

**State of Washington Water Research Center  
Annual Technical Report  
FY 2011**

# Introduction

For nearly 50 years the overall strategic mission of the State of Washington Water Research Center (SWWRC) has been to: i) facilitate, coordinate, conduct, and administer water-related research important to the State of Washington and the region, ii) educate and train engineers, scientists, and other professionals through participation in research and outreach projects, and iii) disseminate information on water-related issues through technical publications, newsletters, reports, sponsorship of seminars, workshops, conferences as well as other outreach and educational activities. While specific emphasis areas have evolved over time, with the competition for water resources continuing to grow, this mission is still vital to the State of Washington today.

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

Important lessons learned from the research and outreach components are disseminated to faculty and stakeholders and used by the Director to shape and enhance the education goal. Research projects are also used as a mechanism to fund graduate and undergraduate students as training the next generation of water professionals is an essential role for universities to fill.

The SWWRC is continuing its intensive efforts to reach out to agencies, organizations, and faculty throughout the State. Activities include presentations to watershed groups, discussions with state agencies, participation in regional water 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 project activities reported in this document must be inserted. These include the internally funded projects as well as the national proposals awarded to the SWWRC. These projects provide a solid core to the diverse efforts of the SWWRC. Water quantity and quality issues continue to be a major concern in the State of Washington due to the endangered species act, population growth, industrial requirements, and agricultural activities. Emerging issues such as water resources management in the face of global warming, water reuse, energy-related water quantity and quality considerations, ecological water demands, and storm water runoff regulations are also beginning to raise concerns.

## Research Program Introduction

In accordance with its mission, the SWWRC facilitates, coordinates, conducts, and administers water-related research important to the State of Washington and the region. Research priorities within the 104(b) program for the State of Washington are established by a Joint Scientific Committee which includes representatives from water resource professionals at state agencies, universities, and the local USGS office. The SWWRC supports competitively awarded internal (within the State of Washington) grants involving water projects evaluated by the Joint Scientific Committee. The SWWRC also actively seeks multidisciplinary research at local, state, and national levels. Meetings between stakeholder groups, potential funding agencies, and research faculty are arranged as opportunities arise. Faculty are notified of any opportunities for individual or collaborative endeavors. The SWWRC also submits proposals to various local, state, and federal agencies on its own behalf.

During FY 2011, two local research projects were selected for funding by the Center: (1) Ecohydrology of Invasive Reed Canary Grass, awarded to Camille McNeely, Assistant Professor, Eastern Washington University and (2) Understanding Toxin Production by Harmful Algae: Vancouver Lake as a Model System, awarded to Gretchen Rollwagen-Bollens, Assistant Clinical Professor, WSU-Vancouver. These projects were competitively awarded based on review and recommendation by the SWWRCs Joint Scientific Board. As described below, these projects address important state issues but are also relevant to national interests. A national project granted to the University of Washington was awarded through the SWWRC. The 104(g) project, West-Wide Drought Forecasting System: A Scientific Foundation for National Integrated Drought Information System (NIDIS) previously awarded to Professor Anne Steinemann at the University of Washington. A progress update is included in this report

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

## Basic Information

<b>Title:</b>	West-Wide Drought Forecasting System: A Scientific Foundation for NIDIS
<b>Project Number:</b>	2006WA180G
<b>Start Date:</b>	9/1/2006
<b>End Date:</b>	8/31/2011
<b>Funding Source:</b>	104G
<b>Congressional District:</b>	7
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Drought, Hydrology, Management and Planning
<b>Descriptors:</b>	Drought Forecast, Drought Mitigation
<b>Principal Investigators:</b>	Anne Steinemann, Dennis Lettenmaier, Andrew Wood

## Publications

1. Wood, A.W. Correcting errors in streamflow forecast ensemble mean and spread. Submitted to Journal of Hydrometeorology (in review).
2. Steinemann, A., 2007, Climate Forecasts for Drought Management, NOAA Climate Prediction Applications Science Workshop, Seattle, March 21, 2007.
3. 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.
4. 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.
5. 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.
6. 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.
7. 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,
8. 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.
9. Fontaine, M., and A. Steinemann, A., 2006, Assessing and Mitigating Drought in Washington State, UW/UBC Hydrology Conference.
10. 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>

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

11. Steinemann, A., 2007, Climate Forecasts for Drought Management, NOAA Climate Prediction Applications Science Workshop, Seattle, March 21, 2007.
12. 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.
13. 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.
14. 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.
15. 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.
16. 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,
17. 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.
18. Fontaine, M., and A. Steinemann, A., 2006, Assessing and Mitigating Drought in Washington State, UW/UBC Hydrology Conference.
19. 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>
20. 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).
21. 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).
22. 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.
23. 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.
24. Shi, X., A. W. Wood, and D. P. Lettenmaier, How Essential is Hydrologic Model Calibration to Seasonal Streamflow Forecasting?, Journal of Hydrometeorology (submitted).
25. 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).
26. 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.
27. 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.
28. 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.

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

San Francisco, California.

29. 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.
30. 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.
31. 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.
32. 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.
33. 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
34. 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.
35. 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.
36. 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.
37. 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.
38. 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.
39. 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/>
40. 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/>
41. 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/>
42. Steinemann, Anne C., 2007, Using Climate Forecasts for Drought Management, Oral Presentation at the 5th Annual NOAA Climate Prediction Applications Science Workshop , Seattle, Washington. March 20-23, 2007.
43. Rosenberg, E., Andrew W. Wood, Q. Tang, Anne C. Steinemann, B. Imam, S. Sorooshian, and Dennis P. Lettenmaier, 2007, Improving Water Resources Management in the Western United States through Use of Remote Sensing Data and Seasonal Climate Forecasts, Poster Presentation at the 5th Annual Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.

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

44. 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.
45. Lettenmaier, Dennis P., Andrew W. Wood and Kostas 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 GC31A-07.
46. Fontaine, Matthew M. and Anne C. 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.
47. Shukla, S., D. Alexander, Anne C. Steinemann, and Andrew W. Wood, 2007, Applications of Medium Range To Seasonal/Interannual Climate Forecasts for Water Resources Management in the Yakima River Basin of Washington State, University of Washington Water Center Annual Review of Research, Seattle, Washington, February 14, 2007.
48. Wood, Andrew W., Anne C. 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 H53C-0648.
49. Fontaine, M., and A. Steinemann, A., 2006, Assessing and Mitigating Drought in Washington State, UW/UBC Hydrology Conference.
50. 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>
51. 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).
52. Shukla, S. and Andrew W. Wood, 2007, Application of LDAS-era Land Surface Models for Drought Characterization and Prediction in Washington State, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H43A-0962.
53. 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.
54. 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.
55. Vano, J. A., and Anne C. Steinemann, 2007, Using Climate Forecast Information in Water Resource Planning: Opportunities and Challenges in the Yakima River Basin, Washington, USA, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H24A-05.
56. Wood, Andrew W., S. Shukla, J. A. Vano, and Anne C. Steinemann, 2007, Connecting Climate, Hydrologic and Drought Predictions to Water Resources Management in Washington State, EOS Transactions, American Geophysical Union, Fall Meeting Supplement 88(52): Abstract H23F-1678.
57. Andreadis, K., Dennis P. Lettenmaier, and Andrew 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.
58. Shukla, S., and Andrew W. Wood, 2008, A Hydrologic Model-based Drought Monitoring System for Washington State, Oral Presentation at the 88th American Meteorological Society Annual Meeting, New Orleans, Louisiana, January 22-24, 2008.
59. Shukla, S. and Andrew W. Wood, 2007, Drought Monitoring: An Evaluation of Drought Indicators Based on Climate and Hydrologic Variables, Poster Presentation at the 2nd Annual Graduate Climate Conference, University of Washington Charles L. Pack Forest Center, Washington. October 19-21, 2007.
60. Vano, Julie A., 2007, Challenges and Rewards of Translating Climate Change Science for Non-scientists: Two Case Studies on Drought, Oral Presentation at the 2nd Annual Graduate Climate Conference University of Washington Charles L. Pack Forest Center, Washington. October 19-21, 2007.

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

61. 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
62. Wood, Andrew W., 2008, 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. [http://www.sercc.com/cpasw\\_abstracts.htm](http://www.sercc.com/cpasw_abstracts.htm)
63. Wood, Andrew 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 20-23, 2007.
64. Wood, Andrew W., 2008, The University of Washington Surface Water Monitor: An Experimental Platform for National Hydrologic Assessment and Prediction, Oral Presentation at the 88th American Meteorological Society Annual Meeting New Orleans, Louisiana. January 22-24, 2008.
65. Wood, Andrew W., J. A. Vano, S. Shukla, and Anne 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. [http://www.sercc.com/cpasw\\_abstracts.htm](http://www.sercc.com/cpasw_abstracts.htm)
66. Wood, Andrew, N. Voisin, and S. Shukla, 2008, Medium-range Ensemble Hydrologic Forecasting for Western Washington State, Poster Presentation at the 88th American Meteorological Society Annual Meeting, New Orleans, Louisiana. January 22-24, 2008.
67. Annual Review of Research, 2008, A Symposium of Water Research, hosted by the University of Washington Water Center, Anne C. Steinemann, Director. USGS research conducted on Grant 06HQGR0190 was featured at this event. Seattle, Washington, February 14, 2008. <http://depts.washington.edu/cwws/>
68. Bohn, T., 2008. 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, Anne C. Steinemann, Director. Seattle, Washington, February 14, 2008. <http://depts.washington.edu/cwws/>
69. Shukla, S. and Andrew W. Wood, 2008, 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, Anne C. Steinemann, Director. Seattle, Washington, February 14, 2008. <http://depts.washington.edu/cwws/>
70. Shi, Xiaogang, Andrew W. Wood, and Dennis P. Lettenmaier, 2008, How Essential is Hydrologic Model Calibration to Seasonal Streamflow Forecasting? *Journal of Hydrometeorology*, 9(6): 1350-1363. DOI: 10.1175/2008JHM1001.1
71. Wang, Aihui, Theodore J. Bohn, Sarith P. Mahanama, Randal D. Koster, and Dennis P. Lettenmaier, 2009, Multimodel Ensemble Reconstruction of Drought over the Continental United States. *Journal of Climate* 22(10): 2694-2712. DOI: 10.1175/2008JCLI2586.1
72. Fontaine, Matthew M. and Anne C. Steinemann, 2009, Assessing Vulnerability to Natural Hazards: Impact-Based Method and Application to Drought in Washington State. *ASCE Natural Hazards Review* 10(1): 11-18. [http://dx.doi.org/10.1061/\(ASCE\)1527-6988\(2009\)10:1\(11\)](http://dx.doi.org/10.1061/(ASCE)1527-6988(2009)10:1(11))
73. Vano, Julie, 2008, Connecting Climate Forecast Information and Drought Predictions to Water Resource Management: Opportunities and Challenges in the State of Washington, Annual Review of Research, A Symposium of Water Research, hosted by the University of Washington Water Center, Anne C. Steinemann, Director. Seattle, Washington, February 14, 2008. <http://depts.washington.edu/cwws/>
74. Vano, Julie A., L. Cuo, M. Elsner McGuire, Richard N. Palmer, A. Polebitski, Anne C. Steinemann, and David P. Lettermaier 2008, Using Multi-Model Ensemble Methods to Assess Climate Change Impacts on Water Management throughout the State of Washington, *EOS Transactions, American Geophysical Union, Fall Meeting Supplement*, 89(53): Abstract GC21B-05

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

75. Keys, P. W., Derek Booth, Anne C. Steinemann, and Dennis P. Lettermaier, 2008, Precipitation Extremes in Washington State: Are They Changing? EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 89(53): Abstract H13D-0960.
76. Rosenberg, E., Qihong Tang, Andrew W. Wood, Anne C. Steinemann, and Dennis P. Lettermaier 2008, Statistical Applications of Physical Hydrologic Models and Satellite Snow Cover Observations to Season Water Suply Forecasts, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 89(53): Abstract H41B-0871.
77. Steinemann, Anne C., 2007, Using Climate Forecasts for Drought Management, Oral Presentation at the 5th Annual NOAA Climate Prediction Applications Science Workshop , Seattle, Washington. March 20-23, 2007.
78. Rosenberg, E., Andrew W. Wood, Q. Tang, Anne C. Steinemann, B. Imam, S. Sorooshian, and Dennis P. Lettenmaier, 2007, Improving Water Resources Management in the Western United States through Use of Remote Sensing Data and Seasonal Climate Forecasts, Poster Presentation at the 5th Annual Climate Prediction Applications Science Workshop, Seattle, Washington, March 20-23, 2007.
79. 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.
80. Lettenmaier, Dennis P., Andrew W. Wood and Kostas 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 GC31A-07.
81. Fontaine, Matthew M. and Anne C. 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.
82. Shukla, S., D. Alexander, Anne C. Steinemann, and Andrew W. Wood, 2007, Applications of Medium Range To Seasonal/Interannual Climate Forecasts for Water Resources Management in the Yakima River Basin of Washington State, University of Washington Water Center Annual Review of Research, Seattle, Washington, February 14, 2007.
83. Wood, Andrew W., Anne C. 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 H53C-0648.
84. Fontaine, M., and A. Steinemann, A., 2006, Assessing and Mitigating Drought in Washington State, UW/UBC Hydrology Conference.
85. 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>
86. 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).
87. Shukla, S. and Andrew W. Wood, 2007, Application of LDAS-era Land Surface Models for Drought Characterization and Prediction in Washington State, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H43A-0962.
88. 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.
89. 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.
90. Vano, J. A., and Anne C. Steinemann, 2007, Using Climate Forecast Information in Water Resource Planning: Opportunities and Challenges in the Yakima River Basin, Washington, USA, EOS Transactions, American Geophysical Union, Fall Meeting Supplement, 88(52): Abstract H24A-05.
91. Wood, Andrew W., S. Shukla, J. A. Vano, and Anne C. Steinemann, 2007, Connecting Climate, Hydrologic and Drought Predictions to Water Resources Management in Washington State, EOS Transactions, American Geophysical Union, Fall Meeting Supplement 88(52): Abstract H23F-1678.

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

92. Andreadis, K., Dennis P. Lettenmaier, and Andrew 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.
93. Shukla, S., and Andrew W. Wood, 2008, A Hydrologic Model-based Drought Monitoring System for Washington State, Oral Presentation at the 88th American Meteorological Society Annual Meeting, New Orleans, Louisiana, January 22-24, 2008.
94. Shukla, S. and Andrew W. Wood, 2007, Drought Monitoring: An Evaluation of Drought Indicators Based on Climate and Hydrologic Variables, Poster Presentation at the 2nd Annual Graduate Climate Conference, University of Washington Charles L. Pack Forest Center, Washington. October 19-21, 2007.
95. Vano, Julie A., 2007, Challenges and Rewards of Translating Climate Change Science for Non-scientists: Two Case Studies on Drought, Oral Presentation at the 2nd Annual Graduate Climate Conference University of Washington Charles L. Pack Forest Center, Washington. October 19-21, 2007.
96. 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
97. Wood, Andrew W., 2008, 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. [http://www.sercc.com/cpasw\\_abstracts.htm](http://www.sercc.com/cpasw_abstracts.htm)
98. Wood, Andrew 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 20-23, 2007.
99. Wood, Andrew W., 2008, The University of Washington Surface Water Monitor: An Experimental Platform for National Hydrologic Assessment and Prediction, Oral Presentation at the 88th American Meteorological Society Annual Meeting New Orleans, Louisiana. January 22-24, 2008.
100. Wood, Andrew W., J. A. Vano, S. Shukla, and Anne 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. [http://www.sercc.com/cpasw\\_abstracts.htm](http://www.sercc.com/cpasw_abstracts.htm)
101. Wood, Andrew, N. Voisin, and S. Shukla, 2008, Medium-range Ensemble Hydrologic Forecasting for Western Washington State, Poster Presentation at the 88th American Meteorological Society Annual Meeting, New Orleans, Louisiana. January 22-24, 2008.
102. Annual Review of Research, 2008, A Symposium of Water Research, hosted by the University of Washington Water Center, Anne C. Steinemann, Director. USGS research conducted on Grant 06HQGR0190 was featured at this event. Seattle, Washington, February 14, 2008. <http://depts.washington.edu/cwws/>
103. Bohn, T., 2008. 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, Anne C. Steinemann, Director. Seattle, Washington, February 14, 2008. <http://depts.washington.edu/cwws/>
104. Shukla, S. and Andrew W. Wood, 2008, 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, Anne C. Steinemann, Director. Seattle, Washington, February 14, 2008. <http://depts.washington.edu/cwws/>
105. Shi, Xiaogang, Andrew W. Wood, and Dennis P. Lettenmaier, 2008, How Essential is Hydrologic Model Calibration to Seasonal Streamflow Forecasting? *Journal of Hydrometeorology*, 9(6): 1350-1363. DOI: 10.1175/2008JHM1001.1
106. Wang, Aihui, Theodore J. Bohn, Sarith P. Mahanama, Randal D. Koster, and Dennis P. Lettenmaier, 2009, Multimodel Ensemble Reconstruction of Drought over the Continental United States. *Journal of*

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

Climate 22(10): 2694-2712. DOI: 10.1175/2008JCLI2586.1

107. Fontaine, Matthew M. and Anne C. Steinemann, 2009, Assessing Vulnerability to Natural Hazards: Impact-Based Method and Application to Drought in Washington State. *ASCE Natural Hazards Review* 10(1): 11-18. [http://dx.doi.org/10.1061/\(ASCE\)1527-6988\(2009\)10:1\(11\)](http://dx.doi.org/10.1061/(ASCE)1527-6988(2009)10:1(11))
108. Vano, Julie, 2008, Connecting Climate Forecast Information and Drought Predictions to Water Resource Management: Opportunities and Challenges in the State of Washington, *Annual Review of Research, A Symposium of Water Research*, hosted by the University of Washington Water Center, Anne C. Steinemann, Director. Seattle, Washington, February 14, 2008. <http://depts.washington.edu/cwws/>
109. Vano, Julie A., L. Cuo, M. Elsner McGuire, Richard N. Palmer, A. Polebitski, Anne C. Steinemann, and David P. Lettermaier 2008, Using Multi-Model Ensemble Methods to Assess Climate Change Impacts on Water Management throughout the State of Washington, *EOS Transactions, American Geophysical Union, Fall Meeting Supplement*, 89(53): Abstract GC21B-05
110. Keys, P. W., Derek Booth, Anne C. Steinemann, and Dennis P. Lettermaier, 2008, Precipitation Extremes in Washington State: Are They Changing? *EOS Transactions, American Geophysical Union, Fall Meeting Supplement*, 89(53): Abstract H13D-0960.
111. Rosenberg, E., Qihong Tang, Andrew W. Wood, Anne C. Steinemann, and Dennis P. Lettermaier 2008, Statistical Applications of Physical Hydrologic Models and Satellite Snow Cover Observations to Season Water Supply Forecasts, *EOS Transactions, American Geophysical Union, Fall Meeting Supplement*, 89(53): Abstract H41B-0871.
112. Andreadis, K., D. Lettenmaier, and A. Wood, 2007, Drought identification and prediction, *Climate Prediction Applications Workshop*, Seattle, WA.
113. 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/>
114. Clark, E., and D. Lettenmaier, 2010, The impact of groundwater-land surface interactions on hydrologic persistence in macroscale modeling, *Hydrology in the 21st Century: Links to the past, and a vision for the future*, Steve Burges Retirement Symposium. Seattle, WA, March 25, 2010.
115. Clark, E., 2009, Macro-scale hydrology, does shallow groundwater make a difference?, *UW/UBC Hydrology Conference*. Vancouver, BC, September 25, 2009.
116. Fontaine, M, and Steinemann, A., 2007, Assessing and mitigating drought in Washington State, *NOAA Climate Prediction Applications Science Workshop (CPAWS)*, Seattle, WA.
117. Keys, P W, Booth, D, Steinemann, A C, Lettenmaier, D Precipitation Extremes in Washington State: Are they changing? *American Geophysical Union 89(53)*, Fall Meeting Supplement, 2008.
118. Rosenberg, E, Q, Tang, A, Wood, A C, Steinemann, D P, Lettenmaier, 2008, Statistical Applications of Physical Hydrologic Models and Satellite Snow Cover Observations to Seasonal Water Supply Forecasts, *American Geophysical Union 89(53)*, Fall Meeting Supplement.
119. Shukla, S. and A. W. Wood, 2007, Drought monitoring: An evaluation of drought indicators based on climate and hydrologic variables, *Graduate Climate Conference Seattle, WA*.
120. Shukla, S. and A.W. Wood, 2007, Application of LDAS-era land surface models for drought characterization and prediction in Washington State in *Eos Transactions of the American Geophysical Union*, 88(52) Fall Meeting Supplement, San Francisco, CA, Abstract H43A-0962.
121. 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, LA.
122. Shukla, S., and A.W. Wood, 2008, 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/>
123. 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

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

- Washington State, NOAA Climate Prediction Applications Science Workshop, Seattle, WA.
124. Steinemann, A., 2007, Climate forecasts for drought management, NOAA Climate Prediction Applications Science Workshop (CPASW), Seattle, WA.
  125. Vano, J.A., Cuo, L., Elsner McGuire, M., Palmer, R.N., Polebitski, A., Steinemann, A.C., Lettenmaier, D.P., Using Multi-Model Ensemble Methods to Assess Climate Change Impacts on Water Management Throughout the State of Washington, American Geophysical Union 89(53), Fall Meeting Supplement, 2008.
  126. Vano, J.A., 2007, Challenges and rewards of translating climate change science for non-scientists: Two case studies on drought, Graduate Climate Conference Seattle, WA.
  127. 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, 88(52) Fall Meeting Supplement, San Francisco, CA, Abstract H24A-05.
  128. Wood, A., N. Voisin, S. and Shukla, 2008, Medium-range ensemble hydrologic forecasting for Western Washington State, poster, 88th American Meteorological Society Annual Meeting, New Orleans, LA.
  129. Wood, A.W., 2007, Application of LDAS-era land surface models to drought monitoring and prediction, Drought Monitor Forum, Portland, OR.
  130. 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, LA.
  131. Wood, A.W., S. Shukla, J. Vano, and A. Steinemann, 2007, Connecting climate, hydrologic and drought predictions to water resources management in Washington state in Eos Transactions of the American Geophysical Union, 88(52) Fall Meeting Supplement, San Francisco, CA, Abstract H23F-1678.
  132. 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, NOAA Climate Prediction Application Science Workshop, Chapel Hill, NC.
  133. Fontaine, M., and A.C. Steinemann, 2008, Assessing vulnerability to natural hazards: An impact-based method and application to drought in Washington State, ASCE Natural Hazards Review (in press).
  134. Fontaine, M.M., Steinemann, A.C., and Hayes, M.J., 2008, State drought programs: Lessons and recommendations from the Western U.S. ASCE Natural Hazards Review (accepted).
  135. 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.
  136. Shukla, A., A.C. Steinemann, and D.P. Lettenmaier. Drought Monitoring System for Washington State: Indicators and Applications. Journal of Hydrometeorology (in preparation)
  137. Shi, X., A.W. Wood, and D.P. Lettenmaier, 2008, How essential is hydrologic model calibration to seasonal streamflow forecasting?, Journal of Hydrometeorology (submitted).
  138. Wang, A., T.J. Bohn, S.P. Mahanama, R.D. Koster, and D.P. Lettenmaier, 2008, Multimodel reconstruction of drought over the continental United States, Journal of Climate (submitted).
  139. 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.
  140. Annual Review of Research, 2007, 2008, 2009, 2010. A symposium of water research hosted by the University of Washington Water Center, Anne Steinemann, Director, USGS research was featured at this event. Seattle, Washington. <http://depts.washington.edu/cwws/>.
  141. Bohn, T., Feb. 2008. Drought and model consensus: Reconstructing and monitoring drought in the U.S. with multiple models, The Water Center Annual Review of Research. Seattle, Washington. <http://depts.washington.edu/cwws/>.
  142. Shukla, S., and A.W. Wood, Feb. 2008. Application of a land surface model for drought monitoring and prediction in Washington state, The Water Center Annual Review of Research, Seattle, Washington. <http://depts.washington.edu/cwws/>.

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

143. Vano, J., Feb. 2008. Connecting climate forecast information and drought predictions to water resource management: Opportunities and challenges in the state of Washington, The Water Center Annual Review of Research. Seattle, Washington. <http://depts.washington.edu/cwws/>.
144. Shukla, A., A.C. Steinemann, and D.P. Lettenmaier, 2011, Drought Monitoring System for Washington State: Indicators and Applications. *Journal of Hydrometeorology*. 12(1):66-83.
145. Fontaine, M. M., A. C. Steinemann, and M. J. Hayes, accepted, State Drought Programs: Lessons and Recommendations from the Western U.S. ASCE Natural Hazards Review.
146. Rosenberg, E.A., Wood, A.W., and A.C. Steinemann, submitted 2011, Statistical Applications of Physically Based Hydrologic Models to Seasonal Streamflow Forecasts. *Water Resources Research*.
147. Rosenberg, E.A., Clark, E.A., Steinemann, A.C., and D.P. Lettenmaier, 2011, The Utility of Soil Moisture Estimates from a Land Surface Model in Seasonal Streamflow Forecasts, 91st Annual Meeting of the American Meteorological Society, January 23 - 27, Seattle, Washington.
148. Clark, E.A., A.C. Steinemann, and D.P. Lettenmaier, 2011, The Impact of Groundwater-Land Surface Interactions on Hydrologic Persistence in Macroscale Modeling, AMS Annual Meeting, January 27, Seattle, Washington.
149. Shukla, A., A.C. Steinemann, and D.P. Lettenmaier, 2011, Drought Monitoring System for Washington State: Indicators and Applications. *Journal of Hydrometeorology*. 12(1):66-83.
150. Fontaine, M. M., A. C. Steinemann, and M. J. Hayes, accepted, State Drought Programs: Lessons and Recommendations from the Western U.S. ASCE Natural Hazards Review.
151. Rosenberg, E.A., Wood, A.W., and A.C. Steinemann, submitted 2011, Statistical Applications of Physically Based Hydrologic Models to Seasonal Streamflow Forecasts. *Water Resources Research*.
152. Rosenberg, E.A., Clark, E.A., Steinemann, A.C., and D.P. Lettenmaier, 2011, The Utility of Soil Moisture Estimates from a Land Surface Model in Seasonal Streamflow Forecasts, 91st Annual Meeting of the American Meteorological Society, January 23 - 27, Seattle, Washington.
153. Clark, E.A., A.C. Steinemann, and D.P. Lettenmaier, 2011, The Impact of Groundwater-Land Surface Interactions on Hydrologic Persistence in Macroscale Modeling, AMS Annual Meeting, January 27, Seattle, Washington.

## 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.

In this research, we develop a drought forecast and nowcast system for the western U.S., which serves 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 also contributes 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 are working directly with water managers in selected states in the region (Washington, California, and others) to apply this forecast system to water resources decisions.

Our drought forecasting system builds upon the University of Washington's operational West-Wide Hydrologic Forecast System and National Surface Water Monitor. In doing so, we 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 are working with Dr. Randall Hanson and Dr. Michael Dettinger of the USGS California Water Science Center in San Diego. Specifically, we 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 define as the continental U.S. west of the Mississippi River), which serves 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 leverages the existing University of Washington WHFS and SWM. Our specific objectives are as follows:

(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

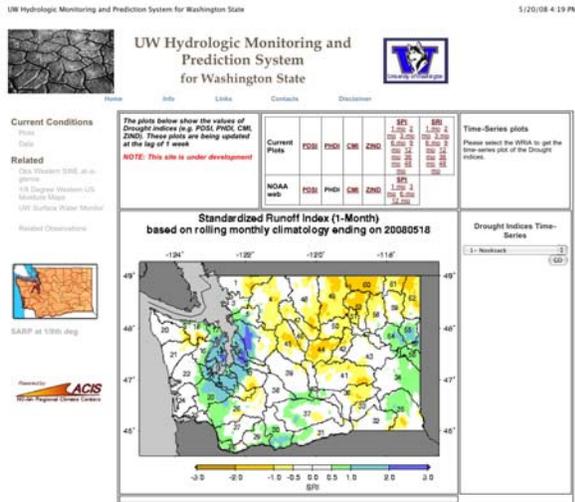
(4) To work with the NDMC, the WGA, and other users (primarily state agencies in the western U.S.) to incorporate the resulting drought nowcasts and forecasts into water management decisions and into drought information systems such as the Drought Monitor/Outlook and NIDIS.

## 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).



We have met with key stakeholders (e.g. federal, state, and regional water officials; irrigation district managers; and 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).

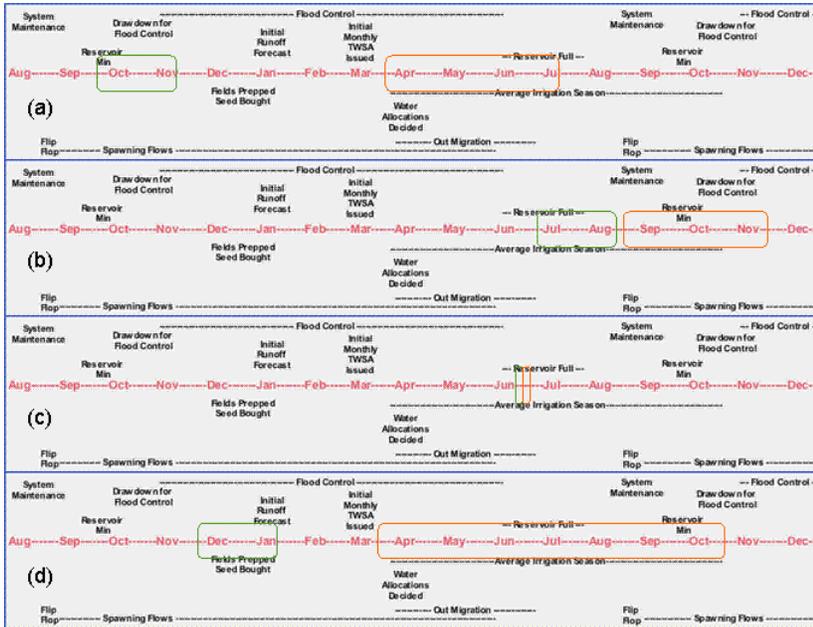


Figure 2. Four identified decision-making realms, with green circles around period in which decisions are made and orange circles around the relevant time of forecast. (a) Filling reservoirs without flooding in winter and spring, (b) maintaining flows for fish in fall, (c) week-to-week operations in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

**Streamflow Forecast vs. Climatology (1960-99)**  
**FORECAST DATE: May 15, 2008**  
 Missouri River at Toston MT (06054500)

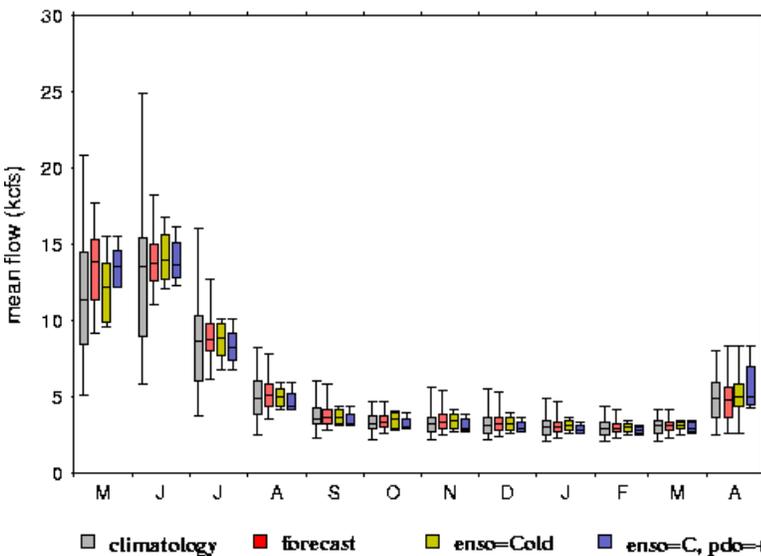


Figure 3. ESP forecast for mean monthly streamflow on the Missouri River at Toston, MT, as of May 15, 2008.

below the 20<sup>th</sup> 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

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 from 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

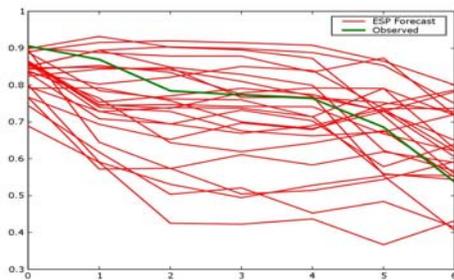


Figure 4: Spatial average soil moisture over AZ-CA starting on Feb. 1, 2006, and progressing through August, as compared with “actual” soil moisture (real-time model estimates).

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 20<sup>th</sup> 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.

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

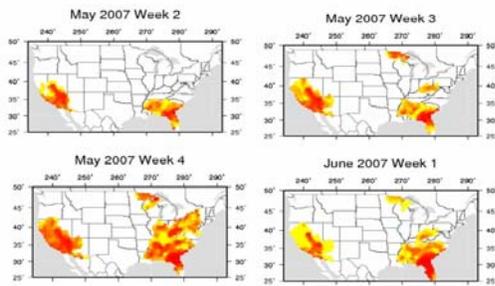


Figure 5: Estimated extent of drought over continental U.S. as of first week of June, 2007, and evolution over previous three weeks. Soil moisture percentiles are relative.

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

The basic concept behind SIMGM is a simple water balance, i.e. the change in water storage within an aquifer over time equals the difference between recharge into and subsurface flow out of the aquifer. Recharge is calculated using Darcy's law as a function of the depth to the water table and the matric potential and mid-element depth of the lowest unsaturated soil layer. The recharge estimate also accounts for an upward flux driven by capillary forces. The CLM implementation of SIMGM uses a simple TOPMODEL-based runoff model to calculate subsurface flow (baseflow) as an exponential function of water table depth. Unlike in TOPMODEL, Niu et al. (2007) estimate saturated hydraulic conductivity as a function of soil texture; in the aquifer, hydraulic conductivity

exponentially decays with depth from that of the lowest soil layer. Water table depth is estimated from the resultant aquifer water storage scaled by the specific yield. Depth to the water table can be within the soil column, in which case the water table depth calculations differ slightly to account for differences in soil and aquifer properties. The water table can also be below the base of the lumped, unconfined aquifer element; hence, there is no prescribed total model depth.

The VIC implementation of SIMGM differs from that of Niu et al. (2007) primarily in the surface runoff scheme. Whereas CLM applies a TOPMODEL-based runoff scheme to parameterize surface runoff as a function of topographically based saturated fraction and water table depth, VIC calculates surface runoff using a more generalized parameterization. Also, the standard VIC model includes 3 soil layers, as opposed to the 10 layers of CLM. In order to maintain the simplicity of the VIC model, we have not altered the 3-layer construct. The thrust of work in this reporting period has been calibration and testing of the VIC model with and without SIMGM.

We have calibrated the VIC model with and without SIMGM over the Little Wabash River, IL, the Bruneau River, ID, the Salmon River, ID, the North Fork Flathead River, MT, and the Yellowstone River, MT. For all of these rivers, VIC reproduces daily streamflow equally well with or without SIMGM. The inclusion of SIMGM does impact the distribution of water in the annual average water budget (Figure 6). Summertime evapotranspiration is higher in SIMGM in the Little Wabash River, where the primary vegetation cover is forest. This leads to lower wintertime baseflow. In the Salmon and North Fork Flathead rivers, evapotranspiration is minimally affected; however the partitioning of streamflow between runoff and baseflow is greatly altered, with near-constant baseflow in the SIMGM implementation, which contrasts the seasonal cycle of baseflow in the standard VIC implementation. We have obtained Ameriflux measurements of latent heat in the Feather River basin and intend to test the performance of VIC with and without groundwater in simulating evapotranspiration.

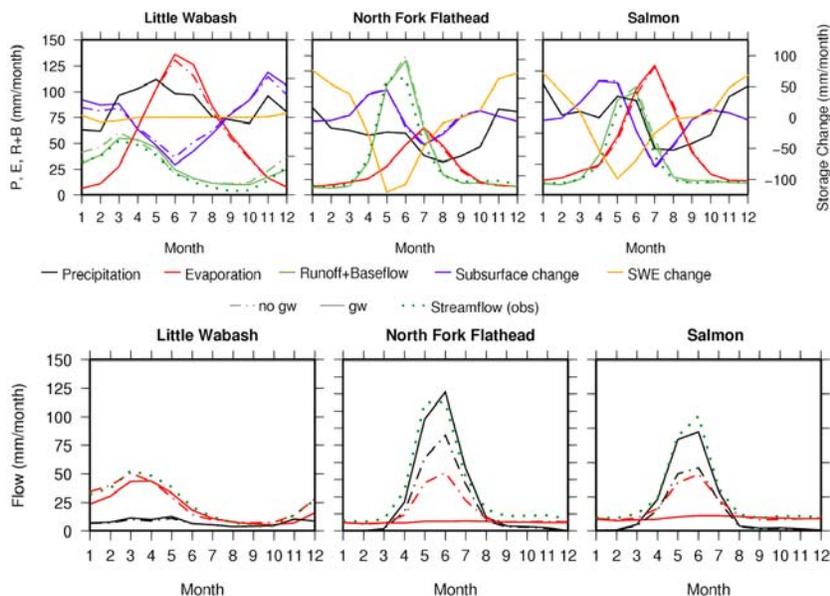


Figure 6. Top panel shows the modeled average annual water balance (1950-1998) for the Little Wabash, North Fork Flathead and Salmon Rivers. Lower panel shows the modeled average annual runoff and baseflow plotted against observed streamflow for the same rivers. Dashed lines are the standard VIC implementation; solid lines show the results with groundwater. Both sets are calibrated to daily streamflow and its natural log. Dotted line shows the observed streamflow, converted to mm/month.

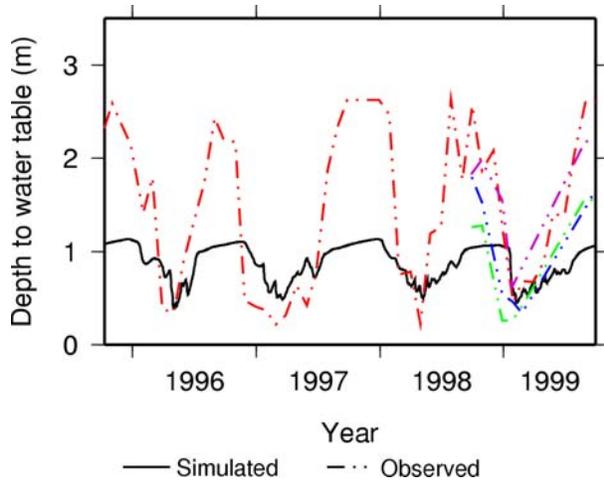


Figure 7. Depth to water table, simulated by VIC with SIMGM for the Little Wabash River (solid) and observed by the ISWS at Olney (blue), Fairfield (green), Dixon Springs (red) and Rend Lake.

levels (~100 ft), whereas VIC with SIMGM models water levels on the order of 3-6 ft deep. This suggests that SIMGM, which is designed to model shallow groundwater, is effectively acting as an additional soil layer in these regions of deep groundwater. This might also explain the baseflow response in these regions.

For droughts, we are particularly interested in whether the persistence of drought conditions will be impacted by the inclusion of groundwater in VIC. To investigate this, we examined the autocorrelation of streamflow and of subsurface storage in each model. Figure 8 shows the results for streamflow in the Little Wabash River. In this case, a slightly autocorrelation (over 1-, 3-, and 6-month lags) occurs when groundwater is modeled; however, this correlation is higher than observed. In the Salmon and North Fork Flathead rivers, on the other hand, the streamflow shows a smaller lagged correlation, which is also closer to the observed, when groundwater is modeled than in the original VIC version. Subsurface storage tends to be highly autocorrelated in both models, though the storage in the groundwater model shows a stronger relationship where the autocorrelation in streamflow is weaker. The similarities in these correlations; however, suggest that the standard VIC model reproduces the

Simulated basin-average water table levels for the Little Wabash River track the timing of seasonal cycle of the observed well level data (from the ISWS climatological shallow groundwater WARM and ICN networks in Illinois) fairly well; however, individual wells tend to become much drier (higher depth to water table) during winter months than simulated water levels (Fig. 7). Water levels match somewhat better at Fairfield (green line in Fig. 7), which is the nearest station. The observations are somewhat incongruent with the model results due to the heterogeneity across scales. There are few groundwater level measurements in the western U.S. that are included in the USGS Climate Response Network (CRN wells deemed unaffected by pumping). The CRN wells in Idaho and Montana measure very deep water

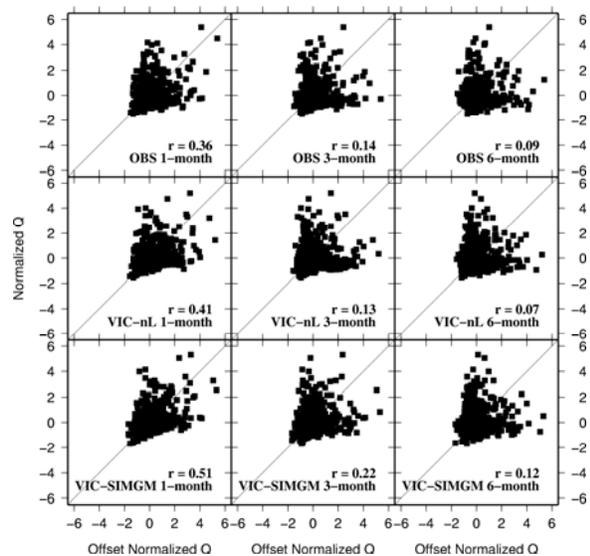


Figure 8. Autocorrelation of streamflow for the Little Wabash River in Illinois. 1-month lag time, 3-month lag time, and 6-month lag time shown from left to right. Top: observed, middle: VIC without SIMGM, bottom: VIC with SIMGM. Correlation coefficients labeled on plot.

persistence of hydrologic conditions equally well as the VIC model with groundwater. A paper summarizing these results is in preparation.

In addition, we manually tuned model parameters to apply VIC and VIC with SIMGM over 10 MOPEX test basins in the Midwest and eastern U.S. As with the fully calibrated basins, we found that the models could be tuned to produce similar streamflow values; however, the distribution of water varied with vegetation and soil types. Again, the biggest differences occur in summertime evapotranspiration and subsurface storage. The persistence of subsurface storage tended to increase in these more humid basins.

We will be conducting additional work to incorporate groundwater level data into the VIC model through calibration or assimilation. Although SIMGM has a moveable lower boundary condition, it is designed for use in shallow aquifers. As such, regions with very deep water levels may need to be masked out in continental application of the VIC model with SIMGM. An implementation of the model in one such semi-arid environment is currently underway for the Colorado River basin. To initialize water table depths in the model, we use a simulated water table climatology that has been validated against water table observations. Figure 9 illustrates these data at their native 30-arcsecond resolution and at aggregated resolutions of 1/16 degree and 1/8 degree, the latter of which is being used for the VIC with SIMGM implementation. As shown, much of the shallow water table data is lost at the coarser resolutions, rendering SIMGM less practical for those grid cells. Thus, how to accurately represent the bank storage effects that are likely responsible for most of the surface/groundwater interaction in this region is still being studied. This question has implications for the effects of interannual carryover storage on drought in the region, which is a central issue of interest in the investigation.

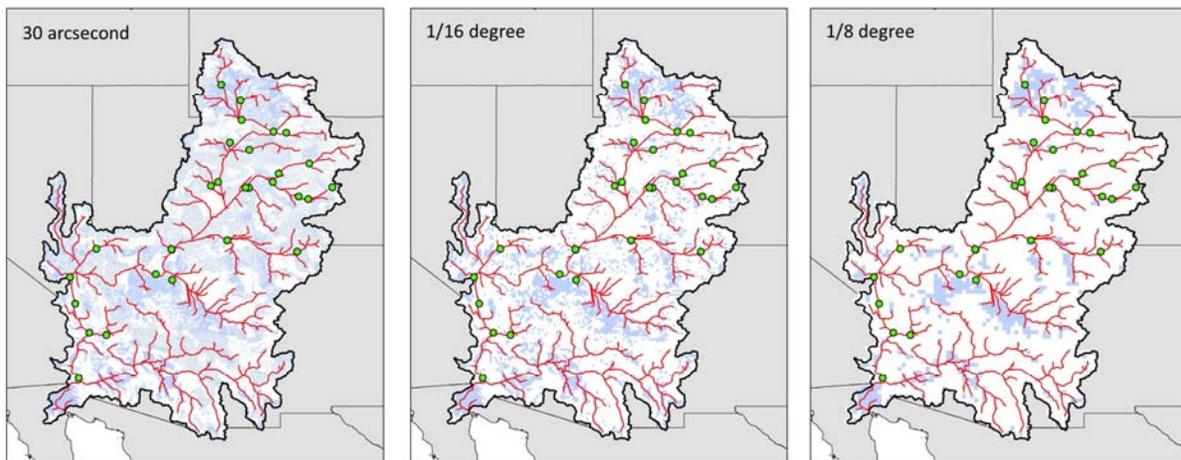


Figure 9. Water table climatology from Miguez-Macho et al. (2008) in the Colorado River basin. 1/16 degree and 1/8 degree maps were derived by aggregating data from their native 30-arcsecond resolution. Water table depths of less than 20 m are shown in blue, and streamflow locations used for calibration are shown with green circles.

In addition, during this past year, we had a unique opportunity to further develop and use the groundwater monitoring and forecast system in applications in California to support the NIDIS (National Integrated Drought Information System) initiative, and drought planning processes underway in the State of California. We are working directly with decision-makers in the use of the system for making water management and agricultural decisions. We have identified regions for applications in California (e.g., Central Valley, Klamath Basin, Southern California Region, Sonoma County), and key decision-makers and stakeholders who have indicated their interest in using the drought monitoring and forecast system developed under this project. Through this collaboration with agencies and NIDIS, our work under the USGS grant is provided even higher visibility and applicability, with a model that could be transferred to other regions in the U.S.

We also have conducted outreach activities with agencies (such as California Department of Water Resources) using the results of this model. Some of this outreach explores methodologies described in a recently submitted paper on statistical applications of physically based hydrologic models for seasonal streamflow forecasts (Rosenberg et al., 2011). In this paper, we developed a hybrid framework that employs gridded observed precipitation and VIC-simulated snow water equivalent (SWE) data as predictors in regression equations adapted from an operational forecasting environment. The approach, which leverages the ability of the distributed model to simulate variables at gridded intervals, was tested in a case study of California’s Sacramento River, San Joaquin River, and Tulare Lake hydrologic regions. As summarized in Figure 10, hybrid forecasts were found to offer overall improvement over those officially issued by California’s Department of Water Resources (DWR). By simulating SWE at the highest elevations, the approach also provided improvements in late-season forecasts when most observing stations are snow-free.

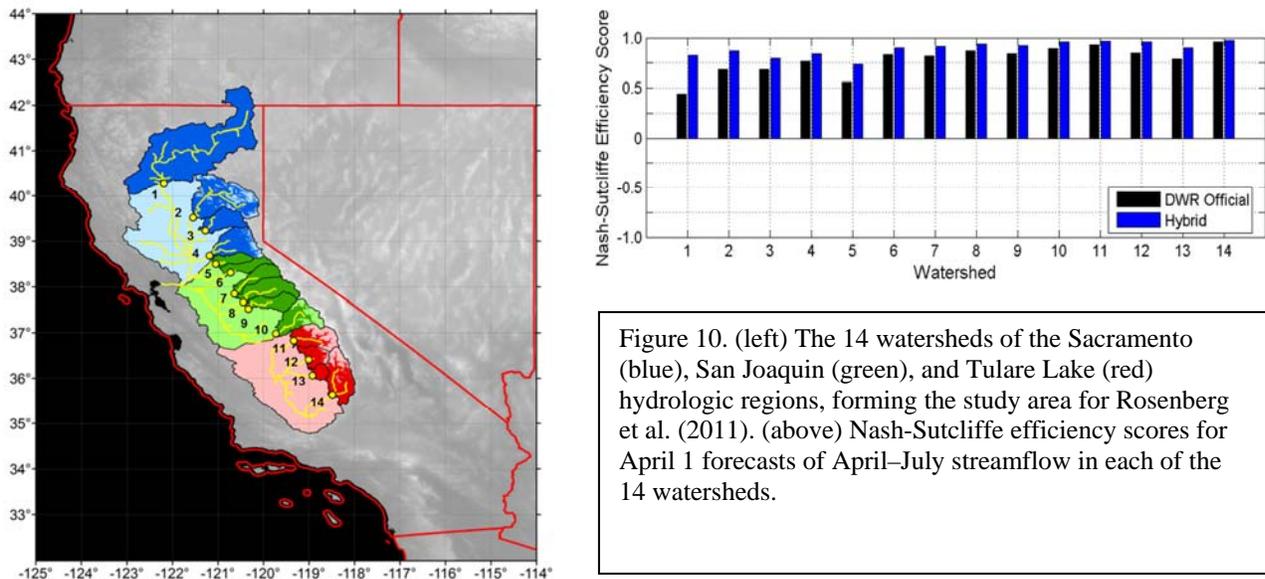


Figure 10. (left) The 14 watersheds of the Sacramento (blue), San Joaquin (green), and Tulare Lake (red) hydrologic regions, forming the study area for Rosenberg et al. (2011). (above) Nash-Sutcliffe efficiency scores for April 1 forecasts of April–July streamflow in each of the 14 watersheds.

Beyond its forecasting ability, the study also demonstrated the ability of a hybrid approach to identify locations with strong predictive skill for potential ground station implementation. This capacity is made possible by combining a search algorithm with a principal components regression methodology adapted from the Natural Resources Conservation Service (NRCS). The results of one such analysis is shown for the Feather River basin in Figure 11, where the “significance” of each hybrid predictor is determined by the product of its regression coefficient and mean climatological value, and shown by the size of its corresponding circle. The findings indicate that, while most of the primary forecast skill is derived from predictors with higher climatological values and better correlations with the predictand, important information is also contained in more transient locations with higher coefficients of variations on the “fringes” of these primary areas. A comparison of these locations with those of existing observing stations suggests that distributed model simulations coupled with statistical analysis can provide a useful tool for expanding existing networks. A follow-up study is currently underway to further explore this issue in other Western watersheds forecast by NRCS.

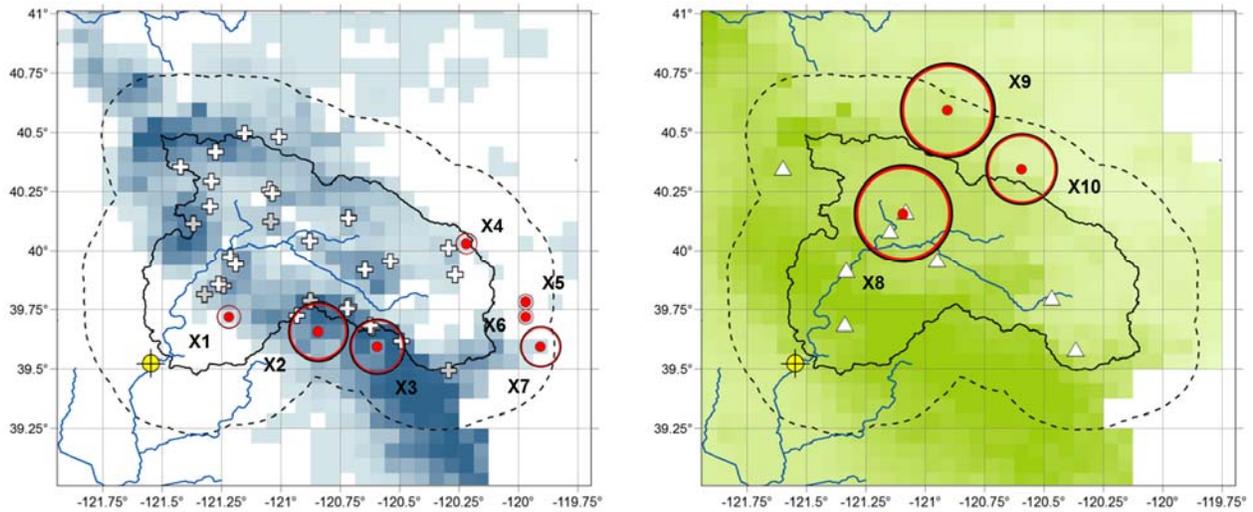


Figure 11. April 1 SWE (left) and October–March precipitation (right) predictor locations for April 1 hybrid streamflow forecasts in the Feather River basin. Climatologies are shown by the darkness of the blue (left) and green (right) backgrounds. Crosses depict existing snow courses and sensors, triangles depict existing rain gauges, and the yellow circle depicts the forecast point at Lake Oroville. Hybrid predictors are identified by red circles, with each size scaled in proportion to the product of its regression coefficient and mean climatological value.

# Understanding Toxin Production by Harmful Algae: Vancouver Lake as a Model System

## Basic Information

<b>Title:</b>	Understanding Toxin Production by Harmful Algae: Vancouver Lake as a Model System
<b>Project Number:</b>	2011WA326B
<b>Start Date:</b>	3/1/2011
<b>End Date:</b>	5/31/2012
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	Washington, 3
<b>Research Category:</b>	Water Quality
<b>Focus Category:</b>	Toxic Substances, Ecology, Water Quality
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Gretchen Rollwagen-Bollens, Stephen M. Bollens

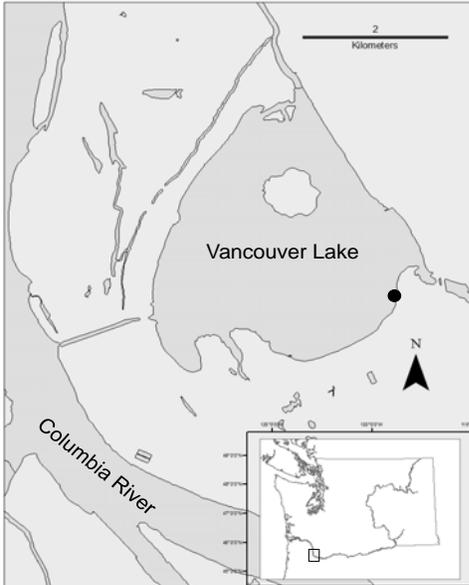
## Publications

1. Lee T, G Rollwagen-Bollens, and S Bollens (in prep), The influence of environmental factors on cyanobacteria blooms and phytoplankton community composition in a shallow temperate lake. To be submitted to Harmful Algae in June 2012.
2. Lee T, G Rollwagen-Bollens, and S Bollens (in prep), qPCR determination of toxic and non-toxic cyanobacteria in a shallow temperate freshwater lake, and relationship to environmental conditions. To be submitted to Applied and Environmental Microbiology in August 2012.
3. Rollwagen-Bollens G, S Bollens, A Gonzalez, J Zimmerman, T Lee, and J Emerson (in revision), Feeding dynamics of the copepod *Diacyclops thomasi* before, during and following filamentous cyanobacteria blooms in a large, shallow temperate lake, *Hydrobiologia*.
4. Rollwagen-Bollens, Gretchen, 2012, Understanding Toxin Production by Harmful Algae: Vancouver Lake as a Model System, State of Washington Water Research Center, Washington State University, Pullman, WA, 18 pgs.

## **Problem and Research Objectives**

Seasonal blooms of cyanobacteria and other algae are natural occurrences in lakes of varying morphology and location, and may naturally increase in frequency as lakes evolve from clean and unproductive states to more shallow and eutrophic conditions (Hutchinson 1973). However, increasing evidence demonstrates that the eutrophication process in lakes is being accelerated by human activity, through sewage and fertilizer inputs, deforestation, road construction, real estate development and other disturbances in lake watersheds, and is contributing to an increase in frequency and intensity of cyanobacteria blooms (e.g. Elser et al. 1990; Dokulil & Teubner 2000; Sellner et al. 2003; Paerl 2008).

Excessive abundance of cyanobacteria may have detrimental effects on lake ecosystems and water quality, including development of surface scums and depleted oxygen levels (Carmichael 1992; Sellner et al. 2003). In addition, many cyanobacteria species can produce potent hepatotoxins that can negatively affect aquatic life and in particular cause harm or even death to humans and other mammals (Codd 1995; Chorus et al. 2000; Codd et al. 2005). However, it is often impossible to visually distinguish between toxigenic and non-toxigenic cyanobacteria species, thus World Health Organization guidelines recommend municipalities restrict access to water bodies when total cyanobacteria abundance exceeds a threshold value (Chorus et al. 2000). This phenomenon is of great concern to water resource managers in Washington State, since cyanobacteria blooms have become an increasing problem in the Pacific Northwest (Jacoby & Kann 2007), and pose particular challenges to human health. Harmful cyanobacteria blooms are of concern to the public, as well, since their use and enjoyment of valued aquatic environments may be prohibited as a result.



**Figure 1.** Map of Vancouver Lake, in Clark County, WA. Filled circle shows location of Vancouver Lake Sailing Club. in Vancouver Lake remains quite poor, with high levels of dissolved nitrogen and phosphorus, high turbidity, and high pH (Bollens & Rollwagen-Bollens 2010).

Vancouver Lake, in Clark County, WA, is a large, shallow lake in the lower Columbia River floodplain that is popular with the local community for swimming, boating, fishing and other recreational activities (Figure 1). Vancouver Lake is also an important habitat for a range of fish species, as well as migrating and resident waterfowl, raptors and songbirds. Historically, Vancouver Lake was a relatively clear, moderately deep (6-8 m) lake flushed twice yearly by the spring and fall freshets of the Columbia River. Dam construction and diking eliminated this natural flushing system, and urbanization in the surrounding drainage basin increased sedimentation rates, such that by 1981 the lake had shallowed to a depth of ~1 m (Gorini 1987).

In response to this, an artificial channel was constructed in 1983 as a means to re-establish flushing by the Columbia River and improve water quality.

However, average depth remains ~1 meter and water quality in Vancouver Lake remains quite poor, with high levels of dissolved nitrogen and phosphorus, high turbidity, and high pH (Bollens & Rollwagen-Bollens 2010).

Most notably, Vancouver Lake has experienced numerous summertime blooms of *Anabaena* and *Aphanizomenon* cyanobacteria over the past 20 years, often necessitating closure

of the Lake to swimming and other recreational use, however the blooms have been variable in intensity from year to year. More recently, cyanobacterial abundance has met or exceeded the threshold established by the World Health Organization for several weeks nearly every summer since 2004, prompting Clark County officials to restrict human contact with lake water during those periods.

Our overall goal for this research project was to better understand the dynamics of toxin production by cyanobacteria in Vancouver Lake, in particular the influence of biological (e.g. grazing pressure by planktonic consumers) and environmental (e.g. temperature, nutrient levels, and turbidity) factors on both the diversity of cyanobacteria and the stimulation of toxin production by particular cyanobacteria taxa. In particular, we pursued three objectives to achieve this goal.

*Objective 1:* Quantitatively measure lakewater toxin concentrations, cyanobacteria taxonomic composition and abundance, and presence and activity of the toxin-producing gene from specially-preserved water samples collected from Vancouver Lake in 2009-2010, as well as new samples collected in 2011, using molecular genetic techniques.

*Objective 2:* Apply these molecular genetic approaches to quantitatively measure cyanobacteria diversity and toxin production in specially-preserved water samples from a series of microzooplankton grazing (dilution) experiments conducted over the full cyanobacteria bloom cycle in 2009.

*Objective 3:* Conduct a multivariate statistical analysis of these samples to test for the relative influence of environmental (temperature, nutrient concentration, turbidity, etc.) factors on cyanobacteria taxonomic composition, abundance and toxin production.

## **Methods, Approach and Facilities**

Field sampling for this project was conducted from the dock at the Vancouver Lake Sailing Club, located on the southeast shore of Vancouver Lake (Figure 1). All analyses were conducted at Washington State University Vancouver.

**Approach 1. Sampling for plankton abundance and composition.** From June-October 2011, lake water was collected from the surface on a weekly basis using a clean, acid-washed bucket. Subsamples for DNA extraction and toxin analysis were taken in triplicate and processed in the lab. For toxin analysis, 50 mL aliquots were filtered through 0.22  $\mu\text{m}$  polycarbonate filters. Both filter and filtrate were frozen ( $-80\text{ }^{\circ}\text{C}$ ) until further analysis. For DNA extraction, 250 mL aliquots were filtered onto 0.45  $\mu\text{m}$  GF/F filters. Filters were frozen ( $-80\text{ }^{\circ}\text{C}$ ) until further analysis. These samples from 2011 were analyzed along with extant samples collected in 2009 and 2010 that were previously subsampled, filtered and frozen as just described.

**Approach 2. Analysis of toxin concentrations in Vancouver Lake.** Analyses for both intracellular and extracellular microcystin toxin from the samples collected from 2009-2011 were conducted using a commercial ELISA kit (Beacon Analytical). Extracellular toxin analysis from thawed filtrate samples was performed according to the manufacturer's protocol. Intracellular toxin levels were analyzed according to Sevilla et al. (2009) and slightly modified. Briefly, intracellular toxins were extracted from cells collected on the 0.22  $\mu\text{m}$  polycarbonate filters using a buffer of 80% methanol, 0.1% tween, and 0.1% TFA, and submerged for 30

minutes. 50  $\mu$ L aliquots of the supernatant were then diluted 1:20 with 5% PBS and then tested with the ELISA kit according to the manufacturer's protocol.

**Approach 3. Molecular analyses of cyanobacteria abundance, diversity and toxin production in Vancouver Lake.** Abundance, taxonomic composition and toxin production of cyanobacteria in dock-collected samples from 2009-2011 were assessed via a series of molecular techniques to isolate, examine and quantify cyanobacteria DNA, generally following the protocols described in Rinta-Kanto et al. (2005). In order to extract DNA, cells collected onto 0.45 GF/F filters were processed using Qiagen's DNeasy blood and tissue kit following the manufacturer's protocol. Cell extracts were then subjected to two separate polymerase chain reaction (PCR) processes to isolate and amplify the extracted DNA. One reaction detected cyanobacteria taxa using 16S rRNA primers to confirm the presence of cyanobacterial DNA. The second reaction was for the detection of toxigenic taxa using published primers for two cyanobacteria genera known to produce toxins, *Anabaena* and *Microcystis*, specifically looking at the *mcyA* and *mcyE* genes. PCR products were extracted and purified using QIAquick PCR purification kit (Qiagen), and sequenced at WSU Vancouver. Sequences have been deposited in the GenBank database and compared to available sequences.

In addition, a quantitative PCR (qPCR) approach was applied to quantify the abundance of toxin and non-toxin producing cyanobacteria taxa. Assays used for qPCR were similar to PCR, except dual-labeled primer probes were used for the detection of toxigenic taxa from PCR and of the cyanobacteria 16S rRNA primers, and then triplicate Taq nuclease assays were performed to quantify gene copies for each sample. Threshold cycle calculations were completed according to published software. Cell abundance and gene copies per sample were calculated using a standard curve determined for each assay.

**Approach 4. Molecular analyses of cyanobacteria abundance, diversity and toxin production under the influence of microzooplankton grazing pressure.** The same protocols for measuring cyanobacteria abundance, composition and toxin production described in Approaches 2 and 3 were also applied to a set of water samples collected and specially preserved from a series of three microzooplankton grazing (dilution) experiments conducted over the course of a large cyanobacteria bloom in Vancouver Lake in 2009. Dilution experiments (Landry & Hassett 1982, Boyer et al. 2011) are designed to concurrently measure cyanobacteria and algal intrinsic growth rates along with the rate of consumption of these cells by microzooplankton (planktonic consumers <200  $\mu$ m in size). These rates are estimated from 24-hr incubations of a set of bottles filled with increasing dilutions of unfiltered lakewater, thus establishing a gradient of microzooplankton grazing pressure on cyanobacteria and algae. Thus we were able to measure differences in cyanobacteria abundance, composition and toxin production under variable grazing pressure at the beginning, height, and decline of a cyanobacteria bloom. \*\*Please note that we leveraged additional support for Approach 4 through a small grant from the Murdock Charitable Trust "Partners in Science" Program, which provided a summer stipend and small materials/supplies fund for a high school teacher to participate in this project in summer 2011.

**Approach 5. Statistical analyses to assess influence of biotic and abiotic factors on cyanobacteria diversity and toxin production.** We employed three statistical approaches to assess the influence of environmental variables on cyanobacteria blooms in Vancouver Lake, using phytoplankton community abundances from monthly lake sampling conducted from 2007 to 2010. First, we performed a cluster analysis on the plankton community abundance and

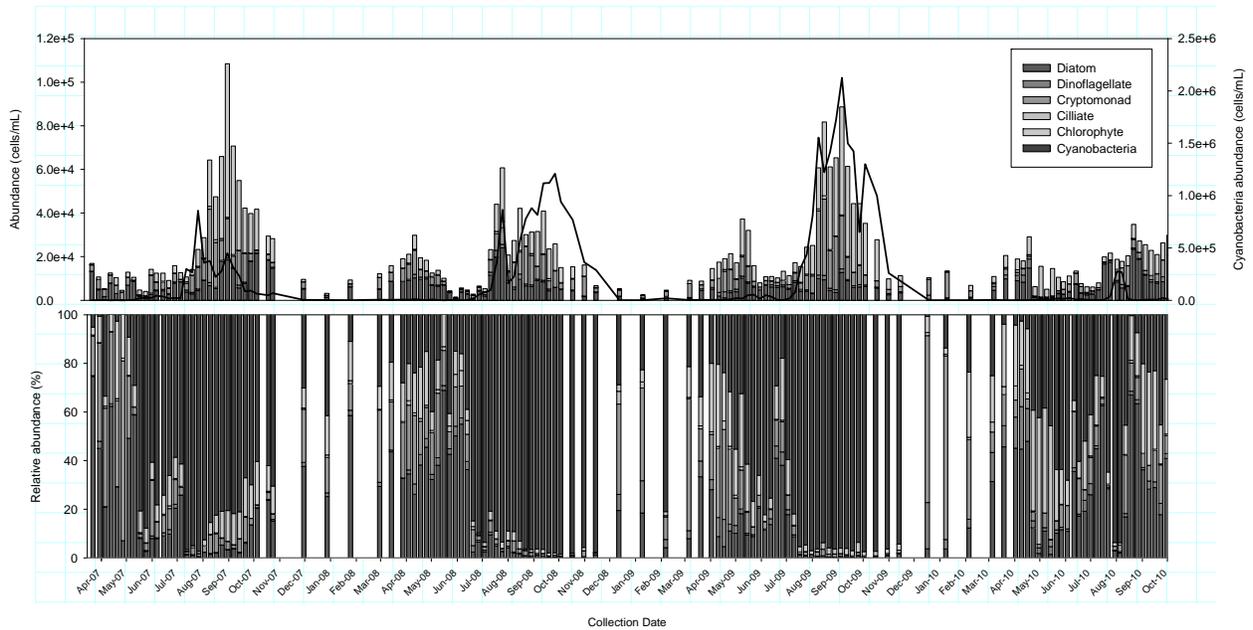
biomass to determine groupings of taxa that were distinguished by taxonomic composition and/or time (season, year). Second, we then used an indicator species analysis to define the particular phytoplankton taxa most closely associated with each cluster. Finally, we used an ordination technique called non-metric multidimensional scaling (NMDS) to identify the relationships between specific environmental variables and the phytoplankton community clusters. Environmental variables in this analysis included nutrient levels, turbidity, light intensity, dissolved oxygen, temperature, depth, and pH. Ordination techniques are very useful in community ecology because they can detect numerous relationships between species, or assemblages of species, and environmental data. NMDS is an effective ordination technique for these data since it can be used with non-normal and discontinuous distributions and does not assume linear or modal relationships such as principal component analysis and correspondence analysis, respectively (McCune & Grace 2002).

### **Principal Findings**

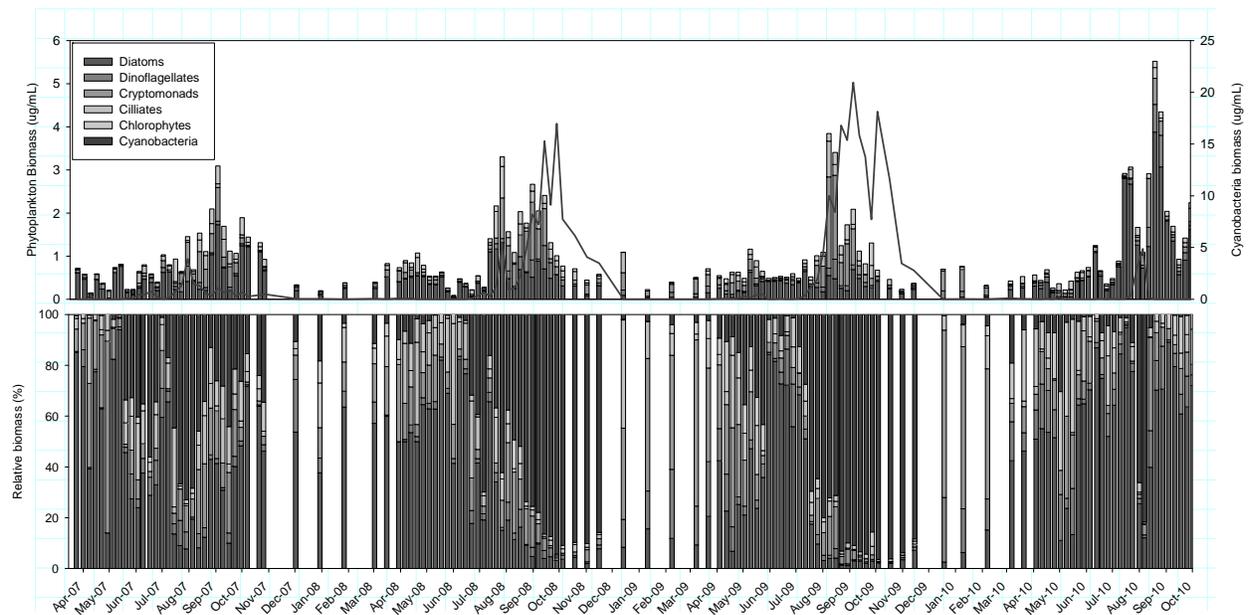
***Phytoplankton community composition 2007-2010.*** A total of 90 distinct phytoplankton species were identified from preserved acid Lugol's samples. However, only 70 species were present in >5% of the sampling efforts, and thus included in the statistical analyses. Each individual species was further classified into six different groups: diatoms (Bacillariophyceae), dinoflagellates (Dinophyta), flagellates (Chrysophyta, Cryptophyta, Euglenozoa, and Synuraphyceae), chlorophytes (Chlorophyta), and cyanobacteria (Appendix 1).

Overall phytoplankton abundance was highest during the late summer months (August-September) and lowest during the winter months (December-February) of each year from 2007 to 2010. The community was most often dominated by diatoms and flagellates, except during late summer cyanobacteria blooms that occurred in each year. The duration and magnitude of these blooms increased each year from 2007 through 2009. In 2010, cyanobacteria abundances and bloom duration were substantially lower than in prior years (Figure 2). In addition to the summer cyanobacteria blooms, non-cyanobacteria algal species (most often diatoms) also bloomed each spring (Figure 2).

The pattern of phytoplankton community biomass and taxa diversity were similar to the seasonal patterns observed in abundance, with spring diatom blooms followed by late summer blooms of cyanobacteria biomass (Figure 3).



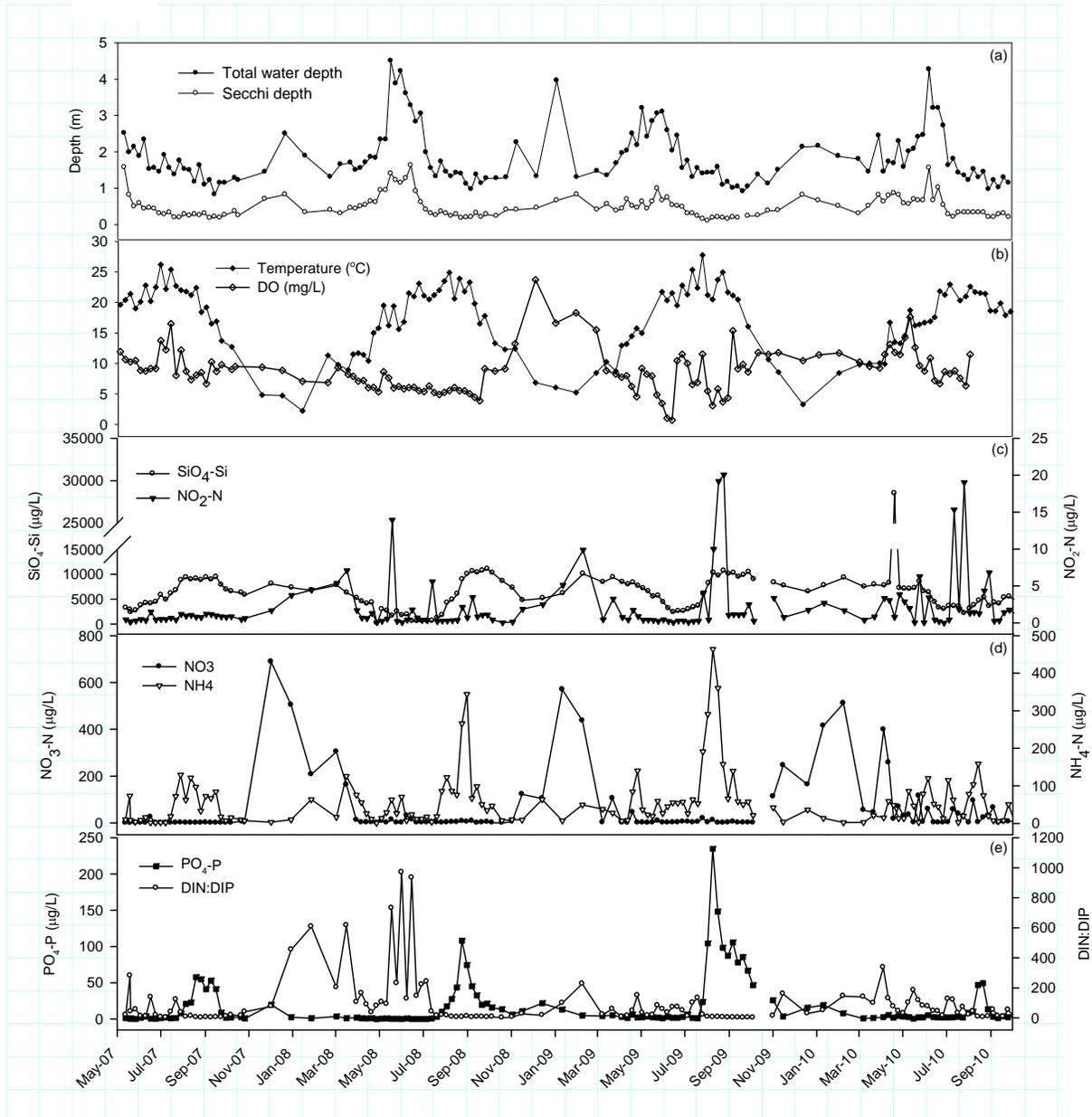
**Figure 2.** Absolute (upper panel), and relative (lower panel), phytoplankton abundance from March 2007 through September 2010.



**Figure 3.** Absolute (upper panel), and relative (lower panel), phytoplankton biomass from March 2007 through September 2010.

***Environmental Variables.*** Total water depth, secchi depth and water temperature all showed strong seasonal variation (Figure 4a). Total water depth ranged from 0.82 m during the

summer to 4.5 m during the spring freshet. Secchi depth ranged from 0.1 m during the summer to 1.6 m during the spring, with increased water clarity during seasonal winter rains and spring freshets. And temperature varied from as low as below freezing during the winter (December 2009) to as warm as 28°C during the summer (Figure 4b).



**Figure 4.** Environmental data collected from May 2007 through September 2010: (a) total water depth and secchi depth, (b) temperature and dissolved O<sub>2</sub>, (c) SiO<sub>4</sub>-Si and NO<sub>2</sub>-N, (d) NO<sub>3</sub>-N and NH<sub>4</sub>-N, (e) PO<sub>4</sub>-P and molar DIN:DIP.

SiO<sub>4</sub>-Si levels throughout the sampling period ranged from 150 – 11,000 µg/L, and were lowest during late spring and early summer months. A slight decrease in SiO<sub>4</sub>-Si concentration

was observed during the winter months, followed by an increase during early spring and late summer months each year (Figure 4c). NO<sub>2</sub>-N levels (<0.06 – 20 µg/L) were variable and did not show any annual or seasonal variation. NO<sub>3</sub>-N concentrations increased during the winter and early spring of each year, with mean highs ranging from 220 – 370 µg/L (Figure 4c). NH<sub>4</sub>-N did not show any discernable seasonal or annual patterns; however, NH<sub>4</sub>-N peaked during the summer months of 2007, 2008, and 2009 (Figure 4d). Annual trends in PO<sub>4</sub>-P were observed, with increased concentrations measured during the summer months of each year, ranging from 49 – 230 µg/L. A small increase in PO<sub>4</sub>-P was also observed during each winter (19 – 22 µg/L). Finally, although DIN:DIP did not show seasonal or annual variability, there were sustained periods of DIN:DIP less than 16:1 during summer months (Figure 4e).

**Cluster and Indicator Species Analyses.** Cluster analysis of phytoplankton species abundance delineated eight significantly different community groups ( $A=0.480$ ,  $p<10^{-8}$ ), numbered 1A through 8A (Table 1). Indicator species analysis applied to the eight clusters described groups 3A and 8A as having higher diversity than other groups, and included all identified cyanobacteria species. Group 3A represented the cyanobacteria bloom of 2007 and group 8A represented the cyanobacteria blooms of 2008 and 2009. In particular, *Microcystis* was significantly associated with group 3A; *Aphanizomenon*, *Anabaena*, and a suite of other less dominant cyanobacteria species were significantly associated with group 8A. Group 7A described four weeks in 2010 that showed a small increase in cyanobacteria abundance, but was significantly different from groups 3A and 8A. Groups 1A and 3A were unique to 2007. Groups 4A and 7A were unique to 2010. Group 2A represented late spring, early summer, and winter conditions of 2007. Group 6A included the spring months of 2008 and 2009, and in 2010 winter, spring, and fall months (Table 1).

**Table 1.** Groups delineated from cluster analysis of phytoplankton abundance. Species associated with each cluster were determined from indicator species analysis ( $p<0.05$ ).

Group	Season/Year	Species
1A	Early Spring 2007	<i>Asterionella</i>
2A	Late Spring/Early Summer 2007, Late Fall 2007, Winter 2007-2008	Euglenoid, Unidentified pennate diatom
3A	Late Summer/Early Fall 2007	<i>Achnanthes</i> , <i>Actinastrum</i> , <i>Aulacosira</i> , <i>Coelosphaerium</i> , <i>Cyclotella</i> , <i>Cymbella</i> , <i>Dictyosphaerium</i> , <i>Epithemia</i> , <i>Golenkina</i> , <i>Gonium</i> , <i>Microcystis</i> , <i>Nitzschia</i> , <i>Nitzschia fruticosa</i> , <i>Scenedesmus dimorphus</i> , <i>Scenedesmus</i> sp., <i>Treubaria</i> , Unknown chlorophyte
4A	Late Spring/Early Summer 2010	<i>Crucigenia</i> , <i>Pediastrum</i>
5A	Late Spring 2008, Late Spring 2009	<i>Fragilaria</i>
6A	Early Spring 2008, Early Spring 2009, Winter 2010, Spring 2010, Fall 2010	<i>Characium</i> , <i>Melosira</i>
7A	Summer 2010	<i>Aulacosira</i> (spiral), <i>Oocystis</i> , <i>Scenedesmus quadricauda</i> , <i>Stephanodiscus</i>
8A	Summer 2008, Summer 2009	<i>Anabaena</i> , <i>Aphanizomenon</i> , <i>Aphanocapsa</i> , <i>Aphanothece</i> , <i>Chroococcus</i> , <i>Kirchnerella</i> , <i>Monoraphium</i> , <i>Schroederia</i> , <i>Synechococcus</i>

Six significantly different clusters were identified based on phytoplankton biomass, numbered 1B through 6B (Table 2). Group 1B included spring 2007 and winter 2007–2008. Group 2B represented the winters of 2008–2009 and 2009–2010. Group 3B represented late spring and late summer conditions of 2010. Group 4B represented the early spring conditions for 2008, 2009, 2010, and mid-summer conditions in 2010. Early summer conditions of 2008 and 2009 were represented by group 5B. Unlike clusters based on species abundance, only one group (6B) represented the seasonal cyanobacteria bloom community of 2007, 2008, 2009, and one sampling date in 2010.

**Table 2.** Groups delineated from cluster analysis of phytoplankton biomass. Species associated with each cluster were determined from indicator species analysis ( $p < 0.05$ ).

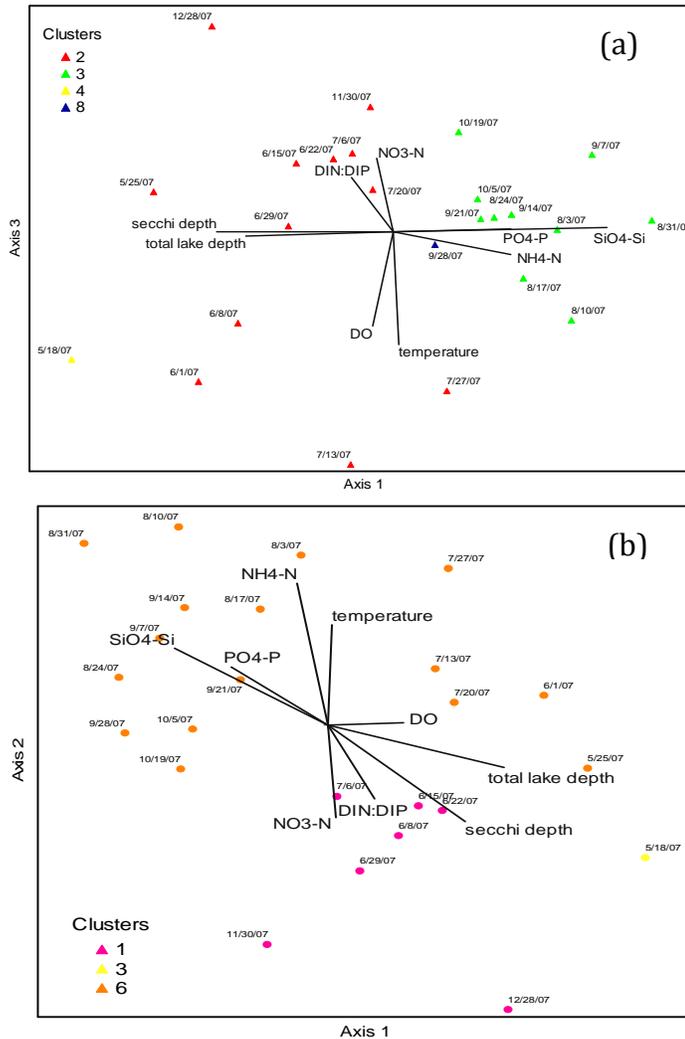
Group	Season/Year	Species
1B	Early Summer 2007, Winter 2007-2008	<i>Achnanthes</i> , <i>Cyclotella</i> , Euglenoid, <i>Gonium</i> ,
2B	Winter 2008-2009, Winter 2010	Cryptomonad, Prolate aloricate ciliate, Thecate round dinoflagellate, Thecate prolate dinoflagellate,
3B	Summer 2010	<i>Aulacosira</i> (spiral), <i>Crucigenia</i> , <i>Oocystis</i> , <i>Stephanodiscus</i> ,
4B	Early Spring 2008, Early Spring 2009	Athecate round dinoflagellate, <i>Characium</i> , <i>Dictyospherium</i> , <i>Fragellaria</i> , <i>Kirchnerella</i> , <i>Melosira</i> , <i>Monophoridium</i> , <i>Scenedesmus quadrauca</i> , <i>Schroederia</i> , <i>Tetrastrum</i> ,
5B	Late Spring 2008, Late Spring 2009	<i>Aulacosira</i>
6B	Summer 2007, Summer 2008, Summer 2009	<i>Actinastrum</i> , <i>Anabaena</i> , <i>Ankistrodesmus</i> , <i>Aphanizomenon</i> , <i>Aphanocapsa</i> , <i>Aphanothece</i> , <i>Coelospherium</i> , <i>Cosmarium</i> , <i>Golenkinia</i> , <i>Microcystis</i> , <i>Nitschia</i> , <i>Nitschia fruticosa</i> , <i>Scenedesmus dimorphus</i> , <i>Scenedesmus sp.</i> , <i>Synechococcus</i> , <i>Tetraedon</i> ,

**Annual associations between environmental variables and the phytoplankton community.** We used the non-metric multidimensional scaling (NMDS) approach to determine which environmental variables contributed to observed inter-annual differences in phytoplankton community composition, using the 2007, 2008 and 2009 combined, and 2010 datasets. Note that cluster group 1A was not included in any of the NMDS analyses due to lack of corresponding environmental data during the sampling times associated with that group.

**2007** Results from NMDS analysis of 2007 phytoplankton community abundance (Figure 5a) showed total lake water depth and secchi depth were associated with spring sampling dates from group 2A, and high DIN:DIP and NO<sub>3</sub>-N levels were associated with winter and spring samples (groups 2A and 3A). Summer sampling dates (group 3A) were associated with increases in PO<sub>4</sub>-P, SiO<sub>4</sub>-Si, and NH<sub>4</sub>-N, and inversely related to total lake water depth and secchi depth. Finally, dissolved O<sub>2</sub> and temperature were associated with sample dates in which abundances were highest (e.g. July and August).

Results of NMDS analyses of phytoplankton community biomass for 2007 showed group 1B samples were associated with high DIN:DIP ratios and increased NO<sub>3</sub>-N (Figure 5b). Late spring and early summer months were associated with increased lake water depth and secchi depth. Dissolved O<sub>2</sub> and temperature increased and peaked during early summer months just

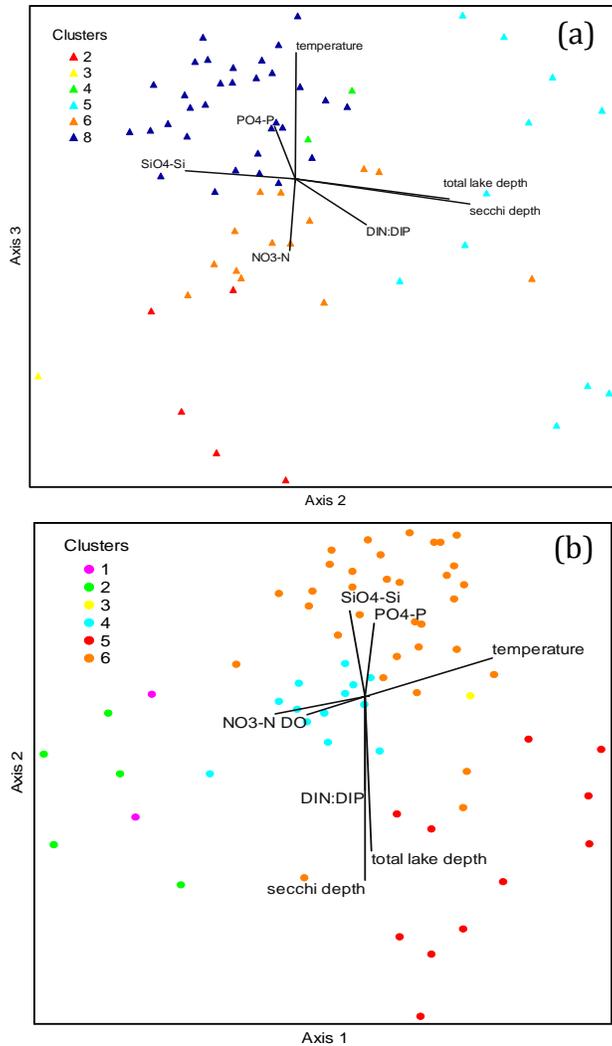
before a rapid increase in  $\text{NH}_4\text{-N}$ . Increased phytoplankton biomass and diversity during late summer months were associated with increased availability of  $\text{PO}_4\text{-P}$  and  $\text{SiO}_4\text{-Si}$ . The majority of species according to biomass were associated with late summer months when  $\text{PO}_4\text{-P}$  was most available ( $r^2 > 0.4$ ). *Anabaena* sp. was associated with  $\text{NH}_4\text{-N}$  and increased temperatures. *Microcystis* sp. and *Coelospharium* sp. are associated with increased  $\text{PO}_4\text{-P}$  (Figure 5b).



**Figure 5.** Ordination of 2007 species abundance (a) and biomass (b) grouped by clusters. Each point represents a sampling date. (a) Axis 1 and 3 represented 47.0% and 18.2%, respectively, of the observed variance. (b) Axis 1 and 2 represented 60.8% and 20.8%, respectively, of the observed variance. Vectors are environmental variables associated with each cluster ( $r^2 > 0.2$ ).

**2008-2009** Ordination results based on phytoplankton community abundance showed that  $\text{SiO}_4\text{-Si}$ ,  $\text{PO}_4\text{-P}$ , and  $\text{temperature}$  were associated with group 8A (Figure 6a).  $\text{DIN:DIP}$ ,  $\text{total lake depth}$ , and  $\text{secchi depth}$  were associated with the late spring phytoplankton community (group 5A).  $\text{NO}_3\text{-N}$  was associated with groups 2A and 6A, which represented winter and early spring months, respectively. Most species were clustered around group 8A ( $r^2 > 0.3$ ), except

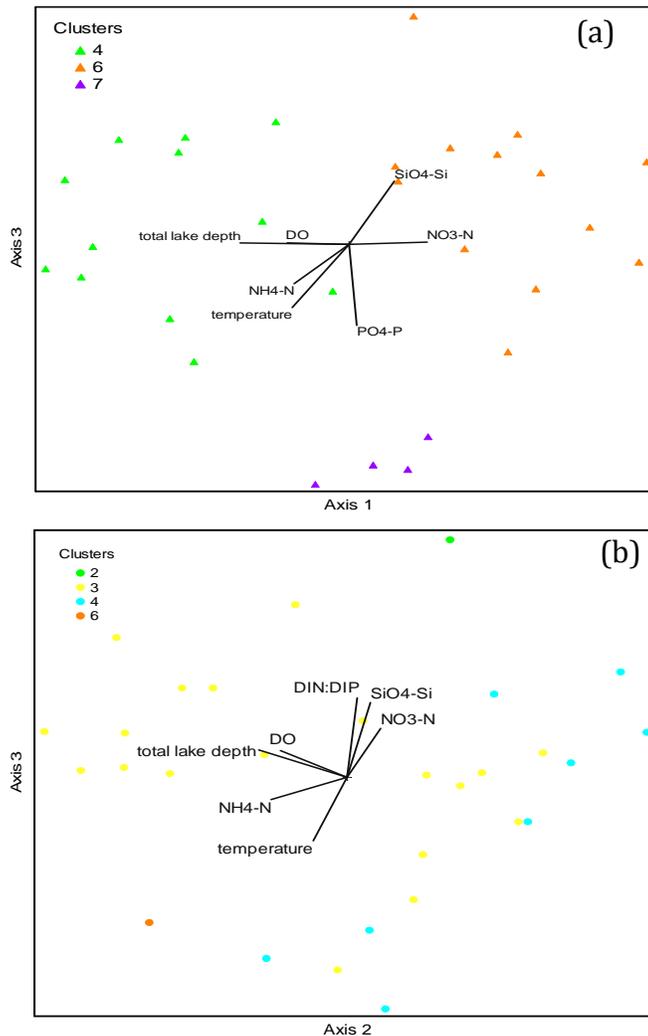
*Melosira* sp. which was associated with group 6A. Flagellates, chlorophytes, and the cyanobacteria species *Aphanizomenon* sp. and *Coelosphaerium* sp. were associated with the beginning of the summer cyanobacteria bloom. *Anabaena* sp., and *Aphanocapsa* sp. were associated with the end of the bloom.



**Figure 6.** Ordination of 2008-2009 species abundance (a) and biomass (b) grouped by clusters. Each point represents a sampling date. (a) Axis 2 and 3 represented 31.6% and 31.8% of the observed variance. (b) Axis 1 and 2 represented 31.4% and 50.2% of the observed variance.

With regard to the phytoplankton community biomass data from 2008 and 2009, clusters 1B and 4B were associated with dissolved O<sub>2</sub> and the annual increase of NO<sub>3</sub>-N (Figure 6b). Increased temperature, PO<sub>4</sub>-P, and SiO<sub>4</sub>-Si were associated with annual cyanobacteria blooms (group 6B). High DIN:DIP and increased lake depth and secchi depth were associated with the late spring phytoplankton community. Although the majority of phytoplankton species were associated with group 6B during warmer temperatures and increased PO<sub>4</sub>-P availability ( $r^2 > 0.3$ ), *Cyclotella* sp. and flagellates were associated with the early spring community (group 4B).

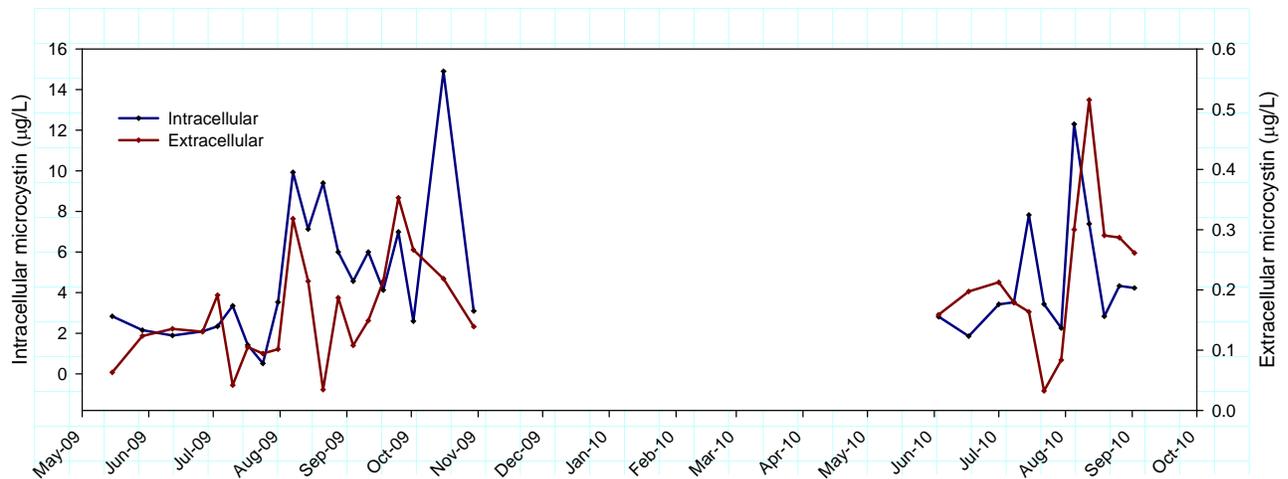
**2010** During 2010, the environmental variables most closely associated with phytoplankton community abundance clusters were dissolved O<sub>2</sub>, temperature, and NH<sub>4</sub>-N (Figure 7a). Increasing temperatures, high lake levels, high dissolved oxygen, and increased fluctuations in NH<sub>4</sub>-N were associated with late spring and early summer months (group 4A). An increase in PO<sub>4</sub>-P was observed in August and was associated with the shortest and smallest bloom observed throughout the sampling period from 2007-2010. Sustained high levels of SiO<sub>4</sub>-Si, and peak annual NO<sub>3</sub>-N levels, were associated with winter and early spring months (group 6A). The majority of species were associated with winter, early spring, and fall months (group 6A,  $r^2 > 0.4$ ). *Anabaena* sp., *Crucigenia*, *Aphanocapsa*, *Aulacosira*, and Cryptomonads were associated with late spring early summer months (group 4A).



**Figure 7.** Ordination of 2010 species abundance (a) and biomass (b) grouped by clusters. Each point represents a sampling date. (a) Axis 1 and 3 represented 15.3% and 37.8% of the observed variance. (b) Axis 2 and axis 3 represented 28.4% and 21.4% of the observed variance, respectively.

The NMDS results based on phytoplankton community biomass for 2010 did not show any discernible groupings based on cluster analysis (Figure 7b). DIN:DIP, NO<sub>3</sub>-N, and SiO<sub>4</sub>-Si were associated with early spring and late summer months. Dissolved O<sub>2</sub>, NH<sub>4</sub>-N, temperature, and total lake depth were associated with late spring and early summer months. Most species clustered around early spring and late summer months when DIN:DIP, NO<sub>3</sub>-N, and SiO<sub>4</sub>-Si were highest ( $r^2 > 0.4$ ). *Anabaena*, *Aulacosira* (spiral), *Aulacosira*, and *Stephanodiscus* were associated with mid-summer months during warmer temperatures.

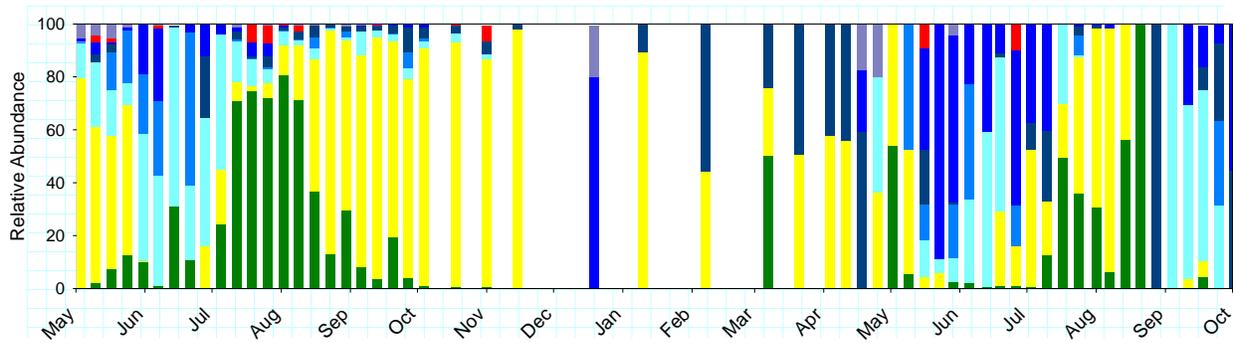
***Cyanobacteria toxin concentrations in 2009 and 2010.*** We measured both intracellular and extracellular levels of the cyanobacterial toxin microcystin from water samples collected during the summer bloom periods in 2009 and 2010 (Figure 8). Intracellular microcystin concentrations were substantially higher than extracellular levels at every sampling period, suggesting that most toxin remained contained in cells. However, the temporal pattern of extracellular and intracellular toxin maxima and minima over the cyanobacteria bloom cycles in both years were comparable, with the highest concentrations near the end of each bloom (Figure 8).



**Figure 8.** Intracellular and extracellular concentrations of the cyanobacteria toxin microcystin measured from water samples collected in Vancouver Lake during summers of 2009 and 2010. Note the difference in scale between the two y-axes.

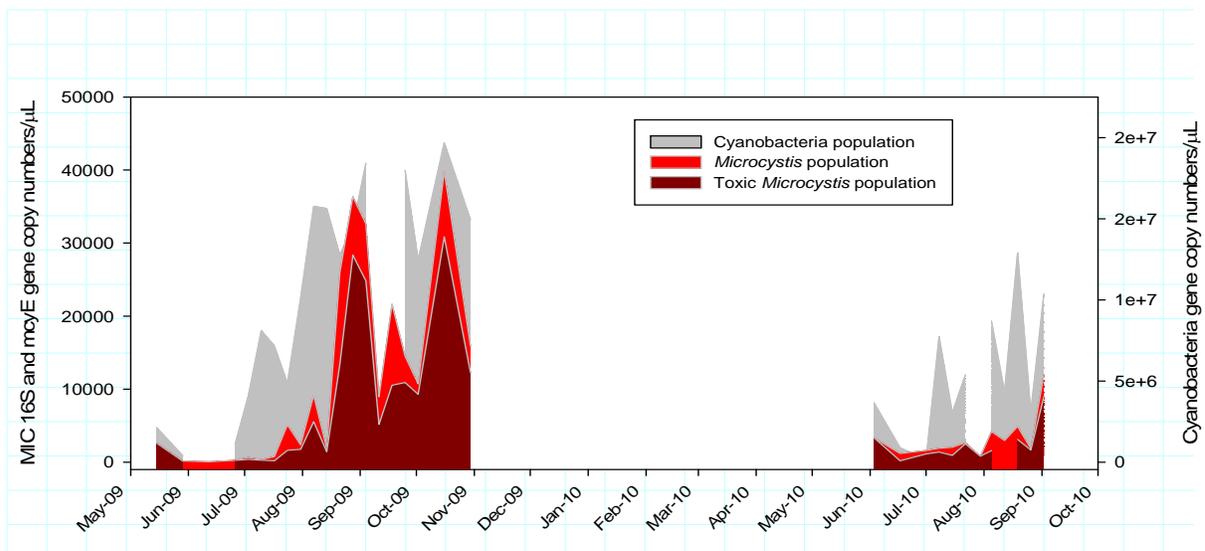
***Genetic analyses of toxic cyanobacteria abundance and diversity in 2009 and 2010.*** We used two different PCR techniques to 1) determine whether any cyanobacteria present in Vancouver Lake during the summers of 2009 and 2010 were capable of producing toxin (i.e. contained the genes necessary for toxin production), and to 2) quantify the abundance of toxin-producing cyanobacteria relative to the total abundance of cyanobacteria present during the blooms of 2009 and 2010.

Traditional microscopical analysis of cyanobacteria populations from Vancouver Lake showed that the blooms of 2009 and 2010 were dominated by *Aphanizomenon flos-aquae* and *Anabaena flos-aquae* (Figure 9).



**Figure 9.** Relative abundance of cyanobacteria species identified from microscopical examination of samples collected in Vancouver Lake from May 2009 to October 2010. *Aphanizomenon* (yellow) and *Anabaena* (dark green) are the dominant cyanobacteria genera during bloom events of 2009 and 2010.

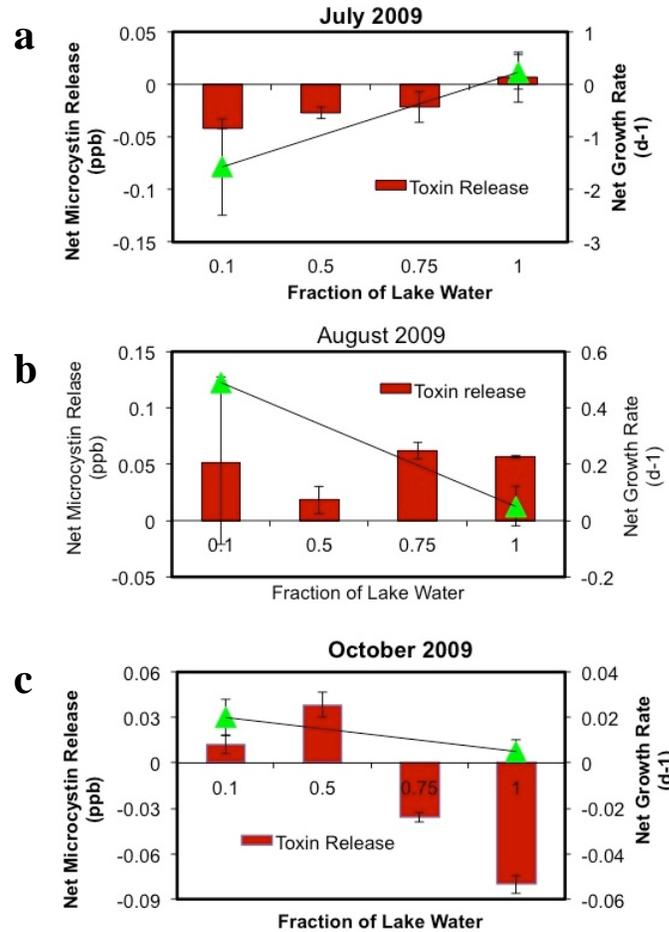
Interestingly, the results of PCR analyses indicated that the only cyanobacteria taxa present in Vancouver Lake that carried the *mcyA* and *mcyE* genes required for microcystin toxin production was *Microcystis* sp. Further analysis using qPCR techniques showed that toxin-producing *Microcystis* sp. was in highest abundance during the overall cyanobacteria bloom periods, but never constituted more than 1% of the total cyanobacteria community at any time during the blooms (Figure 10).



**Figure 10.** Abundance of the total cyanobacteria community, total *Microcystis* sp., and toxin-producing *Microcystis* sp. estimated by qPCR from samples collected in Vancouver Lake during summer and autumn of 2009 and 2010. Note the 3-order of magnitude difference in the two y-axes.

***Cyanobacteria toxin release under variable zooplankton grazing pressure.*** We measured the amount of extracellular microcystin toxin present in treatment and control incubations bottles from three microzooplankton grazing experiments conducted prior to, during, and following the cyanobacteria bloom of 2009 in Vancouver Lake. In July 2009, before the

cyanobacteria bloom, microcystin toxin was released at the highest feeding pressure, but extracellular toxin release decreased over the incubation as feeding pressure decreased. Somewhat unexpectedly, cyanobacteria growth rate was higher in the presence of microzooplankton grazers (Figure 11a).



**Figure 11.** Extracellular microcystin toxin released during microzooplankton grazing (dilution) experiments conducted prior to (panel a), during (panel b), and following (panel c) a cyanobacteria bloom in Vancouver Lake during summer and autumn 2009. Green triangles refer to cyanobacteria growth rates measured during the experiments. The slope of the line connecting the two triangles reflects the intensity of microzooplankton grazing pressure during that experiment.

At the height of the 2009 cyanobacteria bloom in Vancouver Lake, toxin release was highest under high feeding pressure. In addition, cyanobacteria growth rates were high overall, and were lower in the presence of microzooplankton (Figure 11b). In October, as the bloom was waning, microcystin toxin release was highest when microzooplankton feeding pressure was low. Also, cyanobacteria growth rate was extremely low, but increased as microzooplankton feeding decreased (Figure 11c).

## **Significance**

Toxic cyanobacteria blooms in freshwater lakes are an increasing problem worldwide, that are also impacting lakes in Washington State and the Pacific Northwest. Results from this proposed research have provided novel information about the dynamics of toxic cyanobacteria blooms in Vancouver Lake, WA, which may be applicable to other shallow, turbid lakes in this region, and to temperate freshwater systems more generally.

The statistical analyses on the phytoplankton community abundance, biomass and taxonomic composition revealed several important points. First, the cyanobacteria blooms over the study period from 2007 to 2010 differed in their magnitude and composition. The bloom in 2007 was significantly different from the blooms that occurred in 2008 and 2009, and these were all different from the bloom observed in 2010. Cluster and indicator species analyses of the phytoplankton community during the 4-year sampling period revealed distinct groups of phytoplankton species that defined different stages of the cyanobacteria blooms in each year, and ordination showed the particular environmental conditions associated with the distinct community groups. In general, the cyanobacteria blooms were most closely associated with changes in  $\text{PO}_4\text{-P}$  and  $\text{NH}_4\text{-N}$ , as well as lake/secchi depth.

In particular, the use of molecular techniques provided a more comprehensive understanding of toxic and non-toxic cyanobacteria blooms than has been possible to date using traditional microscopical approaches. Our results demonstrated that the most abundant cyanobacteria observed in Vancouver Lake during each bloom (*Aphanizomenon* and *Anabaena*) did not carry the gene necessary for production of microcystin, suggesting that the blooms in Vancouver Lake are likely less harmful than may be inferred based only on total cyanobacteria abundance. However, microcystin toxin was detected in Vancouver Lake (produced by *Microcystis* sp.) and toxin levels did reach maxima during the cyanobacteria blooms; however, the extracellular concentrations of microcystin toxin were consistently below the threshold for health-related lake closure.

Finally, our identification of the potential biotic and abiotic factors associated with cyanobacteria bloom dynamics will provide critical information for natural resource managers to develop strategies for managing blooms based on empirical evidence. For example, since one of the primary factors associated with cyanobacteria blooms in Vancouver Lake was the amount of  $\text{PO}_4\text{-P}$  available, suggesting that measures to reduce nutrient loading into the Lake may be effective for mitigating these blooms. However, our results demonstrating that increased microzooplankton grazing during blooms may increase the release of cyanobacteria toxins, suggests that an effective mitigation strategy should also include attention to the impact of planktonic grazers.

We anticipate that these results will benefit Clark County agencies as they make decisions about Vancouver Lake, but will also be applicable to regional and national resource management agencies who face similar challenges with cyanobacteria blooms in other temperate aquatic systems.

## **References**

- Bollens S and G Rollwagen-Bollens (2008) Biological Assessment of Vancouver Lake. 1<sup>st</sup> year annual report submitted to the Vancouver Lake Watershed Partnership.
- Bollens S and G Rollwagen-Bollens (2010) Biological Assessment of Vancouver Lake. 3<sup>rd</sup> year annual report submitted to the Vancouver Lake Watershed Partnership.
- Boyer J, G Rollwagen-Bollens, and S Bollens. (2011) Microzooplankton grazing on cyanobacteria in Vancouver Lake, Washington, USA. *Aquatic Microbial Ecology* 64: 163-174.
- Buskey E (2008) How does eutrophication affect the role of grazers in harmful algal bloom dynamics? *Harmful Algae* 8: 152-157
- Carmichael WW (1992) Cyanobacteria secondary metabolites – the cyanotoxins. *Journal of Applied Microbiology* 72: 445-459
- Chorus I, I Falconer, H Salas, and J Bartram (2000) Health risks caused by freshwater cyanobacteria in recreational waters. *Journal of Toxicology and Environmental Health Part B* 3: 323-347
- Codd G (1995) Cyanobacterial toxins: Occurrence, properties and biological significance. *Water Science and Technology* 32: 149-156
- Codd G, L Morrison, and J Metcalf (2005) Cyanobacterial toxins: risk management for health protection. *Toxicology and Applied Pharmacology* 203: 264-272
- Davis T, D Berry, G Boyer, and C Gobler (2009) The effects of temperature and nutrients on the growth and dynamics of toxic and non-toxic strains of *Microcystis* during cyanobacteria blooms. *Harmful Algae* 8: 715-725
- Dokulil MT and K Teubner (2000) Cyanobacterial dominance in lakes. *Hydrobiologia* 438: 1-12
- Elser JJ, ER Marzolf, and CR Goldman (1990) Phosphorus and nitrogen limitation of phytoplankton growth in the freshwaters of North America: a review and critique of experimental enrichments. *Canadian Journal of Fisheries and Aquatic Science* 47: 1468-1477
- Elser JJ (1999) The pathway to noxious cyanobacteria blooms in lakes: the food web as the final turn. *Freshwater Biology* 42: 537-543
- Gewant D and S Bollens (2005) Macrozooplankton and micronekton of the lower San Francisco Estuary: Seasonal, interannual, and regional variation in relation to environmental conditions. *Estuaries* 3: 473-485
- Gobler C, T Davis, K Coyne, and G Boyer (2007) Interactive influences of nutrient loading, zooplankton grazing, and microcystin synthetase gene expression on cyanobacterial bloom dynamics in a eutrophic New York lake. *Harmful Algae* 6:119-133
- Gorini RF (1987) Lake restoration by dredging. *In* Management of bottom sediments containing toxic substances: Proceedings of the 13<sup>th</sup> US/Japan Experts Meeting. Baltimore, MD
- Graham E and S Bollens (2010) Macrozooplankton community dynamics in relation to environmental variables in Willapa Bay, Washington, USA. *Estuaries & Coasts* 33: 182-194

- Heisler J, Glibert P, Burkholder J, Anderson D, Cochlan W, Dennison W, Dortch Q, Gobler C, Heil C, Humphries E, Lewitus A, Magnien R, Marshall M, Sellner K, Stockwell D, Stoecker D, and Suddleson M (2008) Eutrophication and harmful algal blooms: A scientific consensus. *Harmful Algae* 8: 3-13
- Hutchinson GE (1973) Eutrophication. *American Scientist* 61: 269-279
- Jacoby J and J Kann (2007) The occurrence and response to toxic cyanobacteria in the Pacific Northwest, North America. *Lake and Reservoir Management* 23:123-143
- Landry MR and RP Hassett (1982) Estimating the grazing impact of marine microzooplankton. *Marine Biology* 67: 283-288
- McCune B and J Grace (2002) Analysis of ecological communities. MjM Software Design.
- Paerl HW (1988) Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. *Limnology and Oceanography* 33: 823-847
- Paerl HW (2008) Nutrient and other environmental controls of harmful cyanobacterial blooms along the freshwater-marine continuum. From: *Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs*. Advances in Experimental Medicine and Biology. Ed. H.K. Hudnell. Springer, Triangle Park, NC.
- Paerl HW and J Huisman (2009) Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. *Environmental and Microbiological Reports* 1: 27-37
- Rinta-Kanto J, A Ouellette, G Boyer, M Twiss, T Bridgeman, and S Wilhem (2005) Quantification of toxic *Microcystis* spp. during the 2003 and 2004 blooms in western Lake Erie using quantitative real-time PCR. *Environmental Science and Technology* 39: 4198-4205
- Rollwagen-Bollens G, S Bollens, A Gonzalez, J Zimmerman, T Lee, and J Emerson (in revision) Feeding dynamics of the copepod *Diacyclops thomasi* before, during and following filamentous cyanobacteria blooms in a large, shallow temperate lake. *Hydrobiologia*
- Sellner KG, GJ Doucette, and GJ Kirkpatrick (2003) Harmful algal blooms: causes, impacts and detection. *Journal of Indian Microbiology and Biotechnology* 30: 383-406
- Sevilla E, H Smienk, L Razquin, A Mata, and M Peleato (2009) Optimization of intracellular microcystin-LR extraction for its analysis by protein phosphatase inhibition assay. *Water Science and Technology* 60:1903-1909
- Smayda T (2008) Complexity in the eutrophication–harmful algal bloom relationship, with comment on the importance of grazing. *Harmful Algae* 8: 140-151

## Appendix 1.

Vancouver Lake [phytoplankton](#) taxa identified and present in >5% of samples.

<i>Achnanthes</i> spp.	<i>Characium</i> spp.
<i>Asterionella</i> spp.	<i>Coelastrum</i> spp.
<i>Aulacosira</i> spp.	<i>Cosmarium</i> spp.
<i>Aulacosira</i> spp. (spiral morphology)	<i>Crucigenia</i> spp.
<i>Cocconeis</i> spp.	<i>Dictyosphaerium</i> spp.
<i>Cyclotella</i> spp.	<i>Eudorina</i> spp.
<i>Cymbella</i> spp.	<i>Golenkinia</i> spp.
<i>Epithemia</i> spp.	<i>Gonium</i> spp.
<i>Fragilaria</i> spp.	<i>Kirchneriella</i> spp.
<i>Gyrosigma</i> spp.	<i>Monoraphidium</i> spp.
<i>Melosira</i> spp.	<i>Oocystis</i> spp.
<i>Navicula</i> spp.	<i>Pediastrum</i> spp.
<i>Nitzschia</i> spp.	<i>Scenedesmus acuminatus</i>
<i>Nitzschia fruticosa</i>	<i>Scenedesmus dimorphus</i>
<i>Stephanodiscus</i> spp.	<i>Scenedesmus linearis</i>
<i>Surirella</i> spp.	<i>Scenedesmus quadricauda</i>
<i>Synedra</i> spp.	<i>Scenedesmus</i> spp.
Unidentified Pennate spp.	<i>Schroederia</i> spp.
Dinophyta	<i>Sphaerocystis</i> spp.
Athecate prolate dinoflagellate	<i>Staurastrum</i> spp.
Athecate round dinoflagellate	<i>Tetrabaena</i> spp.
Ceratium hirundinella	<i>Tetraedron</i> spp.
Thecate prolate dinoflagellate	<i>Tetrastrum</i> spp.
Thecate round dinoflagellate	<i>Treubaria</i> spp.
Chrysophyta	Unknown Chlorophyte
<i>Dinobryon</i> spp.	Cyanobacteria
Cryptophyte	<i>Anabaena</i> spp.
<i>Cryptomonad</i> spp.	<i>Aphanizomenon</i> spp.
Euglenozoa	<i>Aphanocapsa</i> spp.
Euglenoid	<i>Aphanothece</i> spp.
Synuraphyceae	<i>Chroococcus</i> spp.
<i>Mallomonas</i> spp.	<i>Coelosphaerium</i> spp.
<i>Synura</i> spp.	<i>Merismopedia</i> spp.
Ciliophora	<i>Microcystis</i> spp.
Prolate Aloricate	<i>Synechoccus</i> spp.
Prolate Loricata	
Round Aloricate	
Round Loricata	
<i>Tintinnopsis</i> spp.	
Chlorophyta	
<i>Actinastrum</i> spp.	
<i>Ankistrodesmus</i> spp.	
<i>Asterococcus</i> spp.	

# Ecohydrology of Invasive Reed Canary Grass

## Basic Information

<b>Title:</b>	Ecohydrology of Invasive Reed Canary Grass
<b>Project Number:</b>	2011WA328B
<b>Start Date:</b>	3/1/2011
<b>End Date:</b>	9/30/2012
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	Washington: 9th District
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	Hydrology, Acid Deposition, None
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Camille McNeely, Rebecca Louise Brown, Carmen Ann Nezat, Suzanne Marie Schwab

## Publications

1. Gebauer, AD, R Brown, S Schwab, C McNeely, and C Nezat, 2012, "Ecohydrology of invasive red canary grass (*Phalaris arundinacea*): ET Rates", Society for Rangeland Management Annual Meeting, Spokane, WA
2. Gebauer, AD, R Brown, S Schwab, C McNeely, and C Nezat, 2012, "Ecohydrology of invasive red canary grass (*Phalaris arundinacea*)", Ecological Society of America Annual Meeting in Portland, OR
3. McNeely, Camille, 2012, Ecohydrology of Invasive Reed Canary Grass, State of Washington Water Research Center, Washington State University, Pullman, WA, 9pgs.

## Problem and Research Objectives

This project addresses the regional problem of low summer flows in semiarid Eastern Washington streams. Summer flow levels that are below historical levels contribute to poor summer water quality, including levels of fecal coliforms, dissolved oxygen (DO), pH, and water temperature that do not comply with standards established under the federal Clean Water Act (e.g. Carroll 2007, Joy et al. 2009, Tarbutton et al. 2010). Low flow conditions allow higher concentrations of pollutants to develop as they are less diluted (Lee 1969, Allan and Castillo 2007, Carroll 2007, Tarbutton et al. 2010). Low summer stream flows also contribute to poor habitat for salmonids and other aquatic life through higher water temperatures, reduced DO, and reduced habitat area (Mantua et al. 2010). There are a number of likely causes of lower summer stream flows in semiarid Eastern Washington streams. This project investigates the potential for invasive riparian Reed Canary Grass (*Phalaris arundinacea*) to exacerbate low flows through high rates of evapotranspiration.

Reed Canary Grass (*P. arundinacea*) is a European perennial grass that commonly forms monocultures in riparian zones and wetlands of the Midwest and northwest United States (Gelatowitsch et al. 1999, Zedler & Kircher 2004). Most small-order stream reaches in semi-arid Eastern Washington are dominated by this grass which displaces native species, and prevents woody species from establishing within the riparian zone (R. Brown and C. McNeely, personal observation). As with many invasive species (Cavaleri & Sack 2010), rates of primary production and evapotranspiration (ET) are high (Schilling 2007, Schilling & Kiniry 2007), suggesting that *P. arundinacea* has the potential to lower water tables and reduce stream flow. Other invasive riparian species in arid and semi-arid landscapes reduce stream flows through high rates of ET (Le Maitre et al. 2002, Cleverly et al. 2006).

This project assesses the effects of *P. arundinacea* dominance of riparian communities on summer stream flow in semi-arid Eastern Washington. We are evaluating whether *P. arundinacea* is likely to have substantial effects on stream flow compared to native vegetation by determining water sources used by *P. arundinacea* and other riparian plants, and by comparing rates of evapotranspiration between *P. arundinacea* and other vegetation.

We are assessing the effects of *P. arundinacea* on local hydrology by testing the following hypotheses:

1. *P. arundinacea* rates of ET are higher than those of other herbaceous riparian vegetation and lower than those of woody riparian vegetation.
2. *P. arundinacea* accesses shallower groundwater pools than woody vegetation and similar groundwater pools to other herbaceous riparian vegetation.
3. As a result of higher rates of ET compared to non-woody vegetation and different water sources than woody vegetation, *P. arundinacea* has a greater effect on stream flow than either alternate vegetation type.
4. *P. arundinacea* maintains a high rate of primary productivity and ET throughout a longer growing season than other vegetation types, exacerbating its effects on hydrology.

We have used three approaches to assess the changes in ecohydrology of riparian systems due to the invasion of *P. arundinacea*:

1. Monitor stream discharge and riparian water table levels over the summer along semiarid eastern Washington headwater streams to document rates and timing of decline through the growing season. We will also document riparian plant communities present.

2. Direct measurements of ET by *P. arundinacea*, other herbaceous plant species using closed chambers, and by *P. arundinacea*, other herbaceous plant species, and woody plants using stomatal conductance.
3. Use of stable oxygen and hydrogen isotope ratios to identify sources of water used by *P. arundinacea*, other herbaceous plant species, and woody plants.

Our proposal predicted the following responses:

1. Timing of greatest declines in riparian water tables and discharge will correlate with periods of high ET by riparian vegetation.
2. Stomatal conductance at the leaf scale will be highest in *P. arundinacea*, compared to other herbaceous and woody species.
3. ET at the plot scale will be higher for *P. arundinacea* dominated communities than for communities dominated by other herbaceous vegetation accessing the same shallow water sources. However, the higher per area biomass and leaf area of woody plants will result in higher ET at the plot scale compared to *P. arundinacea*, or other herbaceous vegetation.
4. Stable isotope analysis will reveal that *P. arundinacea* and other herbaceous plants use primarily stream water, soil water, and shallow groundwater, with increasing reliance on groundwater over the summer season. Woody vegetation will use a substantially larger portion of groundwater.

## Methodology

We are employing three complimentary approaches to investigate riparian water use by *Phalaris arundinacea*: 1) hydrologic monitoring and documentation of riparian vegetation across eastern Washington headwaters, 2) direct measurements of transpiration using stomatal conductance, and 3) analysis of stable oxygen and hydrogen isotopes to determine the sources of water used by vegetation.

1. To monitor stream flow conditions and groundwater levels in relation to riparian vegetation, we selected nine stream sites within the watersheds of Latah Creek, Rock Creek, Crab Creek, and Cow Creek, Washington that varied in the degree of Reed Canary Grass domination and the presence or absence of riparian trees. Reed Canary Grass cover ranged from 15% to 94%. It was not possible to find sites with no *P. arundinacea* in this region. At each site, we installed a gauging pole to monitor stream flow and 4-10 shallow PVC wells along a transect perpendicular to the stream to monitor groundwater levels. Stream discharge and groundwater levels were determined every 2 weeks from the time of installation until October 2011. Discharge and groundwater levels have been monitored every two weeks beginning April 2012, and this monitoring will continue through the summer 2012 growing season. We are also documenting the phenological stage and period of active growth for dominant riparian plants at these sites to determine if Reed Canary Grass is growing and active for a longer period of time than other riparian plants.

We documented riparian vegetation at 3 cross-stream transects (10 cm wide) spanning the riparian zone at each site during July 2011. One of these three transects contains the groundwater wells for the site. For each riparian plant species present within the 10 cm transect, the distances from the stream where it was found were recorded to the nearest 0.1 m. Depth of soil and soil moisture were also determined along the transects, and the transects are being surveyed geomorphically. These data allow us to determine: 1) relative abundance of species (% cover) for the entire riparian zone at

each site 2) how plant distributions within the riparian zones vary with respect to distance from the stream, height above stream base flow, and height above groundwater level.

When data from the 2012 field season is complete, we will use these data to test our prediction that stream flow and groundwater levels decline fastest during the time of highest riparian plant ET. We can also compare rates of discharge and groundwater declines to variation in plant communities among sites, although many other factors upstream within the watersheds will affect stream flow levels. Finally, information on plant distributions has been used to determine the which plant species (in addition to Reed Canary Grass) are most abundant in different geomorphic positions within the riparian zone and thus most likely to contribute to water loss through ET (currently, and hypothetically if Reed Canary Grass were removed through restoration). We have used these distributions to select the plant species used for ET measurements during summer 2012.

2. We estimated leaf-scale ET rates of *P. arundinacea* and 14 other riparian other species by direct measurements of stomatal conductance at two streams sites using a Li-Cor Photosynthesis System (Dugas et al. 1993, LI-COR 1999) at midday during July 2011. Based on these data, and the extensive surveys of riparian vegetation performed in 2011, we selected species for additional stomatal conductance measurements in 2012. These species include 3 woody shrubs (*Cartaegus douglasii*, *Symphoricarpos albus*, and *Rosa woodsii*), 2 emergent macrophytes (*Typha latifolia*, *Scirpus validus*), and 3 herbaceous plants (*Cirsium arvense*, *Maianthemum racemosum*, and *Urtica dioica*). These measurements will be conducted in mid-May, mid-July, and late August at two stream sites and at multiple distances from the stream within the riparian zone. Six replicate measurements will be made for each species at each site, date, and geomorphic position. Stomatal conductance of Reed Canary Grass will also be measured six times at each of these sampling points. Based on data from 2012, we will also estimate leaf biomass and leaf area in 6 quadrats dominated by each of the test species to estimate plot-scale as well as leaf-scale ET for each species.

3. Finally we will use ratios of stable oxygen ( $\delta\delta^{18}\text{O}$ ) and hydrogen ( $\delta\delta^{\text{D}}$ ) isotopes in xylem water to assess the sources of water used by *P. arundinacea* and other dominant riparian plants. During the summer of 2011 we sampled stream water, groundwater, and plant stem tissue at multiple geomorphic positions along a cross-stream transect at two stream sites in midsummer (July 2011) and late summer (September 2011). Soil water and ground water were collected at multiple depths via mini-piezometers (Baxter et al. 2003) Plant stems were placed in sealed jars on dry ice in the field and have been frozen for xylem water extraction. Plant species sampled included *P. arundinacea*, woody plants, emergent macrophytes, graminoids, and herbaceous plants. Stream and groundwater sample isotope ratios were analyzed at the at UC Davis Stable Isotope Facility. We are currently extracting xylem water using cryogenic distillation (Dawson and Ehlerlinger 1993). Mixing models will be used to determine the relative use of different water sources by each species sampled (Dawson 1993).

## Principle findings and significance

Results in this report are preliminary, as we are continuing to collect data on all of our original research questions.

### Initial findings

Initial data from 2011 comparing stomatal conductance of Reed Canary Grass with other riparian plants found comparable rates of transpiration at the leaf scale. Reed Canary Grass had higher rates of water loss per leaf area than other riparian plants on average, but rates were within the range observed for other plants. Stomatal conductance data for Reed Canary Grass and 18 other riparian species are presented in Figure 1. These species include dominant woody shrubs, graminoids, emergent macrophytes, and herbaceous plants. Although stomatal conductance at the leaf scale does not appear to be dramatically higher for Reed Canary Grass than other riparian species, the density of Reed Canary Grass growth may promote substantially higher ET at the plot scale compared to other plants. By maintaining a very high leaf biomass per area, Reed Canary Grass may both competitively exclude other plants and transpire a relatively large volume of water per area. Figure 2. Shows extrapolated plot-scale ET for Reed Canary Grass and 3 other plant species based on leaf-scale stomatal conductance combined with measurements of leaf biomass per riparian surface area. These species include two woody shrubs (Rose and Snowberry) and suggest that plot-scale ET of Reed Canary Grass may be higher than that of woody vegetation as well as herbaceous plants. The large differences between these species are due to greater biomass of Reed Canary Grass per area rather than differences in stomatal conductance at the leaf scale. During the summer of 2012 we will be collecting replicated biomass samples for all plant species for which we estimate stomatal conductance, and we expect this result to be confirmed and strengthened. If this is the case, Reed Canary Grass causes substantially higher rates of water loss from the riparian zone through ET than other riparian plants, including woody vegetation, which we initially hypothesized would have higher ET than Reed Canary Grass at the plot scale.

We found variability in stream water and shallow ground water stable oxygen ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta\text{D}$ ) isotope ratios at two riparian sites which should provide baseline differences for detecting differences in water sources for riparian plants. Variability in isotope ratios at the two sites appears related to differences in recent evaporation, and suggests different hydrologic patterns for the two sites. Stable oxygen ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta\text{D}$ ) isotope ratios for stream water, potential upstream water sources, and shallow ground water collected from Pine Draw on the Turnbull National Wildlife Refuge (a tributary of Rock Creek) are illustrated in Figure 3. Stream water has more depleted (negative) isotope ratios than an upstream lake, suggesting the stream receives groundwater inputs that have experienced less evaporation than lake water. Importantly, stream water and shallow ground water differed in oxygen ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta\text{D}$ ) isotope ratios, allowing their use as tracers of plant water use. Shallow ground water isotope ratios were less depleted than stream water, indicating effects of evaporation. Interestingly, ground water close to the stream was more enriched than farther from the stream, likely due to recent more rapid evaporation. Stable oxygen ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta\text{D}$ ) isotope ratios for stream water, potential upstream water sources, and shallow ground water collected from Cow Creek below Sprague Lake are illustrated in Figure 4. As for Pine Draw, there is useful variation in isotope ratios for distinguishing plant water sources. However, at this site, groundwater was more depleted than stream water, indicating stream water experienced greater evaporation, likely during residence in Sprague Lake. Differences in groundwater and stream water  $\delta^{18}\text{O}$  and  $\delta\text{D}$  will be used to determine the sources of riparian plant xylem water once cryogenic extraction has been completed.

**Significance**

Our most significant finding so far is that Reed Canary Grass is likely to have disproportionate effects on water loss from riparian zones and stream flow compared to other riparian vegetation in this region as a result of relatively very dense growth. This finding is currently preliminary, and we hope to confirm it with more extensive data during summer 2012. This high rate of ET at the plot scale occurs despite leaf-scale stomatal conductance values that are well within the variability among plant species.

The project will also compare the sources of water used by Reed Canary Grass and other riparian plants and correlate patterns of stream water discharge and ground water levels with riparian plant community structure. We hope to develop an understanding of riparian plant water use in the region that will help us determine whether riparian plant community restoration has the potential to affect stream flow and riparian ground water availability in semi-arid eastern Washington.

## References

- Allan, J.D., and Castillo, M.M. 2007. *Stream Ecology; Structure and Function of Running Waters*, 2<sup>nd</sup> edition. Springer.
- Baxter, C., F.R. Hauer, W.W. Woessner. 2003. Measuring groundwater-stream water exchange: new techniques for installing minipiezometers and estimating hydraulic conductivity. *Transactions of the American Fisheries Society* 132: 493-502.
- Carroll, J. 2007. Palouse River Dissolved Oxygen and pH Total Maximum Daily Load Study; Water Quality Study Design. Washington Department of Ecology. Publication Number 07-03-110.
- Cavaleri, M.A., and L. Sack. 2010. Comparative water use of native and invasive plants at multiple scales: a global meta-analysis. *Ecology* 91: 2705-2715.
- Cleverly, J.R., C.N. Dahm, J.R. Thibault, D.E. McDonnell, and J.E.A. Coonrod. 2006. Riparian ecohydrology: regulation of water flux from the ground to the atmosphere in the Middle Rio Grande, New Mexico. *Hydrological Processes* 20: 3207-3225.
- Dugas, W.A., J.S. Wallace, S.J. Allen, and J.M. Roberts. 1993. Heat balance, porometer, and deuterium estimates of transpiration from potted trees. *Agricultural and Forest Meteorology* 64: 47-62.
- Dawson, T. E. 1993. Water sources of plants as determined from xylem-water isotopic composition: perspectives on plant competition, distribution, and water relations. Pages 465-496 in: *Stable isotopes and plant carbon-water relations*. Ehleringer, J. R. et al., editors. Academic Press.
- Dawson, T.E., and J.R. Ehleringer. 1993. Isotopic enrichment of water in the woody tissues of plants: implications for water source, water uptake, and other studies which use the stable isotopic composition of cellulose. *Geochimica & Cosmochimica Acta* 57: 3487-3492.
- Galatowitsch, S.M., N.O. Anderson., and P.D. Archer. 1999. Invasiveness in wetland plants in temperate North America. *Wetlands* 19: 733-755.
- Joy, J., R. Noll, and E. Snouwaert. 2009. Hangman (Latah) Creek Watershed Fecal Coliform, Temperature, Dissolved Oxygen, and Temperature Total Maximum Daily Load; Water Quality Improvement Report. Washington Department of Ecology. Publication 09-10-030.
- Lee, G.F. 1969. Analytical chemistry of plant nutrients. Pages 646-658 in *Eutrophication: its Causes, Consequences, Correctives*. National Academy of Sciences. Washington, D.C.
- Le Maitre D.C., van Wilgen B.W., Gelderblom C.M., Bailey C., Chapman R.A. and Nel J.A. 2002. Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *Forest Ecology and Management* 160: 143-159.
- LI-COR. 1999. Using the Li-6400 portable photosynthesis system. LI-COR, Inc, Lincoln NE.
- Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Climatic Change* 102: 187-223.
- Schilling, K.E. 2007. Water table fluctuations under three riparian land covers, Iowa (USA). *Hydrological Processes* 21: 2415 – 2424.
- Schilling, K.E., and J.R. Kiniry. 2007. Estimation of evapotranspiration by Reed Canary Grass using field observations and model simulations. *Journal of Hydrology* 337: 356-363.
- Tarbuton, S., J. Carrol, and E. Snouwaert. 2010. Draft Palouse River Fecal Coliform Bacteria Total Daily Maximum Load. Water Quality Improvement Report and Implementation Plan. Washington Department of Ecology. Publication number 10-10-067.
- Zedler, J. B., and S. Kercher. 2004. Causes and consequences of invasive plants in wetlands: Opportunities, opportunists, and outcomes. *Critical Reviews in Plant Sciences* 23:431-452.

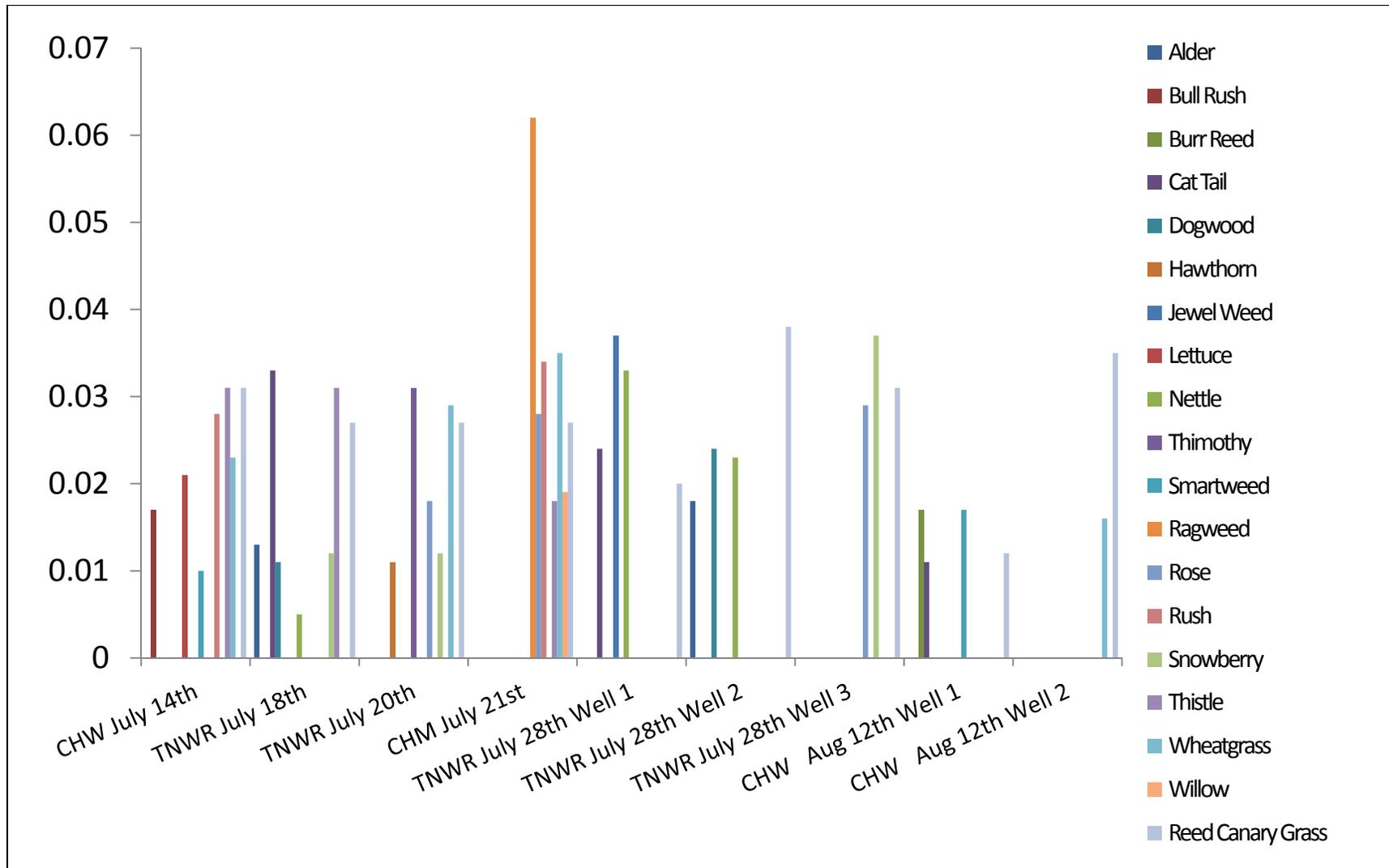


Figure 1. Leaf-area ET rates ( $\mu\text{M cm}^{-2} \text{ s}^{-1}$ ) for Reed Canary Grass (*Philaris arundinacea*) and 18 other riparian plant species measured at 3 riparian sites during July and August 2011.

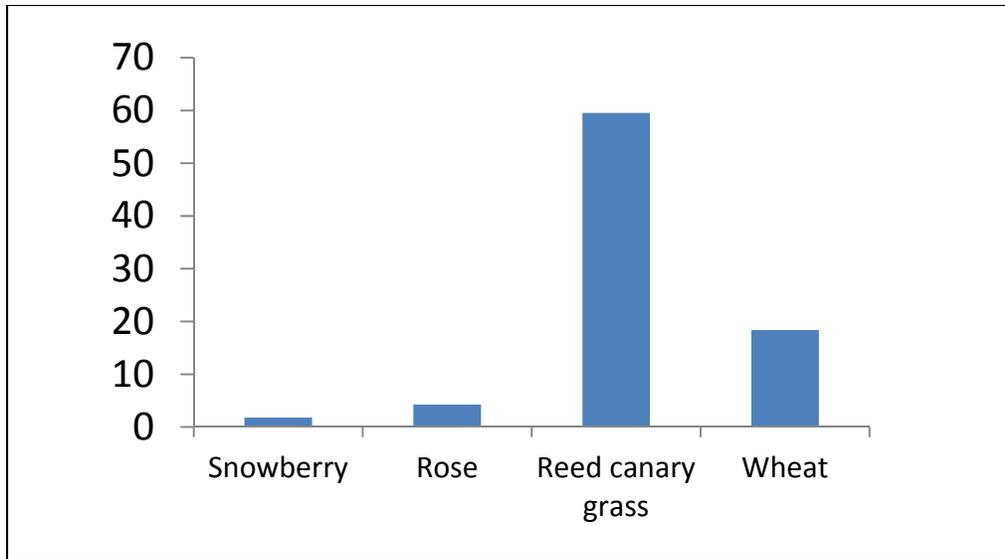


Figure 2. Estimated plot-scale ET rates (g of H<sub>2</sub>O/m<sup>2</sup>/hr) for 4 riparian plant species. Estimates were based on leaf-scale stomatal conductance measurements and leaf-area per plot. Snowberry refers to *Symphoricarpus albus*, Rose refers to *Rosa woodsii*, and Wheat refers to *Elymus repens*.

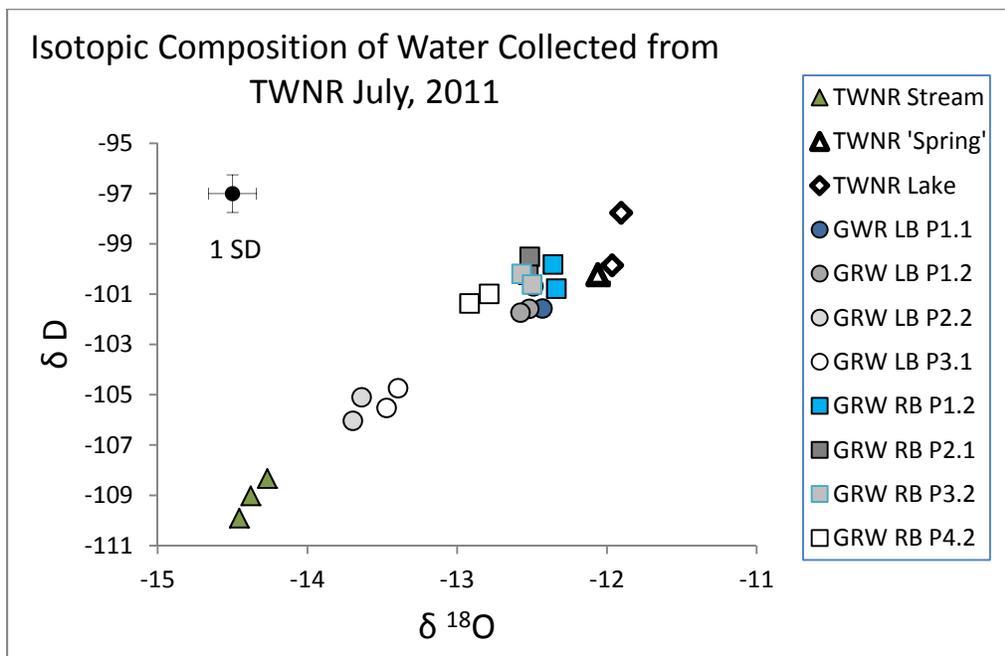


Figure 3. Stable oxygen ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta\text{D}$ ) isotope ratios for stream water, upstream sources (“Spring” and Lake), and shallow groundwater collected from Pine Draw on Turnbull National Wildlife Refuge, July 2011. “GRW” samples indicate shallow groundwater collected from minipiezometers. ‘LB’ indicates left bank of the riparian zone and ‘RB’ indicates the right bank of the riparian zone. Numbers indicate relative proximity to the stream with ‘1’ indicating the piezometers closest to the stream.

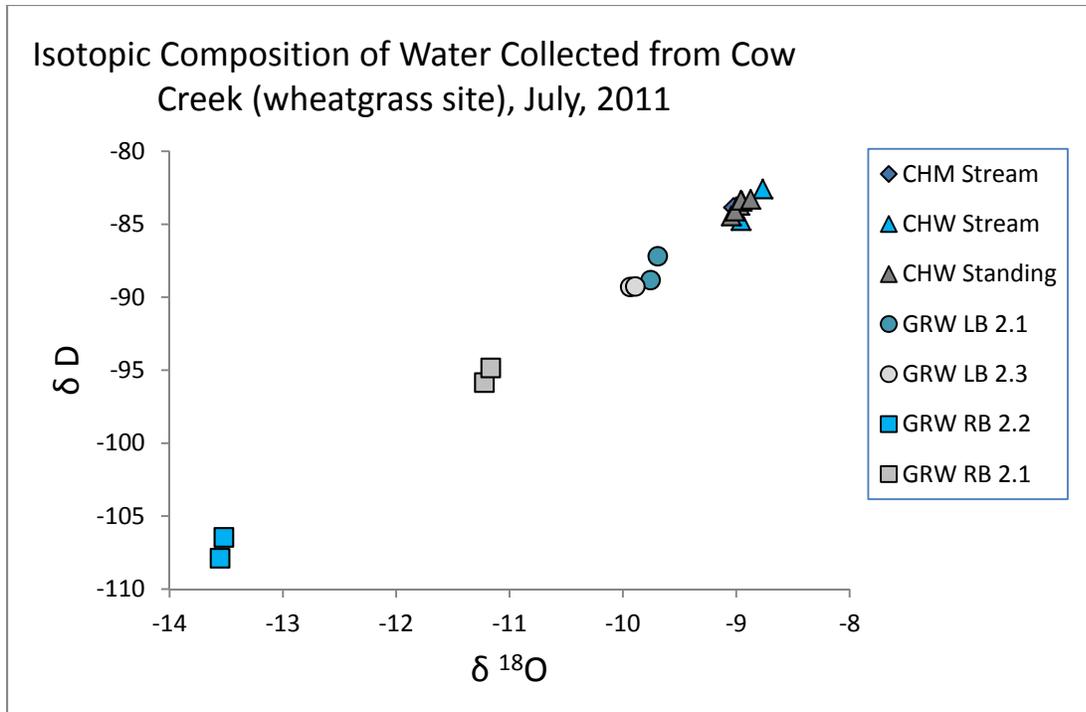


Figure 4. Stable oxygen ( $\delta^{18}\text{O}$ ) and hydrogen ( $\delta\text{D}$ ) isotope ratios for stream water, upstream sources (“Spring” and Lake), and shallow groundwater collected Cow Creek downstream of Sprague Lake, July 2011. “GRW” samples indicate shallow groundwater collected from minipiezometers.

## **Information Transfer Program Introduction**

Public Outreach and Education are critically important components of the State of Washington Water Research Center mission. As agency and stakeholders struggle to comprehend important decisions facing water resources, it is essential that they receive unbiased scientific information. The primary outreach 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. The education goal is typically achieved through faculty and student involvement in public presentations and gatherings to promote and build better two-way understanding of water issues and possible solutions and provide unique educational experiences for tomorrow's water resources professionals. These processes occur through a variety of activities, formal and informal, that raise the visibility of university research results throughout the Pacific Northwest. Federal, state and local agencies, non-governmental organizations, watershed groups, and concerned citizens are in need of interpreted science that can be applied to solving the regions' water problems. The 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

<b>Title:</b>	Information Transfer
<b>Project Number:</b>	2011WA338B
<b>Start Date:</b>	3/1/2011
<b>End Date:</b>	2/28/2012
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	Washington 5th
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	Education, Management and Planning, None
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Michael Ernest Barber, Michael Ernest Barber

## Publications

There are no publications.

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

Continued funding for a USDA-CSREES grant was received. The project helps to coordinate research and extension activities of the Water Research Institutes and Extension Services in Alaska, Idaho, Oregon, and Washington with US EPA Region 10 and the NRCS. Six meetings are held each year and communication between researchers, extension faculty, and government agencies is improved considerably by the activity. This project also provides some of the funding that the SWWRC leverages for support of a biennial water conference related to an emerging theme as identified by a regional steering committee. The November 2011 conference titled, "Water in the Columbia River basin: Sharing a Limited Resource" was another showcase event for the SWWRC. Planning for this conference involved venue selection, call for abstract development, and other related activities. This biennial conference has been highly successful, drawing over 200 local decision makers from around the region and works as an excellent avenue for showcasing SWWRC research efforts. Even with strained travel budgets, this year's event attracted a large number of water resources interests from the region. A student competition in the poster session helps promote the education goal of the SWWRC. The student competition also showcased several SWWRC projects.

SWWRC co-sponsored the Palouse Basin Water Summit; a local event attracting stakeholders and concerned citizens from the bi-state watershed (ID and WA). Participants learn about water conservation, efforts to quantify groundwater resources, and other critical aspects of local watershed planning and management. It was also involved in the Spokane River Forum with presentations regarding aquifer storage options to mitigate surface/groundwater depletion occurring in the region.

SWWRC collaborated with institutes in Colorado, Idaho, Montana and Oregon to host a regional conference on exempt wells in Walla Walla, WA in May 2011. This conference provided a forum for professionals engaged in groundwater development, water management, land planning, and water policy to discuss the impacts that exempt domestic wells have on water supplies and land development at the local and regional level. A summary white paper was developed and placed on our web site.

Director Michael Barber attended the annual NIWR meeting in Washington, DC to interact with other directors from around the country and engage in dialog concerning regional water issues. One outcome of these discussions was that regional institute directors from Colorado, Idaho, Oregon, Montana, and In part due to the success of the 2011 Exempt Well conference, Washington began preliminary collaborating with Institutes in Idaho and Oregon to conduct a regional "Geothermal Energy" conference late 2012 or early 2013. Dr. Barber also attended the UCOWR/NIWR 2011 conference in Boulder, CO, attended a UCOWR Board meeting, and presented an oral presentation on research conducted at WSU.

The SWWRC is also engaged at helping develop a long-term vision for water and agriculture at the national level. Director Barber attended a meeting of 40 water professionals in Monterey, CA to help develop a strategic roadmap.

Maintaining and updating our web site is a continuous process. This is an important avenue for us to present information about the activities of the Center and the research faculty in the state as well as news and events, research reports, and opportunities for research funding. We currently have all our research reports available for download via PDF format allowing for greater access and utilization of study results.

# USGS Summer Intern Program

None.

<b>Student Support</b>					
<b>Category</b>	<b>Section 104 Base Grant</b>	<b>Section 104 NCGP Award</b>	<b>NIWR-USGS Internship</b>	<b>Supplemental Awards</b>	<b>Total</b>
<b>Undergraduate</b>	3	0	0	0	3
<b>Masters</b>	2	1	0	0	3
<b>Ph.D.</b>	1	5	0	0	6
<b>Post-Doc.</b>	0	0	0	0	0
<b>Total</b>	6	6	0	0	12

## **Notable Awards and Achievements**

**2006WA180G**Awarded the American Water Resources Association "Outstanding Chapter of the Year," for work on linking research, education, and societal outreach. 2006. (PI Steinemann was faculty adviser to AWRA student chapter, and four students in chapter were supported by USGS grant.)

**2011WA326B**Lane Graduate Research Fellowship in Environmental Science, awarded to Tammy Lee, 2011.