State of Washington Water Research Center
Annual Technical Report
FY 2010

Introduction

For over 45 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. With competition growing for a finite resource, 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 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.

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.

The SWWRC is continuing its intensive efforts to reach out to agencies, organizations, and faculty throughout the State. Activities include presentations to watershed groups, participation in regional water quality meetings, and personal contacts. A 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. All of these issues will be important drivers of the activities of the SWWRC in the foreseeable future.

Research Program Introduction

In accordance with its mission, the SWWRC facilitates, coordinates, conducts, and administers water-related research important to the State of Washington and the region. Research priorities for the State of Washington are established by a Joint Scientific Committee which includes representatives from water resource professionals at state agencies, universities, and the local USGS office. The 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 on its own behalf.

During FY 2010, three local research projects were selected for funding by the Center: (1) Understanding the Vulnerability of Columbia Basin Irrigated Agriculture to Predicted Climate Changes using a Coupled Hydrological-crop Model, awarded to Jennifer Adam, Assistant Professor, WSU-Pullman, (2) Developing a Novel, Interdisciplinary Approach to Understand Hot Moments in Reservoir Nutrient Transformation, awarded to John Harrison, Assistant Professor, WSU-Vancouver, and (3) Water Quality Parameters Controlling the Photodegradation of Herbicides in Surface Waters in the Columbia Basin, Washington awarded to Olga Furman, Postdoc and Richard Watts, Professor, WSU-Pullman. 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 project, West-Wide Drought Forecasting System: A Scientific Foundation for National Integrated Drought Information System (NIDIS) was awarded to Anne Steinemann, Professor, University of Washington. A progress update is included in this report.

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

Basic Information

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

Publications

1. Wood, A.W. Correcting errors in streamflow forecast ensemble mean and spread. Submitted to Journal of Hydrometeorology (in review).
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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

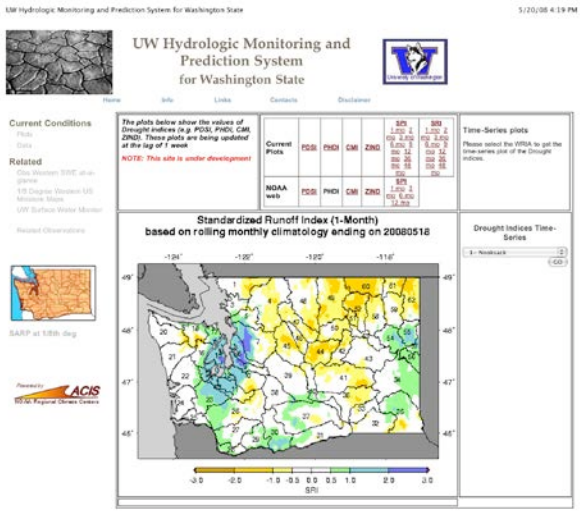
(4) To work with the NDMC, the WGA, and other users (primarily state agencies in the western U.S.) to incorporate the resulting drought nowcasts and forecasts into water management decisions and into drought information systems such as the Drought Monitor/Outlook and NIDIS.

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).

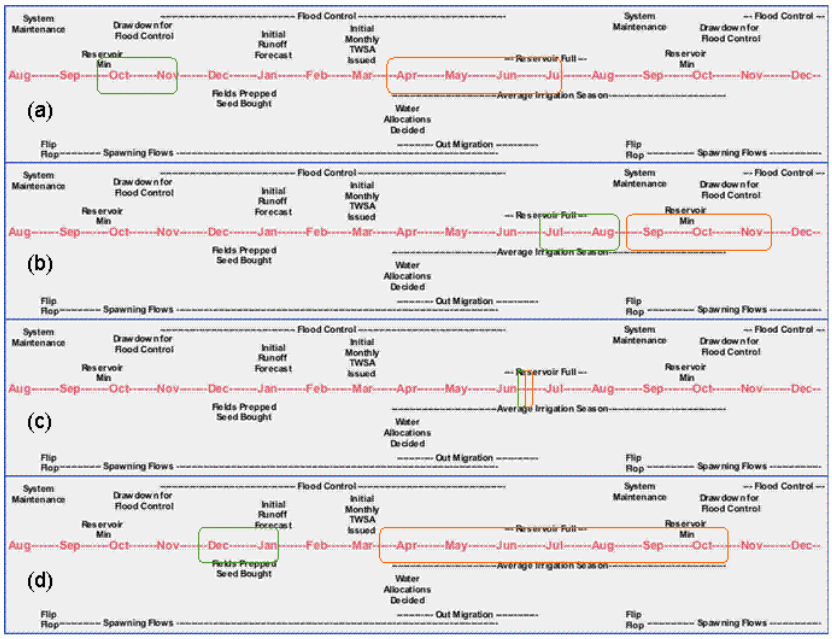


Figure 2. Four identified decision-making realms, with green circles around period in which decisions are made and orange circles around the relevant time of forecast. (a) Filling reservoirs without flooding in winter and spring, (b) maintaining flows for fish in fall, (c) week-to-week operations in 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 below the 20th percentile for soil moisture, SWE, and cumulative runoff for the continental United States are available at http://www.hydro.washington.edu/forecast/monitor/outlook/index.shtml. Ensemble Streamflow Prediction (ESP)-based and CPC outlook-based forecasts of daily streamflow volumes are made near the beginning of each month. These outputs are summarized as monthly hydrograph distribution plots available for several forecasting stations in the west-wide U.S. Region (Figure 3, http://www.hydro.washington.edu/forecast/westwide/sflow/). The ESP ensembles are drawn from sequences of past observations, whereas the CPC outlook ensembles are derived from the CPC's probability of exceedance (POE) forecasts for average monthly temperature and total precipitation in each of 102 climate divisions within the U.S. Probabilistic outcomes will be compared with nominal conditions (as simulated with the VIC model using the true forcings) for the retrospective period, and maps of the accuracy of climate recovery predictions will be produced as a function of season and lead-time. Figure 4 compares the ensembles of

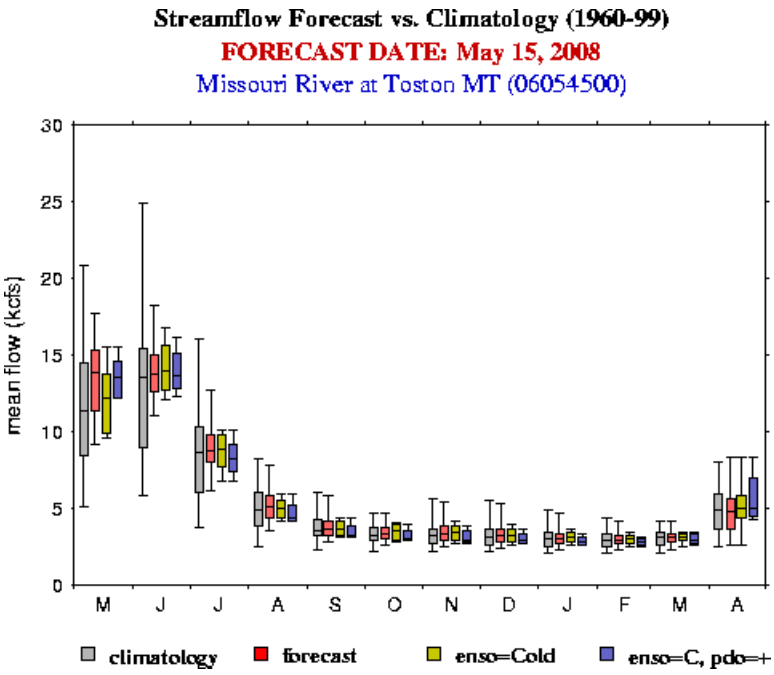


Figure 3. ESP forecast for mean monthly streamflow on the Missouri River at Toston, MT, as of May 15, 2008.

predicted soil moisture, averaged over the Arizona-California portion of the drought, compared with "actual" (real-time) model soil moisture over the 6-month forecast period.

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

The VIC hydrologic model produces near real-time, spatially and temporally continuous fields of drought-related variables such as soil moisture and streamflow (we focus here on soil moisture). Drought is defined locally at each model pixel using a thresholding method, i.e., whenever soil moisture or runoff are below a certain threshold value the pixel is classified as being "in drought." Instead of using the absolute values of soil moisture (or runoff), droughts are identified by expressing each pixel's soil moisture as percentiles of their 1915-2004 respective model climatology. This essentially normalizes the soil moisture and runoff time series to range 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 kind of temporal persistence constraint. This ensures that areas are classified as drought recovered relatively consistently, given that this is a near real-time application. Drought transition probabilities (probability that a pixel will recover if it was in drought the previous 1, 2 or 3 weeks) were calculated from the model climatology. These are then used after the first stage of drought identification (any pixel below the 20th percentile is classified as drought) to retain the temporal persistence in drought areas. The recovery probability threshold is set to 50%, but this can be adjusted accordingly.

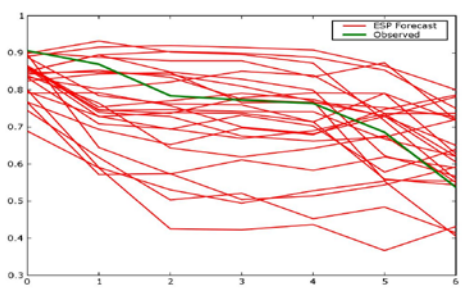


Figure 4: Spatial average soil moisture over AZ-CA starting on Feb. 1, 2006, and progressing through August, as compared with "actual" soil moisture (real-time model estimates).

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

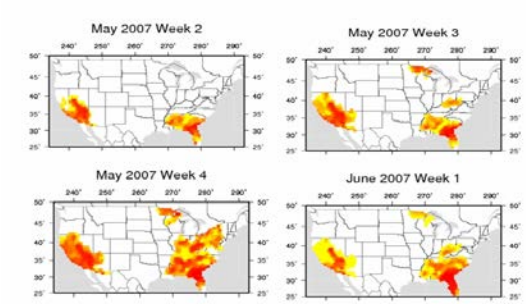


Figure 5: Estimated extent of drought over continental U.S. as of first week of June, 2007, and evolution over previous three weeks. Soil moisture percentiles are relative.

week. We are interacting with CPC personnel who are reviewing the method, but we believe that it has great promise for producing a more objective delineation of drought extent and severity that is currently possible in publications such as the National Drought Monitor.

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

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

After further investigation into techniques for incorporating groundwater into large-scale land surface models, we have 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.

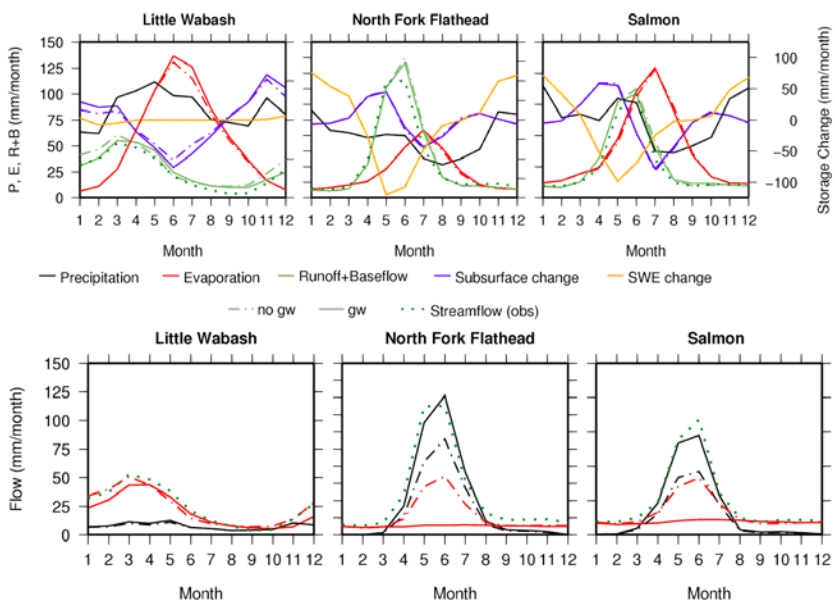


Figure 6. Top panel shows the modeled average annual water balance (1950-1998) for the Little Wabash, North Fork Flathead and Salmon Rivers. Lower panel shows the modeled average annual runoff and baseflow plotted against observed streamflow for the same rivers. Dashed lines are the standard VIC implementation; 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.

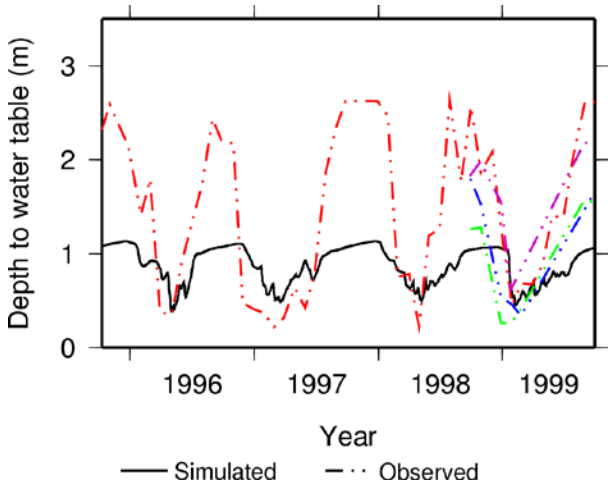


Figure 7. Depth to water table, simulated by VIC with SIMGM for the Little Wabash River (solid) and observed by the ISWS at Olney (blue), Fairfield (green), Dixon Springs (red) and Rend Lake.

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 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

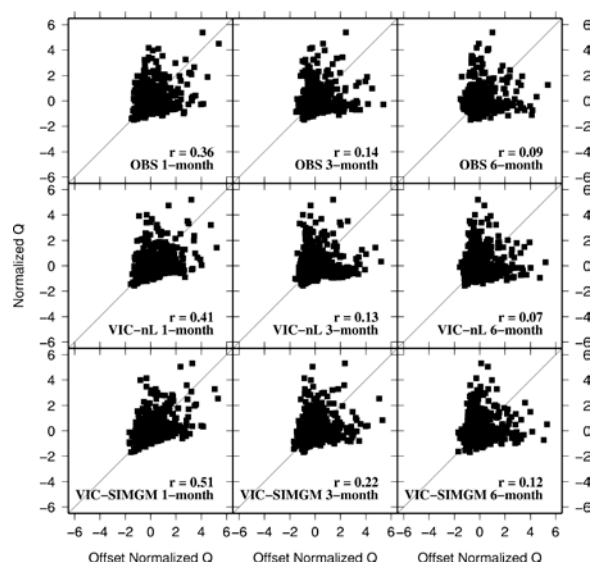


Figure 8. Autocorrelation of streamflow for the Little Wabash River in Illinois. 1-month lag time, 3-month lag time, and 6-month lag time shown from left to right. Top: observed, middle: VIC without SIMGM, bottom: VIC with SIMGM. Correlation coefficients labeled on plot.

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.

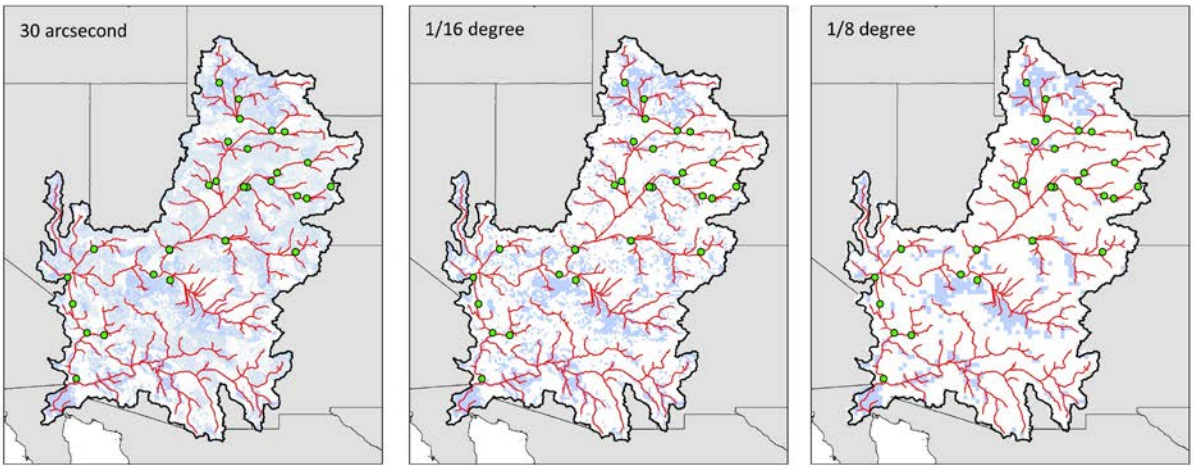
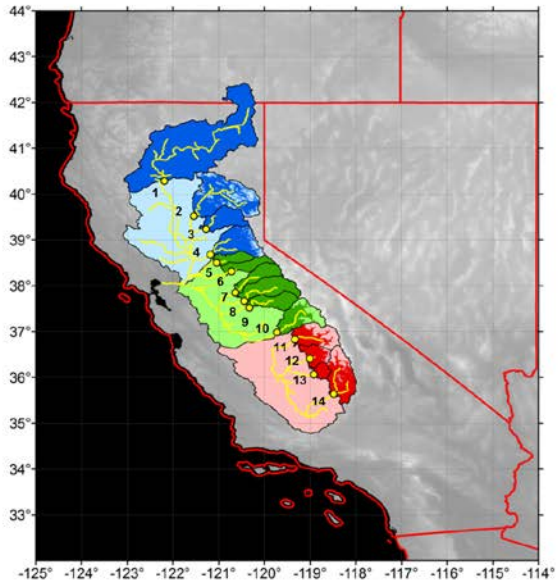


Figure 9. Water table climatology from Miguez-Macho et al. (2008) in the Colorado River basin. 1/16 degree and 1/8 degree maps were derived by aggregating data from their native 30-arcsecond resolution. Water table depths of less than 20 m are shown in blue, and streamflow locations used for calibration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



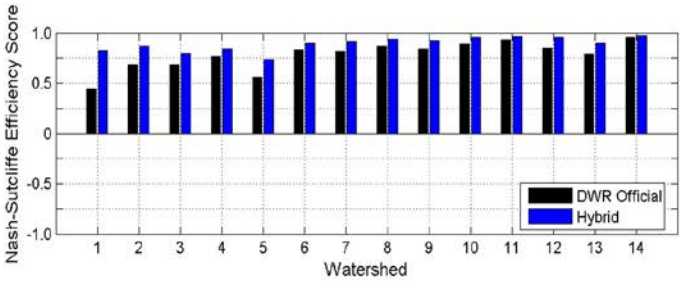


Figure 10. (left) The 14 watersheds of the Sacramento (blue), San Joaquin (green), and Tulare Lake (red) hydrologic regions, forming the study area for Rosenberg et al. (2011). (above) Nash-Sutcliffe efficiency scores for April 1 forecasts of April–July streamflow in each of the 14 watersheds.

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.

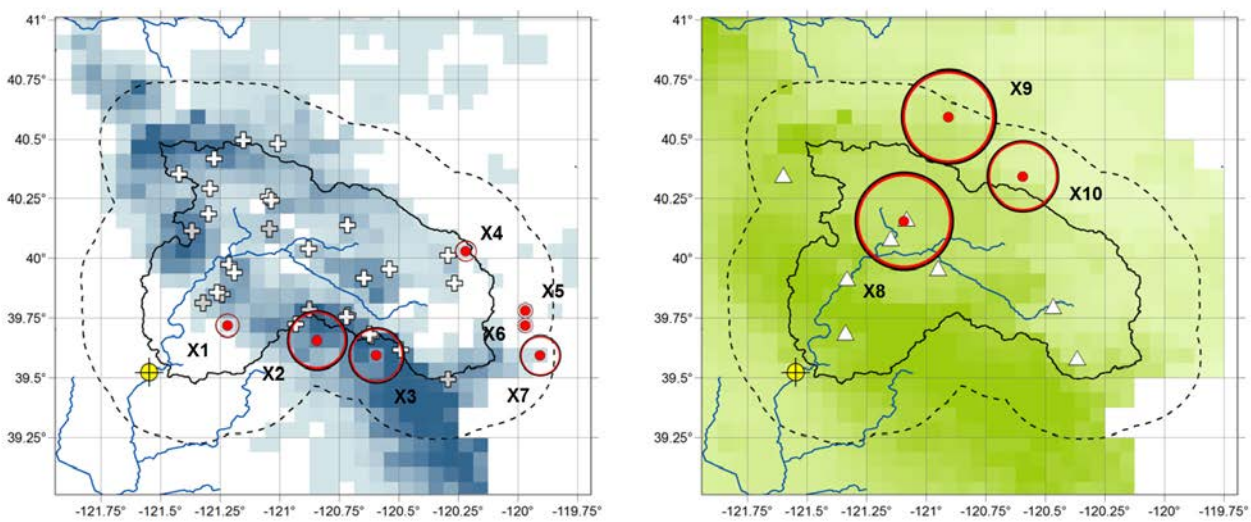


Figure 11. April 1 SWE (left) and October–March precipitation (right) predictor locations for April 1 hybrid streamflow forecasts in the Feather River basin. Climatologies are shown by the darkness of the blue (left) and green (right) backgrounds. Crosses depict existing snow courses and sensors, triangles 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.

Developing a Novel, Interdisciplinary Approach to Understand Hot Moments in Reservoir Nutrient Transformation

Basic Information

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Principal Investigators:	John Harrison, Stephen M. Henderson

Publications

1. Deemer, B.R., J.A. Harrison, and E.W. Whitling, 2011, Microbial Nitrogen Removal and Nitrous Oxide Production in a Small Eutrophic Reservoir: An In Situ Approach to Quantifying Hypolimnetic Process Rates, Limnology and Oceanography, 56(4) 1189-1199, doi:10.4319/lo.2011.56.4.1189.
2. Deemer, B.R., J.A. Harrison, and S. Henderson, 2011, Dam Spill as a Hot Moment for Microbial Nitrogen Removal in a Eutrophic Reservoir, Poster presentation at the annual meeting of the American Society of Limnology and Oceanography, San Juan, PR.
3. Deemer, B.R., and J.A. Harrison, 2010, Patterns of Microbial Nitrogen Removal in a Eutrophic Reservoir: Insights From a New In-Situ Approach, Presentation at the joint meeting of the American Society of Limnology and Oceanography and the North American Benthological Society, Santa Fe, NM.
4. Harrison, John A. and Stephen M. Henderson, 2010, Interacting Hydrological and Biogeochemical Controls on Nitrogen Transformation Hot Spots and Hot Moments in a Eutrophic Reservoir, Emerging topics in biogeochemistry NSF proposal. (Awarded $130,000 as a seed grant)
5. Glavin, Maria (with the assistance of John Harrison), 2010, Is Methane Ebullition an Important Greenhouse Gas Flux in Lacamas Lake?, College of Sciences Undergraduate Mini-grant (Awarded $3,000)
6. Deemer, Bridget, In Progress, Spatio-temporal Dynamics of Denitrification and Greenhouse Gas Production in a Small Eutrophic Reservoir: Quantifying ecosystem services in managed aquatic systems, Ph.D. Dissertation, School of Earth and Environmental Sciences, Washington State University, Vancouver, WA.
7. Deemer, Bridget, 2010, Thermal Stratification Impacts Microbial Nitrogen Removal and Nitrous Oxide Production in a Small Eutrophic Reservoir: An in situ approach to quantifying hypolimnetic process rates, MS Dissertation, School of Earth and Environmental Sciences, Washington State University, Vancouver, WA, 36pp.

1. Problem and Research Objectives

Human-induced nitrogen (N) and phosphorus (P) over-enrichment of surface waters is an important problem in Washington State, throughout the Northwest US, and worldwide. In Washington State, over 700 water bodies have been 303d listed for excessive nutrients, and many eutrophic lakes and reservoirs are prone to problems such as toxic and nuisance algal blooms, hypoxia, and drinking water degradation (WA Depart.of Ecol. 2004). Thus, it is critical to understand transport of nutrients through watersheds, and the biogeochemical processes that account for sources and sinks of bioactive elements like N and P. Dam construction and operation are also important issues, both within Washington State and beyond. Dam construction is one of the major vehicles through which humans affect the hydrological cycle and the downstream transport of bio-active compounds, including N, and P (Vörösmarty et al., 2003; Dumont et al., 2005; Harrison et al., 2009). Model predictions of nutrient transport are sensitive to how reservoirs are treated (Dumont et al., 2005; Harrison et al., 2005; Harrison et al., 2010). In some systems, such as the Colorado and Rio Grande watersheds, reservoirs have been estimated to remove up to 99% of the original N and P load, with some N removal resulting in the production of N_2O, an important greenhouse gas. Despite the critical and variable role reservoirs often play in controlling downstream N and P transport (Kelly 2001; Beusen et al., 2005; Dumont et al., 2005; Ahearn et al., 2005; Harrison et al., 2005; Harrison et al., 2009, Sobota et al., In Prep.), relatively little is known about how reservoirs process nutrients.

Although N and P removal in lentic systems are often characterized using long-term average rates (e.g. Saunders and Kalff 2001; Harrison et al., 2005; Teodoru and Wehrli 2005; Harrison et al., 2009a; Harrison et al., 2009b), N and P removal rates vary on a wide range of time scales. Brief "hot moments" of intense N processing may account for much N removal within lentic systems, but hot-moments for N transformations in lentic systems remain largely unquantified (Groffman et al., 2009). Preliminary observations from Lacamas Lake suggest that nutrient dynamics are greatly affected by brief hot moments for N transformations, specifically springtime stratification and fall dam spill events. Motivated by these observations, we have worked to quantify temporal variability of N dynamics, and test the hypothesis that **episodic renewal of bottom water by dam spills creates a hot moment for N removal. In addition, the development of a novel, interdisciplinary approach to estimate benthic N fluxes, capable of resolving temporal variation in N removal was one of the primary aims of the proposed work.**

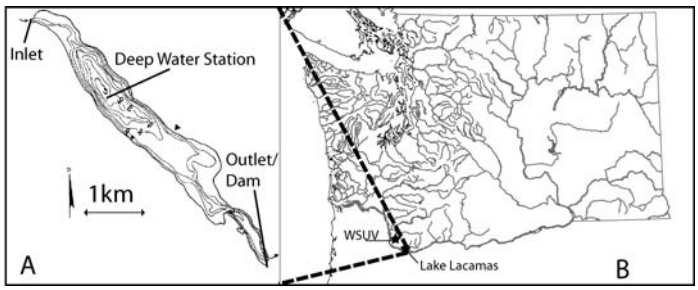

Figure 1. Bathymetry of Lacamas Lake, showing inlet, outlet, and within-lake deep-water sampling station (A), and location of Lake Lacamas in Washington State (B). Note that Lacamas Lake is near WSU Vancouver for ease of sampling.

2. Methodology

This study focused on Lacamas Lake, a highly-impacted (hypereutrophic), monomictic reservoir in Clark County, WA, just 20 freeway miles from WSU-Vancouver (Figure 1). Lacamas Lake is an EPA 303d-listed reservoir currently experiencing high N and P input. Consequently, large nutrient fluxes and strong, measurable concentration gradients develop near the sediment-water interface, (Schnabel and Hutton 2004, Deemer et al. 2011), making the use of flux-gradient techniques feasible (Section 4). Lacamas Lake also experiences predictable, summer hypolimnetic hypoxia and a predictable fall spill event during which ~50% of

the lake's water is released. High N and P concentrations and fluxes, consistent seasonal hypoxia, and predictable reservoir spills make Lacamas Lake an excellent model system in which to study reservoir N and P dynamics.

2.1 Overview

Physical and biogeochemical measurements were synchronized during two Pulse-Coherent Acoustic Doppler Profilers (ADCP) deployments. These deployments, designed to contrast hot times for N removal (fall dam-spill) with baseline conditions (unstratified conditions of late winter and stratified conditions of late-summer), were supplemented with additional biogeochemical measurements. Novel integration of biogeochemical measurements with physical measurements was intended to further test our primary hypothesis.

2.2. Physical measurements

Two ADCPs were used to determine piston velocities through measurement of the turbulent flows that are responsible for mixing N to the lakebed. The instruments (2-MHz Nortek Aquadopps with High-Resolution firmware upgrades) log data internally, are small, self-contained, battery powered, and thoroughly tested through years of refinement, greatly simplifying deployment, recovery, and data processing.

A brief deployment in March 2010 was followed by a more intensive twenty-day deployment immediately before, during, and after the September dam spill. A vertical thermister string (Hobo temperature loggers) recorded minutely temperature every minute at elevations 2.0, 9.3, 10.8, 11.8, and 12.6 m above the lakebed at the Deep Water Station (Figure 1), where total water depth before dam spill was about 16.3 m. A 1.5-m-high bottom-mounted tripod was deployed at the Deep Water Station and instrumented with 2 Nortek Aquadopp ADCPs. Upward- and downward-looking ADCPs measured vertical profiles of 3-dimensional velocity above and below the instruments (which were 1.3-1.5 m above bed) using a pulse-coherent signal to obtain high resolution and low noise (temporal resolution 1 s, vertical resolution 1 cm and 2 cm for downward- and upward-looking ADCPs, and noise about 0.2 mm/s). Along-lake temperature transects were measured using a Hach DS5X Sonde lowered from a small boat.

2.3 Biogeochemical Measurements

2.3.1 Hypolimnion Sampling Across Summer Stratified Period

Samples were collected along a vertical profile (1-2m intervals) at the Deep Water Site (Figure 1) approximately every other week from 16 Jun 2010 to 16 Sep 2010 in order to document changes in bottom water chemistry during the summer stratified period. More temporally resolved sampling of the bottom 4 meters of the hypolimnion was conducted on 8 days during and after the fall dam spill. At each depth a DS5X Sonde was used to take temperature, turbidity, dissolved oxygen, pH, and chlorophyll *a* measurements. Samples were then collected using a Van Dorn sampler at approximately 2m increments. Greenhouse gas samples (for N_2O, CH_4, and CO_2) were taken in 60mL glass Wheaton vials capped with gray rubber butyl and aluminum crimp tops. N_2:Ar samples were collected in 5 ml hollow penny-head, ground-glass-stoppered vials. Filtered (Whatman 0.45uM filters) and unfiltered nutrient samples were taken in 30mL Nalgene bottles. N_2:Ar samples were analyzed on a Pfeiffer Membrane Inlet Mass Spectrometer (MIMS; Kana et al., 1994). Greenhouse gas samples were analyzed on a Thermo Scientific Trace GC Ultra after introducing 20mL He headspace to each Wheaton. Currently, the filtered nutrient samples have been analyzed for PO_4^{3-}, NO_3^-, NO_2^-, SiO_2, and NH_4^+ using a Westco Scientific Instruments Smart Chem 200 analyzer and for ^{56}Fe, ^{57}Fe, Mn, and Rb on an Agilent 7700 Series ICP-MS using a

helium-mode to reduce Ar/O_2 interferences with ^{56}Fe. Unfiltered samples are currently frozen for future total P and Total Kjeldahl N analysis.

2.3.2 Mass Balance Sampling

Inlet and outlet filtered and unfiltered nutrient samples were collected every other week during summer 2010 in order to better understand how the reservoir acts as a sink or source of various nutrient species. Filtered samples have been analyzed for PO_4^{3-}, NO_3^-, NO_2^-, SiO_2, and NH_4^+ using a Westco Scientific Instruments Smart Chem 200 analyzer.

2.3.3 Bottom Water Chemical Gradients

Integrating samplers were developed using water-filled bags of dialysis membrane that equilibrate with surrounding water. The dialysis tubing had a molecular weight cut off (MWCO) of 12-14,000, allowing smaller molecules to pass through, while eliminating the passage of larger particulate organic matter. Dialysis bags, termed "peepers," were filled with deionized water in the lab and then allowed to equilibrate with the lake water. Lab tests indicated that full equilibration occurs over approximately a 7-day period.

We built a minimalistic frame with a pvc base and a steel rod vertical support beam. Three 7-day peeper deployments were focused around the fall dam spill, one the week before the spill, one the week of the spill, and one the week after the spill. For each deployment, four peeper bags were attached at each of three depths (0.1, 0.3, and 0.5 meters above the bed) at the Deep Water Site. Peepers were sampled for N_2:Ar, nutrients, and greenhouse gases on the seventh day of deployment.

2.4 Flux-Gradient method

Piston velocities quantify the strength of turbulent mixing near a boundary. Assuming equal piston velocities for momentum, heat, and chemical tracers (a good approximation for unstratified flows, Monin and Yaglom 2007), the mean turbulent momentum flux[1] (F_u), temperature flux (F_T), and chemical flux (F_C) away from the boundary obey

$$F_u = (u_1 - u_2)k \quad (1), \qquad F_T = (T_1 - T_2)k \quad (2), \qquad F_C = (C_1 - C_2)k \quad (3),$$

where u_j, T_j and C_j are mean water velocity, temperature and chemical concentration at distance z_j from the boundary ($z_2 > z_1$). For steady, horizontally-uniform, turbulent flow sufficiently near a stationary boundary, dimensional consistency demands (Monin and Yaglom 2007)

$$k = \kappa u_* / \ln(z_2/z_1), \quad (4)$$

where the "friction velocity" $u_* = F_u^{1/2}$, and the empirical constant $\kappa = 0.4$.

If the mean velocity is known at two elevations, then (1), (4), and the definition $u_* = F_u^{1/2}$ constitute three equations which can be solved for the three unknowns k, u_*, and F_u. The piston velocity k, is then combined with measured chemical concentration gradients and equation (3) to calculate chemical fluxes. If velocity is known at more than two elevations (we will measure

[1] F_u equals the mean frictional shear stress on the bed divided by water density.

velocity at about 100 elevations), redundant measurements can be used to reduce experimental errors, and to check for consistency with the flux-gradient theory.

In some cases, application of the flux-gradient method may be limited by the difficulty of measuring weak chemical concentration gradients (Eq. 3). In the case of Lacamas Lake, concentration gradients are strong, measureable, and have the sign expected given denitrification within sediments.

In addition to the relationships between fluxes and time-averaged profiles discussed above, dimensional analysis also predicts spectra (Monin and Yaglom 2007) and structure functions (Wiles *et al*. 2006) for turbulent velocity fluctuations. We will exploit these relationships to provide two redundant estimates of piston velocity. Comparison of independent piston velocity estimates provides a consistency check on the validity of flux-gradient theory, as will comparison between these estimates and estimates of N flux based on the mass balance and hypolimnion accumulation approaches.

Physical measurements were used to estimate piston velocity k, which quantifies the strength of turbulent mixing. The piston velocity was combined with chemical measurements to estimate the chemical flux to the lakebed using the equation

$$F_C = (C_1 - C_2)k,$$

where C_j denotes mean chemical concentration at distance z_j from the boundary ($z_2 > z_1$). Piston velocities were calculated from measured mean velocity, and from structure functions (representing small-scale departures from mean velocity owing to turbulent eddies) using theory for unstratified boundary layers (Monin and Yaglom 2007).

3. Principal findings

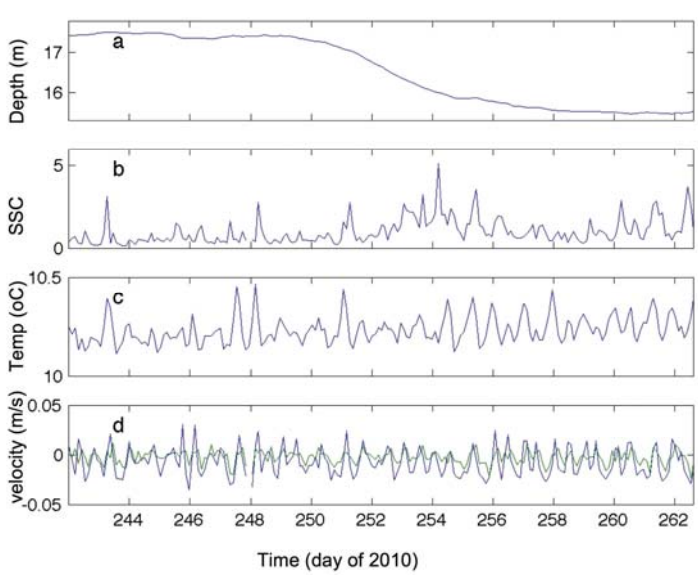

Figure 3. Physical conditions observed before, during, and after dam spill. Water depth (a) decreases owing to dam spill. Suspended sediment concentration (b, relative units) increases during

spill. Near-bed temperature (c) and water velocity (d) oscillate owing to internal seiche, but do not show a clear change with spill.

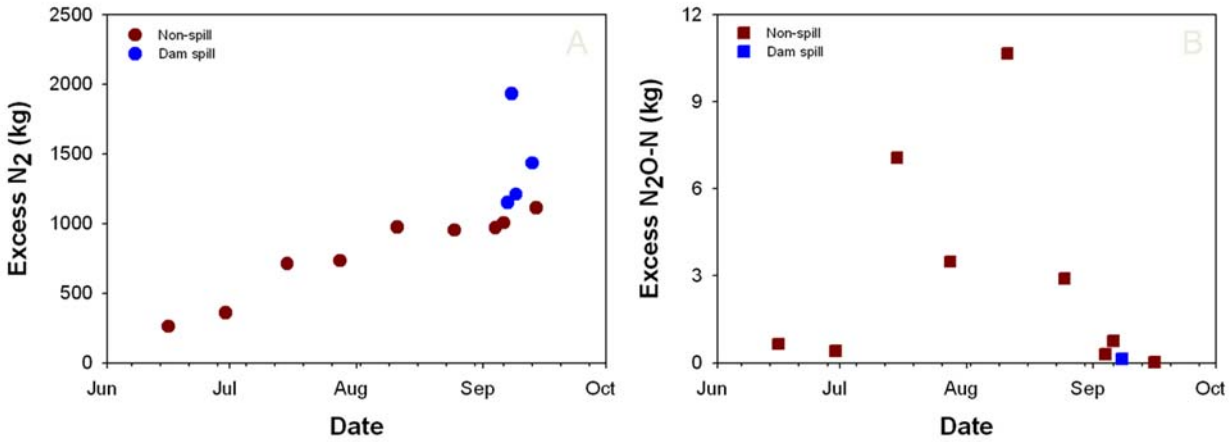

Figure 4. Bottom water N_2 (A) and N_2O (B) masses during the summer stratified (red) and dam spill (blue) periods. While N_2 masses increase during the period near the spill, N_2O masses decrease resulting in low N_2O-N:N_2-N ratios in September.

N_2 concentrations spiked to approximately double pre-dam-spill levels during dam spill (Figure 4), consistent with rapid N removal near the lakebed at this time. There was some simultaneous increase in nearbed sediment suspension (figure 3a,b). However, there was no corresponding clear change in near-bed temperature (figure 3c) or water flows (figure 3d). Lakewide surveys showed that the lake did not overturn during dam spill (figure 5). Piston velocities estimated from mean currents were 0.26-0.91 mm/s, varying owing to an internal seiche with 0.5-1 day period. Piston velocities estimated from structure functions were slightly lower (0.21-0.50 mm/s), possibly owing to sediment- or temperature-induced stratification. Using the piston velocities estimated from structure functions, together with measured concentration gradients, we calculate an N flux of 4,670 – 11,774 umol N_2-N m^{-2} h^{-1} during peak dam spill – some of the highest N_2 fluxes ever reported in a reservoir system. Lakewide N balances confirmed that N processing was very rapid during this time. N_2 flux during dam spill was 35-87-fold as high as average non-spill fluxes calculated using the same approach. Our lab group is currently working to define the mechanisms responsible for increased N_2 flux during dam spill. Preliminary results, which show elevated Rb concentrations during dam spill, suggests that groundwater flux may be an important contributor to chemistry along the sediment water interface at this time. Furthermore, rapid rates of N_2 accumulation during dam spill were not associated with increased N_2O, suggesting that there isn't a tradeoff between N removal and N_2O production during this period.

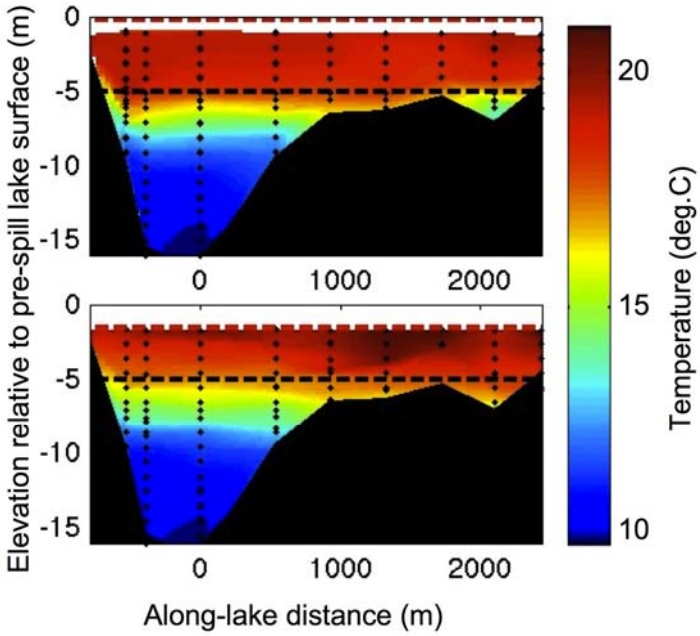

Figure 5. Along-lake sections of temperature (color) near start (upper panel) and end (lower panel) of dam spill. Black dots mark measurement locations. Water level (red dashed line) decreases during spill, but thermocline elevation is fixed near -5 m (black dashed line, drawn for reference), a cap of warm water remains, and deep water is almost unchanged by spill.

4. Significance

To our knowledge, this project was the first to apply a flux gradient technique to estimate chemical fluxes in an aquatic system. The method provided time resolution sufficient to identify very rapid N processing during dam spill. Results are encouraging, justifying further examination of this method (see below).

In addition to developing the flux gradient method, we found an intriguing pattern of rapid N processing during dam spill. Improved understanding of the processes by which spill causes rapid N processing could lead to better management of reservoir pollution.

5. Ongoing research

The results presented here provided important support for an NSF proposal for further research. This proposal has been funded, and throughout 2011-2012 we will conduct additional deployments in Lacamas Lake. Refined peepers will be deployed, with thinner tubes providing faster equilibration and reduced flow disturbance. ADV-temperature eddy correlation measurements and six-beam ADCP systems will provide additional redundant estimates of piston velocity. It is hoped that these extra piston velocity estimates, combined with the improved stratification measurements (6 temperature gauges within 2 m of lakebed), will explain the differences between piston velocities derived from mean-flow and structure-functions. The more extensive deployments will be used to further examine the causes of the rapid N processing during Dam spill.

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Water Quality Parameters Controlling the Photodegradation of Herbicides in Surface Waters in the Columbia Basin, Washington

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Introduction

Central and eastern Washington are agricultural areas where alfalfa, orchards, and wheat represent the largest crop acreages. Pesticides, which include insecticides, herbicides, and fungicides, are applied to crop lands at various times throughout the year. Although the benefits of pesticide use are undisputed, runoff of these xenobiotics into surface water can result in threats to public health and aquatic organisms. Atrazine, bentazon, diuron, and 2,4-D are the most frequently detected herbicides in surface waters in the Central Columbia Basin as well as throughout the entire U.S. (USGS, 2006). These herbicides have relatively high solubilities in water; therefore, they are readily transported into surface waters and ground waters.

Herbicide fate in the environment depends on the rate of application, the physicochemical properties of the herbicide, transport pathways, and transformation processes in soil and water. Herbicide transformation processes include abiotic oxidation and reduction, hydrolysis, photolysis, and biodegradation. Biodegradation is the primary transformation process in soils, and photolysis is the primary transformation pathway in surface waters (Goncalves et al., 2006).

Photodegradation of xenobiotics in surface waters may proceed by direct or indirect pathways. In direct photolysis, the xenobiotic acts as a chromophore (light absorbing substance); the xenobiotic absorbs light energy which then disrupts its chemical bonds resulting in its degradation. The earth's ozone layer filters light of wavelength < 290 nm, while nearly all pesticides absorb light at a wavelength < 290 nm; therefore, direct photolysis is not a dominant pathway of pesticide decomposition (Larson and Weber, 1994). Indirect photolysis occurs when another compound acts as a chromophore and then transfers energy to the xenobiotic, resulting in its decomposition. Common indirect photolysis chromophores include nitrate, minerals, and dissolved natural organic matter (NOM). Several mechanisms may occur when a chromophore absorbs sunlight in a water column.

Nitrate, a highly mobile anion that is ubiquitous in runoff water in the Columbia Basin as a result of fertilizer application, absorbs the near-uv light of sunlight to generate reactive oxygen species. Nitrate-induced photolysis is initiated by the absorbance of sunlight at 313 nm, resulting in the generation of hydroxyl radical ($OH^{\cdot}$) (Larson and Weber, 1994):

$$NO_3^- + H_2O + h\nu \longrightarrow NO_2^{\cdot} + OH^{\cdot} + OH^- \quad [1]$$

$$NO_2^{\cdot} + OH^{\cdot} + OH^- \longrightarrow NO_2^- + {}^{\cdot}O^{\cdot} \quad [2]$$

$$NO_2^- + H_2O + h\nu \longrightarrow NO^{\cdot} + OH^{\cdot} + OH^- \quad [3]$$

Haag and Hoigne (1985) reported that nitrate photolysis is the predominant pathway for hydroxyl radical generation in surface waters. The photochemical activation of nitrate has been described for the degradation of numerous xenobiotics such as dichlorprop and tertbutylazine (Schindelin and Frimmel, 2000), trifluralin (Dimou et al., 2004), fenitrothion (Derbalah et al., 2004), and monolinuron (Nelieu et al., 2004) in natural waters.

Although nitrate-induced photolysis is the dominant pathway for generating the strong oxidant hydroxyl radical, dissolved organic matter is usually the dominant light absorbing material in

surface waters. Common components of dissolved organic matter (DOM) that function as sensitizers include humic and fulvic acids (i.e., aquatic humus) and riboflavin (Larson and Weber, 1994). Aquatic humus absorbs a significant amount of light between 290 and 450 nm, and therefore has significant potential as a photosensitizer in natural waters. Several reactive oxygen species can be formed when natural organic matter is excited by sunlight. One mechanism is the excitation of DOM by a photon to a higher energy level (called a triplet state). When the DOM triplet state returns to ground state, the energy can be transferred to molecular oxygen to form singlet molecular oxygen:

$$^{3}DOM + O_2 \longrightarrow DOM + {}^{\cdot}O_2 \qquad [4]$$

In another proposed mechanism the excited DOM molecule releases an aqueous electron, which is then scavenged by molecular oxygen to generate superoxide ($O_2^{\cdot-}$):

$$*DOM \longrightarrow DOM + e^{-}_{aq} \qquad [5]$$

$$e^{-}_{aq} + O_2 \longrightarrow O_2^{\cdot-} \qquad [6]$$

Superoxide then readily dismutates to hydrogen peroxide (H_2O_2), which can then decompose to hydroxyl radical through reactions catalyzed by transition metals or metal oxide minerals:

$$O_2^{\cdot-} + 2H^{+} \longrightarrow H_2O_2 \qquad [7]$$

$$H_2O_2 \xrightarrow{Me^{n+},\ Me_xO_y} OH + OH^{-} \qquad [8]$$

Hydroxyl radical has the potential to oxidize a wide range of xenobiotics. DOM-sensitized photolysis has been shown to degrade a number of xenobiotics including trifluralin (Dimou et al., 2004), atrazine (Prosen and Zupancic-Krajl, 2005), imazaquin and iprodione (Garbin et al., 2007), alloxydim (Sevilla-Moran et al., 2008), and methyl parathion (Manzanilla-Cano et al., 2008).

The dominant factors that control the photodegradation of pesticides in surface waters have been the subject of numerous investigations. For example, Goncalves et al. (2006) found that nitrate ions accelerated the photodegradation rate of the organophosphorus insecticide quinalphol versus dissolved organic matter, which had a retarding effect on the photolytic rate. In contrast, photodegradation of aqueous pesticides increased in the presence of humic substances (Garbin et al., 2007). Miller et al. (2000) observed that indirect photolysis was the most significant pathway in the photodegradation of carbaryl and alachlor in wetland surface water. The photolytic pathway depended on chemical structure; for example, atrazine was characterized by a higher photodegradation rate in water containing humic acids compared to photodegradation in distilled water; in contrast, diuron photodegradation was retarded in natural water (Durand et al., 1991). Graebing et al. (2002) found that organic carbon has an effect on niclosamide photolysis more than the presence of iron. However, the moisture and depth of illumination were the most important variables in the study.

The proposed research elucidates which of three water quality parameters (nitrate concentration, humic acid concentration, and total suspended solids) control the photolysis rate of two of the most commonly used herbicides in the Columbia Basin of Washington State. Since the physicochemical characteristics of surface waters and herbicides fate and transport are affected by seasonality (USGS, 2006), seasonal effects on the photodegradation of herbicides were also investigated.

Methods and procedures

Sample collection and characterization

Surface water samples were collected from sites in four drainages of the Columbia Basin. The basins include Crab Creek, Lind Coulee, Red Rock Coulee, and Sand Hollow. Sampling sites have been established in these drainages by the U.S. Geological Survey to examine the occurrence, distribution, and transport of pesticides in agricultural irrigation return flows (USGS, 2006). These surface-water drainages from irrigated lands lead to wasteway returns that create irrigation-return flows to major streams and rivers (USGS, 2006). More than 95% of the cropland in Red Rock Coulee, Crab Creek, and Sand Hollow drainage basins is irrigated, whereas only 30% of the cropland in Lind Coulee is irrigated. Sand Hollow drains the western flanks of Royal Slope and flows west, emptying into the Columbia River across from Vantage, Washington. The Crab Creek irrigation-return drainage covers 767 km^2, and its site near Beverly is directly affected by ground-water seepage from Potholes Reservoir (USGS, 2006). Red Rock Coulee drains about 49 km^2 of irrigated agricultural land beginning near the eastern boundary of Grand County and empties into Crab Creek. Lind Coulee basin drains about 1839 km^2; it flows through the town of Lind and empties into Potholes Reservoir.

To examine a possible seasonal effect, samples were collected in May, July and October; i.e., at the beginning, middle, and end of the irrigation season. The surface waters were characterized for temperature and conductivity at the time of sampling. Five samples were collected directly into 1-L borosilicate glass bottles fitted with Teflon-lined caps, shipped on ice to Washington State University, and stored at < 4º C.

Surface water samples were composited and characterized for pH, nitrate and nitrite, dissolved organic carbon, and suspended solids concentrations following Standard Methods (1995) and the procedures listed in Table 1. Subsamples for the analysis of nitrate, nitrite, and dissolved organic carbon were filtered though a 0.45 µm filter. Field blanks and equipment blanks were be analyzed for possible contamination. All analyses were conducted in triplicate.

Table 1. Description of analytical methods used in the current study.

Analyte	Importance	Analytical method
Total suspended solids	Photosensitizer	Method 2540 D (APHA/AWWA/ WEF Standard Methods, 1995)
Nitrite and nitrate	Photosensitizer	Ion Chromatography (IC Anion Column SUPER-SEP 6.1009.000)
Dissolved organic carbon	Photosensitizer	Colorimetry (HACH Method 10129)
Atrazine	Herbicide	Gas Chromatography (Bouaid et al., 1996)
2,4-D	Herbicide	Gas Chromatography (Boucharat et al., 1998)

Photodegradation studies

Unfiltered surface waters and MQ water samples were spiked with 10 mg/L of atrazine and 2,4-D. Irradiation of the samples was performed in quartz tubes (outside diameter = 1.3 cm, inside diameter = 1.1 cm, volume = 10 ml) in the Suntest CPS apparatus (Heraeus, Germany) equipped with a xenon arc lamp and a filter restricting transmission of light below 290 nm. The emitted wavelengths ranged from 290 nm to 800 nm, and irradiation was set at 765 W/m^2 to simulate the sun irradiance. For example, the sunlight intensity at mid-latitude summer at noon is 1.25 kW (Mazellier and Sulzberger, 2001). The temperature within the reactor was kept at 37±2 ºC by using a fan. Dark control samples covered with aluminum foil were exposed in the Suntest equipment to account for other transformation processes such as volatilization and hydrolysis. Photodegradation loss of atrazine and 2,4-D were measured as a function of time. At selected time points, a triplicate set of reactors were analyzed for atrazine and 2,4-D (Table 1).

Analysis

Nitrate and nitrite ion concentrations were measured in surface waters using a Metrohm model 690 ion chromatograph equipped with a Super-Sep anion-exchange column. The mobile phase consisted of 2.5mmol/L phthalic acid, 5% acetonitrile, pH 4.2 (TRIS); the flow rate of mobile phase was 1.5 ml/min.

Methylene chloride extracts were analyzed for atrazine using a Hewlett-Packard 5890A gas chromatograph with a 0.53 mm (i.d.) × 60 m Equity 1 capillary column and electron capture detector (ECD). Chromatographic parameters included an injector temperature of 250˚C, detector temperature of 300˚C, initial oven temperature of 60˚C (held for 5 min), program rate of 15˚C/min, and final temperature of 280˚C.

2,4-D herbicide was derivatized into its 2,4-D methyl ester following the procedure described in Boucharat study (1998), and extracted into hexane for further GC-ECD analysis. Chromatographic parameters included an injector temperature of 280˚C, detector temperature of 300˚C, initial oven temperature of 60˚C (hold for 2 min), program rate of 30˚C/min, and final temperature of 190˚C, and ramped up at the rate of 5˚C/min to the final temperature of 250.

Statistical Analysis

Statistical analyses were performed using the SAS software package version 9.1. Multiple regression analysis and general linear model were conducted to determine 1) relationships between herbicide degradation rates and the concentration of photosensitizers in surface water samples collected from different sites, and 2) which parameter has the highest effect on herbicide degradation rate. The independent variables (water quality parameters) were tested for collinearity, and a t-test was applied to evaluate if water quality parameters have a predictive value in the model (Ott and Longnecker, 2001). A contrast test was performed using a general linear model to compare first-order degradation rates for herbicides across different treatments. A step-wise multiple regression analysis was conducted for each site separately to obtain significant predictors for the photodegradation of atrazine over irrigation period

Results

Surface water samples were collected from sites in four drainages (Crab Creek, Lind Coulee, Red Rock Coulee, and Sand Hollow) of the Columbia Basin on May, July and October 2010. Water quality parameters are summarized in Table 2 and Figures 1-3. Dissolved organic carbon content was similar in the surface waters collected in four drainages at the same time point (Table 2), but varied seasonally showing the highest concentration in July (Figure 2). Nitrate and TSS concentrations varied spatially and seasonally (Table 2, Figures 1 and 3).

As water moves through the Columbia basin, the dissolved solids concentration increases from Lind Coulee to Lower Crab Creek (USGS, 2006), which correlates well with our measurements of in-situ conductivity. Lind Coulee surface waters showed the lowest in situ conductivity, versus Lower Crab Creek showed the highest in situ conductivity value (Table 2). The average TSS concentration was found to be the highest in the Lower Crab Creek, which can be explained again by the movement of water from Lind Coulee towards Lower Crab Creek (Table 2, Figure 3).

Nitrate concentrations did not exceed U.S. EPA Maximum Contaminant Level for drinking water (10 mg/L nitrate-nitrogen) in the four study drainages of the Columbia Basin during the 2010 irrigation season (May-October). Lower Crab Creek is characterized by the lowest percentage of agricultural cropland (USGS, 2006); as a result, the average nitrate concentration was found to be the lowest in the Lower Crab Creek ($p<0.05$). The nitrate concentration was the highest in Sand Hollow stream between four drainages of the Columbia Basin in three seasons ($p<0.05$) (Table 2). These results correlate well with historical measurements of nitrate in the four drainages (USGS, 2006).

Photodegradation kinetics for atrazine and 2,4-D in surface waters are summarized in Tables 3 and 4 and Figures 4-10. The photodegradation of both herbicides (atrazine and 2,4-D) followed first order kinetics in the surface waters (R^2>0.96) (Figures 7-10). Both herbicides did not show a significant loss in the dark during the three seasons (Figures 8 and 10, data are shown only for one season). 2,4-D degradation was 16% in the Sand Hollow surface waters in the dark (Figure 10).

Atrazine

The results of Figure 6 indicate that atrazine alone can photodegrade in MQ water under the Xe lamp showing an average photodegradation rate of 0.025 hr^{-1} (Table 3). Ou et al. (2008) observed a photodegradation rate of 0.059 hr^{-1} under similar conditions, except the pH of the water was 3.5 and the light intensity was 150 W/m^2. The results of our study suggest a direct photolysis of atrazine in water. In addition, some surface waters in the Columbia Basin showed similar photodegradation rates for atrazine relative to photodegradation rates in MQ water ($p>0.05$), suggesting a direct photolysis pathway (Appendix 1). For example, Red Rock Coulee showed a similar photodegradation rate for atrazine (May and October) in comparison to the photodegradation rate for atrazine in MQ water (Appendix 1).

A multiple regression analysis and general linear model were performed to evaluate water quality parameters effects on herbicide photolysis across all sites and three seasons. The results of the general linear model indicate that there are significant site, seasonal, nitrate, DOC and TSS effects on the photodegradation of atrazine in four drainages of the Columbia Basin ($p<0.05$). The results of multiple regression model indicate that the photodegradation of atrazine increased with nitrate concentration; however, dissolved organic carbon was not a significant predictor in the full model. The retarded photodegradation of atrazine in the presence of increased total suspended solids concentration can be explained by competitive light attenuation; and increased photodegradation of atrazine in the presence of nitrate suggests nitrate-induced photolysis.

A step-wise multiple regression analysis was performed for each site separately to obtain significant predictors for the photodegradation of atrazine over irrigation period; and strong collinearity was found between some water quality parameters.

Lind Coulee

Total suspended solid concentrations in Lind Coulee showed the unique predictive value with respect to the photodegradation of atrazine over irrigation time. For example, the highest TSS concentration was observed in July, which correlates well with the lowest photodegradation rate of atrazine in July (Tables 2 and 3).

Lower Crab Creek

The results of multiple regression suggest that nitrate and TSS concentrations were the best estimators to predict atrazine photodegradation in Lower Crab Creek surface waters over the irrigation period. However, both nitrate and TSS showed some collinearity indicating that statistics can be biased. The Pearson correlation was negative between nitrate and TSS

concentrations in Lower Crab Creek waters ($p<0.05$). Nitrate concentrations increased from May to October, and the TSS concentrations decreased over the irrigation time in Lower Crab Creek.

Red Rock Coulee

None of the water quality parameters were found to be significant predictors in the model for photolytic studies conducted at Red Rock Coulee. Also, the photodegradation of atrazine was not statistically different between MQ water and Red Rock waters collected in May and October (Appendix 1). Overall, Red Rock Coulee Basin has the smallest drainage area of 19 mi^2, and contains the lowest TSS concentration between the study sites (Table 2).

Sand Hollow

Both nitrate and DOC concentrations proved to be good predictors for photodegradation of atrazine in surface waters over the irrigation season. The photodegradation rate for atrazine increased with nitrate and DOC concentration over the irrigation time.

2,4-D Herbicide

Photodegradation rates for 2,4-D were higher than photodegradation rates for atrazine, (Tables 3 and 4, Figure 6). These are expected results, since 2,4-D herbicide is hydrophilic and has a mean life in surface waters of about 20 days, versus atrazine, which can persist in the environment for about 1-2 years (Kamble et al., 2004; Rebelo et al., 2007).

The results of the general linear model indicate that there is a significant season, site, nitrate and total suspended concentration effects on the photodegradation rates of 2,4-D in four sites of the Columbia Basin. The results of the multiple regression model showed that there are significant nitrate, DOC, and TSS concentration effects on the photodegradation of 2,4-D over the collection period. A stepwise selection process was used to estimate the best predictors for photodegradation of 2,4-D over time in Columbia Basin surface waters.

Lind Coulee

Dissolved organic carbon concentrations predicted changes of 2,4-D concentrations over time in three different seasons. The highest dissolved organic carbon concentration was found in July, followed by May and October. Different predictors were found in the same water for the two herbicides.

Lower Crab Creek

Multiple regression analysis indicated that total suspended solids have a predictive value for photodegradation of 2,4-D. As the photodegradation rates of 2,4-D increased over the irrigation time, total suspended solids concentration decreased toward the end of irrigation season (October, 2010). As in the case of atrazine, the results of the model indicated the retardation effect of TSS on herbicides photolysis as they filtered the incident light.

Average photodegradation rates for both herbicides over the irrigation season (May-October) was the lowest in Lower Crab Creek surface irrigation system (Figure 6). Lower Crab Creek contained the highest total suspended solids concentrations except for October (Table 2 and Figure 3).

Red Rock Coulee

Significant relationships were found between photodegradation of 2,4-D over time and DOC and TSS concentrations in Red Rock Coulee. However, DOC and TSS concentrations showed strong collinearity indicating that the statistical analysis may be biased.

Sand Hollow

DOC concentration was selected as a good predictor for 2,4 photodegradation rates in Sand Hollow surface waters over irrigation period. For example, the highest total organic carbon was observed in July corresponding to the highest photodegradation of 2,4-D in Sand Hollow surface waters. It is also important to stress that average photodegradation rate for both herbicides over all three seasons was the highest in Sand Hollow surface waters, which can be explained by the highest nitrate concentrations in Sand Hollow (Figure 6).

Conclusions

The photodegradation of the herbicides 2,4-D and atrazine is site-specific and affected by three water quality parameters: nitrate, TSS and DOC in four drainages of the Columbia Basin. The results of the multiple regression models showed that higher nitrate, DOC and lower TSS concentrations will induce the photolytic rate of herbicides in the drainages of Columbia Basin. Different water quality parameters proved to be good predictors for the photodegradation of herbicides over the irrigation period depending on the site. Water quality parameters were collinear in some sites; as a result, it was difficult to separate their effects on the photodegradation rates.

GLM and multiple regression models were also performed to evaluate water quality parameter effects on herbicide photolysis across all sites in each season (May, July and October). Nitrate concentration was found to be the most significant factor affecting the photodegradation of both herbicides (atrazine and 2,4-D) in all four drainages of the Columbia Basin in July. All three water quality parameters (nitrate, TSS and DOC) exhibited significant effects on photodegradation rates of both herbicides across all sites in May and October. However, there is a positive correlation between DOC and TSS concentrations across all sites of the Columbia Basin ($p<0.05$). Therefore, an increase in DOC may not necessarily result in higher photolytic rates of herbicides as it correlates positively with TSS concentrations, and high TSS concentrations inhibit photodegradation rates of both herbicides in the Columbia Basin surface waters. Minimization of TSS concentrations in the surface waters of the Columbia Basin is recommended to maximize rates of photolysis of herbicides in surface waters.

Both direct and indirect photolysis proved to be significant pathways for photodegradation of both herbicides in the Columbia Basin. Previous studies have demonstrated involvement of

hydroxyl radical in the direct and/or indirect photolysis of 2,4-D (Aaron et al., 2010). The photodegradation intermediate products were 2-Cl- and 4-Cl-phenoxyacetic acids, and 2,4-dichlorophenol that are rapidly oxidized to CO_2 and H_2O (Aaron et al., 2010; Kamble 2004). The main photodegradation pathways for atrazine are dealkylation on the amine side-chains, and photosubstitution at the 2-position with the subsequent formation of the 2-hydroxy derivative (Azenha et al., 2003; Lanyi and Dinya, 2005). Subsequent research could potentially elucidate pathways of photodegradation of 2,4-D and atrazine in surface waters of the Columbia Basin.

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U.S. Geological Survey, 2006. Scientific Investigations Report 2006-5005. *Occurrence, distribution, and transport of pesticides in agricultural irrigation-return flow from four drainage basins in the Columbia Basin Project, Washington, 2002-04, and comparison with historical data.* Reston, Virginia.

Table 2. Water quality parameters of Columbia Basin surface water samples collected in spring, summer and fall, 2010.

Month the samples were collected (2010)	Site	*In situ Conductivity, µS/cm*	*In situ temp, ° C*	*pH*	*NO_3^{2-}*	*Dissolved organic carbon, mg/L*	*Total suspended solids, mg/L*
May	***Control (MQ)***	1.0	21.0	6.94	ND[§]	ND	ND
	Lind Coulee	223	19.6	8.16	3.83 ± 0.02[*] A[†]	2.44 ± 0.13 A	17.31 ± 0.67 A
	Red Rock Coulee	396	18.9	8.42	9.11 ± 0.08 B	2.75 ± 0.13 A	6.33 ± 0.88 B
	Sand Hollow	324	21.0	8.22	19.20 ± 0.04 C	2.41 ± 0.31 A	26.63 ± 1.33 C
	Lower Crab Creek	571	19.5	8.44	5.30 ± 0.02 D	2.90 ± 0.03 A	77.9 ± 2.0 D
July	***Control (MQ)***	0.8	21.0	6.70	ND	ND	ND
	Lind Coulee	298	19.0	8.06	7.75 ± 0.02 A	5.08 ± 0.13 A	24.67 ± 0.67 A
	Red Rock Coulee	402	23.1	8.34	7.76 ± 0.11 A	5.10 ± 0.60 A	12.67 ± 0.67 B
	Sand Hollow	364	21.9	8.44	25.59 ± 0.15 B	4.93 ± 0.06 A	32.67 ± 1.76 C
	Lower Crab Creek	557	23.8	8.38	5.22 ± 0.04 C	6.04 ± 0.41 A	53.33 ± 1.33 D
October	***Control (MQ)***	0.8	21.0	6.80	ND	ND	ND
	Lind Coulee	367	15.0		14.57 ±0.18 A	0.92 ± 0.09 A	4.00 ± 0.58 A
	Red Rock Coulee	444	17.0		13.18 ±0.20 B	1.53 ± 0.08 A	4.67 ± 0.88 A
	Sand Hollow	410	16.0		28.79 ± 0.04 C	2.33 ± 0.12 B	39.67 ± 1.67 B
	Lower Crab Creek	586	16.0		9.94 ± 0.04 D	1.56 ± 0.17 A	14.67 ± 0.67 C

[§] ND-non-detectable; NO_2^- was non-detectable in all water samples
[*]Standard error
[†]Means with the same letter are not statistically different ($p<0.05$) within each season; least significant t-tests were used to separate means

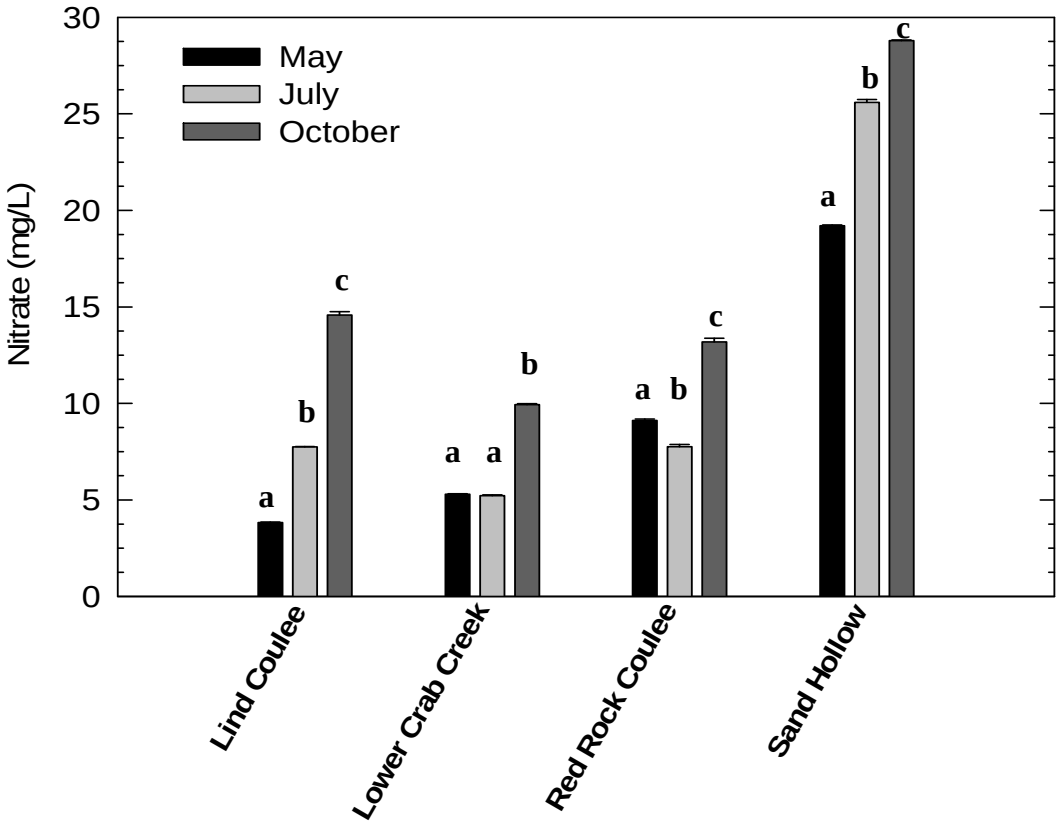


Figure 1. Nitrate concentrations in Columbia Basin surface water samples collected from four drainages in May, July and October, 2010. Means with the same letter indicate no statistical difference ($p<0.05$) between seasons for each site; least significant t-tests were used to separate means.

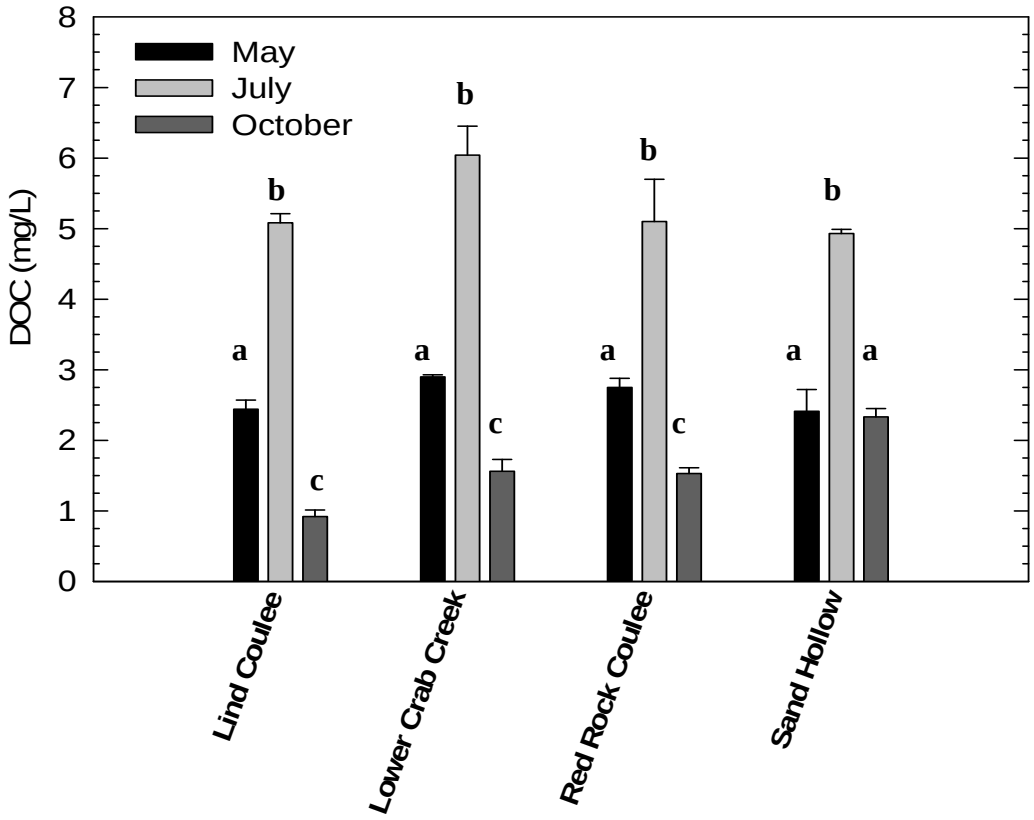


Figure 2. Dissolved organic carbon concentrations in Columbia Basin surface water samples collected from four drainages in May, July and October, 2010. Means with the same letter indicate no statistical difference ($p<0.05$) between seasons for each site; least significant t-tests were used to separate means.

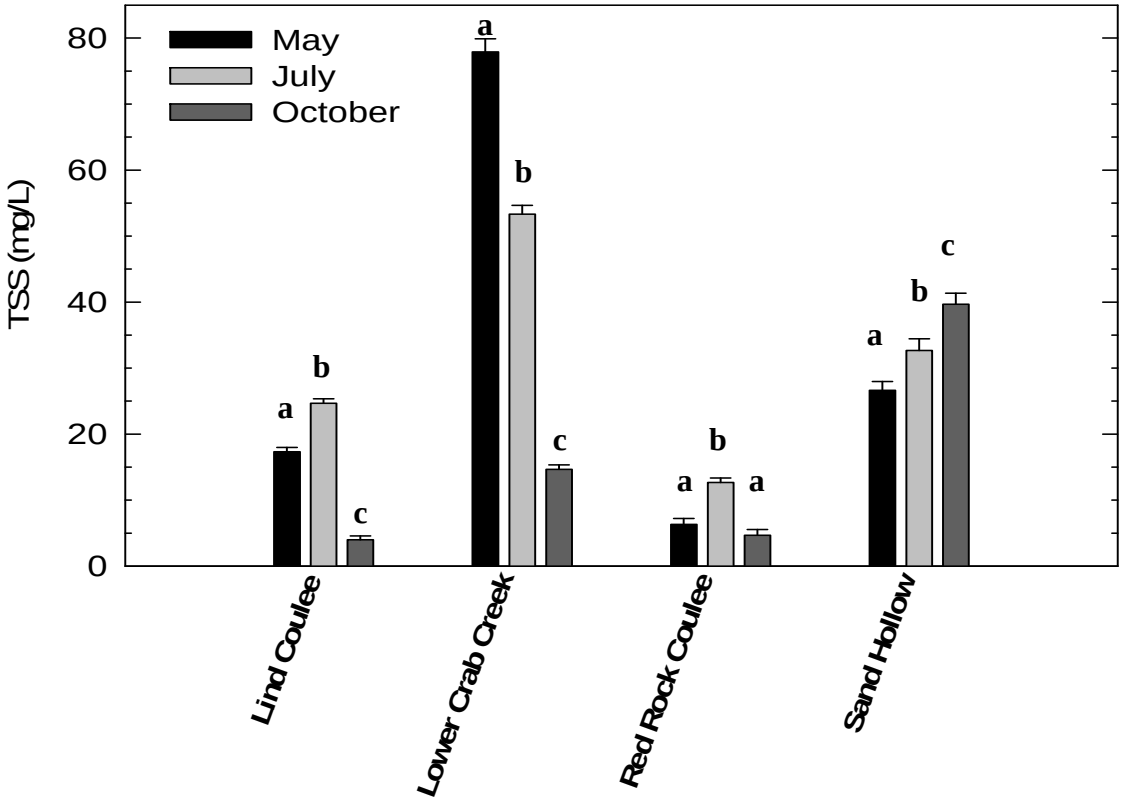


Figure 3. Total suspended solids concentrations in Columbia Basin surface water samples collected from four drainages in May, July and October, 2010. Means with the same letter indicate no statistical difference ($p<0.05$) between seasons for each site; least significant t-tests were used to separate means.

Table 3. SAS parameters for the first-order degradation kinetics of **atrazine** in Columbia Basin surface water samples collected in 2010.

Treatment	May		July		October	
	K (hr^{-1})	R^2	K (hr^{-1})	R^2	K (hr^{-1})	R^2
Control (DI)	0.026*±0.0015[§]	0.98	0.024±0.0011	0.96	0.024±0.0008	0.97
Lind Coulee	0.022±0.0012	0.99	0.021±0.0008	0.97	0.024±0.0006	0.99
Red Rock Coulee	0.026±0.0020	0.97	0.023±0.0008	0.97	0.024±0.0006	0.99
Sand Hollow	0.028±0.0015	0.99	0.038±0.0009	0.99	0.034±0.0006	0.99
Lower Crab Creek	0.015±0.0013	0.96	0.021±0.0013	0.99	0.019±0.0007	0.97

*Linear regressions were performed to calculate first-order rate constants for herbicides degradation using the SAS software package version 9.1
[§] 95% confidence interval

Table 4. SAS parameters for the first-order degradation kinetics of **2,4-D** herbicide in Columbia basin surface water samples collected in 2010.

Treatment	May		July		October	
	K (hr^{-1})	R^2	K (hr^{-1})	R^2	K (hr^{-1})	R^2
Control (DI)	0.029±0.0027	0.98	0.030±0.0009	0.98	0.024±0.0010[§]	0.96
Lind Coulee	0.035±0.0026	0.97	0.039±0.0009	0.99	0.035±0.0007	0.99
Red Rock Coulee	0.055±0.0027	0.99	0.036±0.0007	0.99	0.037±0.0009	0.99
Sand Hollow	0.045±0.0011	0.99	0.054±0.0012	0.99	0.042±0.0016	0.97
Lower Crab Creek	0.028±0.0017	0.98	0.032±0.0014	0.97	0.034±0.0006	0.99

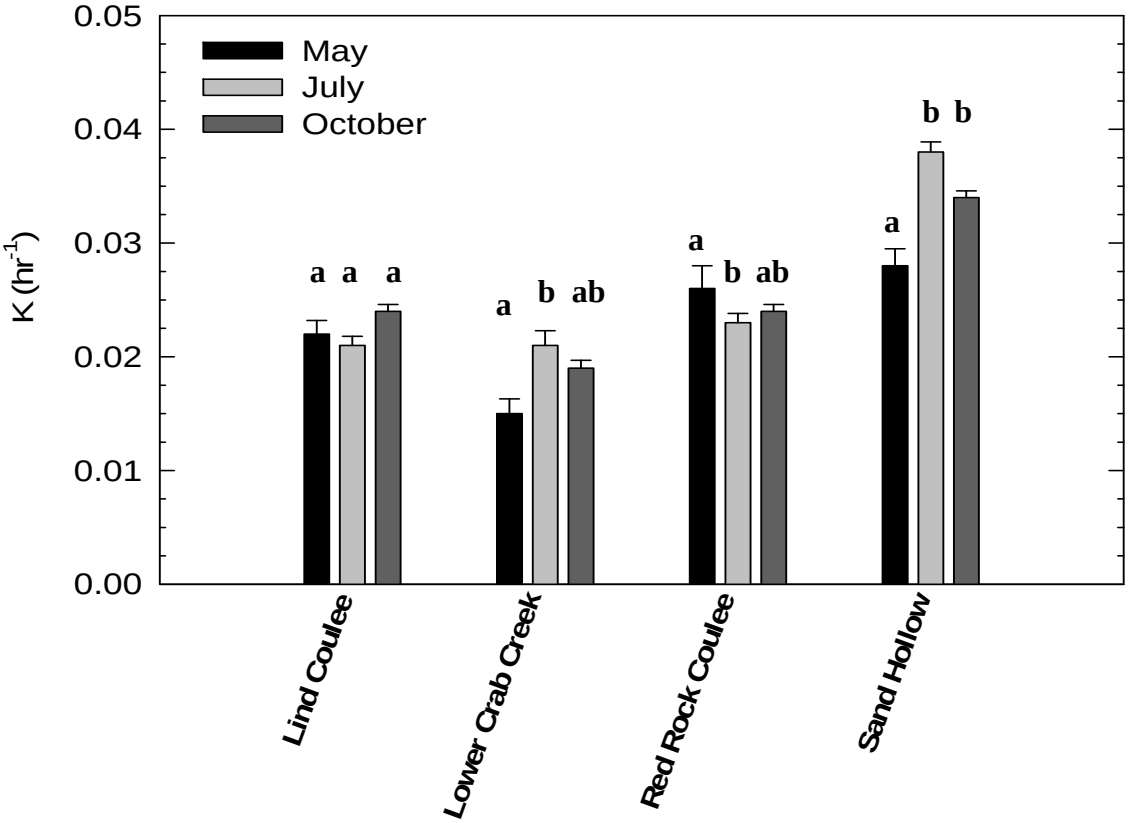


Figure 4. First-order photodegradation kinetics of **atrazine** under simulated solar conditions in Columbia Basin surface water samples collected from four drainages in May, July and October, 2010. Linear regressions were performed to calculate first-order rate constants for herbicides degradation using the SAS software package version 9.1. A contrast test was performed using a general linear model to compare regression coefficients (first-order rate constants for herbicide degradation) across three different seasons.

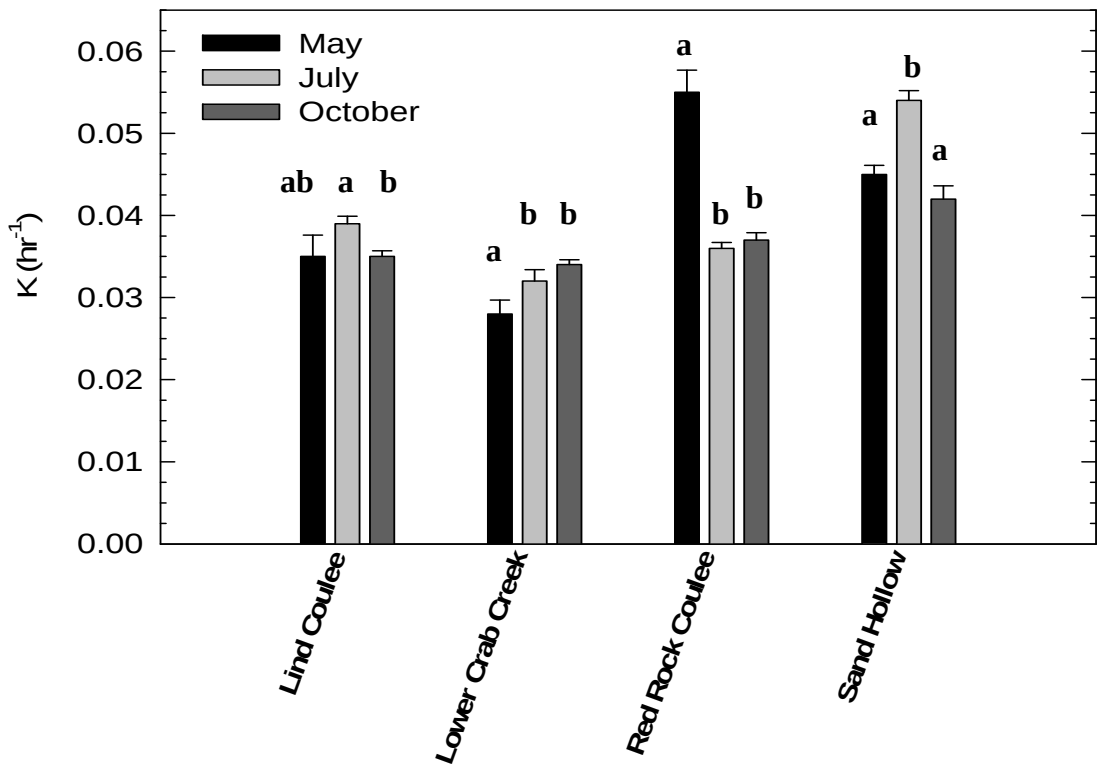


Figure 5. First-order degradation kinetics of **2,4-D** under simulated solar conditions in Columbia Basin surface water samples collected from four drainages in May, July and October, 2010. Linear regressions were performed to calculate first-order rate constants for herbicides degradation using the SAS software package version 9.1. A contrast test was performed using a general linear model to compare regression coefficients (first-order rate constants for herbicide degradation) across three different seasons.

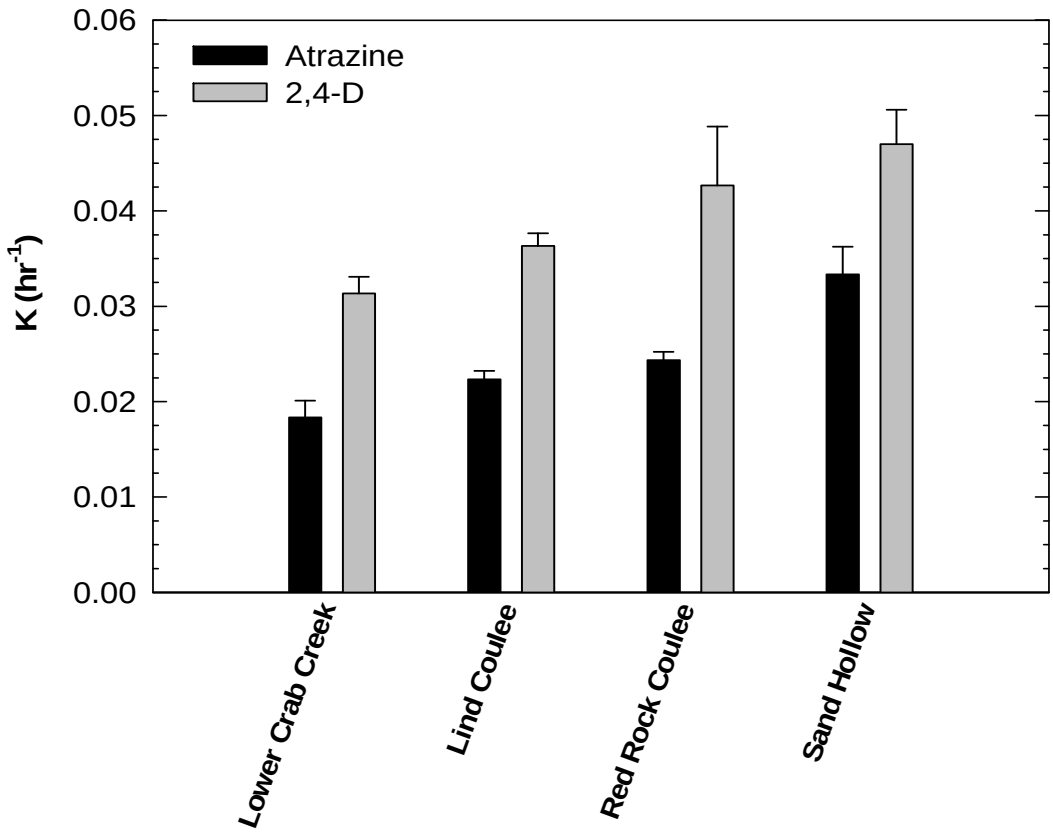
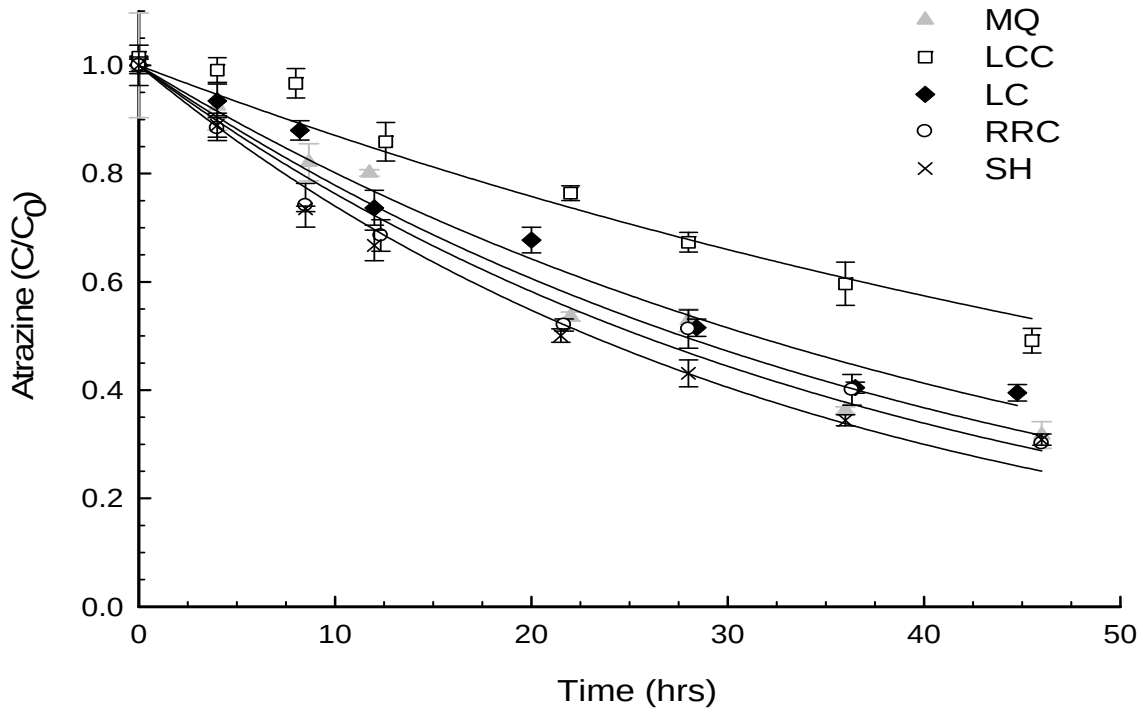
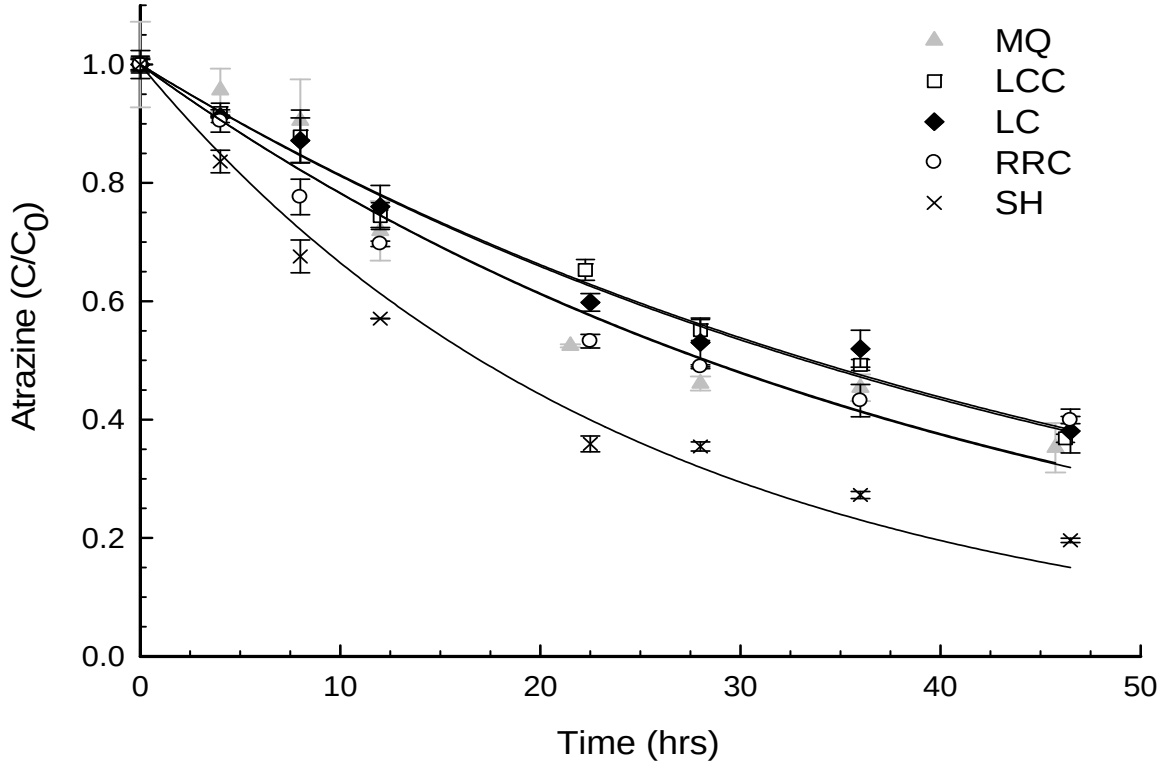


Figure 6. First-order rate constants for **atrazine** and **2,4-D** under simulated solar conditions in Columbia Basin surface water samples collected from four drainages. The first-order rate constants were averaged over irrigation period of May-October, 2010.

(a)


MQ
LCC
LC
RRC
SH
Atrazine (C/C0)
Time (hrs)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50

(b)


MQ
LCC
LC
RRC
SH
Atrazine (C/C0)
Time (hrs)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50

(c)

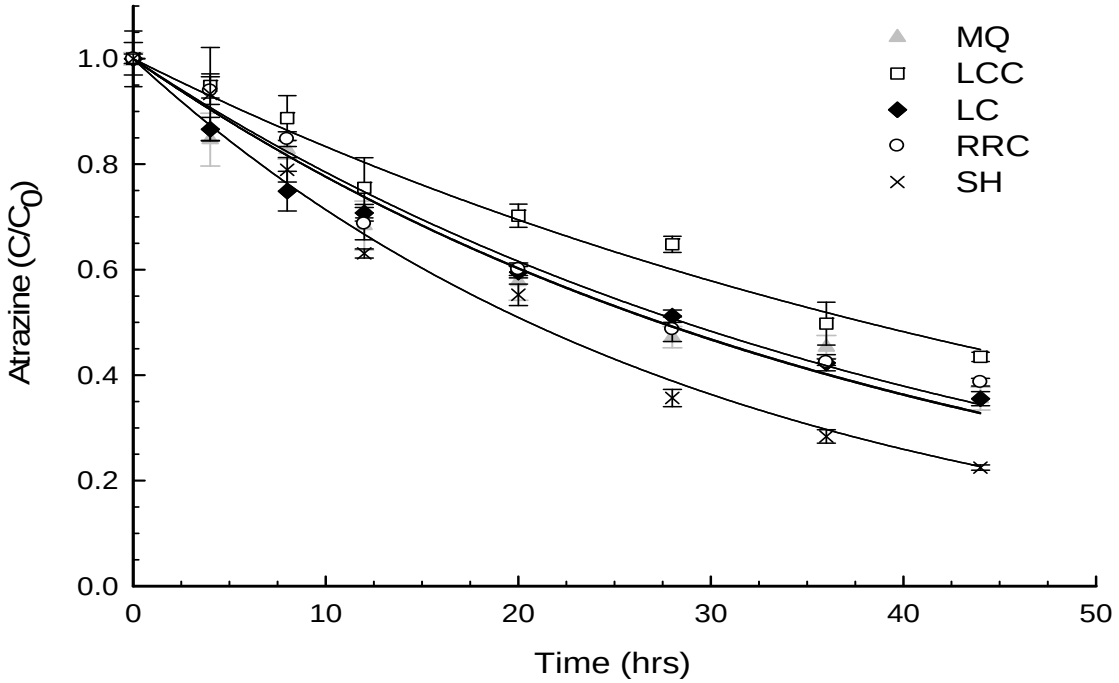


Figure 7. Photodegradation of **atrazine** in Columbia Basin surface water samples collected in a) May, b) July, and c) October, 2010.

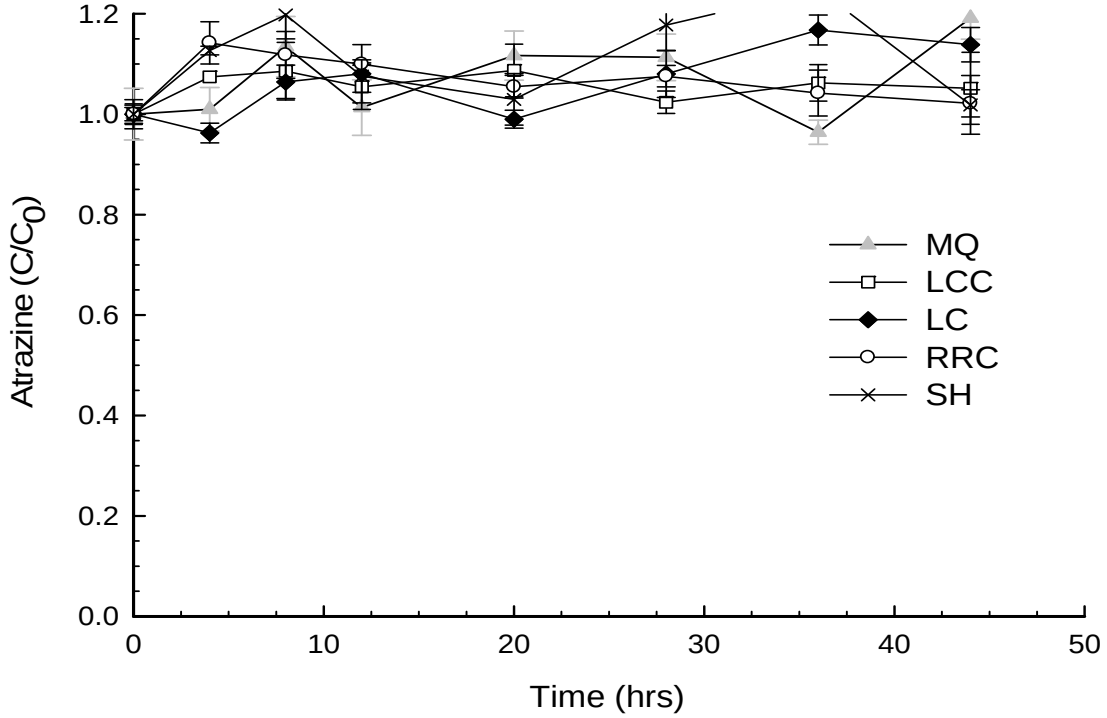
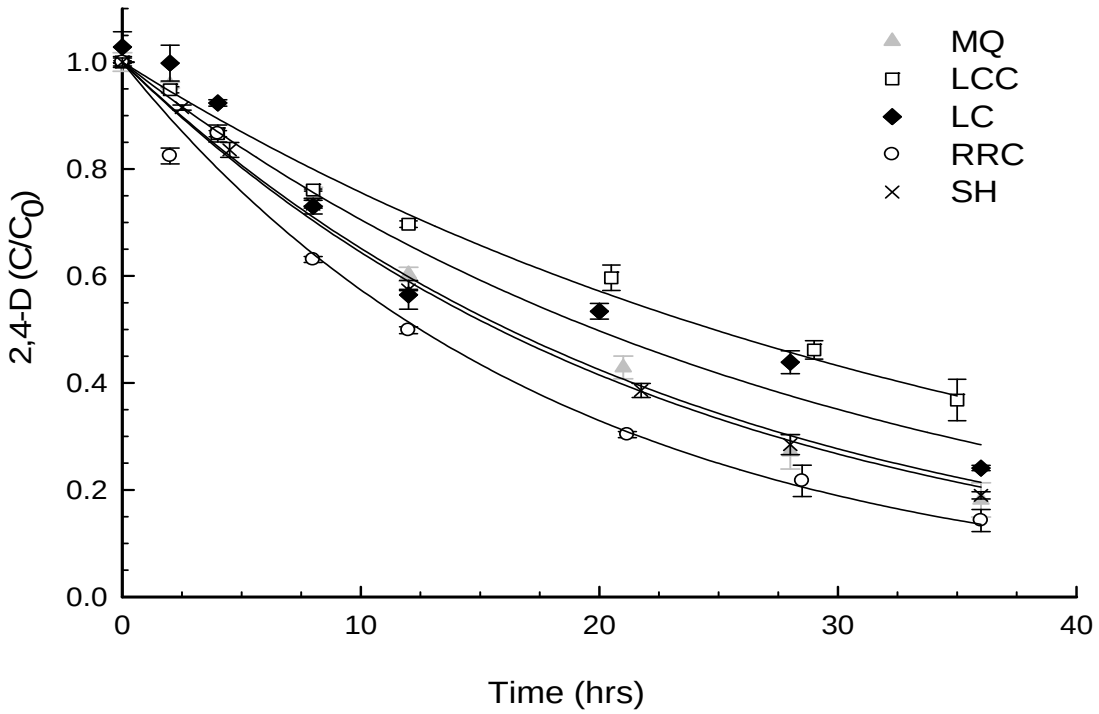
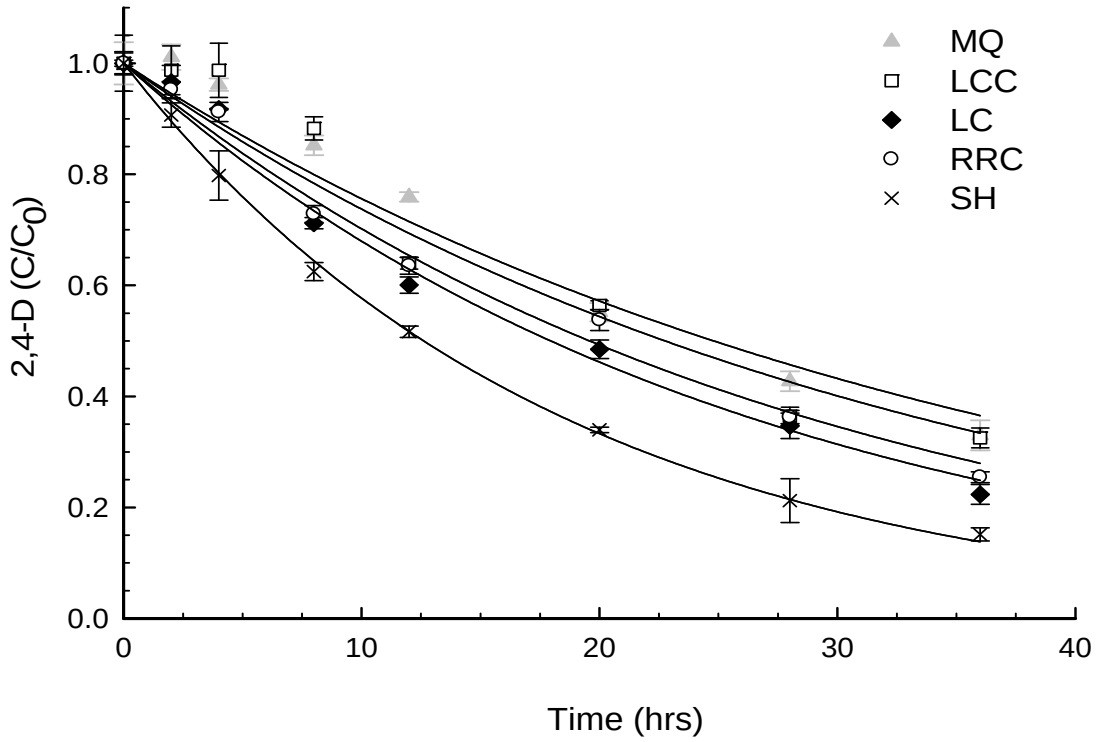


Figure 8. Photodegradation of **atrazine** in Columbia Basin surface water samples in the dark.

(a)


MQ
LCC
LC
RRC
SH
2,4-D (C/C0)
Time (hrs)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40

(b)


MQ
LCC
LC
RRC
SH
2,4-D (C/C0)
Time (hrs)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40

(c)

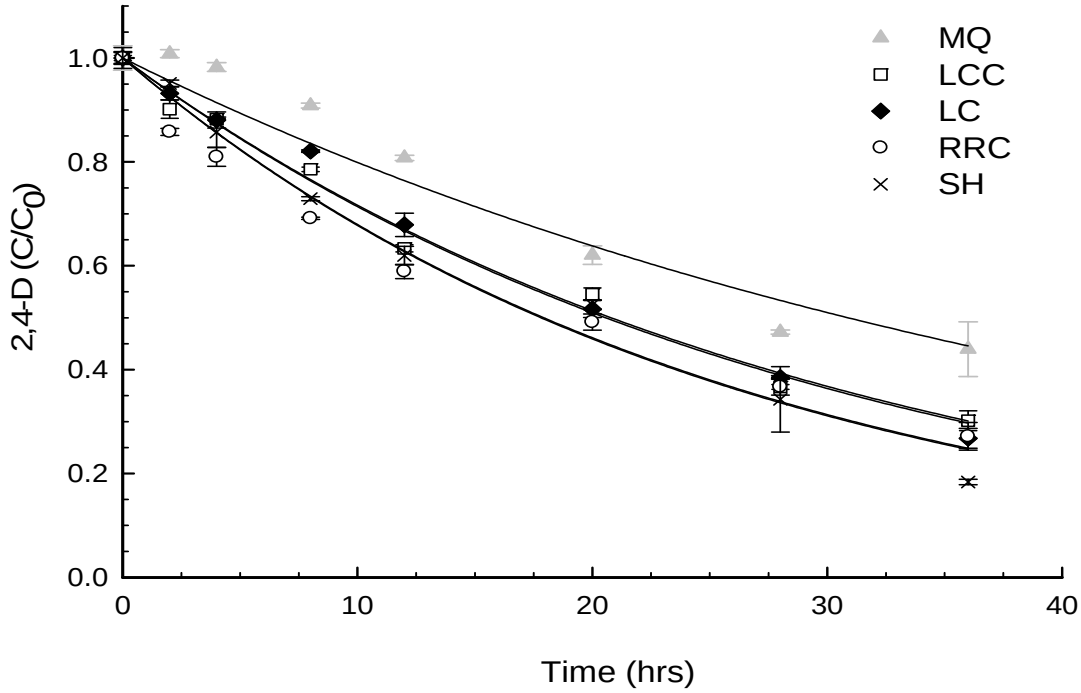


Figure 9. Photodegradation of **2,4-D** in Columbia Basin surface water samples collected in a) May, b) July, and c) October, 2010.

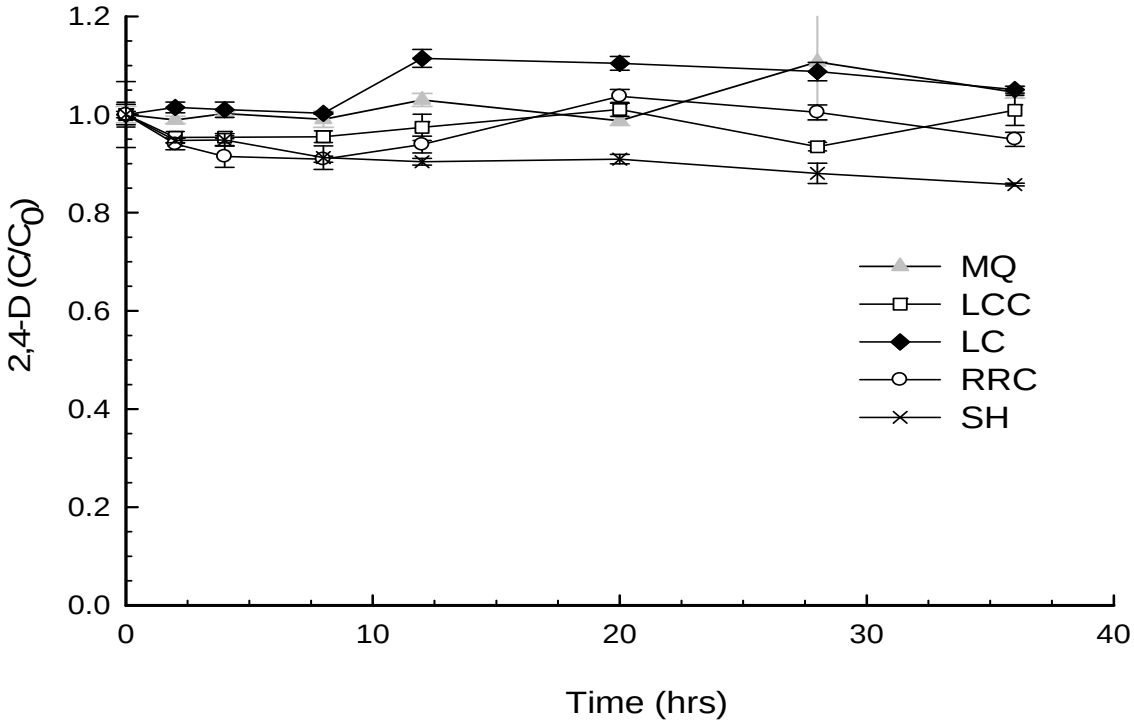


Figure 10. Photodegradation of in **2,4-D** Columbia Basin surface water samples in the dark

Appendix 1a

Comparison between first-order degradation rates for **atrazine** in five waters collected in 2010

May

	Control (MQ)	*Lind Coulee*	*Red Rock Coulee*	*Sand Hollow*	*Lower Crab Creek*
Control (MQ)					
Lind Coulee					
Red Rock Coulee					
Sand Hollow					
Lower Crab Creek					

July

	Control (MQ)	*Lind Coulee*	*Red Rock Coulee*	*Sand Hollow*	*Lower Crab Creek*
Control (MQ)					
Lind Coulee					
Red Rock Coulee					
Sand Hollow					
Lower Crab Creek					

October

	Control (MQ)	*Lind Coulee*	*Red Rock Coulee*	*Sand Hollow*	*Lower Crab Creek*
Control (MQ)					
Lind Coulee					
Red Rock Coulee					
Sand Hollow					
Lower Crab Creek					

Appendix 1b

Comparison between first-order degradation rates for **2,4-D** in five waters collected in 2010

May

	Control (MQ)	***Lind Coulee***	***Red Rock Coulee***	***Sand Hollow***	***Lower Crab Creek***
Control (MQ)					
Lind Coulee					
Red Rock Coulee					
Sand Hollow					
Lower Crab Creek					

July

	Control (MQ)	***Lind Coulee***	***Red Rock Coulee***	***Sand Hollow***	***Lower Crab Creek***
Control (MQ)					
Lind Coulee					
Red Rock Coulee					
Sand Hollow					
Lower Crab Creek					

October

	Control (MQ)	***Lind Coulee***	***Red Rock Coulee***	***Sand Hollow***	***Lower Crab Creek***
Control (MQ)					
Lind Coulee					
Red Rock Coulee					
Sand Hollow					
Lower Crab Creek					

Note: yellow cells show no significant difference across different treatments ($p>0.05$). A contrast test was performed using a general linear model to compare regression coefficients (first-order rate constants for herbicide degradation) across five different treatments.

Understanding the Vulnerability of Columbia Basin Irrigated Agriculture to Predicted Climate Changes using a Coupled Hydrological-crop Model

Basic Information

Title:	Understanding the Vulnerability of Columbia Basin Irrigated Agriculture to Predicted Climate Changes using a Coupled Hydrological-crop Model
Project Number:	2010WA317B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	Washington 5
Research Category:	Climate and Hydrologic Processes
Focus Category:	Water Quantity, Climatological Processes, Agriculture
Descriptors:	
Principal Investigators:	Jennifer Adam, Fok-Yan Thomas Leung, Claudio Stockle

Publications

1. Chinnayakanahalli, K.J., J.C. Adam, C.O. Stöckle, and R.L. Nelson, A Coupled Hydrological and Process-Based Crop Dynamics Model for Studying Climate Change Impacts on Water Resources and Agricultural Production. (In preparation)
2. Malek, K., et al., Effects of Climate Change on Yakima River Basin Agriculture. (In preparation)
3. Rajagopalan, K., K.J. Chinnayakanahalli, J.C. Adam, C.O. Stöckle, and M. Barber, Assessing the Impact of Climate Change on Irrigation Demand, Water Availability and Cropping Patterns in the Columbia River Basin. (In preparation)
4. Dinesh, S. T., Climate Change Impacts on Water Rights Modeling, PhD Dissertation, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA. (In preparation)
5. Chinnayakanahalli, K.J., J.C. Adam, C. Stockle, R. Nelson, and M.E. Barber, 2010, A Coupled Hydrological and Process-Based Crop Dynamics Model for Studying Climate Change Impacts on Water resources and Agricultural Production, AGU Fall Meeting Abstracts, San Francisco, CA, Dec. 13-17.
6. Chinnayakanahalli, K.J., J.C. Adam, C. Stockle, R. Nelson, and M.E. Barber, 2010, A Coupled Hydrological and Process-Based Crop Dynamics Model for Studying Climate Change Impacts on Agriculture and Water Resources, WSU Water Forum, Spokane, WA, Nov. 4-5.
7. Adam, J.C., K.J. Chinnayakanahalli, C. Stockle, and M.E. Barber, 2010, Climate Change Impacts on Water Supply and Irrigation Water Demand in the Columbia River Basin, UCOWR/NIWR Annual Conference, Seattle, WA, Jul. 13-15.

1 Introduction

1.1 Background

The Columbia River Basin (CRB) that drains the major portion of Pacific Northwest (PNW) is the fourth largest river in US in terms of discharge (Krammerer, 1990), and drains 265 thousand square miles of area covering seven states of US and the province of British Columbia, Canada (Figure 1.1). Historically, the abundance of water in the CRB has led to extensive development over the last 60 years in PNW (Hamlet and Lettenmaier, 1999) and has enabled CRB to sustain myriad human and natural interests-namely hydroelectric power, agriculture, navigation, fish stocks, recreation (Bonneville Power Administration et al., 2001), municipal and industrial use. However, the ability of the CRB to meet future water demands in the PNW region is predicted to be reduced under a changing climate (Elsner et al., 2010)

The hydrological cycle of the western United States is expected to be significantly affected by climate change (IPCC 2007). Vast areas of the Pacific Northwest (PNW) are likely to experience decreased snowpack, increased winter flooding, and reduced summer flows (Elsner et al. 2009, Hamlet and Lettenmaier 2007). Agricultural production is also anticipated to be impacted by climate change (Stockle et al. 2009) and to face challenges in areas that depend on highly used water resources.

Agriculture is a vital part of the economy in the PNW. In 2008, wheat production accounted for $1.7 billion, the third largest value in the United States (USDA-NASS, 2009). The eastern side of the Cascade Mountains, which receives only 5-25” of rain annually, is particularly vulnerable to drought. In the last decade, there have been 10-20% yield losses during severe drought years, with an average of $90 million/year (USDA-NASS, 2009). This water-poor region is sensitive to potential changes in the regional hydrological cycle associated with global climate change.

The ultimate challenge is to anticipate the probable effects of climate change on the hydrological cycle and make sound land use, water use, and agricultural management decisions that will promote the sustainability of PNW irrigated agriculture while protecting water supply for other uses (such as instream flows, hydropower, and municipal needs) and water quality. The immediate challenge is to assess the vulnerability of both surface water supply and agricultural production to projected climate change and to educate water resource and agriculture stakeholder groups on the potential range of impacts.

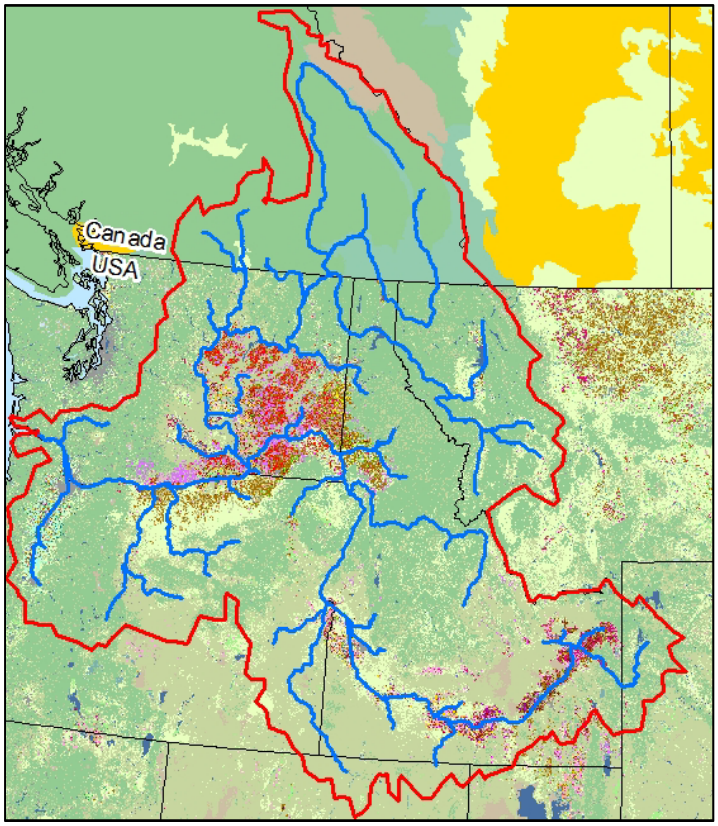


Figure 1.1. Our study domain is the Columbia River Basin (red boundary).

1.2 Objectives

Our long-term goal is to develop a system of decision support tools that would allow PNW agricultural producers, water resource managers, and policy makers to anticipate the effects of climate change and to optimize water and land management practices and produce regulations accordingly. The overall objective of this project is to create maps over the CRB showing the range of changes in surface water availability and irrigated crop yield due to projected climate changes by the year 2040.

The specific objectives of this project are to:

1) Determine the range of uncertainty in future CRB climate

We applied statistically-downscaled results from Global General Circulation Model (GCM) simulations of future climates in 2040 (a common benchmark year) to evaluate the impacts of climate change on CRB hydrology. Two emissions scenarios and ten Global Climate Models (GCMs) were used to estimate the uncertainty in future greenhouse gas emissions.

2) Evaluation of a regional-scale coupled hydrological and crop model for the CRB

We are evaluating the capability of dynamically-linked hydrology and crop growth models to reproduce historical crop yield estimates for each county located within the CRB.

3) Produce interactive GIS maps showing the range of climate change impacts on surface water availability and crop yield

The coupled hydrology/crop model is being applied to the CRB for each of the projected future climate change scenarios. The data are being used to develop a set of interactive Geographical Information System (GIS) maps that will be distributed to stakeholder groups to understand the vulnerability of surface water and irrigated agriculture to climate change.

4) Communicate results

We are using our contacts through WSU Extension to organize and perform an outreach effort to disseminate the maps and to educate the stakeholder groups as to their use and importance.

2 Methods

2.1 Modeling Framework

2.1.1 Overview of the Modeling Framework

This section provides an overview of the biophysical modeling framework of this project (Figure 2.1). The coupled model VIC-CropSyst uses climate and crop distribution data (WSDA/USDA) to model the different components of hydrology (runoff, baseflow, etc…) and crop phenology (crop transpiration, yield, biomass etc) for each grid cell (1/16th degree or ~ 40 km^2). Runoff and baseflow from grid cells are routed through the stream network to obtain streamflow hydrographs at any point of interest on the network. Streamflows are used as input to a reservoir system model, ColSim, to account for irrigation and other withdrawals.

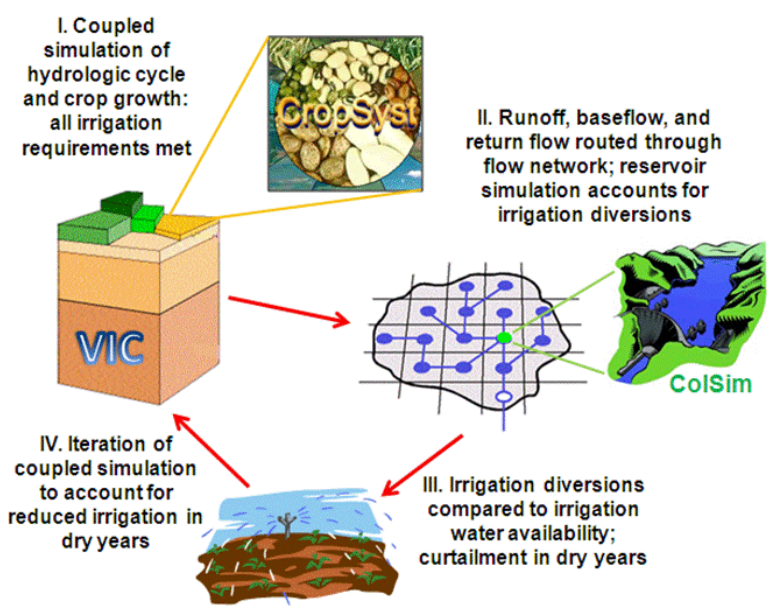


Figure 2.1. Biophysical modeling framework.

In the first iteration, crops water demand was fully satisfied (full irrigation) and the irrigation water amounts were tracked. The output from ColSim when compared with the irrigation diversions quantifies the available water for irrigation. The VIC-CropSyst model was executed again but with reduced irrigation based on the available water to obtain the crop yield under reduced irrigation.

The reduced irrigation availability (due to curtailment and physical water constraints) as well as the crop yields from VIC-CropSyst under reduced irrigation can be given as inputs to economic modeling (not described in this report) to determine the short-term and long-term adaptations of agricultural producers.

2.1.2 Descriptions of Individual Models

2.1.2.1 Variable Infiltration Capacity (VIC) Hydrology Model

The VIC model uses physically based mathematical formulations to calculate energy and water balance components. A model is termed physically-based when its parameters, in principle, can be observed and measured. The VIC model uses meteorological forcing data (daily minimum and maximum temperature, precipitation and wind speed), soil, terrain and land cover inputs to compute energy (e.g., latent and sensible heat) and water balance (e.g., surface runoff, infiltration and baseflow) components. The VIC model is run at a grid cell scale and uses the time-before–space conceptualization; i.e., the entire period of simulation is executed for a grid cell before moving to the neighboring grid cell. The VIC model saves the time series of runoff and baseflow generated at each grid cell. A separate routing model (see Lohmann et al., 1998) then performs the streamflow routing as an off-line process after all the grid cells in the basin are executed by VIC. A more detailed description of the latest VIC model is described by Gao et al. (2010).

The VIC model (Liang et al., 1994; 1996) has been widely used to study regional hydrology of the North America (Christensen et al., 2004; Vanrheenen et al., 2004; Hayhoe et al., 2007; Maurer, 2007). More specifically VIC has been implemented to assess the climate change impacts over the CRB (Hamlet and Lettenmaier, 1999; Payne et al., 2004; Elsner et al., 2010) for different Intergovernmental Panel on Climate Change (IPCC) future scenarios (1995, 2001 and 2007).

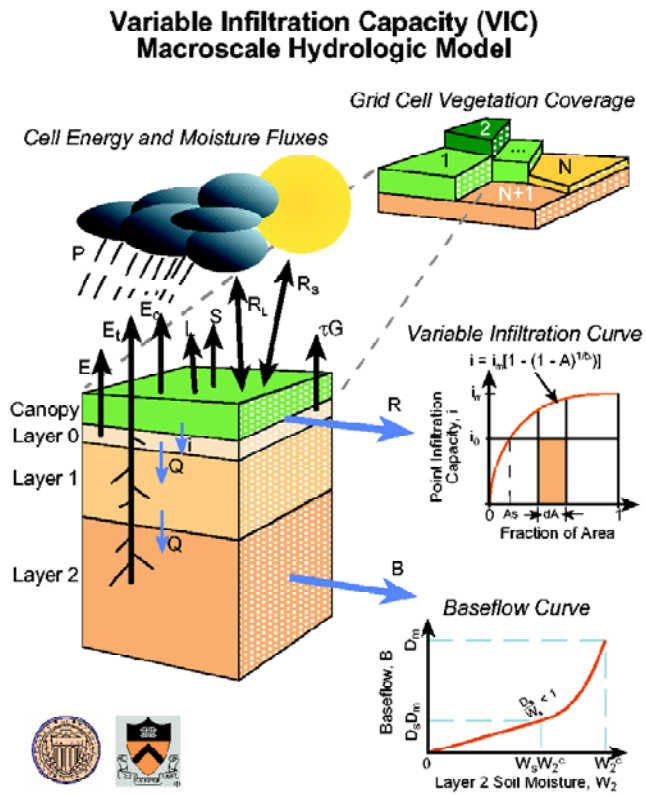


Figure 2.2. Overview of the VIC model.

2.1.2.2 Cropping Systems Model- CropSyst

To provide crop simulation capabilities, the CropSyst model, developed and maintained by one of the Co-PIs in this project is being used (Stöckle et al., 1994; Stöckle et al., 2003). CropSyst is a cropping systems model based on mechanistic principles, allowing for applications to a large number of crops in any world location. CropSyst is a multi-year, multi-crop model developed to serve as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity, nutrient cycling and fate, and the environment. Management options include crop rotation, cultivar selection, irrigation, nitrogen fertilization, tillage operations, and residue management. Depending on the process, CropSyst calculations are made at hourly or daily time steps. For this project, a simplified version of CropSyst that focus on water use and productivity was extracted for coupling with the VIC model.

CropSyst has been evaluated and used in the PNW (e.g., Pannkuk et al., 1998; Peralta and Stöckle, 2002; Marcos, 1997; Marcos, 2000; Stöckle and Jara, 1998; Kemanian, 2003; Kemanian et al., 2007) and in many other locations worldwide (e.g., Stöckle et al., 2003; Sadras, 2004; Pala et al., 1996; Benli et al., 2007; Todorovic et al., 2009). In addition to capabilities to evaluate cropping systems, carbon sequestration dynamics and greenhouse gas emissions (e.g., Badini et

al., 2007, Stockle et al., 2010a, Kemanian and Stöckle, 2010), CropSyst was recently enhanced to assess the effect of climate change on agricultural systems, particularly regarding plant responses to increasing warming and atmospheric carbon dioxide. These capabilities were utilized to assess the impact of climate change on agriculture in eastern Washington (Stöckle et al., 2010b), and to assess the potential for carbon sequestration and carbon credits in the same region (Stöckle et al., 2010a; Zaher et al., 2010).

2.1.2.3 Columbia Reservoirs System Model- ColSim

Reservoir operations will be simulated using the Columbia River Simulation Model (ColSim) which considers the physical characteristics of the CRB water management system (reservoirs, run-of-river dams, diversions, and return flows) and its reservoir operating policies (Hamlet and Lettenmaier 1999). ColSim generates a set of reservoir rule curves as a function of operating policy for the following objectives: flood control, hydropower, instream flow targets for fish, agricultural withdrawals, and recreation.

2.1.3 Coupling VIC and CropSyst

The two physically based models were integrated so as to enable seamless running of the coupled VIC-CropSyst model for all of the selected crops across the CRB. The land cover distribution within a grid cell controls when the crop model is invoked within the VIC model. Figure 2.3 shows an example of the land cover distribution in a grid cell. Note that VIC does not recognize the geographical location of a land cover type within a grid cell. It only knows that there are so many land- cover types and their proportion within the grid cell. For this example, traditional VIC would be run once for the non-crop type land-cover and CropSysyt will be invoked twice for simulating the crop growth for two different crops. The fluxes generated from the three sub-grid run would be aggregated based on their land-cover proportions in the grid cell.

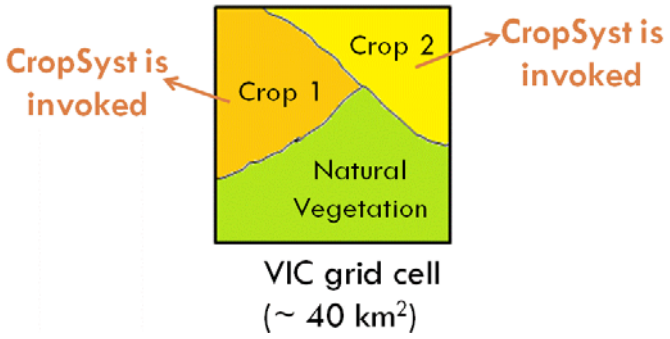


Figure 2.3. An illustration of land-cover distribution in a VIC grid cell.

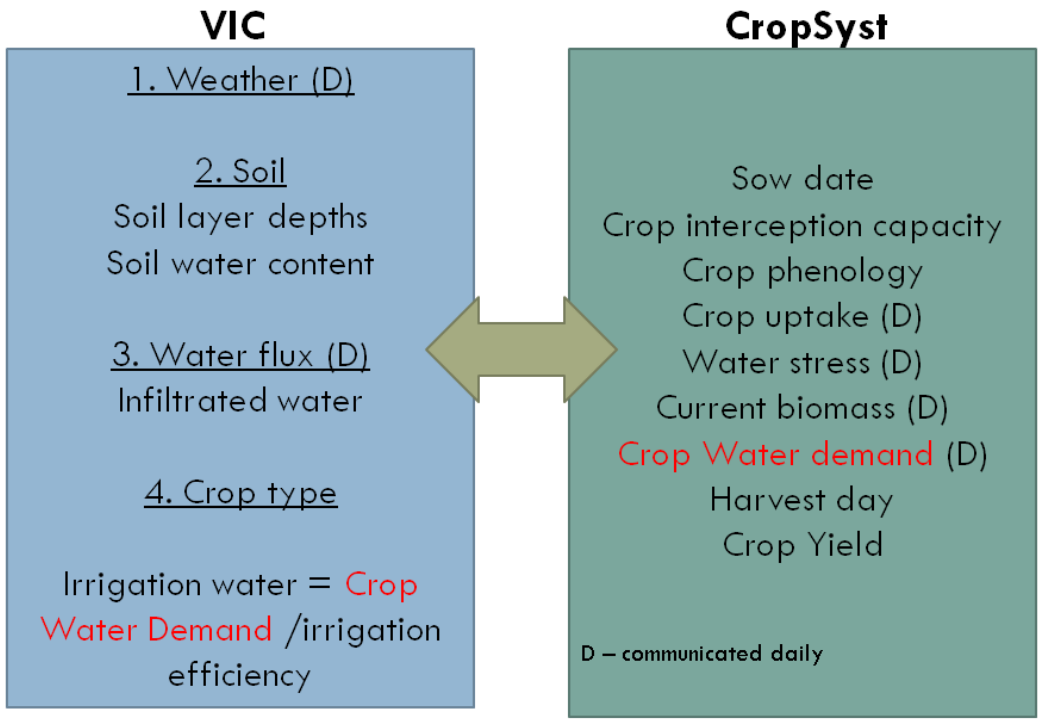


Figure 2.4. Variables communicated between VIC and Cropsyst models.

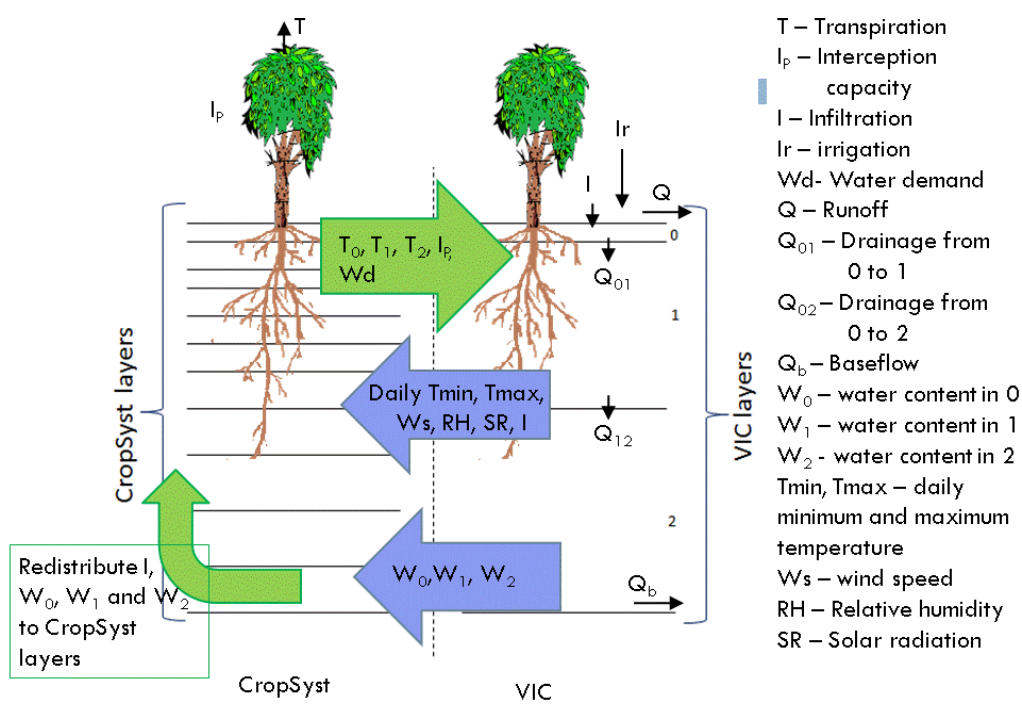


Figure 2.5. The schematic of VIC-CropSyst integration.

Figure 2.4 shows the group of variables that are communicated between VIC and the CropSyst models when CropSyst is invoked for each crop land-cover type. Figure 2.5 illustrates the overall interaction between the two models. When the model encounters a crop land-cover type in a grid cell, communication between the two models is initiated. On the first day of the simulation, VIC communicates to CropSyst the crop type and soil characteristics (such as soil texture, density, and porosity). For all time steps, the weather information such as daily minimum and maximum temperature, wind speed, solar radiation and relative humidity, is passed on to the CropSyst model. Based on the daily temperatures data, the CropSyst model looks for an appropriate sowing day for each crop. This day can differ from crop to crop, based on the optimum accumulated number of degree days required by the crop. When an appropriate sowing day is found, the CropSyst model indicates to the VIC model that crop growth has begun. On the sowing day, VIC passes the soil water content information from different VIC soil layers to CropSyst. This information is then not exchanged between the models until the next sowing date the following year.

One of the main differences between VIC and CropSyst hydrology is in the way they characterize their subsurface profile. VIC is usually run with three soil layers while CropSyst has many more depending on the depth of the soil (see Figure 2.5). For the rest of the growing season, each model does its own subsurface drainage but the CropSyst model communicates back to VIC the transpiration or the water uptake such that VIC soil moisture can also be updated. Transpiration is a function of the crop's growth stage and the weather conditions. The transpiration amounts are used by the VIC to update its soil water contents thereby closing the water balance loop. This also influences the drainage pattern in VIC and hence the baseflow generation (which always occurs from the bottom soil moisture layer).

The interception potential provided by CropSyst is used by VIC to estimate the interception water amount during a precipitation event. The water infiltrating into the soil layer is based on the variable infiltration framework of VIC and passed on to CropSyst. This amount is used by the CropSyst model to update its corresponding soil water contents.

At each time step, CropSyst determines the water stress and the need for irrigation. The VIC model then adds the required irrigation water amount to the top of the soil layer. The VIC model uses efficiency of the irrigation system employed for that crop in that grid cell to add the appropriate amount of water to the soil.

When the crop reaches maturity, CropSyst harvests the crop and communicates back to VIC the crop yield. CropSyst also sends back variables such as current growth stage and biomass of the crop. Comparison of harvest day and day of emergence determines the length of the growing season for each crop.

2.2 Data

2.2.1 Historical and Future Meteorological Data

Most of the previous implementations of VIC in the US (e.g., Maurer et al. 2002) have used a 1/8th degree latitude/longitude resolution. For this study, VIC runs were performed at a more refined 1/16th degree latitude/longitude spatial resolution at a daily time scale (as developed by Elsner et al. 2010). The finer spatial scale better resolves the smaller basin within the CRB. For running VIC at this resolution, spatially and temporally corresponding distributed meteorological data for both historical and future climate scenarios were needed. The Climate Impact Group (CIG) at the University of Washington (UW) has created such datasets for studying the climate change scenarios in the PNW (Hamlet et al., 2010).

Hamlet et al. (2010) extended the work of Hamlet and Lettenmaier (2005) to grid the National Climatic Data Center (NCDC) Cooperative Observer (COOP) network and Environment Canada (EC) station data to produce daily time series of minimum and maximum temperature, precipitation and wind speed at 1/16th degree spatial resolution for the period 1915- 2006. Monthly precipitation was rescaled for orographic effects based on the Precipitation Regression on Independent Slopes Model (PRISM; Daly et al., 1994). This dataset was used in this project to drive VIC-CropSyst for the historical period 1970-2000. Further details on creation of these historical meteorological data can be found in Chapter 3 of Hamlet et al. (2010).

Nakicenovic and Swart (2000) describe 40 greenhouse gas emission scenarios that were used in the Atmosphere-Ocean General Circulation Model (AOGCM; a.k.a. GCM) simulations used in the Intergovernmental Panel on Climate Change (IPCC) reports. These scenarios are grouped within four narrative storylines which are meant to represent plausible alternative futures based on projections of trends in population, economic and social development, energy and technology, and land use. They assume that no climate policies are implemented, such as carbon trading or taxes. Three of these scenarios are typically used to represent high, mid, and low emissions and are designated by the IPCC as A2, A1B, and B1, respectively. A1B and B1 are currently the most commonly-applied scenarios over the PNW.

For the IPCC Fourth Assessment Report (AR4), these emissions scenarios were used to force 23 AOGCMs, as described by Randall et al. (2007). Uncertainty in the response of each AOGCM arises from the effects of internal variability (which is minimized by taking a climatological average of a 20-30 year period) and by the uncertainty in model structure, which is due to the discretization of the equations of the equations of motion and the parameterization of sub-grid scale processes (Meehl et al. 2007). Running a large number of AOGCMs all forced with the

same input parameters and emissions scenarios is called a multi-model ensemble and is used to diagnose the uncertainty in predicted climate due to AOGCM response.

The climate variables of interest to this project are mid-21st century daily and monthly precipitation and temperature at a 1/16th degree resolution over the CRB. The uncertainty in the climate projections due to greenhouse gas emissions will be assessed by considering two emissions scenarios, A1B (higher) and B1 (lower); whereas the uncertainty due to AOGCM response will be assessed by multi-model ensemble for ten of the IPCC AR4 models that have archived results for any of the A1B and B1 scenarios. The IPCC AOGCM simulations are described by Randall et al. (2007) and archived by the Program for Climate Model Diagnostics and Intercomparisons (PCMDI).

Typically, AOGCM simulations are performed on a 4°x5° or 2°x2.5° grid. Downscaling AOGCM results to a finer grid resolution (1/16th ° in our application) is necessary for them to be useful at regional and local scales. We will apply a recent adaptation of the Bias Correction Statistical Downscaling method (BCSD; Wood et al. 2004) in which AOGCM-simulated climate is bias corrected using an empirically-based method that maps the probability density functions of the monthly AOGCM precipitation and temperature onto the historical gridded climate observations which have been aggregated to the scale of the AOGCM prior to downscaling. An adaptation, recently developed by Alan Hamlet at the University of Washington and termed the "hybrid" method, combines this bias correction technique with the non-transient "delta change" method (e.g., Hamlet and Lettenmaier 1999) such that a distribution of possible year 2040 climate realizations are created (rather than an evolution of climate state between now and 2040).

2.2.2 Crop Data

2.2.2.1 Crop Land Data Layer

The land cover and its parameterization are important drivers of evapotransipiration, interception, infiltration and the runoff components of the hydrologic cycle. Hamlet et al. (2010) used land cover classification derived from Maurer et al. (2002) for running the VIC model over the PNW (Figure 2.6). The land use classification generally used by VIC has only one class categorized as crop land and is parameterized as corn. For building the ability to simulate different crop mixes under the VIC-CropSyst framework, we extended the VIC land use data to include a full range of crop types (Table 2.1).

Table 2.1. The crops selected for simulation by VIC-CropSyst.

Main crops		**Generic vegetables**	**Other pastures**	**Lentil/Wheat type**	**Berries**	**Other Fruit trees**
Winter Wheat	Lentil	Onions	Grass hay	Oats	Caneberry	Pear
Spring Wheat	Mint	Asparagus	Bluegrass	Bean, green	Blueberry	Peaches
Alfalfa	Hops	Carrots	Hay	Rye	Cranberry	
Barley	Grape, Juice	Squash	Rye grass	Barley		
Potato	Grape, Wine	Garlic		Bean, dry		
Corn	Pea, Green	Spinach		Bean, green		
Corn, Sweet	Pea, Dry					
Pasture	Sugarbeet					
Apple	Canola					
Cherry						

The crop distribution in the CRB and within VIC grid cells were derived from two data sources: (1) the 2008 crop land data from Washington State Department of Agriculture (WSDA) for grid cells within Washington, and (2) from the 2009 United States Department of Agriculture (USDA) cropland data layer for grid cells outside of Washington (Figure 2.7). Both the WSDA and USDA datasets have information at the field scale which is fine compared to the VIC grid cell resolution. Due to this, crops grown only in a small proportion (defined as 1%) of the VIC grid cell area are selected for simulation. This reduces the number of crops per VIC grid cell and, therefore, the computational time for simulations.

One of the main reasons for using the WSDA dataset within Washington was the additional information on irrigation management that was available with this dataset. The WSDA dataset has spatial information about whether a particular crop was irrigated or not, and the crop specific irrigation system used across the state. This was important for considering irrigation losses due to different irrigational methods. However, for crops outside Washington, we do not have such information and rely on simple rules based on the type of crop and the grid cell annual precipitation to decide if a crop is irrigated or not. Based on this rule, high value crops such as apples, grapes, and potatoes are always irrigated and the other crops such as spring and winter wheat are irrigated only if the annual average precipitation of that grid cell is less than 200 mm.

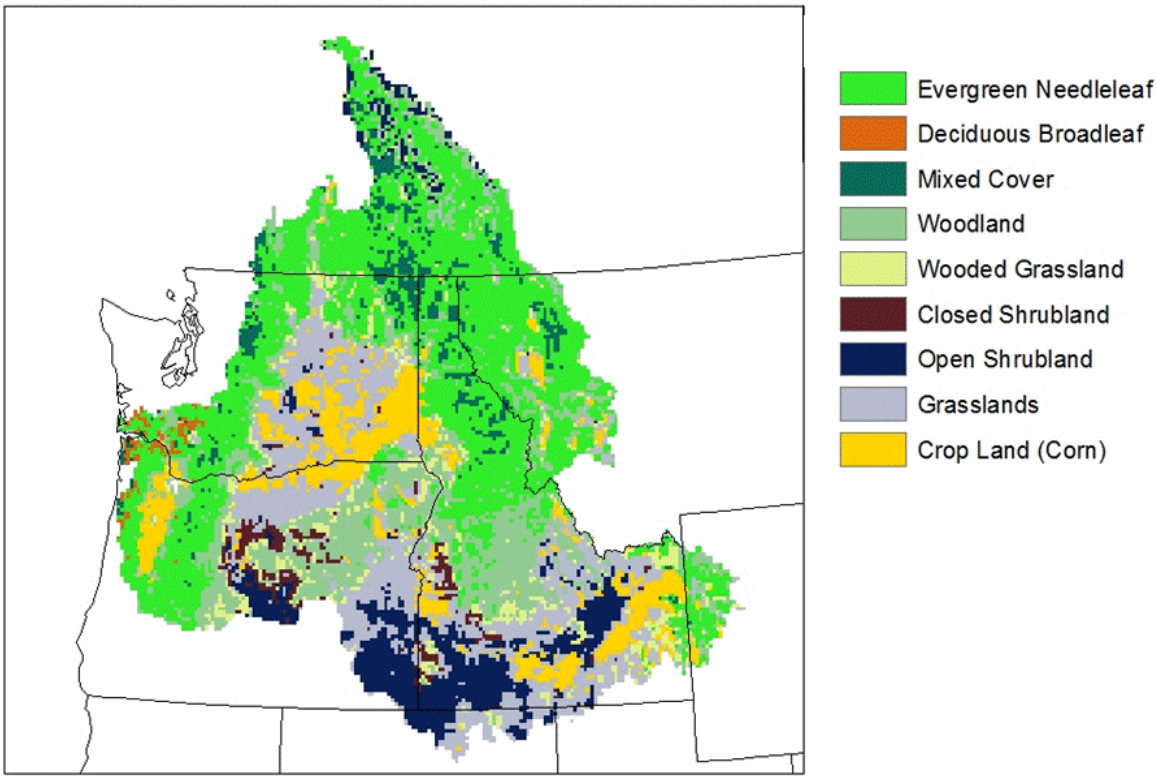


Figure 2.6. Traditional VIC land cover characterization.

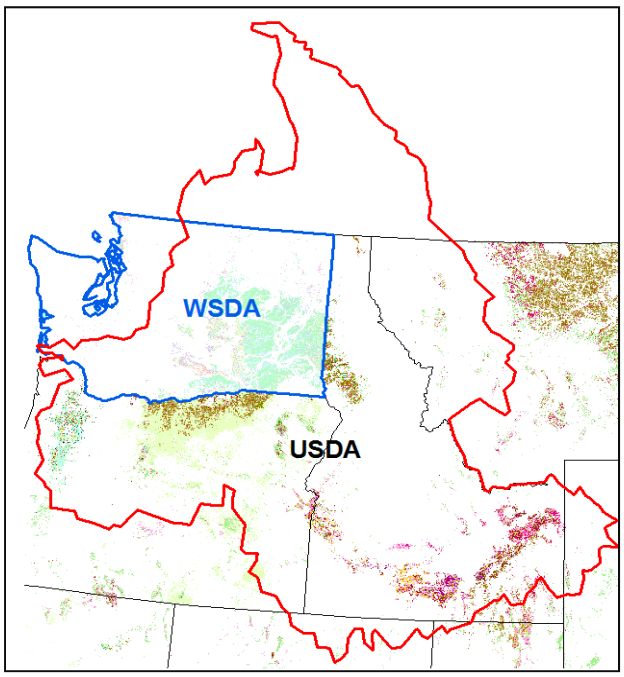


Figure 2.7. Crop land use from WSDA (for Washington State) and USDA (for the rest of CRB) datasets. No crops are simulated in the Canadian portion of the CRB.

2.2.2.2 Crop Parameterization

In addition to land cover related crop inputs, the VIC-CropSyst model also requires crop specific parameters which vary spatially. Crop specific parameters were compiled based on Co-PI Stockle's experience with running CropSyst in the CRB and this process created one input file for each crop being simulated. These crop parameter files have information such as different temperature thresholds for attaining growth stages, root depth at emergence, etc.

2.2.3 Water Rights Data in Washington State

The Washington Department of Ecology provided us their water rights database. The database has information related to the water right priority date, purpose of use, appropriated water amount, point of withdrawal/diversions and the place of use of the water right. We decided to use this information in two different ways in our modeling effort. The first was to get a split between surface and ground water use at the VIC grid cell level and the second was to model the curtailment process of water rights.

2.2.3.1 Split of Surface Water and Ground Water Allocation

We use information related to the place of use of a water right to get a spatial distribution of ground water rights and spatial water rights. This information was used to get a split between ground water and surface water allocations at a VIC grid cell resolution. VIC-Cropsyst used this information to decide how much of the irrigation demand will be supplied by surface water and how much by ground water. Figures 2.8 and 2.9 show the distributions of surface versus groundwater rights in Washington.

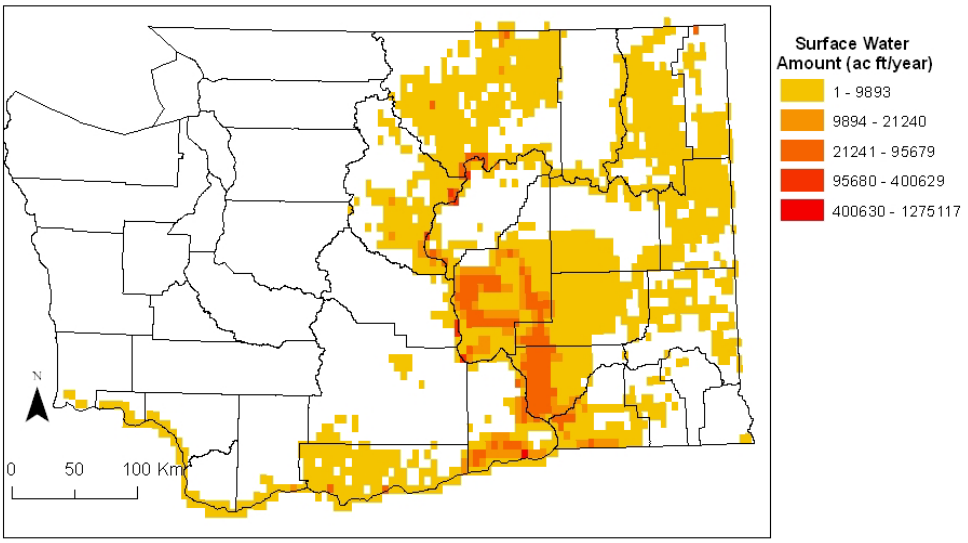


Figure 2.8. Surface water amount (acre feet per year). This accounts for approximately 9 million acre feet.

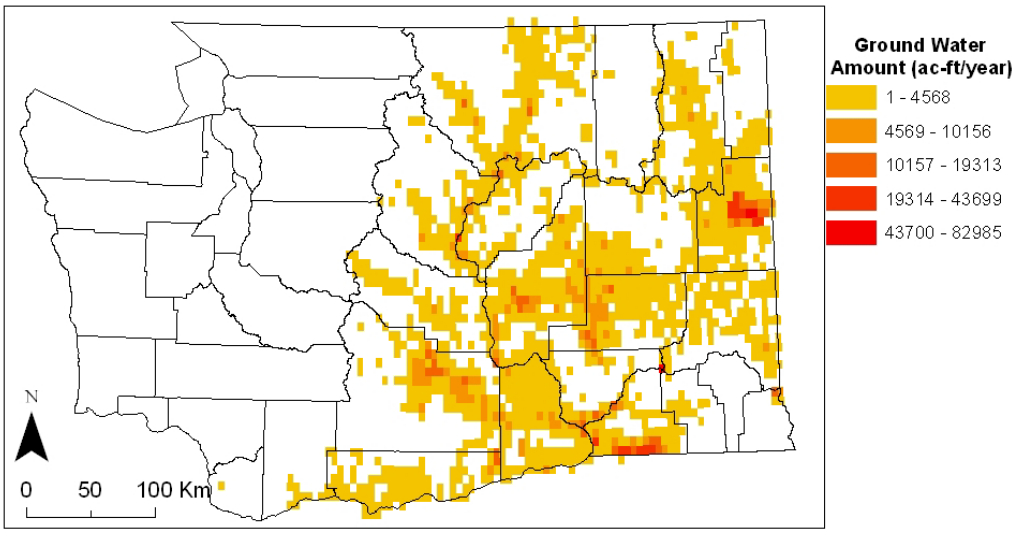


Figure 2.9. Ground water amount (acre feet per year). This accounts for approximately 3 million acre feet.

2.2.3.2 Curtailment of Interruptible Water Rights

Interruptible water rights are those that can be curtailed in low flow years. We modeled the process of curtailment of water rights in the Washington part of the CRB. When curtailment happens, water availability for irrigation used in VIC-CropSyst is modified to accordingly to reflect this. The flow target based on which curtailment decisions are made may be based on Washington Administrative Codes (WAC) or low flow provisions inserted into individual water rights called Surface Water Source Limitations (SWSL). In the WRIAs belonging to the Yakima region, interruption of rights is based on a calculation of the Total Water Supply Available (TWSA). The Department of Ecology provided us a list of interruptible water rights along the Columbia Mainstem, Snake River, along tributaries in Yakima, three Water Resources Inventory Areas (WRIAs) in the central Washington region (Methow, Okanogan, Wenatchee) and three WRIAs in the Eastern Washington Region (Walla Walla, Little Spokane and Colville). The interruptible water rights include both surface water rights and ground water rights (see Figure 2.10, which shows the interruptible water amount by place of use and accounts for approximately 1.98 million acre feet). However, for this study we modeled curtailment of surface water rights only.

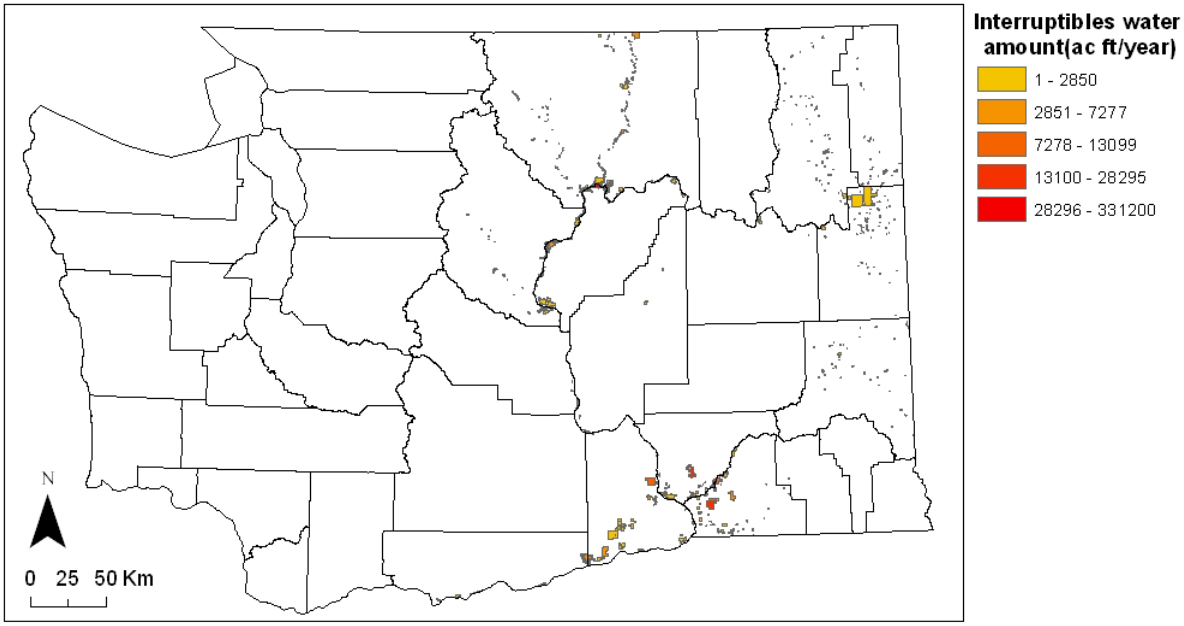


Figure 2.10. Water amount (by place of use) for interruptible water rights.

2.2.3.2.1 Columbia Mainstem Interruptibles

There are approximately 380 interruptible water rights along the Columbia Mainstem. These water rights are regulated as per WAC 173-563. For the Columbia Mainstem, the March 1st forecast of April through September runoff at the Dalles Dam determines whether or not the interruptible program will be run in a particular year. If this forecast is greater than 88 million acre feet, the year is not considered a low flow year. If the forecast is between 60 and 88 million acre feet, then voluntary conservation is encouraged. If the predicted runoff at Dalles is less than 60 MAF, the interruptible water right holders are informed that they may be curtailed in the following season. In such an event, users call in to a number every week to check whether the predicted average weekly flows fall below the minimum specified in the WAC and to know whether or not they would be curtailed that week. The Director of the Department of Ecology may reduce the minimum average weekly flows by up to 25% in a low flow year, as long as the outflow from Priest Rapids is at least 36,000 cfs, and as long as total flow between April and September is at least 39.4 million acre feet. The amount of the reduction (from 0-25%) is based on the March 1 forecast, as well as information provided in the WAC (See Figure 2.11). For our modeling effort we make the assumption that this reduction decision will be made every time the interruptibles on the Mainstem are curtailed.

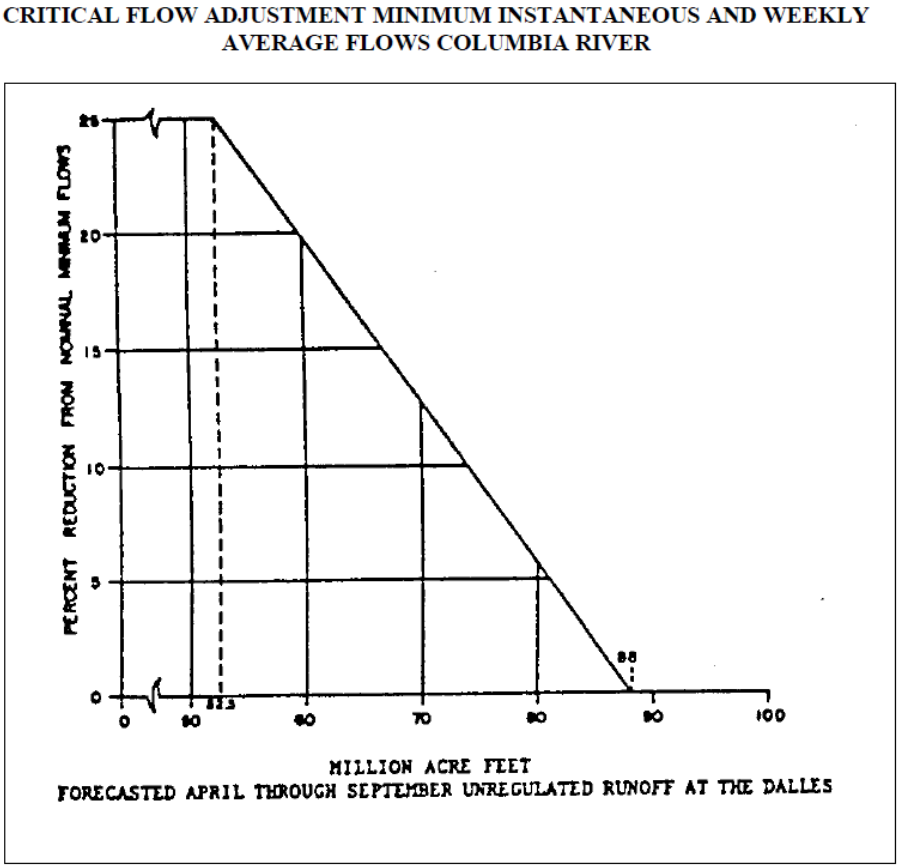


Figure 2.11. Critical flow adjustment for the Columbia Mainstem

There are nine control points with target flows for the respective management reaches along the Columbia Mainstem. Water rights holders upstream of Priest rapids are controlled by flows at their respective control point (closest downstream control point) as well the flow at Priest Rapids. Other water rights holders are controlled by flows at their respective control points. The WAC flow requirements at various control points along the Columbia Mainstem are listed in Table 2.2.

In addition to the above WAC requirements, the US Fish and Wildlife Service offers a Biological Opinion (BiOp) and recommends flow targets. In every year that the BiOp flows are not met, the water rights affected by these flows are curtailed and the water right holder has to rely on other rights in their portfolio or follow mitigation practices. This is something that the model does not account for currently and will be incorporated in the future.

Table 2.2. WAC requirements along the Columbia Mainstem

	Chief Joseph	Wells and Rocky Reach	Rock Island and Wanapum	Priest Rapids	McNary	John Day	The Dalles
Jan	30,000	30,000	30,000	70,000	60,000	60,000	60,000
Feb	30,000	30,000	30,000	70,000	60,000	60,000	60,000
Mar	30,000	30,000	30,000	70,000	60,000	60,000	60,000
Apr 1-15	50,000	50,000	60,000	70,000	100,000	100,000	120,000
Apr 16-25	60,000	60,000	60,000	70,000	150,000	150,000	160,000
Apr 26-30	90,000	100,000	110,000	110,000	200,000	200,000	200,000
May	100,000	115,000	130,000	130,000	220,000	220,000	220,000
Jun	80,000	110,000	110,000	110,000	200,000	200,000	200,000
Jun 16-30	60,000	80,000	80,000	80,000	120,000	120,000	120,000
Jul	60,000	80,000	80,000	80,000	120,000	120,000	120,000
Jul	90,000	100,000	110,000	110,000	140,000	140,000	140,000
Aug	85,000	90,000	95,000	95,000	120,000	120,000	120,000
Sept	40,000	40,000	40,000	40,000	60,000	85,000	90,000
Oct 1-15	30,000	35,000	40,000	40,000	60,000	85,000	90,000
Oct 16-30	30,000	35,000	40,000	70,000	60,000	85,000	90,000
Nov	30,000	30,000	30,000	70,000	60,000	60,000	60,000
Dec	30,000	30,000	30,000	70,000	60,000	60,000	60,000

2.2.3.2.2 Central Washington Interruptibles

The central Washington region has interruptibles subject to WAC rules as well as SWSLs. Data related to SWSLs were not provided for the central region. In addition to curtailment related to instream flows, water users are also regulated against each other, at least in some adjudicated portions of the basins. However, this is not captured in our model. The Methow WRIA has instream flows established on 12/28/1976. The Okanogan has instream flows established on 7/14/1976. The Wenatchee has instream flows that were set 6/3/8 and amended 12/11/07. There have been no water issued that are subject to the 2007 flows in Wenatchee.

Although there are multiple control points in these WRIAs, in reality interruptibles are controlled by a fewer control points (as per personal communications with the Department of Ecology). For example, all interruptible in Methow are controlled based on flows at Methow River near Pateros, interruptibles in Wenatchee are controlled against flows at Wenatchee River near Peshastin and Monitor only. This is the process we followed in this modeling effort.

2.2.3.2.3 Eastern Washington Interruptibles

This region includes Lower Snake and Middle Snake WRIAs which are along the Snake River as well as the Walla Walla, Little Spokane and Colville WRIAs which have water rights subjects to WAC rules as well as SWSLs.

Along the Snake River (Lower Snake and Middle Snake WRIAs), there are no instream flows rules in WAC. However, the Department of Ecology has a 1974 Agreement with the Washington Department of Fish and Wildlife (WDFW) called the Snake River Water Rights Policy. The policy

established a 12,000 cfs base flow for the mainstem of the Snake River in WA (measured just below the confluence of Snake and Clearwater rivers) and set aside 2000 cfs of water for consumptive use. Water rights with a priority date after July 26, 1973 are subject to a base flow of 12,000 cfs plus a flow of 800 cfs necessary to satisfy existing rights with priority dates through July 26, 1973. The first right issued after July 26′ 1973 is subject to regulation when the flow falls below 12,800 cfs and the last right issued will be subject to regulation when the flow falls below 14,000 cfs.

Walla Walla has instream flows that were set 12/14/1977 and amended 8/12/2007. There were no water rights subject to either flows in the list provided to us by Ecology. Little Spokane has instream flows in WAC filed on 1/6/1976. Colville has instream flows in WAC that were filed on 7/22/1977. Although the Little Spokane and Colville WRIAs have multiple control points listed in the WAC, in reality water rights are controlled by flows at one point only: Dartford for Little Spokane and Lower Colville for Colville. This is the process we follow in our model.

Interruptible water rights in the Eastern region that originated before the WAC filing date are assumed to be SWSLs. Because these have not been adjudicated, it is unclear how they are regulated. We assume that SWSLs will be managed like interruptibles subject to WAC rules for our modeling purposes. Therefore, this will not result in a situation where senior water right holders with SWSLs have more stringent flow requirements than the WAC rules applicable to more junior water right holders.

Walla Walla WRIA has no interruptibles subject to WAC rules. So all interruptible rights are subject to SWSLs which, as mentioned earlier, will be considered as being subject to WAC rules for our modeling purposes. To simplify the modeling process, we made the assumption that, similar to some other WRIAs discussed, curtailment for all interruptibles in the Walla Walla will be based on flows at the most downstream control point in the Walla Walla River.

2.2.3.2.4 Yakima Region Interruptibles

The three WRIAs that are part of the Yakima Region (Naches, Upper Yakima and Lower Yakima) are regulated slightly differently. Instead of an on/off mechanism which we saw in the earlier sections where some water right holders are shut off during low flow time periods, the Yakima follows a system of prorating the water right amount in periods of shortage. Water rights holders are classified as proratable right holders (with water rights dated May, 1905) who can be curtailed in times of water shortage and non proratable water right holders (with priority dates earlier than May, 1905) who are not subject to curtailment. Estimates of TWSA (which is a sum of forecast runoff, usable return flow and available storage) are made at regular time

intervals every year. If TWSA is not adequate to meet all needs including instream flow targets, the proratable water rights holders receive only a prorated amount (a percentage of their water right amount) such that the reduced water allocation accounts for the expected shortage.

3 Results

3.1 Uncertainty in Future CRB Climate

Data for this analysis was downloaded from the Columbia Basin Climate Change Scenarios Project website at http://www.hydro.washington.edu/2860/. These materials were produced by the Climate Impacts Group at the University of Washington in collaboration with the WA State Department of Ecology, Bonneville Power Administration, Northwest Power and Conservation Council, Oregon Water Resources Department, and the B.C. Ministry of the Environment.

Figure 3.1 through 3.4 show the routed streamflows at Revelstoke dam, Dalles, Parker and Ice Harbor (see Figure 3.5 for their locations) for historical climate as well as 20 GCM scenarios (generated from 10 GCMs and two emission scenarios). The ensemble average streamflow for the 20 GCM scenarios are also plotted. In general, winter flows are predicting to increase while summer flows are predicted to decrease, with large negative consequences for irrigated agriculture.

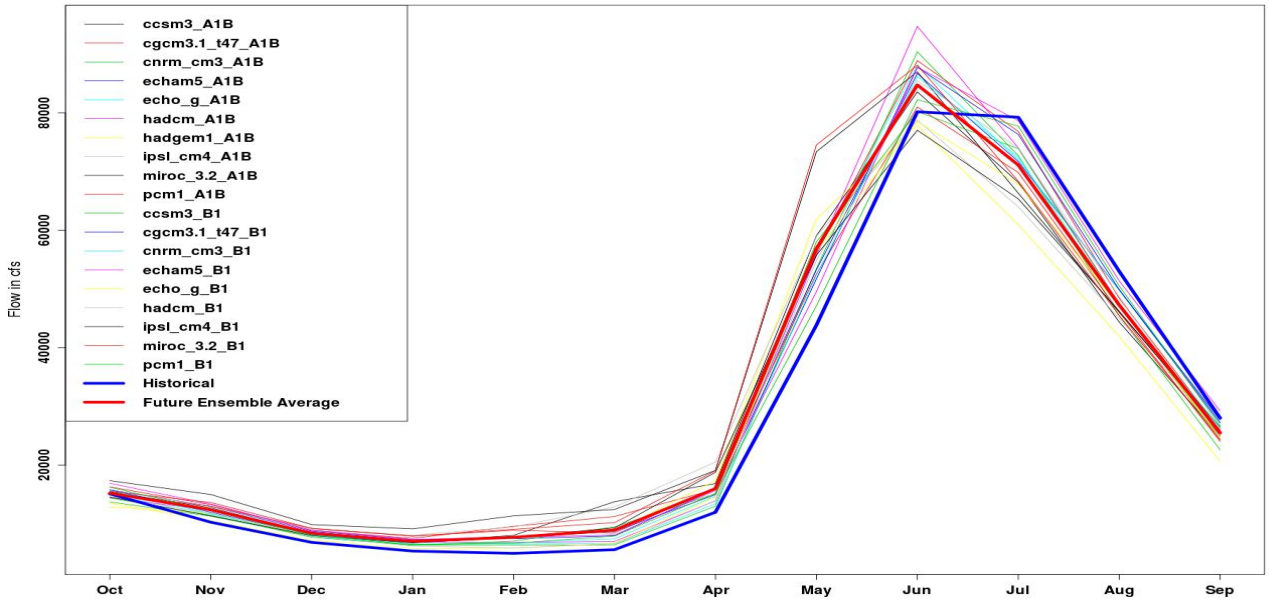


Figure 3.1. Routed streamflow from VIC at Revelstoke dam in Canada.

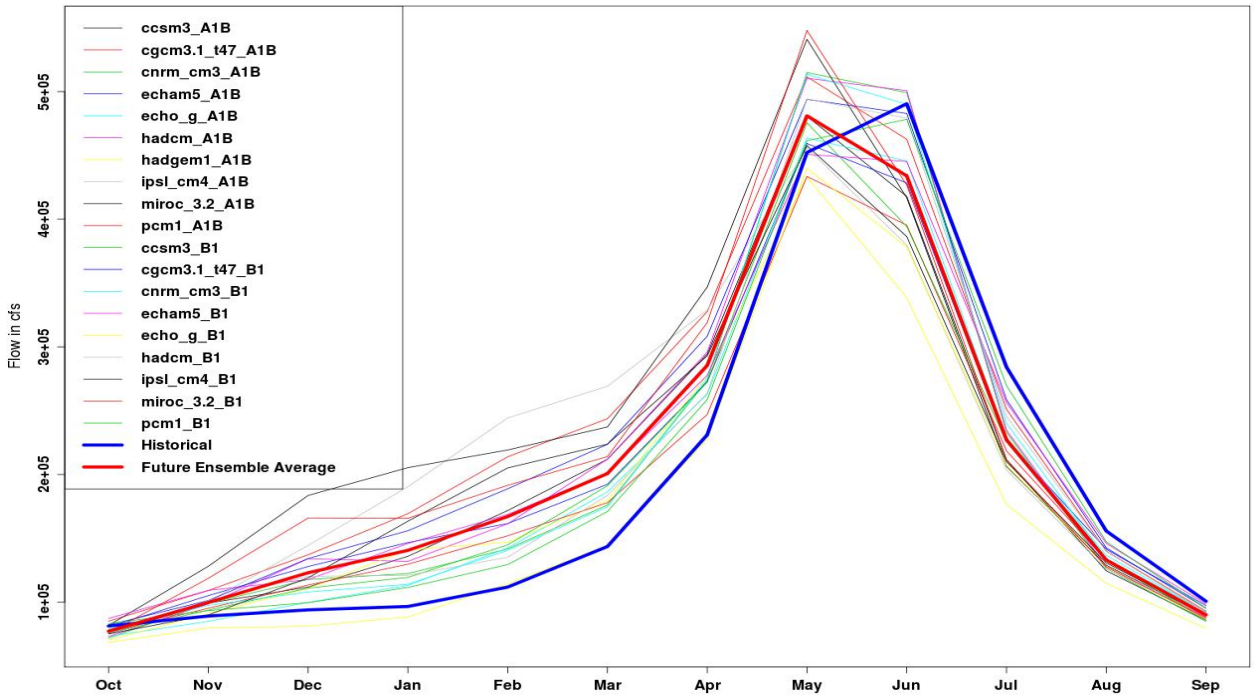


Figure 3.2. Routed streamflow from VIC at Dalles, Columbia River.

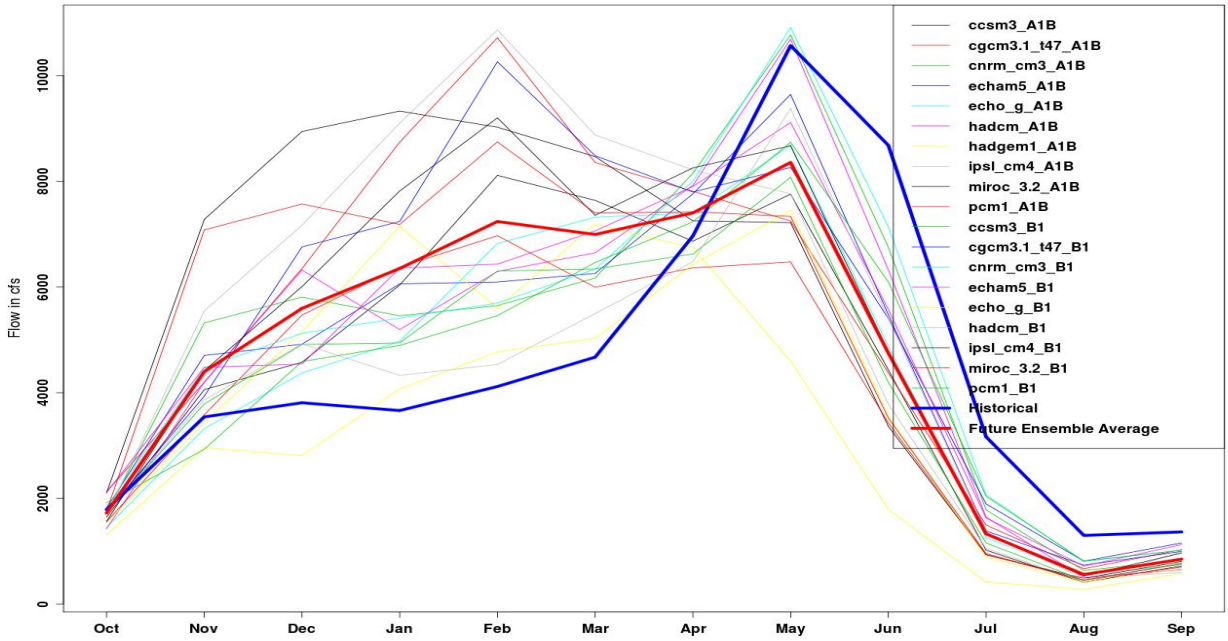


Figure 3.3. Routed streamflow from VIC at Parker, Yakima River.

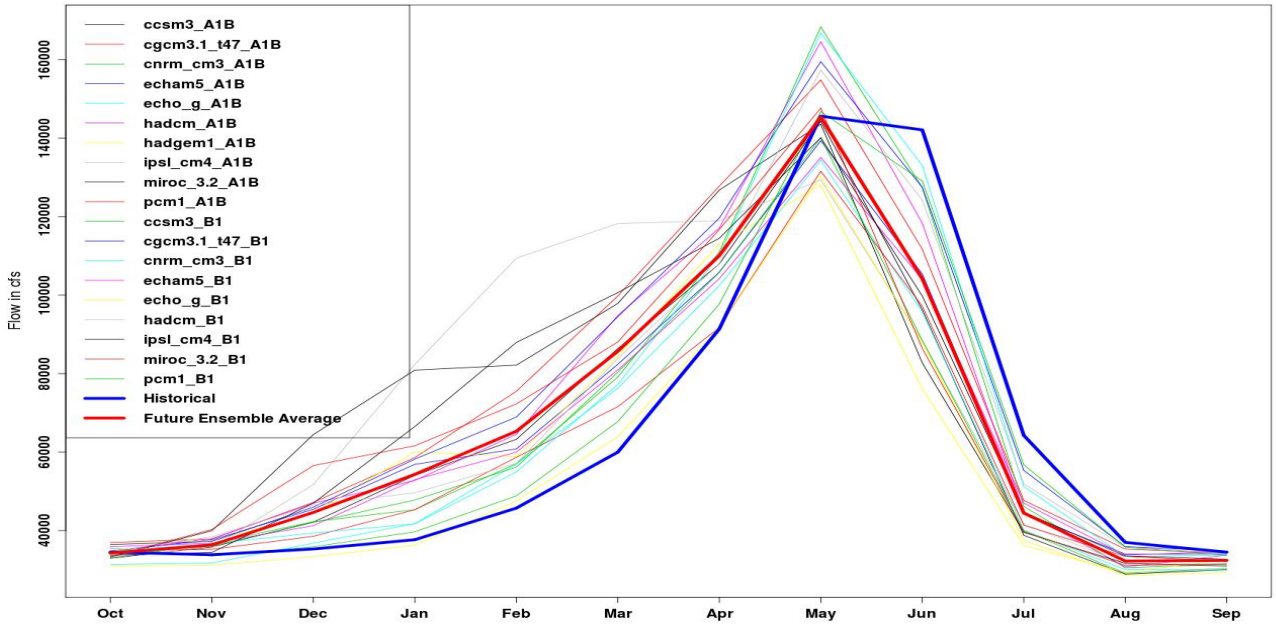


Figure 3.4. Routed streamflow from VIC at Ice Harbor, Snake River.

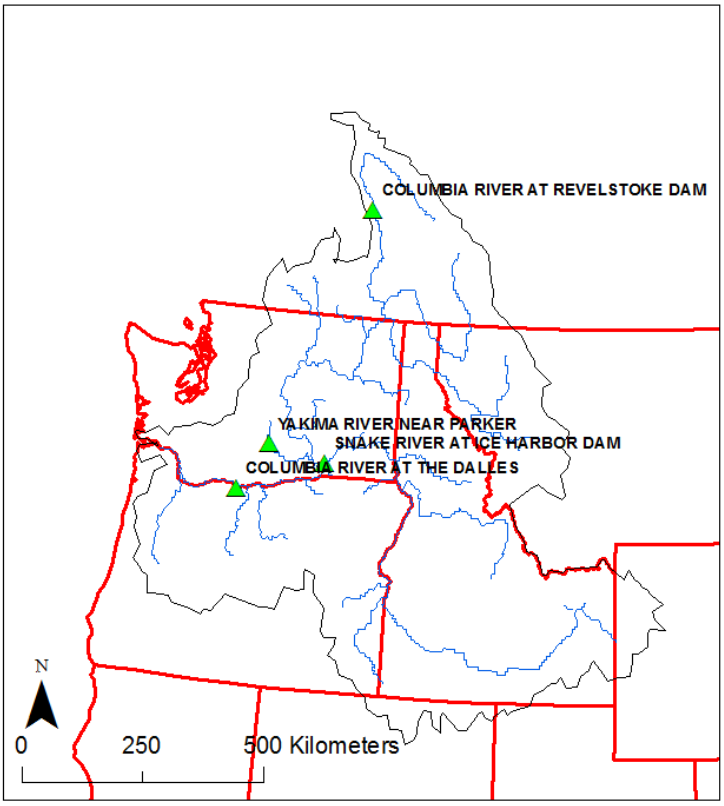


Figure 3.5. Streamflow gauge stations in the CRB presented in this report.

3.2 VIC-CropSyst run over the CRB

Applying 1% area threshold to eliminate crops with very small area resulted in crop distribution with up to 16 crops in some VIC grid cells. The major crops selected for simulation by this method are listed in Table 2.1. Herein we show representative results for winter wheat.

Figure 3.6 shows the average yield in tonnes/hectare from the simulation period for the winter wheat. The colored cells are the places where winter wheat was grown according to the USDA crop land data layer. These values cannot be directly compared to the NASS values without adjusting for tuber mass and lack of weeds/pest component in the model. Also the grid cell values need to be aggregated at least to the county scale for comparison with the NASS values which are available only at county, state or country scale. Figure 3.7 shows the county level yield numbers in that can be used for comparison with the NASS values. The figure demonstrates that Yakima County has the highest yield in tones/hectare for winter wheat. This may be due to winter wheat being irrigated in the Yakima valley. High yield does not necessarily mean high production of the crop. To identify the high production county, we scaled the yield with the winter wheat acreage to create a county-averaged production map (Figure 3.8). This analysis reveals that Whitman County (green region in Figure 3.8) has the highest winter wheat

production. Comparison can be made to the USDA National Agricultural Statistics Service (NASS) at the county level (see Figure 3.9), although the NASS values are expected to be lower than the modeled yields because we have yet to adjust yield values for pests and droughts.

The dynamic modeling of the crop growth can also show other interesting patterns in the other crop production related variables as maturity day in the year (Figure 3.10) and crop water uptake (Figure 3.11). These are important variables to explore the impact of the changing climate.

More exhaustive analyses (including climate change impacts on crop viability) are still underway via other funding sources (see note on dual submission at top) and will be completed by the end of the year.

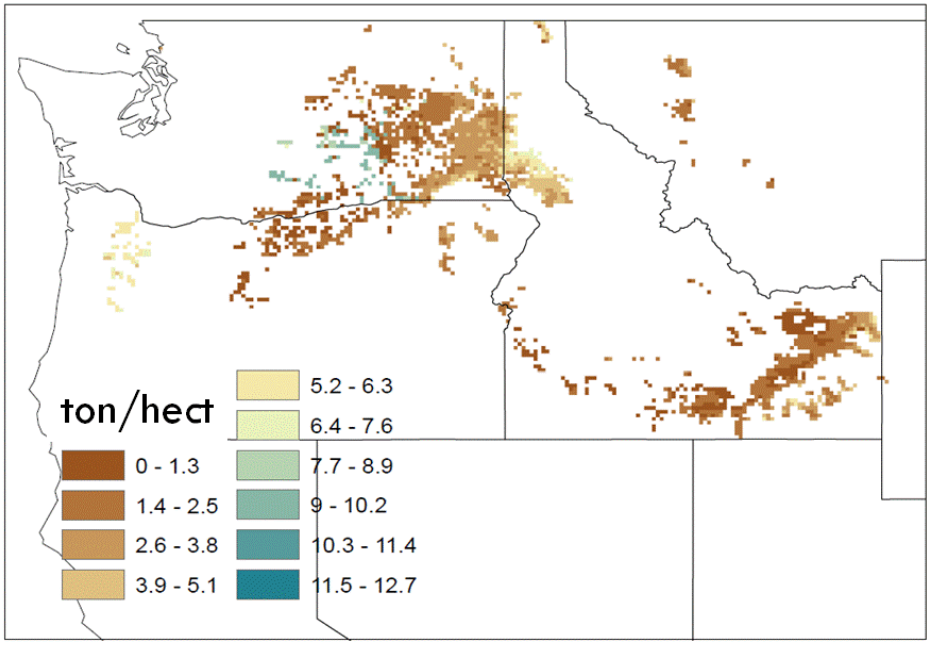


Figure 3.6. Winter wheat yield (in tonnes /hectare) simulated by VheIC-CropSyst model.

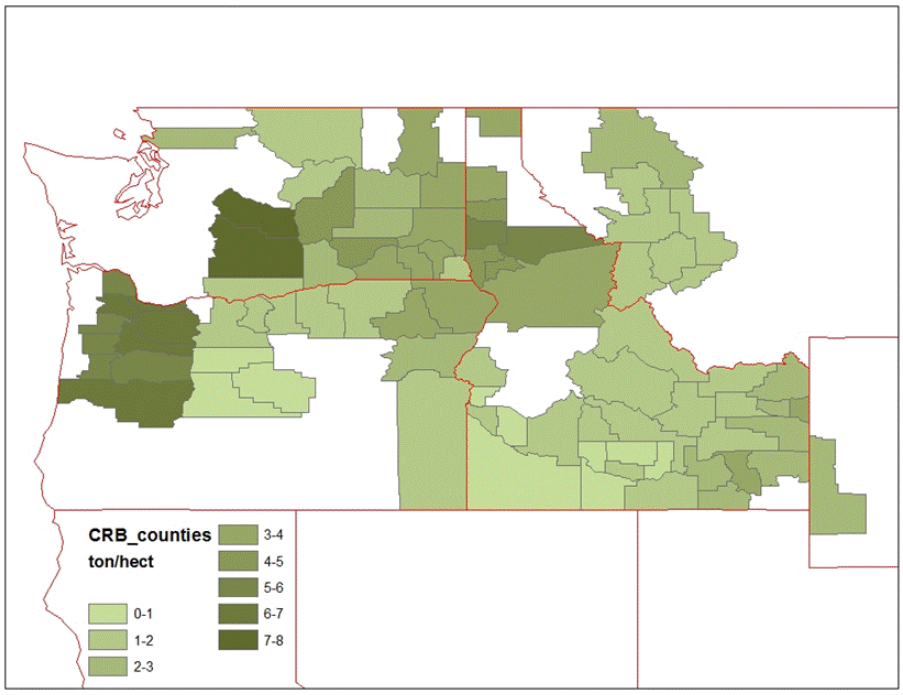


Figure 3.7. County average winter wheat yield (in tonnes/hectare) from the VIC-CropSyst model.

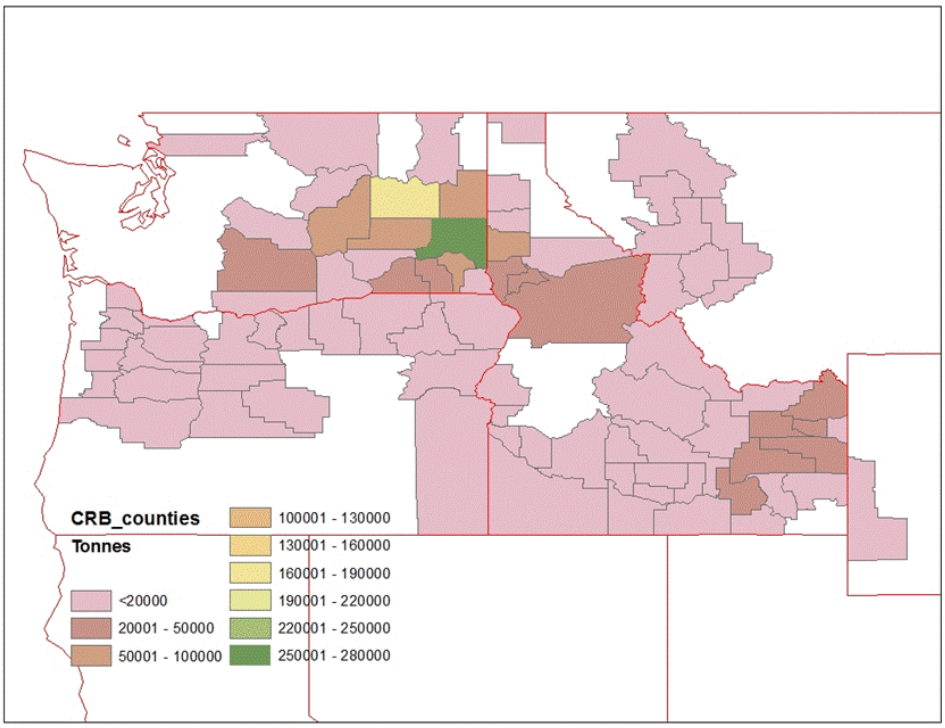


Figure 3.8. Winter wheat production in each county estimated by the VIC-CropSyst model.

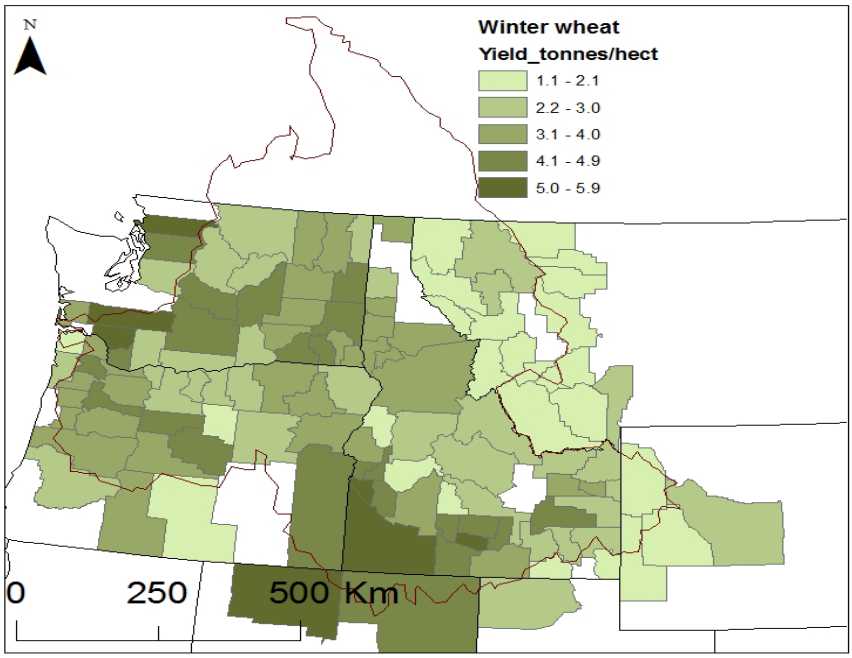


Figure 3.9. County average winter wheat yield (in tones/hectare) from USDA NASS statistics.

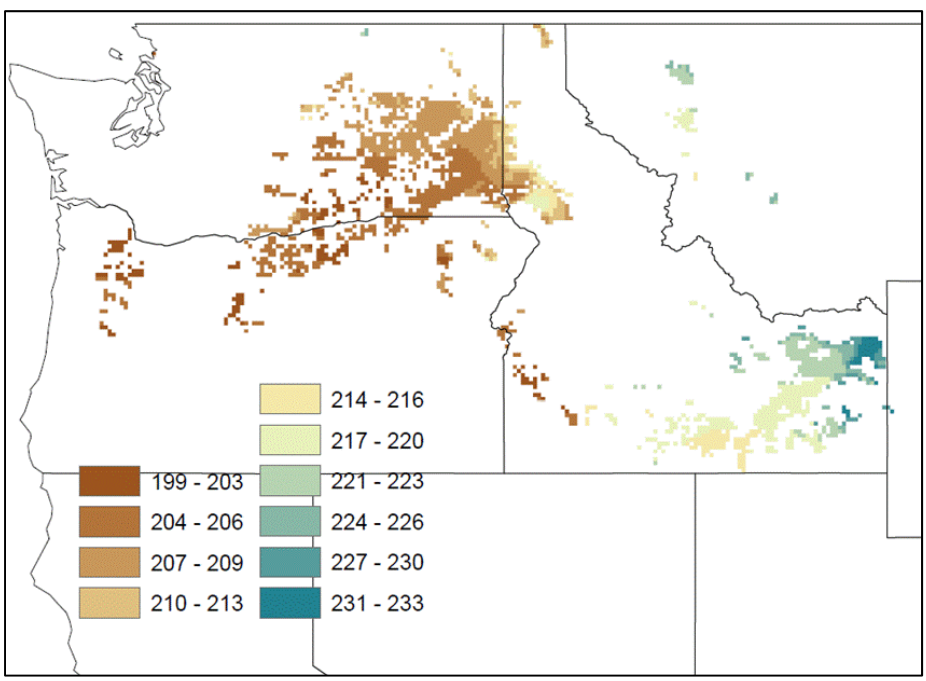


Figure 3.10. Day of maturity in the calendar year for winter wheat as modeled by the VIC-CropSyst model.

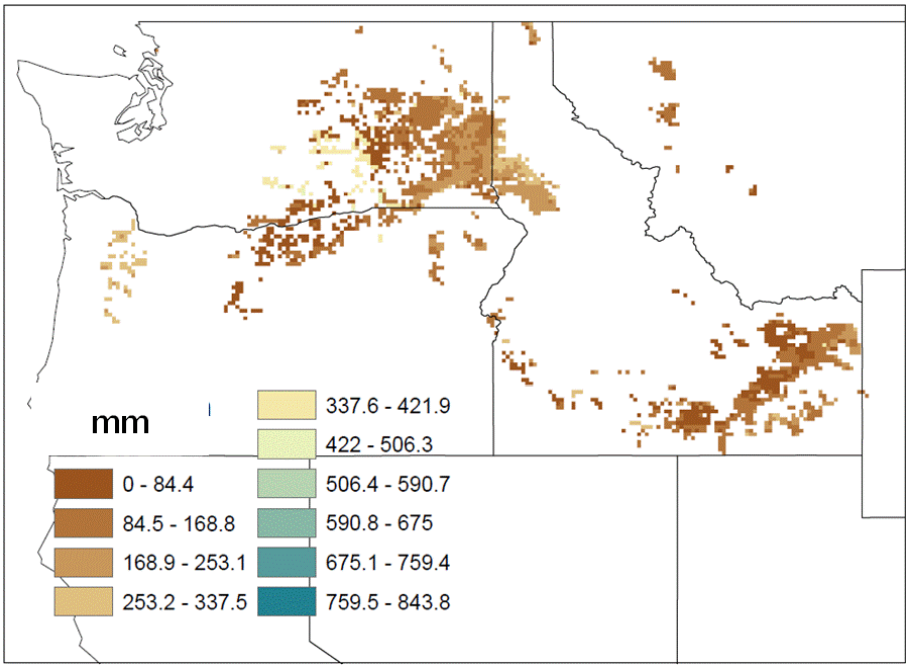


Figure 3.11. Annual average water uptake (mm) of winter wheat simulated by the VIC-CropSyst model.

3.3 Communication of Results

The outreach portion of this project is ongoing via funding from the Washington State Department of Ecology (see not on dual submission at top) and for a report on Columbia Basin Water Supply and Demand Forecast for the Washington State Legislature. Outreach products include (1) a 35-page legislative report with a summary of all results, (2) a website with an overview of the results and more details information than the legislative report, and (3) a full technical report with full details on methodology and results. Furthermore, available through the website will be introductory webinar-style videos detailing each aspect of the study. Through WSU Extension, we will use the information in the webinars and on the website to elicit feedback from stakeholder groups in the basin. This will allow us to improve how we visually portray and communicate the results so that they can make the most impact.

4 Discussion and Conclusions

The streamflow from VIC runs based on the climate driving data from the 20 GCMs show considerable uncertainty around the ensemble average but the signal for a shift in hydrograph to earlier months is noticeable. The amount of uncertainty varies spatially, there is more

uncertainty in estimates of Yakima River streamflow at Parker as compared to other locations. The hydrology of some areas could be more sensitive to climate change (smaller difference in climate leading to larger differences in streamflow) than others depending on the local drivers of the hydrology in the region.

The VIC-CropSyst does not model the effects of pests and weeds on crop production. In this version of the crop model, it was assumed that crop would grow under perfect health conditions with no pest or nutrient limitation. However, the crop growth was simulated as a function of climate and water availability. Adding the nutrient component to the model is being planned for future work.

The NASS statistics show a significant increasing trend in the yields of many crops for the last 30 years of data. This is attributed to the advances in technology and improved management practices. These affects are again not modeled by the VIC-CropSyst model and hence it would be not appropriate to compare the increasing trend of yields to the more or less constant year to year values from the VIC-CropSyst model. Therefore our comparison was based on the simulated period between 1996- 2006 when the yield values in the NASS dataset is relatively stable. The other challenge for model evaluation is that NASS dataset does not have information on all the crops that are simulated. For future work, it would be desirable to compile such statistics for all simulated crops from other sources. The modeled values after correction for tuber loss and pest affects, showed values comparable to the ones in the NASS database for the major crops.

The modeling framework described herein is the first step towards our long-term goal of producing a fully operational decision support tool that can be used to test various water and agricultural management strategies. This tool can be used to promote the sustainability of PNW irrigated agriculture while protecting water supply for other uses (such as instream flows, hydropower, and municipal needs) and water quality.

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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

Title:	Information Transfer
Project Number:	2005WA114B
Start Date:	3/1/2009
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	Washington 5th
Research Category:	Not Applicable
Focus Category:	Education, Management and Planning, None
Descriptors:	Outreach, Information Transfer
Principal Investigators:	Michael Ernest Barber

Publications

1. Barber, M. and B. Bower, 2006, Evaluating Diversion Alternatives Affecting Environmental Flows and Temperatures, Presentation at UCOWR/NIWR Annual Conference, Increasing Fresh Water Supplies, Santa Fe, New Mexico.
2. Simmons,R., M. Barber, and J. Dobrowloski, 2006, Washington State University - Providing Solutions to Critical Water Issues, National Association of State Land Grant Universities and Colleges, NASULGC Science Exhibit on the Hill, Washington, D.C.
3. Barber, Michael E., Robert Mahler, and Marc Beutel, 2007, A Framework for Evaluating the Hydrologic and Economic Repercussions of Bioenergy Development within the Columbia River Basin in the USA, presented at World Water Week, Stockholm, Sweden, August 2007.
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27. Chinnayakanahalli, K., J. Adam, C. Stockle, R. Nelson, and M. Barber, 2010, A Coupled Hydrological and Process-Based Crop Dynamics Model for Studying Climate Change Impacts on Water Resources and Agricultural Production, 2010 American Geophysical Union Fall Meeting, Poster Presentation, San Francisco, CA, December.
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29. Ullman, J., M. Barber, and B. Johnson, 2010, Evaluation of Instream Flow Assessment Methods for Low-Flow and Intermittent Streams in the Snake River Watershed, 2010 UCOWR/NIWR Annual Conference, HydroFutures: Water Science, Technology and Communities, Seattle, WA, July.
30. Wang, G., S. Chen, J. Wu, and M. Barber, 2010, Tillage Management Impacts on Soil Moisture in the Pataha Creek Watershed, 2010 UCOWR/NIWR Annual Conference, HydroFutures: Water Science, Technology and Communities, Seattle, WA, July.
31. Adam, J., K. Chinnayakanahalli, C. Stockle, and M. Barber, 2010, Climate Change Impacts on Water Supply and Irrigation Water Demand in the Columbia River Basin, Poster Presentation, 2010 UCOWR/NIWR Annual Conference, HydroFutures: Water Science, Technology and Communities, Seattle, WA, July.
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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 upcoming November 2011 conference titled, "Water in the Columbia River basin: Sharing a Limited Resource" is on track to be another showcase for the SWWRC. Planning for this conference has 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. A student competition in the poster session helps promote the education goal of the SWWRC. A student competition showcases 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.

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 Washington began collaborating to conduct a regional "Exempt Well" conference in spring 2011. Dr. Barber also attended and assisted with organizing the UCOWR/NIWR 2010 conference in Seattle, WA, attended a UCOWR Board meeting, and presented an oral presentation on research conducted at WSU.

SWWRC co-sponsored a water resources research forum attended by the WSU Vice President for Research, the Governor's Chief of Staff, and over sixty water-related faculty. The goals of the forum were to educate the upper administration regarding expertise, identify future research initiatives that were vital to the state and region, and provide an opportunity for faculty interaction across disciplines. SWWRC also sponsored several graduate student presentations at the evening portion of the event. The SWWRC also sponsored a graduate seminar on water resources and will continue to look for opportunities to expand these efforts.

In 2010 we concluded our strategic regional surface water initiative funded by the Department of Energy through the Inland Northwest Research Alliance (INRA). The project involved the Water Institutes and other researchers at the Universities of Alaska, Idaho, Utah State and Washington State, as well as other regional universities (Boise State, Idaho State, Montana, and Montana State). The project involved bi-monthly conference calls aimed at establishing a regional needs assessment (recently completed) and coordinating research and education programs integrating water science, policy, and decision making. The project took on a task of developing a regional water data portal called "ICEWATER" modeled after the NSF HIS system to allow data sharing which still continues.

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.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	0	0	0	0	0
Masters	5	1	0	0	6
Ph.D.	3	5	0	0	8
Post-Doc.	0	0	0	0	0
Total	8	6	0	0	14

Notable Awards and Achievements

2010WA305B: Harrison's Lab group sponsored a successful informational booth at the Lacamas Shores July Fourth celebration in 2009 and 2010 and intend to participate again in 2011.

2010WA305B: B.Deemer awarded a NSF NSPIRE IGERT fellowship

2010WA305B: J. Harrison awarded the College of Science Young Faculty Performance Award

2010WA305B: J. Harrison and S. Henderson awarded $130,000 in NSF seed funding to follow up on research developed through this USGS award

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.)