**Climate Science Connections to Vulnerability Assessments Proposal**

**Project title:** Projecting climate change effects on cottonwood and willow seed dispersal phenology, flood timing, and seedling recruitment in western riparian forests

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**Project Summary**

Management target – riparian ecosystems

Our proposed research is aimed at predicting effects of climate change on cottonwood (*Populus* spp.) and willow (*Salix* spp.) regeneration in western North American riparian corridors. Throughout western North America, riparian forests support a large proportion of invertebrate, amphibian, reptile, mammal and breeding bird species (Knopf & Samson, 1994, Naiman *et al.*, 2005, Warner & Hendrix, 1984), provide critical habitat for Neotropical migrant birds (Skagen *et al.*, 2005), supply the allochthonous stream inputs and shade that support aquatic communities (Naiman *et al.*, 2005), and increase regional biodiversity (Sabo *et al.*, 2005). Most of these forests are dominated by native cottonwood and willow trees, as well as exotic trees such as tamarisk (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolia*) (Friedman *et al.*, 2005).

Riparian corridors are recognized as critical habitat for diverse wildlife assemblages in the Great Plains, Plains and Prairie Pothole, Great Northern, and Southern Rockies LCCs. The Great Plains LCC lists prairie rivers, streams and riparian corridors as high-priority habitats for rare fish and birds (http://www.greatplainslcc.org/about/priorities/), including Bell's vireo (*Vireo bellii*), which breeds and has greater nest survival in cottonwood forests (Brand *et al.*, 2010, Swanson, 1999). The Southern Rockies LCC operating plan states that the Colorado River and Rio Grande systems are "highly valuable to both human and natural environments" and "support high concentrations of wildlife, including numerous endemic species" (http://www.usbr.gov/WaterSMART/lcc/docs/srlcc/SouthernRockiesLCCFinalOperatingPlan.pdf). The Plains and Prairie Pothole LCC describes the riparian corridors of the Missouri, Yellowstone, and Red River of the North river systems as "ecological magnets" for wildlife (http://www.fws.gov/midwest/climate/LCC/PPP/documents/PPP_fy11_final_%20projects.pdf). The Great Northern LCC lists riparian systems and the ecological services they provide as one of the agreed-upon values of GNLCC partners (http://nrmsc.usgs.gov/files/gnlcc/pdf/GNLCC_Brochure_Web.pdf).

With regard to specific LCC research priorities, models that inform habitat protection and management of riparian ecosystems are a research priority for the Southern Rockies LCC (Kevin Johnson, LCC coordinator, personal communication). Similarly, the Plains and Prairie Pothole LCC is interested in research that links downscaled climate projections, streamflow hydrology, and riparian forest succession (Mike Olson, personal communication). Climate change effects on riparian vegetation and ecosystem services were recently identified as a research priority in a USBR and USACE survey of federal and non-federal organizations (http://www.usbr.gov/climate/userneeds/docs/LTdoc.pdf).

Western North American riparian ecosystems are already greatly altered by human water management, land development, and biological invasion (Nilsson & Berggren, 2000, Patten, 1998, Tockner & Stanford, 2002). Reduced rates of cottonwood and willow recruitment due to climate change could further reduce riparian wildlife habitat quality by further altering forest composition and structure. Less complex canopy structure would reduce bird diversity and nesting habitat, particularly of canopy-foraging and tall-shrub-foraging guilds (Scott *et al.*, 2003). Reductions in cottonwood abundance and concomitant increases in tamarisk abundance may also reduce bird population size, particularly of canopy- and shrub-nesting species (Brand *et al.*, 2010, van Riper *et al.*, 2008), as well as butterfly and reptile abundance and species richness (Nelson & Andersen, 1999, Nelson & Wydoski, 2008, Shafroth *et al.*, 2005). Fewer cottonwood and willow trees along rivers may also reduce shade and increase streamwater temperatures, and thus reduce abundance of both cold-water and warm-water fish species (Barton *et al.*, 1985, Stefan & Sinokrot, 1993, Whitledge *et al.*, 2006, Zoellick, 2004).

Climate effects on riparian ecosystems

Warmer temperatures, increased drought, and changes in streamflow hydrology due to climate change are expected to alter western North American riparian ecosystems substantially (Perry *et al.*, 2012a, Rood *et al.*, 2008, Stromberg *et al.*, 2010). We propose to examine one aspect of these effects that is currently poorly understood: effects of climate change on the relative timing of native riparian tree seed dispersal and peak streamflow, and effects of those climate-driven changes in timing on tree seedling recruitment.

Currently, cottonwood and willow seed dispersal tends to occur during or just after snowmelt peak flow (Cooper *et al.*, 1999, Stella *et al.*, 2006). This timing increases the probability that the short-lived seeds will settle on bare, moist substrates created by flooding and exposed by flow recession, and high enough above the channel to avoid ice and flood damage, which in turn increases the probability of successful seedling recruitment and forest regeneration (Mahoney & Rood, 1998).

Climate change may reduce cottonwood and willow recruitment by decoupling the timing of seed dispersal from streamflow (Rood *et al.*, 2008). Warmer temperatures are hastening the timing of spring snowmelt peak flows on

snowmelt-dominated rivers across western North America (Perry *et al.*, 2012a). Snowmelt peak flows now occur 10-30 days earlier than a century ago according to historical streamflow records (Clow, 2010, McCabe & Clark, 2005, Moore *et al.*, 2007, Regonda *et al.*, 2005, Rood *et al.*, 2008, Stewart *et al.*, 2005). Models predict that snowmelt peak flows will shift still earlier in the next century (Christensen *et al.*, 2004, Dettinger *et al.*, 2004, Hayhoe *et al.*, 2004, Leung *et al.*, 2004, Maurer, 2007, Scibek *et al.*, 2007, Stewart *et al.*, 2004) , including analyses by Drs. Hay and Viger and S. Markstrom (Hay *et al.*, 2011, Markstrom *et al.*, 2012b). The change in timing is most apparent for rivers with headwaters at lower elevations, where warmer winter temperatures lead to rainfall instead of snowfall, rain-on-snow events, and earlier snowmelt (McCabe & Clark, 2005, Regonda *et al.*, 2005), but is also evident at higher elevations (Battaglin *et al.*, 2011, Clow, 2010).

At the same time, warming is also leading to earlier plant budburst, flowering, and seed dispersal in temperate regions, because temperate plant springtime phenology is largely controlled by temperature cues (Menzel *et al.*, 2006, Parmesan, 2007). Little is known, however, about the temperature requirements for seed dispersal in riparian trees, except for Fremont cottonwood (*Populus fremontii*), Goodding's willow (*Salix gooddingii*) and sandbar willow (*Salix exigua*) seed dispersal along three river reaches in California (Stella *et al.*, 2006). To fill this knowledge gap for west-central North American cottonwood and willow species and genotypes, Drs. Perry and Shafroth collected data on local temperatures and seed dispersal phenology for plains cottonwood (*Populus deltoides* spp. *monilifera*), peachleaf willow (*Salix amygdaloides*) and sandbar willow (*Salix exigua*) in two years and at 14 sites across a latitudinal and longitudinal gradient in the Platte River Basin (Figure 1). We are currently processing these data in preparation for building temperature-driven models of seed dispersal phenology for these species (described in detail below in the Ecosystem response model section).

Given the likely changes in the timing of both peak streamflow and riparian tree seed dispersal, cottonwood and willow seed dispersal could occur substantially earlier or later than snowmelt peak flow under climate change, potentially reducing seedling recruitment. Lower cottonwood and willow survival and recruitment may reduce riparian forest canopy structural complexity and patch diversity, and thus reduce habitat quality for many riparian animals (Perry *et al.*, 2012a). Further, warming may alter the timing of seed release relative to streamflow more for some plant species than for others, and thus change riparian community composition (Rood *et al.*, 2008, Willis *et al.*, 2008). In particular, climate change may favor species that do not rely on tight coupling with the hydrograph for recruitment, including the exotic tree tamarisk, which releases seeds throughout the summer (Cooper *et al.*, 1999, Shafroth *et al.*, 1998), and Russian olive, which releases dormant seeds in the fall. In addition, climate change may favor species that respond to changes in temperature similarly to streamflow, thus maintaining the coupling of seed release and peak streamflow at an earlier date, and species that have high within-population variation in temperature requirements for seed dispersal, and therefore can adapt quickly to new streamflow timing.

Changes in the relative timing of seed dispersal and streamflow will occur within the context of many other effects of climate change on riparian ecosystems. Drs. Perry and Shafroth recently published a comprehensive review paper describing likely effects of climate change on western North American riparian streamflow, vegetation, soil processes, animals, and trophic interactions (Perry *et al.*, 2012a). Their review indicated that warmer temperatures are also reducing summer and base streamflows and altering flood magnitudes, which may increase the relative importance of moisture and fluvial disturbance as drivers of riparian ecosystem responses to global change compared to upland ecosystems. Increased drought and lower summer streamflows, like earlier snowmelt peak flows, are likely to reduce cottonwood and willow abundance, favor drought-tolerant species including tamarisk and Russian olive, and reduce habitat quality for many riparian animals. In addition, Drs. Perry and Shafroth recently tested effects of elevated atmospheric $CO_2$ and drought stress on cottonwood, willow, tamarisk, and Russian olive seedling growth and physiology in a greenhouse experiment (Perry *et al.*, 2012b)

Dr. Hay and colleagues have modeled effects of climatic change on water resources for over 20 years. Most recently, Dr. Hay and colleagues evaluated the hydrologic response of different climate change emission scenarios for the 21st century in selected basins from different hydro-climatic regions across the US (Battaglin *et al.*, 2012, Bjerklie *et al.*, 2012, Chase *et al.*, 2012, Christiansen *et al.*, 2012, Dudley *et al.*, 2012, Hay *et al.*, 2012, Hay & Markstrom, 2012, Hay *et al.*, 2011, Hunt *et al.*, 2012, Koczot *et al.*, 2012, Markstrom *et al.*, 2012a, Markstrom *et al.*, 2012b, Mastin *et al.*, 2012, Risley *et al.*, 2012, Vining *et al.*, 2012, Walker *et al.*, 2012). As part of this study, climatic change research papers were produced that examined: the effects of scale on hydrology (Battaglin *et al.*, 2011); trends in snowfall and groundwater recharge (Bjerklie *et al.*, 2011); impacts on the growing season (Christiansen *et al.*, 2011); effects of baseline conditions (Koczot *et al.*, 2011); changes in spring snowpack (Mastin *et al.*, 2011); statistical comparisons of watershed-scale response (Risley *et al.*, 2011); hydrologic effects of urbanization and climate change (Viger *et al.*, 2011); and impacts on the 1.5-yr flood flow (Walker *et al.*, 2011).

Climate variables currently used

Daily values of precipitation and maximum and minimum temperature are required for the proposed research. The Downsizer software, a GUI-based application for browsing, acquiring, and formatting time-series data for hydrologic models (Ward-Garrison *et al.*, 2009), will be used to retrieve precipitation and temperature data from SNOTEL and NOAA Co-op stations for current conditions. Future conditions can be provided by: (1) statistically downscaled GCM output from Hayhoe (1/8° grids and select stations); (2) bias-corrected, spatially-downscaled (BCSD) output from Maurer and Brekke (http://gdodcp.ucllnl.org/ downscaled_cmip3_projections/dcpInterface.html); 1/8° grids); (3) SHODAN – a tool developed by MoWS using the downscaling approach outlined in Hay *et al.* (2011) and Markstrom *et al.* (2012b); (4) dynamically downscaled 15-km grids from Hostetler *et al.* (2011); (5) 50-km grids from NARCCAP (http://www.narccap.ucar.edu/about/ index.html); and (6) dynamically downscaled 36-km grids from John Stamm (South Dakota WSC, unpubl. data).

Daily values of relative humidity and wind (speed and direction) also are required for one of the models we will use (*SnowModel*) and will be calculated using the *MicroMet* (Liston & Elder, 2006b), a meteorological model that produces high-resolution atmospheric forcings. *MicroMet* assumes that at least one value of air temperature, relative humidity, wind speed, wind direction, and precipitation is available for each time step, somewhere within, or near, the simulation domain. These variables are collected at most meteorological stations or can be extracted from model gridpoint data. Future conditions can be provided by the dynamical downscaling described above, and/or SHODAN.

The data sources outlined above differ with respect to data quality, quantity (time period), resolution, and uncertainty. Current and future conditions will be compared using each data source and ultimately we will use the data sources that are most appropriate for our particular application. We expect to rely on frequent interactions with NCPP by telephone, e-mail, and the proposed workshops to guide our decisions on which climate data sources to use. These conversations will include (1) initial evaluation of the proposed data sources and potential alternative sources that NCPP deems feasible for our study, (2) examination of the quality of historical and projected climate data obtained, and (3) discussions of the effects of climate data source on ecosystem response model projections.

Ecosystem response model

We propose to link hydrological (*PRMS*, *WB*, and *SnowModel*), phenological (*UniForc*), and seedling recruitment (*HEC-EFM*) models to examine effects of changing climate on the relative timing of cottonwood and willow seed dispersal and peak streamflow, and effects on seedling recruitment. Although cottonwood and willow regeneration is important for riparian wildlife habitat across western North America (including all regions covered by the LCCs associated with the NC CSC), we are focusing on the upper South Platte River Basin (uSPRB) as a case study area (25,016 $km^2$; Figure 1), leveraging current hydrologic modeling and seed dispersal phenology work in the uSRPB.

*Hydrologic modeling*

Streamflow in the uSPRB will be modeled on a daily time-step using the Precipitation Runoff Modeling System (*PRMS*) (Hay *et al.*, 2011) and a monthly time-step using the Water Balance (*WB*) model (McCabe & Markstrom, 2007). The *WB* model produces natural streamflow that will be used to help calibrate the volume estimates produced from *PRMS*. In addition, a detailed snowpack model (*SnowModel*) (Liston & Elder, 2006a) will be loosely coupled to *PRMS* and applied at selected headwaters to test whether a more explicit modeling of snowpack is required to predict the effects of climate change on peak snowmelt.

Both *PRMS* and the *WB* model rely on parameters about spatial segregations of a watershed called Hydrologic Response Units (HRUs). For this study, HRUs will be derived at two scales using the approach that the USGS National Research Program (NRP) Modeling of Watershed Systems (MoWS) team has developed to create a logically and spatially consistent geospatial fabric of HRUs for the National Hydrologic Model (NHM) from the National Hydrography Dataset (NHDPlus) of flowlines and catchments. This will have the benefit of enabling outside work to be more easily integrated into the study, including other hydrologic or climate model forecasts, and increasing the impact of the study on a broader geographic region. The first set of coarse-scale HRUs will be ~ 75 $km^2$, which explicitly represents fifth Strahler order drainages in addition to a number of other points of interest (e.g., stream gauges, confluences, reservoirs, nodes defined by the USGS National Water Quality Assessment Program SPARROW model, flood forecasting points [National Weather Service], and locations where flow disappears due to swales and sinks). The second set will feature finer-scale HRUs (~ 1 $km^2$) that more closely match the native resolution of the NHDPlus dataset. The *PRMS* and *WB* models will be applied at the coarse resolution for the entire uSPRB. At selected headwaters, *PRMS* also will be applied at the fine resolution and the spatial and temporal variations and evolution of the snowpack will be compared with those produced by *SnowModel*.

*WB model*: The *WB* model (McCabe & Markstrom, 2007) on coarse resolution HRUs will be used to simulate current and future hydrological conditions in the uSPRB on a monthly time step. This will provide a quick

preliminary/synoptic view of the hydrology and will be a valuable tool when calibrating the *PRMS* model. The *WB* model has been used successfully to assess the hydrologic effects of climate change in numerous contexts (e.g., Gray & McCabe, 2010, Hay & McCabe, 2010). It uses an accounting procedure to compute the allocation of water among various components of the hydrologic system, and includes the concepts of climatic water supply and demand, seasonality in climatic water supply and demand, snow accumulation and melt, and soil-moisture storage (McCabe & Markstrom, 2007). The *WB* model uses distributed-times series of monthly precipitation and temperature as inputs. A multi-objective, step-wise calibration procedure will be employed that uses MODIS snow-covered area, stream gauge data, and any other ancillary data sets deemed appropriate as calibration data sets (see Hay *et al.*, 2006a, Hay *et al.*, 2006b).

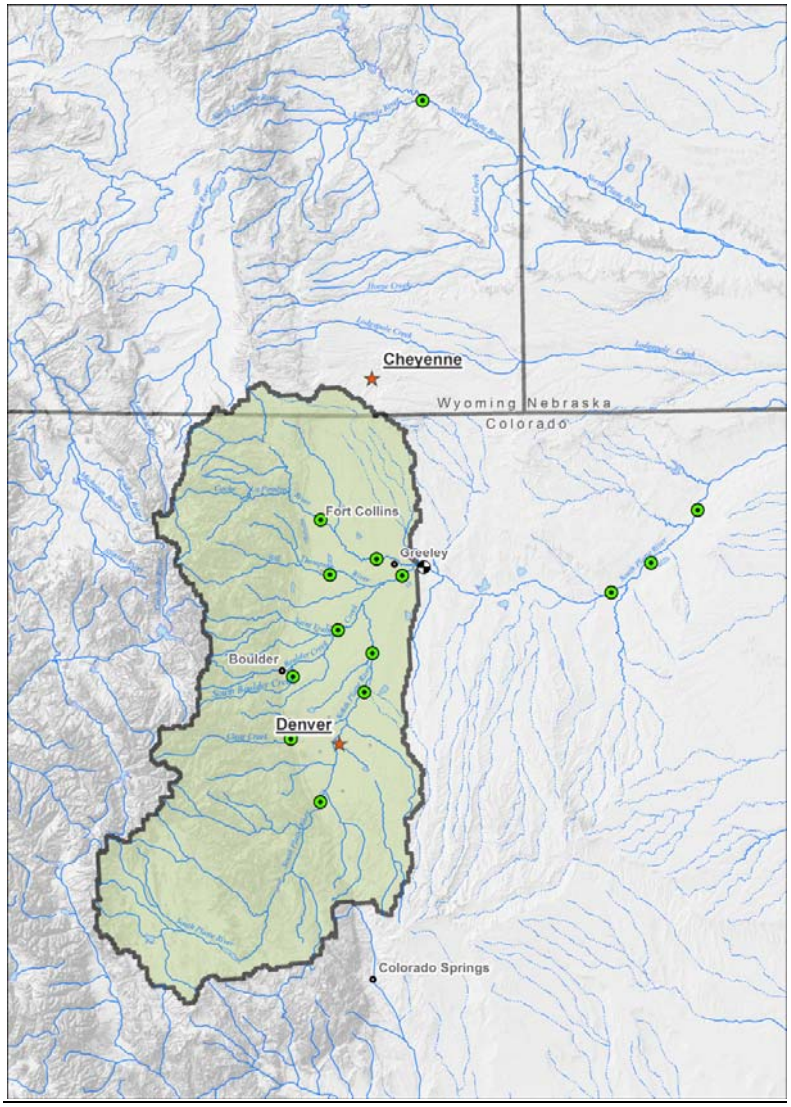


**Figure 1**. Study area of the proposed research. The green shaded area indicates the portion of the South Platte River Basin that will be modeled hydrologically. The black and white circle indicates USGS streamflow gage 06754000, near Kersey, CO. The green circles mark the 14 seed dispersal phenology field sites. The wider range of the phenology sites (relative to the hydrologic area) was selected to increase spatial variation in temperature among sites, thus substituting spatial for temporal variation in temperature for calibration of dispersal phenology models.

*PRMS*: The watershed hydrology model *PRMS* (Leavesley *et al.*, 1983, Markstrom *et al.*, 2008) will be used to simulate current hydrological conditions and project future hydrological conditions in the uSPRB on a daily time step for both coarse and nested fine-resolution HRUs. *PRMS* is a deterministic, distributed-parameter, process-based model used to simulate and evaluate the effects of various combinations of climate and land use on basin response.

Response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water-balance relations, streamflow regimes, soil-water relations, and groundwater recharge. Each hydrologic component used for generation of streamflow is represented within *PRMS* by a process algorithm that is based on a physical law or an empirical relation with measured or calculated characteristics.

Distributed-parameter capabilities of *PRMS* are provided by partitioning a basin into HRUs. For each HRU, a water balance is computed each day and an energy balance is computed twice each day. *PRMS* is conceptualized as a series of reservoirs (impervious zone, soil zone, subsurface, and groundwater; Figure 2) whose outputs by HRU combine to produce the daily basin response using one of three options (Viger *et al.*, 2010): (1) a no-flow routing procedure in which the sum of the responses of all HRUs, weighted on a unit-area basis, produces the daily basin response; (2) a cascading-flow routing procedure; or (3) a Muskingum-flow routing procedure.

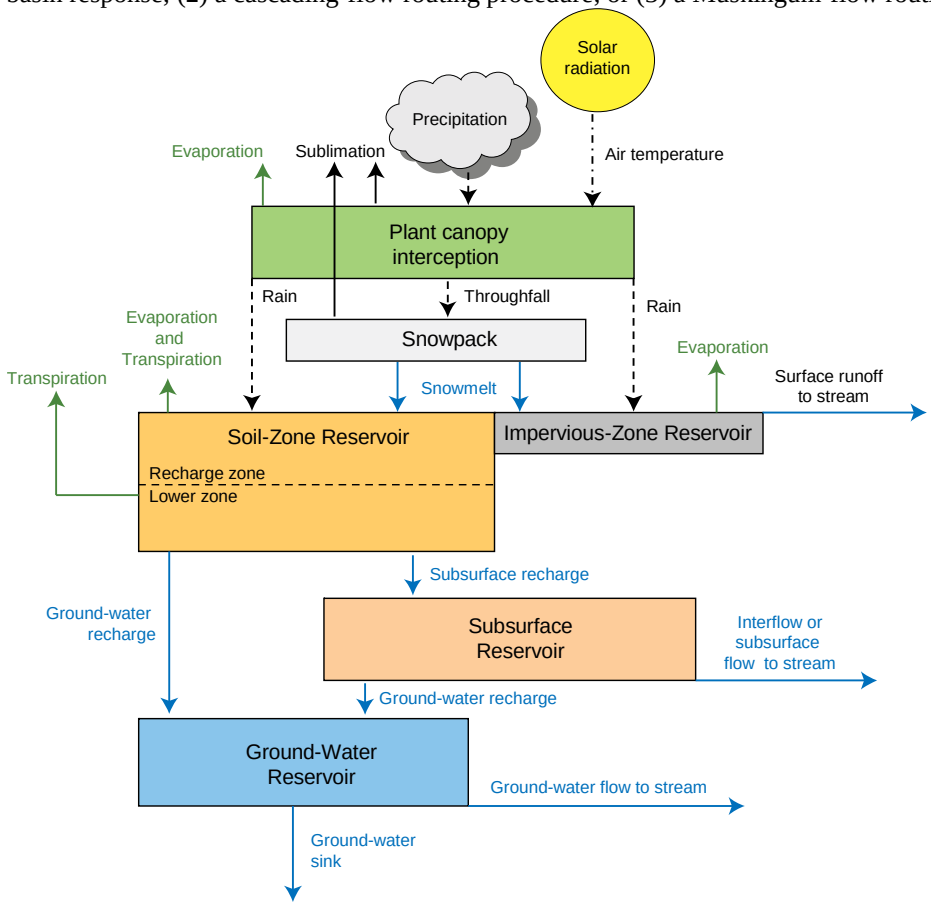


**Figure 2.** Schematic diagram of a watershed and its inputs simulated by *PRMS* (from Markstrom *et al.*, 2008).

<u>*SnowModel*</u>: SnowModel (Liston & Elder, 2006a) will be used to model the spatial and temporal variations and evolution of local area snow properties and characteristics and replace the snow module simulations of *PRMS* at the fine-scale resolution for selected headwater watersheds. *SnowModel* is a spatially-distributed snow-evolution modeling system designed for application in all landscapes, climates, and conditions where snow occurs. It is an aggregation of four sub-models: *EnBal* (Liston, 1995, Liston *et al.*, 1999) calculates surface energy exchanges and snowmelt; *SnowPack* (Liston & Hall, 1995, Liston & Mernild, 2011) simulates snow depth, density, and water-equivalent evolution; *SnowTran-3D* (Liston *et al.*, 2007, Liston & Sturm, 1998) accounts for snow redistribution by wind; and *SnowAssim* (Liston & Hiemstra, 2008) assimilates field and remote sensing datasets.

Processes simulated by *SnowModel* include: accumulation from snow precipitation; blowing-snow redistribution; blowing-snow and static-surface sublimation; interception, unloading, and sublimation within forest canopies; snow-density evolution; and snowpack ripening and melt. *SnowModel* incorporates first-order physics required to simulate snow evolution within each of the global snow classes (i.e., Ice, Tundra, Taiga, Warm Forest [or Alpine], Prairie, Maritime, and Ephemeral) defined by Sturm *et al.* (1995) and Liston and Sturm (2011).

*Phenological modeling*

Seed dispersal phenology (dates of catkin opening) will be predicted using a simplified version of the unified budburst model (*UniForc*) (Chuine, 2000), with separate models for plains cottonwood, peachleaf willow and sandbar willow. *UniForc* predicts when springtime phenological events (e.g., seed dispersal) will occur from mean daily temperatures and four parameters ($b_f$, $c_f$, $F^*$ and $t_1$). Seed dispersal occurs when the state of forcing ($S_f$) reaches the value $F^*$, where $S_f$ is the sum of forcing units accumulated from the date $t_1$, and $b_f$ and $c_f$ are exponents used in calculating forcing units from temperature. More complex versions of the unified budburst model include chilling or photoperiod requirements, but require more data for parameterization and most often do not improve model predictions (Chuine, 2000).

The *UniForc* models will be calibrated and validated using 2010 and 2011 local temperature data (measured with Onset HOBO® dataloggers) and seed dispersal phenology data for 336 trees (98 plains cottonwoods, 98 peachleaf willows, and 140 sandbar willows) in 14 uSPRB sites (Figure 1). The 14 sites were selected to span a latitudinal and longitudinal gradient within and near the uSPRB, thus maximizing variation in temperature among sites and allowing us to substitute spatial climatic variation for temporal climatic variation when calibrating our models. The warmest site (Adams County Regional Park, Henderson, CO) was on average 2.66ºC warmer than the coolest site (Chatfield State Park, Littleton, CO) during the 2010 and 2011 growing seasons.

*Recruitment modeling*

Seedling recruitment will be predicted using the Ecosystems Functions Model (HEC-EFM; USACE, 2009) linked to a HEC-River System Analysis (HEC-RAS) hydraulic model for a representative uSPRB stream segment following Shafroth *et al*. (2010). HEC-EFM analyses involve (1) statistical analyses of relationships between hydrology and ecology, (2) hydraulic modeling, and (3) use of Geographic Information Systems (GIS) to display results and other relevant spatial data. HEC-EFM uses time-series of daily mean flow and stage, and user-defined parameters for variables such as season, duration, rate of change, and frequency of occurrence to compute statistics relevant to an ecological response. Parameters are based on hydrologic drivers of ecosystem processes and the flow requirements of different life stages of the study species. HEC-EFM computes the flow and stage (statistical results) that meet the parameters defined for the ecological responses of interest. This process can be repeated for multiple flow scenarios to gain insights about how different flow regimes may influence ecosystem dynamics.

To model seedling establishment in the uSPRB, we will simulate river stage for predicted hydrographs from our hydrologic modeling (described above) using an existing HEC-RAS model for a representative river reach (e.g., Poudre River in Ft. Collins, CO or Boulder Creek in Boulder, CO). HEC-EFM will be used to integrate these stage-discharge data with seed dispersal phenology predictions from our *UniForc* models to define suitable recruitment locations for plains cottonwood, peachleaf willow, and sandbar willow. Cottonwood and willow seedling recruitment also depends on rates of flow recession that are slow enough that seedlings do not dessicate. The rates for the maximum stage recession that the seedlings would be able to survive (4-6 cm; Amlin & Rood, 2002, Shafroth *et al.*, 1998) also will be entered as statistical parameters in HEC-EFM. Interspecific differences in the timing of seed dispersal and recession rate tolerance can manifest as differences in species relative abundance or spatial separation of species under different flow scenarios.

Incorporating translational climate information with ecosystem response models

We propose to predict changes in timing of seed dispersal relative to snowmelt peak streamflows under different future climate scenarios by forcing our *PRMS*, *WB*, *SnowModel*, and *UniForc* models with historical and projected future climate scenarios. With the model projections, we will examine current and future temporal trends in the length of time between seed dispersal and peak streamflow at five of the 14 uSPRB sites, for which USGS historical streamflow records are available. Then, we will predict effects of these trends on seedling establishment along a specific uSPRB stream segment by forcing our *HEC-EFM* model with historical and projected future dispersal phenology and streamflow.

To make the most informative predictions, we will need to use the best available historical and down-scaled, projected future climate data. We plan to compare the quality of results from the data sources listed in the 'Climate variables' section above for current climate conditions, with guidance from NCPP on additional appropriate data sources to consider for our study region and application. By forcing our models with climate data from multiple sources and SRES climate scenarios, we will evaluate the uncertainty associated with current climate conditions and projected future climate, and how those uncertainties affect the ecosystem response model projections.

Management implications

Our results will be relevant to management of riparian communities throughout much of North America. Plains cottonwood and sandbar willow are the two most common native riparian woody species in the western US

(Friedman *et al.*, 2005), and most native riparian forests are dominated by those and other cottonwood and willow species. Further, the importance of seed dispersal timing relative to streamflow for cottonwood and willow recruitment is widely recognized (Karrenberg *et al.*, 2002, Perry *et al.*, 2012a, Rood *et al.*, 2008, Yarnell *et al.*, 2010). Therefore, changes in phenology and/or streamflow that hinder cottonwood or willow recruitment would affect riparian habitat quality across central and western North America. Our phenological and hydrologic models will allow us to project changes in the relative timing of cottonwood and willow seed dispersal and peak streamflow across the 25,016 $km^2$ uSPRB. Larger-scale projections will be possible in the future with the completion of the NHM by the MoWS team and collaborators, of which the *PRMS* component of this proposal will be a part.

If we find that climate change is likely to reduce riparian seedling recruitment by decoupling the timing of seed dispersal from peak streamflow, our results would have several implications relevant to LCC resource managers. First, ecosystem managers might respond by planning for active revegetation of native riparian forests, especially in high-priority areas for wildlife that depend on cottonwood and willow forests. Propagules (seeds or cuttings) or rooted plants could be planted at appropriate times relative to streamflow, or given supplemental water (Friedman *et al.*, 1995, Rood *et al.*, 2003). In addition, our research on seed dispersal phenology will provide insights into variation in seed dispersal timing among individuals, which might yield opportunities to select genotypes for revegetation that have temperature requirements for seed dispersal that are better suited to a future, warmer climate (Grady *et al.*, 2011). Second, ecosystem managers might plan for lower cottonwood and willow abundance by identifying and promoting alternative riparian tree species that provide similar wildlife habitat to cottonwood and willow stands. Third, on regulated rivers, managers might address these changes by working with water managers to schedule dam releases that favor cottonwood and willow recruitment by releasing stream water in sync with seed dispersal, where water storage and water management requirements allow for such releases (e.g., Rood *et al.*, 2003, Shafroth *et al.*, 2010). Our *UniForc* models of seed dispersal phenology could be used to forecast the timing of tree seed dispersal from local climate data, and thus inform management decisions of when to release water.

Workshops

We will have two workshops involving the proposal team, NCPP staff, LCC staff, and potentially others with relevant management or scientific expertise (e.g., Susan Linner, FWS Ecological Services Colorado Field Supervisor; Mike George,FWS Nebraska Field Office Field Supervisor). The first workshop will occur in summer 2012, with the goal of discussing appropriate climate data sources for the subsequent modeling work and brainstorming additional ways to make the research most useful for both climate change research and riparian ecosystem management. The second will occur in fall 2013, with the goals of communicating research results and discussing future research directions of interest to riparian managers given our model results.

Deliverables

Annual progress reports will be submitted to the NC CSC in December 2012 and 2013. A summary of our results and management implications will be submitted to the Great Plains, Plains and Prairie Pothole, Great Northern, and Southern Rockies LCCs in December 2013.

We plan to publish at least one USGS Fact Sheet describing our research results and their implications for likely effects of climate change on riparian tree seed dispersal phenology relative to streamflow and seedling recruitment. In addition, we expect at least three publications in peer-reviewed journals to result from this project, including examinations of (1) the historic timing of cottonwood and willow seed dispersal relative to peak streamflow in the uSPBR, (2) projected changes in the timing of cottonwood and willow seed dispersal relative to peak streamflow under different future climate scenarios and potential effects on seedling recruitment, and (3) sources of uncertainty in the current and future hydrologic model application.

Research schedule

| Year | Activities |
|---|---|
| 2012 | • Calibrate *PRMS*, *WB*, *SnowModel*, and *UniForc* for the uSPRB<br>• Workshop to initiate NCPP collaboration and incorporate insights from LCCs<br>• Submit annual progress report to NC CSC |
| 2013 | • Link models and force them with historic and projected future climate data<br>• Prepare and submit manuscripts<br>• Workshop to discuss results with NCPP and LCC partners<br>• Submit annual progress report to NC CSC and summary of research findings to LCCs |
| 2014 | • Prepare and submit manuscripts |

**Proposal Data Management Plan**

**Project Title:** Projecting climate change effects on cottonwood and willow seed dispersal phenology, flood timing, and seedling recruitment in western riparian forests

**Data Inputs – Existing Data Collections**

| **1** | **The *PRMS* watershed hydrology model** |
|---|---|
| Description: | The *Precipitation Runoff Modeling System* (*PRMS*) is a deterministic, distributed-parameter, process-based model used to simulate and evaluate the effects of various combinations of precipitation, climate, and land use on basin response (Leavesley *et al.*, 1983, Markstrom *et al.*, 2008). It will be used to simulate current and projections of future hydrological conditions in the study area on a daily time step for both coarse and nested fine-resolution hydrologic response units. |
| Restrictions: | None |
| **2** | **The *WB* watershed hydrology model** |
| Description: | The *Water Balance* (*WB*) model uses an accounting procedure to compute the allocation of water among various components of the hydrologic system (McCabe & Markstrom, 2007). It will be applied on coarse resolution hydrologic response units and will simulate current and future hydrological conditions in the study area on a monthly time step. This will provide a quick preliminary/synoptic view of the hydrology and will be a valuable tool for the more in-depth studies. |
| Restrictions: | None |
| **3** | **The *SnowModel* snowpack simulation model** |
| Description: | *SnowModel* is a spatially-distributed snow-evolution modeling system that simulates accumulation from snow precipitation, blowing-snow redistribution, blowing-snow and static-surface sublimation, interception, unloading, and sublimation within forest canopies, snow-density evolution, and snowpack ripening and melt (Liston & Elder, 2006a). It is an aggregation of four sub-models: *EnBal* (Liston, 1995, Liston *et al.*, 1999) calculates surface energy exchanges and snowmelt; *SnowPack* (Liston & Hall, 1995, Liston & Mernild, 2011) simulates snow depth, density, and water-equivalent evolution; *SnowTran-3D* (Liston *et al.*, 2007, Liston & Sturm, 1998) accounts for snow redistribution by wind; and *SnowAssim* (Liston & Hiemstra, 2008) assimilates field and remote sensing datasets. In addition, *MicroMet*, a meteorological model that produces high-resolution atmospheric forcings (Liston & Elder, 2006a), can be used to calculate daily relative humidity and wind (speed and direction) for *SnowModel*. *SnowModel* will be used to model the spatial and temporal variations and evolution of local area snow properties and characteristics in the study area and replace *PRMS* snow module simulations at the fine-scale resolution. |
| Restrictions: | None |
| **4** | **The Unified Budburst Model (*UniForc*)** |
| Description: | *UniForc* is a simple mathematical model of plant springtime phenology (Chuine, 2000). It will be used to predict seed dispersal phenology from daily mean temperature and four parameters. |
| Restrictions: | None |
| **5** | **The Ecosystems Functions Model (*HEC-EFM*)** |
| Description: | The Ecosystem Functions Model (HEC-EFM) is designed to help study teams determine ecosystem responses to changes in the flow regime of a river or connected wetland. HEC-EFM analyses involve: 1) statistical analyses of relationships between hydrology and ecology, 2) hydraulic modeling, and 3) use of Geographic Information Systems (GIS) to display results and other relevant spatial data. It will be used in conjunction with HEC-RAS to predict locations of successful cottonwood and willow seedling recruitment along a representative study reach in the South Platte River Basin. |
| Restrictions: | None |
| **6** | **River Analysis System (HEC-RAS)** |
| Description: | HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network |

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| | of natural and constructed channels. It will be used in conjunction with HEC-EFM to predict locations of successful cottonwood and willow seedling recruitment along a representative study reach in the South Platte River Basin. |
| Restrictions: | None |
| **7** | **Seed dispersal phenology data** |
| Description: | Data on dates of catkin opening for 336 trees at 14 riparian sites in the South Platte River Basin. Also, temperature measurements, taken every three minutes, from two dataloggers at each site from January 2010 to February 2012. Data are currently stored in Excel spreadsheets and original paper datasheet files at the Fort Collins Science Center. |
| Restrictions: | None |
| **8** | **SNOTEL climate records** |
| Description: | Climate and snow data collected at the NRCS Snow Telemetry (SNOTEL) stations throughout the western US is maintained and distributed by the USDA-NRCS National Water and Climate Center, Snow Survey and Water Supply Forecasting Program through their website (http://www.wcc.nrcs.usda.gov/snow/). This data is generally available real-time, but the quality-controlled version of the data is not available until the following water year or later. NRCS has informed us that there is now a web service which makes this data available (as opposed to scraping it from the web pages or using a "back door" ftp site), but we have been unable to confirm this. |
| Restrictions: | None |
| **9** | **NOAA co-op climate records** |
| Description: | Climate data collected at the NOAA National Climatic Data Center for sites around the globe are made available through their website (http://www.ncdc.noaa.gov). In the past; we have scraped the station data from this site, state by state, by hand, and processed it into a format (NetCDF) that we could use. We kept these files on our own system. Unfortunately, this is not real-time data and the downloading process is very labor intensive. We were recently told that there are now web services that make this data available and are currently investigating this. |
| Restrictions: | Historical daily climate station data was sold by the NCDC to users. We (at the USGS) can get it free of charge because we are a cooperating government agency, but are not able to share it with our cooperators. With the switch to the new web service access, it is not clear whether NCDC still charges for historical station data. |
| **10** | **MODIS remotely-sensed data** |
| Description: | MODIS data (and derived products) from the Terra and Aqua satellite platforms is processed, archived, and distributed by the Land Processes Distributed Active Archive Center (LP DAAC; https://lpdaac.usgs.gov/). In the past we have used MODIS snow-covered-area data to evaluate *PRMS* performance with respect to accumulation and ablation of snowpacks. Also, this data is useful for determining the seasonal snow line when modeling watersheds in mountainous terrain (like the upper South Platte River Basin). For this project, we would like to explore the potential use of MODIS data for identification of burned areas and development of seasonal changes in vegetative cover for our hydrologic models |
| Restrictions: | None |
| **11** | **Stoner, Hayhoe, and Yang statistically-downscaled GCM output** |
| Description: | Statistically-downscaled GCM output for the US from Stoner, Hayhoe, and Yang (1/8$^{\circ}$ grids and select stations) is available through the USGS GDP (http://cida.usgs.gov/climate/hayhoe_projections.jsp) |
| Restrictions: | These data are currently designated as provisional. They are available to USGS personnel and cooperators. They will be publically accessible, with no restrictions, pending USGS Directors approval. |
| **12** | **Maurer, Brekke, Pruitt, and Duffy statistically-downscaled GCM output** |
| Description: | 1/8$^{\circ}$ Monthly, Bias-Corrected, Spatially-Downscaled Climate Projections for the conterminous US by Maurer, Brekke, Pruitt, and Duffy are available through the USGS GDP (http://cida.usgs.gov/climate/maurer_projections.jsp) |
| Restrictions: | None. See the "Terms of Use" at http://cida.usgs.gov/climate/maurer_projections.jsp |

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| **13** | **SHODAN projected climate** |
| Description: | SHODAN is a software program and internal database that can produce statistically downscaled climate data for any station (or set of stations) for which historical (any part of the last half of the 20th century) climate data exist. This program uses the "delta change" method and is based on selected GCM simulations of selected carbon emission scenarios from the IPCC CMIP3 modeling data archive. Although this program has been used extensively in the past, data produced by this program is generally being "phased out" because more current downscaling approaches are being developed. |
| Restrictions: | This program is run internally by USGS personnel on an "as needed" basis. |
| **14** | **Hostetler dynamically-downscaled GCM output** |
| Description: | Dynamically-downscaled climate simulations over North America by Hostetler *et al*. (Hostetler *et al.*) are available through the USGS GDP (http://cida.usgs.gov/climate/hostetlerprojections.jsp) |
| Restrictions: | None. See the "Disclaimer and Terms of Use" at http://cida.usgs.gov/climate/hostetlerprojections.jsp |
| **15** | **NARCCAP projected climate** |
| Description: | Dynamically-downscaled climate simulations over North America at 50-km grids from NARCCAP are available at their website (http://www.narccap.ucar.edu). MoWS project personnel are scheduled to take the multiday NARCCAP data course. |
| Restrictions: | Must be a registered NARCCAP user to access the data |
| **16** | **Stamm dynamically-downscaled GCM output** |
| Description: | Dynamically-downscaled climate simulations over the conterminous US at 36-km grids from John Stamm (South Dakota Water Science Center) and collaborators were recently given to USGS FORT scientists, and will become publicly available soon. |
| Restrictions: | None |
| **17** | **USGS streamflow records** |
| Description: | Streamflow data for the US are collected, maintained, and distributed by the USGS (http://waterdata.usgs.gov/nwis). We will use mean daily and monthly streamflow data from selected streamflow gauges within the study area to calibrate the *PRMS* and *WB* models. |
| Restrictions: | None |
| **18** | **National Elevation Dataset** |
| Description: | The National Elevation Dataset (NED, http://ned.usgs.gov/) is the primary elevation data product of the USGS and is a seamless dataset with the best available raster elevation data of the conterminous US, Alaska, Hawaii, and territorial islands. |
| Restrictions: | None |
| **19** | **National Hydrography Dataset** |
| Description: | The National Hydrography Dataset (NHDPlus, http://www.horizon-systems.com/nhdplus/) is an integrated suite of application-ready geospatial data products including stream network, feature naming, and value-added attributes. |
| Restrictions: | None |
| **20** | **National Land Cover Database** |
| Description: | The National Land Cover Database 2006 (NLCD2006, http://www.mrlc.gov/nlcd2006.php) is a 16-class land cover classification scheme that has been applied consistently across the conterminous US at a 30-m spatial resolution. We also use previous versions of the NLCD where necessary. |
| Restrictions: | None |
| **21** | **USDA-NRCS US General Soil Map** |
| Description: | The USDA-NRCS US General Soil Map (STATSGO2, http://soils.usda.gov/survey/geography/statsgo/) is an inventory of soil association units for the US, based on soil survey data, and on other landscape features and climate where soil survey data are unavailable. |
| Restrictions: | None. These data can be downloaded from the NRCS Soil Data Mart (http://soildatamart.nrcs.usda.gov/SDM Web Application/default.aspx). However, data in this format requires considerable processing before it can be used in a modeling context. The USGS has internal databases of processed soils data, but these are not available for external |

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| | access because it is not our data. |
| **22** | **USDA-NRCS Soil Survey Geographic** |
| Description: | The USDA-NRCS Soil Survey Geographic database (SSURGO, http://soils.usda.gov/survey/geography/ssurgo/) provides soil survey data for selected counties and areas in the US. |
| Restrictions: | None. These data can be downloaded from the NRCS Soil Data Mart (http://soildatamart.nrcs.usda.gov/SDM Web Application/default.aspx). However, data in this format requires considerable processing before it can be used in a modeling context. The USGS has internal databases of processed soils data, but these are not available for external access because they are not our data. |

**Data Inputs – New Data Collection**

| **1** | **Projected seed dispersal phenology** |
|---|---|
| Description: | Projected historic, contemporary, and future dates of catkin opening for three riparian tree species at multiple riparian sites within the 12,016 $km^2$ uSPRB. |
| Data Management Budget: | Approximately 5% of Dr. Perry's budgeted hours and salary will go to management of these data. |
| Protocols: | Dates of catkin opening will be projected by forcing *UniForc* phenology models with historic, contemporary, and projected future climate data. |
| Quality Checks: | When data processing is complete, randomly-selected model runs will be repeated and checked to ensure that the results are equivalent. |
| Exclusive Use: | We plan to make all data publicly available once the project results have been published in peer-reviewed scientific journals. We hope to publish the results quickly, but due to the uncertainty of the peer-review process, we might not make the data publicly available until two years after project completion. |
| Restrictions: | None |
| Contact: | Patrick B. Shafroth, shafrothp@usgs.gov, (970) 226-9327 |
| **2** | **Projected hydrologic response in the uSPRB** |
| Description: | *PRMS*, the *WB* model, and *SnowModel* will be used to produce detailed (spatial and temporal) projections of current and future hydrologic conditions in the uSPRB. The projections will include over 200 variables (some listed by (Markstrom *et al.*, 2008) describing streamflow, components of flow, soil moisture, groundwater, evapotranspiration, and snowmelt. |
| Data Management Budget: | The data will be made available through the data portal at the Center for Data Analytics. The requested budget for this activity is $12K, with $50K being provided in kind. |
| Protocols: | Various. See http://cida.usgs.gov/climate/gdp/ for protocols pertaining to specific data sets. |
| Quality Checks: | All simulations of current hydrologic conditions will be evaluated against measured values of streamflow. Methodology is described by Hay *et al*. (2011) and Markstrom *et al*. (2012b). |
| Exclusive Use: | We plan to make all data publicly available once the project results have been published in peer-reviewed scientific journals. We hope to publish the results quickly, but due to the uncertainty of the peer-review process, we might not make the data publicly available until two years after project completion. |
| Restrictions: | None |
| Contact: | Lauren Hay, lhay@usgs.gov, (303) 236-5034; Nathaniel Booth, nlbooth@usgs.gov, (608) 821-3822 |
| **3** | **Projected seedling recruitment** |
| Description: | Projected historic, contemporary, and future abundance of surviving tree seedlings for three riparian tree species at multiple riparian sites within the 12,016 $km^2$ uSPRB. |
| Data Management Budget: | Approximately 5% of Dr. Perry's budgeted hours and salary will go to management of these data. |
| Protocols: | Numbers of surviving tree seedlings will be projected by forcing *HEC-EFM* recruitment models with historic, contemporary, and projected future streamflow and seed dispersal phenology data. |
| Quality Checks: | When data processing is complete, randomly-selected model runs will be repeated and checked to ensure that the results are equivalent. |

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| Exclusive Use: | We plan to make all data publicly available once the project results have been published in peer-reviewed scientific journals. We hope to publish the results quickly, but due to the uncertainty of the peer-review process, we might not make the data publicly available until two years after project completion. |
| Restrictions: | None |
| Contact: | Patrick B. Shafroth, shafrothp@usgs.gov, (970) 226-9327 |

**Data Outputs – Deliverables, Datasets and Products**

| **1** | **2012 Annual Report to NCPP** |
|---|---|
| Description: | Annual report of project progress up to December 2012 |
| Data Management Budget: | All data included will be managed as part of data collection. The budget allocation is described above in the "Data inputs - new data collection" section. |
| Format: | Microsoft Word document |
| Quality Checks: | Document review by all project investigators |
| Exclusive Use: | None |
| Restrictions: | None |
| Contact: | Patrick B. Shafroth, shafrothp@usgs.gov, (970) 226-9327 |
| **2** | **2012 Annual Report to NCPP** |
| Description: | Annual report of project progress up to December 2013 |
| Data Management Budget: | All data included will be managed as part of data collection. The budget allocation is described above in the "Data inputs - new data collection" section. |
| Format: | Microsoft Word document |
| Quality Checks: | Document review by all project investigators |
| Exclusive Use: | None |
| Restrictions: | None |
| Contact: | Patrick B. Shafroth, shafrothp@usgs.gov, (970) 226-9327 |
| **3** | **Report of Project Findings to LCCs** |
| Description: | Report describing major project results and conclusions |
| Data Management Budget: | All data included will be managed as part of data collection. The budget allocation is described above in the "Data inputs - new data collection" section. |
| Format: | Microsoft Word document |
| Quality Checks: | Document review by all project investigators |
| Exclusive Use: | None |
| Restrictions: | None |
| Contact: | Patrick B. Shafroth, shafrothp@usgs.gov, (970) 226-9327 |
| **4** | **USGS Fact Sheet - climate change effects on phenology and recruitment** |
| Description: | USGS Fact Sheet describing our research results and their implications for likely effects of climate change on riparian tree seed dispersal phenology relative to streamflow and seedling recruitment |
| Data Management Budget: | All data included will be managed as part of data collection. The budget allocation is described above in the "Data inputs - new data collection" section. |
| Format: | USGS Fact Sheet |
| Quality Checks: | USGS internal review process |
| Exclusive Use: | None |
| Restrictions: | None |
| Contact: | Patrick B. Shafroth, shafrothp@usgs.gov, (970) 226-9327 |
| **5** | **Journal article – historic seed dispersal phenology** |
| Description: | Scientific paper on the historic timing of cottonwood and willow seed dispersal relative to peak streamflow in the upper South Platte River Basin |
| Data Management Budget: | All data included will be managed as part of data collection. The budget allocation is described above in the "Data inputs - new data collection" section. |
| Format: | Scientific journal article |
| Quality Checks: | USGS internal review process and scientific journal external review process |
| Exclusive Use: | None |

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| Restrictions: | None |
| Contact: | Patrick B. Shafroth, shafrothp@usgs.gov, (970) 226-9327 |
| **6** | **Journal article – climate change effects on seed dispersal phenology** |
| Description: | Scientific paper on projected changes in the timing of cottonwood and willow seed dispersal relative to peak streamflow under different future climate scenarios, and projected effects on cottonwood and willow seedling recruitment on a specific South Platte River Basin stream segment |
| Data Management Budget: | All data included will be managed as part of data collection. The budget allocation is described above in the “Data inputs - new data collection” section. |
| Format: | Scientific journal article |
| Quality Checks: | USGS internal review process and scientific journal external review process |
| Exclusive Use: | None |
| Restrictions: | None |
| Contact: | Patrick B. Shafroth, shafrothp@usgs.gov, (970) 226-9327 |
| **7** | **Journal article –uncertainty in the current and future hydrologic model application** |
| Description: | Scientific paper on the sources of uncertainty in the current and future hydrologic model application |
| Data Management Budget: | All data included will be managed as part of data collection. The budget allocation is described above in the “Data inputs - new data collection” section. |
| Format: | Scientific journal article |
| Quality Checks: | USGS internal review process and scientific journal external review process |
| Exclusive Use: | None |
| Restrictions: | None |
| Contact: | Lauren Hay, lhay@usgs.gov, (303) 236-5034 |

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fax (970) 226-9230
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**Professional Preparation**

| | | | |
|---|---|---|---|
| Ph.D. | Arizona State University | 1999 | Plant Biology |
| M.S. | Colorado State University | 1993 | Forest Sciences/Ecology |
| B.A. | University of California, Santa Barbara | 1989 | Environmental Studies/Geography |

**Relevant Appointments**

| | |
|---|---|
| 1991-present | Research Ecologist and other positions, U.S. Geological Survey (NBS, USFWS) |
| 1988-1991 | Various teaching and research assistantships |

**Research Summary**

Dr. Shafroth's research is focused on riparian ecosystems, primarily in arid and semi-arid regions of the western US. He and colleagues have worked on understanding relationships between surface and ground-water hydrology, fluvial processes, and the dynamics of native and introduced riparian plants. This research has often been conducted in the applied context of riparian ecosystem restoration.

**Selected Publications**

Perry, L.G., D.C. Andersen, L.V. Reynolds, S.M. Nelson, and P.B. **Shafroth**. 2012. Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America. *Global Change Biology* 18:821-842.

Stromberg, J.C., P.B. **Shafroth** and A.F. Hazelton. 2012. Legacies of flood reduction on a dryland river. *River Research and Applications* 28:143-159.

Nagler, P.L., E.P. Glenn, C.S. Jarnevich, and P.B. **Shafroth**. 2011. Distribution and abundance of saltcedar and Russian olive in the western United States. *Critical Reviews in Plant Sciences* 30:508-523.

Beauchamp, V.B. and P.B. **Shafroth**. 2011. Floristic composition, beta diversity and nestedness of reference sites for restoration of xeroriparian areas in semi-arid western USA. *Ecological Applications* 21:465-476.

Andersen, D.C. and P.B. **Shafroth**. 2010. Beaver dams, ecological thresholds, and controlled floods as a management tool in a desert riverine ecosystem, Bill Williams River, Arizona. *Ecohydrology* 3:325-338.

**Shafroth**, P.B., A.C. Wilcox, D.A. Lytle, J.T. Hickey, D.C. Andersen, V.B. Beauchamp, A. Hautzinger, L.E. McMullen, and A. Warner. 2010. Ecosystem effects of environmental flows: modeling and experimental floods in a dryland river. *Freshwater Biology* 55:68-85.

Acker, S.A., T.J. Beechie, and P.B. **Shafroth**. 2008. Effects of a natural dam-break flood on geomorphology and vegetation on the Elwha River, Washington, U.S.A. *Northwest Science* 82:210-223.

**Shafroth**, P.B., V.B. Beauchamp, M.K. Briggs, K. Lair, M.L. Scott, and A.A. Sher. 2008. Planning riparian restoration in the context of *Tamarix* control in western North America. *Restoration Ecology* 16:97-112.

Stromberg, J.C., S.J. Lite, R. Marler, C. Paradzick, P.B. **Shafroth**, D. Shorrock, J. White, and M. White. 2007. Altered streamflow regimes and invasive plant species: the *Tamarix* case. *Global Ecology and Biogeography* 16:381-393.

Friedman, J.M., G.T. Auble, P.B. **Shafroth**, M.L. Scott, M.F. Merigliano, M.D. Freehling and E.R.Griffin. 2005. Dominance of non-native riparian trees in western USA. *Biological Invasions* 7:747-751.

**Shafroth**, P.B., J.R. Cleverly, T.L. Dudley, J. Stuart, J.P. Taylor, C. van Riper, and E.P. Weeks. 2005. Control of *Tamarix* in the western U.S.: implications for water salvage, wildlife use, and riparian restoration. *Environmental Management* 35:231-246.

**Shafroth**, P.B., J.M. Friedman, G.T. Auble, M.L. Scott, and J.H. Braatne. 2002. Potential responses of riparian vegetation to dam removal. *BioScience* 52:703-712.

**Shafroth**, P.B., J.C. Stromberg, and D.T. Patten. 2002. Riparian vegetation response to altered disturbance and stress regimes. *Ecological Applications* 12:107-123.

**Shafroth**, P.B., G.T. Auble, J.C. Stromberg, and D.T. Patten. 1998. Establishment of woody riparian vegetation in relation to annual patterns of streamflow, Bill Williams River, Arizona. *Wetlands* 18:577-590.

**Shafroth**, P. B., G. T. Auble, and M. L. Scott. 1995. Germination and establishment of the native plains cottonwood (*Populus deltoides* Marshall subsp. *monilifera*) and the exotic Russian-olive *(Elaeagnus angustifolia* L.). *Conservation Biology* 9:1169-1175.

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**Professional Preparation**

| | | | |
|---|---|---|---|
| Ph.D. | University of Minnesota, St. Paul | 2001 | Applied Plant Sciences |
| B.A. | Swarthmore College | 1995 | Biology |

**Relevant Appointments**

| | |
|---|---|
| 2008-present | Research Scientist I (riparian ecology), Colorado State University, Ft. Collins, CO |
| 2003-2008 | Research Associate (invasion ecology), Colorado State University, Ft. Collins, CO |
| 2003-2004 | Postdoctoral Researcher (forest ecology), SI, Inc. (RMRS, USFS), Ft. Collins, CO |
| 1996-2001 | NSF Graduate Fellow (invasion ecology), University of Minnesota, St. Paul, MN |

**Research Summary**

Dr. Perry's research is focused on effects of environmental change, including climate change, elevated $CO_2$, biological invasion and nitrogen pollution, on plant community composition and restoration, particularly in riparian and wetland ecosystems. With regard to climate change effects on riparian forest ecosystems, she recently produced a comprehensive literature review on effects of elevated $CO_2$ and climate change on riparian ecosystems in western North America, and conducted the first test of effects of elevated $CO_2$ on seedling growth and drought-tolerance in native and exotic riparian woody species.

**Selected Publications**

**Perry** LG, Andersen DC, Reynolds LV, Nelson SM, Shafroth PB. 2012. Vulnerability of riparian ecosystems to elevated $CO_2$ and climate change in arid and semiarid western North America. *Global Change Biol*. 18:821-842.

**Perry** LG, Blumenthal DM, Monaco TA, Paschke MW, Redente, EF. 2010. Immobilizing nitrogen to control plant invasion. *Oecologia* 163:13-24.

**Perry** LG, Cronin SA, Paschke, MW. 2009. Native cover crops suppress exotic annuals and favor native perennials in a greenhouse competition experiment. *Plant Ecol* 204:247-259.

**Perry** LG, Thelen GC, Ridenour WM, Callaway RM, Paschke MW, Vivanco JM. 2007. Concentrations of the allelochemical (±)-catechin in *Centaurea maculosa* soils. *J Chem Ecol* 33:2337-2344.

**Perry** LG, Galatowitsch SM. 2006. Light competition for invasive species control: a model of cover crop - weed competition and implications for *Phalaris arundinacea* control in sedge meadow wetlands. *Euphytica* 148:121-134.

**Perry** LG, Johnson C, Alford ÉR, Vivanco JM, Paschke MW. 2005. Screening of grassland plants for restoration after spotted knapweed invasion. *Rest Ecol* 13:725-723.

**Perry** LG, Thelen GC, Ridenour WM, Weir TL, Callaway RM, Paschke MW, Vivanco JM. 2005. Dual role for an allelochemical: (±)-catechin from *Centaurea maculosa* root exudates regulates conspecific seedling establishment. *J Ecol* 93:1126-1135.

**Perry** LG, Galatowitsch SM. 2004. The influence of light availability on competition between *Phalaris arundinacea* and a native wetland sedge. *Plant Ecol* 170:73-81.

**Perry** LG, Galatowitsch SM, Rosen CJ. 2004. Competitive control of invasive vegetation: a native wetland sedge suppresses *Phalaris arundinacea* in carbon-enriched soil. *J Appl Ecol* 41:151-162.

**Perry** LG, Galatowitsch SM. 2003. A test of two annual cover crops for controlling *Phalaris arundinacea* invasion in restored sedge meadow wetlands. *Rest Ecol* 11:297-307.

**Perry** LG, Neuhauser C, Galatowitsch SM. 2003. Founder control and coexistence in a simple model of asymmetric competition for light. *J Theor Biol* 222:425-436.

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**Professional Preparation**

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|---|---|---|---|
| Ph.D. | University of Colorado | 1996 | Geography |
| M.S. | University of Arizona | 1986 | Hydrology |
| B.S. | Tufts University | 1982 | Geology |

**Relevant Appointments**

| | |
|---|---|
| 2007-present | Project Chief of the Modeling of Watershed Systems research group, National Research Program, USGS, Denver, CO. |
| 1989-2007 | Research Hydrologist, project member of the Precipitation-Runoff Modeling research group, National Research Program, USGS, Denver, CO. |
| 1986-1989 | Hydrologist, USGS, New Jersey District Office. |

**Research Summary**

Dr. Hay's research has the broad goal of understanding precipitation-runoff processes and developing improved hydrologic models. Specific objectives are to investigate watershed hydrologic processes to: (1) improve understanding of watershed system dynamics; (2) develop computer models to simulate and evaluate the effects of various combinations of precipitation, climate, and land use on streamflow, sediment yield, and other hydrologic components; and (3) develop procedures and techniques to estimate model parameters using measurable watershed and climatic characteristics. Past research objectives included: (1) spatial and temporal distribution of climate variables for hydrologic modeling; (2) statistical and dynamical downscaling of atmospheric models; (3) hydrologic forecasting; and (4) model calibration.

**Selected Publications**

**Hay** LE, McCabe GJ, Wolock DM, Ayers MA. 1992. Use of weather types to disaggregate general circulation model predictions. *Journal of Geophysical Research*, 97(D3).

**Hay** LE, Wilby RL, Leavesley GH. 2000. A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. *J. Am. Water Resources*, 36(2).

**Hay** LE, Clark MP, Wilby RL, Gutowski WJ, Leavesley GH, Pan Z, Arritt RW, Takle ES. 2002. Use of regional climate model output for hydrologic simulations. *J. Hydrometeorology*, 3.

**Hay** LE, Clark MP. 2003. Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in three mountainous basins in the western United States. *J. Hydrology*, 282.

Clark MP, **Hay** LE. 2004. Use of medium-range numerical weather prediction model output to produce forecasts of streamflow. *J. Hydrometeorology*, 5(1).

**Hay** LE, Clark MP, Pagowski M, Leavesley GH, Gutowski, WJ, Jr. 2006. One-way coupling of an atmospheric and a hydrologic model in Colorado. *J. Hydrometeorology*, 7(4).

**Hay** LE, Leavesley GH, Clark MP, Markstrom SL, Viger RJ, Umemoto M. 2006. Step-wise, multiple-objective calibration of a hydrologic model for a snowmelt-dominated basin. *J. Am. Water Resources*, 42(4).

**Hay** LE, McCabe GJ, Clark MP, Risley JC. 2009. Reducing streamflow forecast uncertainty: Application and qualitative assessment of the upper Klamath River Basin, Oregon. *J. Am. Water Resources*, 45(3).

**Hay** LE, McCabe GJ. 2010. Hydrologic effects of climate change on the Yukon River Basin. *Climatic Change*, 100(3-4).

**Hay** LE, Markstrom SL, Ward-Garrison C. 2011. Watershed-scale response to climate change through the twenty-first century for selected basins across the United States. *Earth Interactions*, 15(17).

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**Professional Preparation**

| | | | |
|---|---|---|---|
| Ph.D. | University of Colorado | 2011 | Geography (Geographic Information Science) |
| M.A. | University of Colorado | 2004 | Geography (Geographic Information Science) |
| B.S. | University of Toronto | 1992 | Geography |

**Relevant Appointments**

| | |
|---|---|
| 2007-present | Geographer, U.S. Geological Survey, National Research Program, Modeling of Watershed Systems (MoWS), Denver, CO |
| 1995-2007 | Physical Scientist, U.S. Geological Survey, National Research Program, Precipitation-Runoff Modeling Systems, Denver, CO |
| 1994-1995 | Physical Science Technician, U.S. Geological Survey, Branch of Petroleum Geology, Denver, CO |

**Research Summary**

Dr. Viger's approaches, software (for example, the GIS Weasel), and training materials for geographic analysis in hydrologic simulation modeling have been used throughout the US, as well as internationally. He provides consultation within and outside the USGS and has represented USGS interests to other organizations. His primary research interests are integrated simulation modeling, spatial analysis for the delineation and characterization of landscape features for modeling, and geoinformatics. Roland is active in the Community of Practice for Integrated Environmental Modeling (CIEM), the USGS Community for Data Integration (CDI), and in the development of national hydrologic modeling systems. He is currently a member of the USGS Core Science Systems Strategic Science Planning Team.

**Recent Committees and External Activities**

Strategic Science Planning Team for Core Science Systems
Coordinator/Leader for USGS Community for Data Integration

**Selected Publications**

Bjerklie DM, Trombley TJ **Viger** RJ. 2011. Simulations of historical and future trends in snowfall and groundwater recharge for basins draining to Long Island Sound. *Earth Interactions*, 15, 1-35, http://dx.doi.org/10.1175/2011EI374.1.

Gellis AC, Pavich MJ, Ellwein AL, Aby S, Clark I, Wieczorek ME, **Viger** RJ. 2011. Erosion, storage, and transport of sediment in two subbasins of the Rio Puerco, Mexico. *Geological Society of America Bulletin*, B30392.1 doi:10.1130/B30392.1.

Mennis J, **Viger** R, Tomlin CD. 2005. Cubic map algebra functions for spatio-temporal analysis. *Cartography and Geographic Information Science*, 32, 17–32.

Markstrom SL, Hay LE, Ward-Garrison CD, Risley JC, Battaglin WA, Bjerklie DM, Chase KJ, Christiansen DE, Dudley RW, Hunt RJ, Koczot KM, Mastin MC, Regan RS, **Viger** RJ, Vining KC, Walker JF. 2012. Integrated watershed-scale response to climate change for selected basins across the United States. U.S. Geological Survey Scientific Investigations Report 2011–5077, 143 p. (available online at http://pubs.usgs.gov/sir/2011/5077/)

**Viger** RJ. 2008. The GIS Weasel: an interface for the treatment of geographic information in modeling. *Computers & Geosciences*, 34, 891–901.

**Viger** RJ, Leavesley GH. 2007. The GIS Weasel User's Manual. U.S. Geological Survey Techniques and Methods, Book 6, Chap. B4.

**Viger** RJ, Hay LE, Jones JW, Buell GR. 2010. Effects of including surface depressions in the application of the Precipitation-Runoff Modeling System in the Upper Flint River Basin, Georgia. U.S. Geological Survey Scientific-Investigations Report 2010–5062, 36 p. (available online at http://pubs.usgs.gov/sir/2010/5062/).

**Viger** RJ, Hay LE, Jones JW, Buell GR, Markstrom SL. 2011. Hydrologic effects of urbanization and climate change on the Flint River Basin, Georgia. *Earth Interactions*, 15, 1-25. http://dx.doi.org/10.1175/2010EI369.1.

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**Professional Preparation**

| | | | |
|---|---|---|---|
| Enrolled in PhD. Program | | | Geoinformatics, Hydrology and Modeling<br>Friedrisch-Schiller University, Jena, Germany |
| M.S. | University of Colorado | 1989 | Civil, Environmental, & Architectural Engineering |
| B.S. | University of Colorado | 1987 | Civil, Environmental, & Architectural Engineering |

**Relevant Appointments**

| | |
|---|---|
| 2007-present | Hydrologist, U.S. Geological Survey, National Research Program, Modeling of Watershed Systems (MoWS), Denver, CO |
| 1993-2007 | Hydrologist, U.S. Geological Survey, National Research Program, Precipitation-Runoff Modeling Systems, Denver, CO |
| 1992-1993 | Hydraulic Engineer for the U.S. Bureau of Reclamation, Denver, CO |
| 1991-1992 | Engineer for Waterloopkundig Laboratorium (Delft Hydraulics), Delft, The Netherlands |
| 1990-1991 | Professional Research Assistant, University of Colorado, Boulder, CO |
| 1989-1990 | Research Assistant, International Institute for Applied Systems Analysis, Laxenburg, Austria |

**Research Summary**

Simulation of daily stream temperature at a watershed scale: coupling PRMS to an in-stream temperature model resulted in a useful new interdisciplinary simulation model, which can be used for further watershed process research and resulted in a valuable tool for USGS personnel to conduct watershed modeling studies.

Co-PI for the "Integrated watershed scale response to global change in selected basins across the United States" project: funded by the FY08 GCC program. In this project, selected IPCC carbon emission scenarios were evaluated for hydrologic effects by downscaling Global Climate Model projections and simulating them with PRMS. My role in this project was to gather the 14 PRMS applications from the WSC personnel and ensure that they ran correctly with the climate change projections.

Research and development of the GSFLOW simulation model: coupling PRMS with MODFLOW. Before the GSFLOW project started, I developed the prototype that proved that this approach would work. Subsequently, NRP and OGW personnel jointly developed the initial version, which was publicly released in 2008.

**Selected Publications**

**Markstrom** SL, Hay LE. 2009. Integrated watershed scale response to climate change for selected basin across the United States. *Water Resources Impact*, 11, 8-10.

**Markstrom** SL, Niswonger RG, Regan RS, Prudic DE, Barlow PM. 2008. GSFLOW-Coupled ground-water and surface-water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005). U.S. Geological Survey Techniques and Methods 6-D1, 240 p.

Leavesley GH, **Markstrom** SL, Viger RJ, Hay LE. 2005. USGS Modular Modeling System (MMS) — Precipitation-Runoff Modeling System (PRMS) MMS-PRMS, *in* Singh, V., and Frevert, D., eds., Watershed Models. Boca Raton, Fla., CRC Press, p. 159-177.

Leavesley GH, Hay LE, Viger RJ, **Markstrom** SL. 2003. Use of a priori parameter-estimation methods to constrain calibration of distributed-parameter models, *in* Duan, Q., Gupta, H.V., Sorooshian, S., Rousseau, A.N., and Turcotte, eds., Calibration of Watershed Models, Water, Science and Application 6, American Geophysical Union, p. 255-266.

**Markstrom** SL, McCabe G, David O, 2002. Web-based distribution of geo-scientific models. *Computers and Geosciences*, 28, 577-581.

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**Professional Preparation**

| | | | |
|---|---|---|---|
| B.S. | University of Washington | 1982 | Atmospheric Sciences |
| M.S. | University of Alaska | 1986 | Snow, Ice, and Permafrost Geophysics |
| Ph.D. | Montana State University | 1991 | Mathematics/Engineering |

**Relevant Appointments**

| | |
|---|---|
| 2006-present | Senior Research Scientist, Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO |
| 1994-2006 | Research Scientist, Department of Atmospheric Science, Colorado State University, Fort Collins, CO |
| 1991-1994 | Research Scientist, NASA/Goddard Space Flight Center, Climate and Radiation Branch and Hydrological Sciences Branch |

**Research Summary**

Dr. Liston's professional focus has been the research and parameterization of land-surface hydrology and boundary layer processes for local- regional- and global-scale land-atmosphere interaction models operating at climate, and shorter, time scales. In addition, he has been actively involved in process studies and modeling of snow and ice found in high-latitude and high-elevation environments. He has over 100 refereed journal publications on snow-related topics.

**Selected Publications (only subset of first-author publications shown)**

**Liston GE**, Hiemstra CA. 2011. The changing cryosphere: Pan-Arctic snow trends (1979-2009). *J. Climate*, 24, 5691-5712.

**Liston GE**, Hiemstra CA. 2011. Representing grass- and shrub-snow-atmosphere interactions in climate system models. *J. Climate*, 24, 2061-2079.

**Liston GE**, Hiemstra CA. 2008. A simple data assimilation system for complex snow distributions (SnowAssim). *J. Hydrometeorology*, 9, 989-1004.

**Liston GE**, Hiemstra CA, Elder K, Cline DW. 2008. Meso-cell study area (MSA) snow distributions for the Cold Land Processes Experiment (CLPX). *J. Hydrometeorology*, 9, 957-976.

**Liston GE**, Birkenheuer DL, Hiemstra CA, Cline DW, Elder K. 2008. NASA Cold Land Processes Experiment (CLPX): Atmospheric analyses datasets. *J. Hydrometeorology*, 9, 952-956.

**Liston GE**, Haehnel RB, Sturm M, Hiemstra CA, Berezovskaya S, Tabler RD. 2007. Simulating complex snow distributions in windy environments using SnowTran-3D. *J. Glaciology*, 53, 241-256.

**Liston GE**, Elder K. 2006. A distributed snow-evolution modeling system (SnowModel). *J. Hydrometeorology*, 7, 1259-1276.

**Liston GE**, Elder K. 2006. A meteorological distribution system for high-resolution terrestrial modeling (MicroMet). *J. Hydrometeorology*, 7, 217-234.

**Liston GE**, Winther J-G. 2005. Antarctic surface and subsurface snow and ice melt fluxes. *J. Climate*, 18, 1469-1481.

**Liston GE**. 2004. Representing subgrid snow cover heterogeneities in regional and global models. *J. Climate*, 17, 1381-1397.

**Liston GE**, Sturm M. 2004. The role of winter sublimation in the Arctic moisture budget. *Nordic Hydrology*, 35, 325-334.

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**Professional Preparation**

| | | | |
|---|---|---|---|
| M.S. | University of Wisconsin, Madison | 2010 | Water Resources Engineering |
| B.S. | University of Wisconsin, Madison | 2008 | Civil and Environmental Engineering |

**Relevant Appointments**

| | |
|---|---|
| 2010-present | IT Specialist and Project Manager, Center for Integrated Data Analytics, USGS Wisconsin Water Science Center, Middleton, WI |
| 2006-2010 | Field and Laboratory Research Assistant, Water Group, University of Wisconsin, Madison, WI |
| 2007-2008 | Teaching Assistant, Civil and Environmental Engineering, University of Wisconsin, Madison, WI |
| 2005-2008 | Project Manager and Co-chair, University of Wisconsin Concrete Canoe Team, Madison, WI |
| 2004-2005 | Carpenter's Assistant, TDS Custom Construction, Madison, WI |
| 2000-2004 | Manager – Buyer, Carl's Paddlin' Canoe and Kayak Center, Madison, WI |

**Research Summary**

David Blodgett's great interest in water grew from his love of paddle-sports. Designing and building canoes and kayaks beginning in middle school taught him to learn independently by research and experimentation. His first real job was in canoe and kayak specialty retail where he reached the level of manager and buyer but was drawn away to pursue higher education. He briefly worked in custom remodeling as a laborer while working on an undergraduate degree in Civil Engineering. For two semesters, he worked full time on his undergraduate degree that led into a research assistantship in sediment transport and bank erosion. His experience leading the highly successful UW - Madison concrete canoe team gave him perspective and valuable leadership experience. His undergraduate research continued with an emphasis on hydrologic modeling and radar indicated rainfall analysis. He received a master's degree in water resources engineering in January 2010. He is currently applying his background and training in management, environmental modeling, geospatial information science, and environmental data analysis at the USGS Center for Integrated Data Analytics as an IT specialist and project manager.

**Notable Accomplishments**

Design and construction engineer, paddler and technical presenter for national champion concrete canoe team 2006.
Project manager, lead engineer, paddler and technical presenter for national champion concrete canoe team 2007.
Project manager for national champion wastewater treatment plant design team in Metcalf and Eddy Student Design Competition.

**Selected Publications**

**Blodgett** DL, Booth NL, Kunicki TC, Walker JL, Viger RJ. 2011. Description and testing of the Geo Data Portal: Data integration framework and Web processing services for environmental science collaboration. U.S. Geological Survey Open-File Report 2011–1157, 9 p.

**Blodgett** DL, Booth NL, Kunicki TC, Walker JL, Jessica L. 2012. Description of the U.S. Geological Survey Geo Data Portal Data Integration Framework. IEEE JSTARS, accepted and reviewed manuscript.

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**Professional Preparation**

| | | | |
|---|---|---|---|
| B.S. | University of Wisconsin, Madison | 1997 | Civil and Environmental Engineering |

**Relevant Appointments**

| | |
|---|---|
| 2009-present | Lead Architect, USGS Center for Integrated Data Analytics (CIDA, http://cida.usgs.gov), Middleton, WI |
| 1999-2009 | Project Chief and IT Specialist, USGS Wisconsin Science Center, Madison, WI |
| 1997-1999 | Hydraulic Engineer, USGS Wisconsin Science Center, Madison, WI |

**Research Summary**

Mr. Booth currently co-leads CIDA in Middleton, WI. CIDA is comprised of 30 environmental and computer scientists with computing facilities in Wisconsin and at USGS EROS Data Center focused on providing innovative data management and software solutions for various USGS and partner projects. He also serves as Data Synthesis Lead for the USGS National Water Quality Assessment Program (NAWQA) and USGS representative on various regional, national and international committees.

**Current Projects and Responsibilities (2012)**

- Co-chair, White House Subcommittee on Water Availability and Quality (SWAQ) Task Force on Water Information Sharing
- Data Synthesis Lead, USGS National Water Quality Assessment (NAWQA) Program
- Member, USGS Science Strategy Planning Team for Core Science Systems
- USGS representative, Integrated Water Resources Science and Services (IWRSS) Interoperability Working Group
- USGS representative, Open Geospatial Consortium (OGC) / World Meteorological Organization (WMO) Hydrology Domain Working Group
- Member, Great Lakes Observing System Enterprise Architecture Expert Advisory Panel, NOAA Great Lakes Environmental Research Laboratory
- Lead, USGS Backbone to Great Lakes Observation System (GLOS)
- Lead, USGS National Water Census Portal
- Technical Lead, USGS / USEPA Water Quality Data Exchange
- Technical Lead, US National Groundwater Monitoring Network Data Portal
- Co-lead, US / Canada OGC Groundwater Interoperability Experiment
- Co-lead, USGS / NOAA OGC Surface Water Interoperability Experiment
- Technical Lead, USGS National Climate Change and Wildlife Science Center (NCCWSC) Data Network
- Lead, NAWQA Spatially Referenced Regressions On Watershed Attributes model (SPARROW) Decision Support System

Literature Cited


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Barton DR, Taylor WD, Biette RM (1985) Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. *North American Journal of Fisheries Management,* **5**, 364-378.

Battaglin WA, Hay LE, Markstrom SL (2011) Simulating the potential effects of climate change in two Colorado basins and at two Colorado ski areas. *Earth Interactions,* **15**, 1-23.

Battaglin WA, Hay LE, Markstrom SL (2012) *Watershed scale response to climate change—East River Basin, Colorado. U.S. Geological Survey Fact Sheet 2011–3126*.

Bjerklie DM, Hay LE, Markstrom SL (2012) *Watershed scale response to climate change—Pomperaug River Watershed, Connecticut. U.S. Geological Survey Fact Sheet 2011–3122*.

Bjerklie DM, Trombley TJ, Viger RJ (2011) Simulations of historical and future trends in snowfall and groundwater recharge for basins draining to Long Island Sound. *Earth Interactions,* **15**, 1-35.

Brand LA, Stromberg JC, Noon BR (2010) Avian density and nest survival on the San Pedro River: importance of vegetation type and hydrologic regime. *Journal of Wildlife Management,* **74**, 739-754.

Chase KJ, Hay LE, Markstrom SL (2012) *Watershed scale response to climate change—South Fork Flathead River Basin. U.S. Geological Survey Fact Sheet 2011–3124*.

Christensen NS, Wood AW, Voisin N, Lettenmaier DP, Palmer RN (2004) The effects of climate change on the hydrology and water resources of the Colorado River Basin. *Climatic Change,* **62**, 337-363.

Christiansen DE, Hay LE, Markstrom SL (2012) *Watershed scale response to climate change—Clear Creek Basin, Iowa. U.S. Geological Survey Fact Sheet 2011–3127*.

Christiansen DE, Markstrom SL, Hay LE (2011) Impacts of climate change on the growing season in the United States. *Earth Interactions,* **15**, 1-17.

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Clow DW (2010) Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. *Journal of Climate,* **23**, 2293-2306.

Cooper DJ, Merritt DM, Andersen DC, Chimner RA (1999) Factors controlling the establishment of Fremont cottonwood seedlings on the upper Green River, USA. *Regulated Rivers - Research & Management,* **15**, 419-440.

Dettinger MD, Cayan DR, Meyer M, Jeton AE (2004) Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900-2099. *Climatic Change,* **62**, 283-317.

Dudley RW, Hay LE, Markstrom SL, Hodgkins GA (2012) *Watershed scale response to climate change—Cathance Stream Basin, Maine. U.S. Geological Survey Fact Sheet 2011–3128*.

Friedman JM, Auble GT, Shafroth PB, Scott ML, Merigliano MF, Preehling MD, Griffin EK (2005) Dominance of non-native riparian trees in western USA. *Biological Invasions,* **7**, 747-751.

Friedman JM, Scott ML, Lewis WM (1995) Restoration of riparain forest using irrigation, artificial disturbance, and natural seedfall. *Environmental Management,* **19**, 547-557.

Grady KC, Ferrier SM, Kolb TE, Hart SC, Allan GJ, Whitham TG (2011) Genetic variation in productivity of foundation riparian species at the edge of their distribution: implications for restoration and assistent migration in a warming climate. *Global Change Biology,* **17**, 3724-3735.

Gray ST, Mccabe GJ (2010) A combined water balance and tree ring approach to understanding the potential hydrologic effects of climate change in the central Rocky Mountain region. *Water Resources Research,* **46**, doi:10.1029/2008WR007650.

Hay LE, Battaglin WA, Markstrom SL (2012) *Watershed scale response to climate change—Yampa River Basin, Georgia. U.S. Geological Survey Fact Sheet 2011–3117*.

Hay LE, Leavesley GH, Clark MP (2006a) Use of remotely-sensed snow covered area in watershed model calibration for the Sprague River, Oregon. In: *Joint 8th Federal Interagency Sedimentation Conference and 3rd Federal Interagency Hydrologic Modeling Conference, April 2-6, 2006.* pp Page. Reno, Nevada.

Hay LE, Leavesley GH, Clark MP, Markstrom SL, Viger RJ, Umemoto M (2006b) Step-wise, multiple-objective calibration of a hydrologic model for a snowmelt-dominated basin. *Journal of American Water Resources,* **42**, 877-890.

Hay LE, Markstrom SL (2012) *Watershed scale response to climate change—Flint River Basin, Georgia. U.S. Geological Survey Fact Sheet 2011–3116*.

Hay LE, Markstrom SL, Ward-Garrison C (2011) Watershed-scale response to climate change through the twenty-first century for selected basins across the United States. *Earth Interactions,* **15**, 1-37.
Hay LE, Mccabe GJ (2010) Hydrologic effects of climate change on the Yukon River Basin. *Climatic Change,* **100**, 509-523.
Hayhoe K, Cayan D, Field CB *et al.* (2004) Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences of the United States of America,* **101**, 12422-12427.
Hostetler SW, Alder JR, Allan AM (2011) *Dynamically downscaled climate simulations over North America: Methods, evaluation, and supporting documentation for users. U.S. Geological Survey Open-File Report 2011-1238*.
Hunt RJ, Walker JF, Westenbroek SM, Hay LE, Markstrom SL (2012) *Watershed scale response to climate change—Black Earth Creek Basin, Wisconsin. U.S. Geological Survey Fact Sheet 2011–3129*.
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Knopf FL, Samson FB (1994) Scale perspectives on avian diversity in western riparian ecosystems. *Conservation Biology,* **8**, 669-676.
Koczot KM, Markstrom SL, Hay LE (2011) Effects of baseline conditions on the simulated hydrologic response to projected climate change. *Earth Interactions,* **15**, 1-23.
Koczot KM, Markstrom SL, Hay LE (2012) *Watershed scale response to climate change—Feather River Basin, California. U.S. Geological Survey Fact Sheet 2011–3125*.
Leavesley GH, Lichty RW, Troutman BM, Saindon LG (1983) *Precipitation-runoff modeling system - User's manual. U.S. Geological Survey Water-Resources Investigation Report 83- 4238*.
Leung LR, Qian Y, Bian XD, Washington WM, Han JG, Roads JO (2004) Mid-century ensemble regional climate change scenarios for the western United States. *Climatic Change,* **62**, 75-113.
Liston GE (1995) Local advection of momentum, heat, and moisture during the melt of patchy snow covers. *Journal of Applied Meterology,* **34**, 1705-1715.
Liston GE, Elder K (2006a) A distributed snow-evolution modeling system (SnowModel). *Journal of Hydrometeorology,* **7**, 1259-1276.
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Liston GE, Haehnel RB, Sturm M, Hiemstra CA, Berezovskaya S, Tabler RD (2007) Simulating complex snow distributions in windy environments using SnowTran-3D. *Journal of Glaciology,* **53**.
Liston GE, Hall DK (1995) An energy balance model of lake ice evolution. *Journal of Glaciology,* **41**, 373-382.
Liston GE, Hiemstra CA (2008) A simple data assimilation system for complex snow distributions (SnowAssim). *Journal of Hydrometeorology,* **9**, 989-1004.
Liston GE, Mernild SH (2011) Greenland freshwater runoff. Part I: a runoff routing model for glaciated and non-glaciated landscapes (HydroFlow). *Journal of Climate,* **in review**.
Liston GE, Sturm M (1998) A snow-transport model for complex terrain. *Journal of Glaciology,* **44**, 498-516.
Liston GE, Sturm M (2011) A global snow-classification dataset for Earth-system applications. *In review*.
Liston GE, Winther J-G, Bruland O, Elvehøy H, Sand K (1999) Below-surface ice melt on the coastal Antarctic ice sheet. *Journal of Glaciology,* **45**, 273-285.
Mahoney JM, Rood SB (1998) Streamflow requirements for cottonwood seedling recruitment - an integrative model. *Wetlands,* **18**, 634-645.
Markstrom SL, Hay LE, Regan RS (2012a) *Watershed scale response to climate change—Sagehen Creek Basin, California. U.S. Geological Survey Fact Sheet 2011–3121*.
Markstrom SL, Hay LE, Ward-Garrison CD *et al.* (2012b) *Integrated watershed-scale response to climate change for selected basins across the United States. U.S. Geological Survey Scientific Investigations Report 2011–5077*.
Markstrom SL, Niswonger RG, Regan RS, Prudic DE, Barlow PM (2008) *GSFLOW—Coupled ground-water and surface-water flow model based on the integration of the precipitation-runoff modeling system (PRMS) and the modular ground-water flow model (MODFLOW-2005). U.S. Geological Survey Techniques and Methods 6-D1*.
Mastin MC, Chase KJ, Dudley RW (2011) Changes in spring snowpack for selected basins in the United States for different climate-change scenarios. *Earth Interactions,* **15**, 1-18.
Mastin MC, Hay LE, Markstrom SL (2012) *Watershed scale response to climate change—Naches River Basin, Washington: U.S. Geological Survey Fact Sheet 2011–3123*.

Maurer EP (2007) Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. *Climatic Change,* **82**, 309-325.
Mccabe GJ, Clark MP (2005) Trends and variability in snowmelt runoff in the western United States. *Journal of Hydrometeorology,* **6**, 476-482.
Mccabe GJ, Markstrom SL (2007) *A monthly water-balance model driven by a graphical user interface. U.S. Geological Survey Open File Report 2007-1088*.
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Naiman RJ, Decamps H, Mcclain ME (2005) *Riparia: Ecology, Conservation, and Management of Streamside Communities,* London, UK, Elsevier Academic Press.
Nelson SM, Andersen DC (1999) Butterfly (Papilionoidea and Hesperioidea) assemblages associated with natural, exotic, and restored riparian habitats along the lower Colorado River, USA. *Regulated Rivers-Research & Management,* **15**, 485-504.
Nelson SM, Wydoski R (2008) Riparian butterfly (Papilionoidea and Hesperioidea) assemblages associated with *Tamarix*-dominated, native vegetation-dominated, and *Tamarix* removal sites along the Arkansas River, Colorado USA. *Restoration Ecology,* **16**, 168-179.
Nilsson C, Berggren K (2000) Alterations of riparian ecosystems caused by river regulation. *Bioscience,* **50**, 783-792.
Parmesan C (2007) Influences of species, latitudes and methodologies on estimates of phenological response to global warming. *Global Change Biology,* **13**, 1860-1872.
Patten DT (1998) Riparian ecosystems of semi-arid North America: diversity and human impacts. *Wetlands,* **18**, 498-512.
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Perry LG, Shafroth PB, Blumenthal DM, Morgan JA, Lecain DR (2012b) Elevated $CO_2$ increases seedling growth but not drought tolerance in native and exotic riparian species. *In review*.
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