Modeling Climate Impacts on the Hydrology of Montane Wetland Ecosystems

Final Project Report

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Introduction

Despite the widely acknowledged importance of wetlands to both human society and the natural environment, the location, habitat characteristics, hydrologic characteristics, and sensitivity to climate of wetlands are all poorly understood and documented. This project focused specifically on modeling the effects of climate change on montane wetlands in the western U.S. We collected wetland water level data and developed new approaches for modeling the hydrologic behavior of wetlands in response to observed climate variability and climate change using relatively simple models. We report on these efforts in Chapter 1 of the report, which reproduces the final draft version of a journal article entitled Hydrologic Impacts of Climate Change on Montane Wetlands in WA, OR, and CA (Lee *et al*. 2013).

One of the key obstacles to the research discussed in Chapter 1 was the difficulty in obtaining observed wetland water level data, which is extremely limited (only five sites were found to support the study). In collaboration with Dr. Maureen Ryan (Smith Fellow), Dr. Wendy Palen (Simon Fraser University), Dr. Michael Adams (USGS) and others, a new wetland monitoring protocol has been developed that simultaneously measures water temperature and water levels in wetlands using inexpensive i-Button sensors. This new protocol is currently being used to monitor a group of ~225 wetlands in Washington. A journal article is in preparation (Ryan *et al*. 2013), but we report briefly on these advances in monitoring approaches in Chapter 2 of this report.

Chapter 3 of the report gives an overview of the Pacific Northwest Wetlands Symposium supported by the project in collaboration with EcoAdapt on November 8, 2012 [http://ecoadapt.org/workshops/pnw-wetlands-symposium].

The NPLCC supported research reported here provides a foundation for continued wetland research funded by a two-year grant from the PNW Climate Science Center. These efforts will include ongoing modeling and monitoring using both in situ and remote sensing techniques, and detailed biological assessment of impacts to amphibians in mountain environments in response to climate change.

References

Lee, S-Y, A.F. Hamlet, M. Ryan, W. Palen, M. Halabisky, 2013: Hydrologic Impacts of Climate Change on Montane Wetlands in WA, OR, and CA, (in preparation, to be submitted to Global Change Biology).

Ryan, M. *et al*. , 2013: A new wetland monitoring protocol to support biological and hydrological assessment, (in preparation).

Chapter 1. Journal Article (final draft, to be submitted to Global Change Biology)

Hydrologic Impacts of Climate Change on Montane Wetlands in WA, OR, and CA

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Abstract

Wetlands are globally important ecosystems that provide critical services for natural communities and human society, such as water storage and filtration, wildlife habitat, agriculture, recreation, nutrient cycling, and carbon sequestration. They are also considered to be among the most sensitive ecosystems to climate change, which will exacerbate the already threatened nature of wetlands due to changes in land-use. In montane regions, wetlands are expected to be particularly susceptible to climate-induced changes, but tools to assess the impacts of climate change are severely limited relative to other ecosystem types. To address the need for quantitative assessment tools we developed projections of climate-induced hydrologic changes for a group of montane wetlands in Washington, Oregon, and California based on existing macro-scale hydrologic simulations for the western U.S. The approach relates soil moisture simulated by the hydrologic model to wetland water levels using site-specific regression models fitted to observed wetland data. We then used these models to a) simulate the historical wetland behavior associated with observed climate variability from 1916-2006, and b) assess the impacts of projected climate change on wetlands for the 2040s and 2080s. To better understand landscape scale impacts, we used observed relationships between simulated soil moisture thresholds and drying in summer to construct spatially explicit estimates of probability of drying for intermediate wetlands in the Pacific Northwest for both historical and projected future conditions. Our results show that warmer and drier summers and reduced snowpack associated with climate change are likely to cause earlier wetland drawdown, a more rapid rate of drying, reduced water levels, increased probability of drying, and shortened hydroperiod in montane wetlands, with greatest impacts to biologically productive intermediate hydroperiod wetlands. By the 2080s widespread conversion of intermediate wetlands to ephemeral wetlands is projected in mountain areas in WA.

Keywords: wetland hydrology, climate change, hydroperiod, water levels, probability of drying, ecological

Introduction

Wetlands are widely recognized as critical ecosystems globally (Mitsch and Gosselink 2007; Erwin 2009). Wetlands – broadly defined here as any areas where shallow surface water collects – provide important ecological services that integrate local processes (groundwater recharge, surface water storage and filtration) with global cycles (nutrient cycling, carbon sequestration) while providing food and habitat to a wide range of species (IPCC 2001 and 2007; Mitsch and Gosselink 2007; Johnson *et al.* 2010). Wetlands are also considered among the most vulnerable ecosystems to climate change due to their shallow depths, sensitivity to changing water table height, and changing evaporation rates (Kundzewicz *et al.* 2007; Johnson *et al.* 2010; IPCC 2001 and 2007). Climate-induced changes in wetlands are expected to exacerbate the substantial loss of wetlands that have already occurred (e.g. >50% loss in the contiguous United States; Dahl 1990) due to changing land use and other anthropogenic factors. In mountain areas, wetlands remain largely intact compared to lower elevation regions. However, montane and alpine areas of the globe are experiencing the accelerating impacts observed climate change, which is altering the hydrologic response, structure, and distribution of wetlands across mountain landscapes (Carpenter *et al*. 1992; Burkett and Kusler 2000; IPCC 2001and 2007; Erwin 2009). These impacts are expected to intensify with increased warming and/or precipitation change projected for the 21st century, and particularly so in the western U.S., where snow is an important element of the hydrologic cycle (Mote *et al*. 2005; Hamlet *et al*. 2005 and 2007; Stewart *et al*. 2005).

Despite the ecological importance of wetlands and their sensitivity to climate, scientific resources to assess and manage the effects of climate variability and change on wetlands lag significantly behind that of other ecosystem types as a result of historical neglect and the scientific challenges of studying complex wetland ecosystems (huge numbers of wetlands; wide range of wetland types; highly dynamic nature; broad distribution within diverse ecological contexts, etc.). Observed hydrologic data for wetlands is very limited, and even the most basic information, such as the location of existing wetlands, is frequently unavailable. For example, recent comparisons between high-resolution aerial photographs of wetlands on Mt. Rainier and wetlands catalogued in the same area by the National Wetlands Inventory (NWI) suggest that less than 50% of the existing wetlands were successfully captured in the NWI (Halabisky *et al.* 2013a). Compounding the general lack of observations across the board, most wetland studies that do exist have focused on describing, mapping, or cataloguing the site-specific ecosystem characteristics of wetlands rather than their hydrologic characteristics or sensitivity to climate. Those few studies that did collect hydrologic data generally did so only for a few years, often only one year. Thus hydrologic data for wetlands (e.g. time series data of water levels, surface area, or volume) that would support historical analysis of the effects of climate variability on wetlands is almost entirely lacking.

In other research contexts, hydrologic modeling has proved to be a viable alternative approach when observed hydrologic data are limited (e.g. Hamlet *et al*. 2005 and 2007), and hydrologic models also provide the fundamental tools for quantifying the impacts of climate change (Elsner *et al*. 2010; Hamlet *et al*. 2013a). The hydrologic modeling of wetlands, however, is challenged by many fundamental obstacles. The explicit and physically based modeling of wetlands requires a detailed and integrated understanding of fine-scale surface and subsurface hydrologic processes. The detailed hydrologic information that would support this kind of modeling is almost universally lacking in practice. This is particularly true of small wetlands that are defined by the microtopography of their surroundings, connections to groundwater and small streams, etc. Although detailed hydrologic models of a few individual wetlands have been constructed in specific case studies (Poiani *et al*. 1996; Johnson *et al*. 2005; Johnson *et al*. 2010), the approaches used in these studies cannot be applied widely to landscape-scale assessment of impacts with the limited information that is typically available. As a result, assessment of large-scale ecosystem impacts related to important hydrologic drivers, such as hydroperiod (i.e. the continuous duration and/or overall portion of the year that a wetland holds ponded water) or the probability of seasonal drying, cannot be carried out with these kinds of tools. Thus existing modeling frameworks that have been applied to wetland climate change studies are very limited in their application, and new modeling strategies that avoid exhaustive, physically based approaches are needed.

While simpler modeling approaches are needed, at the same time modeling studies need to capture important ecosystem drivers that are relevant to biological assessments. For wetland-reliant species such as waterfowl, pond-breeding amphibians, aquatic invertebrates, and wetland-obligate plants, changes in wetland water levels, hydroperiod, and probability of drying are likely to affect species distributions, population viability, and local extinction risk (Hanski 2004; Holyoak et al. 2005). Changes in wetlands and wetland-reliant populations will also alter broader ecological networks by altering the connectivity of wetland habitats and the abundance of food available for species that feed on wetland endemics (e.g. herbivores; mesopredators such as many birds, snakes, mammals). Climate-induced hydrologic changes may also interact with non-climate stressors (e.g. disease, pollutants, or introduced species) to affect the population viability of native species (Hansen and Hoffman 2011).

Hydrologic changes will not affect all wetland species equally. Pond-breeding amphibians and invertebrates, which represent a majority of the biomass of montane wetlands, sort grossly along a gradient of hydrologic variation (duration of inundation, pond permanence) in relation to life history and developmental requirements (Wellborn *et al*. 1996; Snodgrass *et al.* 2000). As a result, their vulnerability to climate-induced habitat loss is not evenly distributed (Ryan *et al.* 2013). Fast-developing species will be more sensitive to changes in the timing of pond drying, whereas species with slower life histories (e.g. that require multiple years to successfully complete larval development in high elevation environments) are likely to be most sensitive to the frequency of pond drying. In wetlands not at risk of drying entirely, ecological effects will depend on the distribution of and impacts to microhabitats and shifts in thermal conditions (Tarr and Babbitt 2008; Ryan *et al.* 2013). Therefore understanding climate impacts on different hydrologic classes of wetlands is critical to assessing impacts on particular species and on wetland ecosystems as a whole.

A first critical step in assessing wetland vulnerability, in mountain regions and elsewhere, is to develop methods to project the impacts of climate change on water levels in different hydrologic classes of wetlands. To address this need, we conducted a case study simulating wetlands in several montane areas of Washington (WA), Oregon (OR), and California (CA) to explore new methods for projecting climate impacts on wetlands using relatively simple hydrologic models. Specifically, the approaches developed in this study allow us to quantify how projected reductions in snowpack combined with warmer and drier summers will likely affect the timing and duration of water availability in montane wetlands in the western U.S. These projections can then be used to develop testable hypotheses for wetlands research, develop climate adaptation plans, and provide specific decision support for managers in focal regions tasked with wetlands conservation or restoration. This approach is analogous to successful past collaborative efforts, which have related hydrologic water balance variables from macro-scale hydrologic model simulations to forest growth and disturbance over diverse landscapes (Littell *et al*. 2008 and 2010).

Our choice of geographic area for the case study is partly informed by the fact that near-coastal mountain ranges in the western U.S. are among the most sensitive regions in the world to climate change (Cayan *et al*. 2001; Mote 2003 and 2006; Hamlet *et al*. 2005 and 2007; Mote *et al*. 2005; Knowles *et al*. 2006; Nolin and Daly 2006). Projected climate change impacts in the Pacific Northwest (PNW) include warming in all seasons, increasing precipitation in fall, winter, and spring, and decreasing precipitation in summer (Mote and Salathé 2010). Previous hydrologic modeling studies have shown that such changes would result in loss of mountain snowpack, earlier peak streamflows in areas with substantial snow accumulation, earlier soil moisture recharge in winter, increased evapotranspiration, increased soil moisture stress in late summer, and decreasing river levels during summer low flows (Hayhoe *et al*. 2004; Mote *et al*. 2003; Payne *et al*. 2004; Stewart *et al*. 2004; Daly 2006; IPCC Core Writing Team 2007; Mote and Salathé 2010; Salathé *et al*. 2009; Elsner *et al*. 2010; Hamlet *et al*. 2013a). We hypothesized that these projected changes in hydrologic response in mountain environments would also express themselves as substantial changes in the timing and duration of water availability in montane wetlands. Because the frequency of pond drying at landscape scales is a particularly key filter on species occupancy and habitat use, we estimated changes in this frequency, which are likely to be an important impact pathway in response to climate change.

Materials and Methods

We broadly define wetlands as areas where shallow surface water collects. Following approaches put forward by Girdner and Larson (1995) and Tarr and Babbitt (2008), we use a simple hydrologic classification scheme based on hydroperiod and wetland sensitivity to climate variability to characterize four ecologically relevant types of wetlands (Ryan *et al.* 2013) (Table 1). These four types represent general hydrologic classes of wetlands that can be related directly to more detailed hydrogeomorphic wetland classification systems such as those used in Natural Heritage programs and for conservation decision making (Hruby 2004, WDNR 2011).

Table 1 Hydrologic Classification of Montane Wetland Types

Wetland Classification	Hydrologic Characteristics	Ecosystem Characteristics
Ephemeral	Ephemeral, short-hydroperiod wetlands (also know as "vernal pools") tend to dry in most years, in some cases soon after the cessation of snowmelt or seasonal rains.	Ephemeral montane wetlands are not used by many animal species due to their extremely short period of inundation, but may support wetland plants.
Intermediate	Intermediate-hydroperiod wetlands tend to dry late in the summer or early fall in years with low precipitation. During relatively wet years, they hold water year-round. Water levels fluctuate considerably in the summer.	Intermediate-hydroperiod wetlands support populations of fast-developing amphibians, invertebrates with resting egg stages that can survive desiccation, migratory birds, mesopredators, and wetland-obligate plants.
Perennial	Perennial wetlands do not dry except in the most extreme years, but often lose a substantial percentage of their volume during dry periods.	Perennial wetlands often support the greatest diversity and abundance of amphibians and invertebrates, because they support fast-developing species and those that require multiple years to complete larval development in high elevation environments, while lacking predators such as introduced fish (Bahls 1992). Wetland-obligate plants, birds, and mesopredators, may also rely on perennial wetlands.
Permanent	Permanent wetlands do not dry and lose only a small percentage of their volume during unusually dry periods.	Permanent wetlands support a broad range of mammals and birds, and can be used by the full suite of pond-breeding amphibians and most invertebrates, though the widespread introduction of trout limits actual occupancy to species that are resistant to fish predation. Productivity depends in part on the amount of shallow littoral habitat. Wetland macrophytes.are common.

Observed Wetland Data

As noted in the introduction, observed hydrologic data for wetlands is extremely limited. We obtained observed wetland data (either estimated water volume or depth measurements) from five sites in WA, OR, and CA (Fig 1 and Table 2). These very limited resources were located only after an extensive search using a wide range of available resources (please see acknowledgements). For Mt. Rainier National Park, WA and Olympic National Park, WA one year of observed wetland water level data was available for three different types of wetlands. We used changes in volume for ten montane wetlands in Mt. Rainier National Park, estimated from depth measurements from June through September 1992 (Girdner and Larson 1995) and changes in wetland depth for six montane wetlands in Olympic National Park, measured during the summer of 2000 (personal communication, Dr. Wendy Palen, Simon Fraser University). Multiple-years of observed wetland depth were available for several perennial wetlands in OR (personal communication, Dr. Christopher Pearl, USGS) and CA (personal communication, Justin Garwood, California Department of Fish and Wildlife; Garwood and Welsh 2007).

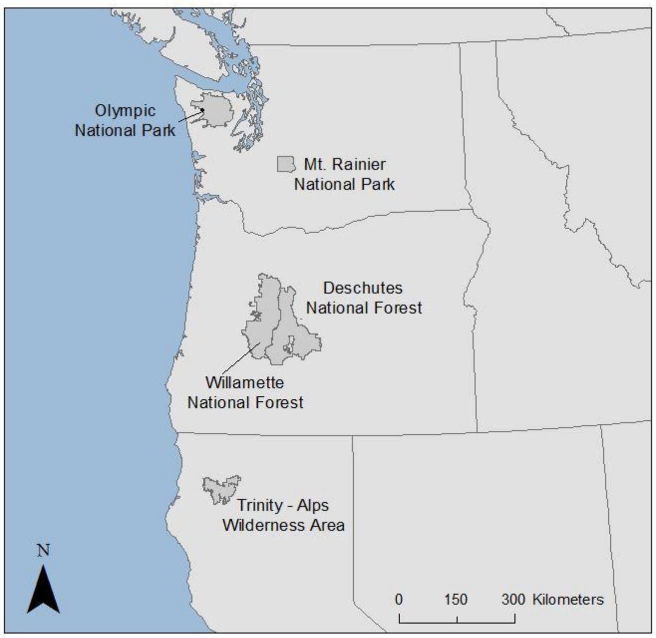

Figure 1. Location of sites with observed wetland data to support montane wetland models in the western U.S.

Table 2. Summary of observed wetland data used in the study.

	Type	Period	Number of Wetlands			Data Source
			Inter-mediate	Perennial	Permanent	
Mt. Rainier National Park, WA	Vol.	Year 1992	4	3	3	Girdner and Larson (1995)
Olympic National Park, WA	Depth	Year 2000	1	3	2	Field data provided by Dr. Wendy Palen

Willamette National Forest, OR	Depth	Years 2003-2006	–	2	–	Field data provided Dr. Christopher Pearl
Deschutes National Forest, OR	Depth	Year 2003, 2006		1		Field data provided Dr. Christopher Pearl
Trinity Alps Wilderness,CA	Depth	Years 2003 – 2007	–	1	–	Field data provided by Justin Garwood

<u>Macro Scale Hydrologic Model</u>

To forecast climate-induced hydrologic change, we used the largely physically-based, macro-scale Variable Infiltration Capacity (VIC) hydrologic model (Liang *et al*., 1994; Cherkauer *et al*., 2003), implemented at 1/16th degree resolution (about 5 km by 7 km) over the PNW and CA. The PNW model implementation, historical simulations, and climate change scenarios are described in detail by Elsner *et al*. (2010) and Hamlet *et al*. (2013a). The VIC model implementation over the western U.S. is described by Littell *et al*. (2011), and the more recent application of the model to CA (not discussed in the report) is based on these same methods. Forced by temperature and precipitation data, the VIC model simulates water balance variables such as snowpack, soil moisture, evapotranspiration, runoff and baseflow in three soil layers comprising the first several meters of soil. Simulations at each VIC grid cell cover an extended historical time period (water years (October to September) 1916 – 2006 for the PNW and 1916 – 2010 for CA). We used these water balance variables to develop empirical models of wetland response as described below.

<u>Climate Change Scenarios</u>

For future simulations in the Pacific Northwest (PNW), we used an ensemble of ten Hybrid Delta (HD) climate change scenarios (Hamlet *et al*. 2013b) for the A1B emissions scenario. The HD scenarios construct a 91-year time series for two future time periods: the 2040s (2030 – 2059) and the 2080s (2070 – 2099) (Hamlet *et al*. 2013a). To visually present results in the WA and OR sites we used simulations based on the ECHAM5 A1B HD climate scenario, which approximates the average conditions simulated by all ten A1B scenarios. All ten HD GCMs scenarios were used to calculate the probability of drying for intermediate wetlands in the PNW, but only the average of these results was used in the figures presented below.

For CA, we used the mean climate change scenario described by Littell *et al*. (2011) based on the Distributed Delta (DD) approach. The choice of an alternative downscaling approach for CA was based on the availability of data from past studies. Similar to the HD approach, the he DD scenarios construct a 95-year time series for two future time periods, which have the same number of years as the observations used in the downscaling. Although there are some differences in details between this downscaling method and the HD approach described above (e.g. length of record, method by which the changes in climate are applied to the historical time series), for the purposes of the experiments reported here these differences are not important. Both methods incorporate the spatial distribution of temperature and precipitation changes from GCMs, and estimate the central tendency of projected changes in climate in each region.

Note that both the HD and DD scenarios have essentially the same time series behavior as historical time series data, and direct comparisons between historical simulations and future projections can be made for individual years (Hamlet *et al* 2013b). For example in Fig 4 we show simulations of the historical water year 1992 plotted against the downscaled “1992” associated with the projected climate of the 2040s and 2080s. The perturbed “1992” associated with the future scenarios has the same basic time series behavior as the observed 1992 (seasonal variations in temperature and precipitation are roughly similar to history), but is warmer, wetter in winter, dryer in summer, etc.

Regression Models of Wetland Water Levels

We used hydrologic water balance variables such as precipitation, potential evapotranspiration, moisture deficit (potential evapotranspiration – actual evapotranspiration), runoff, baseflow and soil moisture in each layer to develop site-specific regression models of wetland water levels, and project the impacts of climate change on different classes of wetlands (Table 1).

As a first step, we used the correlation coefficient (Pearson’s R) to identify the strongest relationships between observed wetland responses and simulated hydrologic variables. In some cases we also applied a low-pass Butterworth filter (Hamming 1989) to the time series of hydrologic variables so that the time series were temporally smoothed. The rapidly responding upper soil layer and more slowly responding lower soil layer in the VIC simulations were the strongest predictors of wetland refill and drawdown, respectively (Fig S1). Secondly, we constructed empirical models of wetland response by fitting regression equations to observed wetland volume or depth data using soil moisture as a predictor. Depending on the observed hydrologic response of different wetlands, we applied different approaches at each site to best capture the observed variability.

Regression Approaches for Washington Wetlands at Mount Rainier and Olympic National Park

Two distinct hydrologic responses were apparent for the Mt. Rainier sites in 1992: a) a relatively gradual drawdown period over the summer months and b) a rapid refill period in fall (left panels, Fig 3). These represent different hydrologic processes. The summer drawdown is the result of the gradual falling of the water table and soil moisture due to drainage and evapotranspiration (ET) in the dry PNW summer. The rapid refill in fall is due to direct precipitation to the wetland and near-surface runoff resulting from substantial precipitation over a few days. To capture both effects, we developed two separate regression models for Mt. Rainier wetlands using the slowly responding lower soil layer in the VIC model as the explanatory variable for the drawdown period and the rapidly responding top soil layer for the refill period, respectively. We switched from the “drawdown” regression equation (based on lower layer soil moisture) to “refill” regression equation (based on upper layer soil moisture) when the lower level soil moisture reached its minimum value in the simulation for each historical water year.

In contrast, changes in observed wetland depths for Olympic National Park showed multiple drawdown and refill periods throughout the summer of 2000 (right panels, Fig 3). For these sites we developed a multiple-regression model using both the top and bottom soil moistures as explanatory variables.

Regression Approaches for Oregon and California Wetlands at the Willamette National Forest, Deschutes National Forest, and Trinity Alps

For wetlands in OR and CA we had two to five years of observed water level data, but these data were available only for one type of wetland, and no data were available for the refill seasons (Figs 4 and 5). Because the observed data were not available for the refill seasons, we developed a regression model using only the bottom soil moisture as an explanatory variable. Because multiple-years of observations were available we had an opportunity to investigate the uncertainty in the projections when fitting to a single year of data (as for the WA sites). We fit a separate regression model for each individual year of data, developed simulations for all years using each of these models, and then calculated the correlation coefficient (R) using all observations and the corresponding simulations for each model. We used the regression model showing the highest correlation coefficient for all the available data to simulate historical wetland response and the associated climate change response. We used the other regression models to estimate the uncertainty in the simulations due to uncertainty in the regression parameters. For the Willamette National Forest site (top panel in Fig 4), for example, the correlation coefficient (R) for the three regression models was 0.649, 0.928 and 0.926 for 2003, 2005 and 2006 data, respectively. Therefore we used the regression model fitted on the 2005 observed data to simulate the historical response (heavy black line in top panel, Fig 4) and used the regression models for years 2003 and 2006 to estimate the uncertainty of the simulation due to uncertainty in the regression fit (gray band in top panel, Fig 4).

Climate Change Projections

Using the site-specific regression models for each site, we then projected the response of each wetland to climate change using the ECHAM5 A1B Hybrid Delta climate change scenario for two future time periods in the PNW (2040s and 2080s), and the mean Distributed Delta scenario for the same time periods in CA (Fig 2). We assumed that the relationships between wetland response and soil moistures will not change with time.

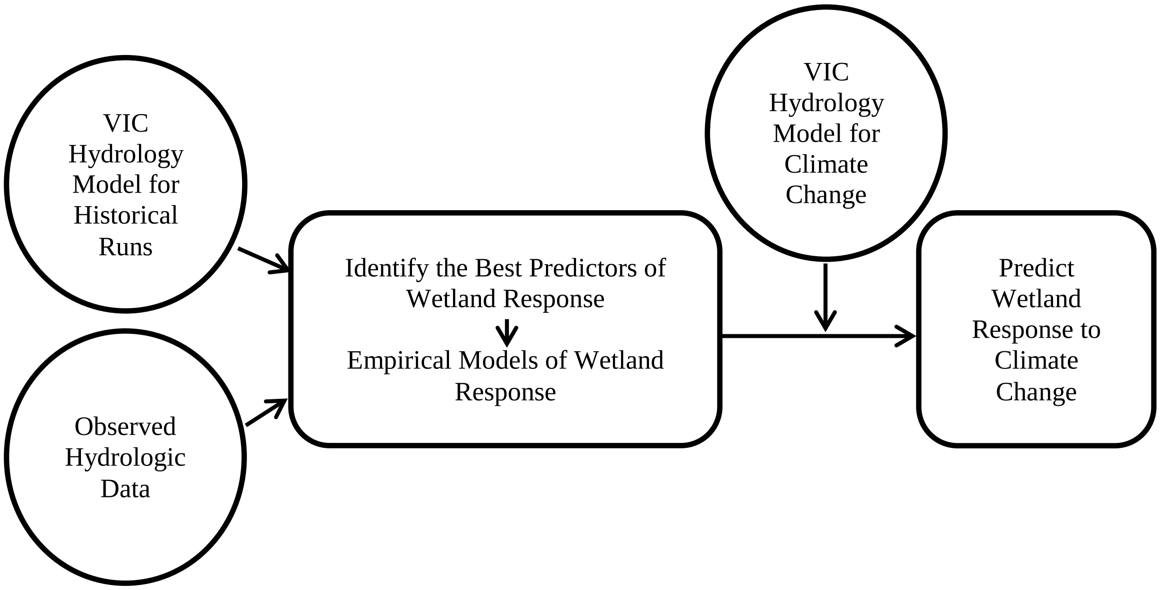

Figure 2. Schematic diagram of hydrologic projections of wetland water levels.

Frequency Analysis

To evaluate the impacts of climate variability and climate change on the probability distributions of minimum wetland water levels, we estimated the cumulative distribution function (CDF) of minimum wetland volume or depth for both the historical runs and two future time periods. We first extracted the minimum wetland volume or depth for each water year. We then ranked the annual minimum values and applied an unbiased quantile estimator based on the method of Cunane (Stedinger *et al*. 1993) to construct the CDF.

A comparison of simulated soil moisture with wetland water levels for intermediate wetlands showed that these ponds tend to dry out (reach 0% of maximum volume or depth) when soil moisture in the bottom VIC soil layer crosses a threshold of 50% of the field capacity (soil at field capacity is fully saturated, but does not drain by gravity). Given the very limited data available it is not very clear how robust this relationship is from site-to-site and year-to-year, but to explore the potential landscape-scale changes in intermediate wetland drying, we adopted the 50% of field capacity as proxy for intermediate wetland drying for each VIC grid cell. For each cell we counted the number of water years for which the annual minimum soil moisture in the lower soil layer was less than 50% of field capacity. We then estimated the probability of pond drying for each grid cell by dividing the number of drying events below 50% field capacity by the number of total water years. Thus the probability of pond drying ranges between 0 and 1, with a higher value indicating more frequent pond drying. We calculated the probability of pond drying for historical runs and for all ten Hybrid Delta A1B scenarios for the 2080s. We estimated the potential change in the probability of pond drying by subtracting the probability of pond drying for the 2080s from that for the historical run, with a positive value indicating an increase in the probability of drying for the 2080s. Values shown in the figures are the average of the ten values for each cell associated with the ten HD scenarios.

Results

Historical Simulations

As discussed above, soil moistures in the bottom and top soil layers were the best predictors of wetland hydroperiod in the drawdown and refill periods (respectively) (Fig S1), so we used these two variables to develop regression models of wetland water levels. Fig 3 shows the performance of these models for the sites in WA for a single year of data, and Fig 4 shows the performance for the OR and CA sites with multiple years of data.

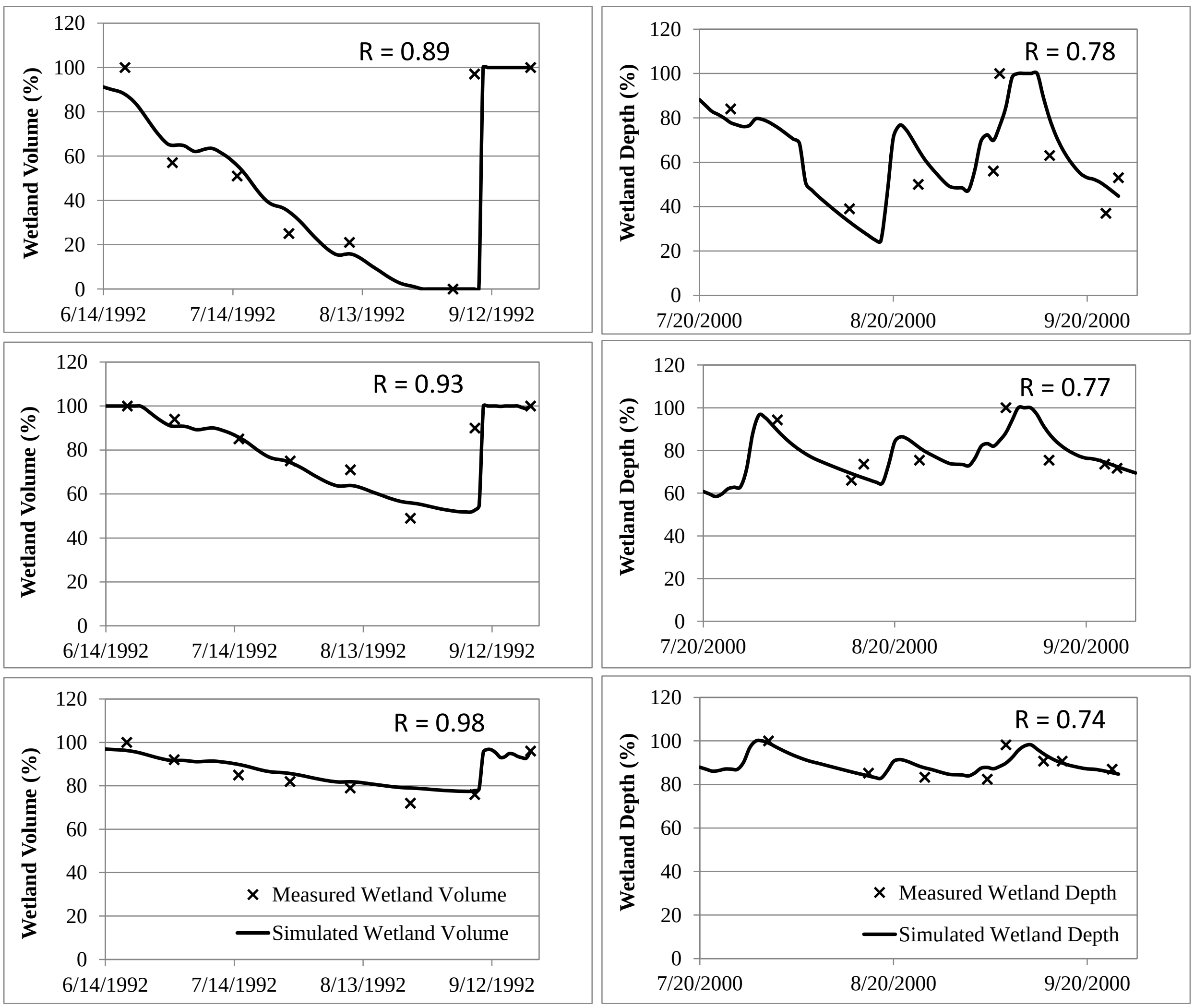

Figure 3. Measured wetland volume for sites in Mt. Rainier National Park, WA (left) and wetland depth for Olympic National Park, WA (right) compared with simulated wetland water levels using the regression models for intermediate hydroperiod wetlands (top), perennial wetlands (middle) and permanent wetlands (bottom).

For the Mt. Rainier sites the modeling approach successfully mimicked the observed gradual drawdown season through early September followed by the rapid refill in fall. The correlation coefficient (R) between observed and modeled wetland responses ranges between 0.89 and 0.98, with the highest value of 0.98 for a permanent wetland. The correlation coefficients for wetlands in Olympic National Park were less than those for the Mt. Rainier sites but were greater than 0.7. Thus the hydrology models apparently do better at simulating the gradual drawdown of the water table due to drainage and evapotranspiration during relatively dry periods than they do refill from intermittent precipitation events during the summer.

The models constructed for sites in OR and CA with multiple years of data also showed good performance overall, but some difference in performance in different years. Generally the observed timing and pattern of drawdown seasons were captured well by simulations, with the exception of the minimum water level for the year 2006 for Deschutes National Forest, OR (middle panel, Fig 4) and the timing of drawdown for the year 2003 in Trinity Alps Wilderness, CA (bottom panel, Fig 4). For the Deschutes National Forest, observed minimum water level for year 2006 was 13% but the simulation minimum was 18-34%. For Trinity Alps Wilderness, the pond started drawdown about one month later in 2003 compared to the other years but simulation was not able to reproduce this timing. These spatial and temporal variations in model performance are expected, and are seen in other comparisons between simulated and observed data at fine spatial scales, such as snow water equivalent measured at individual snow courses (Mote *et al*. 2005). One reason for the discrepancy is that local precipitation is often imperfectly captured in the driving data sets at high elevations.

Having multiple years of data for the sites in OR and CA also allows us to explicitly estimate the uncertainty of fitting the regression parameters on a single year of data. Figure 4 demonstrates that there is considerable uncertainty in the simulations deriving from the limited observed data available and associated regression parameter uncertainty. These results also provide important information about the potential uncertainty associated with the single-year regression fits at Mount Rainier and the Olympic National Park.

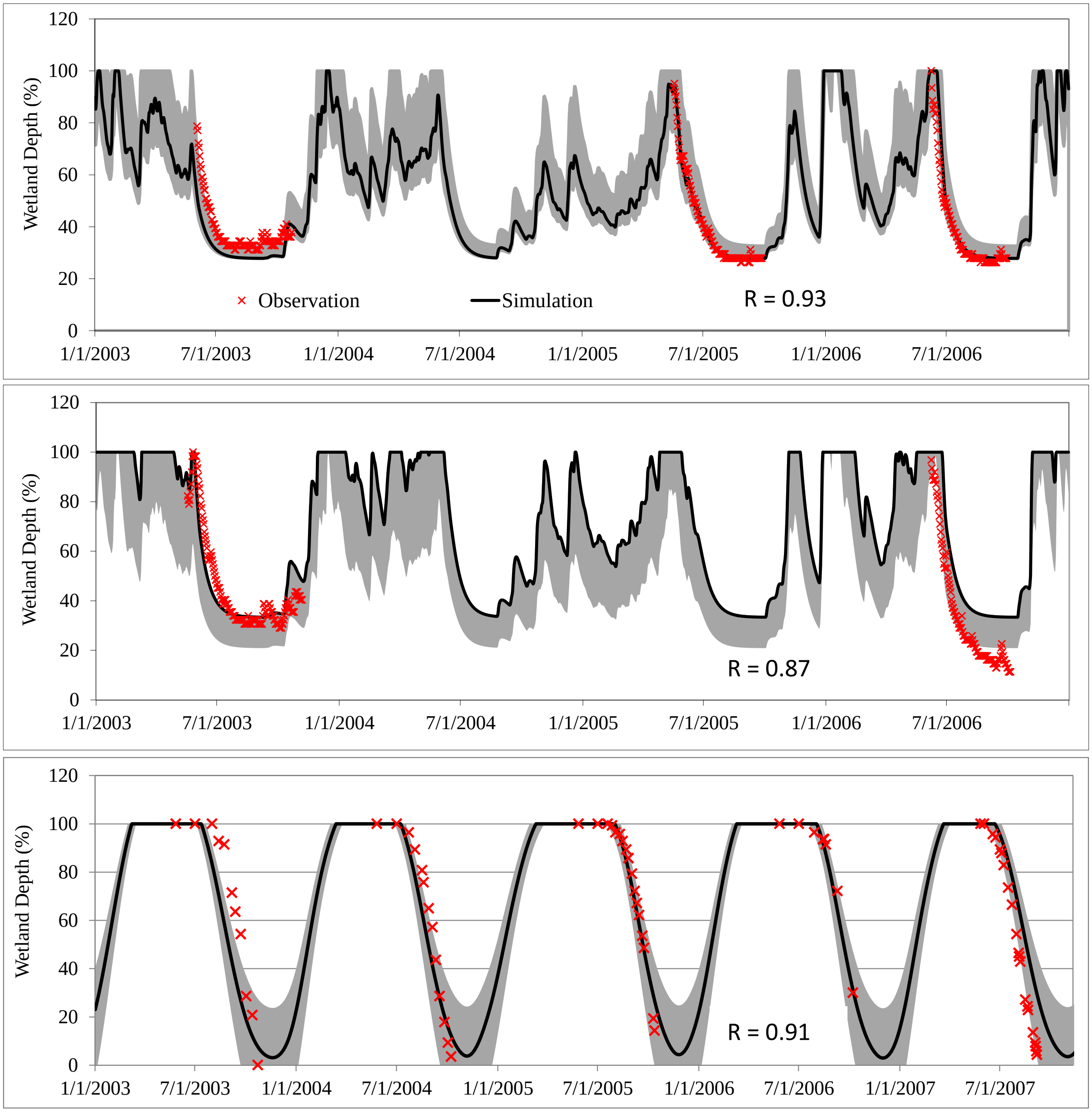

Figure 4. Observed wetland depth compared with simulated wetland depth using the regression model for Willamette National Forest, OR (top panel), for Deschutes National Forest, OR (middle panel) and for Trinity Alps Wilderness, CA (bottom panel). Dark black lines are produced by the regression equation deriving from the best fit from all available years. Gray bands show the range of uncertainty associated with alternate regression parameters deriving from other years of data.

Projections of Wetland Response to Climate Change

Different impacts of climate change on wetlands are projected depending on wetland types and locations but in general the projected effects to wetlands include earlier drawdown, a more rapid recession rate in summer, reduced minimum water levels and a longer dry season in summer (Figs 5 and 6). These changes are also likely to lead to transitions among wetland types. Specifically, shifts from intermediate wetlands to ephemeral wetlands are expected. Due to more rapid recession rate and earlier drawdown in the climate change scenarios, intermediate wetlands are likely to reach their bottom volume earlier, resulting in more frequent and longer dry seasons in summer. Some ephemeral wetlands may essentially disappear, storing water only in unusually wet years. We quantify these potential shifts from intermediate to ephemeral wetlands using changes in the probability of drying in the frequency analysis presented below. Results for perennial and permanent wetlands show reduced water levels for climate change. Perennial wetlands are more sensitive to climate change compared to permanent wetlands. Wetlands in Mt. Rainer National Park are projected to have higher winter wetland volumes compared to those in the historical runs (Fig 5).

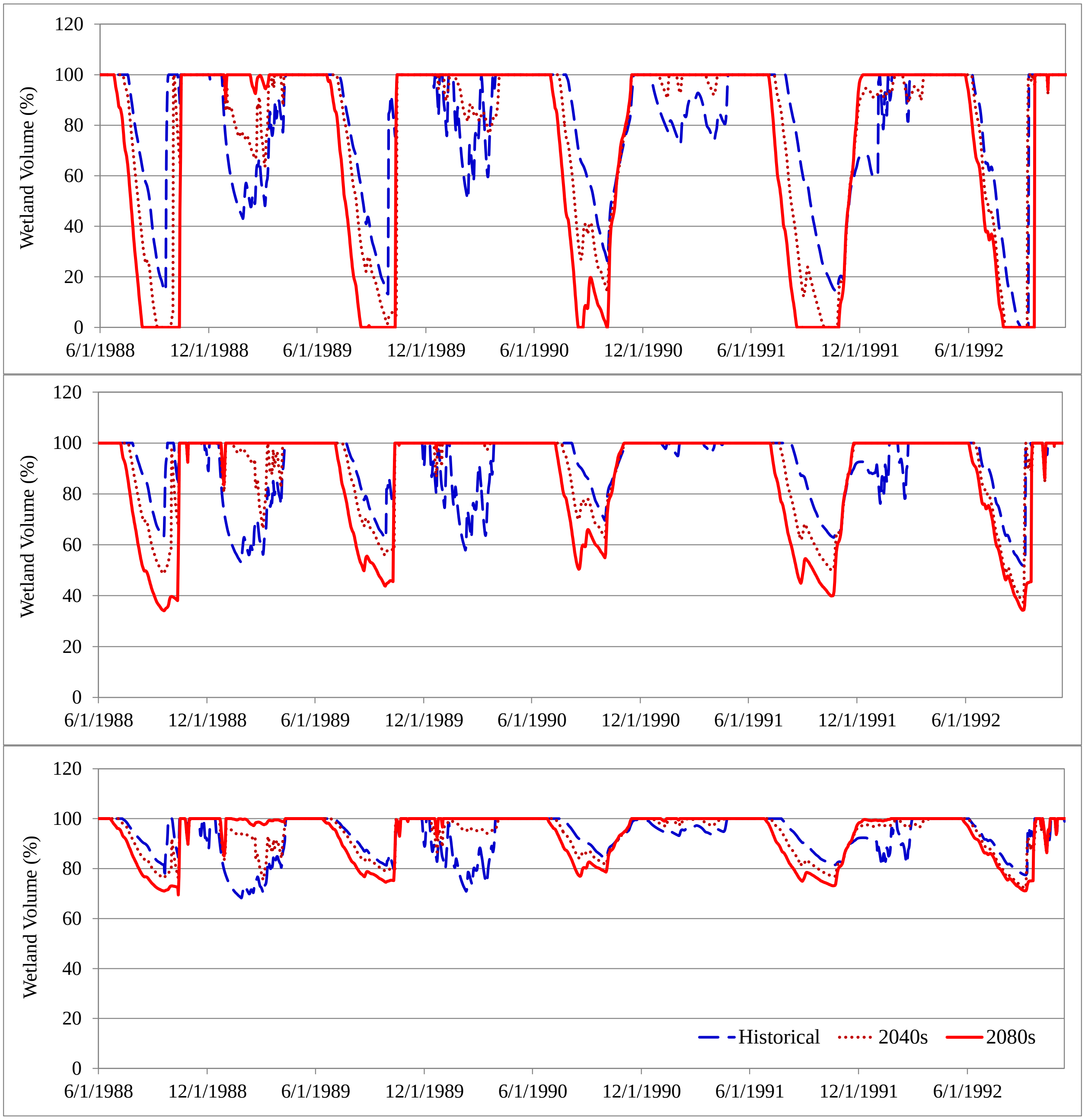

Figure 5. Predicted wetland response to climate change for an intermediate hydroperiod wetland (top), a perennial wetland (middle) and a permanent wetland (bottom) on Mt. Rainier, WA.

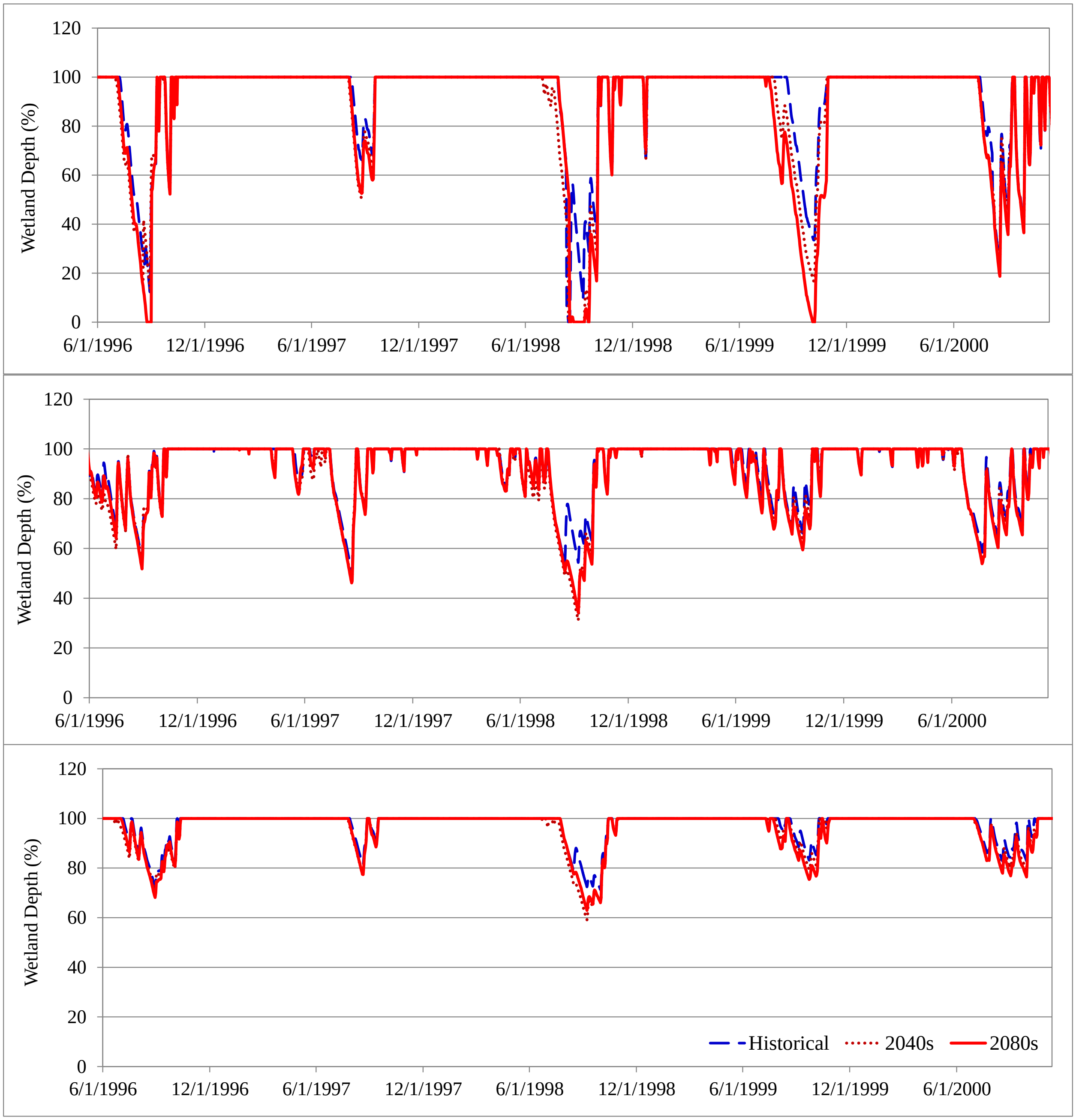

Figure 6. Predicted wetland response to climate change for an intermediate hydroperiod wetland (top), a perennial wetland (middle) and a permanent wetland (bottom) on Olympic National Park, WA from Jun 1996 to Dec 2000.

For sites in OR and CA we estimated the uncertainty of the projections due to regression parameter uncertainty (Fig 7). The estimated uncertainty of projections shows the same directions of the timing of drawdown and minimum water levels for climate change: earlier drawdown and reduced minimum water level in summer, though there is uncertainty in predicting the timing of drawdown and minimum water level. Similar to wetlands at Mt. Rainer National Park, higher winter wetland volumes are projected for montane wetlands in Willamette National Forest and Deschutes National Forest.

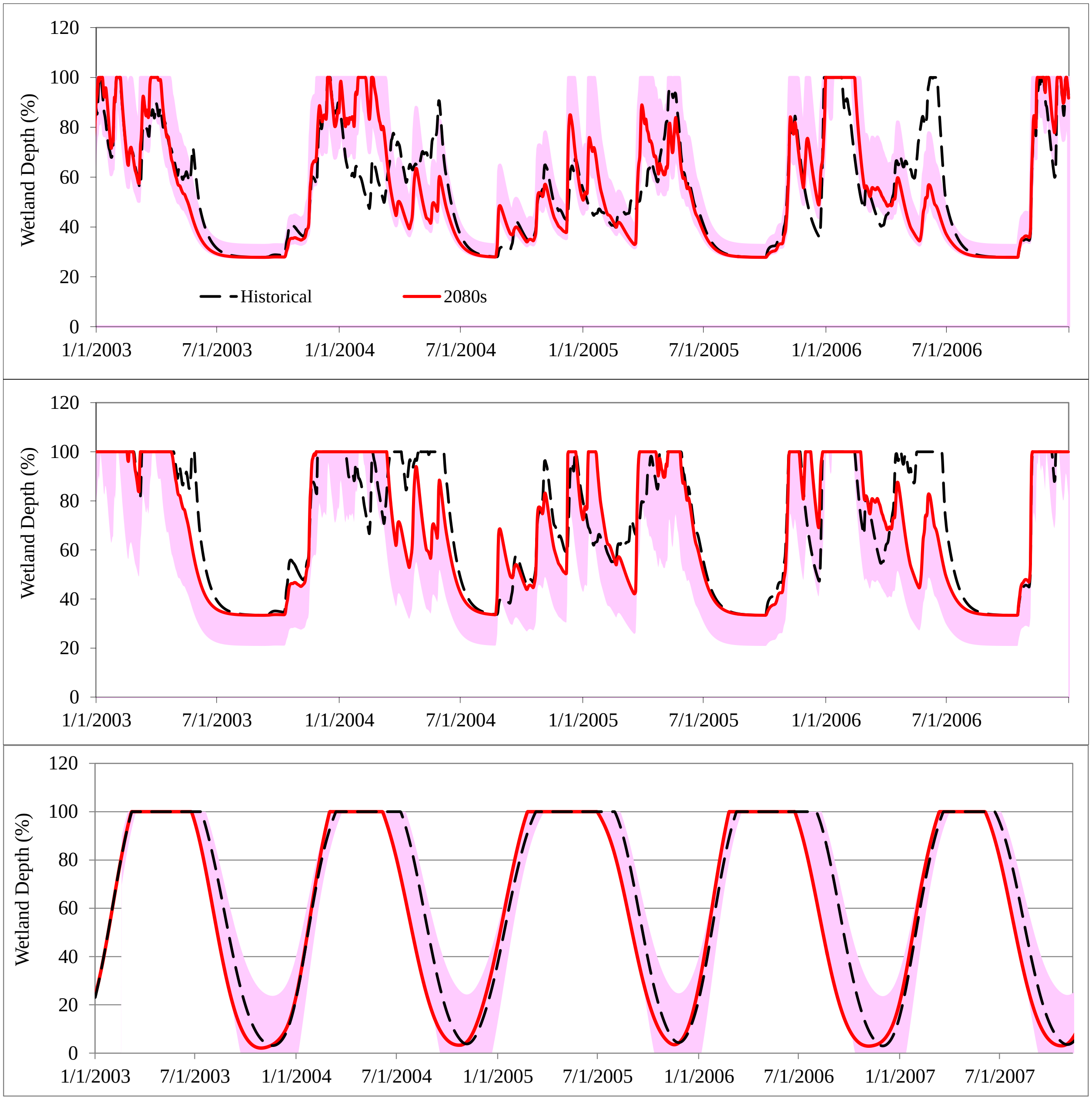

Figure 7. Predicted wetland response to climate change for Willamette National Forest, OR (top panel), for Deschutes National Forest, OR (middle panel) and for Trinity Alps Wilderness, CA (bottom panel). Dotted line represents historical run, solid line show the climate change run for the 2080s and band show the range of uncertainty related to regression parameter uncertainty.

Frequency analysis

Frequency analysis of wetland volume or depth using a greater number of years of simulated data provides an important measure of the true response of a particular wetland site to year-to-year climate variability, and also a clearer analysis of the effects of climate change on water levels. For example, wetlands at Mount Rainier were monitored in water year 1992, which was a severe drought year with very low snowpack in the Cascades. Thus the data for this single year suggest ephemeral characteristics at one of the sites (upper left panel in Fig 3). A wider range of conditions in the hydrologic model simulations from 1916-2006, however, shows that the wetland is actually an intermediate wetland with summer drying occurring about 15% of the time (upper left panel in Fig 8).

Frequency analysis of wetland volume or depth also shows that wetlands at the Mt. Rainier sites (left panels in Fig 8) are likely to experience greater hydrologic changes than those in Olympic National Park (right panels in Fig 8). Overall, water levels in intermediate wetlands are most sensitive to climate change (top panels in Fig 8). For intermediate wetlands at Mt. Rainier, for example, the probability of pond drying is projected to increase from 14% (13 out of 91 years) for the historical run to 87% for the 2080s (upper left panel in Fig 8). This represents a clear shift in hydrologic behavior from an intermediate to ephemeral wetland. Wetlands in Olympic National Park are less sensitive to climate change compared to Mt. Rainier, but nonetheless the projected probability of drying for intermediate wetlands in Olympic National Park increases from 52% for historical run to 65% for the 2080s (upper right panel in Fig 8). While the frequency of drying of perennial ponds in WA is not projected to change substantially, minimum pond volume is projected to decline over time with climate change (middle panels in Fig 8).

Unlike perennial ponds in WA, climate change is not projected to reduce the minimum water levels in the perennial wetlands in OR and CA (Fig S2) compared to historical conditions. Simulated soil moistures in all years are very low in the OR and CA sites, yet water levels are sustained. This supports the hypothesis that these wetlands are coupled to more extensive groundwater sources than the wetlands at Mt. Rainier and Olympic National Park.

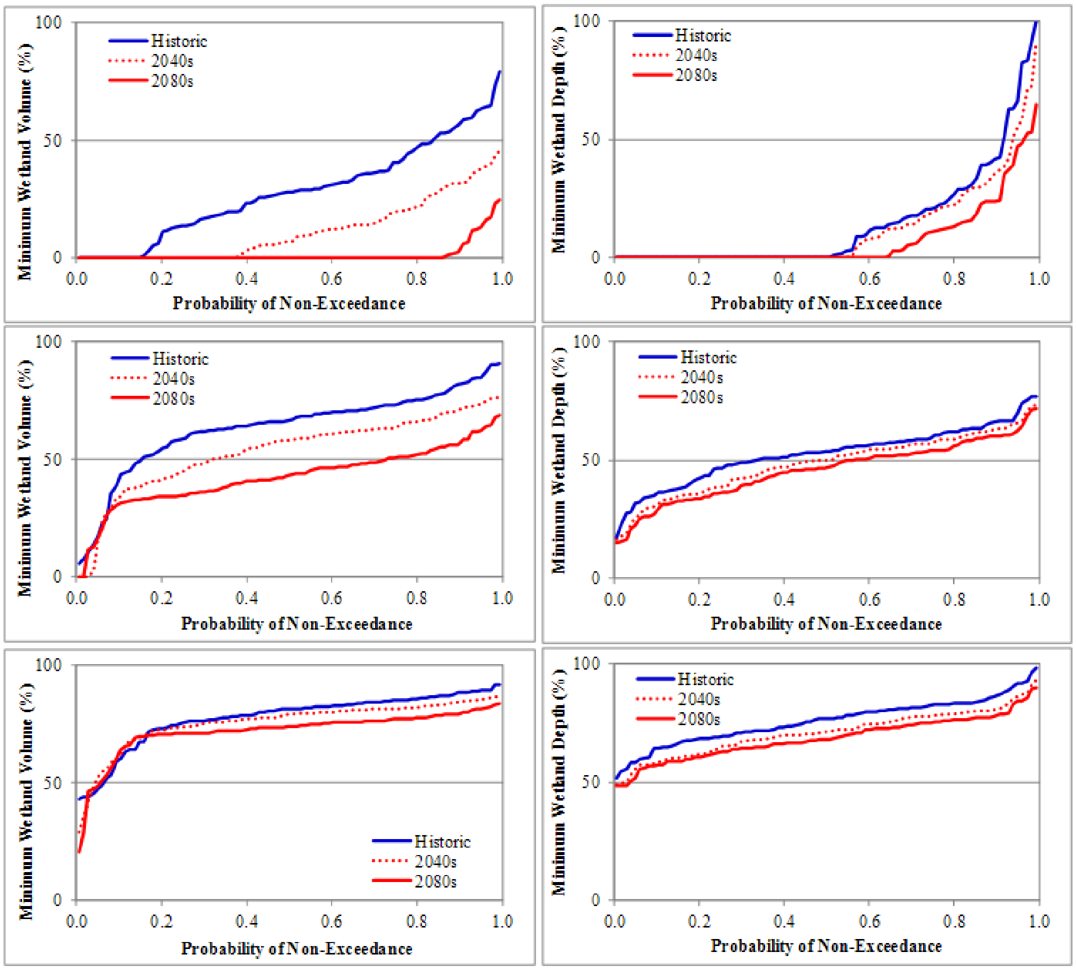

Figure 8. Probability of non-exceedance (percentile) for minimum wetland volume for Mt. Rainier (left panels) and for minimum wetland depth for Olympic National Park (right panels) for intermediate hydroperiod wetlands (top), perennial wetlands (middle) and permanent wetlands (bottom). (The probability of non-exceedance value where the curve first departs from zero is the probability of drying. If the y value is always above zero, then the probability of drying is zero.)

The effects of climate change on wetland drying vary geographically. Fig 9 shows the probability of drying in intermediate wetlands in WA (based on a lower soil moisture threshold of 50% of field capacity), calculated for each 1/16th degree grid cell for historical conditions (1916-2006), and the average of ten 2080s climate change scenarios. Note that lowland areas are typically below the soil moisture threshold every year, and the probability of drying (by this measure) does not change in these areas. In mountain areas, however, the model projects that there will be marked changes in the probability of drying for intermediate wetlands. In general, the results show that intermediate wetlands in the Cascades and Olympics are likely to become increasingly dry under climate change, except for a few high elevation areas on Mt. Rainier. For both the Washington Cascades and Olympic Mountains, the probability of pond drying ranges between 0 and about 0.7 under the 20th century climate. By the 2080s, the probability of drying is greater than 0.8 for all but a few model cells. A comparison between the change in the probability of drying and potential explanatory variables such as elevation, April 1 snow water equivalent, and change in snow water equivalent (SWE) at each cell, and average Dec-Feb temperatures in each cell showed that cells at moderate to high elevations with heavy snowpack in spring show the largest changes in the probability of drying in intermediate wetlands (Fig 10). This supports the hypothesis that the loss of snowpack (Elsner *et al*. 2010; Hamlet *et al*. 2013a) is likely to be one of the most important drivers of change in montane wetlands in western WA.

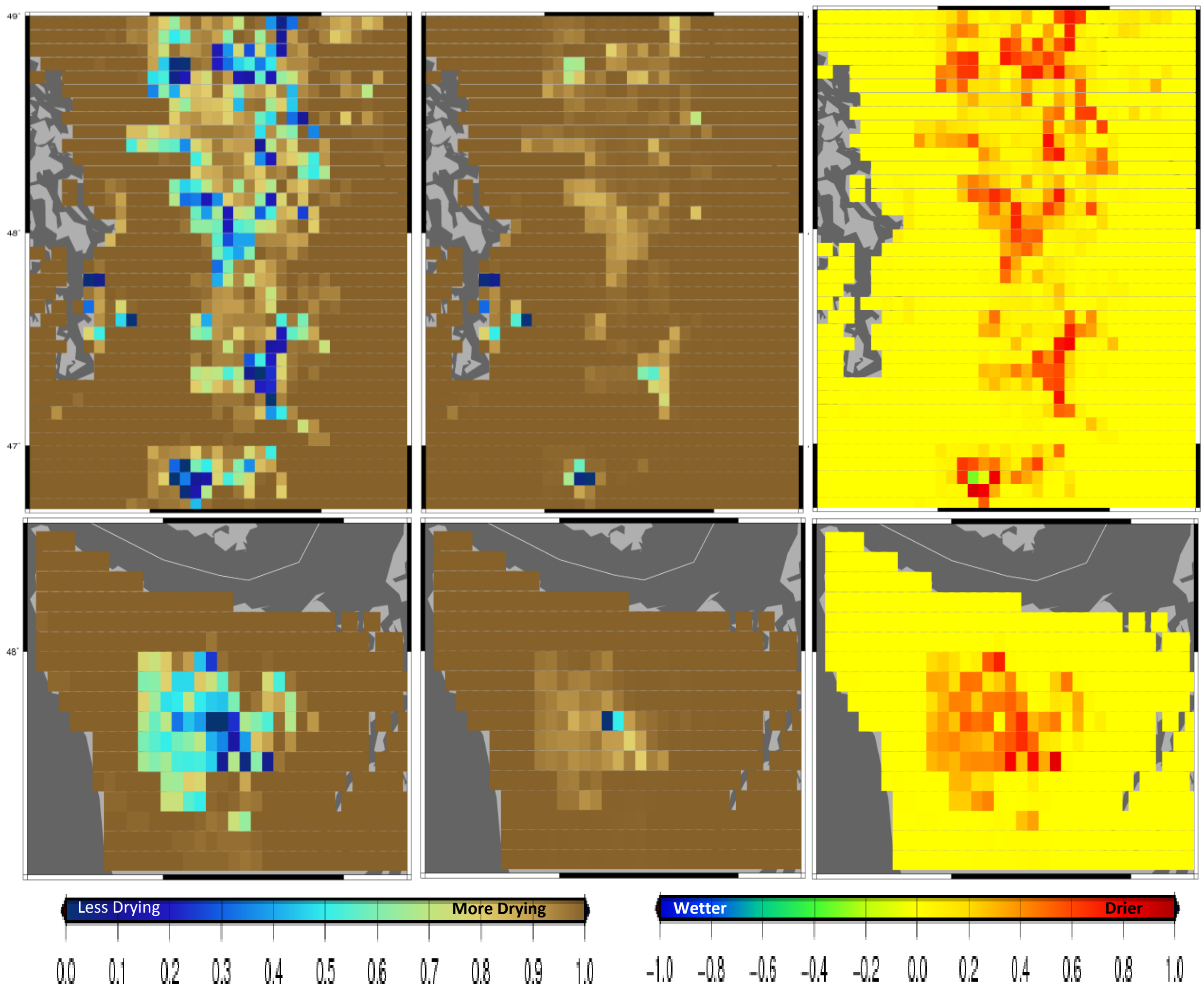

Figure 9. Maps of the probability of drying for intermediate wetlands in the Cascade Mountains in WA (top panels) and for Olympic National Park (bottom panels) for historical runs (left panels), the 2080s (middle panels) and the difference between historical and the 2080s (right panels). Projections for the 2080s are the average value for all ten GCM A1B scenarios.

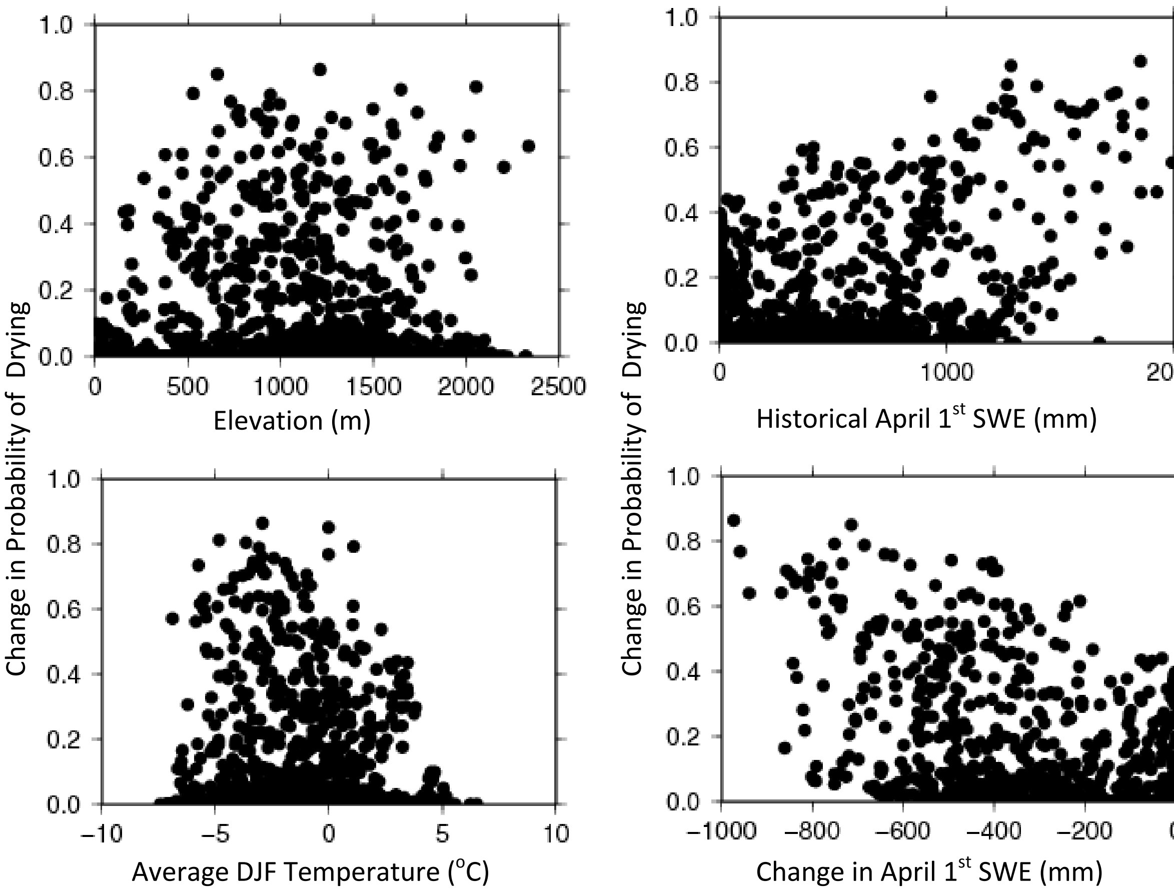

Figure 10. Scatter plots showing cells with positive changes in the probability of drying for intermediate wetlands in the Cascade Mountains and Olympic National Park vs elevation, average DJF temperature, historical April 1st SWE, and changes in April 1st SWE.

Discussion

In developing site-specific regression models for different wetlands we used somewhat different approaches depending on observed hydrologic behavior of specific wetlands. For example, we developed separate regression models for the two distinct hydrologic responses (gradual drawdown and rapid refill) in water year 1992 at wetlands in Mt. Rainier. In contrast, we developed a multiple regression model with two predictors for wetlands in Olympic National Park with repeated drawdown and refill periods in year 2000. Although these approaches worked well in individual years for which data is available, it is not entirely clear whether these apparent differences in wetland hydrologic response are fundamental to the hydrologic response of these sites, or are due to other factors such as variations in summer precipitation in different years. Additional data would be required to explore this question.

The single regression models applied for wetlands in Mt. Rainier, WA, Willamette National Forest, OR, Deschutes National Forest, OR and Trinity Alps Wilderness, CA ($0.87 < R < 0.98$) reproduced the observed wetland response better than the multiple regression model applied to wetlands in Olympic National Park ($0.74 < R < 0.77$). Again, this could be partly due to differences between years when the wetlands were monitored. The estimated uncertainty using multiple years of observations in the OR and CA sites confirmed that our approach is fairly robust, but that uncertainty in regression parameters needs to be considered when fitting to a single year of data. The regression models performed better in some years than others. Errors in local precipitation driving the hydrologic model are likely an important cause of these errors. Wetland water level data at more sites for multiple years is clearly needed to better understand the overall performance of these approaches, but these initial results are nonetheless encouraging.

Most montane wetlands are located either in snow-dominated watersheds or transient mixed-rain-and-snow watersheds where snowmelt is a key water source in late spring and summer. Because a warmer climate is likely to cause less snow accumulation in winter and earlier snowmelt in spring, montane wetlands are likely to be susceptible to climate change, especially in combination with projected drier summers. As a result, all types of montane wetlands we simulated are likely to have earlier drawdown, a more rapid drawdown, reduced water levels and a longer dry season in summer. However, the intensity and duration of climate change effects is projected to differ markedly among the three types of wetlands on which we focused. For example, the hydrology of intermediate wetlands is likely to be the most affected by climate change because of their relatively shallow water depth and high sensitivity to changes in summer water availability. Using estimated probability of drying based on soil moisture thresholds as a metric, our results show that the majority of intermediate mountain wetlands in western WA will shift to ephemeral wetlands by the 2080s.

Comparison between wetlands in WA and those in OR and CA shows that wetlands with seemingly similar hydrologic characteristics are likely to have different sensitivity to climate change depending on local conditions. For example, perennial wetlands in Willamette National Forest, OR and Deschutes National Forest, OR are likely to be less sensitive to climate change in terms of minimum water level compared to those in western WA. For perennial wetlands in OR, simulated summer soil moisture in the VIC simulations was close to residual values nearly every year but the ponds did not dry out (maintaining ~20 % of their maximum depth) under the current climate. This behavior suggests that, unlike the western WA sites, these wetlands are fed by substantial groundwater resources. For the climate change scenarios, these ponds are projected to have earlier drawdown and reach their minimum water level earlier, but without reducing their minimum water level. This supports the argument that groundwater-fed wetlands are less vulnerable to increased frequency of drying when compared to surface water-fed wetlands (Johnson *et al*. 2009). That said, groundwater-fed wetlands could also experience reduced minimum water levels due to a decrease in groundwater recharge and storage, which is not simulated by our hydrologic model. Conversely, potential increases in aquifer storage or water table height (e.g. due to increasing winter precipitation and groundwater recharge) could potentially increase minimum water levels in some groundwater-fed wetlands.

Simulations of montane wetlands in Mt. Rainier, WA, Willamette National Forest, OR and Deschutes National Forest, OR showed that water levels could be higher in winter under climate change compared to the historical runs (Figs 5 and 7). Although elevated soil moisture and water table height are consistent with reduced snow accumulation, more precipitation falling as rain in early winter, and increased winter precipitation (Hamlet *et al*. 2013a), these results should be interpreted with some caution, because we have no observed wetland data at these times of year with which to validate the models.

An important limitation of our work relates to the inability to identify wetland types in different areas with these approaches. Our models are useful in the context of predicting the response of a particular wetlands or wetland types to climate forcing, but soil moisture simulations from the same VIC cells are used to predict multiple types of wetlands (For example, all the sites at Mt. Rainier used in this study are in the same $1/16^{th}$ degree cell—only the regression models are different.). Thus the approaches we explore here are not useful for identifying what wetland types are present in a particular place. For this purpose, remote sensing applications that can both geographically locate and determine the hydrologic characteristics of a large number of wetlands may be the only viable approach (Halabisky *et al*. 2013a and 2013b).

The biological implications of the hydrologic changes described above are likely to be substantial. Loss of wetlands, changes in wetland thermal conditions associated with reduced water levels, and transitions among wetland types will affect the many plant and animal species that rely on them for food, habitat, and water. Cross-ecosystem subsidies; and ecological processes such a nutrient cycling are also likely to be affected (Greig *et al.* 2012; Ryan *et al.* 2013). Changes in the spatial distribution and connectivity of wetlands may affect landscape-scale habitat heterogeneity (an important driver of biodiversity), metapopulation dynamics, and patterns of gene flow (Chesson 2000; Whittaker *et al.* 2001; Hanski 2004). For pond-breeding species like amphibians and invertebrates that are particularly sensitive to the timing of water availability in montane areas, the projected changes in wetland hydrology are likely to reduce recruitment due to earlier drying (e.g., for fast-developing species like frogs) or more frequent drying (e.g., for salamanders with multi-year larval development). This would compound observed losses due to disease (potentially affected by water temperatures), pollution, and the presence of introduced fish (Davidson 2004; Knapp *et al*. 2007; Rohr and Raffel 2010; Piovia-Scott *et al*. 2011; Adams *et al*. 2013; Ryan *et al.* 2013). With more data to better validate the modeling approaches explored here, however, maps of the estimated probability of drying such as those shown in Fig 9 can be used to prioritize areas for fish removal as a tactic for proactive climate change adaptation (Ryan *et al*. 2013). Amphibians and invertebrates are important prey for many montane species, so the effects of population declines could propagate up food webs, negatively affecting the birds, non-avian reptiles, and mammals that rely on them as prey (Polis and Strong 1996; Epanchin *et al*. 2010). Overall, species' exposure will depend on what kinds of wetland habitat they use, the spatial distribution of wetland types across landscapes, and the degree of change in spatial and temporal hydrologic patterns under future climates (Ryan *et al.* 2013).

Our approach successfully related simulated macro-scale hydrologic variables to observed wetland data to project the climate change impacts on montane wetlands in the WA, OR, and CA. Because our methods were applied mostly in wetlands with only a few years of observed hydrologic data (often only a single year), additional research is needed to confirm that our approach is robust over a wider range of wetland conditions. Ongoing research will establish focal field sites and build longer historical data sets via in-situ monitoring of wetlands in diverse ecoregions (Ryan *et al.* 2013). In addition, remote-sensing methods have been developed to improve wetland mapping and reconstruct hydrologic dynamics of wetlands (Halabisky *et al*. 2013b). In future research we will extend our work to test the robustness of our approach over different eco-regions in the PNW using these longer and more comprehensive datasets.

Acknowledgements

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Supplemental material

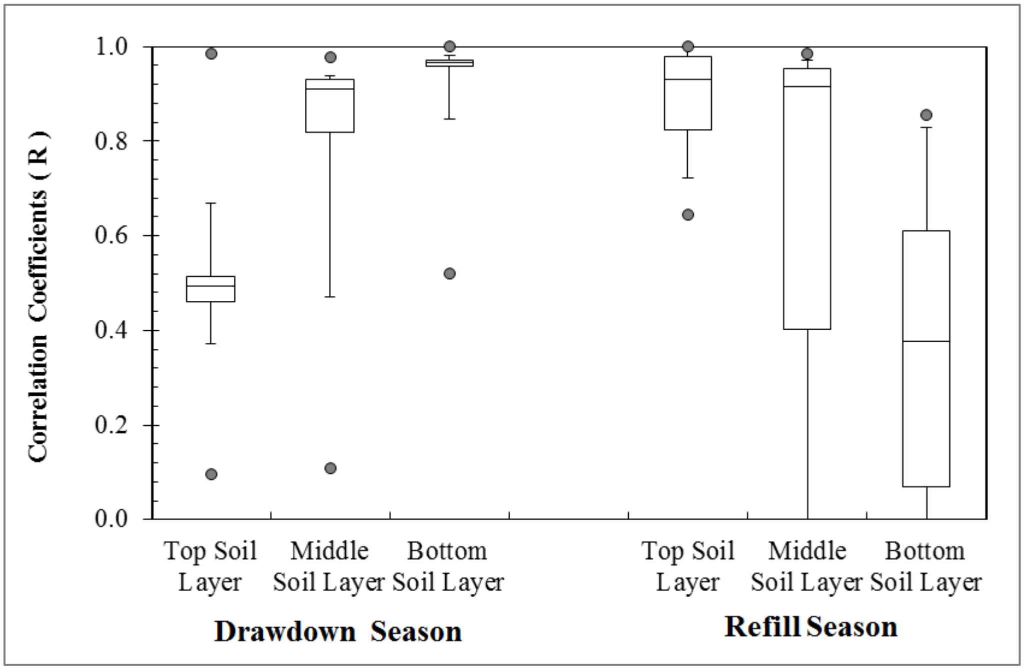

Figure S1. Summary of correlation coefficients (R) between observed wetland data and a temporally smoothed simulated soil moisture in the top, middle and bottom soil layers during drawdown and refill seasons. Middle line of the box indicates median R, box indicated 25th and 75th percentiles, whiskers indicate 10th and 90th percentiles and circles indicate range of values.

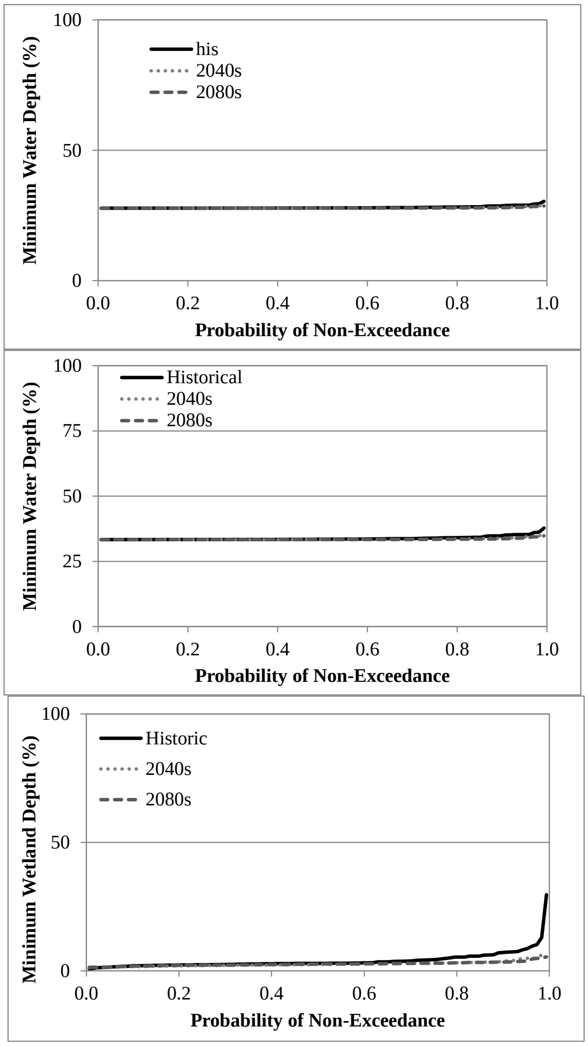

Figure S2. Probability of non-exceedance for minimum wetland depth for Willamette National Forest, OR (top panel), for Deschutes National Forest, OR (middle panel) and for Trinity Alps Wilderness, CA (bottom panel).

Chapter 2. Overview of a New Wetland Monitoring Protocol

Dr. Maureen Ryan (Smith Fellow, 2012) in collaboration with this project and a group of amphibian biologists including Dr. Wendy Palen at Simon Fraser University and Dr. Michael Adams at the USGS, has developed a new monitoring protocol for montane wetlands. The core of this protocol is the simultaneous monitoring of air and water temperature, wetland area, and water depth using inexpensive i-Button temperature sensors. The i-buttons are deployed in a set of redundant transects intersecting the deepest section of the wetland (Fig 1). The i-Buttons are connected together with strings to facilitate both locating the instruments and retrieving them. When underwater, the i-Buttons measure water temperature at the bottom of the wetland at a range of different depths. When exposed to air by falling water levels, the i-Buttons respond to the diurnal air temperature signal, which is easily observed in the temperature record (Fig 2). The location and depth of each i-Button is recorded during placement, so both water level and areal extent of the wetland can be estimated by identifying those i-Buttons that have become exposed to the air at a particular point in the time series. Table 1 provides a list of sites that are currently being monitored using the new protocol. The first field season was summer, 2012, and a second field season is planned for summer, 2013. The data from this new field campaign, combined with in situ biological monitoring, will greatly strengthen our ability to test the new modeling approaches developed in this project, and will support a much more detailed assessment of the response of PNW amphibian populations to climate change due to changing water levels and temperature.

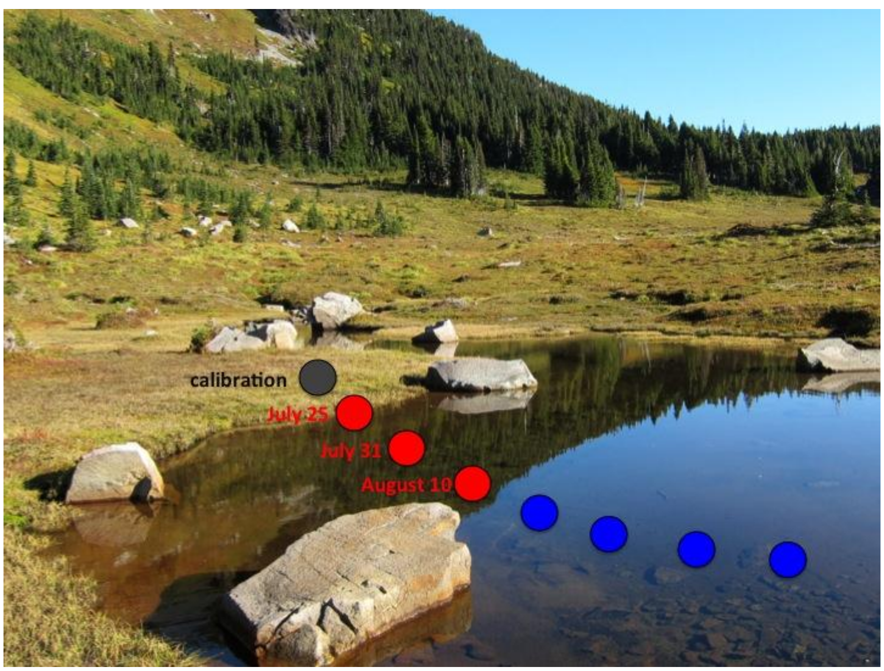

Figure 1. Example of a typical deployment of i-Buttons in a mountain wetland. Red markers show dates of drying of particular i-Buttons over the summer months. Blue markers represent i-Buttons that remained submerged for the entire summer. The calibration i-Button is always exposed to the air.

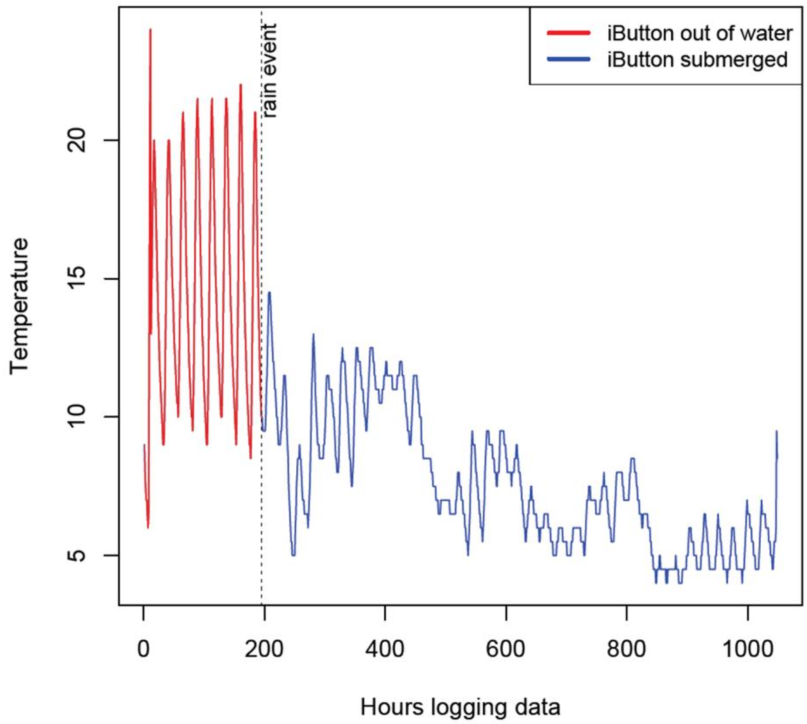

Figure 2. Temperature time series downloaded from an i-Button showing the difference in recorded data when the i-Button is exposed to air vs. submerged in water.

Table 1. Field sites monitored in 2012 using the new wetland monitoring protocol

Geographic Location	**Site and Monitoring Descriptions**
Mount Rainier National Park	Multiple surveys or ibuttons in 13 ponds in Mazama Ridge/High Lakes; 26 ponds in Palisades; 23 ponds in Spray Park
Olympic National Park	Multiple surveys or ibuttons in 23 ponds around Deer Lake; 16 ponds around Potholes; 32 ponds in Seven Lakes Basin; 33 ponds in Upper Lena Lakes region; plus point surveys in 3 ponds around Mink Lake and 24 ponds in Wye Lakes Basin.
North Cascades National Park	Multiple surveys or ibuttons in Pyramid Lake, Thunder Pond, and a riparian wetland in Big Beaver drainage; plus point surveys in 5 ponds around Dagger Lake/Twisp Pass and 18 ponds in Middle & Tapto Lakes region.
Puget Sound Lowlands	Multiple ibuttons in two wetlands near Bellingham
Eastern Washington	Multiple ibuttons in > 10 wetlands in Grant Co., WA

Chapter 3 Pacific Northwest Wetlands Symposium

An important objective of the project was to share new wetland information, monitoring approaches, and future projections generated by the project with wetland scientists, planners, and managers via a symposium, and to obtain feedback on important needs associated with managing wetlands in a changing environment. The symposium was hosted in collaboration with EcoAdapt [http://ecoadapt.org/about], a non-profit organization focused on climate change adaptation. The symposium was held at Woodland Park Zoo in Seattle on November 8, 2012, and was attended by about 50 participants listed below. A website provides access to the agenda, presentations, and supporting materials [http://ecoadapt.org/workshops/pnw-wetlands-symposium]. The symposium was very successful in calling attention to important monitoring and modeling needs associated with wetlands, their vulnerability to a changing climate and human land use, and important management concerns related to wetland conservation and restoration in a changing environment.

List of Symposium Participants:

Alan F. Hamlet	UW	Research Associate Professor	hamleaf@uw.edu
Regina Rochefort	North Cascades National Park	Science Advisor	regina_rochefort@nps.gov
Wendy Palen	Simon Fraser University	Assistant Professor	wpalen@gmail.com
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Maureen Ryan	University of Washington/Simon Fraser University	Postdoctoral Fellow	ambystomo@gmail.com
Eric Mielbrecht	EcoAdapt		
Se-Yeun Lee	UW		
Lara Hansen	EcoAdapt	Chief Scientist and Executive Director	lara@ecoadapt.org
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Teresa H Vanderburg	ESA	Vice President	tvanderburg@esassoc.com
Patricia Tillmann	National Wildlife Federation	Research Associate	tillmannp@nwf.org

Amy LaBarge	City of Seattle, Seattle Public Utilities, Watersheds	Forest Ecologist	amy.labarge@seattle.gov
Dwayne Paige	City of Seattle, Seattle Public Utilities, Watersheds		
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Emilie Blevins	TNC		
Bill Kirchner	USFWS		
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Marshall Gannett	USGS		
David Chapin	City of Seattle, Seattle Public Utilities, Watersheds		
Howard Ferguson	WA Dept Fish & Wildlife	District Wildlife Biologist	howard.ferguson@dfw.wa.gov
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Jill Silver			
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Joe Rocchio	WA DNR		

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John Gamon	WA DNR Program Manager		
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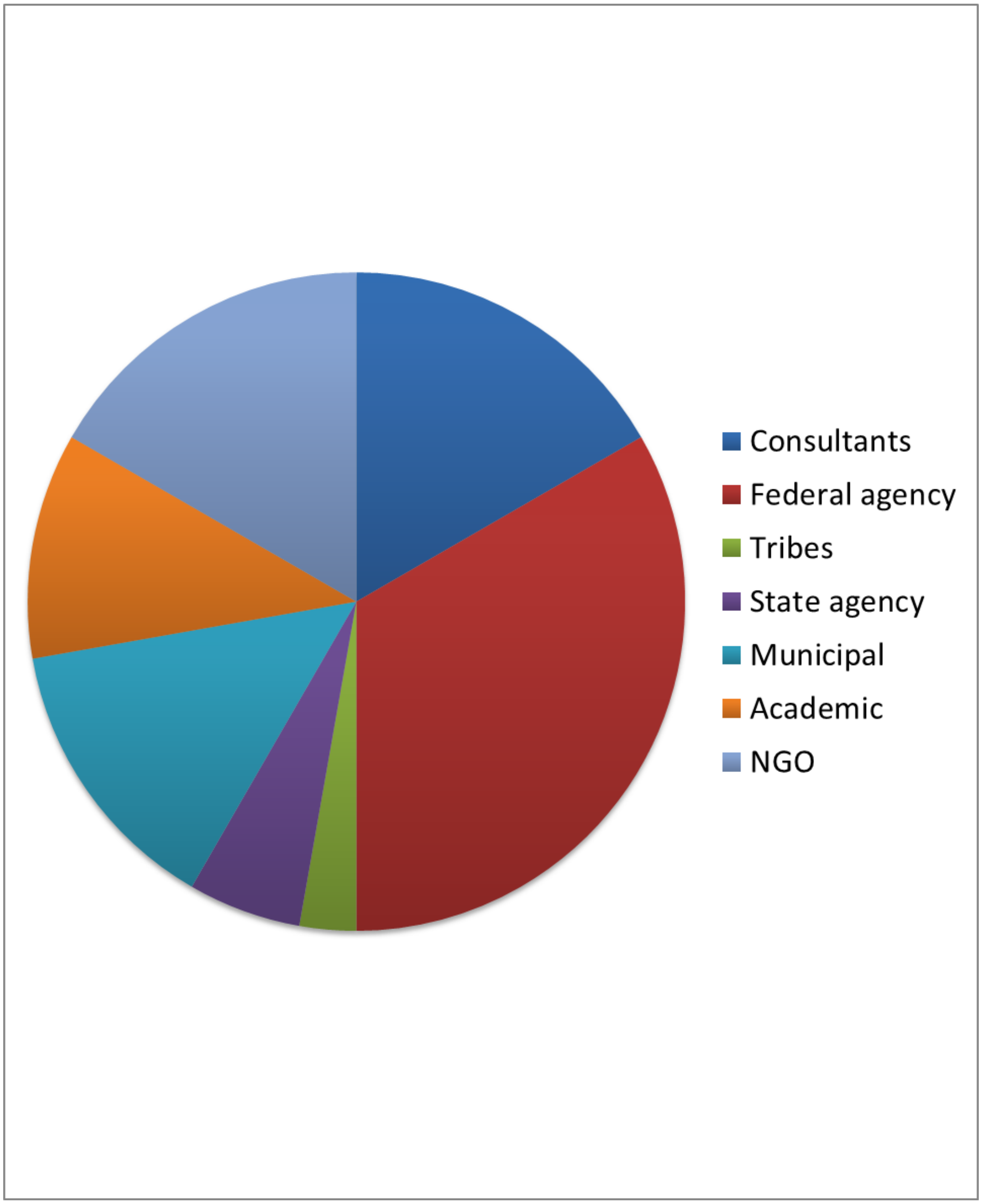
Rae Parks	WWU		
Barbara Samora	Mount Rainier National Park	Biologist/Research Coordinator	barbara_samora@nps.gov
Chris Lauver	National Park Service	Research Coodinator, Pacific Northwest CESU	chris_lauver@nps.gov
Mignonne Bivin	NOCA		
Andrew Bryden	USDA Forest Service, Mt Baker Snoqualmie NF	South Zone Hydrologist	abryden@fs.fed.us
Rachel Lipsky	USDA Forest Service	Environmental Coordinator	rslipsky@fs.fed.us
Ron Tressler	Seattle City Light	Ecologist	ron.tressler@seattle.gov
Scott Powell	Seattle City Light		



Breakdown of Symposium Participants (excluding symposium organizers)

Symposium Goals and Approach:

Pacific Northwest Wetlands Symposium: New Resources for Mapping & Climate Adaptation

November 8, 2012, 9am-4pm, Woodland Park Zoo, Seattle, WA

Workshop Detail

This one-day interactive workshop is designed as a forum for introducing and exchanging feedback on a new suite of wetlands mapping and climate adaptation resources for Pacific Northwest freshwater wetlands. The wide range of mandates, needs, and ecological contexts under which wetlands ecologists work highlights the importance of good information exchange among resource developers and managers, to support the production of tools that are both useful (for actual resource management) and used (in the workflow). This workshop is designed to facilitate that exchange and to enhance and build connections among managers, consultants, and researchers from many institutions in the Pacific Northwest region.

Goals for the workshop include:

- Presentation of new wetlands products and how they can be used
- Exchange of feedback to inform development of the next generation of products
- Discussion of management and research needs and how to address these
- Enhanced connections among wetlands researchers and managers in the region

Intended Outcomes

- Enhanced awareness of resources to support wetland management & climate adaptation planning
- Increased capacity of participants to use new resources
- Increased capacity of participants to incorporate climate adaptation into management
- Implementable activities developed by participants to employ the ideas developed in the workshop
- New connections to support collaboration in wetlands research and management across institutions
- Enhanced awareness of the importance of wetlands

Products to be explored include:

- Hydrological projections for wetlands for the 2040s and 2080s
  - Ephemeral, semi-permanent, and permanent wetlands
  - Multiple geographic scales (individual pond to whole Pacific Northwest)
- Remote sensing methods for detecting wetlands using NAIP and LiDAR
- Climate adaptation applications of the above products

Morning sessions: Introduction to new methods and products for mapping and projecting climate impacts on freshwater wetlands, and applications and case studies of how these tools may be used to support vulnerability assessments and climate adaptation planning & implementation to increase the resilience of wetland-reliant species.

Afternoon sessions: Discussion of current and future needs and uses of these products to guide development of the next generation of products and enhance applicability and information transfer. Discussions will involve both the whole group & breakout groups.

Target audience: Local, state, tribal, and federal agency managers and research biologists; restoration ecologists; consultants; academic freshwater ecologists; and hydrologists.

Geographic focus: Freshwater wetlands on the East and West sides of the Cascade and Olympic Ranges and lower British Columbia, including riparian wetlands, springs, wet meadows, small ephemeral pools, large permanent ponds and lakes, across a range of ecological contexts (forest, alpine, and arid lands).

Symposium Agenda:

Pacific Northwest Wetlands Symposium

November 8, 2012 • Woodland Park Zoo, Seattle, WA

Symposium Agenda

9:00 Welcome by Lara Hansen & Maureen Ryan
9:30 Introduction to vulnerabilities of wetlands & wetlands management: Alan Hamlet
9:45 Introduction to new products and how they can be used

- 9:45 Se-Yeun Lee: Wetlands hydrologic projections
- 10:00 Meghan Halabisky: Remote sensing, extending the hydromodel
- 10:15 Maureen Ryan: Applications of new tools for research & management

10:30 Open floor for questions
10:50 Break
11:00 Presentations by practitioners

- 11:00 Lara, Maureen & Regina Rochefort: Overview & federal wetlands management
- 11:10 Joe Rocchio (Washington DNR): Pacific Northwest Wetlands Classification
- 11:20 Allison Aldous (The Nature Conservancy): Groundwater & Wetlands Conservation
- 11:30 Eric Mielbrecht (EcoAdapt): Yale Framework Approach to Climate Adaptation
- 11:40-12:00 Discussion

12:00 Lunch (provided at no cost)
1:00 Breakouts

- What is your mission? What are you trying to do?
- How is your goal likely to be affected by climate change?
- What can you do about it?
- How can the tools presented help you make better decisions given climate change?

2:15 Break
2:30 Breakout continued

- What can none of these tools help you do that you feel is necessary before you take action?
- Feedback within breakout

3:30 Report back from breakouts
3:50 Conclusions & evaluations