State of Washington Water Research Center Annual Technical Report FY 2008

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, and 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 Director's primary research interests in surface-groundwater interaction, remote sensing, and stormwater. The Center is also involved in international research and educational 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. Our web page is continually updated to share timely 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 as well as provide opportunities for leveraging. 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, energy production, 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 stormwater runoff regulations are growing to the point where they are beginning to raise significant concerns. All of these issues will be important drivers of SWWRC activities in the foreseeable future.

Research Program Introduction

In accordance with its' stated 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 (within the State) 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 apprised of any opportunities. The Center also submits proposals on its own behalf.

During FY 2008, three local research projects were selected for funding by the Center: (1), Reservoir Sediments: Biofilter or Environmental Liability? by John Harrison, (2) Towards Phosphorus Removal: Evaluating Biogenic Iron Oxides for Renewal Filtration by Jeremy Rentz, and (3) Assessing Pathogen Fate and Transport through Riparian Buffers in an Agricultural Watershed by Jeffrey Ullman. As described below, these projects address state issues but are also relevant to national interests.

One national project (West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS) is currently being run through the SWWRC to a University of Washington researcher. An update of this project is presented in this report.

West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS

Basic Information

Title:	West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS
Project Number:	2006WA180G
Start Date:	9/1/2006
End Date:	8/31/2010
Funding Source:	104G
Congressional District:	7
Research Category:	Climate and Hydrologic Processes
Focus Category:	Drought, Hydrology, Management and Planning
Descriptors:	Drought Forecast, Drought Mitigation
Principal Investigators:	Anne Steinemann, Dennis Lettenmaier, Andrew Wood

Publication

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2. Rosenberg, E., Andrew W. Wood, Q. Tang, Anne C. Steinemann, B. Imam, S. Sorooshian, and Dennis P. Lettenmaier, 2007, Improving Water Resources Management in the Western United States through Use of Remote Sensing Data and Seasonal Climate Forecasts, Poster Presentation at the 5th Annual Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.
3. Shukla, S., D. Alexander, A. Steinemann, and A. W. Wood, 2007, Applications of Medium Range To Seasonal/Interannual Climate Forecasts For Water Resources Management in the Yakima River Basin of Washington State, Poster Presentation at the 5th Annual Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.
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Synopsis Report to the US Geological Survey
Reporting Period: March 1, 2008 to May 31, 2009
Project 2006WA180G

TITLE	West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS
INVESTIGATORS	Anne Steinemann, Dennis Lettenmaier, Andrew Wood
START DATE	9/1/2006
END DATE	8/31/2009
CONGRESS. DISTRICT	Washington 7th
FOCUS CATEGORIES	Drought, Hydrology, Management and Planning
DESCRIPTORS	Drought Forecast, Drought Mitigation

PROBLEM AND RESEARCH OBJECTIVES

Drought is the costliest natural hazard in the U.S., averaging $6-8 billion in damages annually (FEMA, 2004). The 1988 central U.S. drought alone cost almost $62 billion (NCDC, 2006). Forecasts and real-time assessments of drought offer the potential to mitigate drought impacts. However, current drought monitoring systems for the western U.S. lack a predictive component for specific hydrologic indicators. Further, given that hydrologic impacts account for most drought losses, USGS data are essential to making drought forecasts useful.

We propose to develop a drought forecast and nowcast system for the western U.S., which will serve as a scientific framework for prediction and assessment of agricultural (soil moisture) and hydrologic (streamflow) drought in the region. This work, in collaboration with USGS personnel, will provide early warning capabilities and science-based indicators that are critical for the National Integrated Drought Information System (NIDIS), an effort of the Western Governors' Association (WGA), the National Drought Mitigation Center (NDMC), NOAA, the USGS, and other agencies. Our work will also contribute to the U.S. Drought Monitor, which currently uses our National Surface Water Monitor, by incorporating USGS data into methods to characterize and forecast drought conditions, persistence, and recovery. Further, the PIs and their students will work directly with water managers in selected states in the region (Washington, California, and others) to apply this forecast system to water resources decisions.

Our proposed drought forecasting system will build upon the University of Washington's operational West-Wide Hydrologic Forecast System and National Surface Water Monitor. In doing so, we will extend the Variable Infiltration Capacity (VIC) macroscale hydrology model to utilize, via data assimilation methods, USGS hydrologic data in ways not currently exploited by prominent drought information services, such as the U.S. Drought Monitor.

Our specific objectives are to (1) implement a version of the VIC model that represents near-surface groundwater directly and thus can incorporate USGS well level data; (2) assimilate observations not presently used in the West-Wide system that are highly relevant to drought, such as USGS streamflow data from HCDN and similar stations, soil moisture information, and USGS well data; (3) produce probabilistic forecasts of drought persistence and recovery using ensemble prediction methods that incorporate climate forecasts out to one year; and (4) work with the WGA, the NDMC, and other users, such as state water agencies, to incorporate the resulting drought forecasts and nowcasts into drought information systems and water management decisions.

In addition to interactions with the WGA and the NDMC, we will work closely with Dr. Randall Hanson and Dr. Michael Dettinger of the USGS California Water Science Center in San Diego.

Specifically, we will work with Drs. Hanson and Dettinger in (1) testing VIC predictions of well level anomalies at selected locations in California, (2) development of algorithms for assimilation of USGS well level and streamflow data, as well as other hydrologic data, into the drought forecasting system, (3) obtaining retrospective and real-time hydrologic data, and (4) validation of drought nowcasts and forecasts across the western U.S. study domain.

METHODOLOGY

The overall goal of the proposed project is to develop a drought forecast and nowcast system for the western U.S. (which we will define as the continental U.S. west of the Mississippi River), which can serve as a scientific framework for assessment and prediction of agricultural (soil moisture), and hydrologic (streamflow) drought in the region, and as the scientific core of NIDIS. The system will leverage the existing University of Washington WHFS and SWM. Our specific objectives are:

(1) To implement a version of the VIC model that represents near-surface groundwater (water table) directly, based on a simple groundwater model of Niu et al. (2007). This model will be capable of incorporating USGS well level observations via data assimilation in areas where there is strong connectivity between groundwater and surface water systems;

(2) To develop procedures for assimilating observations that are not presently incorporated in the WHFS but are highly relevant to drought, such as USGS well data, USGS streamflow data from HCDN and similar stations not greatly affected by water management, and soil moisture from such sources as the NRCS SCAN network and state networks where such data are available;

(3) To develop methods for producing probabilistic forecasts of drought persistence and recovery, using ensemble prediction methods that incorporate official NOAA CPC ensemble climate forecasts for lead times out to one year; and

(4) To work with the NDMC, the WGA, and other users (primarily state agencies in the western U.S.) to incorporate the resulting drought nowcasts and forecasts into water management decisions and into drought information systems such as the Drought Monitor/Outlook and NIDIS.

PRINCIPAL FINDINGS AND SIGNIFICANCE

A Washington statewide drought monitoring system has been implemented using the VIC hydrologic model at 1/16 degree (about 6 km grid mesh). This system provides real-time, daily updating analyses (maps, datasets, and time series of hydrologic variables) that characterize hydrologic conditions throughout the state, presented via a website (http://www.hydro.washington.edu/forecast/sarp/). It also presents a weekly update of the current drought status in terms of drought indices, including Palmer Drought Severity Index (PDSI), Palmer Hydrologic Drought Index (PHDI), Crop Moisture Index (CMI), and Z Index (ZIND), as well as a daily update of 1, 2, 3, 6, 9, 12, 24, and 36 month averaged values of Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI). Work has begun to prepare the statewide monitoring system with an embedded focus region of the Yakima River Basin as the initializing state for 2 week to 1 year lead hydrologic forecasts, from which it will be possible to obtain drought onset and recovery predictions. These will be based on both ensemble streamflow prediction (ESP) techniques advanced by the National Weather Service, and NCEP Climate Prediction Center seasonal outlooks. To this end, the Climate Prediction Center's new consolidated forecast (not previously available to the public) has been obtained and is being evaluated in the Washington State domain. In addition, preliminary work to develop methods for forecast error reduction has resulted in a published paper (Wood and Schaake, 2008).

To supplement existing drought characterization methods, we developed a method known as the standardized runoff index (SRI), which is calculated as the unit standard normal deviate associated with the percentile of hydrologic runoff accumulated over a specific duration. This method is similar to the standardized precipitation index (SPI), but relates to a hydrologic variable, runoff, rather than a climatic variable, precipitation. Such an approach better accounts for the effects of seasonal lags in hydrologic response to climatology. For example, SPI does not account for the effects of decreased snowmelt on summer conditions. Maps of SPI and SRI, based on a rolling climatology, are updated daily for the continental U.S. at ½ degree spatial resolution as part of the U.W. Surface Water Monitor (Figure 1, http://www.hydro.washington.edu/forecast/monitor/indices/index.shtml). The development of this index and its comparison with SPI are presented in a published paper (Shukla and Wood, 2008).

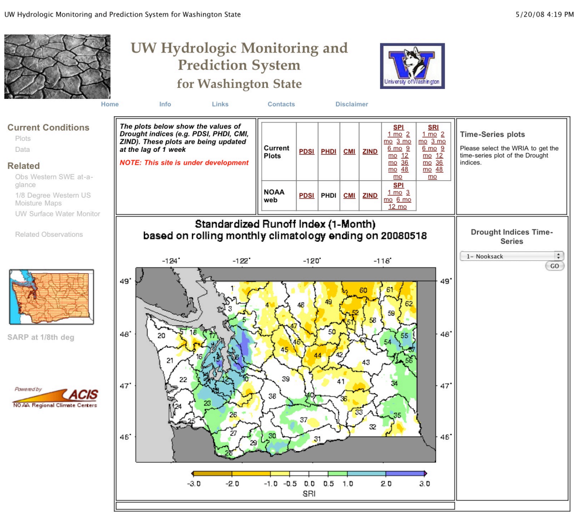

Figure 1. Screen shot of UW Hydrologic Monitoring and Prediction System for Washington State showing standardized runoff index (SRI, 1-month) using a rolling monthly climatology ending on May 18, 2008.

We have met with key stakeholders (e.g. federal, state, and regional water officials, irrigation district managers, farmers) in the Yakima River Basin, Washington, to assess their needs. We discussed current organizational decision processes, current uses of forecast information, needs for NOAA forecast products, barriers to forecast use, and potential net benefits of using the NOAA-CPC forecasts and the drought forecast information developed by this project. In this process, we identified four decision-making realms: (1) filling reservoirs without flooding in winter and spring; (2) maintaining flows for fish in fall; (3) week-to-week operations in summer; and (4) agricultural decisions in winter for irrigation season. The relevant decision timing relative to forecast timing for each of these operational periods were also assessed (Figure 2).

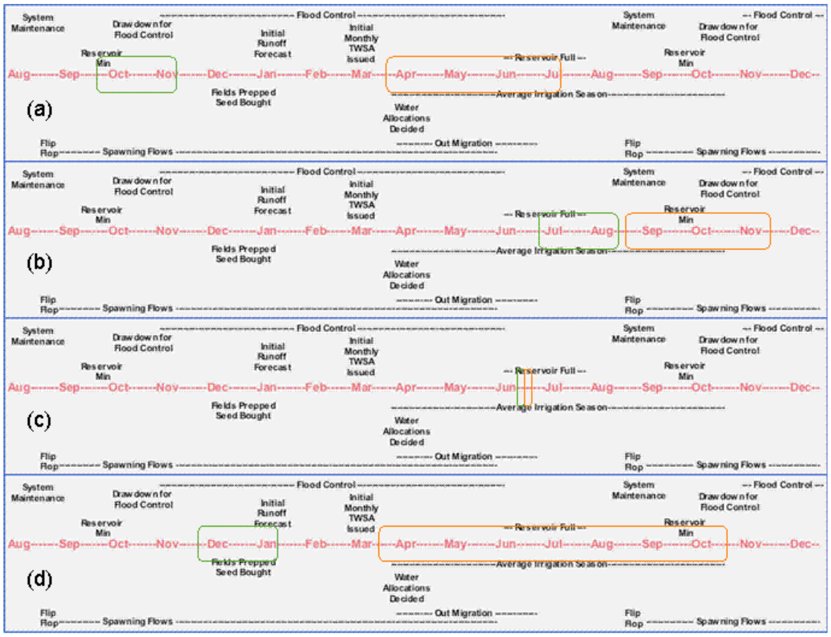

Figure 2. Four identified decision-making realms, with green circles around period in which decisions are made and orange circles around the relevant time of forecast. (a) Filling reservoirs without flooding in winter and spring, (b) maintaining flows for fish in fall, (c) week-to-week operations in summer, and (d) agricultural decisions in winter for irrigation season.

We have implemented and tested a drought recovery strategy, based on initializing VIC with current (soil moisture) conditions, and running forward in time with ensembles of future climate conditions. Maps of median forecast percentile and the forecast probability of conditions below the 20th percentile for soil moisture, SWE, and cumulative runoff for the continental United States are available at http://www.hydro.washington.edu/forecast/monitor/outlook/index.shtml. Ensemble Streamflow Prediction (ESP)-based and CPC outlook-based forecasts of daily streamflow volumes are made near the beginning of each month. These outputs are summarized as monthly hydrograph distribution plots available for several forecasting stations in the west-wide U.S. Region (Figure 3, http://www.hydro.washington.edu/forecast/westwide/sflow/). The ESP ensembles are drawn from sequences of past observations, whereas the CPC outlook ensembles are derived from the CPC's probability of exceedance (POE) forecasts for average monthly temperature and total precipitation in each of 102 climate divisions within the US. Probabilistic outcomes will be compared with nominal conditions (as simulated with the VIC model using the true forcings) for the retrospective period, and maps of the accuracy of climate recovery predictions will be produced as a function of season and lead-time. Figure 4 compares the ensembles of predicted soil moisture, averaged over the Arizona-California portion of the drought, compared with "actual" (real-time) model soil moisture over the 6-month forecast period.

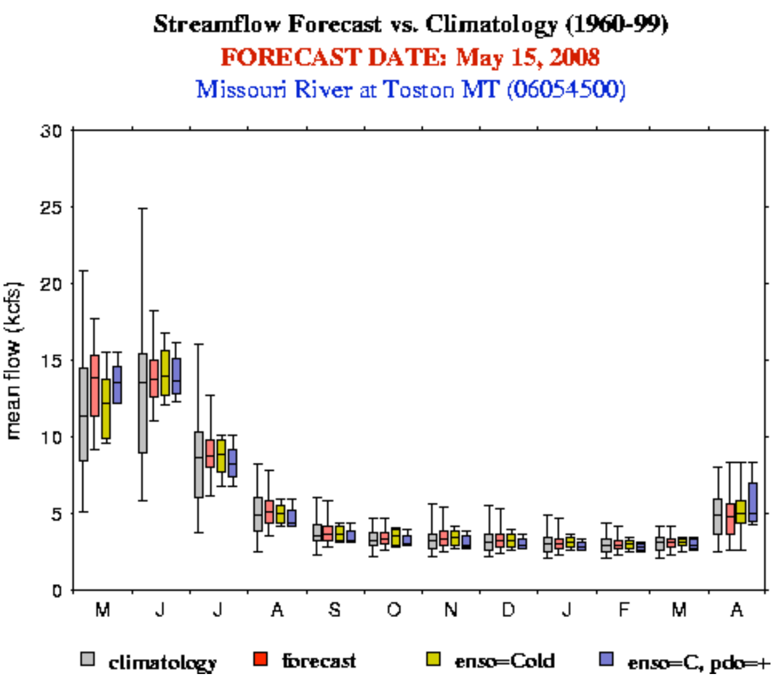

Figure 3. ESP forecast for mean monthly streamflow on the Missouri River at Toston, MT, as of May 15, 2008.

We have also implemented a drought nowcast system in real-time, and are in the process of implementing a drought forecasting system over the western U.S. domain, using methods similar to those illustrated in Figures 3 and 4, at one-quarter degree spatial resolution (our current Surface Water Monitor uses one-half degree resolution). We have recently implemented a drought identification system at the SW Monitor native ½ degree resolution. We summarize the method below.

The VIC hydrologic model produces near real-time, spatially and temporally continuous fields of drought-related variables such as soil moisture and streamflow (we focus here on soil moisture). Drought is defined locally at each model pixel using a thresholding method, i.e. whenever soil moisture or runoff are below a certain threshold value the pixel is classified as being "in drought". Instead of using the absolute values of soil moisture (or runoff), droughts are identified by expressing each pixel's soil moisture as percentiles of their 1915-2004 respective model climatology. This essentially normalizes the soil moisture and runoff time series to range of 0 to 1 across the domain. The threshold chosen here is 0.2, which corresponds to severe drought, with severity being calculated as the percentage remainder of the subtraction of the soil moisture (or runoff) percentile from unity.

Soil moisture and runoff spatial fields are estimated and used to produce weekly maps, which are then used in the drought identification procedure. In order to keep a certain temporal continuity in the areas identified as drought from one time step to the next, we have to apply some kind of temporal persistence constraint. This ensures that areas are classified as drought recovered relatively consistently, given that this is a near real-time application. Drought transition probabilities (probability that a pixel will recover if it was in drought the previous 1, 2 or 3 weeks) were calculated from the model climatology. These are then used after the first stage of drought identification (any pixel below the 20th percentile is classified as drought) to retain the temporal persistence in drought areas. The recovery probability threshold is set to 50%, but this can be adjusted accordingly.

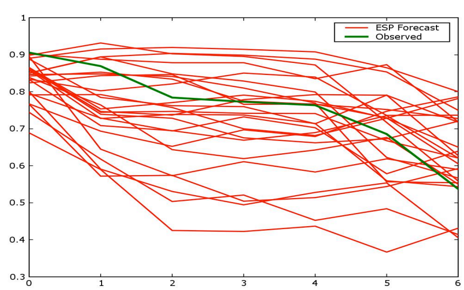

Figure 4: Spatial average soil moisture over AZ-CA starting on Feb. 1, 2006, and progressing through August, as compared with "actual" soil moisture (real-time model estimates).

The algorithm continues by applying a spatial median filter using a 5x5 window, in order to attain some spatial smoothing by minimally distorting the actual percentile values. The initial partitioning of the image then follows, by grouping adjacent pixels that are in drought into clusters. This fragmented image is then adjusted by merging clusters that are sufficiently close in terms of distance, and eliminating drought clusters that occupy less than the area of 20 model pixels. The final step includes the reclassification of pixels that are within larger drought areas as being in drought, by examining the neighborhood of each pixel not in drought within a radius of 3 model pixels. This procedure results in a map of drought areas, and also allows for their consistent tracking through time. Figure 5 shows results of application of the method over the continental U.S. starting in early May, 2007, as droughts were evolving in both the southeastern and southwestern U.S., and proceeding through the first week in June, 2007. The spatial limits of drought are updated once per week. We are interacting with CPC personnel who are reviewing the method, but we believe that it

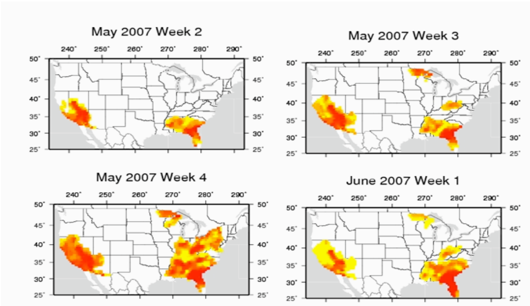

Figure 5: Estimated extent of drought over continental U.S. as of first week of June, 2007, and evolution over previous three weeks. Soil moisture percentiles are relative

has great promise for producing a more objective delineation of drought extent and severity that is currently possible in publications such as the National Drought Monitor.

In streamlining our implementation of the ESP approach to streamflow forecasting, we explored the necessity of calibration when applying an ESP approach to seasonal forecasts. This work looks at bias reduction via model calibration versus "training" a bias removal technique on retrospective simulation error statistics and removing bias during post-processing. Forecast error, as measured by the coefficient of prediction, of these two methods was found to be similar for each case, and in many cases, the reduction is greater for post-processing bias correction, by percentile mapping, at the seasonal scale. This work has been accepted for publication (Shi et al., 2007).

Since soil moisture in land surface models is dependent on model dynamics, we have investigated the use of multi-model ensembles. Tests of model-specific sensitivities in identifying and reconstructing drought events, based on model-predicted soil moisture, were conducted using six land surface/hydrology models over the continental United States for the period 1920-2003. We also applied two ensemble methods to combine results from all of the models. Combining models is thought to minimize any model errors. All models and the two ensembles identified the spatial patterns of major drought events. The spatial distribution of drought severity and duration was plausible for all models; however, models differed in these aspects. Differences between models were greater in the western U.S. than in the eastern U.S. due to precipitation differences. Deeper soil columns led to longer soil moisture memory. The multimodel ensembles have been implemented into the real-time drought nowcast system of the U.W. Surface Water Monitor. This work has been submitted for publication.

After further investigation into techniques for incorporating groundwater into large-scale land surface models, we have incorporated the simple groundwater model (SIMGM) developed for the Community Land Model (CLM) by Niu et al. (2007) into VIC. This model is much more computationally efficient than the Liang et al. (2003) VIC-ground model, which we originally proposed implementing, and has been successfully run globally, with results that closely match water table levels derived from the Gravity Recovery and Climate Experiment. SIMGM includes a lumped-unconfined "aquifer" as a single integration element beneath the soil column. The hydraulic properties, including specific yield and exponentially decaying hydraulic conductivity, of this layer differ from those of the soil layers.

The basic concept behind SIMGM is a simple water balance, i.e. the change in water storage within an aquifer over time equals the difference between recharge into and subsurface flow out of the aquifer. Recharge is calculated using Darcy's law as a function of the depth to the water table and the matric potential and mid-element depth of the lowest unsaturated soil layer. The recharge estimate also accounts for an upward flux driven by capillary forces. The CLM implementation of SIMGM uses a simple TOPMODEL-based runoff model to calculate subsurface flow (baseflow) as an exponential function of water table depth. Unlike in TOPMODEL, Niu et al. (2007) estimate saturated hydraulic conductivity as a function of soil texture; in the aquifer, hydraulic conductivity exponentially decays with depth from that of the lowest soil layer. Water table depth is estimated from the resultant aquifer water storage scaled by the specific yield. Depth to the water table can be within the soil column, in which case the water table depth calculations differ slightly to account for differences in soil and aquifer properties. The water table can also be below the base of the lumped, unconfined aquifer element; hence, there is no prescribed total model depth.

The VIC implementation of SIMGM differs from that of Niu et al. (2007) primarily in the surface runoff scheme. Whereas CLM applies a TOPMODEL-based runoff scheme to parameterize surface runoff as a function of topographically based saturated fraction and water table depth, VIC calculates surface runoff using a more generalized parameterization. Also, the standard VIC model includes 3 soil layers, as opposed to the 10 layers of CLM. In order to maintain the simplicity of the VIC model, we have not altered the 3-layer construct.

Initial tests of the water table model and SIMGM parameter sensitivity within the VIC context have begun over the state of Illinois, where the Illinois State Water Survey (ISWS) provides climatological shallow groundwater records from the WARM and ICN networks of monitoring wells. Individual water balance components and the effects of the inclusion of SIMGM versus the standard VIC implementation without additional calibration have been compared. In preparation for the next steps, routing over the Skillet Fork River in southeastern Illinois has been set-up in order to investigate the impacts of SIMGM on the VIC model's accuracy in estimating observed streamflows. We have obtained data from one soil moisture station in this basin from Hollinger and Isard's (1994) extended data set. Skillet Fork basin also contains two ISWS shallow groundwater wells.

Once we are certain that the model is performing as expected in Illinois, we will begin applying the model to catchments in the western U.S., eventually expanding to the entire West-wide Forecast region. We will use groundwater levels from the U.S.G.S. Climate Response Network (CRN) for calibration and validation in this region. With help from Mike Dettinger, we will need to supplement the CRN stations with other active shallow well data and to develop a weighting system based on data quality and likely degree of pumping and agricultural impacts.

Lacamas Lake and other Northwest Reservoirs as Bioreactors: How do Dams Affect Downstream Nutrient Transport?

Basic Information

Title:	Lacamas Lake and other Northwest Reservoirs as Bioreactors: How do Dams Affect Downstream Nutrient Transport?
Project Number:	2007WA193B
Start Date:	3/1/2007
End Date:	8/31/2008
Funding Source:	104B
Congressional District:	Washington 3rd
Research Category:	Water Quality
Focus Category:	Hydrogeochemistry, Water Quality, Nutrients
Descriptors:	Eutrophication, Reservoirs, Nitrogen, Phosphorus, Denitrification, Rhodamine
Principal Investigators:	John Harrison

Publication

1. Harrison, John A., R. Maranger, R.B. Alexander, J. Cornwell, A. Giblin, P. A. Jacinthe, E. Mayorga, S.P. Seitzinger, and W. Wollheim. 2009. The Regional and Global Significance of Nitrogen Removal in Lakes and Reservoirs. Biogeochemistry. Volume 93 (1/2), pp.143-157.
2. Deemer, Bridget R., John A. Harrison, and Elliott Whitling. Nigrogen removal in a small eutrophic reservoir: seasonal patterns and controls. (In preparation)
3. Deemer, Bridget R. and John A. Harrison, 2008, Seasonal variation in denitrification in a small eutrophic reservoir: Lacamas Lake, Camas, Washington. Poster presentation at the Ecological Society of America Annual Meeting, August 3-8, 2008, Milwaukee, Wisconsin.
4. Deemer, Bridget R. and John A. Harrison, 2009, Nitrogen removal and greenhouse gas production during spring stratification in a eutrophic reservoir. Oral presentation at the Ecological Society of America Annual Meeting, August 2-7, 2009, Albuquerque, New Mexico.
5. Budiselic, Zachary, Bridget R. Deemer, and John Harrison, 2009, Sedimentation rates in Lacamas Lake, Camas, Washington. Poster presentation at the Washington State University Vancouver Research Showcase, April 9, 2009, Vancouver, Washington. Winner of the WSU-Vancouver Science Programs Undergraduate Research Award.
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PROBLEM AND RESEARCH OBJECTIVES

Human-induced nitrogen (N) and phosphorus (P) over-enrichment of surface waters is an important problem in Washington State, throughout the Northwest US, and worldwide. In Washington State, 664 lakes and reservoirs and 748 total fresh-water entities have been reported as exceeding the standard for 303d listing with respect to phosphorus (P) concentrations and many lakes and reservoirs have elevated levels of nitrogen (N) as well[1]. These eutrophic lakes and reservoirs are prone to problems such as: 1) loss of swimming, fishing, and aesthetic enjoyment due to nuisance algal blooms, periphyton, and macrophyte growth, 2) loss of aquatic life from dissolved oxygen depletion caused by excess algal and aquatic macrophyte respiration and decay, and 3) loss of drinking water due to the onset of foul odors, clogging of filters, algae toxins, and formation of trihalomethanes (THMs) as water disinfection byproducts[2]. Barring the drinking water concerns, a similar suite of issues is associated with nutrient over-enrichment of coastal waters[3]. Thus it is critical to understand transport of nutrients through watersheds and the biogeochemical processes that account for sources and sinks of bioactive elements like N and P.

Dam construction and reservoir impoundment is also an important issue, both within Washington State and beyond. Washington State contains over 700 reservoirs (National Inventory of Dams), and the Washington State Legislature recently authorized $200 million to plan additional dam construction in Eastern Washington[4]. There are almost 80,000 dams in the US, and globally, dam construction is considered to be one of the major vehicles through which humans are affecting the hydrological cycle and the downstream transport of multiple bio-active compounds, including N, and P[5,6,7]. Predictions of nutrient transport are particularly sensitive to how reservoirs are treated in

[1] Washington State Department of Ecology, 2004, Nutrient criteria development in Washington State: Phosphorus, Publication No. 04-10-033.

[2] WA Depart.of Ecol. 2004

[3] National Research Council, 2000, Clean waters: Understanding and reducing the effects of nutrient pollution. National Academy of Science Press, Washington, D.C.

[4] McClure, R., March 8, 2006, State placing $200 million bet on dam building: expensive push to explore water storage in Eastern Washington, *Seattle Post-Intelligencer*

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[6] Harrison, J. A., S. P. Seitzinger, A. F. Bouwman, N. F. Caraco, A. H. W. Beusen and C. Vörösmarty (2005) Dissolved inorganic phosphorus export to the coastal zone: results from a spatially explicit, global model (NEWS-DIP), *Global Biogeochemical Cycles, 19*, GB4S03, doi:10.1029/2004GB002357, 1-15.

[7] Dumont, E., J. A. Harrison, C. Kroeze, E. J. Bakker and S. P. Seitzinger (2005) Global distribution and sources of DIN export to the coastal zone: results from a spatially explicit, global model (NEWS-DIN), *Global Biogeochemical Cycles, 19*, GB4S02, doi:10.1029/2005GB002488, 1-14.

existing models[8,9]. In some systems such as the Colorado and Rio Grande, reservoirs have been estimated to remove up to 99% of the original N and P load. Yet, relatively little is known about how reservoirs process nutrients. Reservoirs are generally thought to reduce N and P transport by trapping nutrients[10,11,12]. However, the effects of individual dams can be quite variable, and in some systems reservoirs have actually been observed to enhance downstream nutrient transport[13,14].

Research on Lacamas Lake aims to answer several questions pertinent to current understandings of nutrient dynamics in small reservoirs.

Q1: What is the reservoir's annual denitrification flux?
Q2: What is the reservoir's annual flux of two globally important greenhouse gases: CH_4 and N_2O?
Q3: What are the annual nutrient budgets for NO_3^-, NO_2^-, PO_4^{3-}, NH_4^+, and SiO_2?
Q4: How does seasonal stratification influence the factors that control important nutrient processes within the reservoir?

METHODOLOGY

Monthly Monitoring Field Work- June 2007-September 2008

A buoy was set up at the deepest part of the reservoir (DW site; Figure 1) with five Hobo Pro V2 Temperature Loggers attached to it at in order to monitor stratification and mixing of the reservoir. At least monthly sampling was conducted at the DW site, at the bridge where Lacamas Lake narrows into a channel that flows into Round Lake, at the outlet both below and above the dam, and less frequently at the inlet to the reservoir. At each site a DS5X Sonde was used to take temperature, turbidity, dissolved oxygen, pH, and chlorphyll *a* measurements along a vertical profile at 1m increments. Samples were then collected using a Van Dorn sampler at approximately 1m increments. Greenhouse gas samples (for N_2O, CH_4, and CO_2) were taken in 60mL glass Wheaton vials capped with gray rubber butyl and aluminum crimp tops. N_2:Ar samples were collected in 5 ml hollow penny-head, ground-glass-stoppered vials. And filtered (Whatman 0.45uM filters) and unfiltered nutrient samples were taken in 30mL Nalgene bottles.

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[8] Dumont et al., 2005
[9] Harrison et al., 2005
[10] Beusen, A. H. W., A. L. M. Dekkers, A. F. Bouwman, W. Ludwig and J. A. Harrison (2005) Estimation of global river transport of sediments and associated particulate carbon, nitrogen, and phosphorus, *Global Biogeochemical Cycles*, 19, GB4S05, doi:10.1029/2005GB002453, 1-19.
[11] Dumont et al., 2005
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[14] Ahearn DS, Sheibley RW, Dahlgren RA, 2005, Effects of river regulation on water quality in the lower Mokelumne River, California. *River Research and Appliications* 21 (6): 651-670.

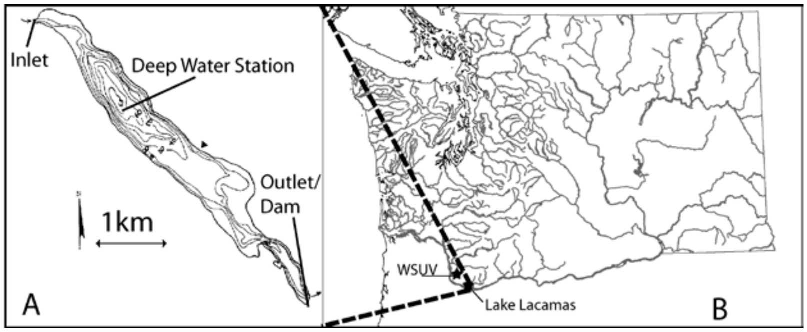

Figure 1. Bathymetry of Lacamas Lake, showing inlet, outlet, and within-lake deep-water sampling station (A), and location of Lacamas Lake (B).

Monthly Monitoring Lab Work

N_2:Ar samples were analyzed on a Pfeiffer Membrane Inlet Mass Spectrometer (MIMS)[15]. Greenhouse gas samples were analyzed on a Hewlett Packard 5890 Series II-Plus Gas Chromatograph after introducing 20mL He headspace to each Wheaton. Currently, a majority of the filtered nutrient samples have been analyzed for PO_4^{3-}, NO_3^-, NO_2^-, SiO_2, and NH_4^+ using a Westco Scientific Instruments Smart Chem 200 analyzer. Unfiltered samples are currently frozen for future total P and Total Kjeldahl N analysis.

Dye Addition Experiments- July 2007 and March 2008

To examine hydrologic mixing and determine a gas transfer coefficient, two dual tracer (Rhodamine-WT and SF_6) additions were conducted on Lacamas Lake, one in July 2007 and one in March 2008. During the first experiment approximately 4 liters of Rhodamine-WT were added to 14 liters of water and SF_6 was bubbled in. The 18 liter Rhodamine-SF_6 solution was then added to the inlet of Lacamas Lake (Lacamas Creek) at 13:35 on July 17 2007. Using a Van Dorn sampler, chosen locations were continuously sampled for SF_6 and Rhodamine-WT. During the second experiment approximately 4 liters of Rhodamine-WT were added to 32 liters of water and SF_6 was bubbled in. The 36 liters of solution was pumped down to 14m at the DW site. Using a Sonde DS5X, a kayaker then followed the center of the plume. Using a Van Dorn sampler, Rhodamine-WT and SF_6 samples were taken from the center of the plume and from, on average, 6 points surrounding the center point. Rhodamine-WT samples were collected in Evergreen tubes and run on a Turner 10-AU Fluorometer. SF_6 samples were collected and analyzed according to the same protocols used for greenhouse gas measurements.

Denitrification Potential Assay- August 2007 and January 2008

Estimates of potential denitrification at the DW site were calculated using the

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[15] Kana, T.M., C. Darkangelo, M.D. Hunt, J.B. Oldham, G.E. Bennett, and J.C. Cornwell. 1994. Membrane inlet mass spectrometer for rapid high-precision determination of N2, O2, and Ar in environmental water samples. Anal. Chem. 66: 4166-4170.

C_2H_2 block method. During the August experiment, nine 60mL glass Wheaton vials were filled with reservoir water from the surface, nine from 5m, and nine from 17m using a Van Dorn Sampler. Nine additional Wheaton vials were filled with sediment and overlying water collected using an Eckman Dredge. Three replicates from each depth were treated as controls and three were fertilized with KNO_3. Helium headspace was introduced and evacuated, and 10mL of C_2H_2 were added to each sample. After three vials from each treatment type were sampled and analyzed for initial N_2O concentrations, samples were incubated for approximately 4 hours and then run on a Hewlett Packard 5890 Series II-Plus Gas Chromatograph for N_2O concentrations. The same procedure was followed for the January experiment except that samples were taken from 5m and sediment only as the water column was well-mixed during this time.

Sediment Traps

In order to quantify reservoir sedimentation rates and assess their organic matter content, three sediment traps were designed and assembled based on Larsson et al. 1986[16]. Sediment was collected, dried, and weighed three times over the course of summer 2008 (May-July, July-August, and August-September) in order to quantify sediment deposition rates. Dried samples were prepared for C:N analysis in Pullman and are currently being analyzed.

N-Fixation Assays

To quantify the degree to which N_2 under-saturation is due to N-fixing plankton activity, N-fixation rates were quantified using the C_2H_2 addition method. We calculated N-fixation rates for both the photic zone (composite Van Dorn sample of surface, 2m, and 4m) and the bottom water (composite Van Dorn sample of 13m, 15m, and bottom) at Lacamas Lake's DW site on three days (7/28/08, 8/15/08, and 9/11/08) during summer stratified conditions. For each zone sampled, 45mL of sample were poured into each of 12 60mL Wheatons for a total of 24 samples. After crimping the caps, 2.25 mL of C_2H_2 was injected in each vial. Duplicate samples were taken from each zone at 0, 15, 30, 60, 120, and 240 minutes after C_2H_2 introduction using 10mL BD luer-lok syringes and Cole Parmer stopcocks. Syringe samples were stored on ice and run on a Hewlett Packard 5890 Series II-Plus Gas Chromatograph for C_2H_4 analysis within 6 hours of collection.

Sediment Core Incubations

In order to both quantify denitrification rates in reservoir sediments and identify factors limiting the process we began setup to conduct a series of sediment core incubations in August 2008. Methods and results from this endeavor will be described in the synopsis report for project 2008235B.

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[16] Larsson, U., S. Blomqvist, and B. Abrahamsson. 1986. A new sediment trap system. Mar. Ecol. Prog. Ser. 31: 205-207.

PRINCIPAL FINDINGS AND SIGNIFICANCE

One critical and previously unaddressed question facing aquatic biogeochemists is the degree to which stratification within lentic systems (lakes and reservoirs) influences within system nutrient cycling and downstream nutrient transport. Our initial results lend insight into the relationship between stratification and nutrient dynamics in a reservoir system. Results from the potential denitrification assays show a potential denitrification approximately three orders of magnitude higher in reservoir sediments than in the overlying water column. Potential denitrification in reservoir sediment was also found to be approximately twice as high in the winter as in the summer. Despite these high potential wintertime rates, N_2:Ar samples from monthly monitoring at the DW site show that N_2 concentrations are significantly higher during summer stratified conditions than during winter mixed conditions (two tailed t-test $p<0.01$, Figure 2B). During summer stratified conditions water below 6m was consistently supersaturated with N_2 whereas winter bottom water was consistently under-saturated with N_2 (Figure 2A). Summertime N-fixation assays did not find any significant N-fixer activity, however our observations of summertime epilimnion N_2 undersaturation suggest that relatively low rates of N-fixation may occur with a high degree of spatio-temporal variability throughout the summer. It should be noted that two of the three N-fixation assays we carried out were conducted during days when the epilimnion was not undersaturated with respect to N_2. While we expect that under-saturation of N_2 in winter bottom water is the result of physical mixing, winter N-fixation and denitrifcation rates should be more thoroughly investigated to better understand the relative importance of winter mixed conditions to system N-removal. Because both physical and biological factors influence ambient N_2 concentrations, we must interpret ambient N_2 concentration data with caution. Still, the high excess N_2 concentrations in summer bottom water strongly suggest high denitrification rates along the sediment-water interface during stratified conditions. Average excess N_2 concentrations below 6m during the summer can account for the

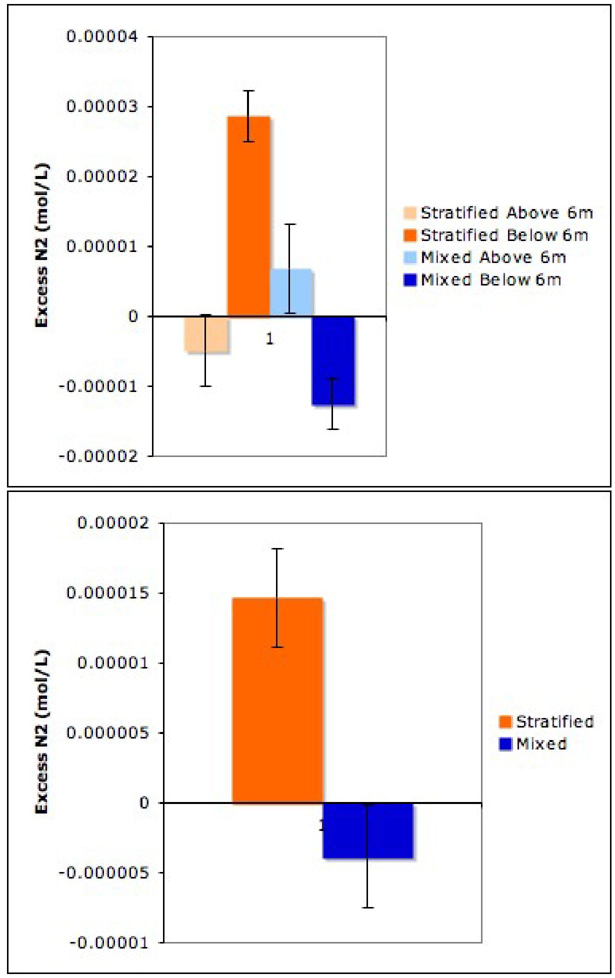

Figure 2. Mean N_2:Ar saturation in bottom versus top water in mixed and stratified conditions (A) and averaged across the entire vertical profile at the DW Site (B). 1 indicates 100% saturation.

removal of over 0.4 mg/L NO_3-N system-wide. It is also interesting to note that N_2 super-saturation steadily increases in the summer in contrast to the low and sporadic excess N_2 concentrations seen in the winter months (Figure 3A). The accumulation of N_2 in the reservoir's hypolimnion over the course of the summer is not explained by a temperature effect and is most likely due to reduced mixing across the thermocline boundary during this time. Conservative estimates of microbial N removal based on this assumption indicate that N removal rates are extremely high during the final stages of stratification (late June to early July, Figure 3B). In fact N_2 accumulation in the hypolimnion over a few weeks in late spring accounted for all the nitrate present in the hypolimnion during winter mixed conditions. Rapid increases in bottom water N_2O concentrations during spring stratification also indicate that this may be a hot moment for N transformations. The spatio-temporal variabilities in our dataset will be discussed in more detail in the synopsis report for project 2008235B and provide foundational support for an Emerging Topics in Biogeochemistry proposal recently submitted to NSF.

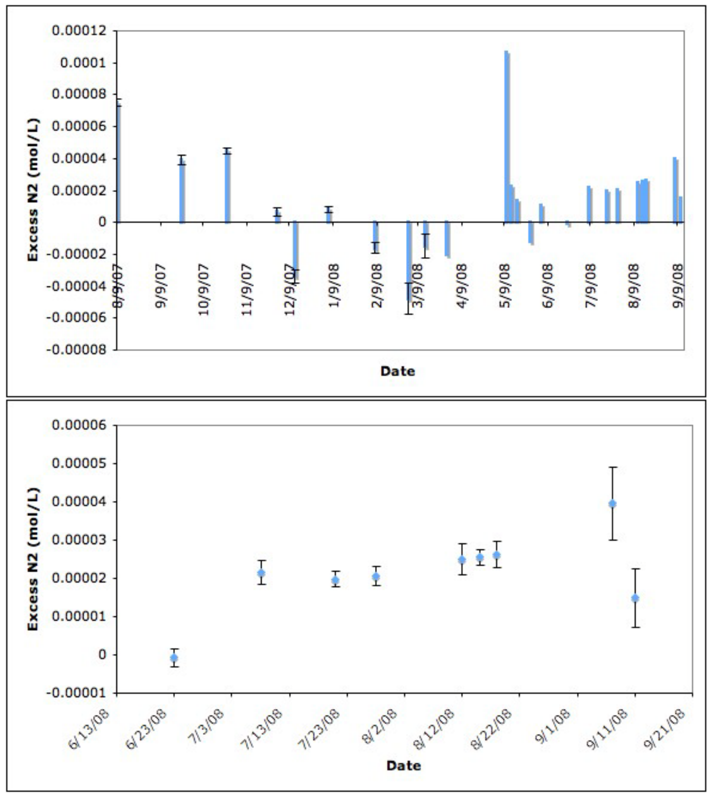

Figure 3. Mean excess N_2 in the hypolimnion on each day sampled (A), and during summer 2008 stratified conditions (B).

Preliminary results from nutrient analyses show significantly higher levels of PO_4^{3-} in the inlet than at the DW site in July (single variable ANOVA, $p<0.05$) and significantly lower levels of PO_4^{3-} near the reservoir outlet than at the DW site in December (single variable ANOVA, $p<0.05$). Such findings emphasize how reservoir nutrient dynamics differ seasonally.

Spring and summer sedimentation rates also suggest seasonal differences in N dynamics. Mean sedimentation rates from May-July (412 $\mu g/cm^2/day$) were approximately double the rates observed from July-August (228 $\mu g/cm^2/day$) or August-September (216 $\mu g/cm^2/day$). This suggests a higher supply of substrate for denitrifiers during the late stages of stratification when denitrification rates appear extremely high.

Through a combination of monthly monitoring and targeted experiments, this project has highlighted the potential spatio-temporal variability in the biogeochemistry of a small freshwater reservoir. In doing so, results have provided the foundation for a proposal to investigate hot moments and hot spots for N transformations within this system. Our finding, that a small reservoir acts as an important N sink, has important implications for modeling N transport at larger scales and for dam management strategies. Sediment incubations and more in-depth data analysis that aim to better explain the controls on reservoir biogeochemical transformations will be further discussed in the synopsis report for project 2008235B.

Reservoir Sediments: Biofilter or Environmental Liability?

Basic Information

Title:	Reservoir Sediments: Biofilter or Environmental Liability?
Project Number:	2008WA235B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	Washington 17
Research Category:	Water Quality
Focus Category:	Hydrogeochemistry, Nutrients, Water Quality
Descriptors:	None
Principal Investigators:	John Harrison

Publication

2. Deemer, Bridget R., John A. Harrison, and E. Whitling. Nitrogen removal in a small eutrophic reservoir: seasonal patterns and controls. (In preparation)
3. Harrison, John A., R. Maranger, R. B. Alexander, A. Giblin, P.A. Jacinthe, E. Mayorga, S. P. Seitzinger, D.J. Sobota, and W. Wollheim. 2008. Controls and Significance of N Retention in Lakes and Reservoirs. Biogeochemistry, 10.1007/s10533-008-9272-x.
4. Harrison, John A., A. F. Bouwman, E. Mayorga, and S. P. Seitzinger. Magnitudes and Sources of Dissolved Inorganic Phosphorus Inputs to Surface Fresh Waters and the Coastal Zone: A New Global Model. Global Biogeochemical Cycles. (Submitted)
5. Seitzinger, S. P. and John A. Harrison, 2008, Sources and Delivery of Nitrogen to Coastal Systems, Chapter 8 in Nitrogen in the Marine Environment, 2nd edition, D. Capone, D. A. Bronk, M. R. Mullholland, and E. Carpenter editors, Academic Press, New York.
6. Deemer, Bridget R., and John A. Harrison. 2009. Stratification Influences Nitrogen Removal in a Eutrophic Reservoir: Potential Implications for Dam mMnagement. Poster presentation at the conference Water and Land Use in the Pacific Northwest: Integrating Communities and Watersheds, November 4-6, 2009. Stevenson, Washington.
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8. Deemer, Bridget R., John A. Harrison, and Kara Goodwin, 2008 Seasonal Variation in Denitrification in a Small Eutrophic Reservoir: Lacamas Lake, Camas Washington. Poster presentation at the Western Division of the American Fisheries Society Annual Meeting, May 4-9, 2008, Portland, Oregon.
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12. Deemer, Bridget R., 2007, Washington State University Studying Lacamas Lake. VIEWS - The Official Publication of the Lacamas Shores Homeowners Association December 2007/January 2008, page 4.
13. Deemer, Bridget R., and John A. Harrison, 2008. Nutrients in Lacamas Lake: Too Much of a Good Thing? Public outreach poster project for the City of Camas, Washington.
14. Deemer, Bridget R. and John A. Harrison, 2008, Seasonal Variation in Denitrification in a Small Eutrophic Reservoir: Lacamas Lake, Camas Washington. Poster presentation at the Washington State University Vancouver Research Showcase, Vancouver, Washington.
15. Freeman, Dawn M. and John A. Harrison, 2008, Phytoplankton and Freshwater Eutrophication: a Look at Lacamas Lake. Poster presentation at the Washington State University Vancouver Research Showcase, Vancouver, Washington.
16. Whitling, Elliott, and John A. Harrison, 2008, Dentrification Potential Assay of Water Column. Poster presentation at the Washington State University Vancouver Research Showcase, Vancouver, Washington. Winner of Undergraduate Student Poster Award.

PROBLEM AND RESEARCH OBJECTIVES

Human-induced nitrogen (N) and phosphorus (P) over-enrichment of surface waters is an important problem in Washington State, throughout the Northwest US, and worldwide. In Washington State, 664 lakes and reservoirs and 748 fresh-water entities have been reported as exceeding the standard for 303d listing with respect to phosphorus (P) concentrations[1] and many lakes and reservoirs have elevated levels of nitrogen (N) as well.[2] These eutrophic lakes and reservoirs are prone to problems such as: 1) loss of swimming, fishing, and aesthetic enjoyment due to nuisance algal blooms, periphyton, and macrophyte growth, 2) loss of aquatic life from dissolved oxygen depletion caused by excess algal and aquatic macrophyte respiration and decay, and 3) loss of drinking water due to the onset of foul odors, clogging of filters, algae toxins, and formation of trihalomethanes (THMs) as water disinfection byproducts.[3] Barring the drinking water concerns, a similar suite of issues is associated with nutrient over-enrichment of coastal waters[4]. Thus it is critical to understand transport of nutrients through watersheds and the biogeochemical processes that account for sources and sinks of bioactive elements like N and P.

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[6] Vörösmarty, C., Meybeck, M., Fekete, B., Sharma, K., Green, P., and Syvitski, J.P.M., 2003, Anthropogenic sediment retention: Major global-scale impact fromt eh population of registered impoundments. *Global and Planetary Change* 39(1/2): 169-190.

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[9] Dumont et al. 2005.

[10] Harrison et al. 2005.

trapping nutrients.[11,12,13] However the effects of individual dams can be quite variable, and in some systems reservoirs have actually been observed to enhance downstream nutrient transport.[14,15]

Previous study at Lacamas Lake has highlighted some of the spatio-temporal variability in system biogeochemistry. Seasonal stratification appears to exert a particularly important influence on nitrogen transformations in the hypolimnion, and is thus expected to influence other nutrient cycling as well. Because reservoirs increase the residence time of water and nutrients in rivers, it is also expected that dam management may play an important role in determining the biogeochemical function of reservoirs.

Research on Lacamas Lake aims to answer several questions pertinent to current understanding of nutrient dynamics in small reservoirs.

Q1: How do carbon (C) and nitrate availability impact summertime denitrification rates and how spatially variable is sediment denitrification between littoral and profundal zones?
Q2: How does stratification and changing oxygen availability influence sediment phosphate flux?
Q3: What are the C and N sedimentation rates of the system and how does this change over time?
Q4: How do chemical concentrations along the sediment-water interface change during the stratification event?
Q5: Does the September dam spill influence hypolimnion chemical concentrations?

METHODOLOGY

Nitrogen Sediment Core Incubations

In order to quantify denitrification rates in reservoir sediments and identify factors limiting the process, we conducted a series of sediment core incubations in August 2008. Using an Eckman Dredge with SCUBA weights attached, sediment cores were taken from the deep water (DW) site. Cores were constructed of 2-1/4" OD, 2-1/8" ID polycarbonate round tubing that were 35cm long. Cores were stoppered on both ends and holes were drilled in the top stopper to attach a sampling tube with a 2-way VWR stopcock and a Kangaroo IV bag for lake water sample replacement. Cores were topped off with bottom water and care was taken to avoid entrainment of air bubbles. Three replicates were constructed with a NO_3^- addition using KNO_3, three were treated with a carbon addition using CH_3COONa, three were treated with a combination of carbon and NO_3- addition, three contained un-amended lake water and sediment, and three contained lake water without sediment (blanks). We sampled the cores approximately every three hours for N_2:Ar, N_2O, NO_3^-, NH_4^+, PO_4^{3-}, and NO_2^- over the course of a 27 hour incubation.

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[11] Beusen, A.H.W., A.L.M. Dekkers, A.F. Bouwman, W. Ludwig, and J.A. Harrison, 2005, Estimation of global river transport of sediments and associated particulate carbon, nitrogen, and phosphorus, *Global Biogeochemical Cycles*, 19, GB4S05, doi: 10.1029/2005GB002453, 1-19.
[12] Dumont et al. 2005.
[13] Harrison et al. 2005.
[14] Kelly, V.J., 2002, Influence of reservoirs on solute transport: a regional-scale approach. *Hydrological Processes* 15: 1227-1249.
[15] Ahearn, D.S., Sheibley, R.W., Dahlgren, R.A., 2005, Effects of river regulation on water quality in the lower Mokelumne River, Californion. *River Research and Applications* 21(6): 651-670.

Sediment Traps

In order to quantify reservoir sedimentation rates and assess sediment carbon and nitrogen content, three sediment traps were designed and assembled based on Larsson et al. 1986[16]. Sediment was collected, dried, and weighed two times over the course of summer 2008 (July-August and August-September) twice during the winter 2009 (January-February and February-March) and twice in the spring (May-July 2008 and March-April 2009) in order to quantify sediment deposition rates. Dried samples were prepared and sent to Pullman for analysis of sediment C and N content.

Potential Denitrification Experiments

In order to ascertain the degree of spatial variability in sediment denitrification activity, we intend to estimate potential sediment denitrification across a depth gradient using C_2H_2 block assays. Samples will be collected in early July from five locations spanning the deep water site to the littoral zone. We will take care to include areas where the thermocline contacts the lake bed, as this is hypothesized to be a zone of high denitrification due to the fluctuating oxygen conditions expected here. Nine 60mL glass Wheaton vials will be filled with sediment and overlying water at each site using the Eckman dredge (for a total of 45 samples). Helium headspace will be introduced and evacuated, and 10mL of C_2H_2 will be added to each sample. After three vials from each site are sampled and analyzed for initial N_2O concentrations, three samples will be incubated with a NO_3-N addition and three control samples will be incubated. After 6-16 hours of incubation, these samples will be analyzed for final N_2O concentrations. N_2O concentrations in headspace will be translated into aquatic N_2O concentrations using Weiss and Price solubility constants[17], and an N_2O evolution rate for each treatment will be determined. If time allows we will also investigate temperature effects by incubating samples from one site at different temperatures.

Hypolimnion Sampling Across the Stratification Event

We took samples along a vertical profile (1-2m intervals) at the DW Site at approximately weekly intervals across the stratification event in order to document changes in bottom water chemistry during the onset of hypoxia. We followed the sampling and analysis protocol as was explained in the synopsis report for project 2007WA139B. Briefly, at each depth a DS5X Sonde was used to take temperature, turbidity, dissolved oxygen, pH, and chlorphyll *a* measurements. Samples were then collected using a Van Dorn sampler at approximately 1m increments. Greenhouse gas samples (for N_2O, CH_4, and CO_2) were taken in 60mL glass Wheaton vials capped with gray rubber butyl and aluminum crimp tops. N_2:Ar samples were collected in 5 ml hollow penny-head, ground-glass-stoppered vials. And filtered (Whatman 0.45uM filters) and unfiltered nutrient samples were taken in 30mL Nalgene bottles. N_2:Ar samples were analyzed on a Pfeiffer

[16] Larsson, U., S. Blomqvist, and B. Abrahamsson. 1986. A new sediment trap system. Mar. Ecol. Prog. Ser. 31: 205-207.
[17] Weiss, R.F., and B.A. Price. 1980. Nitrous-oxide solubility in water and seawater. Marine Chemistry 8(4): 347-359.

Membrane Inlet Mass Spectrometer (MIMS)[18]. Greenhouse gas samples were analyzed on a Hewlett Packard 5890 Series II-Plus Gas Chromatograph after introducing 20mL He headspace to each Wheaton. Currently, a majority of the filtered nutrient samples have been analyzed for PO_4^{3-}, NO_3^-, NO_2^-, SiO_2, and NH_4^+ using a Westco Scientific Instruments Smart Chem 200 analyzer. Unfiltered samples are currently frozen for future total P and Total Kjeldahl N analysis.

Mass Balance Sampling

Inlet and outlet filtered and unfiltered nutrient samples were collected during summer 2008 and winter 2008-2009 in order to better understand how the reservoir acts as a sink or source of various nutrient species. Summer samples have been analyzed while winter samples are currently frozen for future analysis.

Phosphate Sediment Cores

In order to better understand the environmental controls on internal loading of phosphate from lake sediments to the water column, we will conduct incubations of sediment slurries under oxygen rich and anoxic conditions. We will also evaluate the relative importance of biotic and abiotic processes contributing to sediment phosphorus release by comparing living and "killed" (autoclaved) sediments. Each treatment will consist of three replicate vials incubated over a period of 24 hours.

PRINCIPAL FINDINGS AND SIGNIFICANCE

One critical and previously unaddressed question facing aquatic biogeochemists is the degree to which stratification within lentic systems (lakes and reservoirs) influences within-system nutrient cycling and downstream nutrient transport. Intensive monitoring during a springtime stratification event as well as targeted sediment incubation experiments show that the onset of hypoxia is a dynamic and active time for nutrient transformations. Results also suggest that physical mixing events including dam spill play an important role in the system's capacity to both remove nitrogen and produce greenhouse gases.

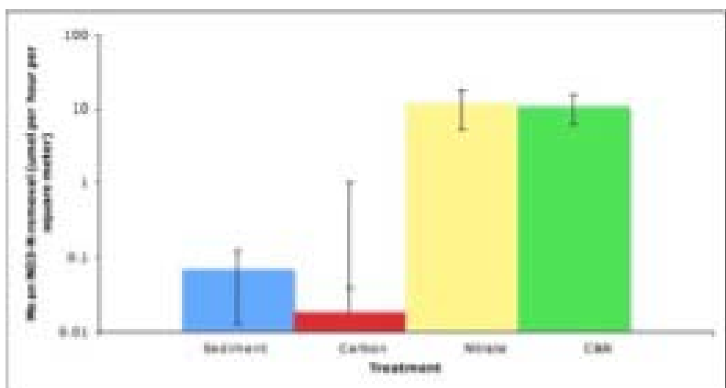

Figure 1. Mean NO_3-N removal by treatment type in August 2008 sediment cores.

Nitrogen sediment core incubations revealed that sediment nitrate removal was significantly limited by nitrate with no carbon co-limitation apparent (ANOVA, $p=0.001$, Figure 1). The hypoxic hypolimnion may be the primary driver of limited nitrate supply

[18] Kana, T.M., C. Darkangelo, M.D. Hunt, J.B. Oldham, G.E. Bennett, and J.C. Cornwell. 1994. Membrane inlet mass spectrometer for rapid high-precision determination of N_2, O_2, and Ar in environmental water samples. Anal. Chem. 66: 4166-4170.

across the sediment-water interface, both through chemical (no oxygen for nitrification) and physical (thermocline as a transport barrier) means. Based on these results, we expect that physical

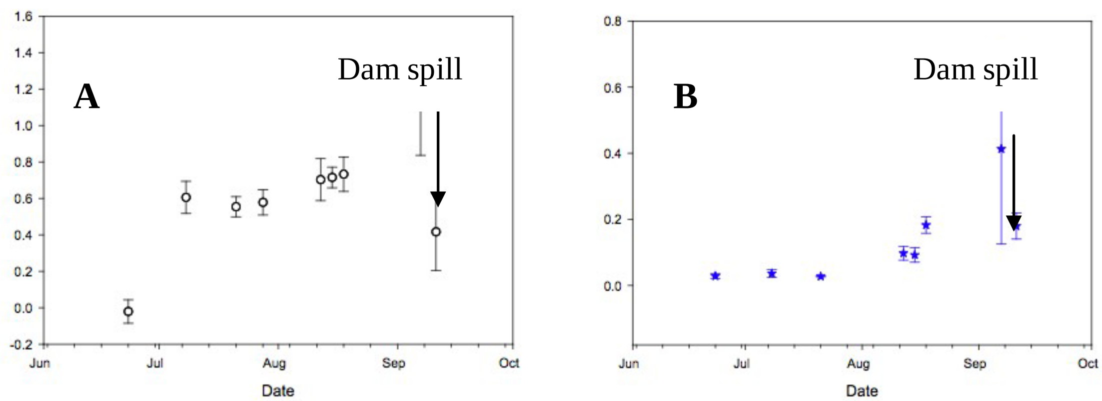

Figure 2. N_2 (A) and N_2O (B) concentrations in the hypolimnion during the summer 2008. Standard error bars shown.

mixing events such as heavy rainfall, heavy wind, wind direction shifts, or change in dam spill may partially alleviate nitrate limitation during summer months and increase the reservoir's overall N-removal rate. Changes in hypolimnion gas concentrations during dam spill strongly suggest that dam spill can destabilize the thermocline (Figure 2) thus potentially mixing oxidized species towards the sediment-water interface.

Sampling across the stratification event reveals rapid increases in hypolimnion N_2O concentrations that are strongly negatively correlated with ambient dissolved oxygen concentrations (R^2=0.78, Figure 3). We also observed an extreme jump in bottom water N_2 concentrations late in the stratification event (Figure 2A, between first and second point) suggesting that microbial N removal is boosted during this time. The onset of strong stratification in early July then appears to cap gas exchange across the thermocline such that N_2 and N_2O accumulate in the hypolimnion throughout the summer. Fall dam spill, then, appears to destabilize the thermocline allowing N_2 and N_2O to escape to the atmosphere.

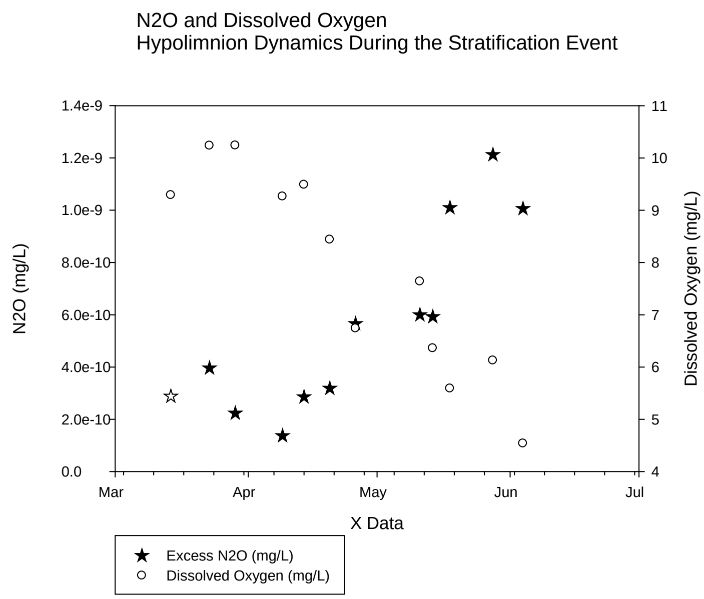

Figure 3. Dissolved N_2O and O_2 concentrations across the stratification event.

A conservative estimate of microbial N removal rate late in the stratification event (based on an assumption that gas is accumulating in the hypolimnion) emphasizes the magnitude of N removal during this time. In fact, denitrification over this short two-week period removes an amount of N equivalent to all wintertime nitrate dissolved in the water column. Our in-situ summer denitrification estimate, calculated using the hypolimnion accumulation approach, falls within the bounds of denitrification rates reported for other reservoir systems (Figure 4). We are aware of only one other study, conducted in an estuary, that has looked at in-situ N_2 accumulation as a proxy for denitrification rate[19], making these results a novel contribution to methodology in denitrification research. It is also interesting to note that the rate estimate we find using this in-situ approach is notably higher than the rate estimates produced by more traditional laboratory based incubation experiments in the same system. The summer mass balance denitrification rate estimate (35.6 umol N m^{-2} h^{-1}) is not included in Figure 4, but is less than half the size of the hypolimnion accumulation rate estimate. This highlights the accuracy limitations associated with using spatially and temporally discrete sampling and black box estimates to capture system-wide rates and provides strong support for a new in-situ method for measuring denitrification rates in stratified lentic systems.

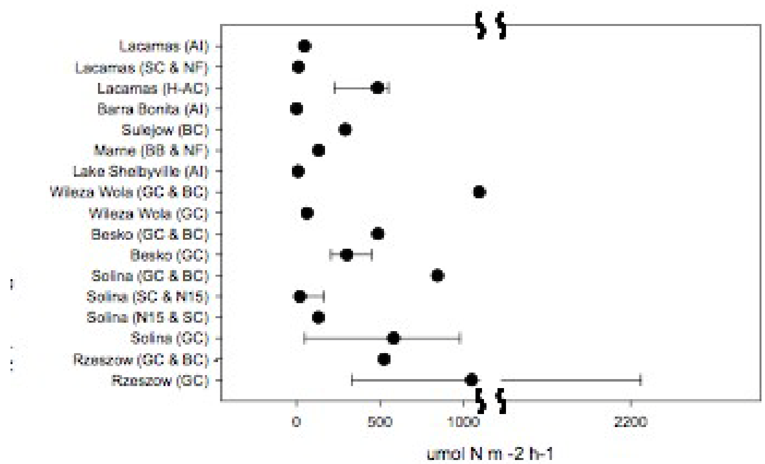

Figure 4. Published denitrification rates in other reservoir systems* as well as rates quantified in our lab. Method approaches are abbreviated in parentheses: Acetylene Inhibition (AI), Sediment Cores (SC), Nitrate Flux (NF), Hypolimnion Accumulation (H-AC), Benthic Chambers (BC), Gas Chromatography (GC), and ^{15}N Isotope Pairing (N15).

Ongoing research will attempt to identify spatial and temporal hot spots and hot moments for N removal. A better understanding of both the variability and overall magnitude of reservoir N removal has important implications for system modeling and potentially for dam management practices. Phosphorus cores will also help us gain a better understanding of the impact of bottom-water hypoxia on other nutrient transformations and fluxes. Sampling has also yielded an extensive greenhouse gas concentration record. We expect that future analysis of N_2:N_2O ratios will provide us with useful information on how the reservoir may act as both a bio-filter and a greenhouse gas source. Following analysis of Lacamas sediment samples we will also have a better understanding of the relative importance of sedimentation in system N cycling. Overall, research on sediment processes at Lacamas Lake has shown that the reservoir is an important N sink, has supported the development of an exciting new in-situ method for quantifying system N removal, and emphasizes the spring stratification event as a hot moment for system biogeochemical cycling.

[19] Kana, T.M., J.C. Cornwell, and L. Zhong. 2006. Determination of denitrification in the Chesapeake Bay from measurements of N_2 accumulation in bottom water. Estuaries and Coasts 29: 222-231.

Towards Sustainable Phosphorus Removal: Evaluating Biogenic Iron Oxides for Renewable Filtration

Basic Information

Title:	Towards Sustainable Phosphorus Removal: Evaluating Biogenic Iron Oxides for Renewable Filtration
Project Number:	2008WA239B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	Washington
Research Category:	Engineering
Focus Category:	Nutrients, Water Quality, Treatment
Descriptors:	Batch Equilibrium, De-sorption, Iron-Oxidizing Bacteria
Principal Investigators:	Jeremy Rentz, David Yonge

Publication

1. Cordray, Antoine, 2008, Phosphorus Removal Characteristics of Biogenic Ferrous Iron Oxides, MS Thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, Washington, 72 pages.
2. Rentz, Jeremy A., Haley R. Falconer, Thomas Leake, Cameron Turtle and Andrew E. McDonald, 2009, Biogenic Iron Oxides: A Regenerable Sorbent for Phosphorus and Heavy Metals, Presentation at the 2009 Conference of the Association of Environmental Engineering and Science Professors, Grand Challenges in Environmental Engineering and Science: Research and Education, July 26 to July 29, 2009, Iowa City, Iowa.

PROBLEM AND RESEARCH OBJECTIVES

Achieving phosphorus discharge regulations is a principle concern for municipal and industrial wastewater treatment operations, particularly with the current trend toward increasingly stringent phosphorus limits. In the State of Washington thirty seven lakes are currently impaired specifically by excess phosphorus inputs (www.epa.gov/owow/tmdl/). In order to restore these lakes, Total Maximum Daily Load (TMDL) allocations will be developed for all rivers, creeks, streams and tributaries that drain into the lakes. Additionally, three hundred seven Washington water bodies are currently impaired due to low dissolved oxygen levels, a problem that will be rectified in part by limiting phosphorus discharges through additional TMDLs. While the State of Washington will clearly be impacted by development of phosphorus TMDLs, this problem is a nationwide issue. More than four thousand water bodies are impaired by excess nutrients (nitrogen and phosphorus).

Current phosphorus treatment strategies are poor treatment options when discharge limits significantly less than 1.0 mg P/L are required, as is likely the case for many phosphorus TMDLs nationwide. Generally, enhanced biological phosphorus removal (EBPR) yields effluent concentrations around 1.0 mg P/L, suggesting the technology will require improvements to meet future performance standards. Chemical precipitation can achieve low discharge limits, but cost of chemical additives becomes prohibitive. Alternative treatment methods utilizing iron-oxide rich matrices effectively remove phosphorus from water, but extended long term use is limited by finite removal capacities. Thus, novel sustainable processes removing phosphorus from water and wastewater are required to meet discharge limitations and restore our nation’s impaired waters.

This project specifically investigated biogenic iron oxides produced by microaerobic, iron-oxidizing bacteria. These unique bacteria grow at near neutral pH (5.5 to 7.5) and deposit iron oxides as a growth by-product. They are found in groundwater seeps (Emerson and Revsbech, 1994), freshwater wetlands (Weiss *et al.*, 2007), and clogged wells and pipes (Ralph and Stevenson, 1995). The objective of this project was to evaluate phosphorus removal by biogenic iron oxides in order to determine feasibility as a wastewater treatment alternative. Two specific tasks were completed to accomplish this objective: (1) characterize sorption of phosphorus to biogenic iron oxides and (2) determine phosphorus release from biogenic iron oxides. The rationale for these studies was that a fundamental understanding of the interactions between biologically produced iron oxides and phosphorus would provide a strong foundation for future studies designed to transfer this innovative treatment scheme to full scale applications.

METHODOLOGY

Sixteen biogenic iron oxide samples were collected between April 2008 and August 2008 from four different freshwater locations, including Moose Creek Reservoir, ID, Myron Lake in Yakima, WA, Spring Lake, WA and Rainbow Lake, WA. Each site was visually characterized by significant amounts of red-orange iron oxides. All samples were collected between using sterile plastic pipettes or plastic buckets and transferred to autoclaved glass bottles. Samples were concentrated by letting the biogenic iron oxides settle during collection, decanting overlying water, and filling bottles with additional iron oxides. In situ parameters were also measured for the water directly overlying collected iron oxides, including pH, temperature, and ferrous iron (Hach FerroVer). Samples were transported to the lab on ice and stored at 4ºC prior to analysis and experimentation.

Biogenic iron oxides were chemically, physically, and morphologically characterized to compare samples with each other and with other iron-based substrates. Total iron was determined using the Hach FerroVer method following a 24 hour oxalic acid (0.25M) digestion (Rentz et al., 2007); three replicates were conducted for each sample. Total solids content and organic content were determined by gravimetric methods using four replicates per sample. Iron oxide morphology was captured for each sample using a Leica DMLB light microscope with SPOT software (Diagnostic Instruments Inc.); acridine orange (10 mg/L) was used to visualize microbial cells. Aqueous total organic carbon and phosphorus were measured using the Hach Method 10129 and Hach Method 8048, respectively. pH of the settled sample supernatant was also recorded.

Prior to use in batch equilibrium or desorption experiments, the biogenic iron oxides were washed with a 100 mM sodium chloride solution to remove background phosphorus. A dilute saline solution was used as an isotopic solution that would not interfere with subsequent experimentation. This procedure replaced between 40% and 60% of initial water. All samples were once again chemically and physically characterized following this wash step.

Batch equilibrium experiments were performed using standard methods (Rentz et al., 2009). Saline washed biogenic iron oxide samples were evenly distributed to sterile plastic tubes. The nature of the sample determined the total iron concentration in the reaction tubes. Fresh and gelatinous iron mats were supplied at 150 mg Fe/L. Experiments on older and settled biofilms required 350 mg Fe/L. The volume of washed sample added to the tubes was adjusted accordingly. Initial phosphorus concentrations from 0.163 to 20.9 mg P/L were created using a 326 mg P/L stock solution and were examined with five replicates each. DI water was added to achieve a final 50 mL tube volume. All tubes were mixed by rotation (20 r.p.m.) for 24 hours, a time kinetic studies previously suggested was adequate to reach equilibrium (Rentz et al., 2008). Tubes were then centrifuged (4100 r.p.m. for 10 min) and supernatant phosphate concentrations were measured for each tube using Hach Method 8048.

The desorption experiments also used a modified batch equilibrium process. A 24 hour rotation cycle was run with 16 reaction tubes containing 20.9 mg P/L and saline washed samples as described previously. The tubes were then centrifuged and the supernatant phosphate was measured. Supernatant (30 mL) was removed and replaced with one of four stock solutions: deionized water, a 0.1 M saline wash solution, a 0.01 M KCl solution and a 0.01 M NaOH solution. Each solution was conducted in quadruplicate. These tubes were rotated again for 24 hours, centrifuged, and the supernatant phosphate concentration measured. Again 30 mL of supernatant was replaced by an equal volume of desorption solution. This 24 hour cycle was repeated four times. Prior to phosphorus analyses, pH was adjusted to 6-8 with 0.3 M MES buffer solution.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Moose Creek and Rainbow Lake microbial iron mats were physically and chemically different from Myron Lake and Spring Lake. Two different types of biogenic iron oxide biofilms were encountered, *fresh* and *old*. Fresh samples from Myron Lake and Spring Lake were light orange in color, had a gelatinous consistency and were comprised primarily of iron oxide sheaths attributed to *Leptothrix ochracea*. Alternatively, old samples were brown-orange, were settled in the water column and contained a variety of different iron oxides that may or may not be attributed to iron-oxidizing bacteria. The two samples also differed considerably on a chemical basis. The fresh samples contained low total iron concentrations, between 222 and 575 mg Fe/L, and low total solids values, from 0.317 to 3.19 g/L. In contrast, the old samples contained iron concentrations from 2412 to 3378mg Fe/L and total solids concentrations of 3.08 to 8.85 g/L.

All samples showed potential for phosphorus adsorption and produced expected sorption isotherms (Figure 1). The Langmuir equation (R^2 = 0.939 to 0.972) provided a better fit than the Freundlich equation (R^2 = 0814 to 0.895), suggesting that biogenic iron oxides were saturated with phosphorus. Despite visual and chemical differences between fresh and old samples, sorption maximum was statistically no different for these samples. However, we are investigating this further in our current research. When normalized to sorbent mass, maximum phosphorus sorption ranged from 7.2 to 28.0 mg P/g solids and when normalized to iron content values ranged from 24.2 to 54.9 mg P/g Fe. While most researchers do not report iron normalized values, the iron oxides in the samples are responsible for observed sorption and they may prove to be an important design parameter.

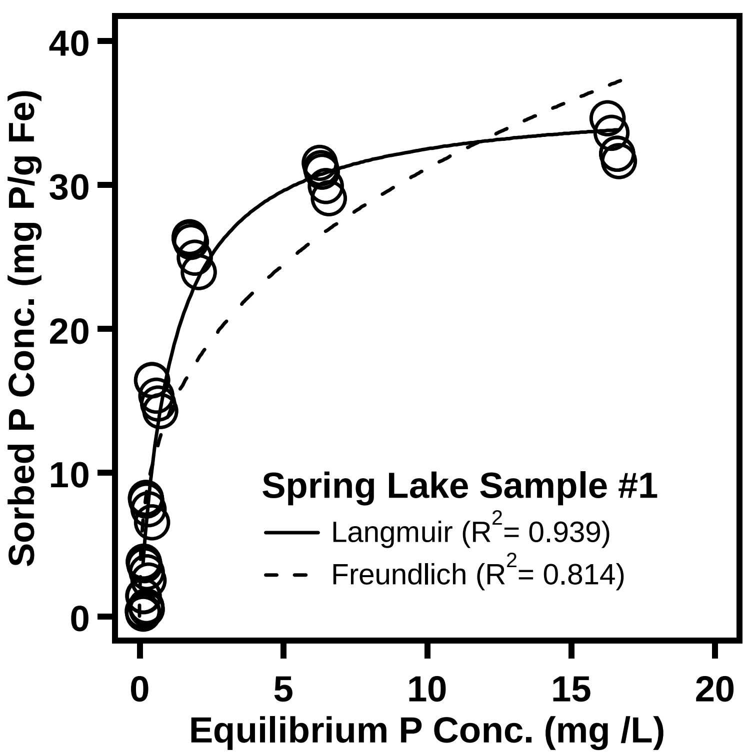

Figure 1. *Representative isotherm showing phosphorus sorption to biogenic iron oxides. Langmuir and Freundlich equations were fit using non-linear regression (Igor Pro).*

Our biogenic iron oxides compared favorably with previous studies that evaluated iron rich or iron-oxide containing substrates (Figure 2). The wide variety of substrates examined previously included, iron oxide coated sand, engineered materials (gypsum and brick), pure iron oxides (goethite and akaganeite), and recycled materials (tailings and two juniper fibers). While we have only begun evaluating biogenic iron oxides for phosphorus removal, these comparisons suggested that future research is warranted.

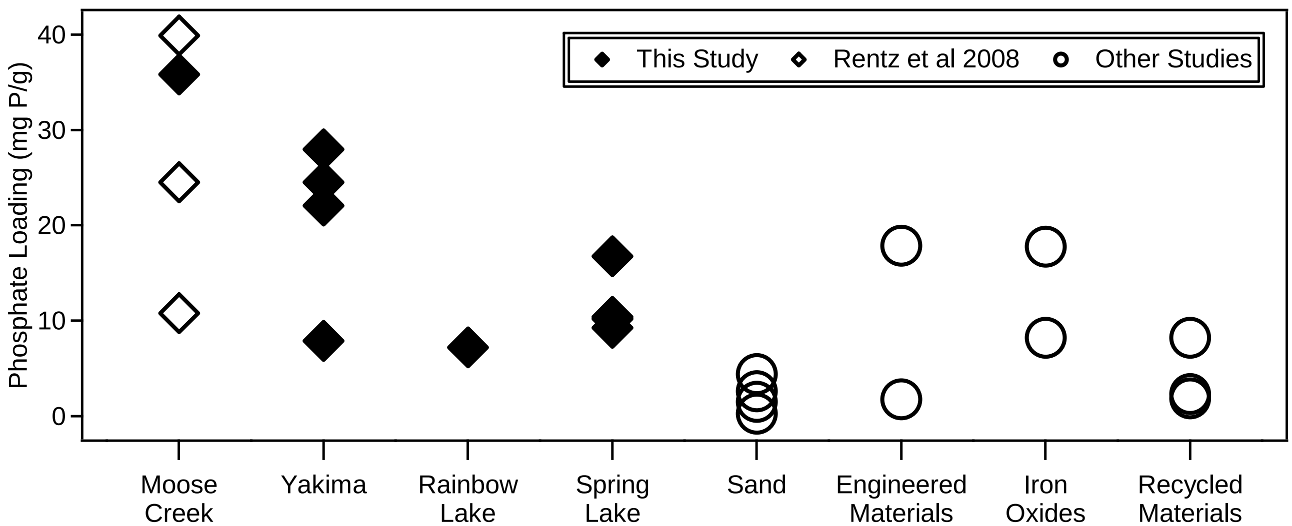

Figure 2. *Maximum phosphate loadings for various iron rich substrates. The values represented by the circles were either synthetic or natural sorbents investigated in previous studies. Sand substrates were determined from Boujelben et al. (2008), Arias et al. (2006), and Del Bubba et al. (2003). Engineered Materials were gypsum and brick, respectively, issued from Bastin et al. (1999) and Boujelben et al. (2008). Iron oxides were pure materials; goethite and akaganeite studied in Chitraker et al. (2006). Recycled materials were tailings from Zeng et al. (2004) and juniper fiber (precipitated acid mine drainage onto plant fibers) from Han et al. (2005).*

The potential for phosphorus recycling was limited for biogenic iron oxides under our test conditions. Phosphorus release was low for all chemicals except a basic solution (Figure 3), where greater than 100% recover was observed for all four samples examined. Presumably, all phosphorus that was added during the initial sorption experiment was desorbed and excess was due to cell lysis. However, this mass balance could not be completed with our experimental methods. DI water released 40.60% of sorbed P on average, but again the contribution of microbial cell lysis is unknown. Previous laboratory experience showed that DI water lysed cells and phosphorus could be recovered from our field collected samples. Finally, KCL solution released on average 30.37% P and the saline solution 20.23%. These two isotopic solutions should not lyse microbial cells and likely represent actual phosphorus desorbed. While phosphorus release was limited, our results match the published literature where phosphorus sorption to iron oxides has not been described as reversible (Zeng et al., 2004; Arias et al., 2006). For example, Zeng et al. 2004 observed 13 to 14% P release using a solution of KCL.

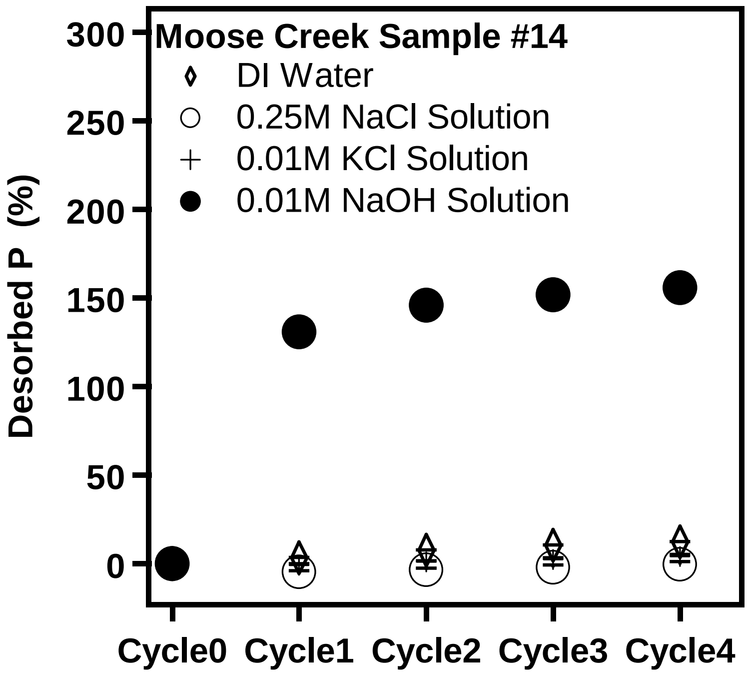

Figure 3. *Representative phosphorus desorption from biogenic iron oxides facilitated by various solutions. Cycle 0 represented the first batch equilibrium run. Cycle 0 was used to adsorb phosphorus prior to desorption. Desorption occurred during Cycles 1 to cycle 4, each lasting 24 hours. Error bars represent the standard deviations from the mean of four replicates.*

Results from this study showed that biogenic iron oxides were a good substrate for phosphorus removal and suggested that future research should be conducted to evaluate whether the technology can be transferred to pilot scale applications or full scale implementation. Several limitations and concerns were identified, which must be addressed for successful use. First, the wide range of sorption capacities must be understood, so that removal efficiencies can be predicted. We are currently attempting to quantify surface area as a parameter that may better predict sorption capacity. Second, a reasonable recycle strategy must be devised in order to make this process sustainable. Because ferrous iron will likely be needed as an input to the system, any phosphorus recovered would help offset these costs.

In addition to use as a process for the wastewater industry, man-made biofilters could also be used to address no point source pollution. Prime candidates include farm runoff and stormwater, where ditches could be modified to serve as a habitat for the iron-oxidizing bacteria that would be exploited. Here, seasonal flows and the growth needs of the iron-oxidizing bacteria would need to be further investigated to produce reliable treatment.

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Zeng, L., Li, X., Liu, J., 2004. Adsorptive removal of phosphate from aqueous solutions using iron oxide tailings. Water Research 38, 1318-1326.

Assessing Pathogen Fate and Transport through Riparian Buffers in an Agricultural Watershed

Basic Information

Title:	Assessing Pathogen Fate and Transport through Riparian Buffers in an Agricultural Watershed
Project Number:	2008WA248B
Start Date:	3/1/2008
End Date:	2/28/2009
Funding Source:	104B
Congressional District:	WA 5th
Research Category:	Water Quality
Focus Category:	Non Point Pollution, Agriculture, Surface Water
Descriptors:	Riparian Buffers, Pathogens, Fecal Indicators, E. coli
Principal Investigators:	Jeffrey Layton Ullman, Karen Killinger, Joan Q Wu

Publication

1. Paternostre, Guillaume. 2008. Assessing the Role of Physicochemical and Biochemical Soil Characteristics on Escherichia coli Attachment. M.S. Thesis. Department of Civil and Environmental Engineering, College of Engineering and Architecture, Pullman, Washington. 92 pages.
2. Paternostre, Guillaume, 2009, Assessing the Role of Physiocochemical and Biochemical Soil Characteristics on E. Coli Attachments, in Lessons in Continuity and Change in the Fourth International polar Year, presented by the Inland Northwest Research Alliance (INRA), Fairbanks, Alaska, March 4-7, 2009. page 65.

PROBLEM AND RESEARCH OBJECTIVES

Bacterial contamination prevents 604 waterbodies from meeting designated water use criteria in the State of Washington, primarily resulting from nonpoint source pollution. Fecal contamination from nonpoint sources in agricultural watersheds often results from livestock having direct access to streams and riparian areas, which can lead to degraded drinking and recreational waters. Failure to meet water quality standards designed to prevent pathogen-related illnesses represents a critical issue facing agricultural sustainability in Washington, as bacterial loads from diffuse sources inhibit beneficial uses and present a significant human health risk.

Riparian buffers represent a Best Management Practice (BMP) that can exclude livestock from surface waters and limit off-site transport of nonpoint source pollutants. These natural filters function by increasing sediment deposition, enhancing infiltration and providing soil and vegetative adsorptive surfaces. Riparian buffers have similarly been shown to encourage pathogen retention during overland flow, as soil particles act as important pathogen vectors due to bacteria preferentially adhering to solid substrates. Despite these initial findings, appropriate design parameters essential in minimizing pathogen contamination from livestock operations have not been quantified. Despite initial findings, appropriate design parameters essential in minimizing pathogen contamination from livestock operations have not been quantified. Furthermore, the extent these buffers affect pathogen fate and transport remains largely unknown.

The lack of fundamental knowledge on pathogen movement in the environment not only represents an important problem in trying to reduce pathogen-related health risks originating from agricultural sources, but also hinders riparian buffer adoption and management. Collaborating with the Washington Department of Ecology and the Palouse Conservation District, this project aimed to fill this knowledge gap. Thus, the project goal was to assess bacterial fate and transport at varying spatial scales (laboratory and watershed) to aid in the development and implementation of better riparian buffers. The following specific objectives were followed to support this goal:

1) **Quantify pathogen sorption in soils** - Laboratory analysis used representative soils that may be found in riparian buffers to characterize properties that contribute to bacterial/pathogen retention.
2) **Characterize water quality and fecal coliform presence in watershed -** Watershed-scale monitoring provided baseline data to identify linkages between land use impacts and water quality.

METHODOLOGY

Due to the potential health risks and associated publicity, *E. coli* O157:H7 was identified as the pathogen of focus in this study, along with two non-pathogenic *E. coli* strains (K12 and H4H). Fecal coliform bacteria was selected for assessment in the watershed monitoring component, because it is the fecal indictor parameter used by the Washington Department of Ecology and provided compatibility with previous and ongoing monitoring studies in the watershed. Appropriate QA/QC protocol was followed throughout the study.

Methods for Objective 1: Limited studies exist that examine bacterial sorption to soils. Batch experiments adapted from Gantzer et al. (2001) and Guber et al. (2005; 2007a) were used, as they follow similar methods used by PI Ullman for chemical sorption analysis.

Six soils collected from throughout Washington that displayed disparate physicochemical characteristics were used to assess *E. coli* attachment. The first experiment investigated correlations between soil physicochemical characteristics and *E. coli* H4H. The second experiment investigated the differential attachment properties displayed by *E. coli* O157:H7, *E. coli* K12 and *E. coli* H4H for two of the soils. Different *E. coli* strains were used to determine if disparate behavior exists between the pathogenic *E. coli* O157:H7 that presents a human health risk and other *E. coli* strains. The use of multiple strains is important because environmental monitoring typically only examines "generic" *E. coli*, and it needs to be determined if this approach accounts for the pathogenic strain.

For both experiments, solutions of the three *E. coli* strains were added at different concentrations to soils to create soil-water suspensions of selected ratios. Preliminary experiments showed that an equilibrium time was reached after 2 hours, and that maintaining the solutions at 8°C resulted in no change in *E. coli* populations over this time period. Thus, the spiked solutions were shaken for 2 hours at 8°C and subsequently centrifuged to remove the soil from suspension. Bacterial concentrations in the supernatant were enumerated using standard plating techniques using appropriate agars (e.g., MacConkey agar). The attached bacterial cells were calculated by the difference between the amount applied and that recovered in the supernatant. Sorption data was fitted to the appropriate standard isotherm equation (e.g., Langmuir).

Methods for Objective 2: Water quality samples were taken monthly at strategic sites on the North Fork Palouse River based on conversations with the Palouse Conservation District. Fecal coliform concentrations were determined using standard filtration techniques. Phosphorus, nitrate and ammonia concentrations were also determined for these samples to evaluate correlations between bacterial levels and other water quality parameters. In addition, ancillary data (dissolved oxygen, pH, salinity, conductivity and temperature) were recorded using a YSI multi-probe meter.

PRINCIPAL FINDINGS AND SIGNIFICANCE

Correlations between *E. coli* H4H attachment and 12 soil physicochemical properties were assessed in the first experiment. Soil physicochemical analysis was conducted in Dr. Kennedy's laboratory (USDA-ARS) for the six soils. Percent clay content and percent organic matter exerted a strong positive relationship with bacterial attachment (R^2 values of 0.86 and 0.87, respectively), while soil pH demonstrated a significant negative association ($R^2 = 0.84$). It is hypothesized that surface area and available binding sites are the primary attachment mechanism related to clay content; the negative charge typical of soil particles likely did not influence attachment as bacterial cells also exhibit a negative charge. However, this charge effect likely contributed to the pH relationship, as lower pH values result in more positive charges in the soil slurry. Organic matter provides a large surface area for bacterial binding, as well as a complex lattice-type structure that may entrap bacterial cells.

Isotherms for the different soils each followed a Freundlich sorption model with all R^2 values greater than 0.94. Freundlich coefficients varied considerably between soil types, ranging from 0.64 for the low-clay, low-organic matter soil to 3.86 for the high-clay, high-organic matter soil.

For the second sorption experiment, bacterial attachment parameters presented no significant difference between *E. coli* strains. As far as we can determine, this is the first comparison of binding efficiency for pathogenic and non-pathogenic strains. This is an important finding, as it answers the question whether field monitoring for "generic" *E. coli* is representative of the behavior exhibited by *E. coli* O157:H7.

The field monitoring component of this project found no significant relationship between fecal coliform bacteria and the other water quality parameters analyzed. Similarly, no significant association was found relating the presence of riparian buffers and fecal coliform levels. These results were further confounded by no relationship between locations in proximity to livestock operations. It is hypothesized that the majority of fecal coliforms in the North Fork Palouse River originate from wildlife, as higher bacterial levels were typically associated with more remote areas devoid of livestock and housing development.

Award No. 08HQGR0149 Alternative Cover Design and Construction for Solid Waste Landfills in Arid Regions

Basic Information

Title:	Award No. 08HQGR0149 Alternative Cover Design and Construction for Solid Waste Landfills in Arid Regions
Project Number:	2008WA297S
Start Date:	8/22/2008
End Date:	12/31/2008
Funding Source:	Supplemental
Congressional District:	WA 7
Research Category:	Not Applicable
Focus Category:	Management and Planning, Models, Hydrology
Descriptors:	Ground Water, Landfills, Vadose Zone Hydrology, Evapotranspiration, Final Covers
Principal Investigators:	Michael Ernest Barber

Publication

1. Albright, W. and Benson, C. 2008), Store-and-Release Covers for Waste Containment: Principles and Practice, Project Report Submitted to US Geological Survey and US Environmental Protection Agengy. 135pp. This report will also be published as a book by ASCE Press.

PROBLEM AND RESEARCH OBJECTIVES

The objective of this project was to prepare a guidance document regarding design and construction of store-and-release covers for solid waste landfills based on lessons learned from the Alternative Cover Assessment Program (ACAP).

METHODOLOGY

The methodology consisted of writing a report summarizing all elements of ACAP in an easy to understand and implement format. Emphasis was placed on how to apply the lessons learned in ACAP rather than the detailed scientific research that formed the basis of ACAP. Presentations from a workshop series conducted by the PI and subcontractor W. Albright were used as the basis for the report.

PRINCIPAL FINDINGS AND SIGNIFICANCE

The report was created to provide engineers, designers, and regulators with the basic principles behind selection and design of store-and-release (S&R) covers for waste containment. Much of the document is derived from observations and lessons learned from USEPA's Alternative Cover Assessment Program (ACAP). The document begins with two chapters discussing basic issues affecting the selection of S&R covers, where they are appropriate and under what circumstances, and key factors to be considered by the engineer, regulator, and owner. Two subsequent chapters provide principles of soil physics and plant physiology that are relevant to design and evaluation of S&R covers. This fundamental information is incorporated into two chapters on design. The first of these chapters covers preliminary design. A method to compute cover thickness is described that is based on balancing infiltration to be stored with storage capacity within the cover. The second chapter discusses computer modeling to validate or refine a design, to assess sensitivity, and to evaluate "what if" questions. The last chapter describes what can be expected in terms of field performance and methods for monitoring performance. Data from ACAP are described along with inferences that can be made about performance expectations in other locations in the US.

Information Transfer Program Introduction

Education and Public Outreach are critical components of the State of Washington Water Research Center's mission. The primary goal of information transfer activities 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 formal and informal activities 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 unbiased interpreted science that can be applied to solving the regions' water problems. The Center makes substantial efforts to facilitate the process through both independent and partnership opportunities. 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:	3/1/2007
End Date:	2/28/2009
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

1. Barber, M. and B. Bower, 2006, Evaluating Diversion Alternatives Affecting Environmental Flows and Temperatures, Presentation at UCOWR/NIWR Annual Conference, Increasing Fresh Water Supplies, Santa Fe, New Mexico.
2. Simmons,R., M. Barber, and J. Dobrowloski, 2006, Washington State University - Providing Solutions to Critical Water Issues, National Association of State Land Grant Universities and Colleges, NASULGC Science Exhibit on the Hill, Washington, D.C.
3. Barber, Michael E., Frank Loge, A. Al-Omari, and M. Fayyad, 2008, Water Quality and Quantity in Jordan s Dead Sea Wadis, Water International 3(3): 369-379.
4. Sorenson, Fred and Michael E. Barber, 2009, Region 10 Water Quality Conference: Building Transboundary Partnerships, Poster Presentation at the USDA National Water Quality Conference, St. Louis, Missouri, February 2009.
5. Barber, Michael E., 2009,Future Solutions: Educational Needs in the Jordan River Watershed, oral presentation at the conference Transboundary Water Crises: Learning from Our Neighbors in the Rio Grande (Bravo) and Jordan River Watersheds, Las Cruces, New Mexico, January 2009.
6. Mahler, Robert and Michael E. Barber, 2008, Change in Public Attitudes and Behaviors over Time about Water Resource Issues in the Pacific Northwest Region of the USA, presentation at World Water Week, Stockholm, Sweden, August 2008.
7. Barber, Michael E., M. O Neill, and M. Landers, 2008, Needs Assessment for a Multilateral Middle East Regional Water Training Initiative, presentation at the 2008 UCOWR/NIWR Annual Conference, International Water Resources: Challenges for the 21st Century, Durham, North Carolina, July 2008.

In order to achieve the goals outlined in the introduction, the following information transfer activities were conducted. It is important to recognize that several of these activities are highly leveraged with activities related to other research projects being conducted by the SWWRC. Nevertheless, without some support from the program, these activities would not be possible or as frequent.

The SWWRC Director was invited by the US Environmental Protection Agency to participate in a public forum discussing nitrate contamination of drinking water in the Yakima basin. Federal, state, tribal, and local government agencies as well as concerned citizens and dairy farmers met to discuss issues, potential solutions, and next-steps associated with reported nitrate levels reaching 50 mg/L (well above the 10 mg/L water quality criteria). The SWWRC helped provide the independent sound science aspect of the meeting.

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 US EPA Region 10 and the NRCS. Six meetings are held each year and communication between researchers, extension faculty, and government agencies is improved considerably by the activity. This project also provides some of the funding that the SWWRC leverages for support of a biennial water conference related to an emerging theme as identified by a regional steering committee. Planning for the November 2009 conference began during this year involving venue selection, call for abstract development, and other related activities. This highly successful conference draws over 200 local decision makers from around the region and works as an excellent avenue for showcasing SWWRC research efforts. Student competition in the poster session helps promote the education goal of the Center.

SWWRC co-sponsored the Palouse Basin Water Summit; a local event attracting stakeholders and concerned citizens from the bi-state watershed (ID and WA). Participants learn about water conservation, efforts to quantify groundwater resources, and other critical aspects of local watershed planning and management.

Director Michael Barber attended the NIWR meeting in Washington, DC to interact with other directors from around the country. He also attended a UCOWR meeting in Durham, NC to attend a NIWR Board meeting and present an oral presentation on work in Jordan. At the invitation of the New Mexico Water Institute, he also gave a presentation at their international conference on transboundary water issues.

We were also asked to participate in a one-day symposium on watershed management and research in the Walla Walla watershed. This was sponsored by a local NGO and had participation from Oregon and Washington state, tribal, and local officials.

SWWRC sponsored a mini-retreat for water resources research attended by the WSU Vice President for Research and over a dozen water-related faculty. The goal of the retreat was to educate the upper administration regarding expertise and identify future research initiatives that were vital to the state and region. The Center also sponsored a graduate seminar on water resources and will continue to look for opportunities to expand these efforts.

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 other researchers at the Universities of Alaska, Idaho, Utah State and Washington State, as well as other regional universities (Boise State, Idaho State, Montana, and Montana State). The project involves bi-monthly conference calls aimed at establishing a regional needs assessment (recently completed) and coordinating research and education programs integrating water science, policy, and decision making. The project recently took on a task of developing a regional water data portal called “ICEWATER” modeled after the NSF HIS system to allow data sharing.

Maintaining and 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. We currently have all our research reports available for download via PDF format allowing for greater access and utilization of study results.

The Water Center Director traveled to Jordan to participate in an educational effort whereby Iraqi agricultural specialists were brought to Jordan for a week long training session of water resources management in arid climates. This was part of a larger effort between WSU and several other universities aimed at improving lifestyles in Iraq through improved, state-of-the-art technology transfer.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	6	0	0	0	6
Masters	6	1	0	0	7
Ph.D.	0	3	0	0	3
Post-Doc.	0	0	0	0	0
Total	12	4	0	0	16

Notable Awards and Achievements

One of the Center's Program Directors (Marc Beutel, Environmental Limnology) was recently awarded a prestigious Career Grant from the National Science Foundation based in-part on some of his initial mercury cycling work funded by our 104(B) Program.

Publications from Prior Years

1. 2002WA190G ("Using Environmental Tracers to Improve Prediction of Nonpoint Pollutant Loadings from Fields to Streams at Multiple Watershed Scales") - Articles in Refereed Scientific Journals - Nitrate in Tile Drainage of the Semiarid Palouse Basin, by C. Kent Keller, Caroline N. Butcher, Jeffrey L. Smith, and Richelle M. Allen-King.a 2008.Journal of Environmental Quality 37:353-361. doi:10.2134/jeq2006.0515
2. 2004WA76B ("Three-dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality") - Articles in Refereed Scientific Journals - Heterogeneous Characteristics of Streambed Saturated Hydraulic Conductivity of the Touchet River, South-Eastern Washington USA, by Randal Leek, Joan Q. Wu, Li Wang, Timothy Hanrahan, Michael E. Barber, and Hanxue Qiu. 2009. Hydrological processes 23:1236-1246. doi:10.1002/hyp.7258.