Understanding Hydrologic Processes in Semi-Arid Cold Climates

Michael Barber, Marc Beutel, Brian Lamb, and Richard Watts
Washington State University

Introduction

Water shortages destabilize economies and ecosystems. A report to the Washington State legislature summarizing the response to the drought of 2001 identified maintaining critical energy supplies, aiding State agriculture, protecting public water supplies, safeguarding fish and stream flows, and firefighting preparation as important issues caused by droughts. An economic assessment of the 1999 drought by the US Department of Agriculture estimated farmers lost over $1.3 billion dollars. Water shortages are caused by complex interactions between climate variability, ecosystem processes, and increased demand from human activities. In the semi-arid region of the northwestern U.S., water availability during drought periods has already reached crisis levels and the problems are expected to intensify as the effects of global climate change and population growth continue to alter the supply and demand patterns. Many of the problems are critical to this region because hydropower, agriculture, navigation, fish and wildlife survival, water supply, tourism, environmental protection, and water-based recreation are vital to state economies and our way of life. The complex scientific questions being raised involve physical, chemical and biological stressors that require multidisciplinary approaches. In order to assess the spatial and temporal nature of hydrologic responses, consistent and comprehensive long-term data sets are needed. Because the breadth of potential phenomenon, CUAHSI conducted a series of workshops that identified the five priority science topics as: 1) linking hydrologic and biogeochemical cycles, 2) sustainability of water resources, 3) hydrologic and ecosystem interactions, 4) hydrologic extremes, and 5) fate and transport of chemical and biological contaminants. Each of these can be addressed by three cross-cutting themes involving: a) forcing, feedbacks, and coupling, b) scaling, and c) prediction and limits to predictability.

In response to these needs, we would like to propose the Spokane River drainage basin as a long-term hydrologic observatory. As illustrated in Figure 1, the Spokane River basin is located in eastern Washington and northern Idaho and is a tributary of the Columbia River. The watershed consists of several major surface water tributaries as well as natural and man-made lakes and reservoirs. With headwaters beginning in the Rocky Mountains, the drainage area is approximately 17,200 km^2 (6,640 mi^2). In addition to providing an excellent study area for examining many conventional water resource problems, the Spokane River watershed also presents a unique opportunity for investigating many of the hydrologic processes found in semi-arid cold climates. Snowfall in the watershed varies spatially between 35 inches near the mouth of the basin to over 112 inches at the headwaters. Similarly, precipitation varies between 16 inches near the City of Spokane to over 35 inches near Mullan, Idaho. Significant site characteristics of the watershed include:

Rivers – Coeur d'Alene, St. Joseph, St. Maries, Little Spokane and Spokane

Lakes – Coeur d'Alene, Hayden, Liberty, Long, and Newman

Groundwater – Sole source Spokane/Rathdrum Prairie Aquifer

Precipitation – Highly variable: rain, snow, rain-on-snow

Mountains – Rockies

Land Uses – Forest, Municipal (Urban and Suburban), Agriculture, and Recreation

Industrial Uses – Hydropower and Process water

Tribal lands – Coeur d'Alene and Spokane Tribes

Fisheries – Fish populations include endangered cutthroat trout and tribal subsistence issues

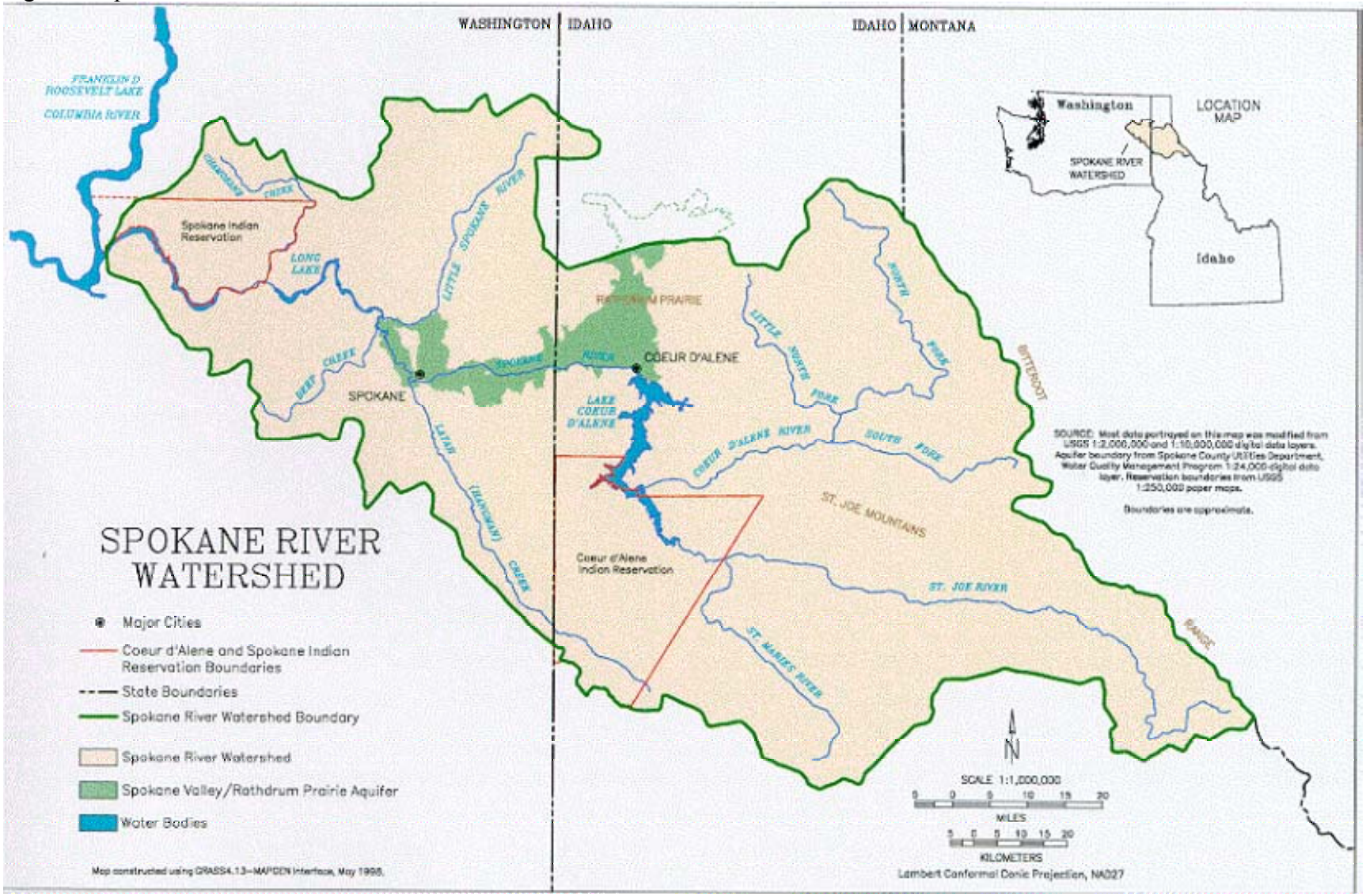
Environmental – Heavy metals (arsenic, cadmium, lead, and zinc), nutrients, fecal coliform

Restoration Activities – Mining, sediments, temperature, flow, and other pollutants

Interstate Water Right Issues – Idaho and Washington are currently debating allocation of waters

These varied hydrologic uses provide a unique opportunity to address many common challenges faced by water resource professionals. This broad array of issues encompasses science, engineering, agriculture, social sciences, economics, fisheries, and a host of other disciplines. In addition, because precipitation patterns in this semi-arid region tend to be temporally distributed, storage and global climate change issues are significant.

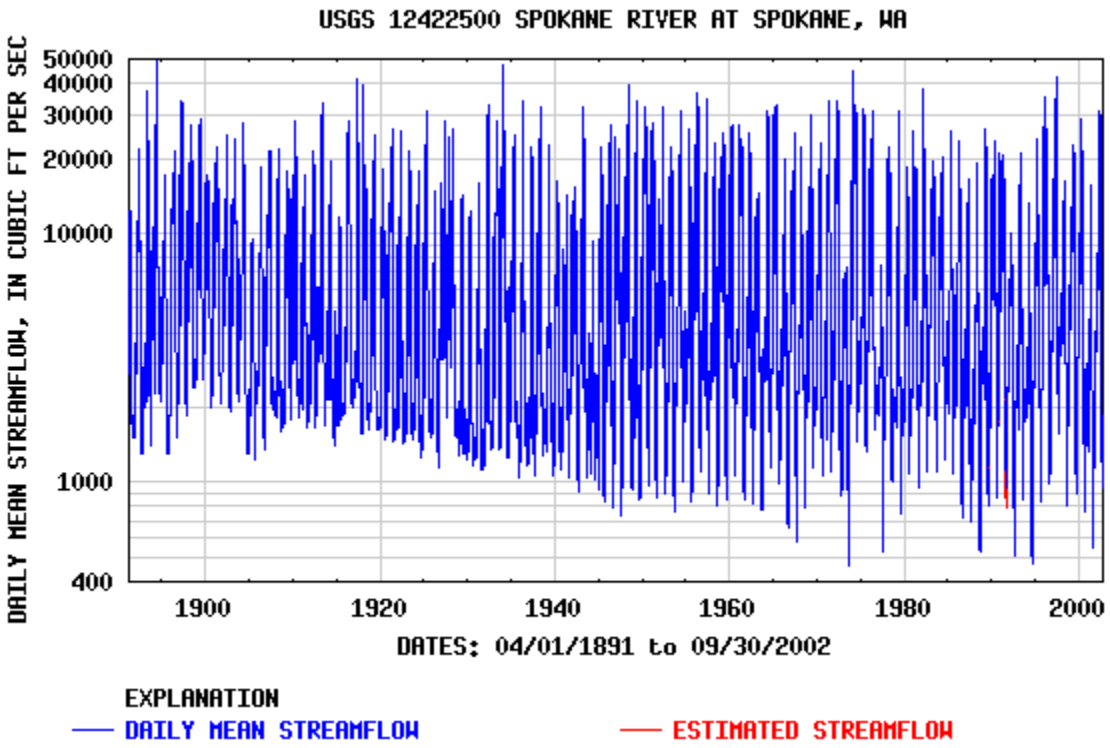
Figure 1. Spokane River Watershed



Existing Hydrologic Data Sources

There are numerous sources of historic and on-going hydrologic data collection activities that would be important to many water resource professionals. The USGS operates stream gages throughout the basin including the station at Spokane that has been in continuous operation since 1891. The Washington Department of Ecology and several watershed groups are installing and operating a network of stream gages on smaller streams and rivers. The Little Spokane River basin will have approximately 15 gages installed to provide a dense level of coverage.

Figure 2. Long-term gaging record on Spokane River



In addition to providing convenient access, Spokane International Airport has been collecting weather data since 1890. Long-term records such as this are crucial in helping assess global climate change issues. NOAA operates a NEXRAD facility that has unobstructed views of the Spokane Valley and Latah Creek watersheds so research involving the use of radar predictions in regions susceptible to snow can be investigated. NRCS operates a series of Snotel stations that monitor snow and snow-water-equivalents in mountainous areas although more stations are needed to address spatial variability. The Washington Department of Ecology collects flow and water quality data associated with TMDL issues at a number of locations. The USGS and the City of Spokane have also been collecting well data to assess groundwater changes. EPA has been collecting water quality data related to historic and continuing mining operations in the upper watershed. The Idaho Department of Environmental Quality and the Idaho Department of Water Resources have been collecting additional quality and quantity information. Researchers at Eastern Washington University, Washington State University and the University of Idaho have

been collecting macroinvertebrate data at select locations sporadically throughout the past decade.

WSU researchers have also been collecting air quality information associated with grass burning issues and overall quality in an attempt to improve prediction models.

Scientific Study Questions

Surface Water

Surface water quantity and quality are dramatically influenced by rain-on-snow events in many cold weather climates. Key questions include, from a quantity viewpoint, how are infiltration and runoff processes impacted by rain-on-snow events? From a quality perspective, what is the fate of pollutants washed off from frozen soils?

Heavy precipitation events, coupled with seasonal spring snowmelt or saturated ground conditions, create severe flood events for many areas in the United States. Such floods rank among the most dangerous of all natural hazards in terms of property damage and loss of life. In fact, floods and winter storms cost the United States an estimated $3.4 billion and 150 lives each year. This problem is particularly acute in the Northwestern US due to rugged mountainous terrain, vast land areas, and sparse data stations. Two broad strategies for reducing loss of life and property damage exist through: ***i***) improvement of real-time flood forecasting abilities and associated mitigation and warning strategies, and ***ii***) amelioration of flood estimation risks and associated land use management practice decisions. This proposed project addresses the use and limitation of remote sensing data and NEXRAD data in the first category - flood forecasting. By linking remotely sensed estimates of snow pack and spatial observations of precipitation and mesoscale wind and temperature predictions, the project expects to improve early warning times and reliability during flooding events.

The primary objective is to develop a real-time runoff prediction model for flooding events in complex terrains using remotely sensed data for input parameter determination. By combining a state-of-the-art weather prediction model (MM5) with real time NEXRAD radar data and a neural network based runoff model, quicker, more reliable management decisions involving flood mitigation and increased response times will be possible. MM5 will be used to develop multiple day (6 hr to 5 day) forecasts that identify potentially dangerous weather conditions. Remotely sensed data will evaluate moisture conditions or snow cover within the watershed and a runoff model will predict flood magnitudes based on existing conditions and weather forecasts. At shorter time intervals, model predictions will be replaced by NEXRAD data, thus generating more reliable predictions of flash-flooding events. This will result in substantial savings of both money and human lives.

Groundwater

The Spokane Valley/Rathdrum Prairie (SVRP) aquifer serves nearly 500,000 people in the states of Idaho and Washington. In 1978, due to increased public concern over the resource, EPA designated SVRP aquifer as a “Sole Source Aquifer,” making it the second aquifer in the nation to receive this special designation (IDEQ, 2000). Formed as the result of a series of catastrophic floods during the last Glacial Age, the SVRP aquifer is comprised primarily of

unconsolidated coarse-grained sands, gravels, cobbles and boulders. The Spokane River exhibits highly complex hydraulic connections with the aquifer (Gearhart and Buchanan 2000; Caldwell and Bowers 2003). Stream reaches immediately downstream of the Post Falls Dam are thought lose up to 600 cfs to the aquifer. Water with a different ionic signature returns at downstream locations with an average of 200 cfs discharging through springs into the lower Little Spokane River. Several short-term investigations have been carried out to quantify capture zones, stream/aquifer interactions, and an overall water budget for the basin. However, rather than definitively answering these important questions, most studies have alluded to the lack of long-term monitoring data as a justification for large uncertainties in model results which translates into policy decisions based on inconclusive data. The reasons for these uncertainties provide the basis for several relevant science questions which would be addressed through instrumentation of the watershed. The questions to be addressed would be:

a. Can artificial recharge be used to restore historic aquifer characteristics?

b. What is the magnitude of mountain-block runoff across the aquifer boundaries?

c. How does urbanization change the recharge areas and local water quality?

d. Do infiltration and evapotranspiration processes significantly vary with depth to water table?

e. How does the timing of return flows impact stream ecology?

Lake Limnology

Mining operations have lead to elevated heavy metals contamination that impact the downstream waterbodies including Lake Coeur d'Alene. In addition, several bays around the lake are experiencing signs of eutrophication due to septic systems and suburban runoff. A key question is how is algal primary productivity affected by zinc speciation and chelator formation in lakes and will this vary with increased/decreased nutrient addition?

The availability and toxicity of zinc have been found to be dependent on Zn^{2+} aqueous speciation. A study of zinc complexation in New Zealand found that zinc speciation in a couple of lakes down there was dominated by its complexation to natural organic ligands. Calculated free Zn 2+ concentrations for both lakes were in the low picomolar range (5—48 pM). Such low free Zn 2+ levels may limit the growth of some phytoplankton in both lakes. Researchers studying metals in the Chesapeake Bay said that knowledge of their chemical forms and concentrations is critically important to identifying and quantifying the bioavailability of these metals as nutrients and toxicants, and in understanding their fate and transport and biogeochemical cycling. They also found that most metals have been found to be predominantly complexed by organic chelators (ligands) in natural waters. These chelators exist in extremely low concentrations (10-9 M), but they form extremely strong complexes with the metals-- 3 to 4 orders of magnitude stronger than their corresponding EDTA complexes. However, almost nothing is known about the chemical nature of these chelators. The watershed and lake would be

monitored for chemical constituents, algal and zooplankton communities, and fish stomach contents to determining the roles that metals and nutrients play in lake environments.

Global Climate Change

Preliminary investigations indicate that global climate change will be responsible for shortening the snow fall period and lengthening the summer drought period. While the total precipitation totals may not change dramatically, even a small increase in the drought period will put additional strain on summer supplies, instream flow requirements, recreational activities, and economic development.

Remote Sensing

Watershed assessment plans are vital tools that allow state and federal agencies and local community groups to collaboratively implement comprehensive water quantity, quality, and aquatic habitat improvements in drainage basins throughout the United States. The plans, based on the current state of knowledge in the watershed, map out opportunities for improvements in water allocation and protection, predict the impacts of these enhancements, and identify critical data gaps and assumptions. The watershed assessment process is a never-ending cycle of planning, implementing, and reviewing. Watershed assessments are adaptive management documents meant to evolve with time as additional information concerning basin response is obtained. Most initial assessment plans suffer from the lack of precise information at the watershed scale. ASTER, MODIS (Aqua and Terra), and LANDSAT data imagery provide significant amounts of basin-scale information necessary to help perform watershed assessments. The advantage of MODIS over other platforms is the availability of temporal and spatial data as scales useful to watershed managers and engineers.

In agricultural communities all over the world, many environmental mitigation plans call for reducing soil sediments and pollutant loads to streams, improving shade and temperature regimes in riparian areas, and estimating water consumptive use demands. Data to populate the variety of hydrologic models use to predict the responses of these three common components are generally quite sparse. However, remotely sensed data from MODIS imagery appear to be well suited for several related areas such as: 1) improving the spatial and temporal extent and character of riparian buffer zones, 2) quantifying the effects of stream shading/riparian zones on stream and air temperatures, and 3) refining estimates of evapotranspiration necessary for completing water balances.

There are numerous functional definitions of riparian areas. Essentially riparian areas are plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent lotic and lentic water bodies. The mitigating influence of riparian zones in reducing the delivery of sediments and degrading, adsorbing, volatilizing, and transforming nutrients and pesticides as they are carried from fields by water has been recognized as an important element in overall management of agricultural properties. As a result, an essential component of watershed analysis is an understanding of the spatial and temporal density and connectivity of riparian corridors. In addition, a monitoring mechanism for evaluating the success of riparian restoration projects is needed.

Knowledge about changes in the existence, physical condition, and connectivity of riparian corridors along streams and rivers in agricultural areas requires the development of higher resolution indices. However, to be useful at the watershed scale, these indices must be scalable up to the 250 m pixel resolution available from the MODIS sensors aboard the Aqua and Terra satellites. However, knowledge about changes in the existence and connectivity of riparian corridors along streams and rivers requires the development of higher resolution indices. This research project proposes to use airborne visible near infrared images, having a ground pixel resolution of 0.22 to 0.5 meters depending on airplane flight altitude, to correlate information from TERRA, AQUA, and LANDSAT 5&7 satellites. To help quantify agricultural buffer zones, one task will be to determine the correlation parameter(s) for spatial and temporal subpixel analysis as a function of riparian zone width.

The second task involves investigating the relationships between changes in land surface temperatures (LST) in agricultural land use areas and these riparian zones, stream shading, and surface water temperatures. Microclimates within riparian zones are cooler and moister than open area crops. The canopy cover (tree shading) and wind blockage properties of riparian zones can cool streams and rivers and thus improve aquatic species habitat. Many riparian corridors are being planned for this purpose although the slow growing nature of trees will keep actual results from being known for years. The hypothesis is that by using MODIS data measuring stream, field, and riparian temperatures, relative differences in the rate of surface heating measured by Terra and Aqua can be used with other information to establish a pattern. MODIS offers LST at 1-km resolution. Assimilated ground temperature from the GEOS DAS (DAS_35) will provide 3-hour estimates combining MODIS ground temperature information with pressure, temperature, wind, and moisture observations.

The third task involves improving the reliability of evapotranspiration estimates at the watershed scale. The Penman-Monteith method is a preferred method of computing evapotranspiration (ET) from agricultural crops. However, the model requires estimates of temperature, albedo, reference crop height, and short wave radiation at crop surface that are not typically available in rural environments. Moreover, the type of crop impacts the growth stage water use coefficients. Allen et al. (1989) previously related the reference crop height to the LAI. However, more work needs to be done on each of these parameters to improve the utility of remotely sensed data. Through a combination of high resolution images, ground-based measurements, and MODIS imagery, improved predictions for ET will be generated.

Partnership Opportunities

There are ample opportunities for partnerships within the watershed on both the Idaho and Washington sides of the border. Federal, state, and local agencies, NGOs, and university researchers are constantly monitoring water quantity and quality issues in the Pacific Northwest due to the importance of water on our way of life.