State of Washington Water Research Center Annual Technical Report FY 2005

Introduction

The mission of the State of Washington Water Research Center (SWWRC) is to:

i) facilitate, coordinate, conduct, and administer water-related research important to the State of Washington and the region,

ii) educate and train engineers, scientists, and other professionals through participation in research and outreach projects, and

iii) disseminate information on water-related issues through technical publications, newsletters, reports, sponsorship of seminars, workshops, conferences as well as other outreach and educational activities.

The SWWRC has developed a multi-pronged approach to accomplish these goals. To promote research and outreach, the SWWRC has been organized into five program areas: Watershed Management, Groundwater Systems, Environmental Limnology, Vadose Zone Processes, and Outreach and Education. These programs have helped prepare several multidisciplinary research proposals and provide better links between faculty and the SWWRC. These are in addition to the Directors primary research interests in surface-groundwater interaction, remote sensing, and stormwater. The Center is also involved in international research and education activities.

The SWWRC is continuing its intensive efforts to reach out to agencies, organizations, and faculty throughout the State. Activities include presentations to watershed groups, participation in regional water quality meetings, and personal contacts. A new dynamic web page has been created to share information with stakeholders.

It is within this overall context that the USGS-funded project activities reported in this document must be inserted. These include the internally funded projects as well as the national proposals awarded to the Center. These projects provide a solid core to the diverse efforts of the SWWRC. Water quantity and quality issues continue to be a major concern in the State of Washington due to the endangered species act, population growth, industrial requirements, and agricultural activities. Emerging issues such as water resources management in the face of global warming, water reuse, energy-related water quantity and quality considerations, and storm water runoff regulations are also beginning to raise concerns. All of these issues will be important drivers of the activities of the SWWRC in the foreseeable future.

Research Program

In accordance with its mission, the SWWRC facilitates, coordinates, conducts, and administers water-related research important to the State of Washington and the region. Research priorities for the State of Washington are established by a Joint Scientific Committee which includes representatives from water resource professionals at state agencies, universities, and the local USGS office. The Center supports competitively awarded internal grants involving water projects evaluated by the Joint Scientific Committee. The Center also actively seeks multidisciplinary research at local, state, and national levels. Meetings between stakeholder groups, potential funding agencies, and research faculty are arranged as opportunities arise. Faculty are apprized of any opportunities. The Center also submits proposals on its own behalf.

During FY 2005, three local research projects were selected for funding by the Center: (1) Using Stable Isotopes to Trace Nitrate Sources and Surface Water-Groundwater Interactions in the Upper Yakima River Drainage, (2) Removal of the Human Pathogen Giardia Intestinales from Ground Water, and (3) Oxygenation for the Management of Sediment Mercury Release from Aquatic Sediments. As described below, these projects address state issues but are also relevant to national interests.

Two national projects are currently being run through the SWWRC: (1) Collaborative Research: Hydraulic and Geomorphic Controls on the Evolution of Cluster Bedforms in Gravel-Bed Streams and (2) Using Environmental Tracers to Improve Prediction of Nonpoint Pollutant Loadings from Fields to Streams at Multiple Watershed Scales. Updates of these projects are also presented in this report.

Two other projects were funded through the USGS/Water Institute partnership. One project involves a USGS project in Jordan where the SWWRC assists by hiring Jordanian nationals to conduct research to Improve Groundwater Management in Jordan. The second project involved funding from our local USGS office in Tacoma to assist in developing a Preliminary Numerical Flow Model Development for the Spokane Valley-Rathdrum Prairie Aquifer.

Using Stable Isotopes to Trace Nitrate Sources and Surface Water-Groundwater Interactions in the Upper Yakima River Drainage

Basic Information

Title:	Using Stable Isotopes to Trace Nitrate Sources and Surface Water-Groundwater Interactions in the Upper Yakima River Drainage
Project Number:	2005WA115B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Washington 4th District
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Surface Water, Nitrate Contamination
Descriptors:	Surface water-groundwater Interactions, Nitrate, Stable Isotope, Yakima River
Principal Investigators:	Carey Alice Gazis

Publication

1. Gazis, Carey A., 2005, Stable Isotope Studies of Surface Water-Groundwater Interactions in the Upper Yakima River Drainage, Washington, "in" Geological Society of America 2005 Annual Meeting, Salt Lake City, Utah, October 16-19, 2005, Abstracts with Programs 37(7) p. 213.
2. Gazis, Carey A. and Sarah Taylor. 2005. Geochemical Studies of Surface Water-Groundwater Interactions in the Upper Yakima River Drainage, Washington (poster), "in" Proceedings of the Conference Groundwater Under the Pacific Northwest: Integrating Research, Policy, and Education, November 2-3, 2005, Stevenson, Washington. http://www.swwrc.wsu.edu/conference2005/proceedings/Nov_2/Poster%20Session/Gazis.C.abstract.htm

PROBLEM AND RESEARCH OBJECTIVES

The Yakima River basin is one of the most intensively irrigated areas in the country, with approximately 500,000 acres irrigated. In addition, the river is typical of the arid west in that many other constituencies (e.g. municipal water suppliers, fisheries, recreational users) are placing demands on the limited water supply. This research addressed the question of how irrigation practices impact surface water-groundwater interactions and water quality in the upper Yakima River basin. The research objectives were:

1. To identify recharge and discharge zones for groundwaters from different levels in the Ellensburg aquifer;
2. To constrain flow paths of groundwater in one direction and characterize their seasonal variations;
3. To determine the extent to which irrigation waters infiltrate wells in the area and trace the fate of these irrigation waters;

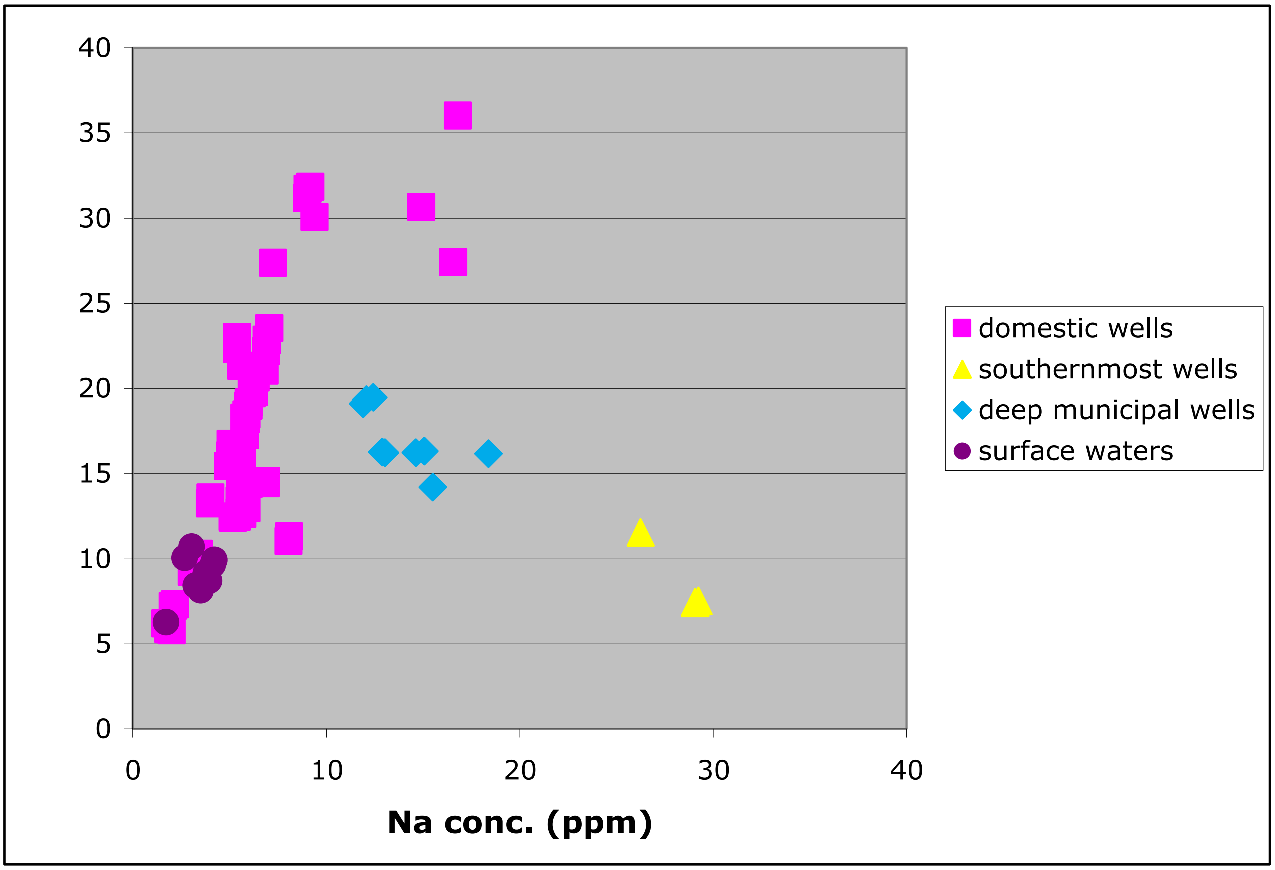
METHODOLOGY

Twenty-five wells, positioned along a transect perpendicular to the Yakima River were sampled every two months throughout the year. Most of these wells are completely within the Ellensburg formation, a volcaniclastic sedimentary unit that is over 1000 meters thick in parts of the Ellensburg basin. Alkalinity, pH, conductivity, and dissolved oxygen content were measured in the field during sampling. In the laboratory samples were processed and analyzed for: 1) stable isotope composition using a gas source isotope ration mass spectrometer (IRMS); 2) major ion concentrations using and ion chromatograph (IC); and 3) trace element concentrations using a inductively coupled plasma mass spectrometer (ICP-MS). These data were compared to similar data for streams, irrigation water, and precipitation.

PRINCIPAL FINDINGS AND SIGNIFICANCE

H and O isotopic compositions for these groundwater samples, are compared to local stream water, irrigation water and precipitation data and interpreted in terms of mass balance models to determine the contributions of geochemically distinct source waters (e.g. snowmelt, irrigation waters) to the groundwater and how these contributions change seasonally. Local precipitation and surface waters form a local meteoric water line on a δD- $\delta^{18}O$ plot with equation: $\delta D = 6.6\ \delta^{18}O - 10.7$. Irrigation waters and their source, the Yakima River, generally fall above this local meteoric water line with relatively heavy isotopic compositions. Groundwaters from some of the shallow domestic wells also tend to be isotopically heavier and plot near the local surface and irrigation water, particularly when sampled during the irrigation season. Often these shallow groundwaters also have elevated nitrate and sulfate concentrations. These geochemical characteristics indicate that these groundwaters are mixing with surface waters throughout the year, including nitrate-rich irrigation waters during the irrigation season. Groundwaters from deeper wells are isotopically lighter and have a narrower range of values, comparable isotopically to spring snowmelt. The two southernmost domestic wells, which draw from an aquifer in the Columbia River basalts, are isotopically distinct, with δD values that are lower than all but the lightest winter precipitation.

Major cations in groundwaters and surface waters are typically dominated by magnesium and calcium. However, the southernmost wells have relatively high concentrations of sodium, while deep municipal wells have intermediate sodium concentrations (See figure). Anion geochemistry is dominated by bicarbonate. Concentrations of selected trace elements (Ti, V, Cr, Mn, As, Rb, Sr, Ba) tend to be distinctly different from well to well, but remain relatively constant throughout the year in any given well.



These geochemical patterns can be interpreted in terms of a water-rock interaction and anthropogenic effects due to current and past land use practices. Waters within different aquifers (e.g., Ellensburg formation vs. Columbia River basalts) and different subaquifers (e.g., different units within the Ellensburg formation) retain distinct geochemical signatures that are acquired through water-rock interactions. In addition to their natural chemistry, groundwater samples from some wells have relatively high concentrations of arsenic, which may be due to interaction with soils in areas where arsenical pesticides were used on orchards. The geochemical signatures derived from interactions with soils and rocks remain relatively constant throughout the year, unlike changes due to irrigation practices. Locations where irrigation waters mix with domestic well water have been identified using nitrate and sulfate concentrations and stable isotope ratios. We are currently looking in more detail at the spatial patterns of these geochemical variations.

Removal of the Human Pathogen Giardia intestinales from Ground Water

Basic Information

Title:	Removal of the Human Pathogen Giardia intestinales from Ground Water
Project Number:	2005WA116B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Washington 5
Research Category:	Ground-water Flow and Transport
Focus Category:	Water Quality, Toxic Substances, Water Use
Descriptors:	Giardia, Pathogen, Reactive Barrier, Drinking Water
Principal Investigators:	Dirk Schulze-Makuch, C Kent Keller, Joan Q Wu

Publication

1. Rust, Colleen, Dirk Schulze-Makuch, Robert S. Bowman, and Diane K. Meier. 2005. Field Testing of a Prototype Filter System for the Removal of the Human Pathogen Giardia intestinales from Ground Water "in" EOS Transactions, American Geophysical Union, 86(52), Fall 2005 Annual Meeting Supplement, Abstract H23B-1431.
2. Schulze-Makuch, Dirk, Colleen Rust, Robert S. Bowman, and Diane K. Meier. 2005, Developing a Prototype Filter System for the Removal of Human Pathogens from Drinking Water, "in" Geological Society of America 2005 Annual Meeting, Salt Lake City, Utah, October 16-19, 2005, Abstracts with Programs 37(7) p. 473.
3. Rust, Colleen, Dirk Schulze-Makuch, and Robert S. Bowman. 2005. Removal of the Human Pathogen Giardia intestinales from Ground Water, presentation at the 2005 National Ground Water Summit, April 17-20, 2005, San Antonio, Texas.

PROBLEM AND RESEARCH OBJECTIVES

Microbial contamination of groundwater is a serious concern worldwide. For many countries, groundwater provides approximately 40% of the potable water used for human consumption. Cyst-forming protozoans such as *Giardia intestinales* and *Cryptosporidium parvum*, viruses such as Hepatitis A, and even pathogenic bacteria such as certain *E. coli* strains can survive for extended periods of time in ground water systems with temperatures of less than 10°C, migrate significant distances, and are relatively resistant to standard municipal water system chlorination practices. Though dormant outside the host, as few as ten cysts can result in a human infection (Casemore et al., 1997).

Pathogenic bacteria, viruses, and protozoans tend to be negatively charged in the pH range of most ground waters. Thus, naturally occurring and modified materials such as surfactant-modified zeolites (SMZ), which have net positive surface charges and hydrophobic properties, are suitable as barriers to impede pathogen migration in aquifer systems (Fig. 1). In our experiments SMZ has been used to remove E. coli and the bacteriophage MS-2 from sewage water with a high success rate (E. coli 100%, MS-2 > 90%) (Schulze-Makuch et al., 2002; Schulze-Makuch et al., 2003). Testing was conducted both in the laboratory and the field to test the removal efficiency of SMZ for *Giardia intestinales* and its analogs.

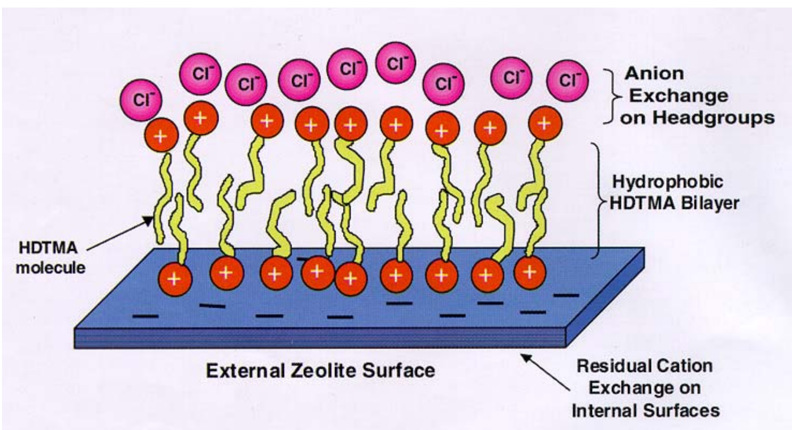


Figure 1: Schematic of the surface of the SMZ from Schulze-Makuch et al. (2002)

The overall goal of this project was to develop and test a zeolite-based filter material for removing *Giardia* and other pathogenic organisms from contaminated drinking water. To achieve this goal we focused on the following specific objectives:

Objective 1: Test three different SMZ formulations, Raw, Cationic, and Hydrophobic SMZ were used in a model aquifer to determine their abilities to remove *Giardia intestinales* and microsphere analogs from water. The outcome of this objective produced quantitative measurements of their removal efficiencies. The coarse-grained Cationic SMZ (1.4-2.4 mm) formulation was further tested at our field site using water amended with microspheres to simulated *Giardia* cyst behavior.

Objective 2: Test the coarse-grained Cationic SMZ (1.4-2.4 mm) formulation, the most promising SMZ formulation (at time of scheduled field test) in the field using water amended with microspheres that simulate *Giardia intestinales.* The outcome of this objective helped the development of a prototype filter system and validation of the laboratory results for removing *G. intestinales* from drinking water.

METHODOLOGY

Three different SMZ formulations were prepared using zeolite from the St. Cloud mine in Winston, NM (Bowman et al., 2001) (Table 1). Five different experimental runs were conducted under varied conditions with microspheres (Polystyrene, 6-7.9 µm) and viable *Giardia* cysts (7-10 µm) for fine cationic SMZ (0.4-1.4 mm, #1440), coarse cationic SMZ (1.4-2.4 mm, #814), hydrophobic SMZ, and raw zeolite, and sand only, and a 10-cm wide barrier of SMZ to test the removal efficiency of SMZ for *Giardia intestinales* using the *Giardia* cysts and microsphere analogs. The Plexiglass model aquifer (dimensions of 2.2 cm wide x 53 cm long) was filled with coarse silica sand (0.210-1.19 mm, 99.4 % silicon dioxide) to mimic realistic natural field conditions (Fig. 2). $CaCl_2$ water, typical of Western US water chemistries, was used flush the system and to be used as a baseline, and then bromide, microspheres (analog for *Giardia*) and *Giardia intestinales* cysts were used. In all laboratory experiments, the hydraulic gradient was set at 0.07 by controlling the hydraulic head in the inlet and outlet reservoirs. The arrival of the tracer down gradient of the SMZ barrier was compared to the arrival in the absence of the barrier to evaluate the effectiveness of each SMZ formulation.

For the fine cationic SMZ, 5 mL of a 0.1-M potassium chloride solution was injected into the model aquifer and 1-mL samples were taken periodically from Wells 1 & 2. The electrical conductivity of these samples was measured in order to set up appropriate sampling times for the subsequent runs with microspheres and *Giardia*. For all tested filter material, microspheres (1.0% w/v) and *Giardia* cysts ($5*10^6$ cysts) were injected during two separate runs into the model aquifer and 1-mL samples were taken from Wells 1 & 2. The samples were then analyzed using standard iodine stained cell counting methods with a bright line hemacytometer and a light microscope. Triplicate counts were done on each sample for both the microspheres and the *Giardia* cysts.

The coarse-grained Cationic SMZ (1.4-2.4 mm) formulation was further tested at our field site using water amended with microspheres to simulated *Giardia* cyst behavior. The field site is an existing multiple well site at the University of Idaho in Moscow (Fig. 3). The wells are completed in the Lolo Basalt Formation; a highly heterogeneous and anisotropic fractured basalt aquifer system typical of the subsurface of most of eastern Washington and northeastern Oregon. The injection well (T16D) and pumping / sampling well (V16D) are separated by 7.6 meters (25 feet), are connected by a known E fracture zone at 21.3 meters below ground (70 feet) (Fig. 3).

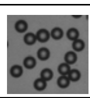
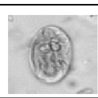
 	**Hydrophobic**	**Fine Cationic**	**Coarse Cationic**	**Raw Zeolite**	**Sand Only (no barrier)**	**Lehner, 2004 Hydrophobic**
8 um Microspheres (Fluorescent Polystyrene)	**99.8 %**	98.2 %	86.9 %	96.9 %	*N/A*	5 µm Microspheres 99.2 %
8 um Giardia Cysts (non-viable)	**100.0 %**	67.1 %	76.2 %	37.5 %	66.7 %	10 µm Microspheres 67.2 %

Table 1: Removal rates of SMZ formulations during the laboratory experiments

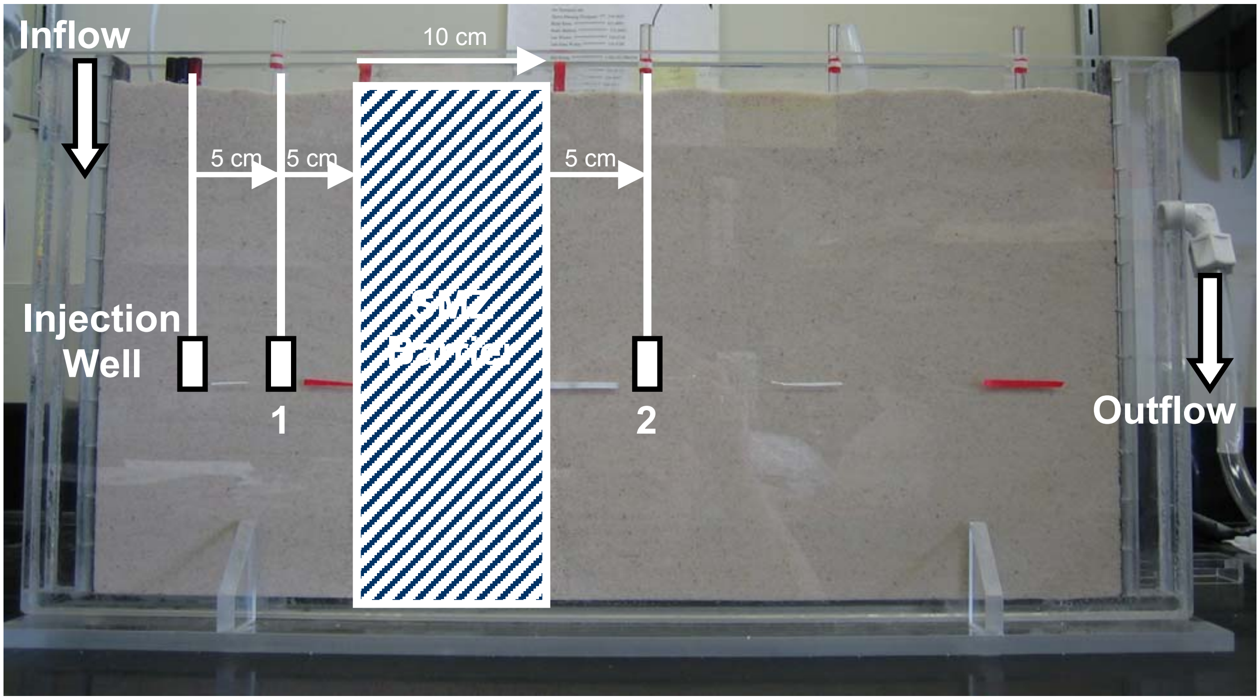


Figure 2: Model aquifer set-up with a 0.07 gradient

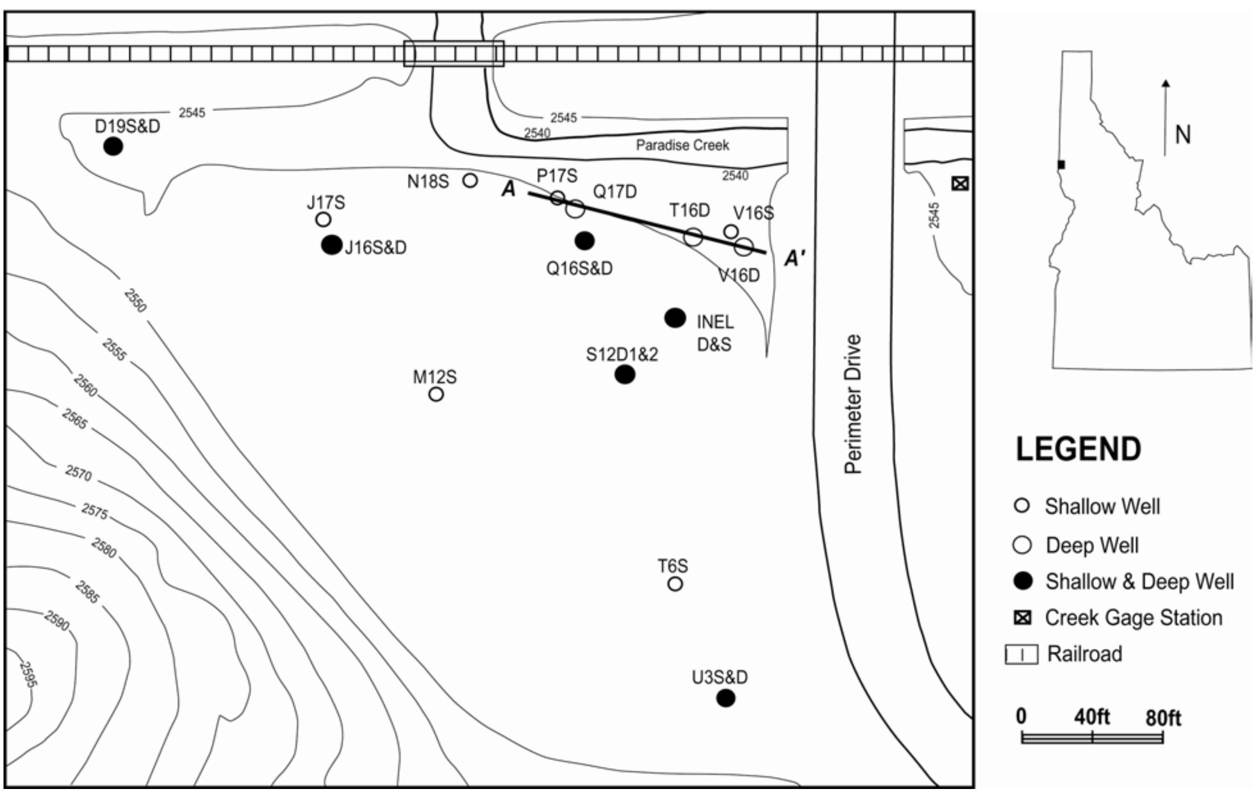


Figure 3: Well Locations at UIGRS (modified from Pardo Figure 1.1)

The SMZ pathogen field filter (Fig. 4) was installed directly in the well bore and the concentrations of microsphere-amended ground water were measured before and after filtration. The pumping well (V16D) was pumped at a constant rate of 0.92 L/sec (13 gpm) to force a gradient through the E Fracture Zone from T16D to V16D. Three slugs were injected an hour after each other at time zero (10 µm Yellow/Green Fluorescent microspheres plus Bromide), one hour after (6-7.9 µm Nile Red Fluorescent microspheres), and two hours after (1 µm Red Fluorescent microspheres). Pumping over an extended period was continued for 13 hours in order to test the lifetime of our prototype filter system. Our tests and results were targeted at developing a prototype filter system for removing a multitude of human pathogens in drinking water.

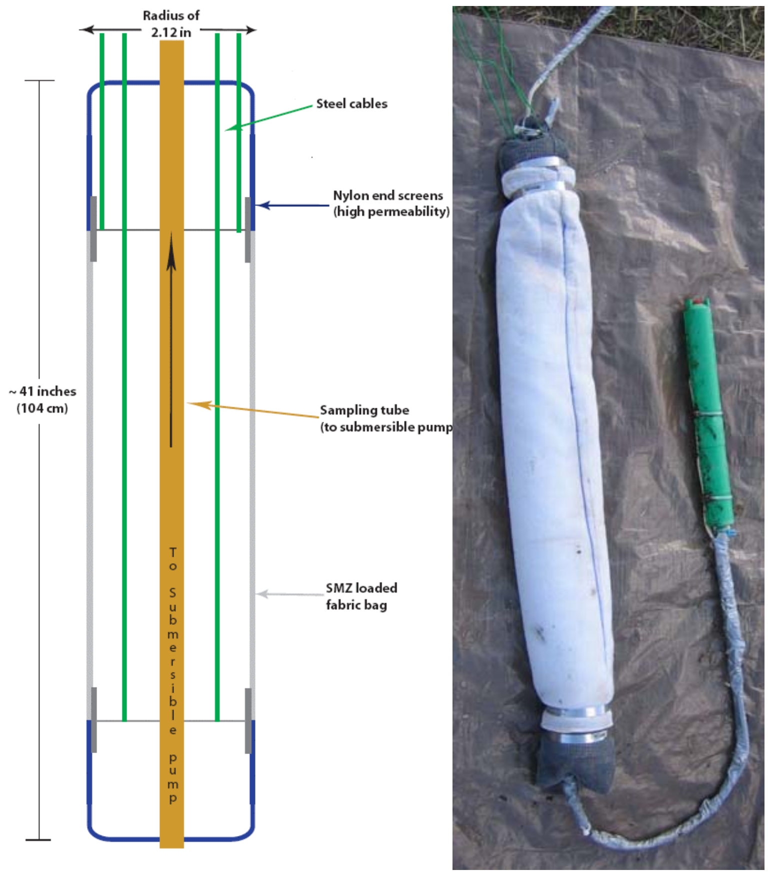


Figure 4: SMZ pathogen filter filled with Coarse Cationic SMZ, with a green electrical submersible sample pump

Figure 5: Microsphere concentrations with Coarse Cationic SMZ (1.4-2.4 mm, #814)

Counting of the field samples is not complete. Every sample taken in the field was filtered on a 0.4 µm black filter, placed on a glass slide, and counted on a Fluorescent microscope at 100 x with oil.

In addition to microsphere slugs, we investigated the presence of in situ *E. coli* and Total Coliforms in the shallow aquifer. The well site is located in close proximity (Fig. 3) to Paradise Creek which drains the local watershed. Previous physical hydrology studies have suggested (Li, 1991) that Paradise Creek feeds all the UIGRS wells. If this proved to be true we would have a continuous source of natural organic contaminates that could be tested with our SMZ filter. Samples were taken in Paradise Creek, before and after the filter to be incubated and quantified for *E. coli* and Total Coliforms (Fig. 6). After a 24 hour incubation period, no *E. coli* was found before or after the SMZ filter within the aquifer, but it was found in the Paradise Creek samples. Up to > 2000 cells per 100 mL *E. coli* were found in the creek samples. This high concentration may be due to a rain runoff event that occurred during the field test. Total Coliforms were found in Paradise Creek, before and after the filter. Roughly 50% removal rate was shown by the Coarse Cationic SMZ used in the prototype filter.

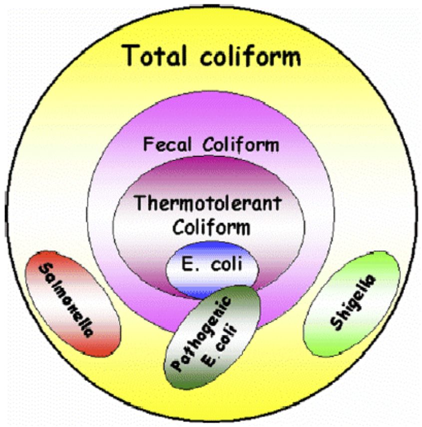


Figure 6: Diagram of the relationship of Total Coliforms and *E. coli* (fecal form).

PRINCIPAL FINDINGS AND SIGNIFICANCE

All formulations of SMZ were effective at removing *Giardia intestinales* cysts from the groundwater, but removal rates were not as high as for bacteria and viruses in the earlier experiments (Schulze-Makuch et al., 2002; Schulze-Makuch et al., 2003). The removal efficiency varied with the particular formulation of the SMZ used (Table 1). The SMZ filtration material with the highest removal rate, shown by our model aquifer runs, was the Hydrophobic SMZ. The field testing using coarse Cationic SMZ was not as effective as shown in earlier laboratory tests.

REFERENCES

Bowman, R.S., Li, Z., Roy, S.J., Burt, T., Johnson, T.L., and Johnson, R.L. (2001) Pilot test of a surfactant-modified zeolite permeable barrier for groundwater remediation. In Physical and chemical remediation of contaminated aquifers; Smith, J.A., and Burns, S., Eds.; Kluwer Academic/Plenum Publishers: New York, pp 161.

Casemore, D.P., S.E. Wright, and Coop, R.L. (1997) p. 65-92, In R. Fayer, ed. Cryptosporidium and Cryptosporidiosis. CRC Press, Boca Raton, FL.

Lehner, T., Schulze-Makuch, D., Langford, R., and Bowman, R.S., (2004) Removal of Pathogenic Parasites using Surfactant-Modified Zeolite Barriers in a Model Aquifer. Master's Thesis, University of Texas at El Paso.

Li, T. (1991). Hydrogeologic characterization of a multiple aquifer fractured basalt system. Moscow, University of Idaho. Ph. D. Dissertation: 1-307.

Pardo, B. G. (1993). Relation between groundwater and surface water at University of Idaho Groundwater Research Site. Moscow, University of Idaho. Master of Science with a Major in Hydrology: 1-127.

Schulze-Makuch, D., Pillai, S. D., Guan, H., Bowman, R.S., Couroux, E., Hielscher, F., Totten, J., Espinosa, I. Y., and Kretzschmar, T. (2002) EOS **83**, 193.

Schulze-Makuch, D., Bowman, R.S., Pillai, S.D., and Guan, H. (2003) Ground Water Monitoring and Remediation, **23**, 68.

Oxygenation for the Management of Sediment Mercury Release from Aquatic Sediments

Basic Information

Title:	Oxygenation for the Management of Sediment Mercury Release from Aquatic Sediments
Project Number:	2005WA119B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Washington, fifth
Research Category:	Water Quality
Focus Category:	Water Quality, Surface Water, Sediments
Descriptors:	Lakes, Hypolimnetic Anoxia, Sediment, Mercury Cycling, Methylmercury
Principal Investigators:	Marc Beutel, Barry Moore

Publication

1. Leonard, Theo M. and Marc W. Beutel. 2006. Control of mercury release from profundal lake sediments using oxygenation. "in" Abstracts, Efficient Sustainability in a Dry Land, Sixth Annual Meeting of the American Ecological Engineering Society, Berkeley, California, April 13-14, 2006, p. 50. http://aeesociety.org/annual_meeting/2006/AEES_Abstract_Booklet_Final.pdf
2. Beutel, Marc and Barry C. Moore. 2006. Oxygenation for the Management of Sediment Mercury Release from Aquatic Sediments. State of Washington Water Research Center, Washington State University, Pullman, Washington. State of Washington Water Research Center Report WRR-27. 14 pages.

PROBLEM AND RESEARCH OBJECTIVES

Mercury bioaccumulation in aquatic food chains is of growing concern due to health effect in upper-trophic-level biota (e.g., humans, birds, fish). Bioaccumulation in the food chain is the result of microbial conversion of ionic mercury (Hg^{2+}) to methylmercury (CH_3Hg^+), which then accumulates in the mussel tissue of biota. For example, greater than 95% of the mercury found in fish is methylmercury. Thus, methylmercury production in aquatic systems is ultimately the cause of many mercury-related fish consumption advisories in the United States. The conversion of ionic mercury to methylmercury occurs in anoxic sediments in lakes and is facilitated by sulfate-reducing bacteria.

The objective of this research was to investigate how aerobic versus anaerobic conditions affect concentrations of mercury in water overlaying lake sediments. We hypothesize that the production and release of methylmercury at the sediment-water interface is partly regulated by the degree of oxygen penetration into surface sediments. Elevated dissolved oxygen levels should inhibit the production and subsequent release of methylmercury by: (1) decreasing the activity of sulfate-reducing bacteria at the sediment-water interface, and (2) promoting the oxidative de-methylation of methylmercury fluxing upwards from deeper sediments by heterotrophic bacteria. The intent of the research was to determine if lake oxygenation, a common lake management technique to improve water quality, could also be used to manage and control the release of methylmercury from anoxic sediments, thereby lowering mercury bioaccumulation in aquatic biota.

Although methylmercury was the target species of mercury for the experiments, budget constraints and technical limitations were such that we focused on total mercury. In addition, while we initially anticipated sending mercury samples outside of WSU for analysis, we instead developed and implemented in-house capabilities to measure mercury. Follow-up experiments will be conducted in the summer of 2006 that will include the evaluation of a number of mercury species in sediment-water interface samples collected from three sites (Deer, American, and Newman Lakes) of varying trophic status and management history.

METHODS

Study Site. The preliminary study site was Deer Lake, located north of Spokane. Based on a recent mercury study by the Washington State Department of Ecology (DOE), the lake has fairly low levels of mercury in sediments but high levels in fish. The maximum depth of Deer Lake is 75 feet while the mean depth is 52 feet. The lake encompasses 1,100 acres and has a volume of 57,000 acre-ft. Its drainage area is approximately 18 square miles. Various reports have labeled the lake as meso-oligotrophic due to its low occurrence of algal blooms and high clarity. The lake thermally stratifies during the summer and exhibits hypoxia (dissolved oxygen < 2 mg/l) in bottom waters in the late fall.

Sediment Collection. Sediment was initially collected with a 15 cm by 15 cm Eckman dredge. Sediment was soft enough to plug the jaws of the dredge, resulting in the collection of a minimally disturbed sediment surface with overlaying water. The dredge was brought to the surface, and a sediment-water interface sample was sub-sampled into a cylindrical Plexiglas chamber 1.8 liters in volume. The sub-sample was collected by slowly pushing the chamber top into the sediment and overlaying water captured in the dredge. A cap and gasket were then mated with the bottom of the chamber by hand while the chamber was still in the sediment. The capped chamber was pulled out of the dredge and bolted onto a round Plexiglas base. Sediment-water interface samples consisted of a sediment core 4-8 cm thick with a surface area of 71 cm^2, and 100-300 ml of overlaying water. A total of four chamber samples were collected. After collection of the sediment-water interface sample, chambers were gently filled with bottom water and transported to the laboratory. We used "dirty hands/clean hands" techniques, conducted intensive pre-cleaning of apparatus used during the fieldwork, and took extra precautions to prevent metals contamination during fieldwork.

Incubations. Once in the laboratory, the four sediment cores were incubated in the dark at 10^{o}C under oxic conditions (23 days), followed by anoxic conditions (27 days), followed by reaerated conditions (14 days). A control chamber was also incubated that included only de-ionized water. Oxic conditions in chamber water were maintained by bubbling with air and anoxic conditions were maintained by bubbling with nitrogen. Water overlaying the sediment was monitored every few days for a suite of compounds including DO, redox, pH, total mercury, iron, and manganese. DO, redox and pH in chamber water was measured with standard probes and meters inserted into an access port. Water samples for metals analyses were drawn from chambers with sterile syringes using pre-cleaned Teflon tubing and discharged into fluoropolymer bottles. After extraction of water samples, chambers were topped up with mercury-free reagent water to maintain a constant volume in each chamber of 1 L.

Mercury samples were preserved with bromine monochloride (BrCl), which oxidizes all forms of mercury to stable dissolved ionic mercury (Hg^{2+}). Total mercury was measured in-house via cold-vapor atomic fluorescence spectrometry (CVAFS) on a Tekran mercury autoanalyzer. In this method stannous chloride ($SnCl_2$) is added to reduce preserved Hg^{2+} to volatile elemental mercury (Hg^0). The Hg^0 is sparged with nitrogen gas onto a gold trap, and then thermally desorbed into an atomic fluorescence spectrometer. Samples for iron and manganese analysis were preserved with nitric acid. Iron and manganese were measured via inductively coupled plasma mass spectrometry (ICP-MS) in the WSU Chemistry Department.

PRINCIPAL FINDINGS AND SIGNIFICANCE

A key outcome of this project was the development of in-house capabilities to analyze total mercury in aqueous samples. We purchased and operated a Tekran mercury auto-analyzer using CVAFS methodology. After much effort and persistence in the lab, we are able to consistently measure total mercury at the part per trillion (ppt) or nanogram per liter (ng/L) level. Our detection limit was around 0.3 ng/L. This summer we will be expanding our analytical capabilities to include methylmercury.

Mercury. Due to apparent contamination issues, the results of our preliminary incubation were inconclusive. When accounting for dilution as a result of sample removal and make-up water addition, chambers (including the control chamber) tended to accumulate mercury at a slow but steady rate during the initial aerated phase. A few days into the anoxic phase chambers showed a dramatic spike in mercury with concentrations rising from around 20 ng/L to around 200 ng/L. Since this spike was also observed in the control chamber with no sediment, is was the result of contamination. During the reaeration phase, mercury decreased rapidly in treatment chambers, dropping by around 100 ng/L. In contrast, mercury levels were steady in the control chamber.

The rapidity of mercury loss after reaeration suggests that the overriding mechanism was physical/chemical versus biological. It is possible that mercury was co-precipitated out of the water column with iron and manganese oxides formed under reaerated conditions. As discussed below, under anoxic conditions sediments released reduced, dissolved iron and manganese into overlaying water. These metals decreased once oxygenated conditions were reestablished. This phenomena merits further research. Co-precipitation may be an important temporal component of the mercury mass balance in productive, stratified lakes.

These preliminary findings also suggest that treatment of lakes with alum (aluminum sulfate) or other metal salts (e.g., ferric chloride), which typically are used to impede phosphate release from anoxic lake sediments, could also be effective at controlling mercury. In fact, one of our future study sites, Newman Lake, has been treated with alum and oxygenated since the early 1990s. Results from the DOE mercury study show that older fish (8 years old) in Newman Lake have more mercury, normalized by length (ug/kg/meter), than younger fish (2 years old). This contradicts typically observations in aquatic systems that show younger fish bioaccumulate mercury more rapidly than older fish. Thus, recent active management of the lake may be reducing the level of mercury bioaccumulation in younger lake biota.

Iron and Manganese. During the first aerated phase, iron and manganese levels tended to decline in water overlaying sediments. The reestablishment of oxygenated conditions likely resulted in the oxidation and subsequent precipitation of the metals as iron and manganese oxides. During the subsequent anoxic phase, iron and manganese steadily increased to greater than 3 mg/L for both metals. Accumulation rates were on the order of 8 $mg/m^2/d$ for iron and 30 $mg/m^2/d$ for manganese. Metals accumulation was the result of the biological reduction of metal oxides in surface sediments by anaerobic microorganisms that utilize iron and manganese as terminal electron acceptors for anaerobic respiration. In some sediments under some conditions, hydrogen sulfide can also chemically reduce metal oxides. During the final reaeration phase iron and especially manganese concentrations decreased. As discussed above, this decrease in metals co-occurred with a rapid drop in mercury in chamber water.

Future Incubations. Three sets of subsequent incubations are planned for summer 2006 from Deer Lake and two additional Washington Lakes. The new sites include Newman Lake, a lake with a history of oxygenation and alum treatment. Intriguingly, as noted above the lake has relatively low levels of mercury in younger fish. The other new site is American Lake. The lake is very similar to Deer Lake in size and depth, but is more eutrophic. Based on lessons learned from the preliminary incubations reported herein, method modifications to minimize contamination will include:

(1) Glass rather than Plexiglas chambers will be used. The use of glass will minimize the loss of mercury via sorption to chamber surfaces.

(2) Make-up water will not be added to chamber incubations. Chambers will be initially filled with a maximum possible amount of overlaying water and sample volumes will be kept to a minimum.

(3) Replicate chambers will be incubated in parallel (three chambers under oxic conditions and three chambers under anoxic conditions) rather than in aerated/anoxic phases. This will compress the duration of the incubations and minimize the volume of sample water removed from each chamber over the course of the incubation.

(4) Gas will not be introduced to chambers. Instead oxic chambers will simply be kept open to the atmosphere while anoxic chambers will be closed airtight.

(5) Probes will not be inserted into chambers. Instead any probe measurements will be made on samples first extracted from the chambers.

Collaborative Research:Hydraulic and Geomorphic Controls on the Evolution of Cluster Bedforms in Gravel-Bed Streams

Basic Information

Title:	Collaborative Research:Hydraulic and Geomorphic Controls on the Evolution of Cluster Bedforms in Gravel-Bed Streams
Project Number:	2002WA12G
Start Date:	8/1/2002
End Date:	7/31/2005
Funding Source:	104G
Congressional District:	Washington FIfth
Research Category:	Engineering
Focus Category:	Sediments, Hydrology, Geomorphological Processes
Descriptors:	Restoration, Bedforms Migration, Stage-Discharge Relations
Principal Investigators:	Thanos N Papanicolaou, Lisa Louise Ely

Publication

1. Hendrick, Ross R., Lisa L. Ely, A. N. Papanicolaou, and Kyle B. Strom, 2004, The role of geomorphic and hydrologic feature on sediment clusters in gravel-bed streams, Washington: A field-based approach, "in" Abstracts with Programs, Geological Society of America Rocky Mountain/Cordilleran Section Meeting, Boise, Idaho, May 3-5, 2005, 36(4):31.
2. Hendrick, Ross R., Ely, Lisa L., Marcell, Janielle L., Papanicolaou, Athanasios N., and Strom, Kyle B., 2005, Tracking the Evolution of Sediment Clusters after High Flow Events, and their Effects on Sediment Transport: Entiat River, Washington: A Field-Based Approach, "in" Abstracts with Programs, Geological Society of America, 37(4):103.
3. Marcell, Janielle L., Ely, Lisa L. and Hendrick, Ross R., 2005, Evolution of Sediment Cluster Morphologies on the American River, Cascade Mountains, Washington, "in" Abstracts with Programs, Geological Society of America, 37(4):45.
4. Marcell, Janielle, 2004, Patterns of Sediment transport in the American River, Cascade Mountains, Washington (poster presentation) "in" Thirteenth Regional Conference on Undergraduate Research, Murdock College Science Research Program, Lewis and Clark College, November 19-20, 2004.
5. Strom, Kyle B., Athanasios N. Papanicolaou, B. Billing, Lisa L. Ely, and Ross R. Hendricks, 2005, Characterization of Particle Cluster Bedforms in Mountain Streams, in Proceedings of the conference EWRI 2005: Impacts of Global Climate Change (Anchorage, Alaska, May 15-19, 2005), by

Raymond Walton, P.E., editor, Reston Virginia.

6. Kramer, Casey, 2005, The Role of Relative Submergence on Cluster Microtopography and Bedload Predictions in Mountain Streams, M.S. Thesis, Civil and Environmental Engineering, The University of Iowa, Ames, Iowa, 99 pages.
7. Hendrick, Ross H., 2005, The Role of Geomorphic Features and Hydrologic Processes on Sediment Clusters in Gravel-Bed Rivers, Washington: A Field-Based Approach: M.S. Thesis, Geological Sciences, Central Washington University, Ellensburg, Washington.
8. Hendrick, Ross R., Lisa L. Ely, and A. N. Papanicolaou. 2004. The role of geomorphic and hydrologic features on sediment clusters in gravel-bed streams, Washington: A field-based approach, "in" Pacific Northwest Ecosystems Then and Now, Proceedings of the 2004 Meeting of the North Pacific International Chapter of the American Fisheries Society, Stevenson, Washington, November 1-3, 2004, p. 3.
9. Papanicolaou, A. N. and Casey Kramer. 2005. The Role of Relative Submergence On Cluster Microtopography and Bedload Predictions in Mountain Streams, "in" Proceedings of the Fourth International Association of Hydraulic Research Symposium on River Coastal, and Estuarine Morphodynamics, RCEM 2005, Gary Parker and Marcelo Garcia, editors, Taylor and Francis Group, London, England, p.1083.
10. Kramer, Casey and A. N. Papanicolaou. 2006. The Effects of Relative Submergence on Flow Patterns around Large Particles in a Gravel Bed River, presented at the World Water and Environmental Resources Congress EWRI 2006, May 21-25, Omaha, Nebraska.
11. Strom, Kyle and A. N. Papanicolaou. 2005. Particle clusters in gravel bed rivers. Presented at the International Conference on Civil and Environmental Engineering, Higashi, Hiroshima, Japan, October 2005.
12. Marcell, Janielle and Ross R. Hendrick. 2005. Evolution of sediment cluster morphologies on the American River, Cascade Mountains, Washington. Presented at CWU Symposium on University Research and Creative Expression (SOURCE), May 19, 2005, p. 72.
13. Hendrick, Ross R., Lisa L. Ely, Janielle Marcell, A. N. Papanicolaou, and Kyle Strom. 2005. Tracking the evolution of sediment clusters after high flow events, and their effects on sediment transport, Entiat River Washington: A field based approach. Presented at CWU Symposium on University Research and Creative Expression (SOURCE), May 19, 2005, p. 52.

PROBLEM AND RESEARCH OBJECTIVES

1. Develop a stage-discharge relation to determine the required flow conditions for cluster development and disintegration in the field at the American and Entiat River sites.
2. Analyze the flux of individual sediment particles through cluster bedforms.
3. Evaluate the role of relative submergence on the formation and evolution of cluster microforms in gravel bed streams and its implications to bedload transport.

METHODOLOGY

Stage data for the American River site was collected and logged for high flows in 2003 and 2004 with the Global Water Instruments water-level recorder, which was installed at the site in Spring, 2003. The discharge at the Entiat River was determined directly from the USGS gage. Channel cross sections were surveyed on both rivers, and velocities at the American and Entiat River sites were calculated using the HEC-RAS water-surface profile model.

Clusters were marked, photographed and surveyed before and after each major high-flow event. Sediment movement within individual clusters was analyzed from photographs.

In the laboratory, an enhancement of the methodology was attempted in order to account for the role of relative submergence on cluster microtopography, a very important feature in gravel-bed rivers that few to none have researched in a systematic way. More specifically, the methodology and experimental design of this research was based on the premise that in natural gravel bed streams, where the height of clast-obstacles is generally of the same order of magnitude with the flow depth, the processes between the interaction of the flow and clasts plays a dominant role in eddy taxonomy and flow prevailing mechanisms.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Entiat River Study Site. On the Entiat River, the evolution of cluster beforms and movement of individual sediment particles within clusters were monitored for 4 peak flows that inundated the study site. The peak flows were Oct., 2003, 57 m^3s^{-1}; Nov. 2003, 13 m^3s^{-1}; May 2004, 39 m^3s^{-1}, and Jan. 2005, 22 m^3s^{-1}. Sediment cluster bedforms had a measurable impact on sediment entrainment during the two intermediate flow events of 22 and 39 m^3s^{-1} that inundated the gravel bar at the study site. Under these flows, the critical shear stress required to entrain sediment particles was 38-51% greater for sediment within clusters than for isolated sediment particles on the gravel bar. All clusters were mobilized during the highest peak in the 2-year record, 57 m^3s^{-1}, which occurred in October, 2003. Therefore the clusters did not significantly impact the overall sediment transport during this event, as the entire bed was mobilized at the study site. No measurable sediment movement occurred within the clusters during the lowest inundation event of 13 m^3s^{-1}. The mean annual peak flow on the Entiat River is ~80 m^3s^{-1}, which means that on average, sediment clusters on this river are are likely at least partially mobilized and reformed on a semi-annual basis. At site 1 on the Entiat River, which had a fairly well-sorted sediment size distribution, the diamond cluster form was the most stable over the 2-year period. At site 2, with a greater range of sediment sizes and larger anchor clasts, all cluster forms were equally stable.

American River Study Site. Six types of clusters were observed at the study site on the American River. The six types include upstream triangle, downstream triangle, diamond, ring, line and transverse line. Our focus was the evolution of the cluster morphologies during periods of moderate peak flows. It was our hypothesis that this evolution would only occur during moderate flow conditions because during high flow periods the clusters would be completely reorganized. On the American River the 2003 peak flow was 31.5 m3/sec and the 2004 peak flow was 24 m3/sec, which are moderate-sized annual peaks compared to the historic record. Our hypotheses were that 1) transverse line clusters are incipient forms that would ultimately transform into upstream or downstream triangles; 2) upstream and downstream triangle clusters are intermediate cluster forms which ultimately form diamond clusters; and 3) diamond clusters are the final cluster form and are therefore the most stable. The results were that no flows during the 2-year period were sufficient to mobilize the sediment clusters, and all cluster forms were therefore stable throughout the study period. In contrast, individual sediment particles were added, moved and removed from the clusters. The diamond clusters experienced the greatest amount of individual sediment movement through the stable cluster bedforms and the transverse lines the least.

Additional analyses include: 1) examination of critical shear stresses involved in sediment entrainment, 2) determination of cluster density at different sites, 3) incorporation of sediment and flow data into the 3STID flow model at the University of Iowa to refine the bed-velocity calculations at the cluster sites and 4) analysis of the geomorphic settings of gravel clusters.

The field study areas on both rivers have experienced below-average peak flows during the 2-year study period. This period of low to moderate flows was advantageous because we were able to investigate the flux of sediment through the stable cluster forms without the complete destruction and reorganization of the clusters. Understanding the sediment movement through the clusters helps determine the sediment flux and transport patterns throughout the stream. The response of the channel bed morphology to flows in unregulated rivers such as the Entiat and American Rivers, has practical implications for river management, channel restoration and maintenance of aquatic habitat in regulated streams by guiding the determination of peak discharges necessary to maintain or mobilize cluster bedforms.

Laboratory component. The laboratory nature of this investigation allowed for the first time the isolation of the relative submergence on cluster formation. This was accomplished through a carefully planned experimental design and facilitated detailed sediment, geomorphological, and flow observations/measurements under well controlled conditions. These observations/ measurements were made for different flow and sediment feeding rates and for different fractions of sediment sizes. The observations and measurements extended to conditions corresponding to the rising limb of a hydrograph. State of the art equipment and laboratory techniques were utilized in order to meet the research needs of this work. Overall, 16 experimental runs were conducted to obtain unique quantitative sediment observations with the addition of 3 experimental runs performed, to quantitatively describe the flow patterns around the clasts.

The results of this study focused on the qualitative evaluation of the bed microtopography for the high and low relative submergence, a quantitative description of the bedload transport rates and their statistical properties, a detailed analysis of the flow characteristics around a clast, and the coupling of flow with bed microtopography observations around a clast for a selected number of experimental runs.

For the low relative submergence, the presence of the fixed clasts indirectly affected the depositional patterns of the incoming sediment by creating troughs within the clast section, which are the areas where the deposition of the incoming sediments predominately occurred.

For the high and low relative submergence experiments clasts/clusters worked as a sink for the incoming sediment, thus affecting the magnitude of the exiting bedload rate and causing perturbations to sediment motion. The cycle of cluster formation and breakup by the flow was observed for all runs. A similar observation regarding cluster breakup has been documented by Strom et al. (2005). Strom et al. (2005) found that clusters worked as a sink and source of sediment.

REFERENCES

Strom, Kyle B., Athanasios N. Papanicolaou, B. Billing, Lisa L. Ely, and Ross R. Hendricks, 2005, Characterization of Particle Cluster Bedforms in Mountain Streams, "in" Proceedings of the conference EWRI 2005: Impacts of Global Climate Change (Anchorage, Alaska, May 15-19, 2005), by Raymond Walton, P.E., editor, Reston Virginia.

Using environmental tracers to improve prediction of nonpoint pollutant loadings from fields to streams at multiple watershed scales

Basic Information

Title:	Using environmental tracers to improve prediction of nonpoint pollutant loadings from fields to streams at multiple watershed scales
Project Number:	2002WA19G
Start Date:	8/1/2002
End Date:	5/31/2006
Funding Source:	104G
Congressional District:	Washington FIfth
Research Category:	Ground-water Flow and Transport
Focus Category:	Non Point Pollution, Nitrate Contamination, Hydrology
Descriptors:	Catchment Hydrology, Environmental Tracers
Principal Investigators:	C Kent Keller, Richelle Allen-King, Shulin Chen

Publication

1. Allen-King, R., 2003, Ground and Surface Water Contributions to Chemical Mass Discharge: Field to Basin Scales, Keynote Address, "in" Abstracts, 4th Symposium on the Hydrogeology of Washington State, April 8-10 2003, Tacoma, Washington, p. 1. http://www.ecy.wa.gov/events/hg/PastSymposia/abstracts2003.pdf
2. Keller, C.Kent, 2003, Using environmental tracers to understand agrichemical transport pathways to Palouse surface water, Invited Presentation to WSU Water Quality Research and Extension Colloquium, April 24, 2003, Washington State University, Pullman, WA.
3. Simmons, Amy N., 2003, Dissolved Pesticide Mass Discharge in a Semi-arid Dryland Agricultural Watershed at the Field and Basin Scale, M.S. Dissertation, Department of Geology, Washington State University, Pullman, Washington, 165 pp.
4. Simmons, A.N., Lauren L. Bissey, Richelle M. Allen-King, C.Kent Keller, and Jeffrey L. Smith, 2003, Estimated dissolved agricultural mass discharges using environmental tracers in a semi-arid dryland agricultural watershed (Abstract), "in" Abstracts with Programs, Geological Society of America Annual Meeting, November 2-5, 2003, Seattle, Washington, Abstracts with Programs 34(7), Paper No. 130-12, p. 316.

5. Simmons, Amy N., Richelle M. Allen-King, C. Kent Keller, and Jeffrey L. Smith, 2003, Dissolved pesticide mass discharge in a semi-arid dryland agricultural watershed at the field and basin scale. Proceedings of the Fourth Symposium on the Hydrogeology of Washington State, April 8-10, 2003, Tacoma, Washington, p. 78. http://www.ecy.wa.gov/events/hg/abstracts_talks.htm
6. Suzuki, Kosuke, C. Kent Keller, and J. Vervoort, 2004. Weathering in and calcium losses from semi-arid agricultural landscapes: Insight from strontium isotope ratios, in EOS Transactions, American Geophysical Union 85(47), F873.
7. Wannamaker, Caroline N., Angela J. Goodwin, C. Kent Keller, Richelle Allen-King, and Jeffrey L. Smith, 2004. Edge of field nitrate loss and oxygen-18 dynamics in a dryland agriculture setting, in EOS Transactions, American Geophysical Union 85(47), F912.
8. Suzuki, Kosuke. 2005. Calcium losses from a semi-arid agricultural field: Insight from strontium isotopes, M.S. thesis, Department of Geology, Washington State University, Pullman, Washington, 62 pp.
9. Wannamaker, Caroline. 2005. Edge of field nitrate occurrence and loss in a semi-arid dryland agriculture setting, M.S. thesis, Department of Geology, Washington State University, Pullman, Washington, 174 pp.
10. Goodwin, Angela J. 2006. Oxygen-18 in surface and soil waters in a dryland agricultural setting, eastern Washington: Flow processes and mean residence times at various watershed scales. M.S. Thesis, Department of Geology, Washington State University, Pullman, Washington, 132 pp.
11. Wannamaker, Caroline N., C. Kent Keller, Richelle M. Allen-King, and Jeffrey L. Smith. 2005. Edge of field nitrate loss in a dryland agricultural setting, "in" Abstracts, 5th Washington Hydrogeology Symposium, 12-14 April 2005, Tacoma, Washington, p. 92. http://www.ecy.wa.gov/events/hg/PastSymposia/abstracts2005.pdf
12. Keller, C.Kent. 2005. Hydrology of nitrate in Missouri Flat Creek Watershed, invited presentation to Washington State University Conference of Extension Personnel, Washington State University, Pullman, Washington, 2005.
13. Keller, C. Kent. 2005. Hydrology of nitrate in Missouri Flat Creek watershed, presentation to WSU Water Quality Research and Extension Colloquium, State of Washington Water Research Center and Cooperative Extension Water Quality Management Group, March 3, 2005.
14. Keller, C. Kent. 2005. Hydrologic elements of the N budget at Cunningham Farm, presented at WSU Field Day, Cunningham Agronomy Farm, 20 June 2005.
15. Keller, C. Kent. 2005. N Pollution: Palouse perspective, hydrogeologic view, presented at WSU Soil Science Research Seminar, 12 September 2005.
16. Keller, C. Kent. 2005. Nitrate in agricultural runoff on the Palouse, presented at FarWest Agribusiness Association Annual Palouse Agronomy Training, December 14 2005, Coeur dAlene, Idaho.

PROBLEM AND RESEARCH OBJECTIVES

Post-WWII fertilization practices have loaded terrestrial and coastal ocean waters with N to unprecedented extents. In the US, tens of thousands of river and shore reaches are considered impaired by the EPA, and many of these impairments are believed to be attributable to agricultural non-point sources. This means that it is important to understand how agricultural practices are related to streamwater N loading, in various climate/cropping associations.

This study considers how field-scale processes influence delivery of nitrogen (primarily as dissolved nitrate, NO_3) to streams. We have hypothesized that in our semiarid dryland farming region, stream NO_3 discharge, from field and small catchment to basin scales, is principally controlled by the response of field-scale flow and transport processes to drainage regime and strongly seasonal hydrology. We are testing this hypothesis by expanding our ongoing study of field-scale processes to include undrained settings, and developing a spatially- and temporally-detailed ^{18}O data set which can be used, in parallel with geochemical data sets, for simultaneous isotope and geochemical hydrograph separations at multiple watershed scales. The isotope data are needed to identify water sources ("new" vs "old"). Used in combination with pathway information from the geochemical tracers, they will help us understand how temporal evolution of soil NO_3 distributions is related to transport times to streams.

METHODOLOGY

Our two field locations are near Pullman, WA, within the Missouri Flat Creek watershed of the South Fork of the Palouse River. The Missouri Flat Creek drainage has a long record of study by USGS and WSU scientists. The fields are subject to typical farming practices and crop rotation, receiving N fertilizer during fall and spring planting, and they represent typical bottom-slope, streamflow-generating locations. The undrained field exhibits intermittent winter-spring surface runoff while the tile-drained field does not. These fields represent the principal settings we assume to control streamflow generation and NO_3 discharges.

The tile-drained location was instrumented in 2001 with suction lysimeters (operated at 0.5 bar) and zero-tension pan lysimeters. These samplers were installed horiontally in triplicate at 0.2, 0.5, and 1.0 m depths from a trench (to permit location of sampler intakes beneath undisturbed field soil). They allow us to sample subsurface-pathway events (pans) as well as resident porewater over a range of saturation conditions (suction). In addition, depth profiles of 5 thermistors and 5 TDR moisture probes were installed via the trench wall. Data from these instruments are logged continuously by the weather station (with precip gauge/sampler) located nearby. With this array, we monitor subsurface conditions above a tile drain which drains approximately 10 ha and outlets 10 m distant. The undrained location has soil-water samplers in parallel with the tile-drained location.

Pressure transducers and dataloggers have been deployed and rating curves developed that measure water discharge from nested 660–7000 ha watersheds.

Conventional analytical methods are used to determine our principal geochemical tracer, electrical conductivity (EC). Each EC result is adjusted to eliminate the effect of NO_3 on that result, so that EC may be taken as an index of weathering progress. Nitrate itself is determined colorimetrically. Oxygen-18 (O-18) is determined by Delta S dual-inlet MS with continuous-flow GasBench autosampler/equilibrator in the Geoanalytical Lab at Washington State Unversity. Its abundance is reported in conventional "δ" per mil notation relative to VSMOW. Strontium stable isotope ratios were determined on column-purified samples redissolved in nitric acid, by Finnigan Neptune MC-ICP-MS in the Geoanalytical Lab.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Again during this reporting period all datasets were extended. Much student and PI effort was devoted to interpretation and writing. Three theses were defended during the current reporting period. This project has now generated four MS theses.

Analysis of TDR, flow and NO_3 concentration data shows that at all gaging stations, NO_3 levels rise immediately upon soil profile wetup and streamflow initiation in the wet season. This implies the existence of a reservoir of dissolved NO_3 which is present both throughout soil profiles (to depths of tile drains) and pervasively across the MFC watershed. However the transport history of that nitrate, in particular the rate of its movement through and extent of its reaction with soil and biota, could not be estimated in that analysis. In other words, we could not answer the questions "How long has that nitrate been in the soil system? When was it applied as fertilizer?"

Most of this period's analysis was devoted to using O-18 data to constrain the mean residence times (MRT) of the waters which carry dissolved NO_3 through soils. These times then provide minimum NO_3 residence times and maximum NO_3 transport rates, assuming NO_3 moves conservatively with soil water. The operating principle, in this application of O-18 as environmental tracer, is to track seasonal variations of its abundance through the watershed of interest, examining how the timing of the variations changes between precipitation source and gauging-station outflow.

The global gauging-station dataset (Figure 1) shows definite O-18 "troughs" occurring during three of the five flow seasons analyzed. The 2002-2003 water year (no "trough" evident) was relatively warm such that volume-weighted precipitation O-18 levels were two per mil greater than during the following, relatively cold water year 2003-2004 when a deep "trough" developed. The magnitude of this trough (and of the others) is approximately that of the decrease in precipitation O-18, relative to the previous year. The implication is that a water-year's outflow carries carries the O-18 imprint of precipitation which falls that same water year, i.e. water MRT in the catchments of interest are on the order of months or less, rather than a year or more. We tested this idea using simple lumped-parameter convolution-integral simulations of catchment O-18 response to precipitation input. The best simulations were based on response functions with MRT set at 4-7 months, which is consistent with the qualitative interpretation.

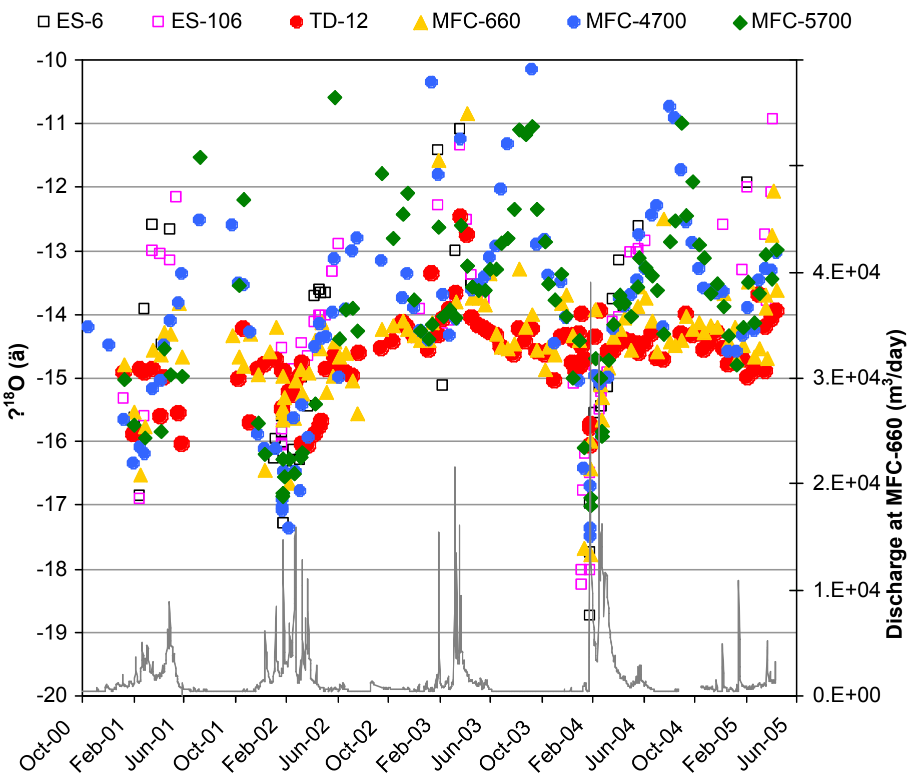


Figure 1. δ [18]O values for all gauging stations, plotted vs. discharge at one station. Numbers in legend refer to estimated catchment areas in hectares, e.g. the tile drain "TD-12" drains 12 ha. ES stations are within fields.

Especially at the largest gauging scales, upward excursions of O-18 values occurred during dry-season, low-flow periods (Figure 1). These values and the accompanying EC values for the same samples are higher than what we observe in any of our soil waters or groundwaters. We therefore attribute these dry-season dynamics to instream processes, probably dominated by evaporation.

Tile-drain runoff from the drained location (TD-12, Figure 2) exhibited steadier O-18 behavior than at any other gauging station, and was much steadier than runoff generated in an ephemeral rill from the nearby undrained location (ES-6, Figure 3). In the latter setting soil-water O-18 dynamics, as shown by the lysimeters, were more effectively propagated to runoff than in the tile-drained setting. This comparison shows that the O-18 dynamics at larger gauging scales (Figure 1) require a substantial component of runoff like that generated at ES-6, i.e. much of the runoff from our fields follows relatively shallow, short flow paths characteristic of our undrained location. This is consistent with findings of our earlier hydrograph-separation studies.

We now know with reasonable confidence that water movement through the study catchments could transport NO_3 , from point of fall field application to where we find it in stream runoff, in a single season. We do not yet know whether that is in fact the characteristic fate of most of the NO_3 in our systems, because the mass which is discharged to runoff may have undergone reactions – particularly biological uptake and re-release – in the subsurface. We plan

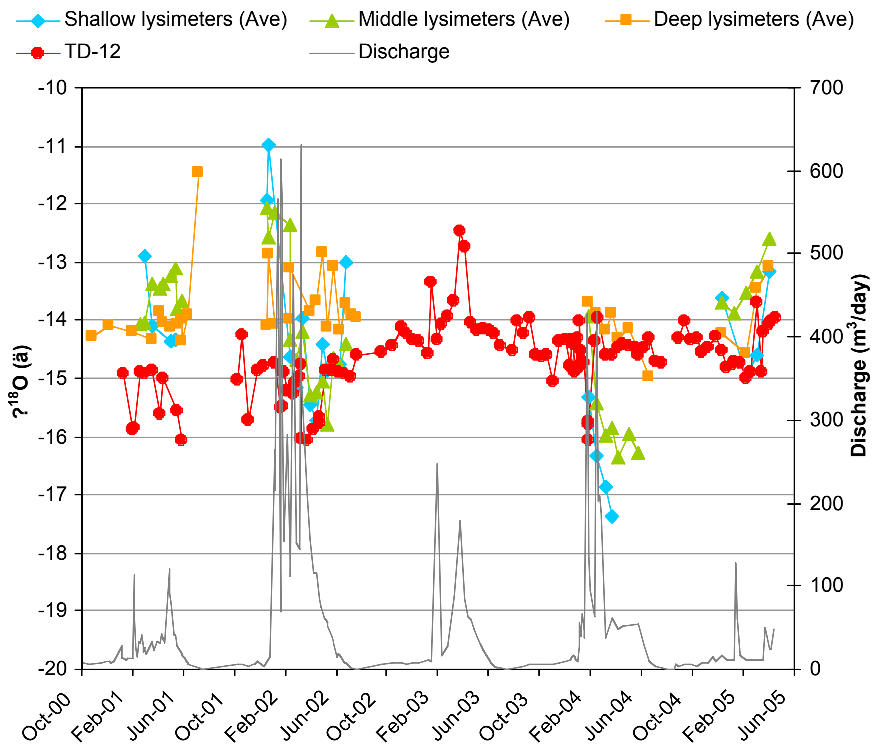


Figure 2. **δ ^{18}O values for the drained location. TD-12 data are from Figure 1; Depths of soil-water lysimetric samplers are 25 cm (shallow), 40 cm (middle), and 85 cm (deep). "Ave" indicates average of replicated samplers yielding water on a given date.**

We plan to investigate this issue by observation of the isotopic composition of the oxygen and nitrogen of the NO_3 itself. That work is beyond the scope of this project.

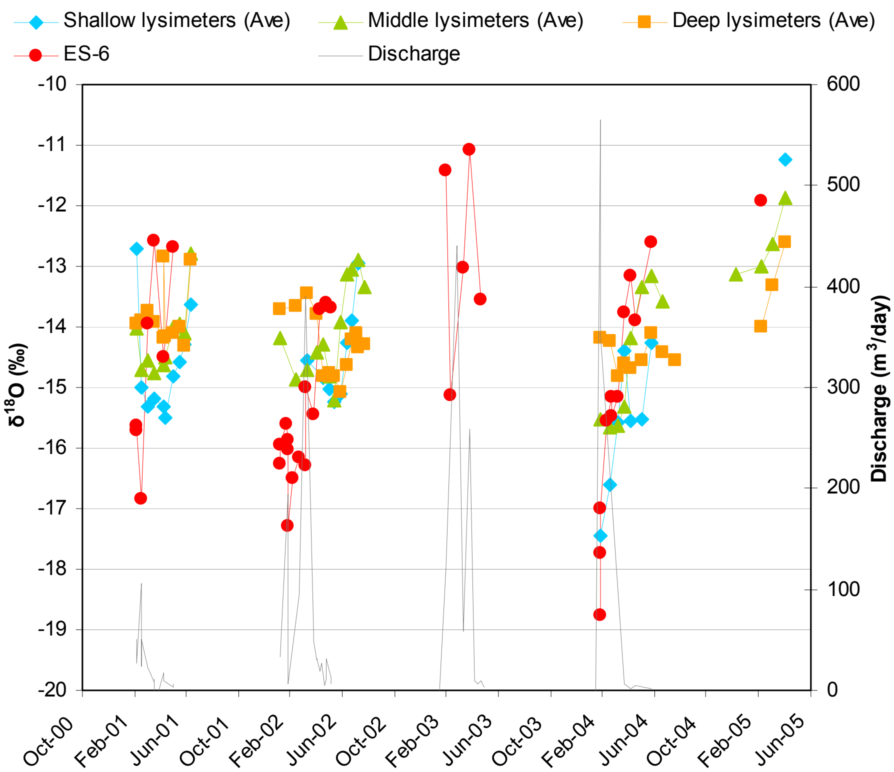


Figure 3. δ [18]O values for the drained location. TD-12 data are from Figure 1; Depths of soil-water lysimetric samplers are 25 cm (shallow), 40 cm (middle), and 85 cm (deep). "Ave" indicates average of replicated samplers yielding water on a given date.

Award No. 05HQAG0001 Improving Groundwater Management in Jordan

Basic Information

Title:	Award No. 05HQAG0001 Improving Groundwater Management in Jordan
Project Number:	2005WA188S
Start Date:	1/1/2005
End Date:	5/31/2007
Funding Source:	Supplemental
Congressional District:	NA
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Water Use, Management and Planning
Descriptors:	Jordan Groundwater Database, Education and Training, Modeling
Principal Investigators:	Michael Ernest Barber

Publication

Problem

While the Hashemite Kingdom of Jordan has about 750 million cubic meters (MCM) of renewable surface and groundwater resources, water demand reached about 1,200 MCM in 2002. The groundwater portion of the total demand is almost double the estimated total annual safe yield of renewable aquifers. This unsustainable practice has led to water-quality deterioration and water level declines, and will lead to severe economic and social impacts on water users and the Jordanian economy. The Ministry of Water and Irrigation (MWI) and the U.S. Agency for International Development (USAID) recognize that the widening gap between available renewable resources and increasing demands necessitates policy and management decisions that will require an improved understanding of Jordanian groundwater systems. This led USAID to establish a project agreement with the U.S. Geological Survey [USGS] to address hydrogeologic data development and use in MWI. The USGS thereupon coordinated with Washington State University to hire three Jordanian hydrogeologists as the project team to be lead by a senior USGS scientist stationed in Amman.

Hydrogeologic data and information, developed to address a variety of issues and concerns, currently reside in a variety of databases and in reports of previous and ongoing studies. Data and information products that describe Jordanian water resources at scales that range from local to national have been developed both independently by MWI staff and jointly with a number of geotechnical entities. Consolidation of these data and information, and development of a means to systematically ensure and describe their quality, will enhance the information base that is part of what is needed in the formulation of MWI policy and management decisions. Enhancement of the consistency of the descriptions and understanding of the various basins will provide an information base of long-term value, and render resource-management decisions more defensible.

The MWI technical staff includes hydrogeologists conversant with development and use of numerical groundwater models; and models of many part of the Kingdom have been developed by both MWI and other technical entities. While the current models provide insight to potential physical consequences of groundwater use, it is of value to link modeling results with socioeconomic considerations. Constrained-optimization modeling is a tool that can provide an augmented level of scenario examination. .

Objectives

In order to satisfy the broad goals described above, the U.S. Geological Survey (USGS) project team, working closely with the MWI, will complete two primary tasks:

1. Enhance MWI hydrogeologic data and information development, management, and analysis, and
2. Develop the capability within MWI to construct and use advanced ground-water management models, and to begin optimization studies of selected areas.

Training of the project team, and current MWI staff, in data and information development, and in development and use of optimization techniques is essential to enhance data-development capabilities within MWI, to help foster productive MWI employees and to enhance current technical capacities within MWI.

Methodology

The project team will develop familiarity with the MWI data base, and with designated analytical tools identified and developed by the team. They will examine all of the ground-water monitoring data in the MWI Water Information System [WIS] to identify data development and quality concerns. Findings will be summarized and provided to MWI in the form of spatial data products and supporting digital files, and in recommendations for improvements in data collection, development, and quality assurance and control.

The USG will provide training to the project team and selected MWI staff in the development and use of optimization techniques in ground-water management. Training will include classroom training in GIS use in data organization and analysis, USGS instruction in ground-water model development and use, and USGS instruction in the development and use of optimization criteria, parameters, constraints, and software.

Principal findings and significance

The project team comprises one female geologist [B.Sc.] and two male hydrogeologists [M.Sc. and PhD]. The project is sited in MWI and is functioning well as a team. It also is functioning well within the Ministry environment and coordinating its activities well with appropriate MWI staff.

The team developed requisite analytical tools using monitoring data available in the WIS and in MWI files. Four ground-water basins in the south of Jordan, out of a total of 12, were used as 'pilot' areas in methods development. Analysis entailed used of simple statistical tools in Excel to examine relevant hydrogeologic data, visual and comparative analyses of hydrographs and continuous chart data, literature and paper file searches, interviews and interaction with MWI, Ministry of Agriculture, Department of Land Surveys, Royal Jordanian Geographic Center, and donor staffs, and development of identified and evolving spatial data products. The team completed analyses of the four basins, assembled and archived the deliverables in digital form, and began analyses of a fifth basin. Data were found to be of variable quality, and causes of the variability were largely identified. The team identified means to correct noted concerns in data collection and development and developed a draft procedure for future MWI use.

A tdy USGS hydrogeologist provided nine weeks of on-site training [three trips] that covered hydrogeologic framework concepts, ground-water model development, and introduction of optimization concepts and software. The individual levels of ability in the team members required revision of the original training agenda to augment comprehension and use of hydrogeologic concepts and modeling techniques.

Two abstracts have been submitted for presentation at a water-related conference at Yarmouk University in Irbid, Jordan late in 2006.

Award No. 05HQAG0139 A Preliminary Numerical Flow Model Development for the Spokane Valley-Rathdrum Prairie Aquifer

Basic Information

Title:	Award No. 05HQAG0139 A Preliminary Numerical Flow Model Development for the Spokane Valley-Rathdrum Prairie Aquifer
Project Number:	2005WA189S
Start Date:	7/16/2005
End Date:	11/30/2005
Funding Source:	Supplemental
Congressional District:	Washington Fifth
Research Category:	Ground-water Flow and Transport
Focus Category:	Models, Groundwater, Management and Planning
Descriptors:	Water Supply, MODFLOW, Interstate Water Policy, Sole Source Aquifer
Principal Investigators:	Michael Ernest Barber

Publication

INTRODUCTION AND RESEARCH OBJECTIVE

The U.S. Geological Survey (USGS), Washington State Department of Ecology (WADOE), and the Idaho State Department of Water Resources (IDWR) have initiated a comprehensive hydrologic study of the Spokane Valley—Rathdrum Prairie (SVRP) aquifer with the goal of determining the spatial and temporal distributions of water stored within the system in order to enhance our understanding of the SVRP aquifer's flow regime. The study will include compilation and evaluation of available geologic, hydrogeologic, and hydrologic data followed by additional data collection leading to the eventual development of a transient groundwater flow model. As shown in Figure 1, the aquifer is a bi-state resource that provides drinking water to public and private concerns in Idaho and Washington. A better understanding of the aquifer is needed to ensure optimum management as the population in the area continues to increase.

It was identified that development of a preliminary steady state groundwater flow model employing the currently available conceptual model based on limited geologic and hydrogeologic data was a must. The preliminary model can and will be refined as more data becomes available. It was also decided that Drs. Akram Hossain and Michael Barber from Washington State University would be responsible for the development of this preliminary model with input and guidance provided by other modeling team members. The objective of this project was to review and incorporate existing reports and information into a preliminary steady state groundwater model.

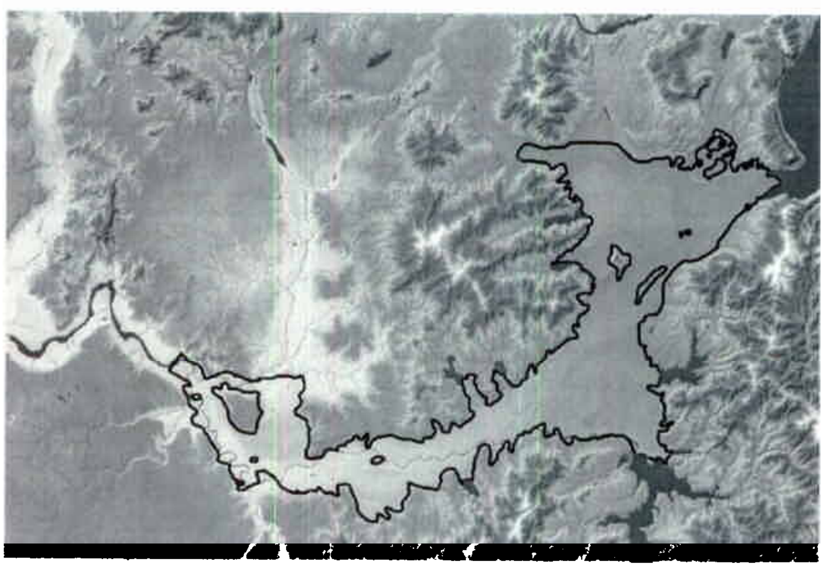


Figure 1: Extent of SVRP study area

METHODOLOGY AND WORK PLAN

The specific tasks associated with this project were to complete the following:

1. Evaluate existing geologic, hydrogeologic, and hydrologic data compiled by the USGS.

2. Evaluate existing groundwater flow models. The evaluation can be done by studying the summary of the groundwater flow models prepared by the USGS. However, at times it may be needed to go beyond the summary for a better understanding.
3. Develop a single-layer preliminary conceptual model.
4. Develop a numerical model employing the preliminary conceptual model. The numerical model will be developed by using MODFLOW 2000 contained in VISUAL MODFLOW developed by Waterloo Hydrogeologic.
    a. The numerical model will identify the boundary appropriately based on the available data and simulate the Spokane River by employing the "River Package" of MODFLOW.
    b. The aquifer will be divided into a number of recharge zones based on the information available from the existing models.
    c. The aquifer will be divided into a number of hydraulic conductivity zones based on the understanding of the existing models.
    d. The model should also include the major abstraction wells. The numbers of abstraction wells are not yet known. It is being assumed that there will be at most 100 such wells.

The preliminary model was completed and given to the modeling team. Currently, the modeling team is working on a modified version of it. The modification was necessary to reflect the team's better understanding of the aquifer based on new data.

PRINCIPAL FINDINGS AND SIGNIFICANCE

The term "steady-state" is used to describe a situation where nothing changes with respect to time. That means no change in boundary conditions, river flow, pumping and no change in water-level elevations. Strictly speaking, true steady-state conditions rarely occur in nature. As an approximation is necessary, the Modeling Team is currently evaluating two approaches to steady-state model calibration, the "point-in-time" and the "time-averaged" methods.

The "point-in-time" approach would calibrate the model to match hydraulic heads and streamflow gains and losses measured during the synoptic field session of September 13-16, 2004. The "average" approach would calibrate the model to match hydraulic heads and streamflow gains and losses averaged over the 2005 Water Year (Oct 1, 2004 to Sept 30, 2005). This approach might better match hydraulic gradients, and therefore would provide better estimates of hydraulic conductivity. The downside is that there are considerably fewer data sets available for the longer time period.

Another important component of the model is recharge from various sources. Aquifer recharge from precipitation is calculated from spatially distributed precipitation depths and potential evapotranspiration (the combined effect of evaporation from land surface and transpiration by growing vegetation). The recharge estimation also accounts for groundwater withdrawals by pumping. A preliminary recharge estimate is given in Figure 2. It is to be noted that better recharge estimates are now available and have been included in the current version of the model.

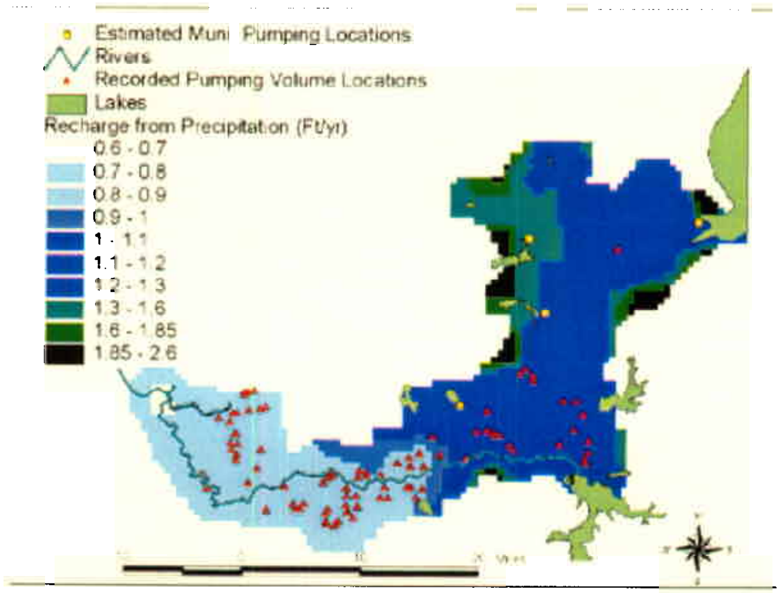


Figure 2: Initial Recharge Distribution

Using a preliminary hydraulic conductivity distribution, the MODFLOW model was calibrated using the "point-in-time" approach to produce the results similar to presented in Figure 3. The modeled water levels show water entering the aquifer from tributary valleys such as Spirit Valley and tributary lakes such as Hayden Lake.

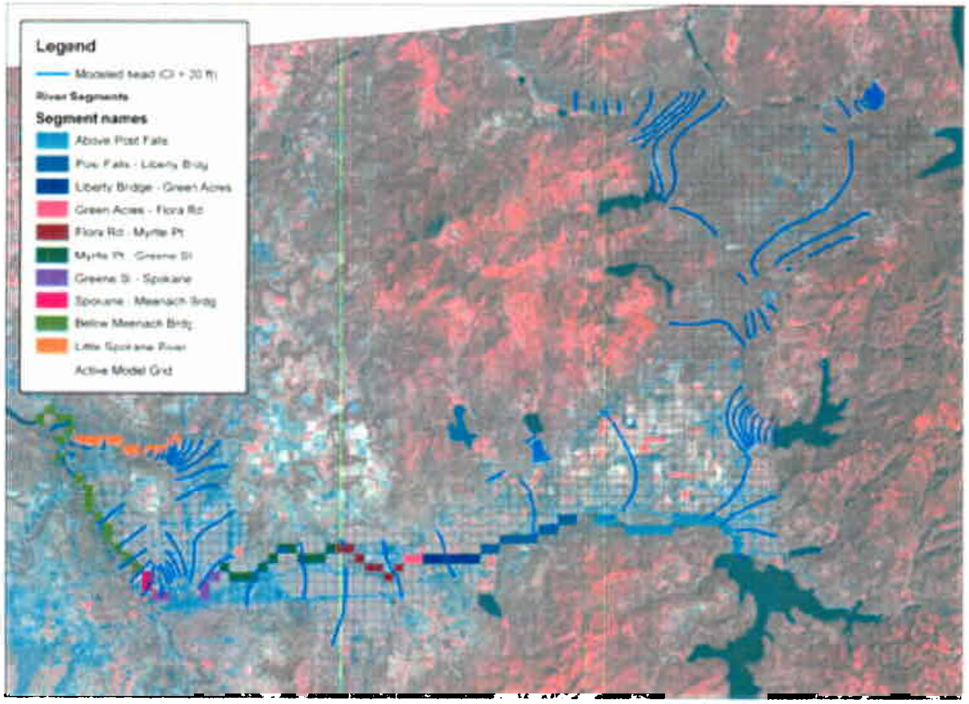


Figure 3: Modeled aquifer head and river segments

A considerable amount of progress has been made in establishing a consistent conceptual model of the SVRP system. Modeling results are encouraging and have identified several areas where more analyses are needed. As these data are generated the model can be easily updated.

Information Transfer Program

The State of Washington Water Research Center believes that Outreach and Education are critically important components to its mission. The primary goal is to facilitate information exchange by providing opportunities for combining the academic work of research universities in the state with potential users and water stakeholders. This process occurs through a variety of activities, formal and informal, that raise the visibility of university research results throughout the Pacific Northwest. Federal, state and local agencies, non-governmental organizations, watershed groups, and concerned citizens are in need of interpreted science that can be applied to solving the regions water problems. The Center makes substantial efforts to facilitate this process. The items described in the following Information Transfer Report constitute the core of the technology transfer activities of the SWWRC.

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2005WA114B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	Washington 5th
Research Category:	Not Applicable
Focus Category:	Education, Management and Planning, None
Descriptors:	Outreach, Information Transfer
Principal Investigators:	Michael Ernest Barber

Publication

In order to achieve the goals outlined in the introduction, the following information transfer activities were conducted.

Meetings with the Spokane/Rathdrum Prairie Aquifer Committee continued into 2005 as part of a joint project with the USGS and the Water Institutes in Idaho and Washington aimed at determining water availability across state boundaries. A public forum was held to discuss issues and preliminary findings with the general public.

Director Michael Barber attended the UCOWR meeting in Portland, Maine to network with regional water professionals, attend NIWR Board meeting, and participate in the conference. He also gave a presentation and a poster at USDA national water conference on projects initiated and facilitated through SWWRC.

SWWRC organized and co-sponsored a two-day regional groundwater conference titled *Groundwater Under the Pacific Northwest* that brought together over 225 registrants. This highly successful conference was well-received and significantly raised the visibility of the SWWRC and university researchers in the region and helped to disseminate important technical and policy related information. The conference was proceeded by both a SWWRC-led half-day workshop on groundwater essentials and a day-long bus tour of local water resource projects. We also began the planning phase of the next regional conference by discussing potential conference themes and identifying possible steering committee participants.

Continued funding for a USDA-CSREES grant was received. The project helps to coordinate research and extension activities of the Water Research Institutes and Extension Services in Alaska, Idaho, Oregon, and Washington with EPA Region 10. Six meetings are held each year and communication between researchers, extension faculty, and government agencies is expanding rapidly.

We continued to actively participate in a strategic regional surface water initiative funded by the Department of Energy through the Inland Northwest Research Alliance (INRA). The project involves the Water Institutes and the Universities of Alaska, Idaho, Utah, and Washington, as well as Boise State University, the University of Montana, Idaho State University, and Montana State. The project involves bi-monthly conference calls aimed at establishing a regional needs assessment and a coordinated research and education program aimed at integrating water science, policy, and decision making.

Updating our Web site is a continuous process. This is an important avenue for us to present information about the activities of the Center and the research faculty in the state as well as news and events, research reports, and opportunities for research funding. This media requires nearly continuous work to ensure that the material is current ant the look of the page is up to date. We also continued the process of having research reports available for download via PDF format rather than mailing of paper copies.

Our database of interested stakeholders is also constantly being updated. Currently over 2,500 names are included. Information for a second database of water resources expertise at Land Grant Universities in the Pacific Northwest, initiated in 2004, was also updated.

The Director participated in a workshop on drought management needs for the State with participants from the University of Washington several state agencies including the Washington Department of Ecology, the Washington Department of Agriculture, the Department of Community, Trade and Economic Development, and the Office of Financial Management.

The Water Center Director traveled to Jordan to coordinate and participate in a research project aimed at educating and training professional staff at the Jordan Ministry of Water and Irrigation. The Center is working with Department Chairs at Washington State University to create interdisciplinary programs in Water Science and Engineering that involve research and education efforts at three Jordanian Universities. This led to a project to assist the USGS with a project to train three junior level hydrogeologists in Jordan. The Director also traveled to the Philippines to serve as the technical project coordinator on a watershed restoration and reforestation.

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	6	1	0	0	7
Masters	4	4	0	0	8
Ph.D.	0	1	0	0	1
Post-Doc.	0	0	0	0	0
Total	10	6	0	0	16

Notable Awards and Achievements

Work funded as part of the 2004 104(B) funded Removal of the Human Pathogen Giardia Intestinales from Ground Water project was selected for presentation the prestigious 2005 National Ground Water Summit in San Antonio, Texas by a geology graduate student, Ms. Colleen Rust.

Publications from Prior Projects

1. 2002WA12B ("Facilitated Transport of Pesticides by Organic Colloids") - Book Chapters - Buchan, G.D., and Markus Flury, 2004, Pathogen transport by water, "in" Encyclopedia of Water Science, edited by B.A. Stewart, and T.A. Howell, doi: 10.1081/E-EWS 120021169, Marcel Dekker, New York.
2. 2002WA12B ("Facilitated Transport of Pesticides by Organic Colloids") - Articles in Refereed Scientific Journals - Jerez, Jose, and Markus Flury, 2006, Humic acid, ferrihydrite, and aluminosilicate coated sands for column transport experiments, Colloids and Surfaces A: Physicochemical and Engineering Aspects, 273, 90-96.
3. 2001WA1041B ("Dye Tracers for Vadose Zone Hydrology") - Articles in Refereed Scientific Journals - Cherrey, K.D., Markus Flury, and James B. Harsh, 2003, Nitrate and Colloid Transport Through Coarse Hanford Sediments under Steady State, Variably Saturated Flow, Water Resources Research, 39, 1165, doi:10.1029/2002WR001944.
4. 2001WA1041B ("Dye Traces for Vadose Zone Hydrology") - Articles in Refereed Scientific Journals - Mon, Jarai, Markus Flury, and James B. Harsh, 2006, A Quantitative Structure-Activity Relationship (QSAR) Analysis of Triarylmethane Dye Tracers, Journal of Hydrology-Amsterdam, 316, 84-97.
5. 2004WA76B ("Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality") - Water Resources Research Institute Reports - Wu, Joan Q. and Timothy P. Hanrahan. 2005. Three-dimensional Characterization of Riverbed Hydraulic Conductivity and its Relation to Salmonid Habitat Quality. State of Washington Water Research Center, Washington State University, Pullman, Washington. State of Washington Water Research Center Report WRR-23. 20 pages.

6. 2004WA76B ("Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality") - Conference Proceedings - Leek, Randal, Li Wang, Joan Q. Wu, Hanxue Qiu, Michael E. Barber, and Timothy P. Hanrahan, 2005. Heterogeneous Characteristics of Water Movement Through Riverbed Sediments of the Touchet River in Southeastern Washington, in Proceedings of the Conference Groundwater under the Pacific Northwest: Integrated Research, Policy, and Education, http://www.swwrc.wsu.edu/conference2005/proceedings/index.html
7. 2004WA75B ("Phosphorus Contamination of Surface Waters") - Articles in Refereed Scientific Journals - Jerez, Jorge, Markus Flury, Jianying Shang, and Youjun Deng. 2006. Coating of silica sand with aluminosilicate clays, Journal of Colloid and Interface Science, 294 (1):155-164.
8. 2004WA75B ("Phosphorus Contamination of Surface Waters") - Articles in Refereed Scientific Journals - Jerez, Jorge, and Markus Flury. 2006. Humic acid, ferrihydrite, and aluminosilicate coated sands for column transport experiments. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 273, 90-96.
9. 2004WA76B ("Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality") - Articles in Refereed Scientific Journals - Greer, R. Cory, Joan Q. Wu, Prabhakar Singh, and Donald K. McCool, 2006, WEPP simulation of observed winter runoff and erosion in the Pacific Northwest, USA, Vadose Zone Journal, 5, 261272.
10. 2004WA76B ("Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality") - Other Publications - Wu, Joan Q, W.J. Elliot, D.C. Flanagan, Donald K. McCool, Markus Flury, and S. Dun, 2005, Water Erosion Prediction Project (WEPP): Continuous model improvement, testing, and applications for watershed assessment and restoration, poster presented at the 2005 USDA-CSREES National Water Quality Conference, February 610, 2005, San Diego, California.
11. 2004WA76B ("Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality") - Other Publications - Wu, Joan Q., W.J. Elliot, and S. Dun, 2003, Modification of the subsurface flow routines in the WEPP (Water Erosion Prediction Project) model, presented at the 2003 American Society of Agricultural Engineers Meeting, July 2730, 2003, Las Vegas, Nevada.
12. 1999WA0014G ("A Watershed Scale Study on No-TIll Farming Systems for Reducing Sediment Delivery") - Articles in Refereed Scientific Journals - Fu, Guobin, Shulin Chen, and Donald K. McCool, 2006, Modeling the impacts of no-till practice on soil erosion and sediment yield with RUSLE, SEDD, and ArcView GIS. Soil and Tillage Research, 85(1-2):38-49.
13. 1999WA0014G ("A Watershed Scale Study on No-TIll Farming Systems for Reducing Sediment Delivery") - Articles in Refereed Scientific Journals - Mancilla, Gabriel, Shulin Chen, and Donald K. McCool, 2005, Rill density and flow velocity distribution, Soil and Tillage Research, 84:54-66.