Montana Water Resources Research Center
Annual Technical Report
FY 2002

Introduction

During FY 2002, Montana experienced its fourth year of drought. Unfortunately, historic records show that drought of this length and severity, and worse, has many precedents in our state. So, we ask: How can we best live in this place where drought is not an emergency state, but a chronic condition? We are a long way from a satisfactory response to this question, but certainly the answer lies in part with focused water research and outreach, and in the education of future water professionals. These are the business of the Montana Water Center.

The second major water issue dominating our headlines and our political discourse is the prospect of coalbed methane development. Broad exploitation of this resource has been deferred in Montana pending completion of environmental studies, but leasing and development decisions affecting extensive areas will soon be made. When coalbed methane is extracted, large volumes of saline water will be released, principally within the watersheds of the Tongue and Powder Rivers. These potential impacts have been the subject of vigorous public debate. The Water Center has sponsored several research projects to elucidate the water resource impacts of coalbed methane development in southeastern Montana.

At the local level, urban and suburban development are occurring at a rapid pace in central and western Montana, and the effects of this development on surface water flows, aquifer characteristics and water quality are hotly debated in many communities. These effects are seldom obvious or easy to predict - science and engineering are needed. Finally, citizen watershed groups throughout the state are devising and implementing solutions to the problems of their local water bodies. The impetus for these activities derives chiefly from the federal Clean Water Act, but problem evaluation, solution implementation and post-project monitoring are led and conducted by the residents of the watersheds themselves. Volunteer water monitoring and citizen management of watershed programs are now widespread nationally, a trend that is positive for the future of the Nations waters. These enlightened citizens are the best possible guardians of their watersheds.

As youll see in this report, during the FY 2002, the Montana Water Center has continued its focus on water quality, fisheries health and assisting small public drinking water systems. We created an Internet-accessible database of several hundred 319" and other publicly-funded watershed projects in Montana, and provided seed grants to investigators working on water quality issues in several areas of the state. The Centers fisheries program included management of the Wild Trout Research Lab, which hosted research projects on whirling disease, fish handling and fish physiology. During this period the Whirling Disease Initiative, coordinated by the Center, involved 28 projects carried out in eight states. Under the aegis of the drinking water program, two treatment technology demonstration projects were conducted, and the Operator Basics interactive training course was completed and distributed via CD-ROM and the Internet. This proved to be extremely popular; to date 8000 CDs have been distributed.

Outreach to water professionals and other Montanans was also a major focus of the Centers work in the year just past. In the water quality arena, the Center coordinated a volunteer monitoring group on the Gallatin River, a blue-ribbon trout stream of south-central Montana, and developed software for volunteers from throughout the state to enter their data to be used in watershed planning. The Center co-sponsored the annual conference of the Montana Section - American Water Resources Association, which drew over 100 professionals and graduate students to Missoula. We continued our long-time sponsorship of Montana Water School, a week-long annual training for 350 operators from public water and wastewater systems. The MONTANA WATER website, the Centers showpiece outreach vehicle, is updated daily to enhance both the breadth of water issues covered and the depth of coverage.

Projects funded through the Water Center during FY 2002 provided support to graduate students in fields ranging from fisheries science to water chemistry. Additionally the Center directly employed several students (working in hydrology, fish culture and database management), and provided cash prizes to exemplary student presenters at the MT-AWRA conference.

The Montana Water Center employs 12 full-time positions in addition to its two Associate Directors and several temporary and student employees. The total budget was approximately $1.9 million, which drew a match from our project partners of $590,000. We are proud of our work and excited by our prospects.

Research Program

The effectiveness of burn-area emergency rehabilitation (BAER) techniques in reducing post-fire soil erosion on the Sula state forest in western Montana.

Basic Information

Title:	The effectiveness of burn-area emergency rehabilitation (BAER) techniques in reducing post-fire soil erosion on the Sula state forest in western Montana.
Project Number:	2002MT1B
Start Date:	5/1/2002
End Date:	7/30/2003
Funding Source:	104B
Congressional District:	at large
Research Category:	Not Applicable
Focus Category:	Geomorphological Processes, Hydrology, Non Point Pollution
Descriptors:	Forest fire; Wildfire; Soil erosion; Erosion control; Burn Area Emergency Rehabilitation; Water quality; western Montana
Principal Investigators:	Scott Woods, Scott Woods

Publication

MONTANA WATER CENTER FY2002 PROGRESS REPORT

Research Synopsis

This study is determining the effectiveness of several techniques that are presently used to reduce soil erosion after forest fires in the western United States. The specific study objectives are to: 1) determine the effectivness of straw wattles, mulching and aerial seeding for reducing hillslope-scale erosion rates, and 2) determine the effectiveness of aerial seeding and mulching for reducing plot-scale erosion rates. Study sites have been identified in two areas of Montana that were affected by forest fires in 2001 and 2002, respectively. The 70,000 acre Moose Fire burned parts of the Flathead National Forest and the Coal Creek State Forest in July and August 2001. The 6,000 acre Redfox Fire burned in an area on the Blackfeet Indian Reservation in July 2002. The study comprises two experimental studies and one observational study.

Our first experiment is assessing the effectiveness of straw wattle installation and straw mulching in reducing post-fire erosion rates from hillslope-scale plots in response to natural rainfall. We are using silt fences to compare the erosion rates from replicated hillslope-scale plots that have been treated with straw wattles or mulching to an untreated control plot. Study plots are located in areas of the Flathead National Forest and the Coal Creek State Forest that burned during the Moose Fire in 2001. Each replicate comprises three adjacent plots (two treatments and a control) that have similar slope and vegetation characteristics. Each plot is approximately 20-50 meters in length, with a 10 meter wide silt fence at the toe of the slope. The plots were installed in August 2002, and the silt fences below each plot were emptied for the first time in early June 2003. Preliminary analysis of these data indicate that there was minimal soil erosion (<1 kg/ha) from any of the plots between August 2002 and June 2003. However we anticipate greater amounts of soil movement in response to rainstorms during the summer of 2003. Silt fences will therefore be emptied, and the accumulated sediment mass measured on a monthly basis in the summer of 2003.

Our second experiment is assessing the effectiveness of aerial seeding and mulching in reducing post-fire erosion rates from small (0.5 m^2) plots in response to simulated rainfall events. The plots for this study are located to the east of St. Mary's Lake, Montana in an area burned

during the 2002 Redfox fire. Each replicate comprises three adjacent plots; the first plot in each replicate was treated by aerial (helicopter) seeding with grasses in spring 2003. The second plot was treated by hand distribution of straw mulch, and the third plot is an untreated control. Both the mulched plots and the control plots were sheltered from the aerial grass seeding by covering the areas with tarpaulin sheets during the seeding operation. In the summer of 2003 we will conduct rainfall simulations over each of these plots to determine the infiltration and runoff rates and the amount of potential soil erosion. The first round of simulations will be conducted in late June 2003, and the second round in late July or early August. Each rainfall simulation will last 1 hour, and the rainfall will be applied at a rate of approximately 80 mm/hr. This rate is much higher than most rainfall events in the study area. However the applied rainfall rate must exceed the soil infiltration rate in order to determine the infiltration capacity of the soil in each plot. Water and sediment produced from each plot will be collected at approximately one minute intervals throughout the simulation. The total amount of runoff from the plot will be determined by summing the volume of water collected at each minute interval. The water samples will be filtered through a 0.45 μm filter paper to collect the sediment. The total amount of sediment eroded from the plot will be obtained by summing the accumulated sediment on each filter paper. We anticipate that erosion rates in the plots treated with straw mulch will be less than those in either the grass seeded plots or the control plots, but that the effectiveness of the grass seeding in reducing soil erosion will increase as the grasses become more established.

The goal of our observational study is to determine the effectiveness of aerial seeding for reducing erosion rates on hillslope scale plots in response to natural rainfall. The study area is the same as that used for our second experiment, to the east of St. Mary's Lake on the Blackfeet Indian Reservation. In August 2002 we installed nine silt fences below hillslopes in the area where aerial seeding was planned. Since the seeding was intended to cover an area of over 400 acres it was not possible to use adjacent untreated hillslopes as a control. Thus in this study we are comparing the measured erosion rates to data on the physical characteristics of each plot. Specifically we are planning to measure the ability of site variables such as slope angle, soil texture, and percent cover to predict variability in erosion rates. Most of the burned areas was left devoid of any ground cover after the fire, so much of the first year regrowth in the study plots will likely be due to the germination of the seeded grasses. Thus by comparing the significance of ground cover for predicting erosion rates to other site factors we can assess how effective the

aerial seeding has been in reducing erosion rates. We anticipate that there will be an inverse relationship between percentage ground cover and erosion rates from the plots. However, previous research suggests that there may be a threshold level of ground vegetation coverage below which the grass seeding has little effect.

Focus Categories

1. GEOMOR
2. HYDROL
3. NPP

Descriptors

Forest fire; Wildfire; Soil erosion; Erosion control; Burn Area Emergency Rehabilitation; Water quality; western Montana.

Pharmaceuticals in Septic System Effluent

Basic Information

Title:	Pharmaceuticals in Septic System Effluent
Project Number:	2002MT3B
Start Date:	3/1/2002
End Date:	9/30/2005
Funding Source:	104B
Congressional District:	at-large
Research Category:	Not Applicable
Focus Category:	Groundwater, Hydrogeochemistry, Non Point Pollution
Descriptors:	Pharmaceuticals, groundwater, septic effluent, Trimethoprim, Diltiazem Cimetidine Acetaminophen Caffeine Carbamazpine
Principal Investigators:	William Woessner, Garon C. Smith

Publication

PROGRESS REPORT

Research Synopsis:

The goal of this research is to determine the potential for individual septic systems to load the shallow groundwater with trace amounts of pharmaceuticals and metabolites. Specific research goals are to:

1. Develop analytical procedures for identifying and quantifying selected target pharmaceuticals in septic systems using high performance liquid chromatography coupled with mass spectrometry (HPLC-MS).
2. Determine probability of the occurrence of targeted compounds in individual septic system effluent.
3. Examine fate of selected compounds during transport through soils.
4. Suggest fate of selected compounds in groundwater systems.

As the literature suggests detecting trace quantities of pharmaceuticals in water and waste water is difficult. As we have initiated this project the majority of our efforts over the last year have been in developing methods applicable for septic system waste water that allow detection of six compounds. The following coumpoundds were chosen because the literature suggested they persist in the waste water, standards could be purchased and available analytical equipment could detect these compounds:

Compound	Common Name	Use
Trimethoprim	Bactrim, Septra	Upper respiratory infections, urinary tract infections, PCP
Diltiazem	Cardizem, Dilacor, Diltia	antihypertensive, high blood pressure, control chest pain
Cimetidine	Tagamet	Treat and prevent ulcers, controls acid production of stomach
Acetaminophen	Tylenol, Valdol, acetaminophen	Analgesic (pain reducer), Antipyretic(fever reducer)
Caffeine	No-Doz	Nervous system stimulant
Carbamazpine	Epitol, Tegretol, Depitol	Anticonvulsant, psychiatric disordors, drug and alcohol withdrawal

Technique development has fostered a relationship with SUNY-Stony Brook and Mr. Mark Benotti who developed analytical techniques for the USGS nationwide investigation. He is currently a PhD. student. The group he works with has developed methods using time-of-flight mass spectrometry (TOF-MS) that overcomes the limitations of typical quadrupole-based MS/MS approaches by providing analyte identity confirmation through accurate mass measurements. We are using the same sophisticated equipment cooperatively at our School of Pharmacy. We have developed a good relationship with Mr. Benotti and he has assisted us in improving our methodology. Dr.

Woessner and Ms. Godfrey attended the 2nd International Conference on Pharmaceuticals (MN) sponsored by the National Groundwater Association where analytical techniques were discussed. This allowed us to directly interact with other researchers attempting to complete similar analyses.

At the completion of the first phase of our research we have developed methods that allow concentration of one to two liters of sample, and techniques to detect the six target pharmaceuticals at the part per billion to sub part per billion level.

We have used sewage influent at the Missoula Waste Water Facility to test and refine our methodology. The next phase of research will sample composite and single family septic tank effluent using city of Missoula maintained S.T.E.P system (septic tank effluent pumping).

Recharge Assessment of the Anaconda Mine near Belt, Montana

Basic Information

Title:	Recharge Assessment of the Anaconda Mine near Belt, Montana
Project Number:	2002MT4B
Start Date:	3/1/2002
End Date:	2/28/2004
Funding Source:	104B
Congressional District:	At-Large
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Geochemical Processes, Toxic Substances
Descriptors:	Acid Mine Drainage, Ground-Water Recharge, Tritium, CFC, Age Dating
Principal Investigators:	Jon C. Reiten, Shawn Reddish

Publication

Title: Recharge Assessment of the Anaconda Mine near Belt, Montana

Start Date: March 1, 2002

End Date: February 28, 2004

Congressional District: Montana

Primary PI: Jon Reiten

Other Co-Investigator: Shawn Reddish

Project Class: Research

Research Update

Recharge Assessment of the Anaconda Mine near Belt, Montana

A 2002 Grant Award

by

Jon Reiten, Assistant Research Hydrologist and

Shawn Reddish, Research Specialist

Montana Bureau of Mines and Geology

Billings, Montana

ABSTRACT

Decades of underground coal mining have resulted in acid mine drainage (AMD), which has contaminated ground-water and surface-water resources in Belt. The acid mine drainage is lowering the pH of Belt Creek and increasing trace metals concentration in the stream. The goal of this project is to define the Hydrogeologic regime in the vicinity of Belt so that recharge to old mine workings, the source of acid mine drainage, can be delineated with a reasonable level of certainty.

By inventorying, sampling, and age dating water from wells wells, springs, adits and seeps we intend to determine if the recharge is local or regional (appendix A). Currently we have investigated and inventoried about 70% of the study area. The inventory process includes identifying GPS coordinates, measuring electric conductivity, pH, oxidation-

reduction potential, dissolved oxygen; and determining the geologic source. This information will be used to screen for the most useful sampling sites. All information is entered into a database accessible by the public.

Water levels at 9 wells and springs are measured monthly monitor the fluctuations of local aquifers (appendix B). Several of these wells and springs will be sampled for tritium and then Chlorofluorocarbons to determine the age of the water. By determining the age of water in the mine workings, methods can be developed to reduce recharge to the acid producing mine workings.

Stream flows at 11 sites are also measured monthly in the study area (appendix C). Differences in flows can determine the gain or losses of surface-water to local aquifers. Field parameters including measuring specific conductivity, pH, oxidation-reduction, and dissolved oxygen are also taken at each site. The AMD discharge is monitored monthly for flow and field parameters and a continual Steavens recorder monitors the AMD discharge.

Mnumber	Site Name	Latitude	Longitude	Township	Range	Section	Tract	Date (dd/mm/yy)	Field SC (umhos/cm)	Field pH	Field test Nitrate (mg/L N)	Total Depth (ft)	Pumping water level (ft)	Static water level from mp (ft)	Yield (gpm)	ORP (mV)	Dissolved oxygen
								Appendix A: Inventory and well summary									
30562	JOHNSON GERALD	47.3052	-110.9765	18N	06E	21	BABB	09/12/02	512	7.42	5	35	35	20	20	276	
32033	FULLER CHARLES H	47.3665	-110.9093	19N	06E	36	BDCD	10/24/02	6.41	7.25	0	45	40	6	40	-53.2	0.24
145604	ASSELS LINDA	47.3994	-110.9304	19N	06E	23	BDBA	10/24/02	652	7.27	0	66	51	40	28	288	7.91
31980	MOE JEFFREY B	47.3939	-110.9306	19N	06E	23	CADB	09/11/02	983	7.36	2	74	70	52	30	195	
186486	DAWSON RANCH	47.3715	-110.8651	19N	07E	32	BADA	09/10/02	1585	7.23	0	200		55	60	81.8	
123498	ARNDT DENNIS	47.3632	-110.9001	19N	06E	36	DACC	10/24/02	458	7.53	0	53		12	12	15.6	5.3
199851	ERIC JOHNSON	47.3099	-110.9593	18N	06E	15	CCCC	09/12/02	485	7.53	0			100.06		55.5	
150504	COBURN JERRY	47.4307	-110.9243	19N	06E	11	ABAC	09/11/02	656	7.66	0.5	300		178	12	80	
177163	SPRAGG ED	47.3592	-110.9026	19N	06E	36	DCDD	09/10/02	463	7.46	0	210		119	20	177	
32040	ASSELS STEVE D	47.3654	-110.9005	19N	06E	36	DABB	10/24/02	475	7.49	0	41	32	12	30	225	6.87
186483	SPILLER LEROY	47.3785	-110.9269	19N	06E	26	DBCB	11/26/02	639	7.32	0	24		18	25	267	7.65
201066	RAY OGLE	47.3149	-110.9475	18N	06E	15	DBAC	09/12/02	553	7.32	0					171	
201069	DAVE FETTER	47.2573	-110.916	17N	06E	1	CCCC	09/12/02	417	7.81	0					147	
201123	GLEN MCCLELAND	47.3774	-110.9262	19N	06E	26	DCBA										
84937	HARRIS JOHN JR	47.3699	-110.9902	19N	06E	29	DD	05/16/03	815	7.21	0	205		140	4.5	180	5.6
123477	WINDER MARTIN	47.3458	-110.8951	18N	07E	6	CCCB	11/26/02	929	7.51	0	403	350	310	18	131	8.7
202581	GENE ERBETTA	47.4318	-110.9159	19N	06E	12	BBBB										
164374	OSTERMAN ARLENE	47.3706	-110.9095	19N	06E	36	BACD	11/26/02	543	7.44	0	320		110	50	188	6.13
202378	DANNY HARDINGER	47.3241	-110.9747	18N	06E	9	CDCA	05/16/03	601	6.86	2	0		0		301	6.49
32015	JIM LARSON RANCH	47.3534	-110.9897	19N	06E	32	DCCB	06/05/03	645	7.27		32	30	14	40	222	5.81
193220	MARY EVANS	47.3689	-110.9154	19N	06E	36	BCBA	05/13/03				500		261			
200058	IKE HAGGESON	47.3746	-110.9127	19N	06E	25	CBDA	11/26/02	879	7.25	0	100	40.5	36.65			3.65
165475	WALLY MCMANIGLE	47.3732	-110.90117	19N	06E	36	BABB	11/27/02	683	7.44	0	50	26.1	17.75		68.2	3.9

Pharmaceuticals in Septic System Effluent

Basic Information

Title:	Pharmaceuticals in Septic System Effluent
Project Number:	2002MT18B
Start Date:	3/1/2002
End Date:	9/30/2005
Funding Source:	104B
Congressional District:	
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Hydrogeochemistry, Non Point Pollution
Descriptors:	Pharmaceuticals, groundwater, septic effluent, Trimethoprim, Diltiazem, Cimetidine, Acetaminophen, Caffeine, Carbamazpine
Principal Investigators:	William Woessner, Garon Smith

Publication

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Development of microbial biobarriers for the control of acid rock drainage from mine tailings.

Basic Information

Title:	Development of microbial biobarriers for the control of acid rock drainage from mine tailings.
Project Number:	2002MT19B
Start Date:	3/1/2000
End Date:	2/28/2001
Funding Source:	104B
Congressional District:	Montana
Research Category:	Not Applicable
Focus Category:	Acid Deposition, Geochemical Processes, Hydrogeochemistry
Descriptors:	Acid Mine Drainage, Biobarriers, Biostimulation, Water Chemistry
Principal Investigators:	Paul Sturman

Publication

Project Title: Development of microbial biobarriers for the control of acid rock drainage from mine tailings.
Focus Categories: ACD, G&G, HYDGEO
Keywords: Acid Mine Drainage, Biobarriers, Biostimulation, Water Chemistry
Duration: March 2000 – March 2001
Principal Investigator: Paul J. Sturman, Center for Biofilm Engineering, 366 EPS Building, Montana State University, Bozeman, MT 59717 (paul_stu@erc.montana.edu) phone (406/994-2102) fax (406/994-6098).

Abstract

Acid rock drainage from hard rock mine lands is a major environmental problem that impacts both ground- and surface water throughout the Western US. Waste rock and mine tailings often contain high concentrations of metal sulfides which, when contacted by oxygen-containing water, leach metals into solution and radically lower the pH of the receiving water. This research sought to further develop an inexpensive and potentially widely applicable treatment technology to utilize indigenous microorganisms within mine tailings to abate ARD at its source. An innovative method to prevent oxygen transport into tailings is the development and maintenance of a biologically active barrier within the near-surface zone of the tailings. This barrier is made up of naturally occurring aerobic and facultative bacteria which utilize dissolved oxygen in the infiltrating water and therefore maintain the reducing conditions which are necessary for pyrite and other metal sulfides to remain bound in mineral form. In addition, the generation of anoxic conditions stimulates the activity of sulfate-reducing bacteria (SRB) within the tailings. SRB produce hydrogen sulfide as a metabolic by-product, which may further react with dissolved metals, promoting their removal as metal-sulfide precipitates. These experiments were performed in laboratory-scale columns filled with acid-producing mine tailings. Objectives for the research were to 1) confirm the ability of nutrient dosing to stimulate indigenous aerobic and facultative bacteria in mine tailings, 2) determine the extent to which effluent dissolved metals can be reduced, 3) determine the longevity of treatment effectiveness, and 4) perform initial work necessary to incorporate these research findings into an appropriate mathematical model. Bacterial populations, particularly general heterotrophic bacteria and SRB, were stimulated in molasses- and whey-treated columns compared to control columns. Column effluent pH was increased from approximately 3 to over 5 as a result of carbon addition. Effluent aluminum, zinc and copper were reduced in treated columns relative to controls. The effectiveness of whey treatment and molasses treatment was compared. Whey was found to be more effective in reducing effluent pH and stimulating favorable bacterial populations. Molasses treatment enhanced the growth of fungi in some cases, which could have an unfavorable effect on pH and metals in solution. Initial modeling work has identified the important constituents that must be included in a predictive mathematical model.

Introduction

Acid rock drainage (ARD) from abandoned hard rock mine lands is a major environmental problem that impacts both ground- and surface water throughout the Western United States and is a major contributor to loss of habitat for fisheries. Abandoned mine lands (AML) often contain unmined mineral deposits, waste rock, and mine tailings which contain high concentrations of metals in the form of metal sulfides. When oxygen-containing rainwater, streamwater, and/or groundwater comes into contact with these materials, chemical oxidation reactions occur which liberate the bound metals into solution and may radically lower the pH of the receiving water. Many AMLs are located on public land (State, US Forest Service, or US Bureau of Land Management) or on patented parcels enclosed by public lands. It is therefore in the public interest to foster innovative, cost-effective solutions to ARD. The purpose of this research was to further develop an inexpensive and potentially widely applicable treatment technology to utilize indigenous microorganisms within mine tailings to abate ARD at its source.

Background

ARD arises from waste rock and mine tailings containing sulfide minerals and lacking adequate acid-consuming carbonate minerals. Sulfide minerals, such as pyrite (FeS_2) are oxidized to form sulfate when oxygenated water infiltrates tailings. This process is described by the following reaction:

$$4FeS_2 + 14O_2 + 4H_2O \rightarrow 4Fe^{2+} + 8SO_4^{2-} + 8H^+ \qquad (1)$$
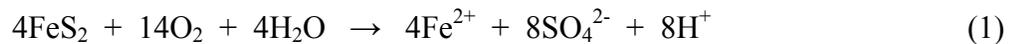
This reaction generates ferrous iron and some acidity. As conditions become more acidic, growth conditions for acidophillic iron and sulfur-oxidizing microorganisms become more favorable. Populations of these naturally occurring and environmentally ubiquitous chemolithotrophs colonize open tailings after placement and accelerate acid production through the cycling of ferrous to ferric iron (Brierley and Brierley, 1996):

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O \qquad (2)$$
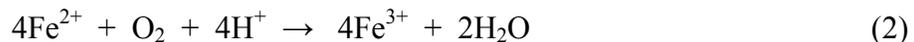
The role of these bacteria (such as *Thiobacillus ferrooxidans*) in accelerating the production of acidic drainage from sulfide-containing mine tailings has been known for decades (Silverman and Lundgren, 1959). The ferric iron produced in reaction (2) is a strong oxidant, which further abiotically oxidizes pyrite (or other mineral sulfides) as follows:

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad (3)$$
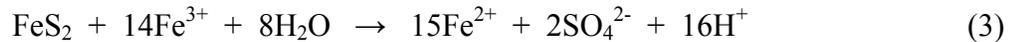
Though reaction (2) consumes some acidity, the overall effect is the regeneration of ferric iron, which can then oxidize more pyrite and generate much more acidity (via reaction 3). It has been estimated that an active population of *T. ferrooxidans* increases the rate of pyrite oxidation up to 6 orders of magnitude over simple abiotic oxidation (Brierley, 1978). The acidity generated in

these reactions further assists the growth and downward migration of *Thiobacilli* through the tailings column by providing the low pH conditions (<3.5) necessary for its growth.

T. ferrooxidans is also capable of oxidizing reduced sulfur species to sulfate as illustrated in the following reactions:

$$H_2S + 2O_2 \longrightarrow SO_4^{2-} + 2H^+ \tag{4}$$

$$S_o + H_2O + 1.5\ O_2 \longrightarrow SO_4^{2-} + 2H^+ \tag{5}$$

$$S_2O_3^{2-} + H_2O + 2O_2 \longrightarrow 2SO_4^{2-} + 2H^+ \tag{6}$$
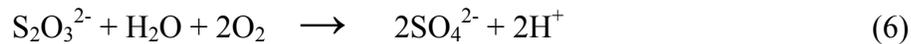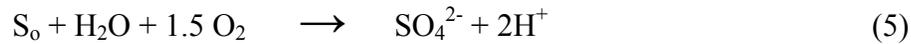
The oxidized and acidic conditions necessary for *T. ferrooxidans* and present in most sufidic mineral tailings would seem prohibitive to both non-acidophilic heterotrophs and anaerobic bacteria, particularly sulfate-reducing bacteria (SRB), which are generally obligate anaerobes and are typically considered acid intolerant (Postgate, 1984). Nonetheless aerobic heterotrophs and SRB have been isolated from tailings piles (Fortin et al., 1996; Fortin and Beveridge, 1997).

The key to breaking the cycle of ferric iron oxidation of pyrite and its subsequent regeneration by *T. ferrooxidans* is the prevention of the initial reaction of pyrite with oxygen and the prevention of *T. ferrooxidans* activity. Bound with iron, the sulfur in pyrite is unable to participate in the microbially catalyzed reactions that cause acid generation. Prevention of oxygen infiltration into tailings is necessary to prevent both the abiotic oxidation of pyrite and the activity of *T. ferrooxidans*. An innovative method to prevent oxygen transport into tailings is the construction and maintenance of a biologically active barrier within the near-surface zone of the tailings. This barrier is made up of naturally occurring aerobic and facultative bacteria which utilize dissolved oxygen in the infiltrating water and therefore maintain the reducing conditions which are necessary for pyrite to remain bound in mineral form. The anaerobic conditions generated by the barrier should also facilitate the growth of SRB deeper within the mine tailings. SRB activity will produce hydrogen sulfide, thus providing a mechanism for the precipitation of dissolved metals as metal-sulfides with a commensurate reduction in toxic metal drainage from the tailings.

The challenge of this work was to stimulate the growth of indigenous populations of general heterotrophic bacteria (GHB) and SRB within the mine tailings to generate anoxic conditions and assist the precipitation of metal sulfides, respectively. Both GHB and SRB have been isolated from mine tailings, though their activity (growth and reproduction) has typically been very low. GHB in mine tailings have not been studied in detail, however the activity of SRB in mine tailings has received more attention. SRB have been widely considered for the treatment of acid rock drainage (ARD) in engineered bioreactors. In such reactors, influent organic carbon, pH, and redox potential can be controlled to the benefit of SRB populations. These controls are not possible within the tailings pile, yet SRB have been recovered from sediments deposited from mine waste effluent streams (Gyure et al., 1990; Herlihy and Mills, 1985). Only recently has their role within acidic tailings piles been studied in detail, however (Fortin et al., 1996). Detailed study of pore-water chemistry and mineralogy in mine tailings at an abandoned Cu and Zn mine in Ontario, Canada (Fortin et al., 1996) indicated that bulk water Eh and pH should not

have been conducive to SRB growth (minimum Eh > 100, maximum pH < 4). Yet intact cores removed from the tailings indicated a color transition from bright orange to gray as depth increased, suggesting a significant change in chemical conditions. Further analysis indicated almost the complete removal of the mobile iron phase as well as a significant drop in sulfate, suggesting SRB may be active. SRB were subsequently enumerated on Postgate's Medium B at pH 3.5, 5.5, and 7.5. Interestingly, SRB growth was observed only at pH 7.5. SRB were evidently active in the tailings based on bulk water chemistry measurements, but they could only be enumerated under conditions that were not apparent in the field. This finding suggests that SRB were not adapted to the low pH conditions in the field, but perhaps were capable of altering their microsite water chemistry to allow them to survive in under these harsh conditions.

The conditions necessary for SRB growth are generally considered to be a reducing environment, available sulfate, and a volatile fatty acid (VFA) carbon source such as formate, butyrate, lactate, etc. The conditions created by the growth of *T. ferrooxidans* and other acidophillic organisms in the surface layers of a tailings pile would seem to provide only the sulfate necessary for SRB growth. Influent water to tailings piles is typically either rainwater or oligotrophic surface water, neither of which contains appreciable concentrations of VFAs. Very low concentrations of formate and acetate were found by Fortin et al. (1996) in the pore water of the tailings pile studied. Their speculation was that these organic acids were either metabolic excretions or decay products of iron-oxidizing bacteria living upstream in the tailings. If this is true, Fe-oxidizing bacteria provide both the necessary electron donor and carbon source for downstream SRB. This still leaves SRB with the issues of very low pH and oxidized conditions to overcome, however, but high concentration of mobile Fe in pore water entering the SRB zone may help explain their ability to overcome these adversities.

Whether bacteria are Gram-positive or Gram-negative, they typically contain a negative surface charge due to the presence of anionic surface structures such as carboxyl, phosphoryl, and amino groups (Beveridge, 1981). Mineral deposition initially occurs on the bacterial cell surface to satisfy this charge imbalance based on the stoichiometric interaction of cations (such as metal species) in solution.   The binding of metals to the cell surface lowers the total free energy of the system, which subsequently initiates further metal deposition (Douglas and Beveridge, 1998). Though the specific mineral phases formed are in response to the anions present on the cell surface, mineral formation is not controlled by the cell, but rather by the chemistry of the cell's environment (Beveridge et al., 1983). It has been noted, however, that bacteria in a highly active metabolic state can inhibit the formation of metallic complexes because their cell wall is highly energized and is proton rich (Urrutia Mera et al., 1992).

In the case of SRB growing in an acidic, Fe-rich environment such as mine tailings, cell surface reactions which precipitate metals are enhanced by the production of hydrogen sulfide, which readily reacts with iron in solution to form insoluble Fe sulfides on both SRB cell surfaces and on the surrounding mineral surfaces (Fortin and Beveridge, 1997). Likewise, other metallic species (Cu, Zn, Pb, Cd) can precipitate as sulfides in close proximity to active SRB. These precipitates may have a beneficial effect for the SRB growing in an oxic or acidic environment. Precipitated metal sulfides readily react with oxygen in solution and thereby act to keep the cell's immediate environment at a low redox potential. Even in oxic zones within mine tailings, SRB have been found to be active, presumably in microsites created by precipitated solids. In these

zones, amorphous Fe-oxide precipitates provide the necessary diffusion barrier to dissolved oxygen to allow SRB to remain active (Fortin and Beveridge, 1997). The generation of alkalinity by SRB is also well documented, which helps explain their survival in low pH environments, particularly where a cell-precipitated diffusion barrier exists. This alkalinity may also cause the precipitation of carbonates within the tailings matrix (Douglas and Beveridge, 1998) which further protects SRB from toxic levels of acidity.

An interesting observation made by Fortin and Beveridge (1997) is that precipitated iron sulfides in the SRB-active anoxic zone of mine tailings mimicked the size and shape of bacterial cells when viewed by transmission electron microscopy (TEM). They suggest that these precipitates are the remains of individual SRB that had been completely encased in Fe-monosulfides. With such a protective coat, it is possible to explain how a single bacterium can alter its microenvironment to exist under hostile low pH, or high Eh conditions.

The ability of SRB to modify their microenvironment and grow under adverse conditions suggests that GHB may respond favorably to efforts to enhance their numbers. These efforts will focus on the addition of easily assimilable organic carbon in the form of carbohydrate and/or protein. The application of organic matter to form microbially reactive barriers to chemically alter groundwater is a nascent but rapidly growing field. Recent reports in the literature document the use of compost, manure and other organic substrates to support microbial populations capable of altering the pH and oxidation-reduction potential (ORP) of influent waters, thus promoting the removal of dissolved metals from solution (Benner, *et al*., 1997). Researchers at the Center for Biofilm Engineering (CBE) together with MSE Technology Applications of Butte, MT have investigated the microbial processes involved with the establishment and maintenance of subsurface and near surface microbial barriers for hydraulic control and microbially catalyzed reactions (Cunningham *et al*., 1997). These experimental systems have shown that biobarriers constructed of aerobic or facultative organisms can successfully remove oxygen from infiltrating water to trace levels. Application of the biobarrier concept to acid producing mine tailings in a controlled laboratory setting is the logical next step in the development of this technology.

The premise of this technology is that the application of a nutrient-containing solution to the surface of acid-producing tailings will stimulate the growth of naturally occurring aerobic and facultative bacteria within the tailings. These indigenous bacteria will then consume all available dissolved oxygen from the infiltrating water as they metabolize the added organic carbon. The need to add other essential nutrients, such as nitrogen and phosphorus, depends on the availability of these compounds in the tailings. The consumption of more energetic electron acceptors (e.g., oxygen and any available nitrate) will likely create conditions favorable for the growth of fermentative organisms and SRB. Sulfate is typically present in high concentrations in mine wastes. Laboratory-scale experiments have demonstrated that biobarriers are capable of generating conditions suitable for SRB growth (James *et al*., 1995).

The stimulation of bacteria in the tailings may also result in decreased infiltration capacity due to the production of bacterial slime (extracellular polysaccharides), thereby resulting in less overall water movement into the tailings. This is not a necessary condition for the successful application of the technology, however, it may assist in reducing overall acid production from the tailings.

Chemical alteration of the infiltrating water is expected to be the primary mechanism of action while physical alteration of the tailings pore space may be a beneficial secondary effect.

Goal and Objectives

The goal of this research was to determine the applicability of bioaugmentation as a strategy to reduce or eliminate acid rock drainage from mine tailing impoundments. Specific objectives for the work were to:

1. Confirm the ability of nutrient dosing to stimulate indigenous aerobic, facultative and anaerobic bacteria in mine tailings columns,
2. Determine the extent to which nutrient dosing results in reductions in dissolved metals in column effluent water,
3. Determine the longevity of treatment effectiveness after application of nutrients in column influent water, and
4. Perform initial work necessary to incorporate these research findings into an appropriate mathematical model.

A post-research objective of this work was to transfer application knowledge gained to other academic and commercial entities to accelerate and enhance field implementation of this technology.

Mine Tailings Source

This research encompasses column experiments using mine tailings collected from the Fox Lake Mine (Lynn Lake, Manitoba, Canada). This site was chosen based on the availability of acid generating mine tailings and the willingness of landowners to allow access. Mine tailings were collected from the tailings surface zone (0-3' depth) in 5-gallon plastic buckets with lids. Tailings were then shipped to Montana State University. Experiments were performed in large diameter (12") columns. Methods, Results, and Discussion of experiments from each system is described below.

Methods and Materials

Column Set-up and Packing - Columns packed with mine tailings from the Fox Lake mine (Lynn Lake, Manitoba) were used to determine the effects of soluble organic carbon additions on tailings pH, oxidation-reduction potential (ORP), tailings mineralogy, and microbial colonization. Three large (12" diameter, 40" length) PVC columns were packed with raw tailings and were subsequently flooded with tap water from the bottom up, to expel excess air from the tailings. The tailings were then allowed to drain under gravity. This flooding procedure was repeated 3 times for each column to approximate field deposition conditions.   The effluent line from each column was fitted with an in-line ORP probe (Cole-Parmer, Vernon Hills, IL). Columns were labeled test column 1(TC1), test column 2 (TC2), and control column (CC). Test

columns 1 and 2 were to receive dissolved carbon and nutrient amendments, while the control column would receive only tap water.

Water Addition - To facilitate the stabilization of chemical and biological parameters within the columns prior to the addition of organic carbon, columns were operated with a daily application of dechlorinated tap water at a rate of 30 ml/min for 25 min./day (total volume: 750 ml/day). Influent water was pH 7.5-8.0. When effluent pH and ORP stabilized (after approximately 3 weeks of operation), baseline conditions of effluent metals and microbiology were established.

Microbial and Metals Analysis - Microbial analyses included the enumeration of total heterotrophic bacteria (THB), sulfur-oxidizing bacteria (SOB), and sulfate-reducing bacteria (SRB). THB were enumerated via serial dilution and plating on R2A agar (Standard Method SM 9215C, Standard Methods for the Examination of Water and Wastewater). SOB were enumerated using most-probable number technique (SM 9240 D.1F) and SRB were enumerated using API recommended practice 38/SRB MPN. Samples taken for metals analysis were filtered (0.2 μm) and acidified to pH 2 with nitric acid then refrigerated to 4ºC and sent to HKM Laboratories (Butte, MT) for analysis. Core samples from the columns were periodically removed for examination via scanning electron microscopy. On 11/14/00, tailings from all 3 columns were sampled to determine microbial colonization and mineral composition. Tailings were sampled using a 0.25-inch diameter steel rod, which was advanced into the columns from the top. Samples were collected from depths of 10", 20", and 38". Mineral composition of the tailings was determined by energy dispersive X-ray spectroscopy (EDS).

Organic Carbon/Nutrient Addition – Organic carbon (first in the form of molasses, then later in the form of cheese whey) was added according to the schedule outlined in Table 1. The timing of nutrient additions was not predetermined, but was based on the pH and ORP response of the columns to treatment. For all additions, the control column received an equal volume of tap water. The organic carbon source was changed from molasses to whey because microbial data indicated a preponderance of fungal growth in the treated columns (particularly TC2). Molasses is a 100% carbohydrate carbon source, high concentrations of which favor fungal growth over microbial growth. Cheese whey contains less carbohydrate (typically ~60%) and significant protein (~15%), which should favor bacterial growth over fungal growth.

Influent Water Regimen – Daily application of dechlorinated tap water at a rate of 30 ml/min for 25 min./day (total volume: 750 ml/day) continued until the first carbon addition (11/10/99). Immediately following the initial carbon treatment, the influent flowrate was decreased to 15 ml/min for 25 min. each day (total volume: 375 ml/day). During the period of daily additions of organic carbon (2/11/00 – 3/24/00) no additional water was added to the columns. Immediately after the daily organic carbon addition ceased, the influent regimen was once again set at 375 ml/day. On 4/17/00 the water addition regimen was changed to a weekly addition of 2 L of water. This decreased the total water volume added per week (from 2.6 L). This change was made because some difficulties were encountered in getting adequate sample volumes from the columns prior to the change. It was suspected that the wicking of influent water back into the room atmosphere was the cause of significant water loss. In addition, the new regimen was thought to be more reflective of field precipitation events.

Table 1: Large Column Carbon and Nutrient Dosing Protocol

Date	Columns	Protocol (each column)
11/10/99	TC1/TC2	3L: 10 g/L molasses, 0.5 g/L fertilizer grade urea, 0.7 g/L K_2HPO_4
1/5/00	TC1/TC2	3L: 10 g/L molasses, 0.5 g/L fertilizer grade urea, 0.7 g/L K_2HPO_4
2/11/00 – 3/24/00	TC1/TC2	Daily addition of 1L: 10 g/L molasses, 0.5 g/L fertilizer grade urea, 0.7 g/L K_2HPO_4
5/5/00	TC2	20L: *Klebsiella oxytoca* culture + 5 g/L molasses + nutrients
7/5/00	TC1/TC2	10L: 10 g/L molasses, 0.5 g/L fertilizer grade urea, 0.7 g/L K_2HPO_4
8/24/00	TC1/TC2	10L: 68 g/L whey + 0.45 ml fungicide TILT (propiconazole)
3/29/00	TC1/TC2	10L: 68 g/L whey + 0.45 ml fungicide TILT (propiconazole)

Test Column 2 Seeding - Because TC2 was significantly more acidic than either TC1 or the control after numerous organic carbon additions, it was seeded with 20 L of a concentrated buffer solution containing *Klebsiella oxytoca* on May 5, 2000. This organism is a facultative heterotroph that is known to be capable of copious slime production. It was added with 5 g/L molasses in the 20-L solution (Table 1).

Results

Effects of first molasses addition – The pH in all columns was approximately 4 at the first molasses addition (Figure 1). During the following 2 months, the pH of TC1 and TC2 increased to highs of 4.87 and 5.11, respectively, while that of the control rose to 4.69. The ORP for the test columns decreased to a low of –13 mV and –150 mV, respectively, for TC1 and TC2. The ORP of the control column decreased slightly to approximately 100 mV (Figure 1). After approximately 60 days, pH and ORP levels in the test columns were again similar to that in the control column.

During the first 30 days of operation (starting 10/11/99), the aqueous metals content of the effluent from all 3 columns decreased for virtually all metals tested, consistent with the leaching of metals from freshly exposed tailings surfaces. The first molasses addition was made to TC1 and TC2 following this 30-day period, when levels appeared relatively stable for most metals, however, several metals, (cadmium, lead) indicated significant variability between columns (Figure 2). The metals sampling events in the weeks following the molasses addition indicated an ephemeral drop in Al, Cd, and Cu in the test columns compared to the control, but overall the first treatment seemed to have little effect on the effluent metals from the test columns (Figure 2). In the weeks following the initial treatment, effluent concentrations for Al, Co, Fe, Mg, and Mn rebounded, while As, Cu, Cd, Pb, and Zn stabilized at the lower level.
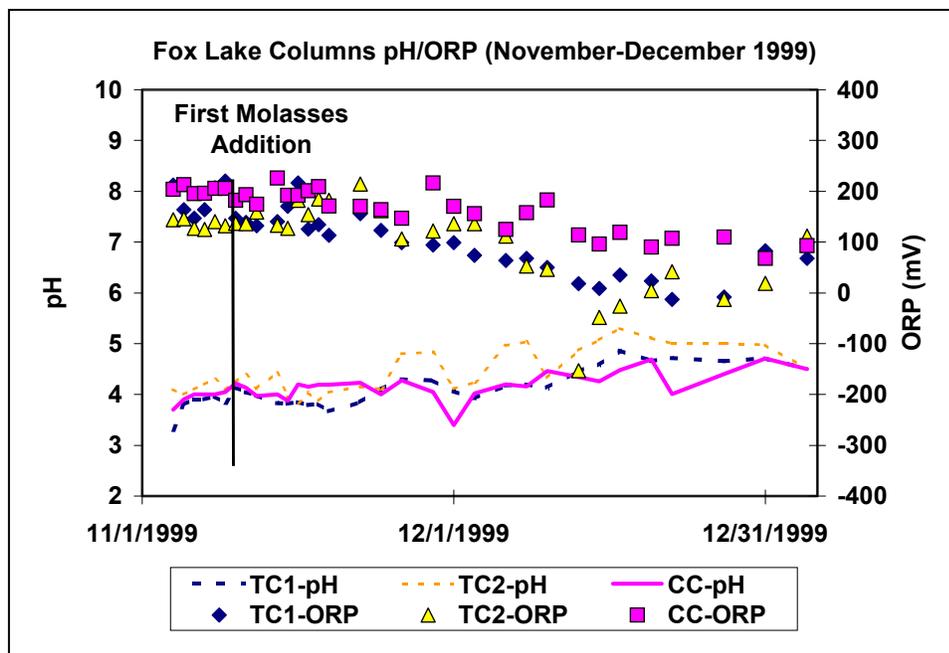
Figure 1. pH, ORP in Fox Lake column effluent (November-December 1999)
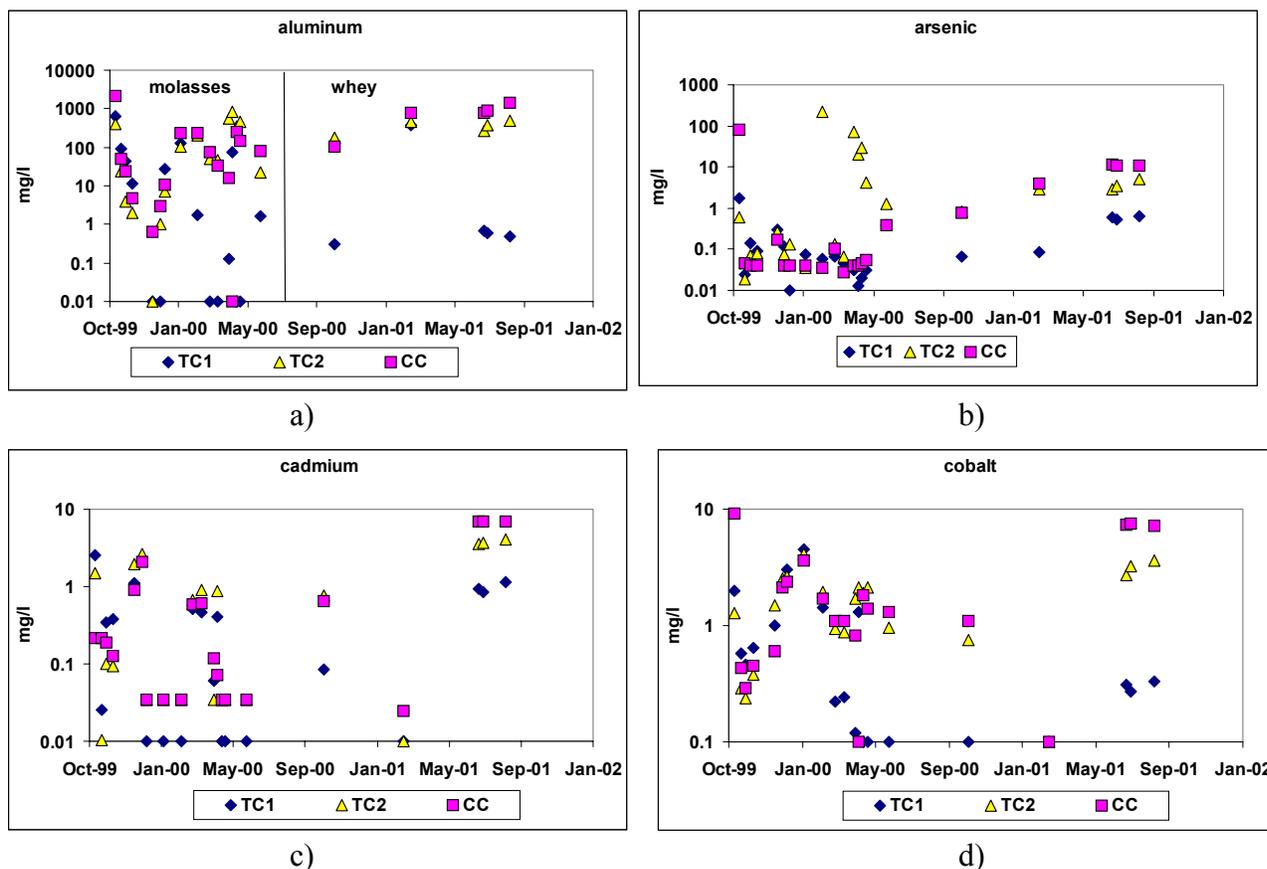
a)

b)

c)

d)

Figure 2 . Dissolved metals in Fox Lake column effluent.

e)

f)

g)

h)

i)

j)
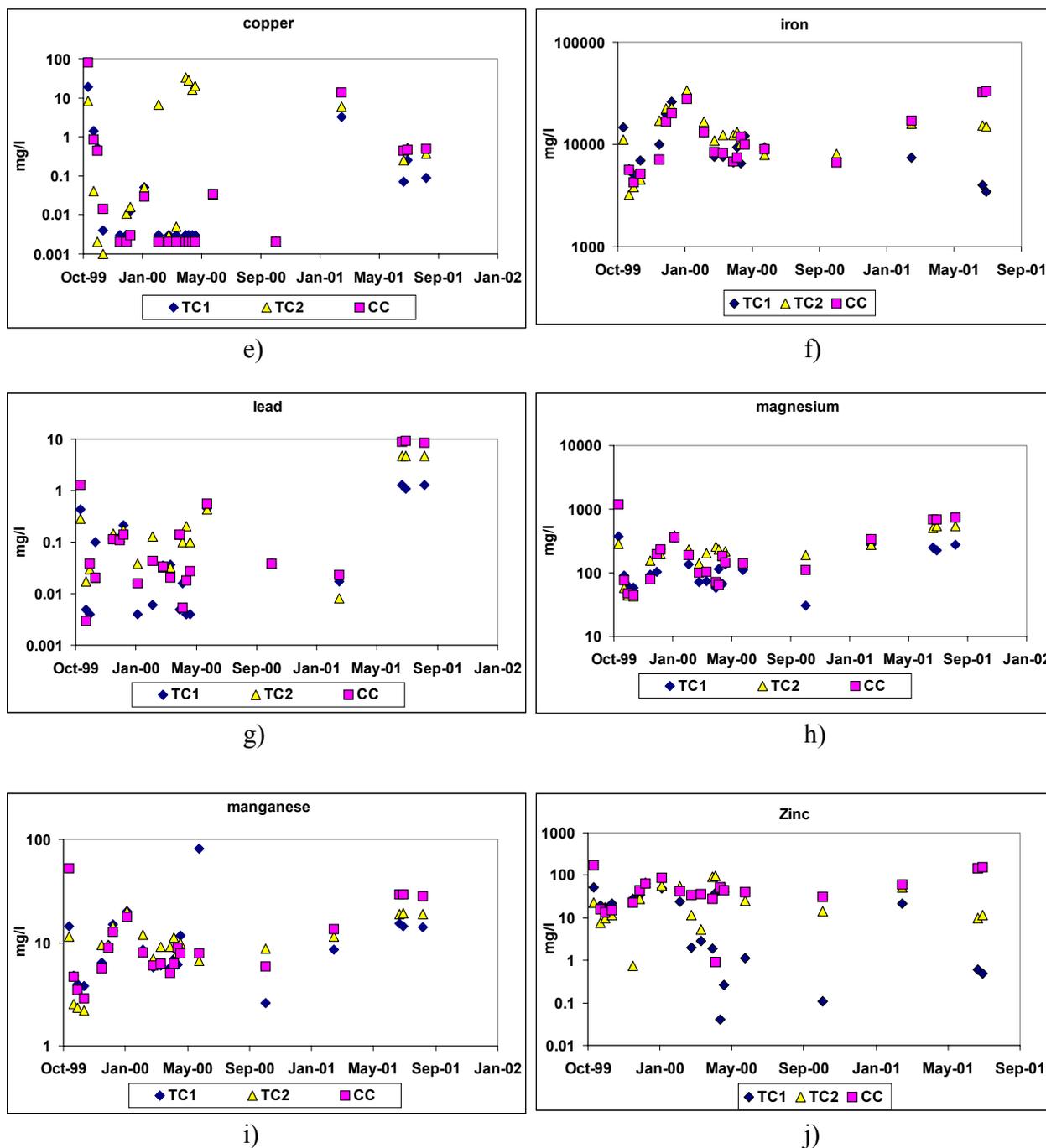
Figure 2. Dissolved metals in Fox Lake column effluent, continued.

The short-lived nature of the effect on pH, ORP, and metals indicated that indigenous heterotrophic bacteria would require further stimulation to produce a significant effect on acidity and dissolved metals from these columns.

Effects of second molasses addition – The second molasses dose was added to the test columns on 1/5/2000. The quantities and molasses concentrations were identical to those used in the first

addition. Following this treatment, daily additions of tap water to all columns continued at a rate of 375 ml/day. The effects of the second molasses addition on column effluent pH varied between the two test columns. Effluent from TC1 increased from pH 4 to pH 5, which was slightly greater than the change noted during the first molasses addition, while little effect was noted in TC2 relative to the control (Figure 3). The longevity of the pH effects in TC1 were also attenuated relative to the first dosing, lasting less than one month. The effects of the second carbon addition on ORP were similarly inconsistent, with TC1 ORP dropping from +50 mV to –30 mV and TC2 remaining relatively constant at +50 mV to +100 mV. During this time, the control column ORP was similar to that in TC2. Dissolved metals concentrations in the test columns were not significantly different from the control column following the second organic carbon addition (Figure 2).

Because the first two additions of organic carbon did not provide a persistent beneficial effect on effluent pH or metals, a daily treatment of molasses was applied to the test columns for a six-week period beginning in February 2000.
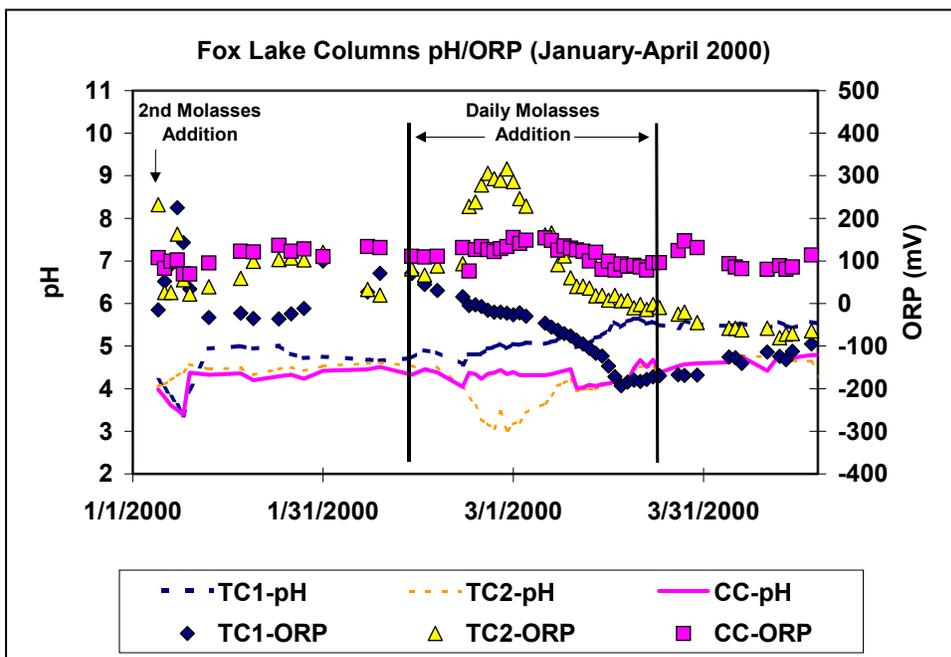
Figure 3. pH, ORP in Fox Lake column effluent (January-April 2000).

Continuous (daily) molasses addition – To promote a sustained beneficial effect on test column effluent pH and metals content, 1 L of a 10 g/L molasses and nutrient solution was added to the test columns on a daily basis from 2/11/00 to 3/24/00. The control column received 1 L/day tap water. During this 41-day treatment period, the pH in TC1 effluent increased from 4.7 to 5.6 while ORP decreased from +50 mV to –180 mV. In TC2, which received identical carbon and nutrient treatments to TC1, pH and ORP responded very differently. During the first 15 days of the treatment period, pH decreased from 4.5 to 3.0 and ORP increased from +80 mV to +300 mV. In the following 25 days, TC2 pH and ORP moderated, with pH increasing to 4.3 and ORP

11

decreasing to approximately 0 mV. During this period, the control column pH and ORP remained stable at approximately 4.5 and +100 to +150 mV, respectively (Figure 3).

Effluent dissolved metals from the test columns generally decreased in TC1 and increased in TC2. Aluminum, cadmium, cobalt, lead, and zinc concentrations decreased with increasing pH in TC1, while concentrations of lead and copper increased in TC2 relative to the control column (Figure 3).

In the 4 weeks immediately following the continuous addition period, the columns were returned to a daily influent regimen of tap water addition at 375 ml/day. During this time, the pH of TC1 remained at approximately 5.5, while that of TC2 and the control column remained approximately 4.75. The control column OPR remained constant at +100 mV, while the ORP of TC1 rose slightly to –100 mV and that of TC2 dropped from 0 to −50 mV (Figure 3). Effluent metals data collected following this period indicated maintenance of the trends seen during the continuous addition period. TC1 showed lower levels of Al, Co, Pb, and Zn than both the control column and test column 2, which showed elevated levels of Al, As, and Cu relative to the control column.

Test columns 1 and 2 responded very differently to the same organic carbon treatments. Whereas TC1 responded in the predicted pattern of decreasing ORP, increasing pH, and lower dissolved metals, TC2 responded in the opposite manner. As expected, the control column maintained relative stability in effluent pH and ORP. The first and second additions of molasses to the test columns had an ephemeral effect on column pH, lasting only approximately 3 weeks. The daily addition of molasses between 2/14/00 and 3/23/00 had a significant effect on the test columns during the addition period and approximately 4 weeks thereafter, however, this effect decreased over time after the daily additions ceased.

Influent water regimen change - Approximately 1 month after the daily additions of organic carbon ceased, the water addition regimen was changed from 375 ml/day during a 25-minute period to 2 L/week added in a slug dose. Immediately following this change, the pH of TC2 dropped dramatically. Within one week of the change, the pH of TC1 and the control column also dropped significantly (Figure 5). TC2 reached a low of pH 1.99 over the next 3 weeks, while TC1 and the control column dropped to pH 3.3 and 3.1, respectively. Microbiological data collected on April 26, 2000 indicated approximately 10^5 IOB/SOB/ml in effluent from all columns, while only TC1 showed the presence of SRB.

The significant drop in pH following the operational change in the columns is thought to be due to an extended contact time between the infiltrating water and the mineral surfaces. It is interesting to note that the ORP of TC1 did not increase as a result of this change, although that of TC2 and the control column increased 400 mV and 200 mV, respectively. The ORP response of TC2 is obviously counter to what is expected as a result of adding organic carbon to a flow-through system. The high ORP observed in TC2 is probably a result of relatively high concentrations of Fe^{+3} in solution caused by the activity of iron-oxidizing bacteria. Ferric iron produced by IOB activity is capable of increasing redox potential to circa +400 mV in the absence dissolved oxygen (Dutrizac and MacDonald, 1974). Total iron measured in column effluent during this period remained stable for all columns. The response of other metals in

solution varied between the columns. In TC1, Cd, Co, Pb, and Zn decreased, while only Al increased. In TC2, Al, As, Cu, and Pb increased while only Cd decreased. Metals were generally stable in the control column, with only Al increasing and Cd decreasing (Figure 3).

Test column 2 seeding – Several days following the addition of a concentrated buffer solution containing *Klebsiella oxytoca* to TC2 on May 5, 2000, the pH of TC2 effluent was measured at its lowest point (1.99) then subsequently increased to 3-3.5 for the following 4 weeks. It is difficult to attribute this increase to the addition of *Klebsiella oxytoca* since pH increased in both the control and TC1 by a similar margin during this period as well, without microbial enhancement. pH increased 2.4, 2.6, and 1.3 units in TC1, TC2, and the control, respectively, attaining similar levels to those observed prior to the change in sampling method (Figure 4). *Klebsiella oxytoca* was never observed in column effluent from TC2, and no increase in heterotrophic bacteria was quantified following this treatment. The response of TC2 to this addition was similar to that from past molasses-only additions.
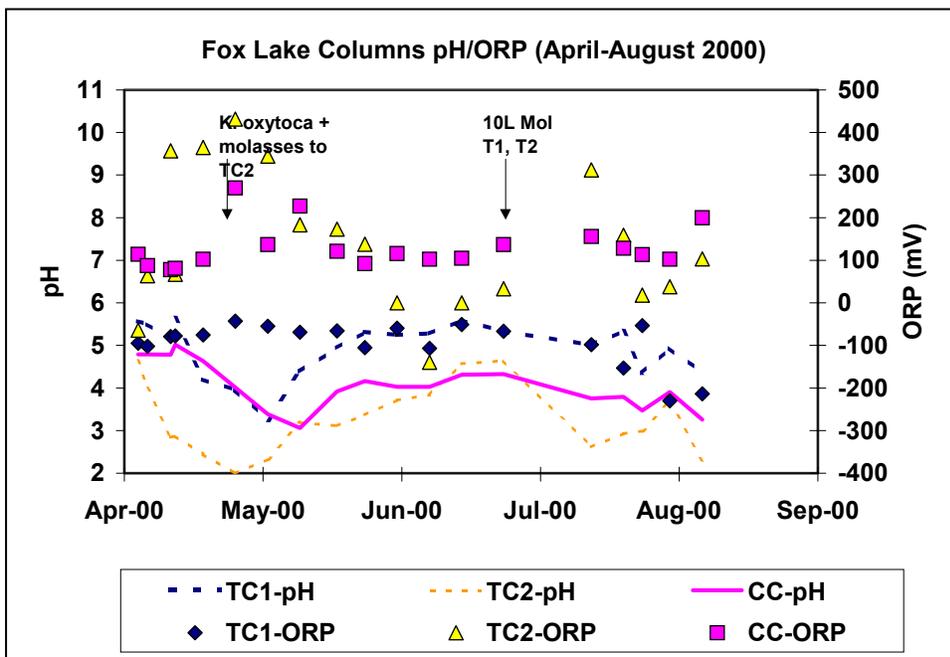
Figure 4. pH, ORP in Fox Lake column effluent (April-August 2000).

Molasses addition – On July 5, 2000, TC1 and TC2 were again dosed with 10 L of molasses solution at a concentration of 10 g/L. As had been the case with previous dosages, TC2 responded with a decrease in pH and an increase in ORP, contrary to expectations. pH in TC2 dropped from 4.6 to 2.6 while ORP increased from 0 to +300 mV. Unlike past molasses treatments, pH in TC1 also decreased immediately following this dosing. Microbial data collected over the course of the experiment indicated increasing fungal growth in all columns, though greatest in TC2 and the control. Fungal colonies were found in all columns during the 5/2/00 sampling event, prior to this molasses addition. Fungal growth in the columns was of concern because of the acidogenic nature of many fungi. No effort had been made to exclude fungal growth from the columns, and in fact, the method of organic carbon addition (large doses

of highly concentrated carbohydrate solutions) could have selected for fungi over bacteria, which are typically better adapted to more oligotrophic conditions. To test this hypothesis and potentially counter fungal growth, a protein-based carbon source was sought as a replacement for molasses. Whey is a protein-based waste product of cheese production, and was used in subsequent treatments.

Whey addition - Cheese whey was obtained from a local dairy and added to tap water at a concentration of 68 g/L. Ten L of this solution was added to each test column on August 24, 2000. To further inhibit fungal growth, 0.45 ml of the commercial fungicide TILT (propiconazole) was also added to the whey solution. Ten L of tap water was added to the control column. In the 4 weeks following this treatment, effluent pH in TC1 and TC2 rose from 4 to 5.5 and 2.5 to 4.5, respectively (Figure 5). Concurrently in the control column, pH rose from 3 to 3.5. As a result of the whey addition, the ORP of TC1 dropped from –100 mV to –300 mV and the ORP in TC2 dropped from +100 mV to –100 mV. The ORP of the control remained in the range of +100 mV to +200 mV during this period. Several metals (Al, Fe, Mn, Mg, Zn) decreased during this period in TC1, while effluent metals concentrations in TC2 and the control remained relatively stable (Figure 2).

In the 4-month period following the initial whey treatment, pH and ORP in TC1 effluent stabilized at 5.5 and –350 mV, respectively (Figure 5). The effect of the treatment waned as of January 2001, however this represents a 2-3 month increase in effectiveness over the molasses treatments. In TC2, pH stabilized at 4.5 for approximately 3 months following the pH increase after the whey treatment. ORP in TC2 initially fell from +100 mV to –100 mV after the whey treatment, but then fluctuated widely between –200 mV and +200 mV. During this period, the control column remained relatively stable at pH 4 and ORP varying between +100 and +300 mV. For a 3-week period in February 2001, the pH in both test columns dropped rapidly to approximately the same level as before the whey treatment. It is interesting to note that ORP in TC1 and TC2 did not increase concurrently with the drop in pH, remaining in the –300 mV range in TC1 and dropping from +100 to –200 mV in TC2.

Second whey addition – On 3/29/01, when pH in the test columns had been stable at approximately 3.9 for several weeks, the test columns were each dosed again with 10 L of the whey solution at 68 g/L. In immediate response to the treatment, the pH in all 3 columns again dropped, probably due to the slug dose of nutrient solution (test columns) and water (control) moving rapidly through the columns before buffering reactions could occur. A similar drop was observed following the final two molasses treatment as well. Immediately following this whey treatment, ORP increased significantly in TC2, from –200 to +400 mV, while TC1 ORP dropped slightly to –400 mV. This spike in ORP in TC2 lasted approximately 6 weeks, after which it dropped back to pretreatment levels of –200 to –100 mV. This 6-week period was also the approximate lag phase necessary for pH to respond favorably to the treatment in both test columns. Beginning in late May 2001, the pH of TC1 increased from 4 to 5.5 and in TC2 from 3.5 to 4.5. TC1 pH remained stable at 5.5 for over 4 months, but TC2 effluent pH dropped back to 4 after only one month, where it remained until the final whey dosing in September 2001.

Third whey addition – On 9/13/01, TC1 and TC2 were dosed a final time with whey solution (identical to that used in previous whey treatments). The timing of this dosing was chosen to

determine the effects of dosing whey to TC1 while the previous treatment was evidently still effective (i.e., pH > 5). As was the case in previous whey treatments, TC1 pH dropped initially (from 5.4 to 4.8), although this drop was much less than in the earlier treatments. TC2 pH dropped from 4 to 2, as it had in the past. The control column showed no immediate response to the water addition (Figure 5). TC1 recovered rapidly from the drop in pH, returning to 5.5 within 2 weeks of treatment. TC2 also recovered more rapidly than past treatments, returning to pH 4 after 5 weeks. ORP in TC1 remained at –200 mV during and after treatment, whereas TC2 increased from –100 to +350 mV in the week following the treatment.
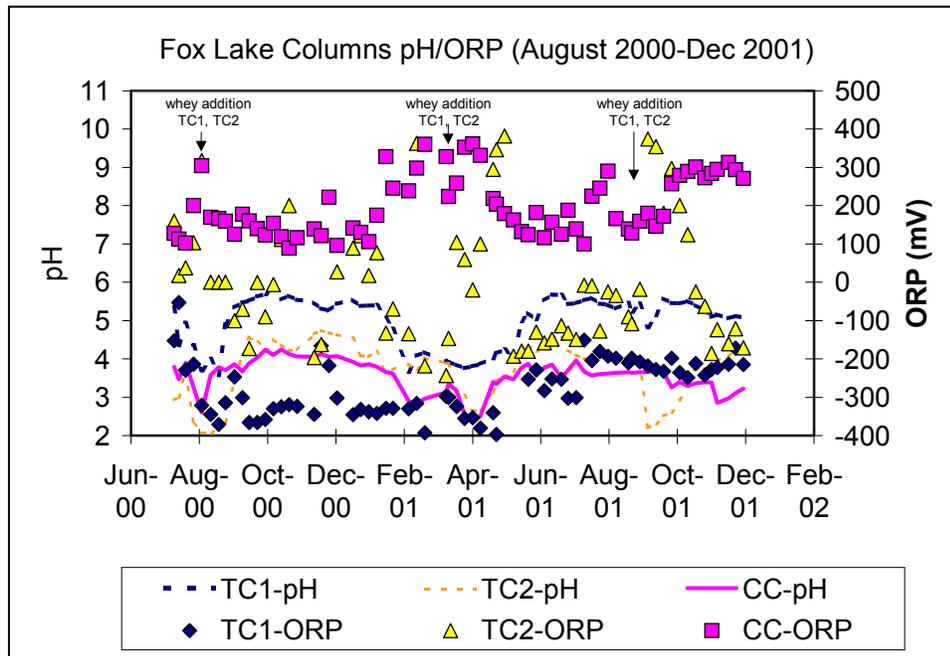
Figure 5. pH, ORP in Fox Lake column effluent (August 2000-December 2001)

Effluent Microbiology – Column effluent samples were analyzed for microbial colonization on a bi-weekly basis for the first 6 weeks of column operation, and on a monthly basis thereafter. Initial samples taken prior to the addition of molasses indicate the presence of significant populations of iron- and sulfur-oxidizing bacteria (SOB) in all columns during the first 3 sampling events (Figure 6). Total heterotrophic bacteria (THB) were present at low levels (approximately 10^0-10^2 MPN/ml during the stabilization phase, while sulfate-reducing bacteria (SRB) were not found in effluent from any of the columns prior to carbon addition. After the first 3 molasses additions to TC1 and TC2, levels of THB in the test and control columns remained relatively stable at 10^1-10^3 MPN/ml. Prior to carbon addition, few fungal colonies were observed growing on the agar plates used to enumerate THB, however after the addition of molasses, fungi dominated THB plates for all 3 columns. Following the daily molasses addition period (2/11/00 – 3/24/00), SRB were enumerated from TC1 at 10^2-10^4 MPN/ml. SRB were not found in effluent from TC2 or the control column during this period. With the exception of the 11/1/99 sampling event, SOB were found at levels of 10^4-10^5 MPN/ml at all times, before and after molasses addition.

a)

b)

c)
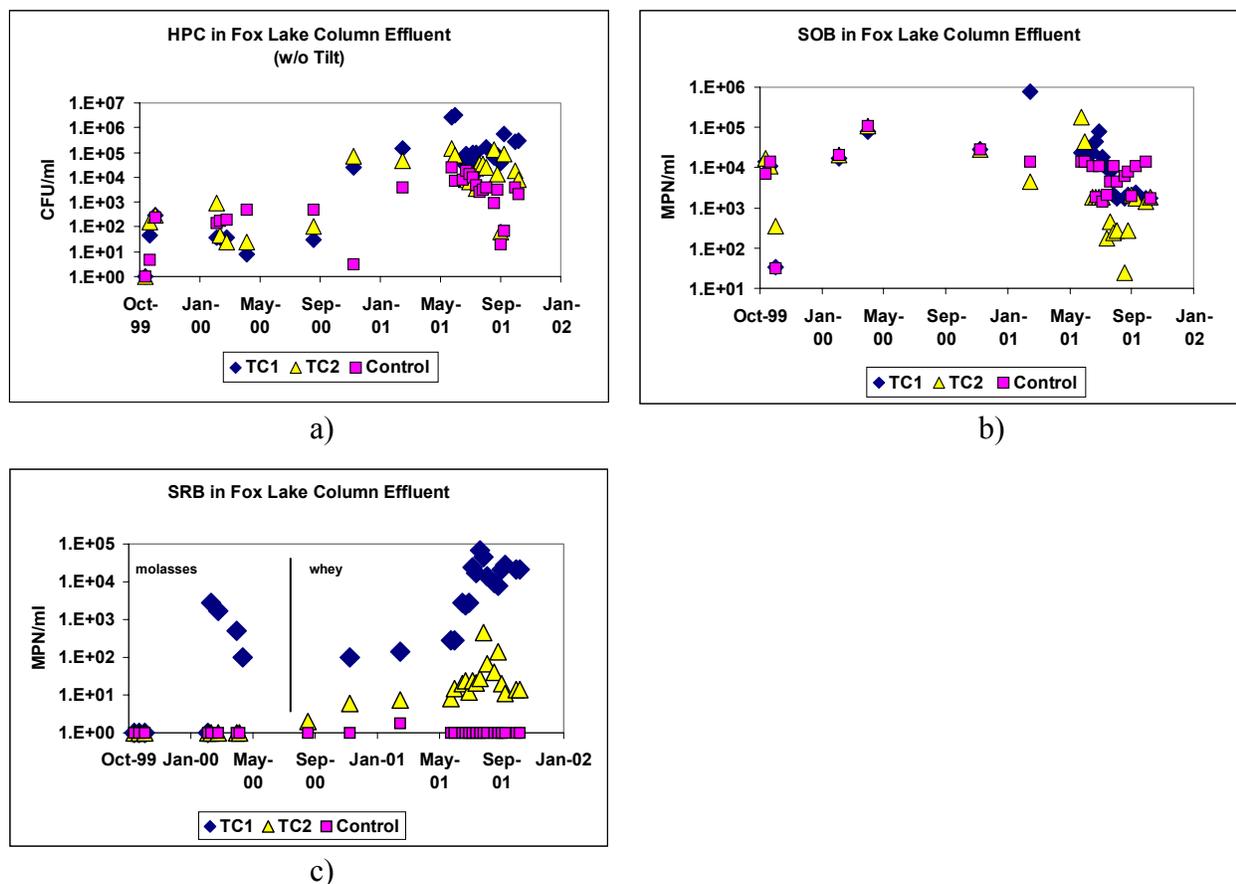
Figure 6 (a-c). Fox Lake column effluent microbial content.

After the commencement of whey treatment in the test columns in August 2000 (noted on Figure 6c), HPC counts in the test columns increased to 10^4-10^6 MPN/ml, although fungal colonies still accounted for approximately half of all colonies enumerated. SOB numbers were evidently not significantly impacted in the control column or TC1, but dropped to 10^2-10^3 MPN/ml in TC2 after repeated whey treatment. Concurrently, SRB numbers increased in both test columns, to 10^4-10^5 MPN/ml in TC1 and to 10^1-10^3 MPN/ml in TC2. No SRB have been enumerated from the control column during the 24 months of operation of this experiment.

Mineral Composition of Tailings - On November 14, 2000, tailings from all 3 columns were sampled to determine mineral composition. Tailings were sampled using a 0.25-inch diameter steel rod, which was advanced into the columns from the top. Samples were collected from depths of 10", 20", and 38". The mineral composition of the tailings at various depths was determined via energy-dispersive x-ray spectroscopy (EDS). The mineral composition (weight percentages) of three scans of the raw tailings is shown in Table 2. The mineral percentages shown under "large area scan" should be considered averages for the raw tailings, whereas those under "low density crystal" and "high density crystal" were recorded under high magnification of relatively small areas. It is apparent that the bulk of the raw tailings are more similar to the low-density scan than the high density scan. Analysis of the atomic percentages of these scans (Table 3) allows the development of stoichiometric relationships between the elements. The

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high-density crystal is composed of iron, sulfur, and oxygen in the ratio of $FeS_{2.5}O_{0.6}$, suggesting a slightly oxidized pyrite. The low-density and large area scans show these elements in the approximate ratio $FeS_{3.2}O_{1.1}$, indicating significantly more oxidation due to weathering. The orange appearance of the tailings suggests an abundance of oxidized iron phases, which typically form as a coating on metal sulfides as a result of weathering.

It is interesting to note that the weight percent of iron does not change significantly between the denser, sulfur-rich areas of the raw tailings and the less dense oxygen-rich areas. Stoichiometrically, it appears that during the weathering process, sulfur atoms are replaced by oxygen at an approximate 1:1 ratio. Approximately 6-8% of the original iron present is also lost (Table 3), but its weight percentage remains relatively constant because the overall mass of the mineral complex is reduced by the replacement of sulfur with oxygen.

Table 2. Mineral Composition of Raw Tailings (weight percent).

Area quantified	Fe	O	S	Si	Ca	Al	Mg
Large area scan	37%	36%	21%	3.9%	1.5%	0.9%	0.3%
High density crystal	38%	7%	55%	0.06%	0.03%	not detected	0.06%
Low density crystal	39%	33%	26%	0.6%	0.9%	0.2%	0.4%

Table 3. Mineral Composition of Raw Tailings (atomic percent).

Area quantified	Fe	O	S	Si	Ca	Al	Mg
Large area scan	17%	59%	18%	3.7%	1.0%	0.9%	0.3%
High density crystal	24%	15%	60%	0.07%	0.02%	not detected	0.09%
Low density crystal	19%	57%	23%	0.6%	0.6%	0.2%	0.5%

EDS analysis of tailings samples taken from the 10", 20", and 38" depths within the 3 columns indicates that oxygen is depleted at all depths in both TC1 and TC2 relative to the control column and the raw tailings (Figure 7a and b). As would be expected due to the accelerated weathering represented by the control column, oxygen levels here exceed the raw tailings at all depths. Sulfur concentrations in the test and control columns generally indicated an enrichment of sulfur at all depths with the exception of the 38" depth in the control column when analyzed by weight. TC1 and TC2 both showed higher weight percentages of sulfur at the 10" depth than the control column, but little difference was indicated at the 20" depth (Figure 7c). When analyzed by atomic percent, TC2 and the control column were not significantly enriched at any depth, however TC1 was significantly enriched at all depths (Figure 7d). The enrichment of sulfur in TC1 is likely the result of the precipitation of metal sulfides in this column due to the activity of SRB. Iron was depleted at the 10" and 20" depths from all columns relative to the raw tailings (Figure 7e and f). The depletion of iron was less pronounced in TC1 and TC2 than in the control column at these depths. At the 38" depth, both test columns indicated iron deposition relative to raw tailings.

The comparison between the high- and low-density crystals in the raw tailings (Tables 2 and 3) indicates that iron content is less sensitive as a diagnostic tool than either oxygen or sulfur content. Because sulfur is evidently replaced by oxygen as a result of the weathering process, calculation of the atomic oxgyen:sulfur ratio may be a useful method of assessing the extent of weathering and, in the test columns, the extent to which this process can be reversed or retarded

by organic carbon addition. The mean O:S ratio of the raw tailings is 3.3, whereas that of the high density area (less weathered) is 0.25. O:S ratios for other areas within the columns are indicated in Table 4. The increased weathering of the control column vs. the test columns is evident, as is the partial reversal of this process in TC1.
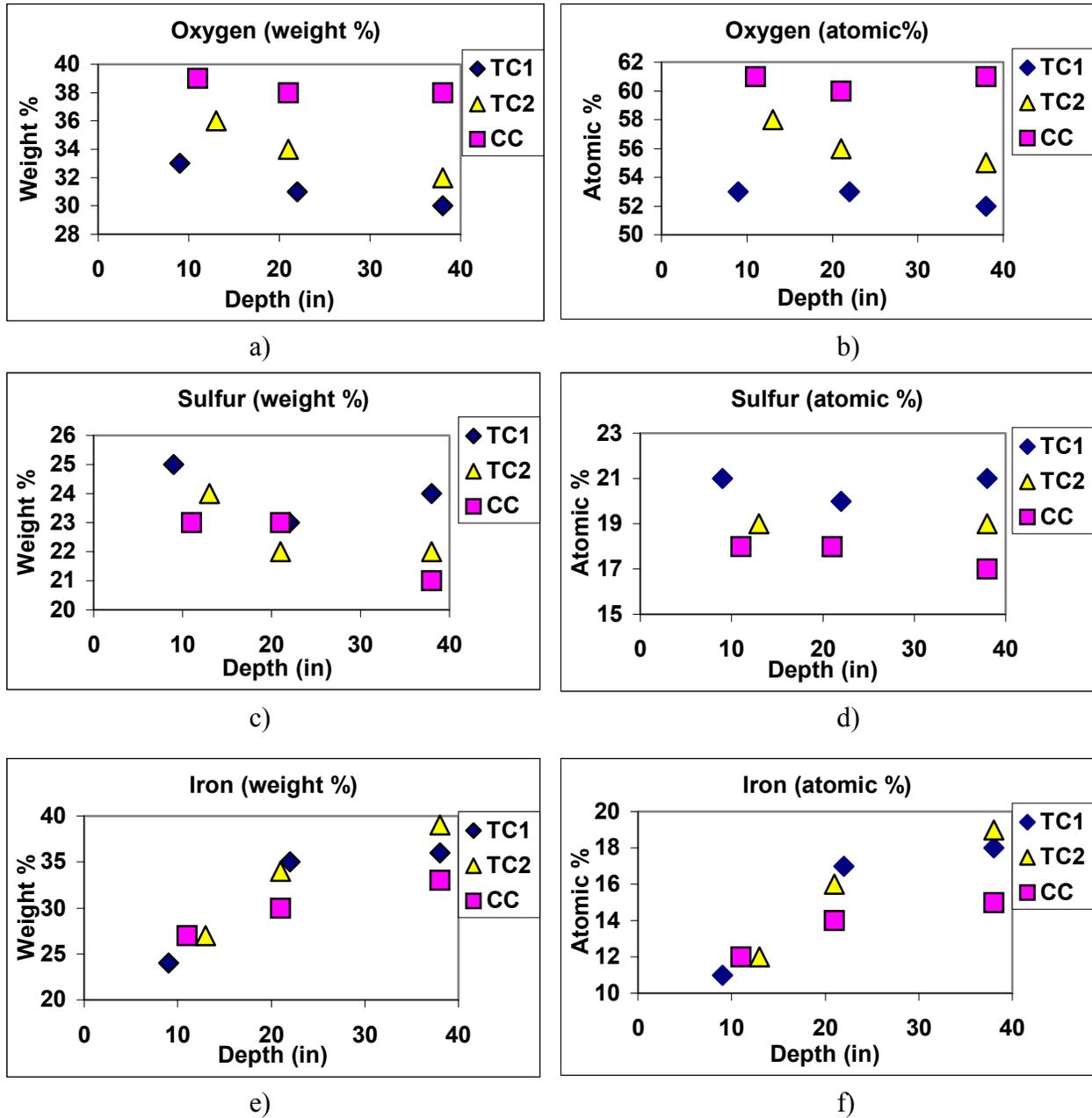
Figure 7. Oxygen, sulfur and iron mineral composition of Fox Lake column tailings with depth.

Table 4. Oxygen:Sulfur Ratio in Tailings Columns.

TC1		TC2		Control	
Depth (in)	O/S	Depth (in)	O/S	Depth (in)	O/S
9	2.5	13	3.1	11	3.4
22	2.7	21	3.1	21	3.3
38	2.5	38	2.9	38	3.6

Discussion

When the ORP and pH data for all 3 columns is plotted on a stability (Eh-pH) diagram for a typical pyrite-containing water system, the differences between the test columns and the control column become apparent (Figure 8). The control column remained in the Fe^{+2} range throughout the experiment, indicating that conditions continuously favored the dissolution of pyrite and subsequent acid production. TC1 started in the Fe^{+2} range, but organic carbon treatment shifted the redox and pH conditions to favor the stable pyrite (FeS_2) phase. Conditions in TC2 varied between these phases throughout the experiment, with no clear stability within one phase. ORP data over time (Figures 3-5) indicate a spike in ORP in TC2 immediately following each organic carbon addition, for both molasses and whey. This behavior was not noted in TC1. In all recent cases of organic carbon addition to TC2, ORP has declined to pretreatment levels in the 6-8 weeks following treatment, when tap water (ORP 700-800 mV) was used for column influent. This ORP pattern in TC2 suggests either the stimulation of microorganisms (bacteria or fungi) which increase iron oxidation in response to organic carbon addition, or the absence of suitable bacteria to utilize the organic carbon for the generation and maintenance of anaerobic conditions (heterotrophs and SRB).
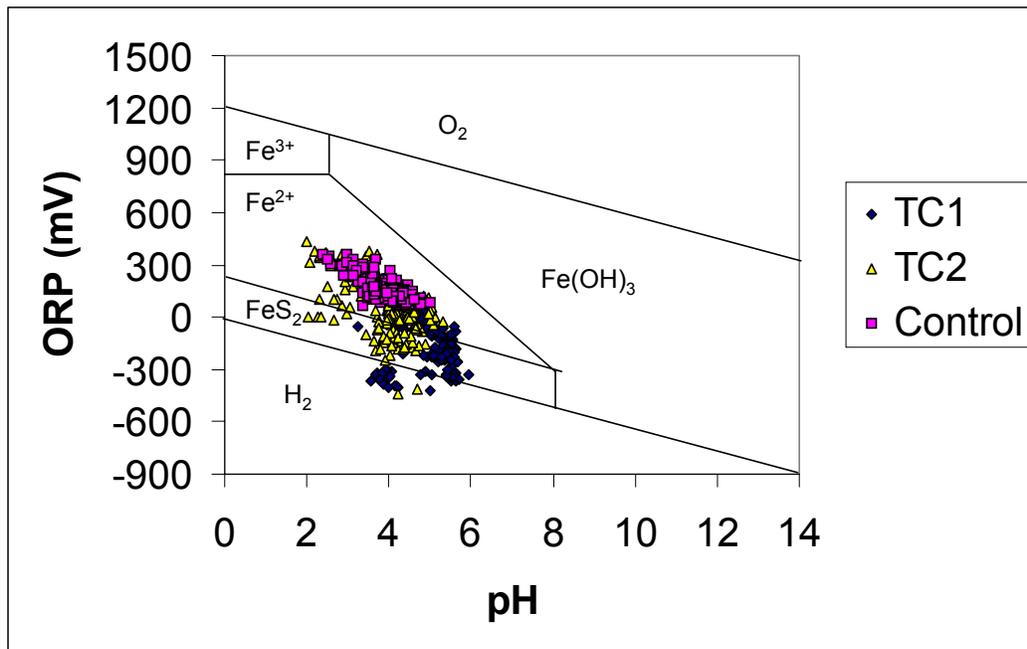
Figure 8. Stability diagram (ORP vs. pH) for all column data points.

Bacterial leaching of pyritic mine tailings is generally attributed to chemolithotrophic, iron-oxidizing bacteria (such as *Thiobacillus ferrooxidans*) which generate Fe^{3+} from Fe^{2+}. Since these bacteria are not dependent on external organic carbon for either energy or a carbon source it is unlikely that organic carbon addition would stimulate these populations to produce Fe^{3+}. In fact, relatively dilute solutions of glucose and citric acid have been found to inhibit the iron-oxidizing activity of *T. ferrooxidans* under aerobic conditions (Frattini, et al., 2000). The presence of organic carbon and anaerobic conditions evidently does not prevent all metabolic activity, however. Other workers (Pronk et al., 1991) have found that under anaerobic conditions *T. ferrooxidans* can utilize organic acids such as formate as an electron donor and ferric iron as the electron acceptor (creating ferrous iron), suggesting that these bacteria may be able to survive long periods of anaerobic conditions. This can help explain why populations of SOB were not observed to decrease in TC1 despite its highly anaerobic conditions and obvious lack of acid production after treatment. This does not explain, however, why TC2 exhibits very high ORP following treatment, however.

A possible explanation of the behavior of TC2 is a lack of adequate aerobic and facultative organisms to fully utilize the dissolved oxygen in the molasses or whey amended treatment water. For each organic carbon treatment, 10 L of water was added to each column. This volume is equal to half the pore volume of the column. It is likely that some channeling occurs in the columns, which could account for the rapid movement of the oxygenated water to the column effluent before aerobic and facultative bacteria could utilize the dissolved oxygen, thereby causing the ORP spikes measured following each treatment. pH in both TC2 and the control column has dropped in immediate response to the treatments, again probably due to the rapid influx of oxygenated water to stimulate SOB. Although TC2 has consistently had less effluent SOB than TC1, it also has fewer effluent HPC, which would be responsible for oxygen removal. Another contributing factor to the high acidity and effluent metals in TC2 is the lack of SRB relative to TC1 (Figure 6c). SRB promote pH buffering through the production of OH^- ions. Furthermore, SRB generate H_2S, which reacts with metals in solutions to precipitate as insoluble metal sulfides. The apparent disparity in SRB populations between TC1 and TC2 (10^4 vs. 10^1 CFU/ml effluent), it is not surprising that effluent from these columns differs so dramatically.

An alternative explanation for the unexpected behavior of TC2 is the stimulation of fungal growth or populations of heterotrophic iron-oxidizing bacteria. The presence of fungi was noted in effluent from all 3 columns, however, while only TC2 exhibited an ORP increase/pH decrease following carbon addition. Fungi have been observed to increase the rate of metal leaching in mining and scrap-metal recovery (Wenberg et al., 1971; Brandl et al., 2001). Likewise, recent work with heterotrophic iron-oxidizing bacteria (such as the mixotrophic *Thiobacillus acidophilus*) has shown that these acidophillic populations are capable of increased rates of pyrite dissolution and acidification when amended with an external organic carbon source (Bacelar-Nicolau and Johnson, 1999). Although sulfur- and iron-oxidizing bacteria in TC2 were observed to decrease in numbers relative to both TC1 and the control column (Figure 6b), the method used to quantify these bacteria may not have fully enumerated heterotrophic iron-oxidizers. Whether the behavior of TC2 was caused by the stimulation of heterotrophic iron oxidizers or fungi, it is evident that a more through understanding of tailings microbiology is necessary to insure the intended performance of this technology.

Although the performance of TC2 was enigmatic, TC1 responded very well to the organic carbon treatments. As was expected, pH increased and ORP dropped for extended period following each treatment (Figures 3-5). Although populations of SOB remained high following treatment, increased SRB growth promoted metals removal from solution (Figure 2). The longevity of effectiveness of the whey treatments (as measured by pH) in TC1 was approximately 6 months under the watering conditions imposed. Less weekly water addition (which would simulate dryer conditions) would be expected to extend the longevity of treatment effectiveness. The dosing rate employed would be expected to prevent the occurrence of acidic drainage from abandoned tailings for at least one field season in temperate climates.

Conclusions

Indigenous bacteria in abandoned mine tailings were stimulated through the periodic addition of organic carbon in the form of molasses and whey. However, laboratory columns treated with identical nutrient solutions responded differently with regard to effluent pH, dissolved metals and microbial flora. Heterotrophic bacteria increased in response to molasses and whey treatments in both test columns, while sulfur-oxidizing bacteria remained relatively constant in the test and control columns. The superior performance of TC1 versus TC2 was evidently due to the significantly higher growth of sulfate reducing bacteria in TC1. The reasons for this difference are not currently known, but are the subject of investigation during ongoing experiments with these tailings columns. This technology shows promise for field implementation as a low-cost, low-maintenance solution to abate acidic discharge from abandoned mine tailings, however, a more thorough understanding of tailings microbial ecology and responses of various populations to carbon addition is necessary to insure successful application in the field.

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Student Support for Assessment of Groundwater Contamination from Subdivisions

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Final Report
Student Support for Assessment of Groundwater Contamination from Subdivisions

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1. Abstract

The Gallatin Valley population grew 34% from 50,463 to 67,831 people between 1990 and 2000.   Approximately two thirds of this growth occurred in rural subdivisions on individual wells and septic systems.   There is concern that there is degradation of ground water from these rural subdivisions.   To test whether degradation is occurring, two mature subdivisions with shallow ground water and a proximity to water-quality impaired streams were chosen to for this study.

The shallow ground water was sampled through installed monitoring wells located up flow, mid flow, and down flow of the subdivision. Deeper ground water was sampled through domestic wells. Both shallow and deep ground water was sampled at times of high and low ground-water level.   All samples were tested for pH, specific conductivity, temperature, dissolved oxygen, total coliform (if present, then also for *E. coli*), chloride, total ammonia as nitrogen, nitrate plus nitrite as nitrogen, and total phosphorus. The water-quality impaired streams in the selected subdivisions were also tested for these parameters up flow, mid flow, and down flow of the subdivision. Discharge was measured for each stream.

Nutrient values are well below maximum contaminant levels with no obvious trends or patterns related to septic system flow lines in the surface water or the ground water. Nitrate plus nitrite as nitrogen averaged less than two milligrams per liter. Total coliform was present in some wells at both subdivisions, but no *E. coli* was found to be present, except in one shallow monitoring well. No discernable septic system influence was found in domestic wells or surface water.

Two nitrate models were tested for accuracy, Bauman-Schafer and Hantszche. The Bauman-Schafer model accurately predicted the Middle Creek subdivision area nitrate results and predicted higher than actual values for the Gardner/Sourdough subdivision area. The Hantszche model attempts to predict an overall degradation and was high for both subdivisions. Phosphorus breakthrough curves were run with no problems found.

2. Problems and Research Objectives

Septic systems have been shown to contaminate ground water at a variety of locations (for example, Yates, 1985, Yates and Yates, 1988, Cogger, 1988, Reneau et al., 1989, Robertson and others, 1991; Ingram 1993; Hantzsche and Finnemore, 1993). Nutrients and pathogens have been identified as parameters that limit water quality for some streams in the Gallatin County Local Water Quality District (LWQD) (Fig. 1), and residential rural subdivision development has been identified as a potential source of this contamination. The nutrient and microbial load delivered to water-quality
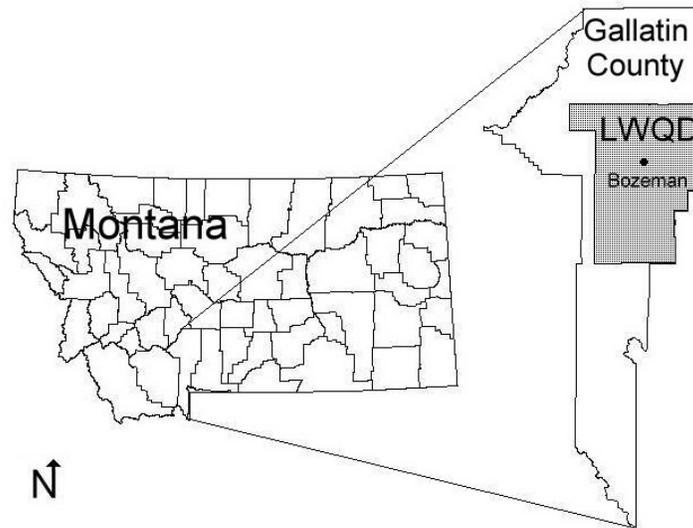
Figure 1. Location of the Gallatin County Local Water Quality District.

impaired streams by shallow ground water that flows beneath subdivisions has not been directly measured. The traditional approach used to assess contamination from septic systems in Gallatin Valley has been to examine countywide trends in groundwater quality, and trends have been elusive (Kendy, 2001, Slagle, 1995; Bauder et al., 1993; Dunn, 1978; Hackett et al., 1960). In 1980, Peavy et al. found no detectable nutrient or microbial contamination adjacent to septic systems in a new subdivision. They suggested the age of the subdivision might be important and that a mature subdivision should be studied. In 1997, the Montana Department of Environmental Quality (DEQ) suggested a reexamination of subdivisions studied by Peavy et al. in 1980 to determine

- if groundwater quality has been degraded below and down flow of subdivisions and

- whether the Bauman-Schafer and phosphorus breakthrough methods (currently used for subdivision review and non-degradation assessment) reasonably predict impacts of development on groundwater quality.

While the DEQ's proposed reexamination is interesting, the original research wells are gone, homeowner cooperation is not assured, and the study areas would require significant travel. An alternative approach is to examine ground water below mature subdivisions (1970's-vintage) in the Gallatin County LWQD, which are thought to contribute nutrient and/or coliform to streams. Such a study could be used to answer several important questions of interest both to the state of Montana and to the LWQD.

1) Is microbiological contamination dominantly from poor well seals, septic contamination, or other sources?
2) Are coliform-contaminated or nutrient-contaminated wells on a flow line that contains one or more septic systems?
3) Are wells that are contaminated with nutrients also contaminated microbiologically?
4) Is the contamination level and type (nutrient/coliform) dependent on the texture of the sediments (finer-grained or coarser-grained) below the subdivision?
5) What nutrient and coliform loads enter and leave a subdivision area via the ground water, and what are the likely loads being delivered to water-quality impaired streams in the LWQD?
6) Do the Bauman-Schafer and phosphorus breakthrough models correctly predict observed concentrations of nutrients below mature subdivisions?

3. Methods

Subdivision Selection

Subdivisions were selected as candidates for the project based on the following parameters and ranking criteria: 1) proximity to a water-quality impaired stream, 2) maturity, 3) shallow groundwater depth, 4) proximity to public groundwater supply, 5) previous contamination history, and 6) the absence of other subdivisions on septic systems directly up flow. Once the list of candidate subdivisions was compiled, the subdivisions were grouped according to substrate material, either coarse or fine. Staff from MSU, LWQD, DEQ, and EPA helped in the final selection process. One

subdivision was selected as a representative of each group. The remaining subdivisions were rank ordered as back-up research sites if needed.

Obtaining permission from the majority of the homeowners was the final step in the selection process. This involved door-to-door inquiries and form surveys. A brochure with relevant information pertaining to the study, complete with contact numbers, was also developed and hand delivered.

Subdivision Sampling

Two sampling rounds were done, one around the time of low ground-water level and one around the time of high ground-water level. Each well, with permission, in the two subdivisions was sampled for pH, specific conductivity, dissolved oxygen, temperature, and pressure using a probe calibrated daily. Also, two sample bottles were filled from each well to be sent to the lab for analysis of total coliform (if present, then also for *E. coli*), chloride, total ammonia as nitrogen, nitrate plus nitrite as nitrogen, and total phosphorus. Samples from domestic wells were taken from sterilized spigots after running water to clear out the water that had been sitting in the pipes.

The installed well points (up flow, mid flow, and down flow) were also sampled twice for the same constituents. Two different types of wells were installed. Three of the wells were two inch steel well points, and a bailer was used to sample these, removing three well volumes prior to sampling. Nine of the wells were one inch slotted PVC, and these were sampled using a foot-valve to remove three well volumes prior to sampling.

The surface water was sampled at the same time the ground water was sampled and for the same constituents. For each stream in the subdivisions, an up flow, a mid flow, and a down flow sample were taken along with one discharge measurement per stream. A DH-40 stream sampler was used to collect the samples. Disinfection of the sampling equipment was done with 70% isopropyl alcohol.

Nitrogen isotope sampling was done later to determine nitrogen sources. Also at this time, phosphorus and nitrate plus nitrite as nitrogen samples were collected filtered and unfiltered to test for effects in sampling methods. Filtration of sample water was found to make a difference in phosphorus results where sediment was involved – the monitoring well samples and the stream samples. Filtration did not affect nitrate plus nitrite as nitrogen results.

4. Principle Findings and Significance

The Middle Creek subdivision area and the Gardner/Sourdough subdivision area are the two sites chosen for the study (Fig. 2). The Middle Creek subdivision area represents the coarser-grained aquifer, and the Gardner/Sourdough subdivision area represents the finer-grained aquifer. Two streams were available for sampling in each subdivision area (Fig. 3 and 4).

The stream sampling results (Tables 1-4) show no obvious pattern of increasing amounts of nutrients or bacteria as the stream flows through the subdivisions, except for chloride, which does show an increasing pattern in the Gardner/Sourdough subdivision area (Table 4). This could be due to a septic influence, but amounts of all nutrients are very low.

The groundwater results for the Gardner/Sourdough subdivision area also show higher chloride numbers at the down-flow end of the subdivision (Fig. 5). All the other groundwater results show no obvious patterns in the amounts of nutrients and bacteria, and the amounts of nutrients are also very low, so no contamination is evident (Tables 5 and 6).

Total coliform bacteria was present in 47% of the Middle Creek subdivision area wells at high water sampling and in 19% of the Middle Creek subdivision area wells at low water sampling. The total coliform bacteria could be a naturally occurring species, so finding just total coliform bacteria is not conclusive of septic influence. No *E. coli* was found in domestic wells, but a down-flow monitoring well on the western side of the Middle Creek subdivision area did have a detection of *E. coli* (Fig. 6). This installed monitoring well is one-inch PVC with a threaded, screw-on cap, so possibility of well contamination from outside the well is not an issue. This detection indicates that contaminated flow lines from septic systems probably exist, but that the contamination does stay in the shallow ground water and does not penetrate the domestic well source water that is deeper. Distance may also be an issue. This monitoring well was less than 100 feet down flow from a septic system.

In the Gardner/Sourdough subdivision area, 45% of domestic wells sampled had detectable total coliform bacteria at high water, and 60% of domestic wells sampled had detectable total coliform bacteria at low water. No *E. coli* was present in the ground water.

No conclusions can be drawn on the source of the total coliform bacteria, whether naturally occurring or a septic source. Test of earwigs, a insect commonly

found around wells, show that total coliform bacteria and *E. coli* are present in large numbers in the earwigs.

No nutrient contamination exists in the subdivision areas studied. All amounts are well below state and federal standards for drinking water quality, and are near background values. No patterns are evident that would show septic influence or any other contamination source in the subdivision areas, other than the higher chloride amounts, which are well below standards, in the Gardner/Sourdough subdivision area. The widely feared contamination of ground water by nutrients and microbes was not documented.

Nitrogen isotopes from five ground-water wells in Middle Creek Subdivision show $\delta^{15}N_{NO3}$ values that range from +4.7 to + 5.9 per mil; water in two ground-water wells in Gardner/Sourdough subdivision show $\delta^{15}N_{NO3}$ values that range from + 1.1 to +2.5 per mil. The highest value came from a shallow up-gradient well before septic contamination was possible. The nitrogen isotope values consistent with nitrogen from soil organic nitrogen or fertilizer not from animals or humans. This result is consistent with findings by Kendy (2001) several miles to the north.

Some differences between the two subdivisions are evident (Figs. 7-8), but besides a grain size difference, the wells in the Gardner/Sourdough subdivision area (average 80-90 feet deep) are also deeper than the Middle Creek subdivision area wells (average 30-40 feet deep). The most notable differences are that the nitrogen isotope values are higher at Middle Creek subdivision. This subdivision area also has a higher dissolved oxygen than the Gardner/Sourdough subdivision area. Also, water temperatures are higher at Middle Creek. Phosphorus values are also higher at Middle Creek.

Loading values (Tables 7-10) were calculated using discharge, measured for the surface water and estimated for the ground water. The load value is calculated by multiplying the concentration times the discharge (with the appropriate unit conversions) to produce a daily load for a constituent of interest.

The Bauman-Schafer nitrate model was tested for accuracy against the observed values. In the Middle Creek subdivision area, the numbers were fairly accurate, but in the Gardner/Sourdough subdivision area, the predicted numbers were significantly higher than the observed numbers.

Testing of the phosphorus breakthrough model did not work, due to the low phosphorus amounts and due to the age of the subdivisions being around forty years.

The breakthrough time usually is over fifty years. Two instances were modeled with a less than fifty year breakthrough, but no evidence of significantly higher phosphorus was observed in the subdivision areas.

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5. Publications / Citations

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6. Student Support

M.S. (Not finished yet)

7. Notable Achievements and Awards

None

Information Transfer Program

INFORMATION TRANSFER PROGRAM

Basic Information

Title:	INFORMATION TRANSFER PROGRAM
Project Number:	2002MT21B
Start Date:	3/1/2002
End Date:	2/28/2003
Funding Source:	104B
Congressional District:	Montana
Research Category:	Not Applicable
Focus Category:	Education, Surface Water, Groundwater
Descriptors:	Public information, technology transfer, drinking water, Montana watersheds
Principal Investigators:	Kendall Watkins, Susan Higgins

Publication

In its mission to mobilize the resources of Montana's public universities to resolve the state's water problems, research along with education and information transfer go hand in hand. University investigators, government partners and the private sector have joined in this effort since the Center's establishment in 1964. During FY 2002, several excellent tools have continued to evolve at the Water Center, all with the goal of getting very good information to people who need it:

1. The Montana Water Center's web-based information transfer efforts have grown to include an expanded expertise directory, research projects database, Montana watersheds groups information source, important events postings, new on-line water resources library checkout, and information clearing house for researchers, educators, agency personnel, and watershed groups. The Montana Water Center continues to build its interactive, information-rich website, *Montana Water* (http://water.montana.edu). An electronic newsletter hosted by the Montana Water Center will be unveiled in Fall 2003.

2. The Montana Water Center's "Annual Report 2001-2002" is used by investigators and the interested public alike to gain insights and information on how USGS-funded investigations can address Montana's water-resource issues.

3. The annual American Water Resources, Montana Chapter meeting in Livingston, Montana was hosted and coordinated in part by the Montana Water Center. This meeting is anticipated annually by water-resource professionals from throughout the state who share information on research methodologies, issues, challenges, and successes. A web-based archive of these vital meetings is found at http://www.awra.org/state/montana/.

4. Outreach and Information Referral - Using the web sites as tools, the Montana Water Center's Communication/Outreach Coordinator continues to provide information to the general public on a daily basis in the form of website updates, e-mail announcements, and responses to requests for information.

Student Support

Student Support					
Category	Section 104 Base Grant	Section 104 RCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	1	0	0	0	1
Masters	20	0	1	0	21
Ph.D.	3	0	0	0	3
Post-Doc.	0	0	0	0	0
Total	24	0	1	0	25

Notable Awards and Achievements

In addition to the productive research conducted under the Montana Water Centers USGS base grant, the Center gladly reports several notable achievements resulting from USGS and other funding sources:

1. Blue Water Task Force. The Blue Water Task Force collects monthly water data at seven stations on the Gallatin River. This effort promotes stewardship of aquatic resources in the Gallatin Valley through community education, citizen involvement, in water quality monitoring, and scientific data collection. The Water Center provides technical expertise, lab facilities, and coordination for the Task Force. Learn more about this notable achievement at http://water.montana.edu/bwtf/default.asp.

2. Ecosystems Restoration Website. The goal of this website has been to provide ecologic restoration tools to designers, managers, and practitioners in a web-based information repository. The site can be accessed at http://ecorestoration.montana.edu.

3. Whirling Disease Research. The Whirling Disease Initiative is overseen by the National Partnership for the Management of Wild and Native Coldwater Fisheries. In FY 2002 the Water Center managed the work of the Partnership through a competitive grant program which examines impacts of and solutions to the national whirling disease dilemma. Fourteen research project culminated in valuable solutions to the disease.

4. Wild Trout Research Laboratory. This lab, managed by the Montana Water Center, supports a large number of whirling disease projects, as well as projects on fish stamina and thermal tolerances.

5. 7th International Symposium on Fish Physiology, Toxicology, and Water Quality. The Water Center developed an agenda and facilitated an highly successful meeting during FY 2002, held in Tallin, Estonia on May 12-15, 2003. A detailed account of this meeting will appear in the FY 2003 Annual Report.

6. Small Systems Technical Assistance -- Drinking Water Assistance Program. The Montana Water Center operates a flagship institution in the eight-center network of Small System Technology Assistance Centers. Project descriptions and resources from all eight centers can be accessed on the TACnet website

maintained by the Montana Water Center at http://water.montana.edu/tacnet/deafult.htm. Of special note for FY 2002 is the Operator Basics Training Series Ground Water Systems National Version 2002 (CD-ROM), an innovative multimedia training program designed to entertain while it instructs. The Montana Water Center program design team developed this training tool.

7. 68th Annual Water School for Water and Wastewater Operators and Managers. Held on the Montana State University campus each year, the Water School provides vital training and information for water professionals across the state. The Water Center is proud to be a partner in developing this exceptional training program.

Publications from Prior Projects