figure 2. CBM well density in the Powder River Basin in Wyoming and Montana.

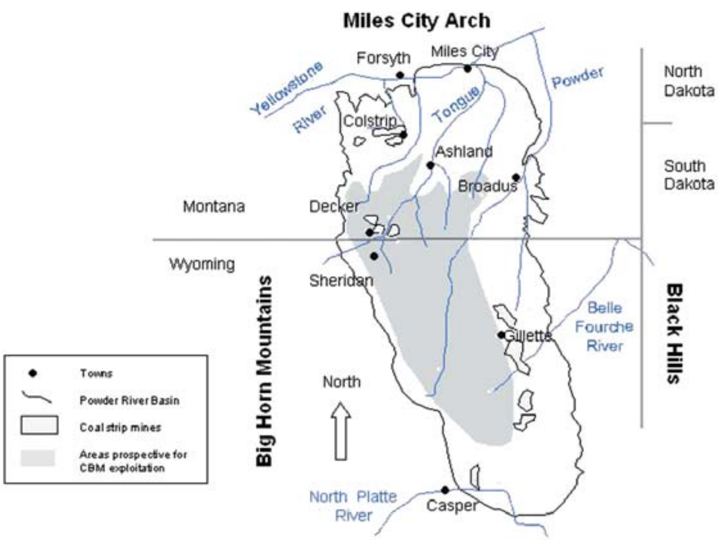


Figure 3. Roughly one-third of the PRB lies in Montana and two-thirds in Wyoming.

Figure 4. Location with multiple CBM wells from 3 stacked coal seams.

sodium (Na^+)-enriched waters. These impacts will continue until CBM production ends and ground-water levels return to baseline conditions due to recharge. Some CBM waters are used by farmers and ranchers for livestock watering, irrigation, and other uses, but disposal of large volumes of saline and sodic CBM water has resulted in lawsuits, as well as a plethora of innovative technologies and approaches to water management. In parts of the Powder River Basin, coal seams are the primary aquifers for agricultural and domestic uses. Therefore, a basic understanding of what CBM is and how it is produced, and the concerns accompanying the CBM waters are important for understanding issues currently confronted by landowners, industry, county conservation districts, and state and federal regulatory agencies.

CBM Description and Origins - The formation of CBM by both biogenic and thermogenic pathways is described by Law and Rice (1993). Biogenic formation of methane (CH_4) occurs in early stages of deposition and burial of sediments due to methyl fermentation and carbon dioxide (CO_2) reduction as organic matter decomposes. These processes require an anoxic environment, low sulfate (SO_4^{2-}) concentration, high pH and may generate CH_4 for tens of thousands of years. Due to the shallow depth of burial, much of this CH_4 may be lost to the atmosphere. With increasing depth during later stages of burial, CH_4 is generated by the reduction of CO_2. This process also occurs under anoxic conditions and requires an active ground-water flow system that is depleted of SO_4^{2-}. Reduction of CO_2 to form CH_4 can occur in any rank of coal, and the CH_4 is not as likely to vent to the atmosphere due to the greater depth of burial. At even greater depths, thermogenic formation of CH_4 occurs due to thermal breakdown of coal. High temperatures and pressures at the requisite depths will covert the coal to high-volatile bituminous or higher rank.

CBM in the Powder River Basin is limited to biogenic origins. Early stage CH_4 may have vented to the atmosphere or may still be in place in the coal. The current ground-water flow system, with ground-water quality dominated by Na^+ and bicarbonate (HCO_3^-) ions, is conducive to the formation of CH_4 by CO_2 reduction. Within the Powder River Basin, the ratio of early stage to late stage CH_4 is not known, nor is it known if CH_4 is still being generated.

CBM Significance as an Energy Source - Domestic CBM resources are estimated to be 700 trillion cubic feet (tcf), 100 tcf of which is estimated to be economically recoverable using today's technologies (Pinsker, 2002). Estimates of the total CBM resources in the Powder River Basin vary from 26.7 tcf (Potential Gas Agency, 2003) to 61 tcf (DOE, 2002). These widely varying estimates demonstrate the problem of discussing impacts due to production, as the magnitude of development is uncertain at this time. The DOE estimates that 39 tcf of the 61 tcf are recoverable, with only 0.9 tcf of that being in Montana. Current U.S. CBM production exceeds 1.25 tcf per year with a significant portion (0.25 tcf in 2001) from the Powder River Basin (Pinsker, 2002).

POWDER RIVER BASIN

The Powder River Basin, located in northeast Wyoming and southeast Montana (Figure 3), is situated between the Black Hills to the east, the Big Horn Mountains to the west

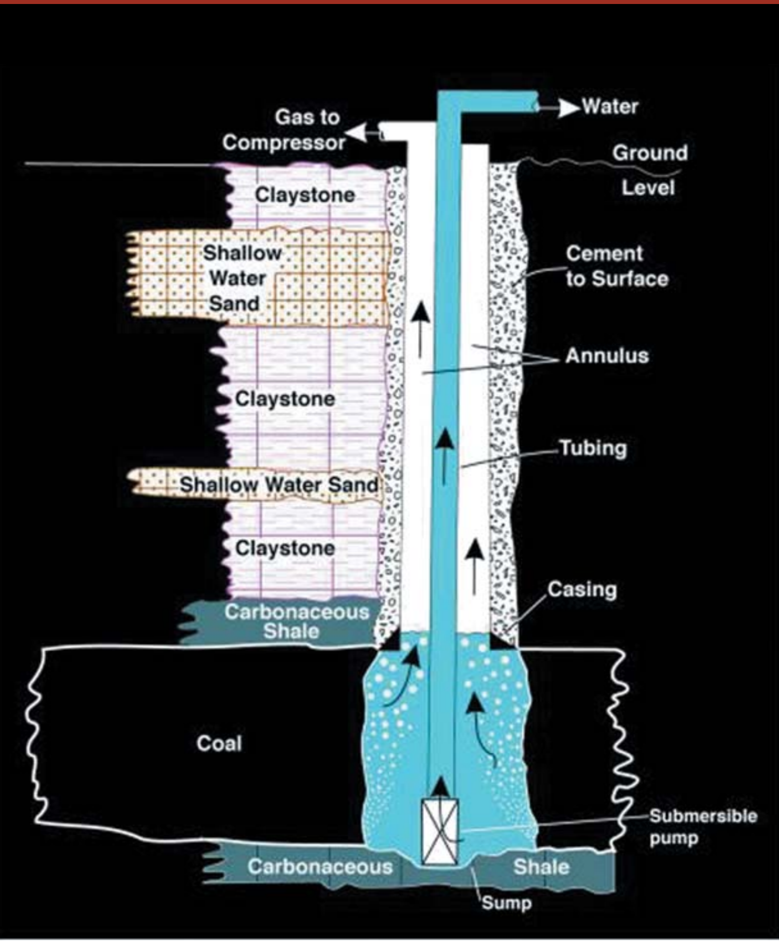


Figure 5. Typical production schematic of a CBM well.

and the Miles City Arch to the north. Land surface generally slopes northward from higher elevations in Wyoming and drains to the Yellowstone River in Montana. The Tertiary Fort Union Formation and the overlying Wasatch Formation are dominant bedrock exposures in Montana. In Wyoming, the Wasatch Formation is widely exposed at the surface. The Tongue River Member of the Fort Union Formation contains coal that is mined in both states and is the source unit for CBM. Montana's coalbeds are shallower than Wyoming's, and exposures along valley and canyon walls enhance CH_4 leaking to the atmosphere.

Ground-water flow in the Powder River Basin is generally from the south to the north. Coal seams are the most continuous water-bearing units and provide an important ground-water resource. Shallow coal seams are readily tapped as water resources (about one well for every two-square miles) and provide water to the abundant springs (one spring for every five square miles) that occur in Montana.

Soils of the Powder River Basin have developed under a climatic regime characterized by cold winters, warm summers and low to moderate precipitation (e.g., rainfall of 12 to 16 inches and snowfall between 36 to 60 inches). Soil textures vary and are influenced by dominant geologic conditions. Wide exposures of the Wasatch formation in Wyoming have led to the development of soils reflecting its sandy character. In Montana, geologic parent materials dominated by interbedded claystone and sandstone units of the Tongue River Member have developed soils that are typically finer textured with higher clay content. Soils are generally alkaline and low in organic matter. Farming is conducted primarily along valleys with perennial streams that support irrigation.

CBM PRODUCTION

Coalbed methane is held on cleat surfaces and in micropores in coal by weak attractive forces between the coal and the gas and by the hydrostatic pressure of ground-water in the coal (Law and Rice, 1993; Rightmire et al., 1984). To produce the gas, water is pumped from CBM wells, reducing the hydrostatic pressure and allowing the gas to desorb. Development involves completing wells in grid patterns, typically with one well per coal seam (Figure 4) in each 80-acre tract.

Due to the very low solubility of CH_4 in water, the gas and water move from the coal seam to the wells as a two-phase fluid. The water enters the pump and is discharged through the water line, while the gas flows up the well casing and is removed through gas lines to a low-pressure compressor (Figure 5). A central, low-pressure compressor receives gas produced from several wells that comprise a pod, and advances the gas to a high-pressure compressor station that receives gas from several pods, moving the gas into pipelines for delivery to market. Production from individual wells in the Powder River Basin is lower than those in other CBM-producing basins, typically peaking at about 200,000 cubic feet per day, before decreasing. Depending on local conditions and production rates, individual CBM wells may be productive for seven to 20 years.

Associated water production and quality - Total CBM-water production in the Powder River Basin is expected to

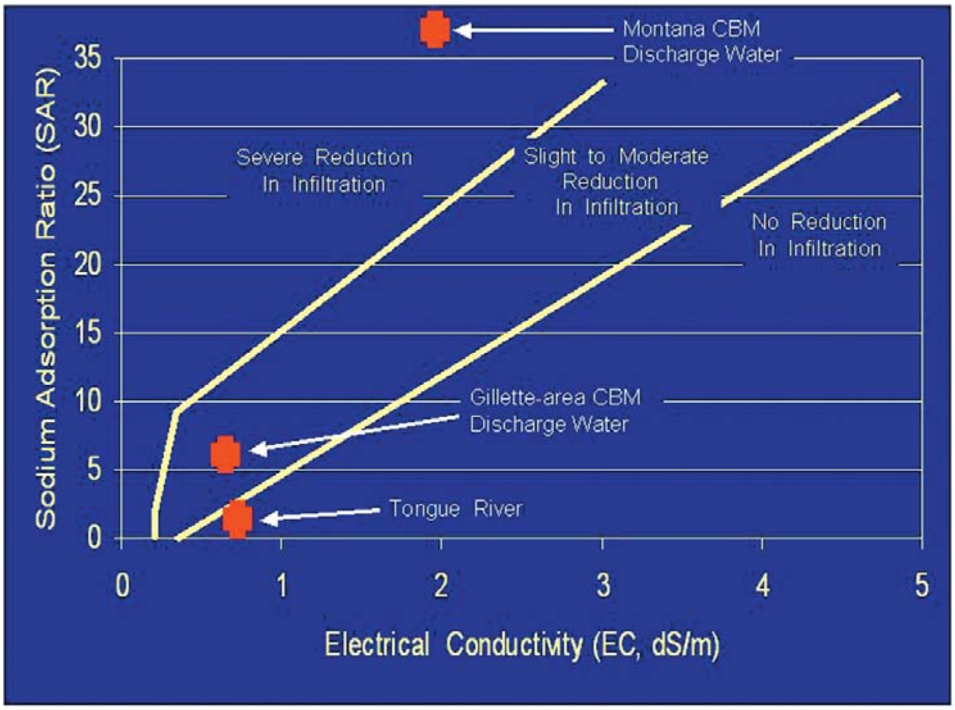
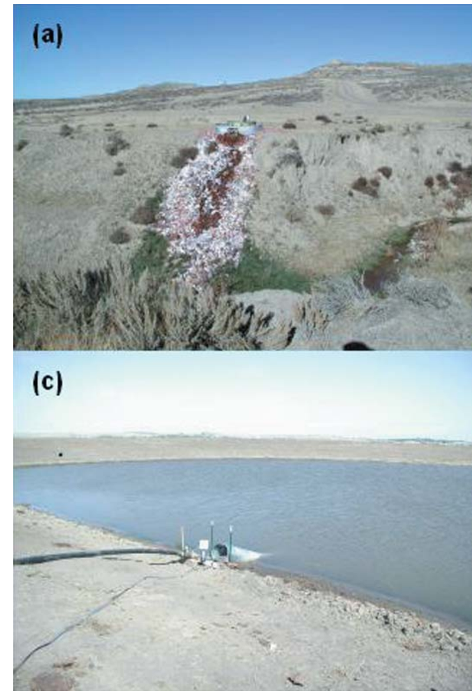


Figure 6. Powder River Basin CBM water SAR and EC values in relation to varying effects of water quality on soils.



Coalbed methane water management choices are influenced by factors such as cost, permitting, and environmental impacts.

peak at close to 400,000 acre-feet per year in 2006. Cumulative CBM-water production during the period 2002 through 2017 is projected to exceed 3,000,000 acre-feet (BLM, 2003). During the initial phase of production, water pressure within each coal seam is high, leading to water production of 30 gpm or more from each well. As CBM production reduces the water levels to near the tops of the coal seams, water production from each well is expected to decrease to less than 5 gpm (BLM, 2003).

Drawdown within the coal aquifers of more than 10 feet can be expected to reach one to two miles outside the producing fields during the early years of production and distances of five to 10 miles or more during long-term production (Wheaton and Metesh, 2002). Overburden and interburden aquifers may also experience drawdown, but to a lesser degree than the producing coal seams. Flow from springs and water available at water-supply wells will be diminished proportionally to the decrease in hydrostatic pressure in the aquifer at the well or spring. Discharge rates from individual CBM wells will vary depending upon time since pumping began, position in the field, size of the CBM field, and local aquifer conditions. Based on three-dimensional modeling of data for southeastern Montana, Wheaton and Metesh (2002) reported that isolated CBM fields of roughly 1,100 wells can expect discharge rates of between three and 20 gpm per well. Cumulative rates may be as high as 25,000 ac-ft per year at start-up and 8,000 ac-ft per year for long-term production, depending on the number of wells brought on line per year. Recovery of water levels in aquifers will begin when CBM production ends. Extent and timing of recovery will depend on distance from the CBM well field, extent of development, proximity to recharge and aquifer characteristics. Complete recovery will require much more time within the CBM well field than outside the field. Based on a modeled scenario (Wheaton and Metesh, 2002) using an isolated CBM well field one-township in size (~23,000 acres), the available head will likely approach 90 percent of pre-development levels outside the production area about five years after production ceases. Within the CBM field, recovery will take longer, and may approach 70 percent within 10 to 15 years.

Water co-produced with CBM in all basins is in a reduced state, dominated by Na^+, HCO_3^- and/or chloride (Cl^-) depending on the depositional setting of the individual coal seam (Van Voast, 2003). CBM water in the Powder River Basin is dominated by ions of Na^+ and HCO_3^- (Rice et al., 2002). Water quality ranges include: pH from 6.8 to 8.0, salinity (EC) levels from 0.4 to 4.0 dS/m, sodium absorption ratios (SAR or the ratio of Na^+ to calcium (Ca^{2+}) and magnesium (Mg^{2+})) from lows of five to extreme highs of 70, and total dissolved solids (TDS) from about 300 to more than 2,000 mg/L. In the southeastern Powder River Basin regions, CBM water generally has low total TDS and SAR. Concentrations increase to the northwest and SAR values of CBM waters in Montana often exceed 50, well beyond the irrigation water suitability limit of 10 (Figure 6).

PRODUCED WATER MANAGEMENT OPTIONS

Coalbed methane water management choices are influenced by factors such as cost, permitting, and environmental impacts. Water issues surrounding CBM are contentious. For

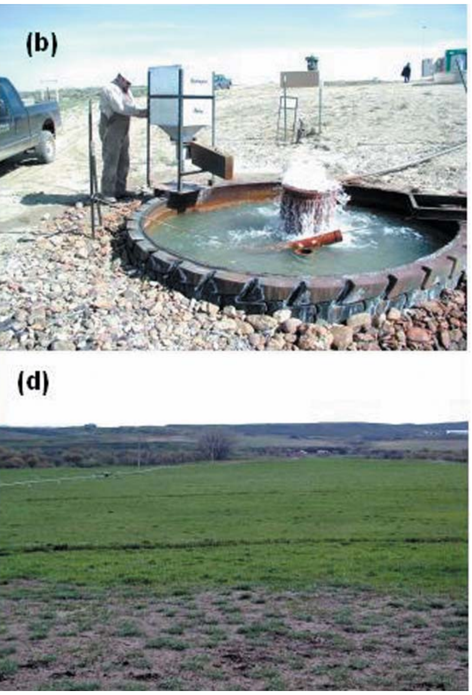


Figure 7.
Various options for CBM water use:
(a) direct discharge over and outfall rock structure;
(b) gypsum treatment;
(c) unlined impoundment reservoir; and
(d) land application using side-roll irrigation.

...direct land application of saline-sodic, high HCO_3^- CBM waters can potentially cause permanent damage to the native soils and vegetation.

example, Powder River Basin farmers and ranchers in Wyoming have expressed discontent over CBM production causing their water wells to be depleted and excess water being discharged on their lands. Use and disposal of CBM waters is one of the primary environmental concerns of the public, resulting in legal and regulatory battles associated with CBM water in Wyoming and Montana, as well as in other CBM regions.

Injection - Over 90 percent of the CBM water in producing regions other than the Powder River Basin is disposed of by injection into wells placed into specific geologic formations. Planning for this method requires detailed information about the receiving aquifers and CBM water qualities. Injection is problematic in the Powder River Basin because of complications arising from managing multiple producing zones and multiple producers. However, in certain areas, such as near Gillette, WY, CBM water is being injected into an aquifer as a form of artificial recharge. This has the dual advantage of disposing of the water without negative surface impacts, and utilizing the water as a resource.

Direct discharge to surface water - The states of Wyoming and Montana allow some CBM producers in the Powder River Basin to release limited amounts of CBM water directly into waterways. Currently, there is a moratorium on additional direct discharge permits, in part, because limits on downstream users are being analyzed. Water directly discharged to a surface-water body is piped from the CBM well to a discharge point and released to the receiving water. Outfall structures are used to minimize erosion and discharge permits are required (Figure 7a).

Treatment - After treatment, producers potentially could release CBM water into streams and other waterways or use the water for irrigation and other beneficial purposes (Figure 7b). As an example, reverse osmosis can be used to reduce the Na^+ and other salt concentrations of produced water. The costs for installing a reverse osmosis unit were estimated by the DOE (2002) at $19,600 per well, plus $0.24 per barrel of water treated, or just over $60 per day at an average water discharge rate of 8 gpm. Treatment methods are effective and can result in high-quality waters that can be used for various purposes. Unfortunately, ion-exchange, reverse osmosis and other similar types of treatment often require large industrial columns and filters, treatment equipment, and operation and maintenance that are very expensive.

Impoundments and infiltration reservoirs - CBM water can be discharged into lined or unlined impoundments (e.g., reservoirs) (Figure 7c). Storage in lined impoundments allows CBM waters to be treated for land application for agricultural purposes or disposal, and provides enhanced control over the timing of discharges such as release to surface-water bodies during non-irrigation seasons. Unlined impoundments allow water to leach into the subsurface environment or percolate into the surrounding soil. Lateral migration of salt and Na^+, impacting surrounding steams and terrestrial ecosystems, has been suggested as a possible consequence of long-term CBM water disposal in unlined impoundments. Recharge to shallow aquifers may be a benefit if the water quality is compatible. Unlined impoundments have been identified by the Bureau of Land Management as the primary process for disposing of CBM in the Powder River Basin of Wyoming.

Land application - Some CBM waters are currently being used for land application on rangelands and for production agriculture; however, direct land application of saline-sodic, high HCO_3^- CBM waters can potentially cause permanent damage to the native soils and vegetation. CBM producers have developed water management programs that include soil treatments such as sulfur (S) and gypsum ($CaSO_4$) applications to prevent problems that might occur due to pH changes, calcium carbonate ($CaCO_3$) formation and Na^+ dispersion and toxicity. Methods for application of CBM water include center-pivot and side-roll irrigation systems, portable water cannons and misters (Figure 7d). Complex site-specific environmental factors, such as topography, land use, soil types and quality, soil hydrologic characteristics, water quality and application rates, and vegetation types and tolerances are considered when determining site-specific application methods, although non-environmental factors, such as equipment installation and operating costs, land-owner agreements, and regulatory environment are also important.

Application of CBM waters with high salinity (EC) can result in reduced water uptake and water stress to plants due to increased energy requirements for plants to obtain soil water. While tolerance to salinity varies among crop types, it is generally accepted that saline conditions have negative impacts on all crops at some level of salinity. Under saline

It is anticipated that CBM gas production will continue to develop at a rapid rate, creating economic benefits and extensive impacts to the environment of the Powder River Basin.

conditions, some ions have toxic effects (e.g., Cl, Na, boron (B)) on plants. At higher pH, availability of micronutrients such as iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn) will be reduced. In addition to the above, salinity can affect soil physical properties. Salinity increases flocculation of clay particles resulting in aggregation, increased permeability and aeration, and better root growth and penetration. However, sodicity has the opposite effect on soils. Sodium causes dispersion of soil clay particles and organic matter, resulting in surface crusting, reduced infiltration and reduced hydraulic conductivity. Clay soils are more vulnerable to sodicity than sandy soils and, because of crystal lattice structure differences, smectitic clays (those dominant in the Powder River Basin) are more vulnerable than kaolinitic clays. Changes in soil physical and chemical properties associated with increased sodicity could, when coupled with poor vegetation cover, alter the resistance of soil to water and wind erosion, thus aggravating the problem caused by application of saline-sodic CBM water.

Vegetation management concerns regarding land application of CBM waters include: 1) changes in relative composition and dominance of vegetation communities from differential tolerances of individual species to altered conditions, 2) establishment of non-native, invasive vegetation species, especially those with aggressive growth characteristics and, 3) the effect of CBM water application on vegetation forage quality, including impacts associated with the application of soil and water amendments and treatments. A productive vegetation community influences the impact from application of saline-sodic CBM water. Studies have indicated that soil structure and soil permeability can be improved and Na^+ removal accelerated by planting hay and pasture grasses or by cropping (Page and Willard, 1946; Skidmore et al., 1986). Investigating the tolerances of native and agricultural plant species to the application of saline-sodic CBM water will provide information to manage for enhanced reclamation potential.

CONCLUSIONS

It is anticipated that CBM gas production will continue to develop at a rapid rate, creating economic benefits and extensive impacts to the environment of the Powder River Basin. Addressing these impacts in a meaningful way will require continuing data collection through monitoring of CBM production and recovery responses and on-going research projects. Data collection should address all aspects of the impacted environment including geology, surface and ground hydrology and water qualities, soils, vegetation, and wildlife. These analyses will include the development of accurate models to provide valuable guidance for permitting and development decisions. Analysis of this information and successful public dissemination of the interpretations will be crucial to developing successful strategies for managing impacts of CBM production. ■

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Call for papers

The American Society of Mining and Reclamation (ASMR) is hereby issuing the first call for contributed papers to be presented at the 22nd national meeting in Breckenridge, Colorado, from June 19 – 24, 2005. This conference is devoted to the transfer of the latest reclamation research results and the latest treatment technology. You are cordially invited to attend and showcase your work. The deadlines for participation are listed below. Technical sessions will include:

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SAMPLE ABSTRACT
(SEND ABSTRACT TO RICHARD BARNHISEL)

MINING INFLUENCED WATERS: THEIR CHEMISTRY AND METHODS OF TREATMENT [1]

T. R. WILDEMAN[2] AND R. SCHMIERMUND[3]

Abstract:

More and more often, in treating waters associated with mining projects, it is not acid rock drainage that is the focus of concern. Consequently, we have coined a new phrase "mining influenced waters" to include all the types of water that can be encountered. These waters can be divided into four categories. For acid rock drainage (ARD), the primary treatment problem is the elimination of mineral acidity in the form of soluble iron and aluminum. For mineral processing waters, the water is usually basic and the primary treatment problem is usually the elimination of cyanide, arsenic and selenium. For marginal waters, the water is circum-neutral, but contains contaminants slightly above aquatic standards. For these waters, the treatment problem is often reducing small concentrations of contaminants in high flows of water. Finally, for residual waters, the primary treatment problem is the removal of high levels of total dissolved solids. For residual waters, there are few treatment options and these waters are becoming a serious environmental problem relative to all types of mining.

Additional Key Words:

aquatic chemistry, acid mine drainage, water treatment, mineral processing, and total dissolved solids.

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Reclamation Research Library

(HTTP://WWW.SIU.EDU/~WILDLIFE/RESEARCH/RECLAIM.HTML)

More than 12,000 references can be found at the Mined Land Reclamation Research Library at the Cooperative Wildlife Research Laboratory of Southern Illinois University at Carbondale, Illinois. The research reports and papers cover more than 50 subjects from Acid Mine Drainage to Wildlife. A large collection of papers can be found for the Wetland topic.

Here is a sample of some of the topics.

AMD: Abatement/Prevention
AMD: Detection, Monitoring, Prediction
AMD: Formation/Treatment
AML Reclamation
Coal Resources
Effects of Mining (Miscellaneous, Blasting, Air Pollution)
Erosion/Sediment
Fly Ash
Hydrology
Impoundments
Overburden Properties
Reclamation: General
Recreation
Reforestation
Refuse
Revegetation
Sediment Ponds
Wildlife and Fisheries
Wetland Development
Wetland Treatment
Wildlife and Fisheries

The Library was initiated in 1950 to serve the needs of staff, students and government personnel in reclamation. Copies of publications are available for review at the library. Requests for papers will be processed as scanned pdf files and sent to the individual via email.

BY SUZETTE R. BURCKHARD, ASSOCIATE PROFESSOR, CIVIL AND ENVIRONMENTAL ENGINEERING, SOUTH DAKOTA STATE UNIVERSITY

Remote Sensing: Will it Work for You?

When working in the reclamation industry, you have a need for current and accurate maps regarding your field sites, as well as historical data on the pre-disturbed condition of the site. If the site is remote and difficult to access or large is size, acquiring this information with a ground crew may be expensive.

For example, you may have a field site thousands of acres in size. You start calculating the amount of personnel time and equipment to evaluate the present condition of the site. Costs for personnel ($400 to $800 per week), travel ($300 to $700 for plane ticket, if needed, $40 per day for a rental vehicle), lodging ($50 to $100 per night), and sampling equipment costs (highly variable) can be very expensive. For a one- week data collection trip, with two people, the costs could run from $2,000 to $4,000, without sampling equipment or analysis. Being optimistic, you assume the team can cover 1,000 acres for sampling during this time period.

For instance, you may be working with a historic smelter site in Montana that covers 65,000 acres. To effectively evaluate this site, it would take this two-person team 65 weeks of good weather. This would not meet your time deadline. If you have a manner to select specific sites to evaluate within the 65,000 acres, you could evaluate those and then statistically average the data to obtain a profile of the disturbed site. This may require that the selected sites be more intensively or specifically measured than initially planned. This would decrease the area that could be covered by the evaluation team. Wouldn't it be nice to access available data that allows you to measure certain parameters regarding the site without the time, expense and effort needed for field reconnaissance?

At present, there are large volumes of satellite and aerial photography information available that could be used in this capacity. The data originates from governmental programs such as National Aeronautics and Space Administration (NASA) and a few new commercial satellite companies that collect data from satellites that orbit the earth, as well as historical aerial photography. Engineering uses for remotely sensed satellite data presently include site control, loss control, environmental impact assessments and historical review of sites. In order to better assess whether satellite or aerial sensed data can help, it is necessary to understand:

- A few basic principles of remote sensing
- Characteristics of different remote sensing information sources
- The nature of the problem you are gathering information on
- The value of the information

In remote sensing systems, a sensor is mounted on a platform – either a satellite or airplane – that senses (measures) spectral radiation. The electromagnetic sensors used to collect data sense different ranges of electromagnetic radiation. Table 1 notes several types of satellites and the sensor ranges they cover. The spectral ranges or bands are used to measure different types of data. Table 2 details the spectral bands and the applications they are suited

Table 1. A summary of several satellite platforms and the spectral ranges (µm) they measure.

		NOAA-AVHRR[1]	Landsat	TM[2]	SPOT[3]	IKONOS*	Quikbird*
	Contact information	http://edc.usgs.gov	http://edc.usgs.gov	http://edc.usgs.gov	http://www.spot.com	http://www.spaceimaging.com	http://www.digitalglobe.com
Spectral Sensor Range	1 (µm)	0.55-0.68		0.45-0.52 Blue	0.50-0.59 Blue	Blue	Blue
	2 (µm)	0.73-1.10		0.52-0.60 Green	0.61-0.68 Green	Green	Green
	3 (µm)	3.55-3.93		0.63-0.69 Red	0.79-0.89 Red	Red	Red
	4 (µm)	10.50-11.50	0.5-0.6	0.76-0.90	0.51-0.73 Panchromatic	Panchromatic	Panchromatic
	5 (µm)	11.50-12.50	0.6-0.7	1.55-1.75			
	6 (µm)		0.7-0.8	10.40-12.50			
	7 (µm)		0.8-1.1	2.08-2.35			
	8[‡] (µm)		10.4-12.6				

1 – National Oceanic and Atmospheric Administration – Advanced Very High Resolution Radiometry
2 – Thematic Mapper
3 – A series of earth orbiting satellites operated by the Centre National d'Etudes Spatials (CNES) of France
‡ – Landsat 3 only
• – spectral ranges are proprietary information, contact company for specifics

Table 2. Applications associated with various spectral ranges.	
Spectral Band (µm)	Application
Blue (0.45-0.50)	Water penetration, land use, soil and vegetation characteristics, sediment
Green (0.50-0.60)	Green reflectance of healthy vegetation
Red (0.60-0.70)	Vegetation discrimination due to red chlorophyll
Panchromatic (0.50-0.75)	Mapping, land use
Reflective (0.75-0.90)	Biomass, crop identification, soil/crop or land/water boundaries
Mid-Infrared (1.5-1.75)	Plant turgidity, droughts, clouds-snow-ice discrimination
Mid-Infrared (2.0-2.35)	Geology, rock formations
Thermal Infrared (10-12.5)	Relative temperature, thermal discharges, vegetation classification, moisture studies

Table 3. Characteristics of various satellite data sets.

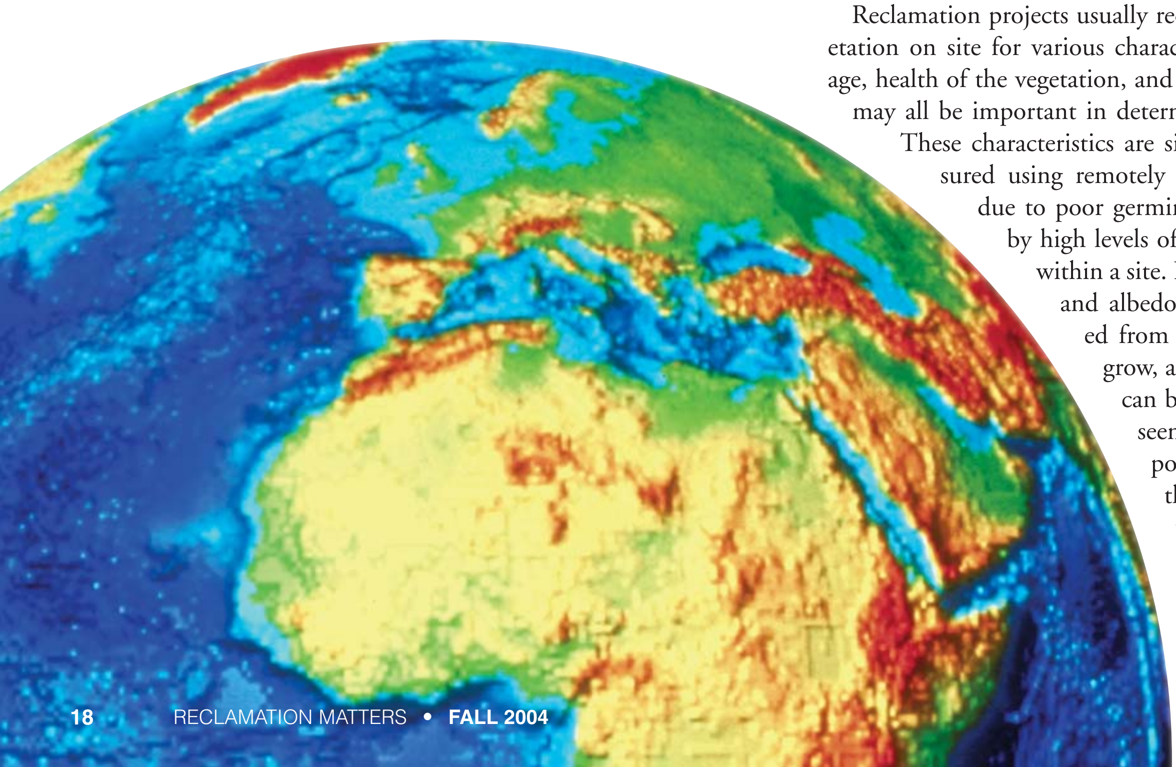
	NOAA-AVHRR	Landsat	TM	SPOT	IKONOS	Quikbird
Spatial resolution	1.1 km	79 m	30 m	20 m (10 m)*	1m	0.66 m
Swath	2700 km	185 km	185 km	117 km (425 km)*	10 km	16 km
Days for Global Coverage/revisit time	1	18	18	26 (2-3)*	3 days	1-4 days•

* (ability to point sensor up to 27˚ from the central position) off- radii pointing capacity

for. Presently, remotely sensed data is used to measure precipitation amounts, snow hydrology, land usage and characteristics, yield estimations for various crops and watershed characteristics. In order to assess each of these measurements, different combinations of sensors are used. Landsat 4, 5, and 6 bands or TM 3, 4, and 5 bands are used for calculating the Normalized Vegetation Difference Index (NVDI), which is used to assess vegetation extent and health. The NVDI changes with the seasons, so an early spring calculation will be different from a fall calculation.

Each sensor system has different resolutions, return times, spectral bands, costs and data processing requirements. To determine the resolution necessary to measure the information you are interested in, you need to determine the smallest-sized object that needs to be identified in the image that results, as well as the overall size of the image that is needed. For example, if the field site has treatment plots that are 100 yards square, a measure of the entire plot in one pixel may give you a general idea of how the vegetation is growing in a particular treatment plot. If you wanted to know how the vegetation was growing across the treatment plot, you would be interested in having a number of pixels across the plot. As far as return times, due to the number of different types of satellites, sensors, spatial and temporal arrangements, sites on earth may be covered every day to every 26th day.

Reclamation projects usually require some monitoring of vegetation on site for various characteristics. The extent of coverage, health of the vegetation, and diversity of growth on the site may all be important in determining maintenance decisions. These characteristics are similar to those presently measured using remotely sensed data. Spotty coverage, due to poor germination of seeds, can be caused by high levels of toxins at a particular location within a site. By monitoring the aerial extent and albedo (amount of radiation reflected from the soil surface) as the plants grow, an accurate record of vegetation can be kept. When bare patches are seen, then further investigation by possibly sending a field team to that particular location can be undertaken. Patchy or poorly growing vegetation may indicate the need for fertilization or other amendments. This would save costs associated



with treating the whole site, based on averaged individual soil sample results. In some cases, toxins in the soil will cause specific physiological growth habits to occur, such as yellowing of leaves, purple splotches, stunting of plants and curling of leaves. These variable growth habits do affect the way the electromagnetic spectra interact with the plants and are reflected by changes in calculations of NDVI, albedo and turgidity. By comparing the calculated plant parameter values from the phytoremediation field site to those for plants grown on uncontaminated soil, differences and possible problems can be studied. For the Anaconda Smelter site shown in the photo, the 'control' plants are those growing in the crop fields located to the north of the smelter site. Note that some field measurements are still necessary to further assess or verify the results you are calculating from the satellite data, but fewer trips are required to monitor the site as a whole looking for problem areas.

Remotely sensed data has a number of advantages and disadvantages. One advantage associated with using remotely sensed data is the lower cost associated with on the ground large-scale measurements. Data availability is increasing. There is also the possibility of having multiple measurements for a single site and that those measurements are spatially averaged due to the remote sensing coverage and resolution. A continuous historical satellite data record exists for most sites on earth into the 1970's or earlier. Earlier than 1970, aerial photographs exist for much of the U.S. from government programs. In order to find historical data for a site, you may want to investigate the United States Department of Agriculture (USDA), which has infrared and black and white aerial photography, along with field data, for soil delineation maps.

Disadvantages associated with remotely sensed data are varied, depending on your needs. The first is the extensive learning curve required to properly manipulate the raw data in order to obtain usable results. But, you can hire others to do this for you. The second is the need for a high-end computer workstation and software, such as Geographic Information Systems (GIS), to manipulate and manage the data. The third is the possibility that the 'scene' you need is actually available. Cloud coverage, weather problems, and technical glitches can result in imperfect data. Another problem may be in the timing of the satellite flight. The flight path of the satellites cannot be altered. For this reason, considering a similar sensor or digital camera system mounted on an airplane may be an excellent solution. There are sensor arrays, similar to satellite sensor arrays, mounted on airplanes and helicopters. One of these is AVIRIS (Airborne Visible InfraRed Imaging Spectroscopy). AVIRIS data has been used by the Environmental Protection Agency (EPA) to indicate acid mine drainage areas in Leadville, Colorado. AVIRIS is a high-end sensor that measures reflectance over an almost continuous range from infrared to ultraviolet.

Lastly, some historical satellite or aerial data may require an additional fee or charge to obtain the data. In most cases, the fee is not substantial but reflects the cost of preparing the data for your usage on the particular computer system you employ. If you, as the contractor, require special aerial flights over a site, the cost will be higher. A comparison of costs to those initially estimated for sending a two person team to a particular field site may find the actual costs to be less than ground sampling, depending on the amount and type of data the contractor needs. A cost savings of 80 percent was noted on one field site that required monthly monitoring of

Table 4. Sources of information on the Internet.

Internet address	Type of information on site
http://edcwww.cr.usgs.gov/	USGS EROS Data Center, repository for many different types of satellite and aerial photography data
http://www.saa.noaa.gov/index3.html	Polar orbiting operational environmental satellites
http://gcmd.nasa.gov/param_search/top.html	Global Change Master Directory data sets
http://fermi.jhuapl.edu/states/states.html	AVHRR
http://seawifs.gsfc.nasa.gov/SEAWIFS.html	SIR-C, global ocean color monitoring mission
http://www.satlab.hawaii.edu/satlab/airsar.html	SAR, multi-frequency radar images
http://radarsat.espace.gc.ca/welcome.html	RADARSAT, Canadian Earth Observation Radar Satellite
http://www.spot.com/	SPOT
http://alexandria.sdc.ucsb.edu/ http://www.lib.berkeley.edu/EART/aerial.html	Digitized aerial photographs
http://terraserver.microsoft.com/	Declassified aerial photographs
http://www.spaceimaging.com	Commercial satellite data
http://www.digitalglobe.com	Commercial satellite data

vegetation. Instead of sending a team each month to the site, the site visits were set at twice each year, with satellite data being used for the other monthly monitoring visits. In initial negotiations to change the type of monitoring, data from the actual visits were compared to data derived from remote sensing sources.

Internet sources of remotely sensed data and information on satellites are shown in Table 4. The data on these sites may be in the form of downloadable images (GIF, TIF, or JPG), GIS files (ARCMap or other format), or ordering information so you can download a file or order a CD-ROM with the file you requested. Depending on your needs, remotely sensed data may be a useful alternative for monitoring field sites. As with any new 'tool,' there are a number of details to be worked out. Presently, research is being conducted on ways satellite data and sensors can be manipulated to use in engineering applications. Additionally, new plug-ins and extensions are available to existing software so that remotely sensed data is more easily integrated. ■

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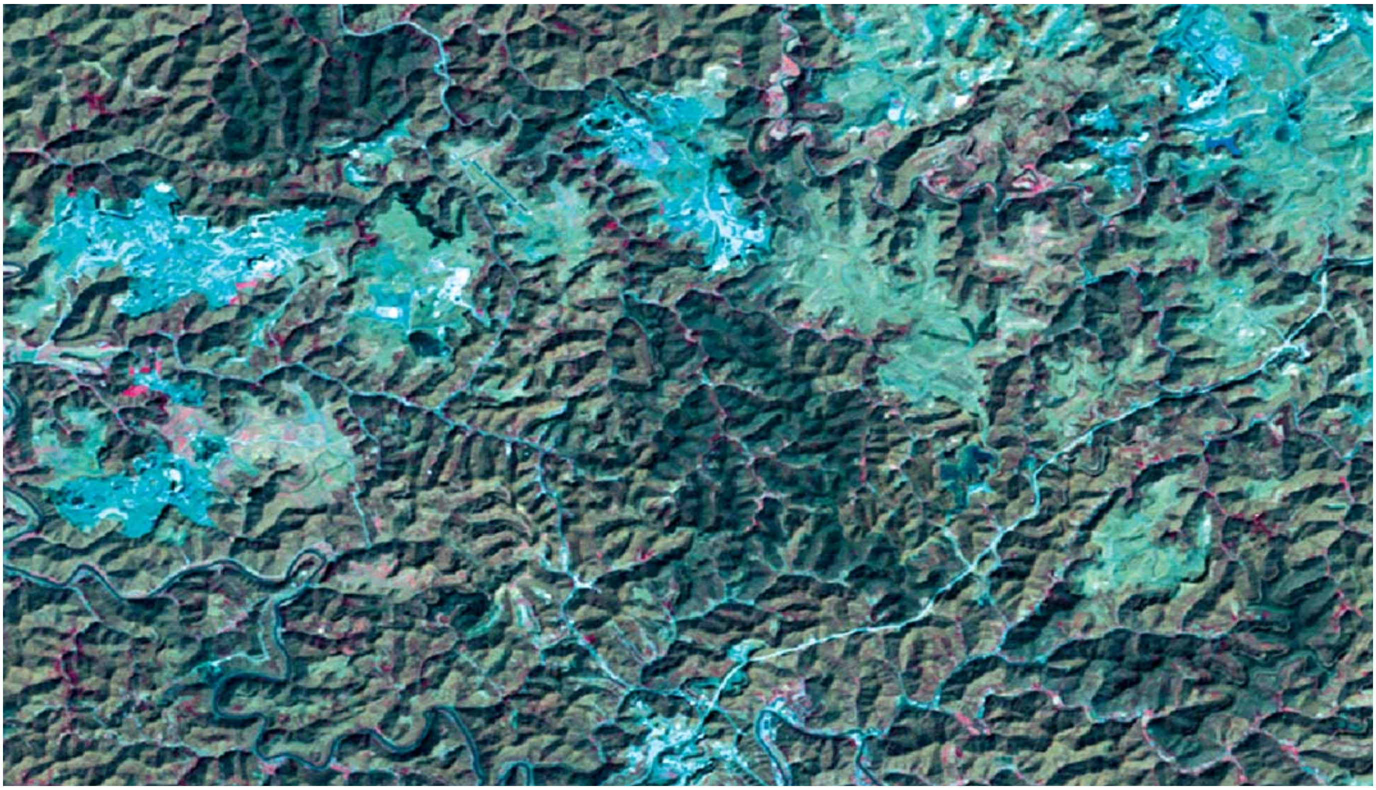


Anaconda Smelter site.

BY RICHARD HAMMACK, JAMES SAMS, GARRET VELOSKI, AND TERRY ACKMAN
U.S. DOE, NATIONAL ENERGY TECHNOLOGY LABORATORY, PITTSBURGH, PA

Airborne Surveys Identify Environmental Problems on Mined Lands

Since 1999, the National Energy Technology Laboratory (NETL) has conducted almost 50 airborne surveys of watersheds in the United States affected by mining or oil and gas production. The intent of the surveys has been to provide a rapid, comprehensive assessment of the site hydrology and to identify environmental problems that may exist. The surveys utilize sensing technologies that were originally developed for other purposes but have been modified to provide useful hydrologic and environmental information pertinent to lands used for the production of fossil fuels. Airborne surveys were found to provide information more quickly and less expensively than equivalent ground investigations. In certain cases, airborne surveys can provide hydrologic information that is not available from any other source. Three case studies are discussed below that illustrate the utility of the airborne approach.

Case Studies

Kettle Creek Watershed, Pennsylvania

Kettle Creek is a mountain stream in the north-central part of Pennsylvania that flows through a rugged, forested gorge. Although few residents still living in the area are old enough to remember the coal mines that were once here, past mining is evident in the unreclaimed surface mines and miles of streams made lifeless by acid mine drainage. Making an inventory of mining-related environmental problems in the 35 square mile Kettle Creek Watershed was a daunting challenge given the size, ruggedness, vegetation, and limited access of the area. What was needed was a rapid means of reconnoitering the entire watershed to locate problem areas so that thorough investigations could be concentrated on small areas of particular concern. This need was met by two remote sensing surveys that could be carried out by low-flying aircraft.

Airborne Thermal Infrared Imagery

A thermal infrared scanner on a small twin engine airplane was used to identify water discharged from underground mines. This technology, which senses small differences in temperature, makes use of the temperature difference between groundwater and surface water to identify areas where groundwater is emerging at the surface. Groundwater, including mine water, is significantly warmer than surface water during the winter or early spring, a leaf-off time of year that is optimal for thermal infrared surveys. These surveys are flown in the early morning hours, just prior to sunrise to minimize the effect of solar heating. Thermal infrared images clearly show locations where warm groundwater emerges at the surface (Fig. 1) but cannot distinguish mine discharges from other types of groundwater. This distinction is based on water chemistry, a determination that is best made by ground observations at the discharge site. The thermal infrared survey of Kettle Creek Watershed identified 103 groundwater discharges, of which 53 turned out to be mine discharges. Because the surveys provided the exact locations of the 103 sites, it was possible to visit all of them, despite the rugged terrain, in just one week! Moreover, of the 53 mine discharges located, 27 were previously unknown. On the other hand, seven previously known mine discharges were not identified by thermal imagery because non-deciduous vegetation (conifers, rhododendron etc.) shielded the mine discharges from the airborne sensors. The value of thermal infrared imagery is that it can quickly direct ground personnel to groundwater discharges where water quality can be rapidly assessed. However, its limited effectiveness in areas with significant amounts of non-deciduous vegetation has to be considered.

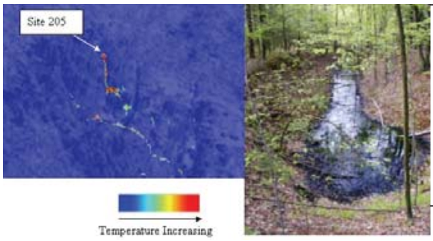


Figure 1. Color-enhanced TIR image showing location of mine discharge (left). Photograph of same mine discharge taken during ground investigation (right)

Helicopter Electromagnetic Surveys

Three months after the thermal infrared survey, residents of the Kettle Creek area witnessed a low-flying helicopter towing a cigar-shaped object or "bird" slowly back and forth across the Kettle Creek Watershed. The pilot was obviously keeping the bird about 100 feet above the ground and had to go up and down often in response to the rugged landscape. The helicopter was conducting an electromagnetic survey that provided information about the location and quality of groundwater. Helicopter electromagnetic (HEM) surveys (Fig. 2) are used to: 1) detect and map pools of acidic water impounded in underground mines where the cover is less than 150 feet; 2) locate concentrations of acid-generating material in surface mine spoil; 3) locate groundwater infiltration zones, and; 4) locate potential areas for seeps and springs.

Figure 2. Helicopter electromagnetic survey of coalbed methane field in the Powder River Basin in Wyoming

Data collected from the HEM survey was used to construct conductivity/depth images (CDIs) that show the vertical distribution of conductivity from the ground surface to depths of about 300 feet. In Figure 3, the water table is depicted as a green-yellow-red band that parallels the topography. Acidic mine pools are denoted by red areas. In areas of the Kettle Creek Watershed where mine maps were available, the mine pools interpreted from CDIs were always located within underground mines. Underground coal mining within the Kettle Creek Watershed was up-dip so that water would freely drain from the mines. Since mining ceased almost a century ago, roof falls have blocked entries and impounded acidic water in parts of these mines. These acidic mine pools are the suspected sources of mine discharges. Accurately knowing the location of such pools is important since in-mine alkaline addition is being considered as a potential water treatment. HEM can locate pools of water in underground mines if: 1) the water is conductive (acid mine drainage is conductive); 2) the overburden is resistive (predominantly sandstone, siltstone, or limestone); and 3) the overburden is not more than 150 feet thick. Water infiltrating through surface mines is made conductive by the contact with weathering spoil material (Fig. 4). After contacting surface mine spoils, the infiltrating water can be seen in CDIs as a slightly conductive zone extending from the surface down to the water table (Fig. 5). Thin, red layers at or near the surface (Fig. 4) denote the location of acid-generating spoil (pyrite-rich spoil) or acid groundwater in a non-reclaimed surface mine. Accurately knowing the location of groundwater infiltration zones and acid generating spoil can focus reclamation efforts on small areas, thereby reducing cost.

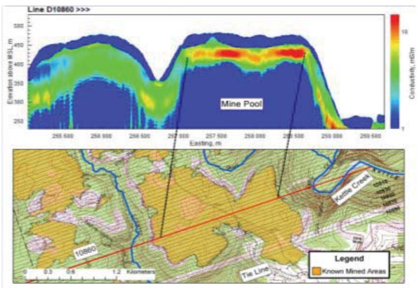


Figure 3. Conductivity/depth image (top) showing the location of underground mine pools (red areas) and the relationship of mine pools to known mined areas (bottom map).

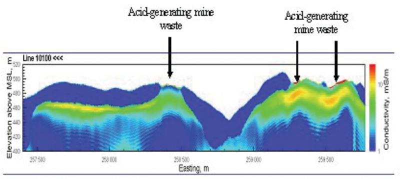


Figure 4. Conductivity/depth image showing location of acid-generating spoil material on surface mined lands.

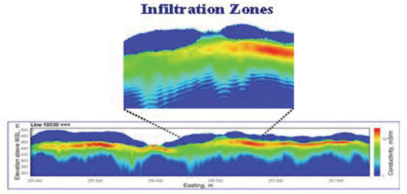


Figure 5. Water infiltration zones below surface mines are denoted by areas where the conductive water table is near the surface.

In CDIs, the likely locations for springs, seeps and wetlands are denoted by areas where the water table is at or near the ground surface (Fig.6). This property of CDIs is useful for predicting mine discharges in areas of non-deciduous vegetation, where thermal infrared imagery is ineffective. In Figure 6, conductive water from an underground mine is flowing down gradient along the water table until it emerges as an acidic seep down slope. In this case, there is no discharge at the elevation of the mine and the seep is well below the mine. Without the CDI, it would not be evident that the acidic water in the seep is from the underground mine.

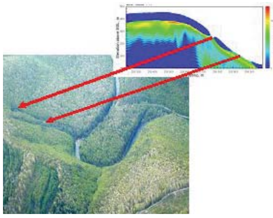


Figure 6. Slope areas where the water table is at the surface are likely locations for seeps and springs.

Sulphur Bank Mercury Mine Superfund Site, California

The Sulphur Bank Mercury Mine (SBMM) Superfund Site is located on the eastern shore of Clear Lake, about 80 miles north of San Francisco. Sulfur, and later, mercury were mined intermittently from this site for almost a century. Mining ceased about 1960 and today, the now-flooded open pit is the most notable visual remnant of past mining. In 1986, the State of California posted a fish consumption advisory for fish taken from Clear Lake because of mercury contamination. Because of its proximity to Clear Lake, SBMM was suspected to be the source of most of the mercury contamination. In 1993, SBMM became an EPA Superfund Site and after some remedial actions were made to fix obvious problems, a comprehensive characterization of the site began. As part of the characterization plan, a dense network of monitoring wells was established at the site to determine the hydrology and chemistry of groundwater.

A 600-ft. segment of land separates the acidic, metal-containing waters of the flooded open pit from Clear Lake (fig. 7). Called the Waste Rock Dam, this area of land is, in reality, a dump area for waste rock excavated from the open pit. It was never intended to be a dam. The water level in the flooded open pit is approximately 13 feet higher than the level of Clear Lake, which creates a hydrologic gradient for groundwater flow through the coarse, broken rock that comprises most of the "dam". Acidic water flowing from the open pit through the Mine Waste Dam was thought to be the predominant source of mercury entering Clear Lake though none of the many wells drilled at the site had found any indication of this. Accurate knowledge of groundwater flow paths through the Waste Rock Dam was needed and the information available from the existing network of groundwater monitoring wells was inadequate. Therefore, NETL was asked to conduct an HEM survey over the SBMM Superfund Site with funding provided by EPA's Mine Waste Technology Initiative.

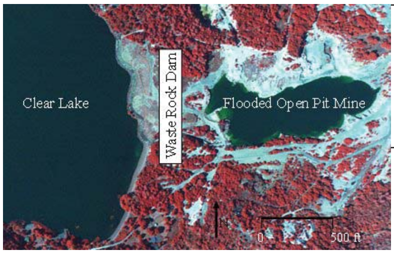


Figure 7. False color infrared air photo of Sulphur Bank Mercury Mine showing open pit and Waste Rock Dam.

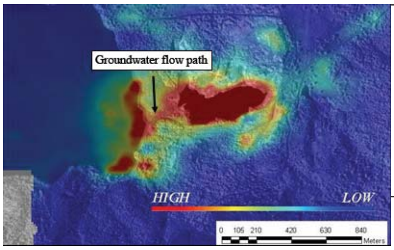


Figure 8. HEM conductivity map (52 kHz) of Sulphur Bank Mercury Mine showing likely flow path taken by conductive groundwater through the Waste Rock Dam.

Figure 8 is a HEM conductivity map that shows the most likely flow path taken by conductive water flowing between the flooded open pit and Clear Lake. This information will help EPA formulate a strategy to prevent the flow of mercury containing groundwater into Clear Lake. Figure 9 is a conductivity/depth image from a flight line across the Sulphur Bank Mercury Mine which shows the location of three groundwater monitoring wells that lie along this flight line. The perforated intervals from the monitoring wells coincide in elevation and thickness with the location of conductive zones in the CDI. Our results show that water bearing zones (perforated zones) exactly coincide with the location of conductors in CDIs about 66 percent of the time. Further improvements in the accuracy of CDIs may allow HEM surveys to be substituted sometimes for traditional hydrologic assessments that use monitoring wells.

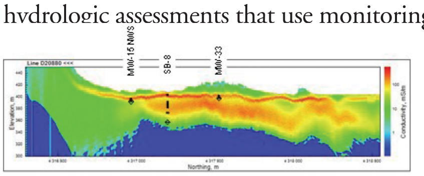


Figure 9. Conductivity/depth image from the Sulphur Bank Mercury Mine showing the relationship between conductors (interpreted to be aquifers) and the perforated intervals in groundwater monitoring wells. Black vertical lines indicate perforated interval; horizontal line through diamond indicates bottom of well.

Powder River Basin, Wyoming and Montana

This region of the U.S. has seen a boom in drilling for coalbed methane (CBM), the natural gas contained in coal seams. Historically, the Appalachian areas of West Virginia, Virginia, Kentucky, and Tennessee, along with the Black Warrior basin of Alabama and Mississippi were the major producers. Today, the Powder River basin (PRB) of northeastern Wyoming and southeastern Montana (Figure 10) has attracted the most interest of the CBM developers. Currently, there are over 25,000 CBM wells drilled in the PRB in Wyoming. Western coalbeds with softer bituminous coals contain a wealth of coalbed natural gas, but produce large quantities of water during the extraction process. Typically produced from coal seam reservoirs at shallow depths, the natural gas is released by pumping groundwater to the surface to reduce the hydrostatic pressure in the coalbeds. Ranchers, conservationists, industry, and state and local governments are all concerned with the fate of the water extracted when the methane is produced. The quality of produced water from CBM wells in the Powder River Basin is quite variable. The average total dissolved solids (TDS) concentration is 850 mg/L, with a range of 370 to 2000 mg/L.

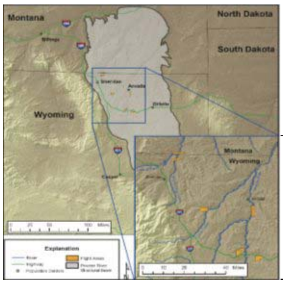


Figure 10. Location of Coalbed methane development and study areas in the Powder River Basin of Wyoming and Montana.

Helicopter Electromagnetic Surveys

Helicopter electromagnetic (HEM) surveys were performed over seven areas in the Powder River Basin of Wyoming and Montana on June 19-29, 2003. The intent of this survey was to evaluate HEM for the large-scale mapping of near-surface aquifers and produced water plumes. The HEM surveys of the Northern Wyoming Site, Powder River Site, and the Tongue River Site provided new insight into the groundwater hydrology of these areas. Examples that demonstrate the utility of the HEM surveys from these study areas are described below.

Infiltration Impoundment - The purpose of an infiltration impoundment is to store produced water until it can infiltrate into underlying shallow aquifers through an intentionally permeable base. An airborne conductivity map of an infiltration impoundment on the floodplain of the Powder River is shown in figure 11. Water seeping from the impoundment appears to dilute or displace the more conductive native groundwater in the alluvial aquifer north of the impoundment.

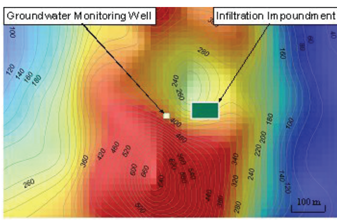


Figure 11. Airborne conductivity map showing a dilution anomaly caused by the infiltration of produced water

Alluvial Aquifer Systems- The flood plain (soils and alluvial aquifer) of the Powder River are more conductive than terrace and upland areas (Figure 12). The groundwater of the Powder River alluvial aquifer is of fair to poor quality due to high concentrations of dissolved solids.

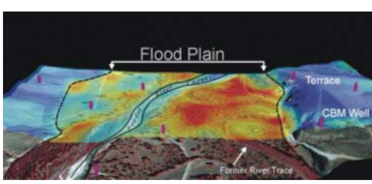


Figure 12. View of Powder River Flood Plain showing results of airborne conductivity survey.

In contrast, airborne conductivity data collected along the Tongue River (Figure 13) shows the floodplain and alluvial aquifer system to be less conductive than upland areas. This airborne technique provides opportunities for improved management of CBM water through mapping of the shallow groundwater system.

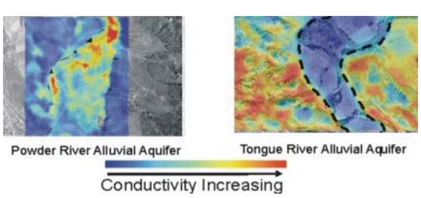


Figure 13. Comparison of airborne conductivity survey for the Powder River and Tongue River Flood Plains.

Detection of Impoundment Leaks - The purpose of a containment basin is to store produced water for irrigation. Containment basins generally have an impermeable liner that prevents the infiltration of produced water into underlying strata. Figure 14 is an airborne conductivity map of a containment basin and surrounding area. This containment basin was built with a clay liner that failed, allowing produced water to reach permeable strata (coal and sandstone) where it traveled laterally through the southwest wall and formed a line of down-slope seeps. Water conductivity at the seep was four times the conductivity of the impoundment water. This implies that the leaking impoundment water is either dissolving salts from the strata through which it is traveling or it is displacing the more conductive native groundwater from this strata.

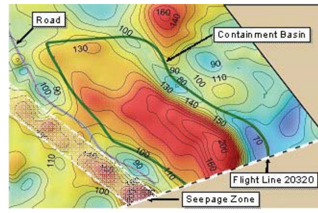


Figure 14. Airborne conductivity map of a leaking containment basin showing down-slope seeps.

Conclusions

Airborne reconnaissance can screen large watersheds quickly and delimit areas of concern for remediation or additional investigation. The airborne TIR survey and follow-up ground investigation at Kettle Creek Watershed were completed in less than two weeks. This airborne/ground survey identified 27 mine discharges that had been missed by a conventional ground survey that had been conducted intermittently over a five-year period.

Although airborne surveys seem expensive, costing as much as $2,500/square mile for TIR (including the cost of data acquisition and processing), the cost of a ground investigation would be much higher, when one considers manpower cost and the time required to survey large areas of rugged terrain on foot. An HEM survey costs about $5,000/square mile, which is inexpensive when compared to the cost of a drilling a dense network of groundwater monitoring wells, the only other source of hydrologic information.

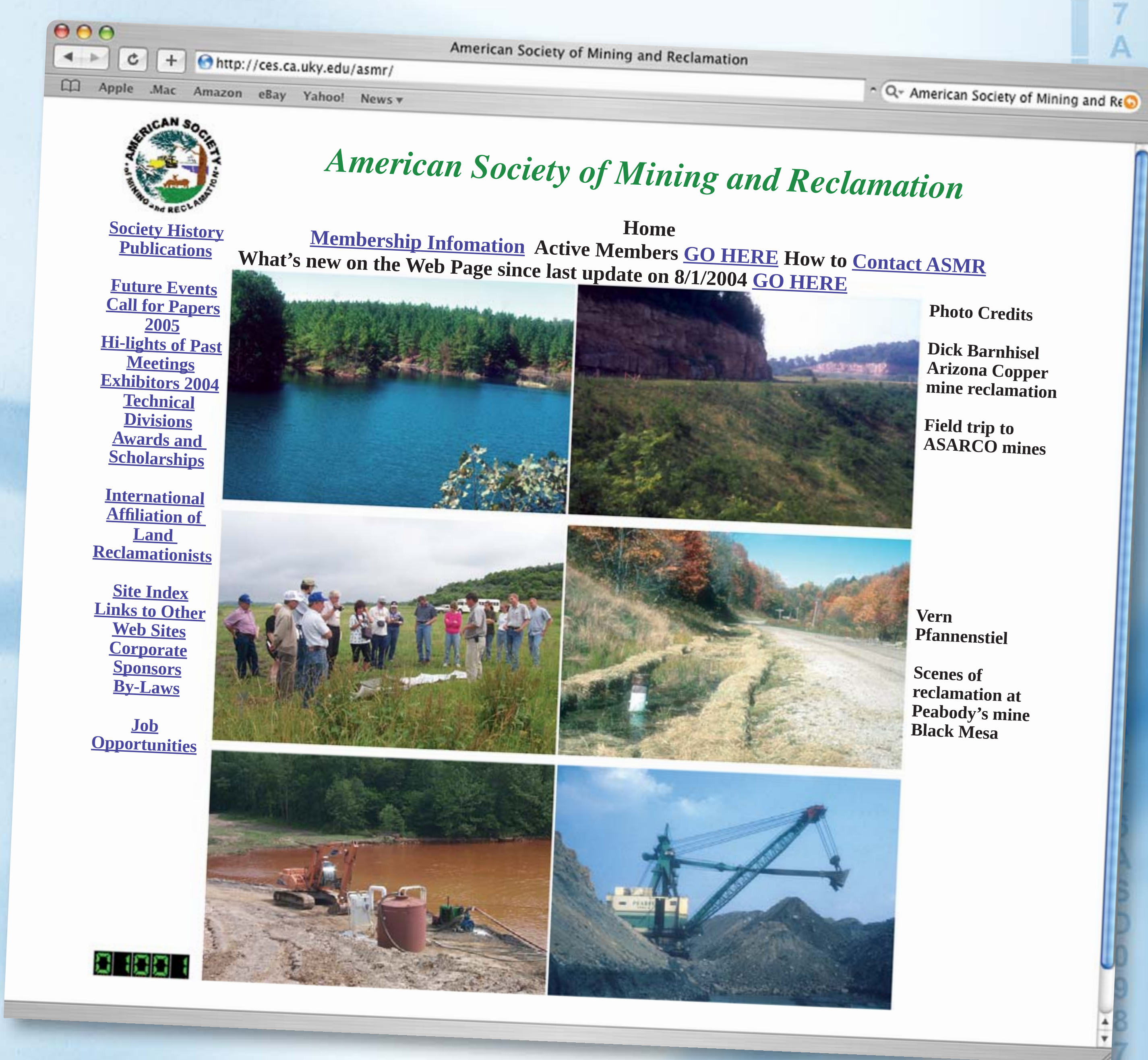
Airborne data and interpretations always need to be validated with limited ground investigations. The locations of groundwater discharges identified in TIR surveys must be field checked to determine whether the water is mine drainage or an unpolluted spring or wetland. Likewise, the processing of HEM data can provide multiple "correct" interpretations (from a geophysical perspective) whereas only one interpretation is correct geologically. Induction logs from drill holes located on HEM flight lines are needed to calibrate data processing and confirm that the resulting CDIs represent actual geologic or hydrologic conditions at the site. The time and cost of these "ground-truthing" activities must be included in the schedule and budget of airborne surveys.

Certain conditions at potential TIR or HEM survey sites can degrade data or make it unusable. The shielding effect of non-deciduous vegetation on TIR imagery has already been mentioned. HEM data is seriously degraded by electrical power lines. When possible, power lines should be avoided or turned off during HEM surveys. Currently, there is no satisfactory way to correct HEM data for power line interference.

NETL Surveys and Data Availability

Results from some of the TIR and HEM surveys flown by NETL are available online at www.netl.doe.gov/ and more areas are being added daily. For additional information pertaining to airborne NETL surveys contact Richard Hammack at (412) 386-6585 or by e-mail at hammack@netl.doe.gov). ■

American Society of Mining and Reclamation Web Site



HIGHLIGHTS OF PAST MEETINGS

People around the outlet pipes for the A/C Vertical Flow Ponds at the Harbison Walker Phase II Passive Treatment system in Ohiopyle State Park, located in Stewart Twp, Fayette.

Bob Beran, Jeff Ankrom and Margaret Dunn stand in front of Settling Pond #4 at the Erico Bridge Passive Treatment System in Venango Twp., Butler County, PA.

People around the outlet of the Anoxic Limestone Drain which is flowing into Settling Pond #1.

Mobile mapping workshop with Bill Joseph.

M.S. Memorial Scholarship Award winner Jonathon Anderson (right) of the University of Wyoming.

Ph. D. Memorial Scholarship Award winner Lyle King (right side), University of Wyoming.


Office of Surface Mining booth at the 2004 meeting in Morgantown, WV.


Some of the members of the West Virginia Acid Mining Task Force.

April 18-22, 2004 | Morgantown, West Virginia

EXHIBITORS OF THE 2004 MEETING


AMD Tour


Discussing the industry

Exhibitor Aquafix


Exhibitor Marshall Miller


Skelly and Loy

Kroff

Mid Atlantic Biosolids Association booth

Carlson

BY LINDA FIGUEROA, RONALD ABEL, MICHAEL HOLMES, EDWARD RAPP AND JUDY BOLIS

Clear Creek Watershed: Reclamation Success from Innovative Partnerships

The western 70 percent of the Clear Creek watershed (400 square miles) has been designated the Clear Creek/Central City Superfund site. The drainage basin ranges in elevation from above 13,000 feet at the continental divide in the Rocky Mountains to one mile high in the Denver Metropolitan area.

The drainage basin has three main tributaries (South Fork, West Fork and North Fork Clear Creek) and numerous smaller tributaries (e.g., Virginia Canyon and Russell Gulch). Clear Creek is used as the primary drinking water source for adjacent mountain communities and several downstream users in the Denver Metropolitan area. Clear Creek also provides a recreational venue for fishing, kayaking and rafting and supports agricultural activities just east of the Rocky Mountains.

The 1859 discovery of gold started a long history of mining activities in the Clear Creek/Gilpin County mining district. Extensive metal mining activities developed that included excavation of deposits that also contained silver, iron, copper, nickel, zinc, cadmium and manganese.

The present day population centers of Clear Creek and Gilpin Counties are centered at historic mining towns: the Blackhawk-Central City area in Gilpin County and Georgetown and Idaho Springs in Clear Creek County. Blackhawk and Central City have experienced a resurgence in population and economic health since the state of Colorado approved limited gambling in 1990 for selected historic mining areas. Tourism is now the major source of revenue for Georgetown and Idaho Springs.

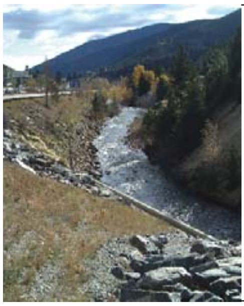


Photo Caption to come

The historic mining activity resulted in extensive metal loading into Clear Creek Watershed that ultimately impacted the major tributaries and

the main stem of Clear Creek. Metals of concern in the Clear Creek Watershed include cadmium, copper, iron, manganese, nickel and zinc.

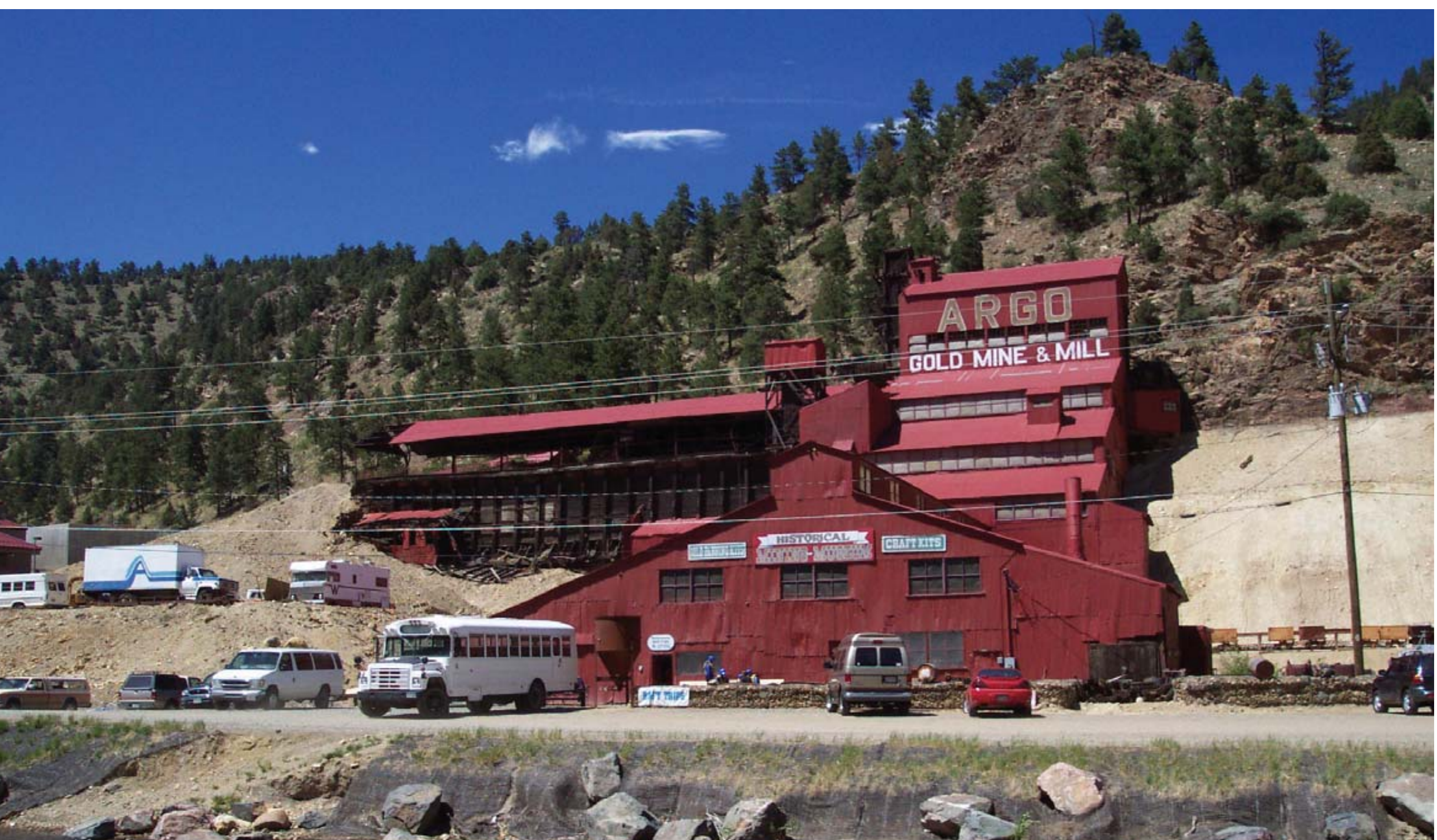
In 1983, a major portion of the Clear Creek Watershed was listed by the Environmental Protection Agency on the National Priorities List as the Central City-Clear Creek Superfund Site. The site contains a few remaining active mines, hundreds of inactive mines and tunnels and 2,000 orphan sites. The Colorado Department of Public Health and the Environment (CDPHE) is the designated lead organization for coordinating mitigation activities. Metal loading sources include mine tunnel drainage and runoff impacted by mine tailing and waste rock piles. The extensive nature of the metal loading modes and the unique conditions (mountainous terrain, climate, multiple sites) in the watershed has led to a multi-prong approach to mitigation activities. Mitigation activities have ranged from active water treatment funded by Superfund to tailings removal funded by private industry to the creation of a "Good Samaritan" foundation to address orphan sites. Reclamation success in the Clear Creek Watershed is linked to innovative partnerships between the watershed stakeholders.

The Argo Tunnel was constructed to drain a number of gold mines between Idaho Springs and Central City and continued to efficiently accomplish this goal long after mining activities were terminated. Remedial investigations in the 1980s identified the Argo Tunnel as a major source of acidity and metal loading to Clear Creek. Superfund dollars were used to construct an active hydroxide neutralization and precipitation treatment system. The Argo water treatment facility began operation in 1998 and has reduced metal loads by 38 percent to Clear Creek main stem.

The economic revitalization of Central City and Blackhawk has resulted in another funding source for mutually beneficial mitigation activities within the Clear Creek/Central City Superfund site. The construction of buildings and parking lots to accommodate the gambling activity required the removal of waste rock and tailing piles.

Private industry participated in the comprehensive remediation of the Gregory Incline mine waste pile and the National Tunnel mine waste pile as development occurred on the casino properties. A parking lot now exists adjacent to the north fork of Clear Creek where the National Tunnel waste pile was formerly located.

Large-scale remediation of more than 2,000 orphans required an innovative approach. Sources are dispersed by nature and by definition have no "potentially responsible parties." The concept of "orphanages" and market-based incentives was developed to achieve net improvements to watershed water quality. In today's regulatory environment, market-based incentives and trades can only be accomplished by the establishment of an "authority" and a Good Samaritan to broker and manage the site remediation. The Clear Creek Watershed Foundation (CCWF) was established in 1999 as a 501(c)3 corporation of Colorado to function as the "Good Samaritan" to execute



The Argo Gold Mine and Mill is now a museum. The site was placed on the National Historic Register by the Department of the Interior in 1977.

the action plan and coordinate the projects. In 2003, EPA region VIII and CDPHE approved the first action plan. The first projects targeted are Virginia Canyon in Clear Creek County and Russell Gulch in Gilpin County, which contain over 1,000 minerals sites exposed to metal mobilizing conditions. Remediation is based on Colorado Division of Minerals and Geology Best Management Practices (http://mining.state.co.us/dmginactive.html) and includes: removal if mineral residuals from waterways, creation of drainage improvements, construction of sediment traps, catch basins and energy dissipaters, provisions for pH adjustment and consolidation and removal of material to a stabilized dry-site orphanage.

Market based trading is critical to the success of the action plan. The basis for trades conforms to the EPA's Water Quality Trading Policy. Another critical element is the healthy stream profile concept. Healthy stream profiles have been constructed for each reach of Clear Creek. The health stream profiles graphically show the target range for a healthy stream reach and the extent that the stream elements meet or do not meet target range. This is a key concept for success as the historic natural mineralization was extensive enough that early prospectors used it to target potential ore bodies. Thus, the historic baseline metals concentration in the Clear Creek/Gilpin county mining district was probably above present day recommended aquatic standards.

The Good Samaritan actions must achieve an overall net improvement to stream water quality in terms of reducing any exceeding amount (e.g. target metal concentration) or insufficiency (e.g. bank vegetation stability). Clear Creek watershed was a good candidate to establish a mechanism to deal with orphan sites because of the ecology and variety of orphan sites, the proximity to a major metropolitan area for economic and environmental return and basin stakeholders that work together and trust each other. The first action plan for Virginia Canyon and Russell Gulch is moving forward and the results of this innovative approach will be available at a future date. ■

The Argo Water Treatment Plan is located adjacent to the main stem of Clear Creek. Over 12,000 tons of metals are removed per year from drainage collected from the Argo tunnel.

The Colorado School of Mines (CSM, http://www.mines.edu) is also located in the Clear Creek Watershed and this has created unique opportunities for collaborative education and research projects that benefit CSM and the Clear Creek Watershed. Students have been involved in monitoring activities and feasibility analysis as part of the design stem curriculum at CSM. CSM has a long history of research activity in the Clear Creek Watershed and in collaboration with CDPHE and EPA region VIII has obtained research funding for projects that include the examination of remediation methods and evaluation of metals loading and fate in the Clear Creek Watershed. Studies have been funded by the EPA via the SITE program, the Rocky Mountain Regional Hazardous Substance Research Center and the Center for the Study of Metals in the Environment.

Much progress has been made in reducing metal loading to the Clear Creek Watershed since 1983. At the end of 2002, 24 large and small clean-up projects have been completed. However, more work remains to bring all stream reaches in the CCW to a healthy profile. The Clear Creek Watershed Forum was formed in 1990 to facilitate the cooperation between the diverse stakeholders in the CCW. Parties involved in the Clear Creek Watershed Forum include: EPA, CCWSF, CDPHE, Private owners, USFS, BLM, private industries, Colorado School of Mines, Clear Creek County, Gilpin County, Central City, Black Hawk, Idaho Springs, CDNR, and UCCWA. The cooperative atmosphere initiated by the Clear Creek Watershed Forum will be important for the Clear Creek/Central City Superfund site to meet realistic metal reduction goals.

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BY WILL CALDICOTT

ViroMine™ Reagent Used to Stabilize Waste Rock at the Gilt Edge Mine Superfund Site in South Dakota

In late 2000, the U.S. EPA (Region VIII) conducted a "Multi Cell Treatability Study" to compare three new technologies that are marketed for the treatment of Acid Rock Drainage (ARD). The objective of the study was to assess the ability of the various treatment options; to reduce the quantity of contaminants in waters from the waste rock areas at the Gilt Edge Mine Superfund Site, and to minimize the impact of these source areas on the downstream aquatic ecosystem and other potentially impacted areas.

EPA envisioned that data acquired during the treatability study would be used to evaluate the potential for cost-effective site remediation at the Gilt Edge Mine site — a 258-acre open pit, cyanide heap-leach gold mine in Deadwood, Colorado. The mine was developed in oxide and sulphide (acid-generating) rock at the headwaters of cold-water fisheries and local water supplies. When the operator went out of business, they left behind 150 million gallons of acidic, heavy metal contaminated water in three open pits. Also left were millions of cubic yards of acid-generating waste rock that needed cleanup and long-term treatment and stabilization.

After the Multi Cell Treatability Study had commenced, EPA Region VIII learned of ViroMine™ reagents developed by Virotec International from Bauxsol™ Technology for mining applications. A unique characteristic of the material is its ability to permanently sequester metals within its matrix. Once bound, metals are non-leachable or recoverable over a wide range of physical and chemical conditions. The material also has significant acid buffering capacity in the form of low-solubility alkaline minerals and ViroMine™ can not be leached out of a treated soil column.

Filling trench with ViroMine™ waste rock mixture and filled trench

The Region VIII project manager was sufficiently interested in Virotec's treatment claims that the company was invited to participate in the evaluation program and a "Trench Trial" was constructed using ViroMine reagents. The Trench Trial was designed to emulate the characteristics of the Multi-Cell study, thus enabling a side-by-side comparison of all technologies.

The application of the technology was simply done by mechanically mixing the desired ratio of ViroMine™ reagent with the waste rock and then the mixed media was placed into a lined trench with a leachate collection system (see Photos 1 and 2). It should be noted that thorough mixing is not necessary as the ViroMine™ does not need to be in direct contact with sulfide particles because contaminated water will eventually come in contact with the reagent during percolation.

In both studies, samples of the worst waste rock on site were analyzed for acid-base

Filling trench with ViroMine™ waste rock mixture and filled trench

accounting, neutralization potential, and target analyte list (TAL) metals. Leach water samples were analyzed for TAL metals and water quality parameters.

After one year of sampling and evaluating all the technologies, the EPA team found that the performance of the ViroMine™ reagent in the Trench Trial had been excellent (see USEPA, 2002, Final Report: Bauxsol Treatability Study Report (2001) Gilt Edge Mine NPL Site, Lawrence County, South Dakota) and had equaled or bettered the best-performing technology in the Multi-Cell study (see USEPA, 2002, Interim Status Report: Multi-Cell Treatability Study Report (2001) Gilt Edge Mine NPL Site, Lawrence County, South Dakota). EPA also noted that the ViroMine™ treatment was significantly different from the other treatments.

The team found that when the ViroMine™ reagent was mixed with waste rock, it neutralized acid and trapped trace metals and metalloids. Subsequent Electron Micro Probe Analyses at the University of Colorado identified that an added benefit to the use of ViroMine™ is sulfide encapsulation, whereas the other technologies relied totally on sulfide encapsulation. Observations at the time also indicated that ViroMine™ reagent remained active in the soil column.

Three years later, the EPA confirms that the single application of ViroMine™ reagent continues to perform (see letter from EPA Region VIII on www.virotec.com). In 2004, the ViroMine™ treatment is still neutralizing acid, trapping trace metals and encapsulating many sulfides. Furthermore, the quality of the discharge water has actually improved over time (see Trench Trial data Table 1).

Early in 2004, EPA Region VIII reviewed all the results obtained so far and in consultation with EPA Office of Research and Development and with Virotec International, decided that two further trials should be conducted with ViroMine™ at Gilt Edge. These trials are currently being conducted and final reports are expected to be released in the third quarter of 2004.

The results of these trials will enable EPA to determine how the product can best be used at the Gilt Edge Mine site and will allow the material to be included in the final feasibility study in 2005. ■

Table 1: Leachate results from the ViroMine™ waste rock stabilization trench

Analyte - Units	Control 2003	Result 2001	Result 2002	Result 2003
pH - SU	1.93	7.66	NA	8.35
Acidity - mg/L as CaCO3	49,000	4	<5.0	<5.0
Alkalinity - mg/L as CaCO3	<5.0	90	62	66
Na - mg/L	9,300	2,970	2,990	570
Ag - µg/L	150	<1.0	1.1	<5.0
Al - µg/L	1,200,000	<55.0	10	66
As - µg/L	35,000	3.1	3.7	<10.0
Ba - µg/L	99	155	27	35
Cd - µg/L	630	<0.41	0.4	<1.0
Co - µg/L	2,200	1.5	11	<10.0
Cr - µg/L	390	<1.0	12	<10.0
Cu - µg/L	33,000	8.2	7.2	<10.0
Fe - µg/L	21,000,000	<22.6	18	120
Hg - µg/L	<0.2	<0.1	0.2	<0.2
Mn - µg/L	34,000	17	0.3	<10.0
Ni - µg/L	1,600	2.1	1.4	<10.0
Pb - µg/L	390	<2.2	2.9	<10.0
Sb - µg/L	500	<3.7	48	<10.0
Se - µg/L	102	41.4	3.9	<8.5
Tl - µg/L	200	<5.2	3.1	<5.0
Zn - µg/L	29,000	42	21	<10.0

Adapted from CDM validated data for EPA Region VIII 2001-2003

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