State of Washington Water Research Center Annual Technical Report FY 2007

Introduction

Established in 1964, the mission State of Washington Water Research Center (SWWRC) is to facilitate, coordinate, conduct, and administer water−related research important to the state and the region; to educate and train engineers, scientists, and other professionals through participation in research and outreach projects; and to 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.

These broad research, education, and outreach goals require the multi−pronged adopted by the SWWRC. 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 areas are in addition to the Director's primary research interests in surface−ground water interaction, remote sensing, and stormwater. These areas are reviewed annually to determine if additional opportunities exist to highlight and promote specializations within the SWWRC faculty and to facilitate outside recognition of expertise. The SWWRC is also involved in international research and education activities.

Lessons learned from the research and outreach components are disseminated to faculty and used by the Director to enhance the education goal. Research projects are also used as a mechanism to fund both graduate and undergraduate education.

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

It is within this overall context that the USGS−funded activities reported in this document must be inserted. These include the internally−funded projects as well as the national awards to the Center. These projects provide a solid core to the diverse efforts of the SWWRC. Water quantity and quality issues continue to be a major concern in the State of Washington due to ecological water requirements permeated via the endangered species act, population growth, industrial requirements, and agricultural activities. Emerging issues such as water resources management in the face of global climate change, sustainable development, water reuse, interstate conflicts, energy−related water quantity and quality considerations, and increased stormwater runoff regulations are also beginning to raise concern. All of these issues will be important drivers of the activities of the SWWRC in the foreseeable future.

Research Program Introduction

In accordance with its core mission, 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 in consultation by a Joint Scientific Committee (JSC) which includes representatives from water resource professionals at state agencies, universities from across the state, and the local USGS office. The SWWRC supports competitively awarded internal grants involving water projects evaluated by the JSC. The SWWRC also actively seeks multidisciplinary research at local, state, and national levels and seeks cooperative efforts with research groups in the state. Meeting between stakeholder groups, potential funding agencies, and research faculty are arranged as opportunities arise. Faculty are apprized of any research opportunities. The SWWRC also submits proposals on its own behalf.

During FY 2007, three research projects were selected for funding by the SWWRC at the recommendation of the Joint Scientific Committee: • Quantifying and Enhancing Nitrogen Removal in Constructed Wetlands, • Lackamas Lake and other Northwest Reservoirs as Bioreactors: How do Dams Affect Downstream Nutrient Transport? • Assessment of Contaminated Sediments Using a Rainbow Trout (Onchorhynchus mykiss) as an Embryonic Exposure Assay As described below, these projects address state issues but are also relevant to national interests.

One national project was conducted through the SWWRC during this period: West Wide Drought Forecasting System: A Scientific Foundation for National Integrated Drought Information System (NIDIS). An update of this project is also presented in this report.

One other project was funded through the USGS/Water Institute partnership. The project involved a USGS project in Jordan where the SWWRC assisted by hiring Jordanian nationals to conduct research to improve Groundwater Management in Jordan. This project ended in December and a synopsis report is provided.

Award No. 05HQAG0001 – Improving Groundwater Management in Jordan

Basic Information

Title:	Award No. 05HQAG0001 – Improving Groundwater Management in Jordan
Project Number:	2005WA188S
Start Date:	1/1/2005
End Date:	1/31/2008
Funding Source:	Supplemental
Congressional District:	NA
Research Category:	Ground−water Flow and Transport
Focus Category:	Groundwater, Water Use, Management and Planning
Descriptors:	Jordan Groundwater Database, Education and Training, Modeling
Principal Investigators:	Michael Ernest Barber

Publication

1. Yousef, Dina A. and William C. Steinkampf, 2006, Using GIS in ground−water management studies, Abstract, Proceedings of the ESRI Middle East and Africa Users Conference, November 2006, Amman, Jordan.
2. Ismail, Ma'moon, 2006, Groundwater depletion in the Shoubak region (Abstract), Yarmouk University Groundwater Conference, September 10, 2006, Irbid, Jordan.
3. Ismail, Ma'moon, William C. Steinkampf, Suhail Sharadqah, and Dina Yousef, 2006, Optimization Modeling Training Using an MWI Ground−water Model: Jordan Ministry of Water and Irrigation. USGS Administrative Report to USAID, 6 p.
4. Steinkampf, William C., 2006, Overview of Extant Ground−water Models: Jordan Ministry of Water and Irrigation. USGS Administrative Report to USAID, 11 p.
5. Steinkampf, William C., Ma'moon Ismail, Suhail Sharadqah, and Dina Yousef, 2006, Ground−water data development in Jordan: Observations and Recommendations. USGS Administrative Report to USAID, 14 p.

Problem

The Hashemite Kingdom of Jordan has an estimated 600 million cubic meters (MCM) of annually renewable surface and groundwater resources. Water demand has been rising yearly and in 2005 reached about 1,400 MCM. The groundwater portion of the total usage was 2-3 times the estimated total annual safe yield. This ground-water mining has led to water-quality deterioration in a few locales and to large water level declines in most pumping areas, and will lead to undesirable economic and social impacts on water users and the Jordanian economy. The ability of the Jordanian Ministry of Water and Irrigation (MWI) to manage and regulate the Kindgom's water resources is constrained by its ability to develop and used hydrogeologic data and information in the development and implementation of water-use policies and controls.

Objectives

The Ministry of Water and Irrigation (MWI) and the U.S. Agency for International Development (USAID) recognize that the widening gap between available renewable resources and increasing demands necessitates policy and management decisions that will require an improved understanding of Jordanian groundwater systems. This led USAID to establish a project agreement with the U.S. Geological Survey (USGS) to address hydrogeologic data development and use in MWI. The USGS thereupon coordinated with the State of Washington Water Research Center to hire three Jordanian hydrogeologists as the project team to be led by a senior USGS scientist stationed in Amman. On completion of the project, the Jordanian staff were in the process of being hired by MWI, as agreed upon by MWI and USAID.

Project objectives were as follow.

1. Enhance MWI skills in the collection, development and use of ground-water data.
2. Develop the capability within MWI to use constrained optimization techniques to support resource-management decisions.
3. Develop a proactive ground-water users group in a designated area.
4. Establish and train the project team for future hire by MWI.

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

Methodology

1. Hydrogeologic data and information, developed to address a variety of issues and concerns, currently reside in a variety of Jordanian databases, and in reports of previous and ongoing studies. Data and information products that describe water resources at scales that range from local to national have been developed both independently by MWI staff and jointly with a number of geotechnical entities.

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

2. Many MWI technical staff members have been introduced to development and use of numerical groundwater models via training courses funded by donor projects and agencies. Ground-water models of many part of the Kingdom have been developed by largely by donor projects. While the current models provide variably useful insight to potential physical consequences of groundwater use, it is of value to link modeling results with socioeconomic considerations. Constrained-optimization modeling is a tool that can provide an augmented level of scenario examination

The project provided training to the project team and selected MWI staff members that included classroom training in GIS use in data organization and analysis, USGS instruction in ground-water information and model development and use, and USGS instruction in the development and use of optimization criteria, parameters, constraints, and softwares.

Principal findings and significance

The project team comprises one female geologist [B.Sc.] and two male hydrogeologists [M.Sc. and PhD]. The project was sited in MWI and functioned well as a team and within the Ministry environment. Team members successfully integrated and coordinated activities with appropriate MWI staff.

1. The team used data and information from the MWI data base, file searches, interviews and interaction with MWI, Ministry of Agriculture, Department of Land Surveys, Royal Jordanian Geographic Center, and donor-project staffs to identify data issues and to develop the analytical approach to be used for data review. MWI's collection and development of ground-water data and information entails the use of equipment and techniques that have not significantly evolved since their introduction in the mid 1980s. Data are collected largely by rote and are not adequately checked. Many data are not entered to the MWI data base. Quality control and assurance procedures do not exist.

Because of these conditions, MWI ground-water data are of variable quality and utility. Fortunately, the causes of the variability were largely identified. The team developed and implemented a suite of procedures to correct noted concerns in data collection and development. Reviews and analyses also led to development of 12 ground-water data packages, one for each ground-water basin in Jordan. The packages are syntheses of existing ground-water data and information. They include GIS maps and linked data and information, Excel files for individual monitoring sites, and summaries of hydrogeologic information and identified problems. Problems identified in historic data likely in many cases can be fixed using the data packages developed by the project team.

2. The level of hydrogeologic capability found within MWI is relatively low for the following reasons. 1) The Jordan educational system does not provide guidance appropriate to technical needs within Jordanian Ministries. 2) There is a surfeit of engineers in the country who are working outside their respective disciplines because of the paucity of jobs. As such, many are hired to fill hydrogeologist positions, within which they learn a modicum of relevant information, but cannot function as might be expected based on job title. 3) Although MWI staff members receive a significant amount of training each year, the training typically is not linked to ongoing or planned job assignments. 4) Experience development within MWI is limited because MWI does not have a coherent ground-water studies program within which staff could be expected to function and grow professionally.

Temporary-duty USGS hydrogeologists provided about 30 weeks of on-site training that covered hydrogeologic framework concepts and information, ground-water model development, and use of constrained optimization concepts, techniques, and softwares. The individual levels of ability in the team members required revision of the original training agenda to augment comprehension and use of hydrogeologic concepts and modeling techniques. This training preceded introduction to optimization techniques. This hydrogeologic base was that upon which optimization training was based. The end result was that the project team developed the ability to design and conduct optimization analyses of ground-water systems, and to include economic aspects in their analyses.

3. The Minister of Water and Irrigation assigned the Shoubak area in southern Jordan as the site for development of a 'pilot' water-users group. The area is one in which the dominant water uses are domestic/municipal and irrigation. The team first developed a hydrogeologic description of the area, then used this knowledge to inform residents and officials in the region of the ground-water situation. These information meetings led to formation of the group that currently is functioning. The group comprises staff from various levels of local-to-national governmental entities, private citizens, NGOs, and investor farmers. The group was developed via a set of meetings and workshops that led to a coherent working entity that assumed control of its actions early in the organizational process. Dialogue between local residents, non-resident investors, and local, regional, and national governmental entities was eventually established and the group identified area water-sector issues and a comprehensive list of potential solutions. The group developed a work plan and associated budget and has begun to function independently.

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:	8/31/2009
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

1. Steinemann, A., 2007, Climate Forecasts for Drought Management, NOAA Climate Prediction Applications Science Workshop, Seattle, March 21, 2007.
2. Rosenberg, E., A. W. Wood, Q. Tang, A. Steinemann, B. Imam, S. Sorooshian, and D. 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.
4. Lettenmaier, D. P., A. W. Wood and K. Andreadis, 2006, A System for Real−time Prediction of Hydrological and Agricultural Drought over the Continental U.S., EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 87(52): Abstract G31A−07.
5. Fontaine, M., and A. Steinemann, 2007, Assessing and Mitigating Drought in Washington State, Poster Presentation at the 5th Annual NOAA Climate Prediction Applications Science Workshop, Seattle, Washington, March 20−23, 2007.
6. Shukla, S., D. Alexander, A. Steinemann A., 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, Water Center Annual Review of Research, University of Washington, Seattle, Washington, February 14, 2007,
7. Wood, A. W., A. Steinemann, D. Alexander,and S. Shukla,2006, Applications of Medium Range To Seasonal/Interannual Climate Forecasts For Water Resources Management in the Yakima River Basin of Washington State, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 87(52): Abstract HC53−0648.
8. Fontaine, M., and A. Steinemann, A., 2006, Assessing and Mitigating Drought in Washington State, UW/UBC Hydrology Conference.
9. Annual Review of Research: A Symposium of Water Research Hosted by the University of Washington Water Center. 2007. February 14, 2007. http://depts.washington.edu/cwws

10. Fontaine, M. and A. C. Steinemann, Assessing Vulnerability to Natural Hazards: An Impact−based Method and Application to Drought in Washington State, ASCE Natural Hazards Review (in press).
11. Fontaine, M. M., A. C. Steinemann, and M. J. Hayes, State Drought Programs: Lessons and Recommendations from the Western U.S. ASCE Natural Hazards Review (in review).
12. Shukla, S. and A. W. Wood, 2007, Application of LDAS−era Land Surface Models for Drought Characterization and Prediction in Washington State (Abstract), EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H43A−0962. San Francisco, California.
13. Shukla, S., and A.W. Wood, 2008, Use of a Standardized Runoff Index for Characterizing Hydrologic Drought, Geophysical Research Letters, 35(L02405), doi:10.1029/2007GL032487.
14. Shi, X., A. W. Wood, and D. P. Lettenmaier, How Essential is Hydrologic Model Calibration to Seasonal Streamflow Forecasting?, Journal of Hydrometeorology (submitted).
15. Wang, A., T. J. Bohn, S. P. Mahanama, R. D. Koster, and D. P. Lettenmaier, Multimodel Reconstruction of Drought over the Continental United States, Journal of Climate (submitted).
16. Wood, A. W., and J. C. Schaake, 2008, Correcting Errors in Streamflow Forecast Ensemble Mean and Spread, Journal of Hydrometeorology, 9(1): 132−148, doi:10.1175/2007JHM862.1.
17. Vano, J. A., and A. C. Steinemann, 2007, Using Climate Forecast Information in Water Resource Planning: Opportunities and Challenges in the Yakima River Basin, Washington, USA, (Abstract), EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H24A−05. San Francisco, California.
18. Wood, A. W., S. Shukla, J. A. Vano, and A. C. Steinemann, 2007, Connecting Climate, Hydrologic and Drought predictions to Water Resources Management in Washington State (Abstract), EOS Transactions, American Geophysical Union, Fall Meeting Supplement 88(52): Abstract H23F−1678. San Francisco, California.
19. Andreadis, K., D. P. Lettenmaier, and A. W. Wood, 2007, Drought Identification and Recovery Prediction, Oral and Poster Presentations at the 5th Annual NOAA Climate Prediction Applications Science Workshop, Seattle, Washington. March 20−23, 2007.
20. Shukla, S., and A. W. Wood, 2008, A Hydrologic Model−based Drought Monitoring System for Washington State, 88th American Meteorological Society Annual Meeting, New Orleans, Louisiana, January 22−24, 2008.
21. Shukla, S. and A. W. Wood, 2007, Drought Monitoring: An Evaluation of Drought Indicators Based on Climate and Hydrologic Variables, 2nd Annual Graduate Climate Conference, University of Washington Charles L. Pack Forest Center, Washington. October 19−21, 2007.
22. Vano, J. A., 2007, Challenges and Rewards of Translating Climate Change Science for Non−scientists: Two Case Studies on Drought, 2nd Annual Graduate Climate Conference University of Washington Charles L. Pack Forest Center, Washington. October 19−21, 2007.
23. Wood, A.W., 2007, Application of LDAS−era Land Surface Models to Drought Monitoring and Prediction, Oral Presentation at the 5th Annual U.S. Drought Monitor Forum, Portland, Oregon. October 10−11, 2007
24. Wood, A.W., 2007, Drought−relevant Information Products Based on LDAS−era Hydrologic Modeling, Poster Presentation at the 6th Annual NOAA Climate Prediction Application Science Workshop, Chapel Hill, North Carolina. March 4−7, 2008.
25. Wood, A. W., 2007, A System for Real−time Prediction of Hydrological Drought Over the Continental U.S., Oral Presentation at the 5th Annual NOAA Climate Prediction Applications Science Workshop, Seattle, Washington, March 20−21, 2007.
26. Wood, A.W., 2008, The University of Washington Surface Water Monitor: An Experimental Platform for National Hydrologic Assessment and Prediction, 88th American Meteorological Society Annual Meeting New Orleans, Louisiana. January 22−24, 2008.
27. Wood, A.W., J. A. Vano, S. Shukla, and A.C. Steinemann, 2008, Applications of Climate Forecast Information in Water Resources Management: Opportunities and Challenges in the Yakima River Basin, Washington, Oral Presentation at the 6th Annual NOAA Climate Prediction Application

Science Workshop, Chapel Hill, North Carolina. March 4−7, 2008.
28. Wood, A., N. Voisin, and S. Shukla, 2008, Medium−range Ensemble Hydrologic Forecasting for Western Washington State, poster, 88th American Meteorological Society Annual Meeting, New Orleans, Louisiana. January 22−24, 2008.
29. Annual Review of Research, 2008, A Symposium of Water Research, hosted by the University of Washington Water Center, A. C. Steinemann, Director. USGS research conducted on Grant 06HQGR0190 was featured at this event. Seattle, Washington, February 14, 2008. http://depts.washington.edu/cwws/
30. Bohn, T., Drought and model consensus: Reconstructing and Monitoring Drought in the U.S. with Multiple Models, Annual Review of Research, A Symposium of Water Research, hosted by the University of Washington Water Center, A. C. Steinemann, Director. Seattle, Washington, February 14, 2008. http://depts.washington.edu/cwws/
31. Shukla, S., and A.W. Wood, Application of a Land Surface Model for Drought Monitoring and Prediction in Washington State, Annual Review of Research, A Symposium of Water Research, hosted by the University of Washington Water Center, A. C. Steinemann, Director. Seattle, Washington, February 14, 2008. http://depts.washington.edu/cwws/

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).

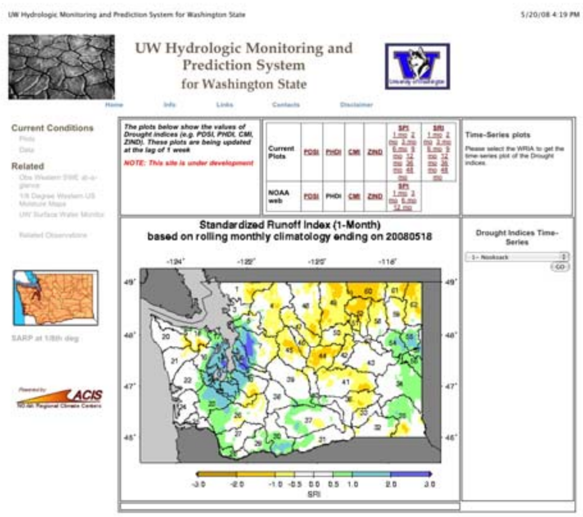

Figure 1. Screen shot of UW Hydrologic Monitoring and Prediction System for Washington State showing standardized runoff index (SRI, 1-month) using a rolling monthly climatology ending on May 18, 2008.

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).

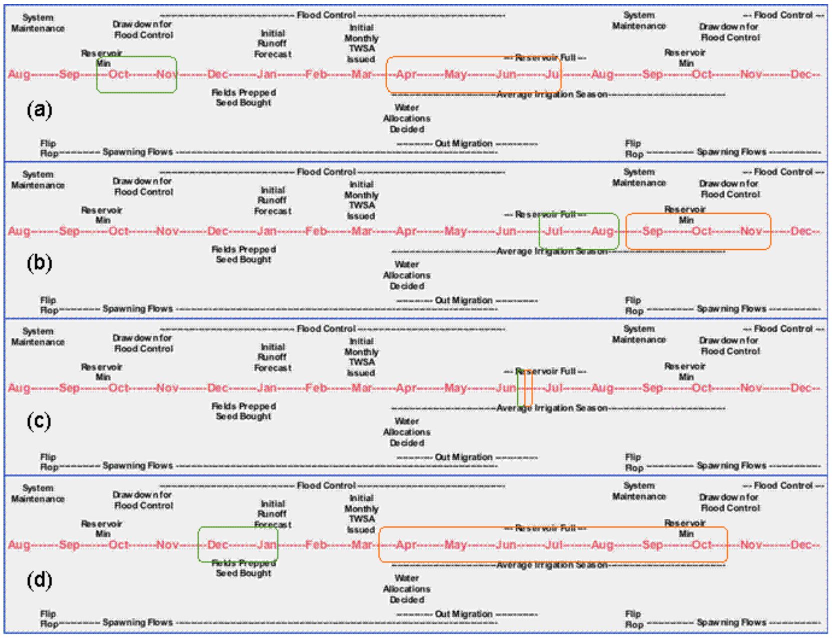

Figure 2. Four identified decision-making realms, with green circles around period in which decisions are made and orange circles around the relevant time of forecast. (a) Filling reservoirs without flooding in winter and spring, (b) maintaining flows for fish in fall, (c) week-to-week operations in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

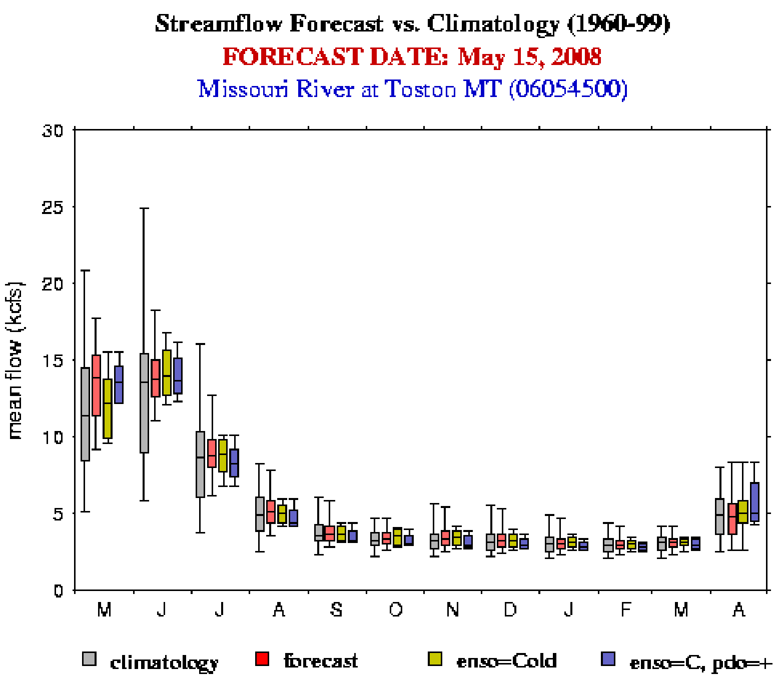

Figure 3. ESP forecast for mean monthly streamflow on the Missouri River at Toston, MT, as of May 15, 2008.

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.

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.

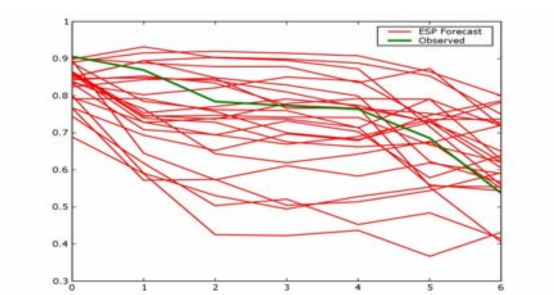

Figure 4: Spatial average soil moisture over AZ-CA starting on Feb. 1, 2006, and progressing through August, as compared with "actual" soil moisture (real-time model estimates).

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

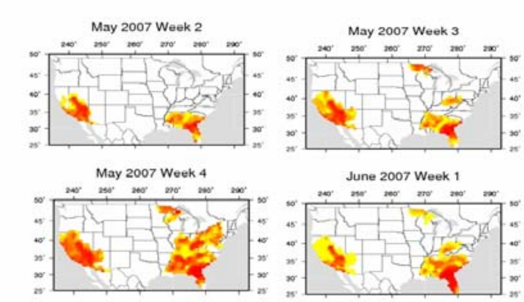

Figure 5: Estimated extent of drought over continental U.S. as of first week of June, 2007, and evolution over previous three weeks. Soil moisture percentiles are relative

week. We are interacting with CPC personnel who are reviewing the method, but we believe that it 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 begun incorporating the simple groundwater model (SIMGM) developed for the Community Land Model (CLM) by Niu et al. (2007). 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 will differ from that of Niu et al. (2007) primarily in baseflow calculation. Whereas Niu et al. (2007) apply a TOPMODEL-based runoff scheme to parameterize lateral transport as an exponential function of water table depth, we will apply the ARNO baseflow formulation (Todini et al., 1996) to both the soil column and the aquifer, as in Liang et al. (2003). We will also explore the sensitivity of SIMGM to other baseflow formulations, such as those of Niu et al. (2007) and Huang et al. (2006, 2008). Also, the standard VIC model includes 3 soil layers, as opposed to the 10 layers of CLM. In order to improve the accuracy of water table depth estimates, we will use an approach similar to that of Wang et al. (2007) to map soil moisture from the standard VIC model to 10 smaller layers prior to performing groundwater calculations, and then to map the redistributed soil moisture back to the 3 VIC layers.

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. Controls and Significance of N Retention in Lakes and Reservoirs. Biogeochemistry. (In Press)
2. Seitzinger, S.P. and John A. Harrison, 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, E. Carpenter Eds., Academic Press, New York. (In Press)
3. 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.
4. 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.
5. 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.
6. 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.
7. 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.
8. 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 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 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*

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

[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 denitrication 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- Ongoing

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. N2: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.

---

[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
[12] Harrison et al., 2005
[13] Kelly VJ, 2001, Influence of reservoirs on solute transport: a regional-scale approach. *Hydrological Processes* 15: 1227–1249.
[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.

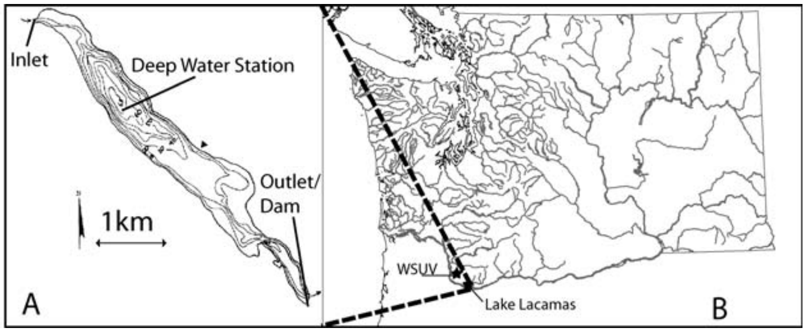

Figure 1. Bathymetry of Lacamas Lake, showing inlet, outlet, and within-lake deep-water sampling station (A), and location of Lacamas Lake (B).

Monthly Monitoring Lab Work- Ongoing

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 portion 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 will be digested using a Block Digester and run again to measure total P and Total Kjeldahl N.

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.

[15] Kana, T.M., C. Karkangelo, 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.

Denitrification Potential Assay- August 2007 and January 2008

Estimates of potential denitrification at the DW site were calculated using the 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 expected to be well mixed during this time.

Sediment Traps- In Progress

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]. Two traps were deployed at two locations on either side of the main site on 5-28-08 at 14:06 and 14:10 and one trap was deployed at the DW site on 6-4-08 at 17:00. Sediment will be collected, dried, and weighed at least three times over the course of summer 2008 in order to quantify sediment deposition rates. Dried samples will then be prepared for C:N analysis in Pullman.

N-Fixation Assay- Planned for this Summer

To account for the degree of N_2 undersaturation that is due to the activity of N-fixing plankton, N-fixation rates will be quantified using the C_2H_2 addition method. We will calculate 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) of Lacamas Lake's DW site. For each zone sampled, 45mL of sample will be poured into each of 12 60mL Wheatons for a total of 24 samples. After crimping the caps, 2.25 mL of C_2H_2 will be injected in each vial. Duplicate samples will be 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 will be 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- Planned for this Summer

In order to both quantify denitrification rates in reservoir sediments and identify factors limiting the process we will conduct a series of sediment core incubations. Using an Eckman Dredge with Scuba weights attached, sediment cores will be taken from the

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

DW site. Cores are constructed of 2-1/4” OD, 2-1/8” ID polycarbonate round tubing and are 35cm long. Cores are stoppered on both ends and holes are 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 will be topped off with bottom water and care will be taken to avoid entrainment of air bubbles. Three replicates will be treated with a NO_3^- addition using KNO_3, three will be treated with a carbon addition using CH_3COONa, three will be a combination carbon and NO_3- addition, three will be regular lake water overlying sediment, and three will be lake water without sediment. We will sample the cores hourly for N_2:Ar, N_2O, and NO_3^- until N_2:Ar increases by more than 5%. A duplicate experiment is planned for a more shallow area within the reservoir.

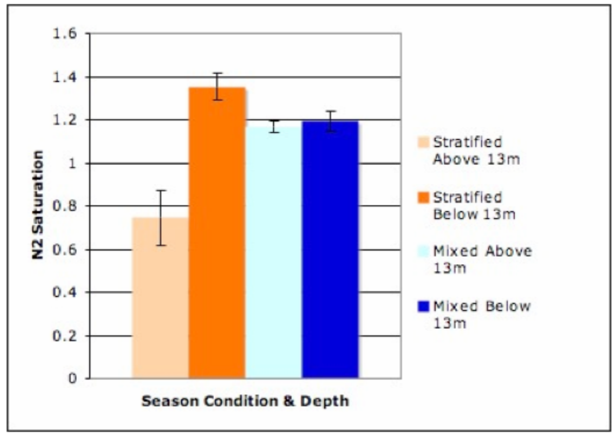

Figure 2. Mean N_2:Ar saturation in bottom versus top water in mixed and stratified conditions (1 indicates 100% saturation).

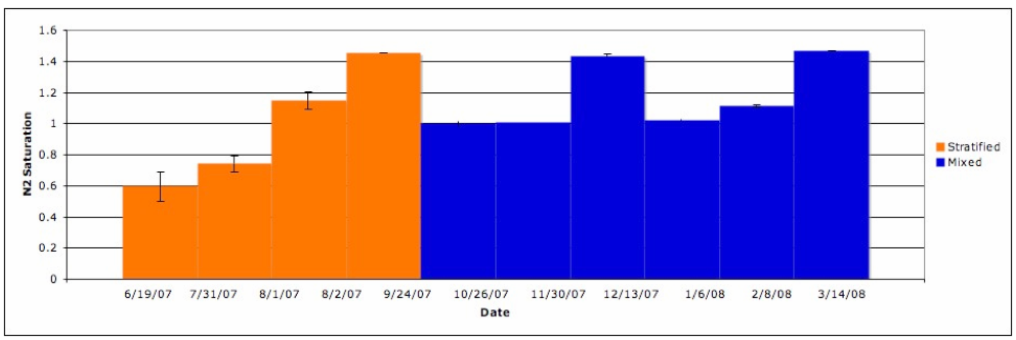

Figure 3. Mean monthly N_2:Ar saturation (1 indicates 100% saturation).

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. N_2:Ar samples from monthly monitoring at the DW site show that during winter mixed conditions the reservoir was supersaturated with N_2 throughout the water column whereas during summer stratified conditions water below 13m was consistently supersaturated with N_2. A general linear model showed significant interaction between season and depth of N_2 super-saturation ($p<0.05$) and significantly higher N_2:Ar below 13m than above 13m ($P<0.05$) (Figure 2). Also interestingly, N_2 super-saturation steadily increases in the summer in contrast to the relatively constant level of super-saturation seen in the winter (Figure 3) These results indicate that DNF plays an important role in reservoir N removal. They also suggest that controls on DNF differ seasonally. A critical next step in quantifying denitrification rates is incorporating seasonal gas transfer velocities and N-fixation rates. Future work aims to quantify an annual DNF flux in order to identify time periods that may be particularly important with regard to reservoir N removal.

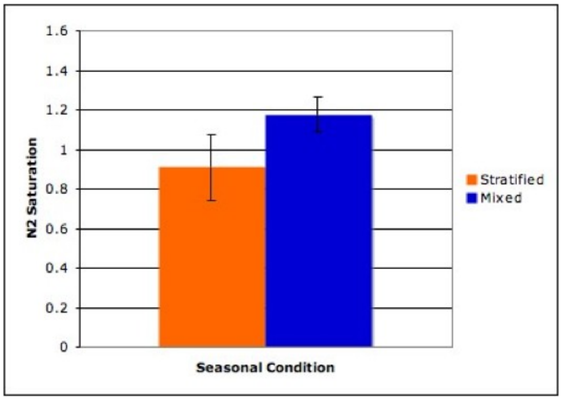

Figure 4. Mean seasonal N_2:Ar saturation (1 indicates 100% saturation).

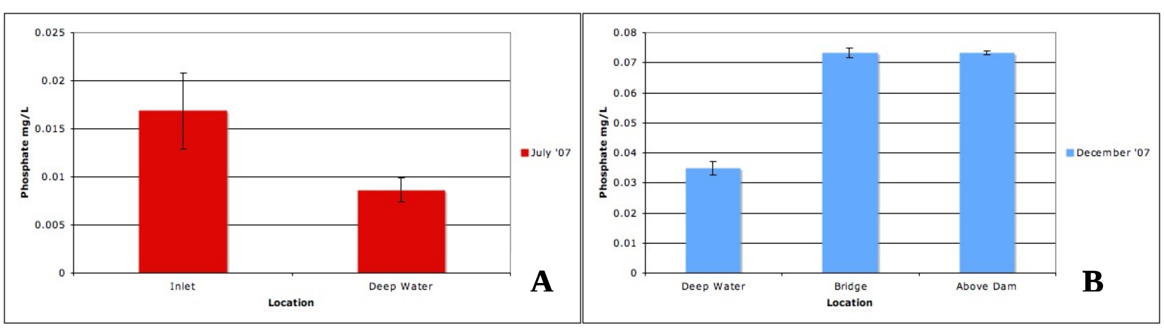

Figure 5. Mean PO_4^{3-} concentrations by location in July 2007 (A) and December 2007 (B).

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-} at the bridge and above the dam than at the DW site in December (single variable ANOVA, $p<0.05$) (Figure 5). Such findings emphasize how reservoir nutrient dynamics differ seasonally.

Further sample analysis along with experiments planned for this summer will help to constrain reservoir denitrification rates, nutrient budgets, and greenhouse gas fluxes as well as potential limiting factors to nutrient processes such as denitrification. These findings are likely to have important implications for modeling N transport at larger scales and for dam management strategies.

Quantifying and Enhancing Nitrogen Removal in Constructed Wetlands

Basic Information

Title:	Quantifying and Enhancing Nitrogen Removal in Constructed Wetlands
Project Number:	2007WA196B
Start Date:	3/1/2007
End Date:	2/28/2008
Funding Source:	104B
Congressional District:	Washington, Fifth
Research Category:	Water Quality
Focus Category:	Wetlands, Water Quality, Nutrients
Descriptors:	Natural Treatment Systems, Constructed Wetlands, Ammonia, Nitrate, Nitrification, Denitrification
Principal Investigators:	Marc Beutel, Troy Peters, Rick Watts

Publication

1. Palmer, Huckleberry R. and Marc W. Beutel. A Mesocosm Study Evaluating Nitrogen Removal in Oxygen Activated Nitrification Wetlands. ASCE Journal of Environmental Engineering. (In preparation)
2. Newton, Crystal D., Marc W. Beutel and E. S. Brouillard. Surface Flow Constructed Wetlands Treating Agricultural Return Flow in the Yakima Valley, Washington, I: Nitrogen Removal. Ecological Engineering. (In preparation)
3. Palmer, Huckleberry R., 2008, High Rates of Ammonia Removal in Constructed Treatment Wetland Mesocosms Using Oxygenation, M.S. Thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, Washington. 19p.
4. Beutel, Marc W. and Huckleberry R. Palmer, 2008, Almost Beyond Wetlands: Enhancing Ammonia Removal in Constructed Treatment Wetlands using Oxygenation. Oral presentation at the American Ecological Engineering Society Conference, June 11−14, Blacksburg, Virginia.
5. Beutel, Marc W. and Huckleberry R. Palmer, 2008, A Mesocosm Study Evaluating Effects of Pure Oxygen Addition on Ammonia Removal in Constructed Treatment Wetlands. Oral presentation at the Inland Northwest Aquatic Riparian, and Wetland Symposium, Spokane, Washington, February 22, 2008.
6. Palmer, Huckleberry R. and Marc W. Beutel, 2007, Effects of Pure Oxygen Gas on Ammonia Removal in Surface Flow Treatment Wetlands. Oral presentation at the Air and Waste Management Association, Pacific Northwest International Section Annual Conference, October 17−19, 2007. Boise, Idaho.

PROBLEM AND RESEARCH OBJECTIVES

Nitrogen pollution of aquatic ecosystems, commonly as ammonia or nitrate, is a growing concern throughout the state. Sources of nitrogen pollution to surface waters can be classified as point or non-point. Point sources are predominantly domestic wastewater treatment plants (WWTPs). With a population of 6.3 million, an estimated one billion gallons of treated sewage are discharged to the environment of each day in Washington. While comprehensive sewage treatment has made great strides in treating the oxygen demand of domestic wastes, treated sewage is rich in nutrients and typically contains 10-20 mg-N/L of ammonia. Major non-point sources of nitrogen include agricultural runoff and urban runoff. Polluted stormwater runoff from urban and agricultural areas is considered “the nation’s largest water quality problem” by the Environmental Protection Agency. Today, agriculture runoff is the primary polluter of the nation’s rivers and lakes, while urban runoff is the primary polluter of coastal waters. Runoff is rich in two key pollutants, sediments (and whatever pollutants are attached) and nutrients. Regarding nitrogen, total inorganic nitrogen levels (ammonia plus nitrate) in urban runoff are typically around 1 mg-N/L while levels in agricultural runoff can range from 5 mg-N/L for fertilized row crops to over 1,500 mg-N/L for animal feed lots.

Constructed wetlands, also known as natural treatment systems (NTS), are especially good at removing nitrate via denitrification, the biological conversion of nitrate to harmless nitrogen gas. However, case studies documenting the effects of environmental parameters on the removal of nitrogen in NTS, particularly treating agricultural runoff, are uncommon. In addition, wetlands are good at removing nitrate but not at removing ammonia. Constructed wetlands remove nitrate at a rate of 100’s of mg-N/m^2/d, but remove ammonia at only 10’s of mg-N/m^2/d. So a wetland ten times larger in size is required to remove ammonia versus nitrate. This is a critical limitation on the use of NTS to remove nitrogen from ammonia-rich waste waters. The objective of this project was to perform: (1) a detailed analysis of nitrogen data from an existing NTS treating agricultural return flows to the Yakima River, and (2) a bench-scale experimental study examining strategies to enhance ammonia removal in constructed wetlands through oxygen addition.

METHODOLOGY

Study Sites. The NTS for the data analysis effort was located near Prosser. The NTS is operated by the Roza-Sunnyside Board of Joint Control (RSBOJC) which is made up of two major irrigation water suppliers in the Yakima Valley. Funded as a TMDL water improvement project by the Washington Department of Ecology, the NTS polishes irrigation return flows prior to their discharge to the Yakima River. The NTS consists of a sedimentation basin followed by two wetland treatment trains. Each treatment train is around two acres and consists of three wetland cells dominated by cattail with areas of open water. Flow rate through each wetland treatment train is ~0.3 cfs and hydraulic residence time is 6-7 days. For the experimental component of the project, wetland plants and sediment for the mesocosm were collected from the UI experimental constructed treatment wetlands located near the Washington-Idaho border. The wetlands polish effluent from the Moscow WWTP before discharging it to Paradise Creek.

Wetland Data Analysis. The data set included bi-monthly water quality at a number of stations. In addition, flow rate data was also measured. Ammonia levels in the influent were negligible while nitrate levels generally range from 2-4 mg-N/L. The dataset was evaluated to determine the first order nitrate removal rate K_n (m/yr), in the sedimentation basin and two wetland treatment trains, using the mass balance equation for plug flow conditions:

$$\ln\left[\frac{C_{in}}{C_{out}}\right] = -K_n \frac{1}{q}$$

Where C_{in} and C_{out} are the inflow and outflow concentrations of nitrate (g/m^3) and q is the hydraulic loading rate (m/yr).

Mesocosm Experimental Methods. Replicate flow-through experimental wetland mesocosms were used to examine the effects of oxygenation on ammonia removal in constructed wetlands. The mesocosms consist of 15 gallon aquariums filled with wetland plants, sediment and water. Inflow was maintained via gravity feed from buckets filled daily with synthetic secondary effluent containing 10 mg/L BOD and 10 mg-N/L ammonia. Two mesocosms were oxygenated by bubbling a side-stream of water from the inlet area of the mesocosms with pure oxygen gas. DO in the side-stream was ~30 mg/L. Two aquariums were used as controls and were not oxygenated.

Analytical Methods. Ammonia and nitrate analyses for the mesocosm experiments were performed in Dr. Beutel's Limnology Laboratory on a Lachat QuikChem QC8500 Automated Ion Analyzer using standard colorimetric methods (APHA 1998). Samples were filtered through a pre-washed 0.45 µm filter then analyzed in real time and/or frozen for later analysis. Mesocosm water was also monitored for DO and temperature. This data was automatically measured and logged using a Hach standard luminescent DO (LDO) IntelliCAL probe and an HQ40d digital meter/data logger.

PRINCIPAL FINDINGS AND SIGNIFICANCE

RSBOJC Wetlands. Average removal rates for nitrate are outlined in Table 1. Values in the table are the average plus/minus one standard deviation (in parentheses) for pooled data from 2003-2006 ($n = 30$ to 35). Nitrate entering the system was around 2 mg-N/L. Levels in outflow were around 0.2 mg-N/L. Overall removal rates were around 90%. K_N values were around 190 m/yr in the sedimentation basin and 150 m/yr in the wetlands. These values are higher than the reported 'central tendency' of K_N value in surface flow NTS, which is around 50-60 m/yr (Treatment Wetlands, Kadlec and Knight, 1996). Areal removal rates in the wetlands were around 140 mg-N/m^2/d, which is on the low end of reported rates which generally range from 100-1,000 mg-N/m^2/d. The system likely has elevated K_N and low areal removal rates because it is under loaded. As a result, effluent outlet concentrations are very low (which translates to high K_N values) and a lot of surface area is being used to treat low levels of nitrate (which translates to low removal rates on an areal basis). This data suggests that the wetlands could be loaded with higher levels of N and still operate efficiently.

K_N values in wetlands showed a strong seasonal pattern, generally ranging from around 50 m/yr in April, 180 m/yr in June/July, and then dropping to around 100 m/yr in September/October. K_N values in the wetlands were also significantly positively correlated with influent temperature ($r^2 = 0.40$, $p < 0.001$) and negatively correlated with outflow DO ($r^2 = 0.54$, $p > 0.0001$). These results reflect the strong temperature dependency of biological denitrification in wetlands. Higher temperatures enhance both the rate of activity of the microbes responsible for nitrate conversion to nitrogen gas, as well as the rate of diffusion of nitrate from the water column to underlaying anoxic muck and sediments. Lower DO levels also enhance denitrification rates since denitrification is an anoxic process.

Table 1 – Summary of Nitrate Removal in RSBOJC Wetlands.

Nitrate				
Concentration (mg-N/L)		Apparent K_N	Removal Efficiency	Removal Rate
In	Out	(m/yr)	(%)	(mg-N/m^2/d)
Sedimentation Basin				
1.95 (0.86)	1.35 (0.74)	187 (163)	34.1 (26.6)	837 (884)
North Wetland				
1.41 (0.73)	0.13 (0.32)	146 (57)	92.6 (13.7)	139 (75)
South Wetland				
1.34 (0.74)	0.17 (0.32)	149 (68)	90.0 (14.9)	146 (83)

<u>Mesocosm Experiment.</u> Table 2 summarizes results of the mesocosm experiments. Values in the table are the average plus/minus one standard deviation for pooled data from duplicate treatments (n ~ 20 for Phase 1 and 6 for phase 2). The experiment included two phases. Phase 1 included a moderate hydraulic retention time (HRT) of 5 days and high oxygen levels (DO ~ 14 mg/L) in the oxygenated treatments. Phase 2 included a low HRT of 2.5 days and lower oxygen levels in the oxygenated treatments (DO ~5 mg/L). DO levels in the non-oxygenated controls was < 1 mg/L. During Phase 1, average ammonia levels dropped from 9.9 mg-N/L in the influent to 8.7 mg-N/L in control effluent and 0.6 mg-N/L in oxygenated mesocosms. During Phase 2, average ammonia levels were 9 mg-N/L in the influent, 9.6 mg-N/L in control effluent, and 2.2 mg-N/L in oxygenated mesocosms. During both phases, nitrate levels were negligible in the influent and effluent from the controls, but averaged around 6.7 mg-N/L in effluent from the oxygenated mesocosms. Thus, oxygen addition resulted in dramatically higher levels of conversion of ammonia to nitrate.

Ammonia removal rates were an order of magnitude higher in the oxygenated wetlands. Average areal removal rates were < 50 mg-N/m^2/d in the controls and as high as 590 mg-N/m^2/d in the oxygenated wetlands. Average removal efficiencies were 75-94% in the oxygenated wetlands compared to < 12% in the controls. Finally, the average apparent first order ammonia removal rate constant (K_A) was 45-49 m/yr in the oxygenated wetlands and < 2.1 m/yr. K_A values in reported in other surface flow wetlands typically range from 5-15 m/yr. The elevated ammonia removal rates under oxygenated conditions suggests that wetland oxygenation could be a useful approach in shrinking the size of the wetland needed to treat ammonia-rich effluent. The next logical step would be a field-scale study evaluating wetland oxygenation for ammonia removal.

Table 2 – Summary of Results from Mesocosm Experiments.

	Phase 1 – 5 d HRT			Phase 2 – 2.5 d HRT		
Parameter	Influent	Control Effluent	Oxygenated Effluent	Influent	Control Effluent	Oxygenated Effluent
DO, mg/L	4.1 ± 1.5	0.6 ± 0.2	14.2 ± 4.2	No data	No data	5.2 ± 1.4
pH	7.9 ± 1.2	6.9 ± 0.3	6.6 ± 0.3	No data	No data	No data
Ammonia, mg-N/L	9.9 ± 1.3	8.7 ± 1.3	0.6 ± 0.4	9.0 ± 0.4	9.6 ± 0.2	2.2 ± 0.2
Nitrate, mg-N/L	0.1 ± 0.1	0.1 ± 0.1	6.7 ± 1.1	0.2 ± 0.1	0.1 ± 0.2	6.6 ± 0.3
Ammonia Removal						
Areal removal, mg-N/m^2/d		51 ± 44	404 ± 59		-52± 42	588 ± 24
Removal efficiency, %		12 ± 11	94.0 ± 4.5		-6.9 ± 5.9	75.5 ± 1.5
K_A, m/yr		2.1 ± 2.0	48.9 ± 11.9		-2.1 ± 1.7	44.6 ± 1.9

Assessment of contaminated sediments using a rainbow trout (Oncorhynchus mykiss) as an embryonic exposure assay

Basic Information

Title:	Assessment of contaminated sediments using a rainbow trout (Oncorhynchus mykiss) as an embryonic exposure assay
Project Number:	2007WA210B
Start Date:	3/1/2007
End Date:	2/28/2008
Funding Source:	104B
Congressional District:	Washington Fifth
Research Category:	Water Quality
Focus Category:	Sediments, Toxic Substances, Water Quality
Descriptors:	None
Principal Investigators:	Jeffrey Layton Ullman

Publication

1. Ullman, Jeffrey L., 2007, Fish Exposure Assays: Assessing Environmental Quality and Remediation Strategies. Oral presentation at the Annual Meeting of the Center for Reproductive Biology (Washington State University and University of Idaho), May 24−25, 2007, Orofino, Idaho.

PROBLEM AND RESEARCH OBJECTIVES

Despite contaminated sediments presenting an environmental health hazard, ecological risk assessments remain largely impeded by a lack of data and guidance. The state of Washington has adopted a robust system of standards to manage contaminated marine sediments, but freshwater sediment evaluation remains on a case-by-case basis. Since sediments display temporal variability and bioavailability can not be directly linked to total contaminant load, more information on the effects of direct contact exposure to sediments by benthic organisms is needed.

Rainbow trout (*Oncorhynchus mykiss*) have been used extensively as a toxicological model for assessing water quality due to low husbandry costs, sensitivity to pollutants and easily quantified physiological responses to contaminants. Due to inadequacies of LD_{50} values (dose response that results in 50% lethality), use of early life stage (ELS) toxicity analysis has increased as a tool to characterize risk in aquatic ecosystems. However, no published studies were found addressing the use of rainbow trout embryos to evaluate toxicity associated with direct contact with sediments.

This project hypothesizes that sub-lethal concentrations of organic contaminants associated with sediments will yield quantifiable health impacts using a variety of indices. Two classes of chemicals, polycyclic aromatic hydrocarbons (PAHs) and polybrominated diphenyl ethers (PDBEs), will be used separately and together to determine synergistic effects. Survival, fluctuating asymmetry, sex reversal, vitellogenin production and embryonic uptake will be examined using all-male clonal lines. This novel approach will provide insight into the toxicological and physiological effects of these compounds, as well as assess the feasibility of using this strategy as an alternative bioassay to determine sediment toxicity. Corresponding examination of sorption behavior of the organic compounds will provide further insight into the bioavailability of sediment-bound pollutants.

METHODOLOGY

Rainbow trout eggs are raised in conjunction with contaminated sediments that consist of both field collected benthic material and prepared sediments spiked to appropriate contaminant concentrations. The systems are semi-static, using periodic water changes that allow for the analysis of contaminant benthic flux.

Toxicological and physiological effects imparted on the trout eggs following contact with contaminated sediments are currently measured by:

1) Survival: Embryos that fail to hatch represent sediment lethality.
2) Fluctuating asymmetry: Deviation from bilateral symmetry can indicate stressful environments and has been demonstrated as an indicator of fish susceptibility to pesticides (Allenbach et al., 1999).
3) Contaminant concentrations in embryos: Total body concentrations are recorded in addition to length and weight

PRINCIPAL FINDINGS AND SIGNIFICANCE

As a results of difficulties in obtaining trout eggs and model renovations, findings on contaminant toxicity remain in the preliminary stages at this time.

However, significant achievements were achieved in method development. Despite reports describing successful rearing of rainbow trout eggs in petri dishes, poor survival resulted despite using numerous variations on this method. We have now moved to a semi-static system that involves 1-gal glass aquaria equipped with air-stones that provides superior survival. Fine sediments, not unexpectedly, also have proven to be difficult to manage in this experiment and we have switched to very coarse textured sediments and small gravel substrates as the primary media. Furthermore, we have also experimented with using newly hatched trout. Larval fish present an appropriate surrogate as this life-stage remains in direct contact with sediments for about a month, but is significantly less sensitive to ambient conditions.

This continuous refinement in methods directly resulted in the grant "Improving Fish Habitat Using Innovative Strategies to Remediate Contaminated Sediments in the Columbia River Basin" (Jeffrey Ullman, principal investigator) funded by the Bonneville Power Administration. The external review panel, the Northwest Power and Conservation Council ranked the proposal #1 out of 52 submissions. A significant portion of the project involves exposure of larval rainbow trout to contaminated sediments and contaminated sediments undergoing remediation for PAHs.

Another significant outcome of this project is the examination of the impacts of PBDEs on juvenile fish. Teaming with Puget Sound area Tribes, we have begun to examine the sub-lethal effects of these flame retardants on juvenile chum salmon (*Oncorhynchus keta*).

Information Transfer Program Introduction

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

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2005WA114B
Start Date:	3/1/2005
End Date:	2/29/2008
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., Robert Mahler, and Marc Beutel, 2007, A Framework for Evaluating the Hydrologic and Economic Repercussions of Bioenergy Development within the Columbia River Basin in the USA, presented at World Water Week, Stockholm, Sweden, August 2007.
4. Barber, Michael E., Chris Pannkuk, M. Fayyad, and A. Al−Omari, 2007, Capacity Building within the Ministry of Water and Irrigation in Amman, Jordan: Successes, Failures, and Lessons Learned, presented at World Water Week, Stockholm, Sweden, August 2007.
5. Water in the Pacific Northwest: Moving Science into Policy and Action, November 7−9, 2007, Stevenson, Washington. Sponsored by CSREES Pacific Northwest Regional Water Quality Program and the State of Washington Water Research Center. Proceedings. www.swwrc.wsu.edu/conference2007_sessions.asp

To achieve the goals outlined in the introduction, the following information transfer activities were conducted.

The SWWRC led a regional effort of Pacific Northwest land grant universities to hold a two-day conference “Water in the Pacific Northwest: Moving Science into Policy and Action.” The event was sponsored in large part by a USDA-CSREES grant to help coordinate Water Resources Research Institutes and Extension in Alaska, Idaho, Oregon, and Washington with EPA Region 10. The conference had several co-sponsors including the Washington State Department of Ecology, the Washington State Department of Transportation, the Inland Northwest Research Alliance and the Oregon Water Research Institute. The conference drew nearly 225 participants including politicians, agency personnel, researchers and stakeholders. SWWRC also coordinated a pre-conference workshop and a bus tour to BPA facilities: both were related to the conference theme. Feedback from the participants rated the conference a huge success.

SWWRC also co-sponsored a local Palouse Water Summit; an annual event aimed at the communities of Pullman, Washington and Moscow, Idaho. The Summit aims to educate people on water use in a declining aquifer and steps being taken to possibly mitigate the problem. Many concerned citizens turn out for this event and attendance is growing each year.

Meetings with the Spokane Valley Rathdrum Prairie Aquifer Committee continued as part of a join project with the USGS and the Water Resources Research Institutes in Idaho and Washington. A model roll-out public forum was held in which the director was one of the speakers.

The director also participated in a Water Task force convened by the Dean of Agriculture at Washington State University aimed at identifying the diverse level of water expertise across the university, opportunities for strengthening research and education programs, and funding opportunities. This report has increased university awareness of water issues, and the SWWRC has been tasked with providing a coordinating role.

We continue to actively participate in a strategic regional surface water initiative funded by the US Department of Energy through the Inland Northwest Research Alliance (INRA). The project involves the Water Resources Research Institutes in Alaska, Idaho, Utah, and Washington as well as Boise State University, University of Montana, Idaho State University, and Montana State University. The project involves bi-weekly conference calls aimed at establishing a regional, coordinated research and education agenda. We completed a needs assessment related to water resources education for the Pacific Northwest.

Our database of interested stakeholders is also constantly updated. Currently over 3,000 names are included. Information for a second database of water resources expertise at Land Grant Universities in the Pacific Northwest was also updated. An Excel spreadsheet of WSU water-related expertise was completed for the Inland Northwest Research Alliance.

Updating our Web site is a continuous process. No major revisions were performed last year but various announcements were added as relevant. We continue to put our research reports and conference abstracts on the web for download via PDF format rather than the historic practice of mailing paper copies.

The SWWRC Director traveled to Egypt to participate in a project involving revitalization of agriculture in Iraq through a multi-university partnership and the WSU International Programs office. The Director also gave an oral presentation at the Stockholm World Water Conference on the issues related to water resources for bioenergy development in the Columbia River basin and gave a poster presentation on the lessons learned in a 4-year education/training program for the Jordanian Ministry of Water and Irrigation conducted by WSU and three Jordanian Universities.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR−USGS Internship	Supplemental Awards	Total
Undergraduate	8	0	0	0	8
Masters	5	1	0	0	6
Ph.D.	0	3	0	0	3
Post−Doc.	0	0	0	0	0
Total	13	4	0	0	17

Notable Awards and Achievements

Publications from Prior Years

1. 2004WA76B ("Three−dimensional Characterization of Riverbed Hydraulic Conductivity and Its Relation to Salmonid Habitat Quality") − Dissertations − Leek, Randal, 2006, Heterogeneous Characteristics of Water Movement through Riverbed Sediments of the Touchet River, Southeastern Washington, USA. MS Thesis. Department of Biological Systems Engineering, Washington State University, Pullman, Washington. 75 pp.
2. 2001WA1041B ("Dye Tracers for Vadose Zone Hydrology") − Articles in Refereed Scientific Journals − Mon, Jarai, Markus Flury, and James B. Harsh, 2006, Sorption of Four Triarylmethane Dyes in a Sandy Soil Determined by Batch and Column Experiments, Geoderma, 133, 217–224.
3. 2002WA12B ("Facilitated Transport of Pesticides by Organic Colloids") − Articles in Refereed Scientific Journals − Jerez, J., Markus Flury, J. Shang, and Y. Deng, 2006, Coating of Silica Sand with Aluminosilicate Clays, Journal of Colloid and Interface Science, 294, 155–164.
4. 2001WA781B ("Biodegradation of Non−point Source Pollutants in Soap Lake ") − Articles in Refereed Scientific Journals − Oie, Celso., C. E. Albaugh, and Brent M. Peyton, 2007, Benzoate and Salicylate Degradation by Halomonas campisalis, an Alkaliphilic and Moderately Halophilic Microorganism, Water Research 41, 1235− 1242.
5. 2000WA4G ("Integration of Surface Irrigation Techniques to Reduce Sediment Loading in the Yakima Basin") − Articles in Refereed Scientific Journals − Szogi, Ariel A., Brian G. Leib, Cristoti A. Redulla, Robert G. Stevens, Gary R. Matthews, and David A. Strausz. 2007. Erosion Control Practices Integrated with Polyacrylamide for Nutrient Reduction in Rill Irrigation. Agricultural Water Management 91:43−50.
6. 2006WA147B ("Transport of Colloids in Soils Studied by Geocentrifuge Techniques") − Articles in Refereed Scientific Journals − Flury, Markus, and Hanxue Qiu, 2008, Modeling Colloid−facilitated Contaminant Transport in the Vadose Zone, Vadose Zone Journal, 7:682–697.
7. 2006WA147B ("Transport of Colloids in Soils Studied by Geocentrifuge Techniques") − Articles in Refereed Scientific Journals − Sharma, Prabhakar, Hesham Abdou, and Markus Flury, Effect of the Lower Boundary Condition and Flotation on Colloid Mobilization in Unsaturated Sandy Sediments, Vadose Zone Journal, in press.
8. 2006WA147B ("Transport of Colloids in Soils Studied by Geocentrifuge Techniques") − Articles in Refereed Scientific Journals − Sharma, Prabhakar, Markus Flury, and E. D. Mattson, Studying Colloid Transport in Porous Media using a Geocentrifuge, Water Resources Research, (in press)
9. 2004WA91B ("Benthic Organisms and Flow Field Interactions: Improving Linkages and Descriptions") − Articles in Refereed Scientific Journals − Stone, Mark C. and Rollin H. Hotchkiss, 2007, Evaluating Velocity Measurement Techniques in Shallow Streams, Journal of Hydraulic Research, 45:752−762.
10. 2004WA91B ("Benthic Organisms and Flow Field Interactions: Improving Linkages and Descriptions") − Articles in Refereed Scientific Journals − Stone, Mark C. and Rollin H. Hotchkiss, 2007, Turbulence Descriptions in Two Cobble−Bed River Reaches, Journal of Hydraulic Engineering, 133:1367−1378.
11. 2004WA91B ("Benthic Organisms and Flow Field Interactions: Improving Linkages and Descriptions") − Conference Proceedings − Stone, Mark C., Rollin H. Hotchkiss, and Ryan R. Morrison, 2006, Turbulence Observations in Cobble−bed Rivers, "in" Examining the Confluence of Environmental and Water Concerns, Proceedings of the World Environmental and Water Resources Congress Randall Graham, editor, Omaha, Nebraska, May 21–25, 2006. doi:10.1061/40856(200)157
12. 2005WA119B ("Oxygenation for the Management of Sediment Mercury Release from Aquatic Sediments") − Articles in Refereed Scientific Journals − Beutel, Marc W., Theo M. Leonard, Stephen R. Dent, and Barry C. Moore, 2008, Effects of Aerobic and Anaerobic Conditions on P, N, Fe, Mn and Hg Accumulation in Waters Overlaying Profundal Sediments of an Oligo−mesotrophic Lake, Water Research. 42:1953−1962.

13. 2005WA119B ("Oxygenation for the Management of Sediment Mercury Release from Aquatic Sediments") − Dissertations − Leonard, Theo M., 2006, Effects of Oxygenation on Release of Mercury from Profundal Lake Sediments, M.S. Thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, Washington. 34 pp.
14. 2002WA19G ("Using environmental tracers to improve prediction of nonpoint pollutant loadings from fields to streams at multiple watershed scales") − Dissertations − Moravec, Bryan George, 2008, Oxygen−18 Dynamics in Precipitation and Streamflow in a Semi−Arid Agricultural Watershed, Eastern Washington, M.S. Thesis, School of Earth and Environmental Sciences, Washington State University, Pullman, Washington 280 pp.
15. 2002WA19G ("Using environmental tracers to improve prediction of nonpoint pollutant loadings from fields to streams at multiple watershed scales") − Articles in Refereed Scientific Journals − Keller, C. Kent, Caroline N. (Wannamaker) Butcher, and Richelle M. Allen−King, 2008, Nitrate in Tile Drainage in Semiarid Palouse Basin, Journal of Environmental Quality, 37:353−369. doi:10.2134/jeq2006.0515
16. 2002WA19G ("Using environmental tracers to improve prediction of nonpoint pollutant loadings from fields to streams at multiple watershed scales") − Conference Proceedings − Moravec, Bryan G., C. K. Keller, R. David Evans, Jeffrey L. Smith, Caroline N. Wannamaker Butcher, and Angela J. Goodwin, 2006, Going After Nitrate: Utilizing Oxygen Isotopes to Identify Nitrogen Cycling Mechanisms in Soil, “in” EOS Transactions, American Geophysical Union, Fall Meeting Supplement, December 11−15, 2006, San Francisco, California, 87(52), Abstract H11F−1298.