# MONTANE MEADOWS IN THE SIERRA NEVADA: CHANGING HYDROCLIMATIC CONDITIONS AND CONCEPTS FOR VULNERABILITY ASSESSMENT

*Joshua H. Viers, Sabra E. Purdy, Ryan A. Peek, Anna Fryjoff-Hung, Nicholas R. Santos, Jacob V. E. Katz, Jason D. Emmons, Danielle V. Dolan, and Sarah M. Yarnell*

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# OVERVIEW

The meadows of the Sierra Nevada and southern Cascade Range are an iconic resource that embodies the spirit and grandeur of the American West. The stunning vistas across meadows observed by early inhabitants were maintained by a dynamic interplay of biotic and abiotic forces, and functioned to bridge aquatic and terrestrial ecosystems. Meadows are not only key habitat for fishes, amphibians, birds, and mammals alike, but also provide enumerable ecosystem services to humans. Chief among these services is water regulation, in which meadows serve to attenuate flood flows, sustain base flows, and filter out undesirable constituents. Unfortunately, meadows of the Sierra Nevada are highly degraded throughout the range.

This technical report provides guidance for resource managers in considering conservation and restoration options for meadow ecosystems considering that the very foundation of meadow ecosystems—the dynamic interplay of surface and ground waters supporting unique vegetation—will likely change in time due to global atmospheric warming and resultant regional hydroclimatic alteration. This report begins by establishing a context for the nature, importance, and organization of montane meadows with a specific focus on a study region inclusive of the Sierra Nevada and portions of the southern Cascade Range (i.e., the upper Pit River complex and portions of the Modoc Plateau). The report then proceeds with an overview of climate change and potential impact to meadows with specific discussion of general trends and projected outcomes, regional differences, and a comprehensive review of potential impacts on hydrological processes. This review is complemented by a discussion of how hydroclimatic alteration may impact meadow dependent species, and which indicator species are likely to be most beneficial for monitoring and management from a conservation standpoint.

The montane meadows of the Sierra Nevada have endured more than 150 years of intensive human use of ecosystem-based services, not limited to regulating services (e.g., water filtration), provisioning services (e.g., grazing), and aesthetics. Unfortunately, this resource is likely undervalued as the intensive human uses have led to widespread ecosystem degradation in the form of erosion, incision, loss of water table, encroachment of xeric and non-native vegetation, loss of native species, and exacerbated disturbance regimes, such as catastrophic wildfire. Thus, even in the absence of hydroclimatic alteration, it would be important to inventory and assess the integrity of this important resource, and further to establish a framework for its long-term conservation and functional restoration where warranted.

In the following pages we provide a number of analyses and tools that resource managers should find helpful as they begin to assess local conditions that increase vulnerability to hydroclimatic alteration, and begin to promote conservation and restoration activities that promote ecosystem resilience. Among these components are: a series of conceptual models intended to focus future assessments on the physical underpinnings of hydroclimatic alteration and ecohydrological responses; a focused geographic analysis of amphibians as indicator proxies for meadow vulnerability across the Sierra Nevada; and a thorough set of appendices to serve as a stepwise vulnerability assessment strategy that narrows to the use of indicator species for conservation and restoration strategies, accompanied by detailed information for selected indicator species that describe natural history characteristics, physiological tolerances, and habitat preferences.

## WHAT IS A SIERRAN MEADOW?

Meadows are ecosystems defined by a unique assemblage of biotic and abiotic factors, including soil characteristics, hydrology, and vegetation. In California's Sierra Nevada and Southern Cascade mountains, meadow ecosystems are defined by the presence of shallow groundwater (< 1 m depth), fine-textured surficial soils, and the dominance of herbaceous vegetation (Weixelman *et al.* 2011). No two meadows are identical, however. It is the combination of vegetation, hydrology, and geomorphic processes that defines a meadow, its initial formation and successional evolution through time.

The presence of tree and shrub species is typically limited by a persistent and high water table, which favors hydric herbaceous species. Thus, it is not common for riparian thickets to form streamside within meadows. Geomorphic and hydrologic processes also play a major role in defining meadow characteristics. Depending upon surrounding topography and relation to the water table, meadows can act as sources of recharge to, sinks for, or discharge from groundwater. The duration, amount, and source of water entering a meadow, as well as directional flow, origin and whether water remains in or leaves the meadow system are governing factors in evaluating individual montane meadow ecosystems.

Ecologically and hydrologically functioning montane meadows provide a variety of ecosystem services. They serve as wetlands; filtering water, attenuating floods, providing highly productive habitat and refuge from high flows when inundated (Loheide *et al.* 2009; Lowry *et al.* 2011). Meadows also support adjacent lacustrine and riparian ecosystems by stabilizing streambanks and shorelines, improving water quality by filtering sediments, and providing key pathways for hydrologic cycling (Woltemade 2000; Hammersmark *et al.* 2008).

### *What are montane meadows?*

Meadows are ecosystems defined by a unique assemblage of biotic and abiotic factors, including soil characteristics, hydrology, and vegetation. Generally, montane meadows meet the following criteria:

- Found at elevations higher than 500 m in mountainous terrain;
- Composed of one or more plant communities dominated by herbaceous species;
- Support plants that use surface water and/or shallow groundwater (usually at depths of less than one meter);
- Woody vegetation, like trees or shrubs, may occur and be dense, but are not dominant; and
- Finely textured surficial soils are present.

*(adapted from Weixelman et al. 2011)*

## IMPORTANCE OF SIERRAN MEADOWS

Montane meadows within the Sierra Nevada and Cascade ranges of California account for less than one percent of the total area in the study region (see sidebar); however, they are incredibly dynamic and important ecosystems providing invaluable functions and services to surrounding habitats and downstream human and natural communities (Kattleman & Embury 1996).

Despite the vital role meadows play in broadly maintaining ecosystem services and biodiversity, they have been identified as one of the most altered, impacted and at-risk landscapes in the range (Keeley *et al.* 2003; Loheide *et al.* 2009). The most prevalent historic alterations to Sierran meadows include livestock grazing, railroad grades, diversions and ditching, and culverts from roads. When meadows become impaired, the first signs of impact occur in the stream channel (Purdy *et al.* 2011). Bank stability and vegetative cover may be reduced by any number of stressors, which then begin to erode under the dynamic force of water. The result is a widening of the channel and continued erosion of stream banks. Eventually, the channel area becomes so large that the stream does not have adequate volume to overtop the banks during periods of peak runoff, thereby concentrating the water's energy inside the stream banks where it continues to erode downward, cutting deeply incised channels into the soft meadow soils. This, in turn, often results in a drop in the water table, which can lead to a shift in the plant community from herbaceous perennial vegetation to upland vegetation. At this point, most, if not all, critical wetland properties of the meadow are lost (Purdy *et al.* 2011).

## FORM AND FUNCTION OF SIERRAN MEADOWS

### HYDROLOGIC STRUCTURE

Montane meadows of the Sierra Nevada are largely defined by their hydrology (Weixelman *et al.* (2011). For the mid- to high-elevation portions of the range, meadows typically receive a consistent water supply from snowmelt. Snowmelt not only provides surface water, but also recharges groundwater, which in turn provides elevated soil moisture conditions and baseflow during the growing season. To distinguish how hydrologic processes can transform a meadow, it is necessary to consider a

### *How many meadows are there in the Sierra Nevada?*

Various entities have attempted to estimate the number and area of meadows in the Sierra Nevada, utilizing various methods and a broad range of geographic focus, from the individual watersheds to the entire extent of the Sierra Nevada. Unfortunately, none of the resultant datasets comprehensively covers the Sierra Nevada, due to coverage gaps and inadequate extent. Furthermore, many datasets overestimate meadow area by 100% or more (Hunt & Nylen 2012).

To definitively answer the question of how many meadows are in the Sierra Nevada, we inventoried and assembled all known and available GIS data layers for meadows. Each layer was prioritized based on method (e.g., field delineation with GPS, digitizing from aerial photographs, regional vegetation maps, etc.), age, and feature representation, and then assigned a confidence ranking. Spatial gaps were remedied with additional digitizing. All data layers were then spatially reconciled by summing confidence rankings and extracting features with at least three low-ranking source layers. All waterbodies, as well as meadow polygon features < 1 acre, were excluded from the resulting data layer.

Based on our rigorous data analysis, we estimate that there are 17,039 meadows in the Sierra Nevada, covering 191,900 acres (77,659 hectares).

fully-functioning meadow system with a stable hydrological regime. In this scenario, water is continually entering and leaving the system, creating a hydrologic cycle and budget specific to the location over a period of time (e.g., hourly, daily, seasonally, annually). There are four primary water sources for montane meadows: snowmelt, overland flow within the basin, surface flow entering via stream and spring networks, and direct precipitation (Lord *et al.* 2011) (Figure 1). Water is lost from a meadow primarily through surface outflow and evapotranspiration. There are a variety of pathways for water to travel through a meadow system, thus hydrologic changes often occur in concert between physical and biological drivers. Because process cascades and feedback loops exist (both physical and biological), biogeophysical processes can rapidly change the state of meadow hydrology through time and across space. The following discussion clarifies the detailed linkages between physical and biological drivers in a meadow, such that implications of hydroclimatic alteration can be more fully understood.

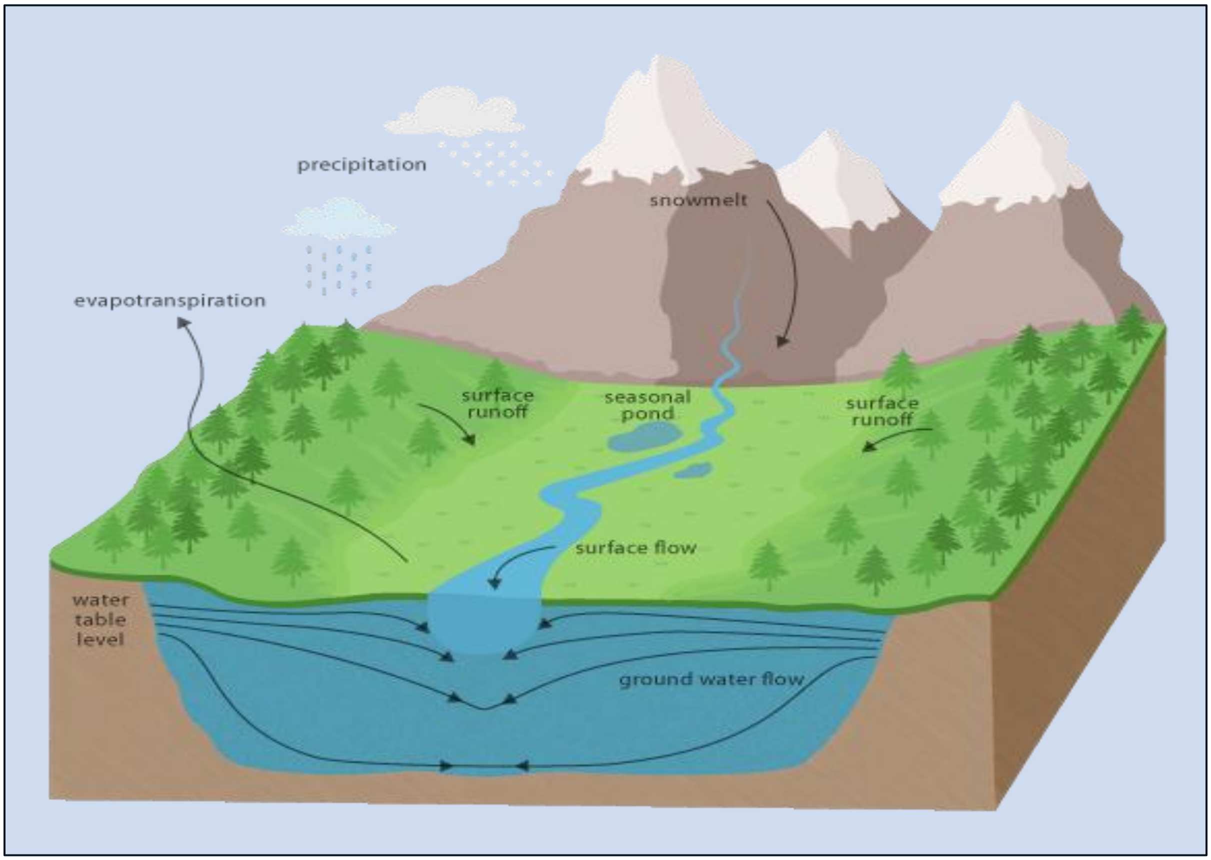


**Figure 1. The hydrologic cycle applied to a meadow. Arrows indicate pathways for the movement of water in its various forms.**

For much of the Sierra Nevada, snowmelt is often the most important water supply, as its source (snowpack) is a relatively consistent reservoir promoting efficient groundwater recharge through a diurnal flux of snowmelt pulses. Gradual melting allows for periods of saturation and infiltration, maintaining a consistent groundwater table elevation (typically < 1 m below the land surface) (Loheide & Gorelick 2007). A high groundwater table is essential for hydrophilic meadow plants, which often have elevated rates of transpiration (Castelli *et al.* 2000; Galatowitsch *et al.* 2000; Elmore *et al.* 2006; Loheide & Gorelick 2007). Although a high groundwater table is necessary to sustain meadow plants, periodic flooding is often necessary to maintain meadow functioning (Hammersmark *et al.* 2008; Hammersmark *et al.* 2010). A dynamic feedback between meadow hydrology and vegetation is maintained by the evolution of fibrous root systems in meadow vegetation that provide excellent bank stability and reduce bed sheer stress, thus limiting channel incision (Micheli & Kirchner 2002). The resistance to channel evolution due to stable stream banks amplifies overbank flooding events (Loheide & Gorelick 2005), thereby promoting additional groundwater recharge, the extension of baseflow, and the persistence of meadow vegetation (See Figure 2).

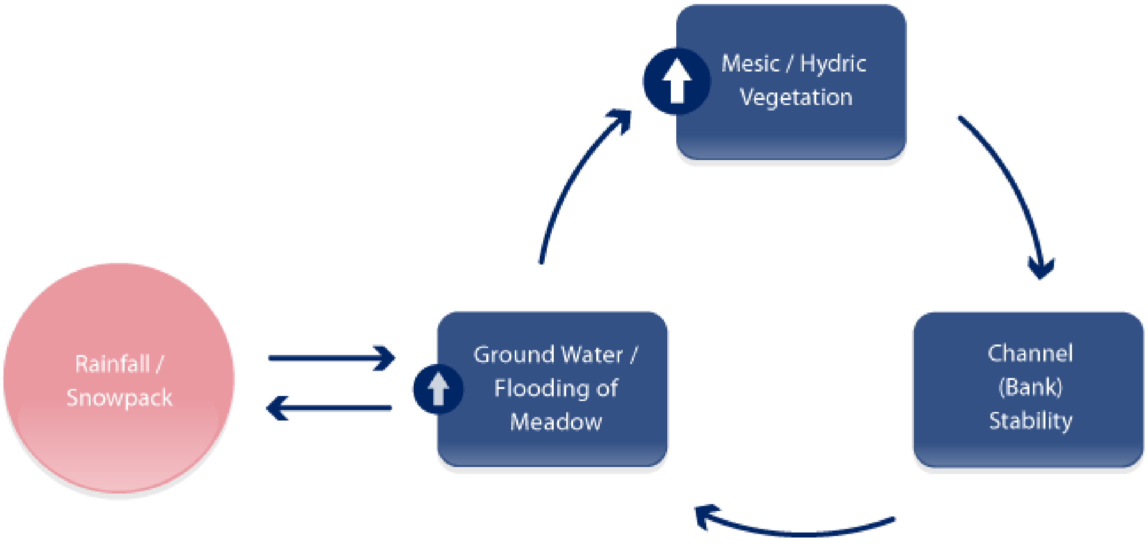


**Figure 2. Process and function in a meadow.**

A variety of factors can disrupt the dynamic feedback within healthy montane meadows resulting in a fundamental process shift towards channel incision. Typically initiated by a decrease in groundwater level, channel incision creates a dramatic feedback cycle that furthers and maintains a state of impairment (Figure 3a & 3b). As groundwater levels decrease, a shift towards xeric vegetation occurs as hydrophilic plants senesce. The loss of dense, fibrous root systems allows for bank erosion, which decreases channel stability and furthers channel incision. Increased channel capacity reduces flooding of the meadow as flows are more quickly conveyed downstream, which in turn decreases groundwater recharge, further exacerbating impaired conditions (Schilling *et al.* 2004). Currently, most impaired Sierran meadows are, or have become, highly eroded due to anthropogenic factors such as grazing, hydrologic regulation or construction of roads. However, hydroclimatic changes have the potential to further degrade currently impaired meadows as well as alter conditions for unimpaired meadows. In subsequent sections, discussion focuses on hydroclimatic forcing increasing the magnitude of rainfall precipitation events and decreasing groundwater recharge due to less snowpack, accelerating the “incision cycle”.

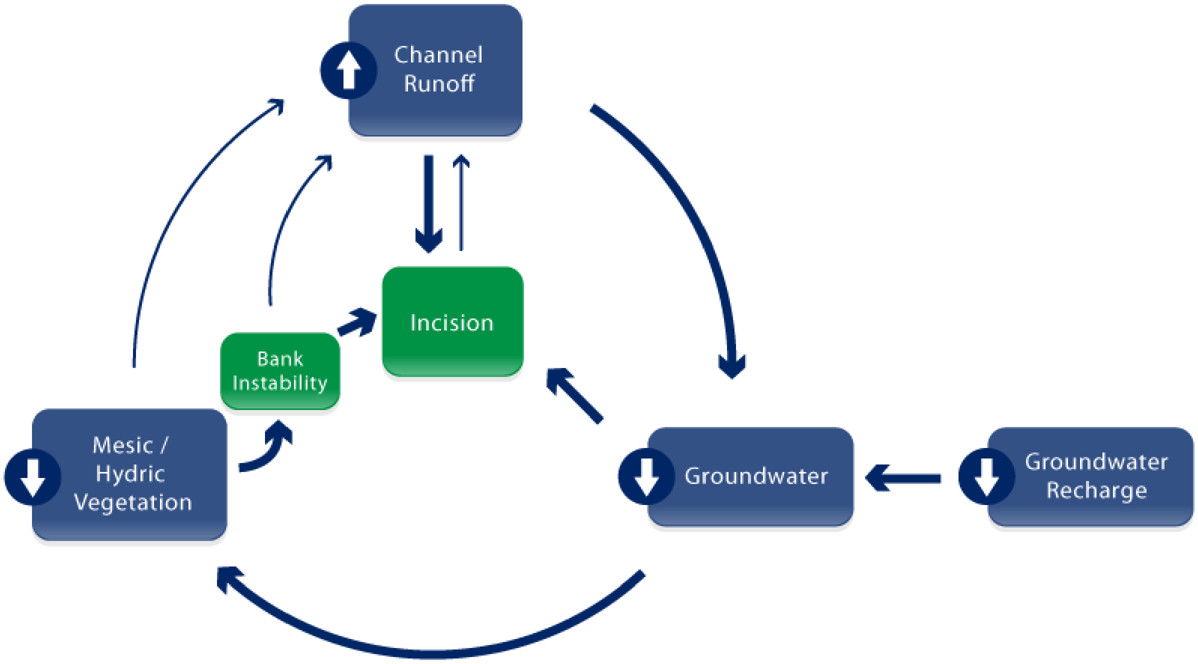


Figure 3a. The "Incision Cycle" of an impaired meadow.

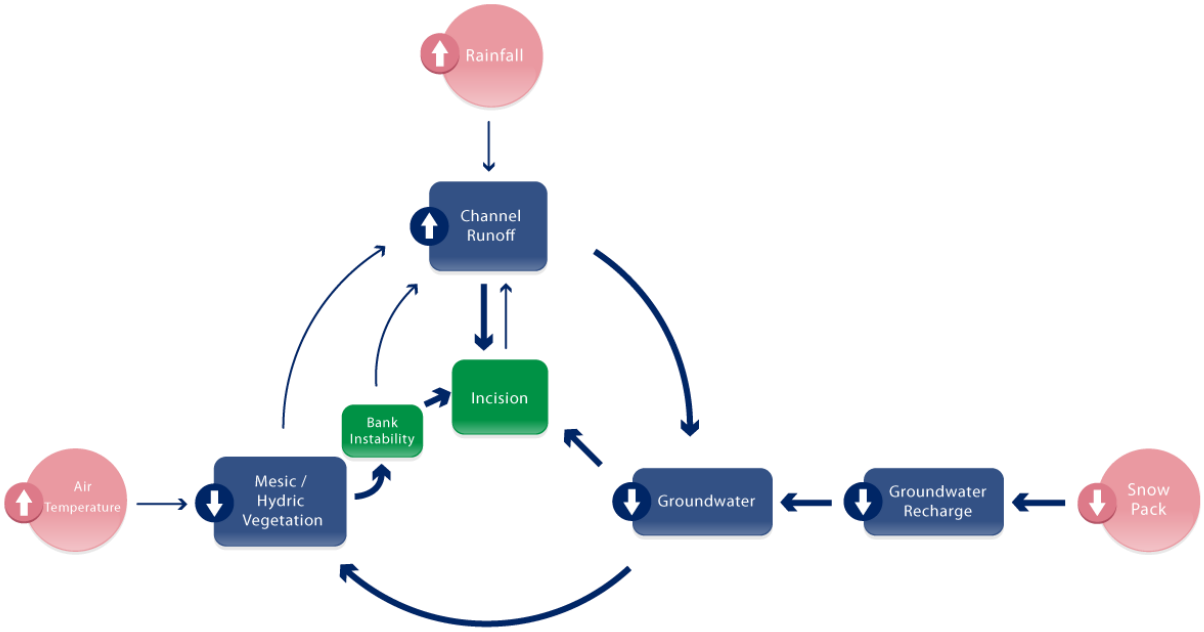


Figure 3b. Accelerated "Incision Cycle" due to hydroclimatic forcing and altered hydrology.

## MEADOW TYPES AND COMMUNITY STRUCTURE

Meadows in the Sierra Nevada support high biodiversity of both vegetation and faunal communities, but are non-uniformly distributed throughout the range (Figure 4). In its simplest form, though, the most important driver of community structure is the flow regime: the presence and absence of surface water, flowing water versus standing water, and the duration of inundation. Each are critical factors is shaping the hydrogeomorphic (HGM) type of a meadow, and its community composition, structure, and function. Vegetation structure and density are particularly important in determining how bird and mammal species utilize meadows. Thus, integrating HGM into meadow conservation and restoration planning is a necessary step to evaluating meadow condition and expected community structure, and response to future change.

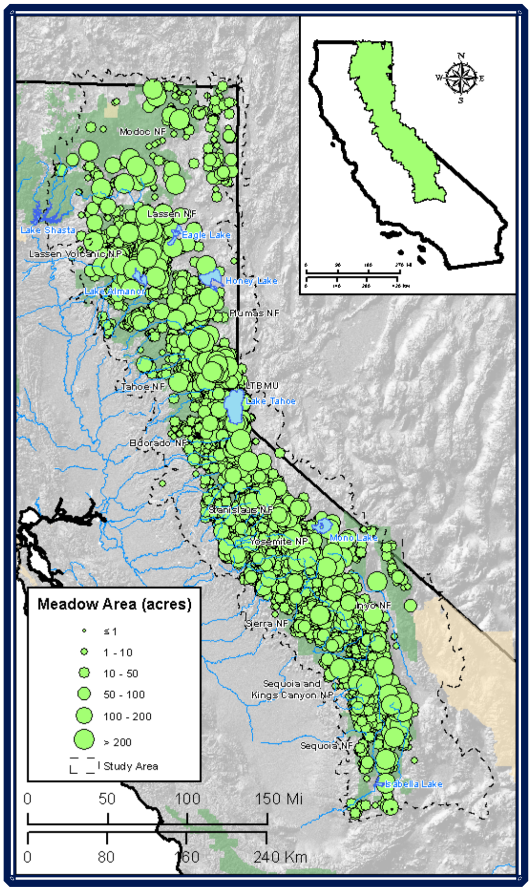


**Figure 4. Sierra Nevada meadows are non-uniformly distributed across the range. See Appendix C for a detailed description of data developed for this report.**

Based on the work of Weixelman *et al.* (2011), this report discusses the importance of hydrologic setting in the watershed, how water behaves in meadows (e.g., subsurface flow, surface flow, riparian channel, seeps and springs, etc.), topographic gradient, soil formation and type, and moisture regime. By defining the functional characteristics of a given meadow and factors that influence its condition, the connections can be made between meadow HGM types and the larger ecological community (i.e., dependent species and habitat structure).

The most important drivers of community structure in meadows are the presence or absence of surface water and the duration it is available within the year. Weixelman *et al.* (2011) identify meadow types lacking surface water for a large proportion of the year as "**subsurface**" and "**dry**" type meadows. These meadows range from having a considerable amount of available subsurface water to being quite dry, whereas the vegetation community structure reflects the amount of water available and the depth of the water table (Castelli *et al.* 2000; Micheli & Kirchner 2002; Auble *et al.* 2005; Elmore *et al.* 2006; Coles-Ritchie *et al.* 2007; Loheide & Gorelick 2007; Bayley & Guimond 2008; Hammersmark *et al.* 2009). Wetter subsurface meadows will support typical mesic (moist) and hydric (wet) meadow communities dominated by herbaceous perennial vegetation, such as sedges (*Carex* spp.) and rushes (*Juncus* spp.). They may also support riparian shrubs, such as willows (*Salix* spp.) and alders (*Alnus* spp.), in varying densities. Drier meadows will trend more towards vegetation communities dominated by grasses (Poaceae) and support a much higher proportion of annual and perennial forbs and shrubs characteristic of the upland vegetation community (Castelli *et al.* 2000; Chambers *et al.* 2004). The lack of surface water in these meadows results in an overall community structure more similar to upland communities. These dry meadow types are extensively utilized by rodents and deer that browse the herbaceous vegetation, and are also frequented by predators of rodents and deer. These types typically do not support aquatic taxa such as fish or aquatic macroinvertebrates. Although, some macroinvertebrates that can inhabit moist soil during their pupal stages may be present, and flying aquatic adults may be found throughout if surface water is nearby. The presence of birds is largely determined by vegetation structure within and around the meadow. Riparian shrub height and canopy complexity are primary drivers for avian species presence or absence (Seavy *et al.* 2009).

Meadows that contain surface water for a significant portion of the year are characterized as: "**Peatland**," "**Depressional**," "**Lacustrine Fringe**," "**Discharge Slope**," and "**Riparian**" types. The primary drivers of vegetation community functioning and structure are: amount of available water, soil type and depth (i.e., organic peats vs. mineral soils), slope, water table depth, aspect and exposure, and disturbance regime (Allen Diaz 1991; Castelli *et al.* 2000; Shafroth *et al.* 2002; Elmore *et al.* 2003; Darrouzet-Nardi *et al.* 2006). These meadows can range from open, herbaceous dominated systems to impenetrable riparian shrubfields. Peat wetlands possess very specific water chemistry and tend to contain unique vegetation communities that presumably support unique faunal communities, particularly invertebrates. Terrestrial animals such as birds, rodents, deer, skunks, foxes, and bears will use these meadows according to the habitat structure, and thus the resources they provide to those species will vary considerably by meadow.

**Pacific mountain onion (*Allium validum*) is often found in the montane meadows of the Sierra Nevada.**

The most important driver of aquatic communities is flowing water (lotic) versus standing water (lentic). Lotic waters typically support fishes as well as macroinvertebrate communities that are indicative of cooler temperatures, coarser substrates, higher dissolved oxygen and less tolerance of sediment and organic pollution though these conditions can vary considerably based on the individual characteristics and condition of the stream. Lentic waters, especially smaller bodies, typically support amphibians (though many contain fish) and an invertebrate community typical of standing waters with fine substrates. These conditions result in invertebrate communities dominated by tolerant taxa such as diptera (true flies), annelids and turbellaria, as well as other species that do not require high levels of dissolved oxygen, can endure warmer water temperatures, and tolerate fine sediments.

Of the HGM types that sustain surface water for a significant portion of the year, riparian and discharge slope meadows are generally dominated by flowing water, while depressional and lacustrine fringe meadows contain predominantly standing water. This too can vary considerably based on time of year and habitat complexity. In the Sierra Nevada, the highest elevation waters were historically fishless (elevations > 2600 m). Lacustrine fringe meadows and wet meadows with significant areas of lentic water were prime historical habitat for amphibian species such as mountain yellow-legged frogs (*R. muscosa, R. sierrae*). Yosemite toads (*A. canorus*) and Pacific chorus frogs (*P. regilla*) readily breed in the more ephemeral habitats associated with lentic zones in wet meadows. Due to ubiquitous stocking of non-native hatchery trout—a predator and competitor of amphibians—the late 19th and early 20th century saw a dramatic shift in species composition of nearly all Sierran lakes and streams (Knapp & Matthews 2000; Knapp 2005; Epanchin *et al.* 2010; Matthews & Preisler 2010). While fish and lentic amphibians may occasionally be found in the same locale, the typical condition is not one of co-occurrence, particularly if predatory fish species are present. Depressional meadows (both ephemeral and perennial) frequently contain salamanders and newts (*Ambystoma* and *Taricha* spp.) as well as Pacific chorus frog larvae. Sierran garter snakes (*Thamnophis* spp.) are very common in all of the wet meadow types, but are particularly abundant in areas where there are high densities of breeding amphibians.

# CLIMATE CHANGE & POTENTIAL IMPACT TO MEADOWS

## GENERAL CLIMATIC TRENDS

The Sierra Nevada, due in part to its importance to California's water supply, has been the focus of many studies in the past decade that have sought to better understand how regional climate change from global climate warming will impact hydrologic systems. These studies consistently indicate that, by end of century, global climate warming will likely result in substantial increases in air temperature for most if not all of California, and that precipitation will likely decrease (Vicuna & Dracup 2007; Cayan *et al.* 2008; Franco *et al.* 2011). Though forecasts vary, models show end-of-century warming of approximately 1.5 °C to 6 °C above the 1961-1990 mean for summer months state-wide (Franco *et al.* 2011). Warming in the Sierra Nevada is expected to experience the highest relative departure from this baseline (Hayhoe *et al.* 2004). Though much of California is expected to retain a characteristic Mediterranean climate of cool, wet winters and warm, dry summers, atmospheric warming is expected to result in a greater fraction of total precipitation as winter rain, as opposed to snow, and concomitant earlier snowmelt (Cayan *et al.* 2008; Young *et al.* 2009; Das *et al.* 2011b). Combined with decreases in overall precipitation, these changes are anticipated to result in more precipitation-driven runoff in winter and reduced snowmelt runoff in spring, leading to a general shift in runoff timing to earlier in the year and reduced annual runoff (Vicuna & Dracup 2007; Cayan *et al.* 2008; Young *et al.* 2009). Extreme floods are also anticipated to become more frequent and more severe (Das *et al.* 2011a; Dettinger 2011). Several studies show that these changes have already been observed over roughly the past half-century, including greater warming (Barnett *et al.* 2008; Bonfils *et al.* 2008), less precipitation as snow (Knowles *et al.* 2006; Barnett *et al.* 2008), earlier snowmelt and onset of spring (Cayan *et al.* 2001), and a shift in runoff to earlier in the year (Stewart *et al.* 2005; Barnett *et al.* 2008; Hidalgo *et al.* 2009). These are profound effects, both observed and anticipated, that have a number of consequences for hydrological cycling and meadow functioning. It is important to note, though, that such changes will not be steady or incremental through time, nor uniform across space.

## REGIONAL DIFFERENCES IN THE EFFECTS OF CLIMATIC CHANGE

There appear to be significant regional differences in the predicted impacts of climate change in the Sierra Nevada. Null *et al.* (2010) indicate three broad types of changes in hydrology for the Sierra Nevada:

1) Change (generally decreasing) in mean annual flow (MAF);

2) A shift (earlier) in centroid timing (CT), which is the date in the water year at which time half of the years runoff has flowed past the watershed's outlet; and

3) A longer period of low-flow duration (LFD) in the summer months. Each of these changes—annual flow, its timing, and duration—impacts riparian and aquatic resources differently.

Likewise, most hydroclimatic models indicate a non-uniform response to climate warming based on elevation, soil depth, and area of land cover type. In other words, not all places in the Sierras will undergo similar forces of change, principally air temperature and precipitation. Further, meadow response to changing hydroclimatic conditions is likely to vary depending on several factors, such as geologic structure and permeability, permeability of soils, meadow dimensions, and presence of hydric and mesic vegetation (see Appendix A for a hierarchical approach to evaluating hydrologic setting).

The broad implications of the Null *et al.* (2010) study are that the northern watersheds (generally the lowest elevation at the Sierra crest) project the greatest decrease in MAF, the high watersheds of the southern-central Sierra Nevada will have the most change in CT (trending earlier), and the central Sierra Nevada will have the greatest increase in LFD (extended periods of low flows). These regions further differ from one another significantly in terms of hydrological development and infrastructure (i.e., number of dams, dam size, diversions, hydroelectric development, levees, and water rights), size of downstream communities, flood risk, and other variables (Dettinger *et al.* 2004; Null *et al.* 2010). Thus, the compounded and cumulative impact of hydroclimatic alteration will likely intensify as drainage area increases.

Overall, the northern Sierra Nevada appears to be of greatest vulnerability to climate change driven alterations in hydrology that will impact aquatic ecosystems. This is primarily due to the higher rate of change in precipitation from snow to rain (Dettinger *et al.* 2004; Young *et al.* 2009; Null *et al.* 2010; Vicuna *et al.* 2011). Managed systems will be particularly impacted as reservoir inflows will be flashier, with higher magnitudes and shorter duration, potentially leading to more frequent spills. As a result, the risk of downstream flooding will increase (Das *et al.* 2011a; Dettinger 2011), while power generation and extended water storage opportunities will decrease (Vicuna & Dracup 2007; Vicuna *et al.* 2011). In unregulated systems, soil moisture and ground water recharge, particularly in natural water storage features such as meadows, may be limited as high flows are quickly conveyed downstream. (Null *et al.* 2010). These shifts in hydrology have important implications for hydric and mesic plants species that require a high water table and annual periods of inundation from extended snow melt.

Central and southern Sierra systems will be somewhat more buffered because of their higher elevation headwaters along the Sierra crest. However, the mid-elevation areas (1500-3000 meters), which contain the bulk of montane meadows, will face many of the same issues, such as decreasing snowpack, as the northern Sierra (Null *et al.* 2010). Moreover, meadow systems will be particularly vulnerable to flashy runoff events and increased sediment loads, particularly those already affected by channel and bank instability, incision, and decreased water tables. Flash floods carrying heavy sediment loads and debris can tear away at unstable meadow stream channels, drastically increasing incision and erosion in single events, resulting in a continuous positive feedback of decreased ecological integrity (see Figure 3b) (Herbst & Cooper 2010; Purdy *et al.* 2011; Weixelman *et al.* 2011). These effects could be further magnified in areas that have experienced forest fires, which is of increasing risk under climate change scenarios (Westerling & Bryant 2008).

## POTENTIAL ALTERATIONS TO HYDROLOGIC PROCESSES

The hydrology of montane meadows is the driving force behind meadow community structure (Castelli *et al.* 2000; Chambers *et al.* 2004; Loheide & Gorelick 2005; Loheide & Gorelick 2007; Weixelman *et al.* 2011). However, the hydrological cycle is driven by global circulation of atmospheric water, and for the Sierra Nevada, it is anticipated that climate warming will shift much of the precipitation from snow to rain, particularly in the 1500–3000 m ranges

(Dettinger & Cayan 1995; Dettinger *et al.* 2004; Stewart *et al.* 2004; Young *et al.* 2009). This shift has a variety of hydrologic impacts. Snow acts as a high-elevation reservoir of water that is retained until spring and summer runoff. If precipitation comes in the form of rain instead of snow, it runs off immediately, particularly in basins with thin soils, greater instances of exposed bedrock and less vegetation cover to absorb water. Thus, water leaves the Sierra Nevada creeks and rivers in high-volume, instantaneous bursts that can be difficult to capture and manage by downstream reservoirs. Further, these increased, intermittent flows alter channel morphology and stream bank stability, which in turn decreases the quality, quantity, and duration of habitat availability for aquatic taxa (Shafroth *et al.* 2002; Moir *et al.* 2006; Paetzold *et al.* 2008; Lowry *et al.* 2011; Wenger *et al.* 2011a; Wenger *et al.* 2011b).

Climate change is expected to cause specific trends in the Sierra Nevada including an increase in air temperature, decrease in snowpack, earlier snowmelt timing, increase in baseflow duration, and decrease in groundwater discharge (Table 1). Within the last century, air temperature has shown an observable increase of 1-2° C (Cayan *et al.* 2001; Regonda *et al.* 2005; Stewart *et al.* 2005), and is expected to continue to rise in the future (Hayhoe *et al.* 2004; Maurer 2007; Anderson *et al.* 2010; Pan *et al.* 2011). An increase in air temperature is the primary driver of the expected shift from snowfall to rain-dominated precipitation (Regonda *et al.* 2005; Pan *et al.* 2011), resulting in decreased snowpack (Kapnick & Hall 2010; Reba *et al.* 2011). Snowpack is expected to melt more rapidly and disappear earlier in the season (Fritze *et al.* 2011; Reba *et al.* 2011), limiting the duration of snowmelt induced stream flow and groundwater recharge. Concomitant shifts in earlier timing of peak evapotranspiration and soil moisture are anticipated to follow (Hamlet *et al.* 2007). The relationship between Sierra Nevada meadow distribution across the study region, expressed in Figure 5 as density (hectares of meadow per $km^2$ of watershed), and the percent of snowpack and runoff varies through the year. Watersheds with high meadow density retain ~50% of snowpack during Q2 (April-June) and receive substantial runoff during Q3 (July-September) (Figure 5). While these patterns vary depending on elevation and latitude, there is a strong link between the presence of meadows and climate driven hydrology, and alteration to hydrologic parameters that drive meadow formation, maintenance, and resilience to degradation (Table 1).

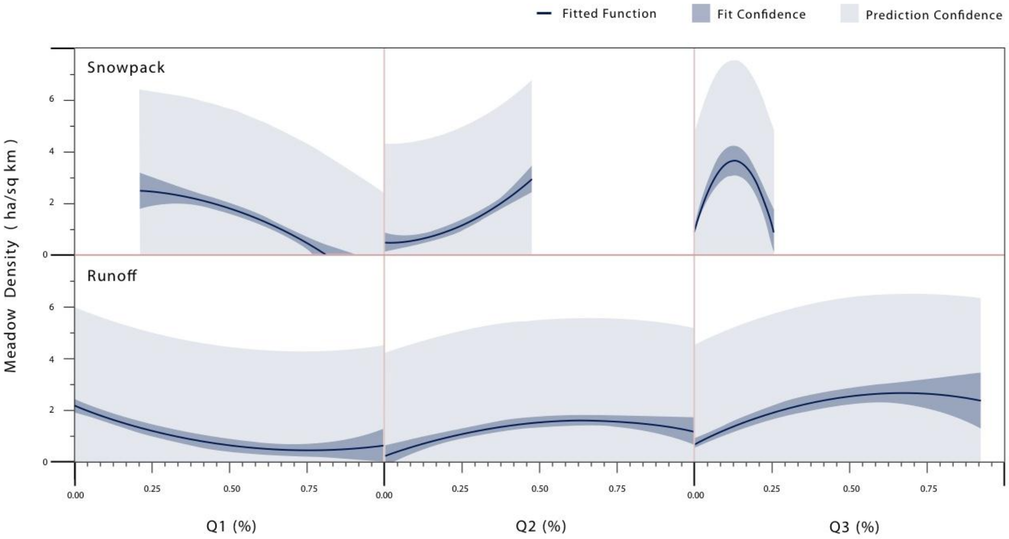
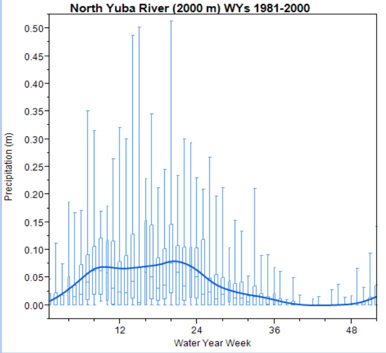
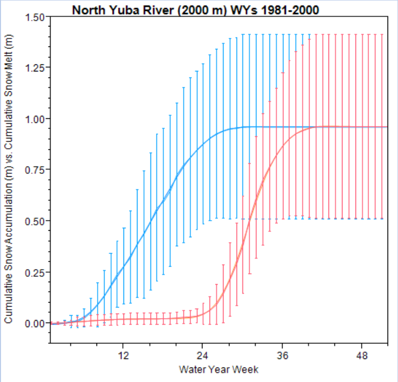
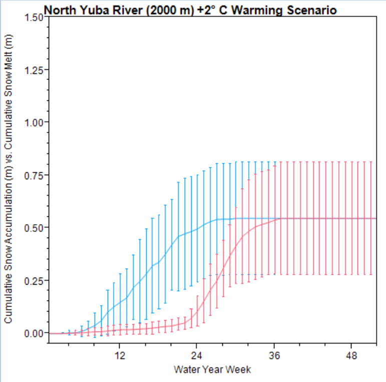
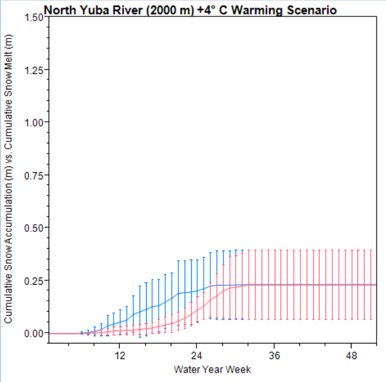


Figure 5. Meadow Hydrology Graph. Modeled relationships between meadows developed in Appendix C (y-axis) and percent of snowpack and runoff by quarters (Q1 Jan-Mar, Q2 Apr-Jun, Q3 Jul-Sep) (x-axis). Hydrological data are from Flint et al. (2011) for period 1980-2000.

**Table 1. Hydroclimatic changes for the Sierra Nevada. See examples from Yuba Basin at ~2000m elevation.**

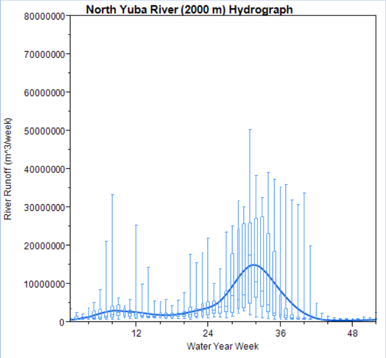
| Hydrological Parameters of Interest | | | |
|---|---|---|---|
| **Precipitation**<br>More rain and less snow is anticipated, though total precipitation is likely to remain consistent for Mediterranean-Montane climate characterized by high interannual variability, though storm seasons will end earlier across the Sierra Nevada (Maurer *et al.* 2007). Graph shows mean and 95% confidence interval for observed precipitation across 20 water years. | | **Observed Precipitation**<br><br> | |
| | **Modeled Historical Conditions (Calibrated to Observations)** | **Modeled Future Conditions with +2° C Atmospheric Warming (Without Change in Precipitation)** | **Modeled Future Conditions with +4° C Atmospheric Warming (Without Change in Precipitation)** |
| **Snow Pack**<br>A general decrease in total snow pack volume, as well as earlier melting of snow, due to atmospheric warming is anticipated across the Sierra Nevada. Graphs show 20-year mean under historical conditions (1981-2000) and simulated conditions under different atmospheric warming scenarios without altering precipitation amount or timing as per Young *et al.* **(2009)**. (Error bars represent one standard deviation from the mean.) | <br> | <br> | <br> |

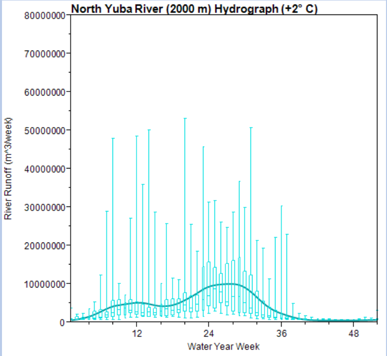
## Hydrological Parameters of Interest

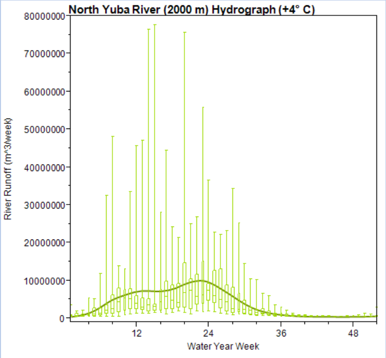
## Observed Climate

### Runoff

Discharge to rivers and streams will change in timing and volume, with earlier timing for peak runoff events and total volume, as well as higher magnitude flows and greater variability in winter months. Hydrograph depicts river runoff ($m^3$/week) across 20 water years with fitted quantiles as per Young *et al.* **(2009)**.



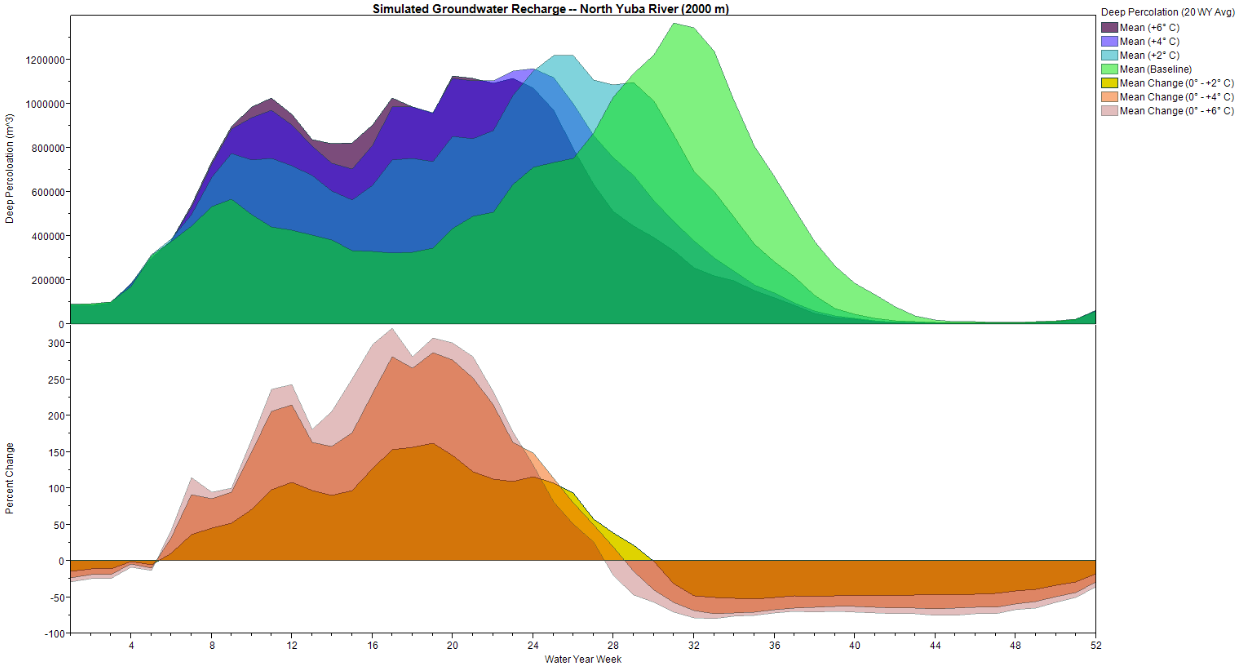




### Groundwater

Groundwater recharge is anticipated to decrease due to less infiltration, as a result of a shortened snow melt period and absence of diel snowmelt fluxes to gradually refill meadow aquifers (Loheide & Lundquist 2009). As a result, decreasing water tables stress hydric and mesic vegetation, promoting xeric conditions; coupled with higher magnitude flows this results in eventual channel incision and ultimate state shift to non-meadow conditions (Loheide & Gorelick 2007).

### Groundwater Infiltration with Atmospheric Warming Scenarios (and Without Change in Precipitation)



# INDICATOR SPECIES & POTENTIAL IMPACTS FROM HYDROCLIMATIC ALTERATION

## MEADOW-DEPENDENT AQUATIC ANIMALS

The biological effects of lower mean annual flow, earlier centroid timing (CT), and longer low flow durations will result in an overall decrease in available habitat for aquatic species, particularly for cold water fishes such as salmonids and sculpins (Wenger *et al.* 2011b). Furthermore, earlier timing and longer low flow duration will force aquatic biota to withstand more days at thermally challenging temperatures (Cristea & Burges 2010; Wenger *et al.* 2011a; Wenger *et al.* 2011b). Broad scale studies of the western United States have pointed to alarming synergistic effects of hydroclimatic alteration of flow regime, elevated water temperatures and biotic interactions resulting in severe range reductions (~50%) for inland salmonids (Wenger *et al.* 2011b). Despite inherent uncertainty in these broader projections, similar conditions are projected for the Sierra Nevada. Recent studies of unregulated flow conditions for the west slope Sierra Nevada suggest that rivers and streams are likely to face ~1.5 °C increase in water temperature for each 2 °C increase in air temperature (Null *et al.* 2012). This may favor warm water fishes, such as native suckers and minnows, or non-native bass and sunfish, in circumstances in which year round flows remain (Baltz *et al.* 1982; Baltz *et al.* 1987; Baltz & Moyle 1993; Wenger *et al.* 2011a). These conditions will likely result in the extirpation of all fishes in small order streams that hover on the border of becoming ephemeral.

Other riparian-associated species are likely to face challenges as well. For example *Anaxyrus canorus*, the Yosemite Toad, lays its eggs in ephemeral snowmelt ponds, puddles, and rivulets in central Sierra montane meadows (Karlstrom 1962; Sherman & Morton 1993; Morton & Pereyra 2010). Decreased mean annual flow, less overall snow volume, and warmer daily air temperatures will potentially decrease the number of days of standing water available for clutches to metamorphose from tadpoles to toadlets, likely increasing clutch mortality

### *Key Aquatic Indicator Species of Sierra Nevada Meadows*

**Fishes:**

- Salmonids
  - California Golden Trout (*Oncorhynchus mykiss aguabonita*)
  - Eagle Lake Rainbow Trout (*Oncorhynchus mykiss aquilarum*)
  - Redband Trout (*Oncorhynchus mykiss* spp.)
  - Lahontan Cutthroat (*Oncorhynchus clarki henshawi*)
- Cyprinids
  - Pikeminnow (*Ptychocheilus grandis*)
  - Speckled Dace (*Rhinichthys osculus*)
  - Lahontan Redside (*Richardsonius egregius*)
  - Tui Chub (*Siphateles bicolor spp.*)
- Catostomids
  - Mountain sucker (*Catostomus platyrhynchus*)
  - Sacramento sucker (*Catostomus occidentalis*)
- Cottids
  - Riffle sculpin (*Cottus gulosus*)

**Amphibians:**

- Mountain yellow-legged frog complex (*R. sierrae and R. muscosa*)
- Yosemite Toad (*Anaxyrus canorus*)
- Pacific Tree Frog (*Pseudacris regilla*)

**Reptiles:**

- Garter snakes (*Thamnophis couchii, sirtalis, & elegans*)

*Please refer to Appendix A for a complete discussion of the potential impact of climate induced hydrologic alteration to these species.*

in an already declining species. Concurrently, continued or worsening channelization in montane meadows from flashy storms may worsen effects by increasing drops in the water table. A similarly declining amphibian species, the mountain yellow legged frog (*Rana muscosa* and *R. sierrae*), has a tadpole stage lasting 3-4 years (Knapp & Matthews 2000; Lacan *et al.* 2008b). They have largely been extirpated from their preferred habitats of deep alpine lakes by the ubiquitous stocking of non-native trout into historically fishless lakes throughout the Sierra Nevada, with remaining populations found in more climatically marginal tarns and ponds, which may not remain suitable habitat in the future (Knapp *et al.* 2001a; Knapp *et al.* 2001b; Knapp 2005; Matthews & Miaud 2007; Lacan *et al.* 2008b; Matthews & Preisler 2010). Further, the presence of tightly coupled trophic cascades in montane meadow ecosystems will likely result in non-aquatic species, such as birds (e.g., Epanchin *et al.* 2010), being impacted by hydrologic alteration. To better understand potential ecosystem and community change, the inventorying and monitoring of indicator species is an important mechanism to evaluate conservation action.

## INDICATOR SPECIES

There are several aquatic and riparian dependent animals commonly found in or associated with montane meadows in the Sierra Nevada and their streams that can serve as indicator species for meadow functioning, integrity, and potential alteration. Indicator species can defined in several ways and serve various functions, such as umbrella or keystone species (see Lindenmayer *et al.* 2000 for expanded discussion), but are used more broadly here to represent indicators of environmental change with a specific focus on hydroclimatic alteration.

The species discussed herein represent a broad spectrum of taxa that have widely varying habitat preferences and needs. Each of these species responds differently to environmental variations in flow, temperature, timing, and habitat. By assessing the life history needs and habits of each of these species or assemblages of species, resource managers may be better able to assess changing meadow function and condition as indicated by changes in community composition. Whether or not a species persists in a given location cannot simply be determined by thermal tolerance, but is influenced to a greater or lesser degree by a suite of traits including behavior, food preferences, physical and chemical parameters, mobility and available habitat, to name a few. The ability to identify species and concomitant life history characteristics that may be vulnerable to hydrologic alteration will help managers recognize changing conditions and management needs earlier, thereby enabling them to formulate conservation strategies in the face of observed changes. Examples of species traits that might support persistence through climatic and hydrologic change include long life, high fecundity, broad physiological tolerances for temperature and dissolved oxygen, mobility, ability to use alternative food sources as available, tolerance to high flow events, and ability to take advantage of ephemeral habitats. In addition, recognizing the key characteristics of the meadow in question and the likely trajectory of hydrologic change will further illuminate the expected community responses, where to focus conservation efforts, and how best to manage and protect associated resources within a changing climate. Table 2 relates tolerance for hydroclimatic change by selected aquatic indicator species. A fuller development of tolerance criteria and life history strategies is presented in Appendix B .

## FISHES

Fishes are the most ubiquitous of the indicator species and are distributed over most of the Sierra Nevada (Figure 6). It is important to note, however, that large portions of the Sierra Nevada were historically fishless due to glaciation in the Holocene. Three fish indicator species diversity hotspot regions emerge from the mapping conducted by Santos et al. (In Review): Modoc Plateau, Tahoe Basin and Eastern Sierra Nevada, and South-Central Sierra Nevada Foothills. Of these, the Tahoe Basin and Eastern Sierra Nevada have the highest richness of indicator fish species (Figure 7).

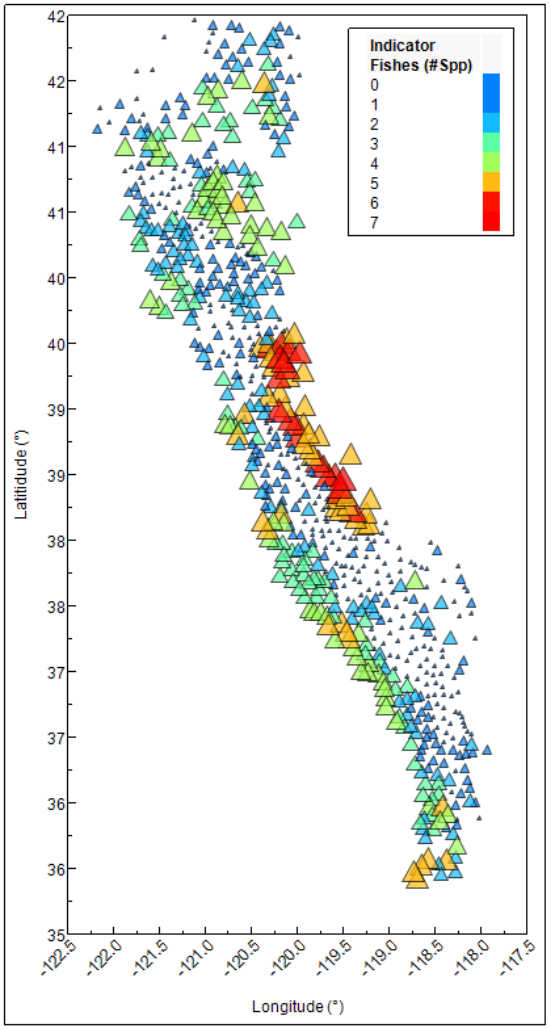


**Figure 6. Map of Fish Indicator Richness. This map depicts diversity (richness) by the presence of indicator species within HUCs across the study area. The mid-montane, Eastern Sierra, and Modoc/Feather drainage areas are notable for their richness. Data are from PISCES (Santos *et al.* In Review).**

### SALMONIDS

Members of the family Salmonidae (trout, salmon, and whitefish) are among the most sensitive fishes found in the Sierra Nevada. They require cold, clean water (lethal temperatures for most salmonids range from 24–27 ˚C, and sub-lethal effects are observed at 22–24 ˚C), feed on benthic macroinvertebrates and small fish, and spawn in the spring/ summer months (Moyle 2002). Eggs are by far the most sensitive life stage of this family, requiring temperatures in the 10–16 ˚C range, and very specific stream flows and depths to provide maximum oxygen to the developing embryos. Juvenile trout also require highly specific conditions for rearing: shallow backwater and floodplain habitats with abundant protein-rich food sources such as zooplankton and small macroinvertebrates, segregation from adult fish, and adequate cover to protect them from predation.

Habitat changes associated with hydrologic alteration, such as flashy rain-fed floods, will have negative effects on trout spawning success, as eggs can easily be washed away or smothered by sediment deposits. Longer low flow durations will be particularly hard on salmonids because of the concurrent increase in water temperature, greater number of days spent near thermal tolerances, and reduction in available habitat. Salmonids typically establish and defend territories, with larger fish exhibiting dominance over smaller fish, which may force smaller fish and juveniles into less suitable habitats, thereby reducing fitness (Moyle 2002). Further, the presence of more tolerant species, particularly predatory non-native fishes such as bass and bluegill, adds competition to the physical stress and shrinking available habitat, further challenging trout's ability to persist in a given stream. In areas expected to become more rainfall dominant, the timing of spawning and rearing may be seriously impacted. However, the demonstrated plasticity of salmonids may allow them to adapt, given adequate numbers and free access to spawning areas.

## CYPRINIDS

Members of the family Cyprinidae (minnows, carp, and goldfish) possess a wide range of life histories ranging from tiny speckled dace to large predatory pikeminnow. Cyprinids are typically more tolerant of warmer water temperatures and low dissolved oxygen content than trout species, and can inhabit a wide array of habitats ranging from cold, clear alpine streams and lakes, to warm, sluggish low gradient streams found in the Sacramento–San Joaquin drainages. Cyprinids have a variety of adaptations which allow them to be highly successful in the variety of environments they inhabit. These include: high fecundity, shoaling behavior, well-developed sense of hearing and smell, specialized pharyngeal teeth, and long lives.

Cyprinids are typically spring and summer spawners, depending on location and elevation, and likely cue their spawning based on receding high spring flows. Both juvenile and adults readily utilize floodplain habitat to feed on the abundantly present insects and plankton, and for velocity refuge during times of high flow. Hydrologic alteration effects in their range will likely have the most impact on spawning and juvenile rearing stages. Eggs can be washed away or buried during flashy, rain-fed runoff events, snow melt-driven cues and available habitats may no longer exist, and some areas may lose year round water. Their increased thermal tolerance will allow cyprinidae to persist in areas rendered inhospitable to trout. Maintaining intact stream channels with good connectivity to the floodplain is particularly important for this group, which will extensively utilize inundated meadow habitats.

## CATOSTOMIDS

Members of the family Catostomidae (“suckers”) are widely distributed throughout the Sierra Nevada. While they lack the species and life history diversity of the Cyprinid family (both members of the order Cypriniformes), they possess numerous distinctive characteristics that enable them to be highly successful in a wide variety of environmental conditions. Castomid habitat ranges from the large, low gradient rivers of the Central Valley and low foothills to tiny alpine streams, lakes, and even some reservoirs.  They are tolerant of lower dissolved oxygen levels and warmer temperatures than trout, and have exceptionally well developed hearing. Most Castomid species are bottom feeders that use their fleshy, protrusable mouths to suck up small invertebrates, algae, and detritus. A few species, though, feed on plankton. Catostomids are typically most active at night, presumably to avoid diurnal predators. Castomids are generally opportunistic and can rapidly recolonize habitats. Those associated with the terminal alkali lakes (Eagle Lake and Goose Lake) may require different management strategies, particularly in light of potential drying events in drought years.

## COTTIDS

Members of the genus *Cottus* (freshwater sculpins) are small, benthic predatory fishes that lie on the bottom of rocky, riffled streams using their cryptic markings to hide from both predators and potential prey. They are common in permanent headwater streams and favor riffle habitats with swift flows. Sculpins tend to be less mobile than trout and other fishes, and dispersal is slow, particularly because their benthic larvae rear close to where they hatched. Cottids have a fairly narrow range of environmental tolerances. While they can recover after localized extirpation, it requires a significant length of time. Sculpins are strong indicator species because of their poor dispersal abilities and restricted habitat requirements. They require highly saturated dissolved oxygen levels, which limits their distribution mainly to flowing water. This factor alone can sometimes be the cause of local extinctions. While sculpins thrive in riffles with moderate to high velocities, their lack of a swim bladder allows them to take shelter amidst the substrate and avoid high flows. Sudden, flashy high flow events may negatively affect sculpin populations, especially if flows are high enough to stimulate bed load movement, displacing them from their hideouts and flushing them downstream.

## AMPHIBIAN & REPTILES

Several riparian-associated amphibian species in the Sierra Nevada have adapted life histories to montane meadow ecosystems, and these species provide a unique method of measuring hydroclimatic change because they link terrestrial and aquatic environments. Furthermore, as indicators of global hydroclimatic change, amphibians are unique; the typical life cycle includes aquatic development of eggs and larvae, and terrestrial activity as adults, which links individuals to multiple habitats and trophic levels (Power and Dietrich 2002, Wake and Vredenburg 2008). Therefore, many amphibians are particularly sensitive to changes in the ecosystem due to their physiology and life histories (Davidson et al. 2002, Beebee and Griffiths 2005, Vredenburg and Wake 2007).

Although amphibian species have persisted through the last four mass extinctions (the earliest occurring approximately 364 million years ago), and all three orders of amphibians escaped extinction (Wake and Vredenburg 2008); amphibian populations continue to decline on local and global scales at rates that far exceed those of other vertebrate groups (Stuart et al. 2004, Alford et al. 2007, Sodhi et al. 2008). Human activities have been directly linked to many of the key factors in this recent era of amphibian decline, including climate change, invasive species introductions, habitat fragmentation, and habitat destruction (Karr and Chu 2000, Stuart et al. 2004). Therefore, current amphibian declines may not only represent a severe change in the balance of global biodiversity, but also indicate significant and widespread ecological degradation. This degradation may have ramifications not only for amphibians, but all species that rely on the benefits that “ecosystem services” (Daily 1997) provide, such as drinking water, food supply, purification of human and industrial wastes, and habitat for plant and animal life (Wilson and Carpenter 1999).

Amphibians associated with high elevation montane habitat in the Sierra Nevada can be categorized as semi-perennial lentic breeding species such as the mountain yellow-legged frog and long-toed salamander that generally overwinter for several years as larvae before metamorphosing; or as shallow water perennial breeding species such as the Pacific chorus frog or Yosemite toad, which complete development from egg to post-metamorphosis within one year. Semi-perennial developing species adapted to overwintering under ice face greater risks of predation and desiccation associated with higher temperatures and evapotranspiration rates, which may shift available littoral habitat area around permanent water bodies as more precipitation falls as rain instead of snow. Greater climatic variability within years also increases the potential loss of sensitive larvae constrained to rearing habitats due to aseasonal stochastic climatic events (e.g., larvae may be scoured or flushed from habitat). Similar threats exist for faster developing species such as the Yosemite toad, dependent on snowmelt for stable shallow riparian meadow habitats. One of the primary causes of larval mortality for Yosemite toad is desiccation of breeding pools (Kagarise Sherman 1984, Sherman and Morton 1993), as this species is limited to alpine meadows in a relatively narrow elevational zone, and dependent on ephemeral pools for breeding, vulnerability to hydroclimatic alteration will likely very high (Sherman and Morton 1993). Hydroclimatic alteration in these systems will potentially shorten breeding and rearing windows, and increase the risk of larval desiccation or egg scour during more variable spring and summer months. For generalist species such as the Pacific chorus frog, the use of a wide range of high elevation lakes and ponds, in both permanent and temporary waters, and shorter development times may provide more resilience to hydroclimatic alteration in comparison with other Sierra Nevada aquatic vertebrates. Pacific chorus frogs do not appear to have declined from their historical range, or they are not declining as precipitously as other aquatic species such as the Yosemite toad or mountain yellow-legged frog (Lannoo 2005).

**Table 2. Hydroclimatic Alteration Tolerance by selected Aquatic Indicator Species.**

| | Species | Tolerance for Increased Temperature | Tolerance for Decreased Flow | Predicted Outcome |
|---|---|---|---|---|
| **Fish** | | | | |
| **Oncorhynchus spp.** | Golden trout (*Oncorynchus mykiss aguabonita*) | LOW | MODERATE | Impairment likely |
| | Redband trout (*O.m. subsp)* | LOW | MODERATE | Impairment likely |
| | Eagle Lake rainbow (*O.m. aquilarum)* | LOW | MODERATE | Impairment likely |
| | Lahontan cutthroat (*O. clarki henshawi)* | LOW | LOW | Impairment highly likely |
| | Paiute cutthroat (*O. clarki seleneris)* | LOW | LOW | Impairment highly likely |
| | Rainbow trout (O. mykiss) | LOW | MODERATE | Impairment likely |
| **Cyprinid spp.** | Sacramento Pikeminnow (*Pteichocheilus grandis)* | HIGH | LOW | Unknown |
| | Speckled Dace (*Rhinicthys osculus*) | MODERATE | MODERATE | Resilient |
| | Hardhead (*Mylopharodon conocephalus*) | MODERATE | MODERATE | Resilient |
| | Roach (*Lavinia symmetricus*) | HIGH | MODERATE | Resiliency likely |
| | Sacramento hitch (*Lavinia exilicauda*) | HIGH | HIGH | Resiliency expected |
| | Lahontan redside (*Richardsonius egregius*) | HIGH | HIGH | Resiliency expected |
| | Tui chub (*Siphateles bicolor sp.)* | MODERATE | MODERATE | Resilient |
| **Sculpinidae** | Riffle sculpin (*Cottus gulosus*) | LOW | MODERATE | Impairment likely |
| **Catostomidae** | Mountain sucker (Catostomus platyrhynchus*)* | MODERATE | MODERATE | Sustainable |
| **Amphibians** | Sierra Nevada Yellow Legged Frog (*Rana sierrae)* | HIGH | MODERATE | Resiliency likely |
| | Yosemite Toad (*Anaxyrus canorus*) | MODERATE | HIGH | Resiliency likely |
| **Reptiles** | Sierra Garter Snake (*Thamnophis couchii*) | HIGH | HIGH | Resiliency expected |

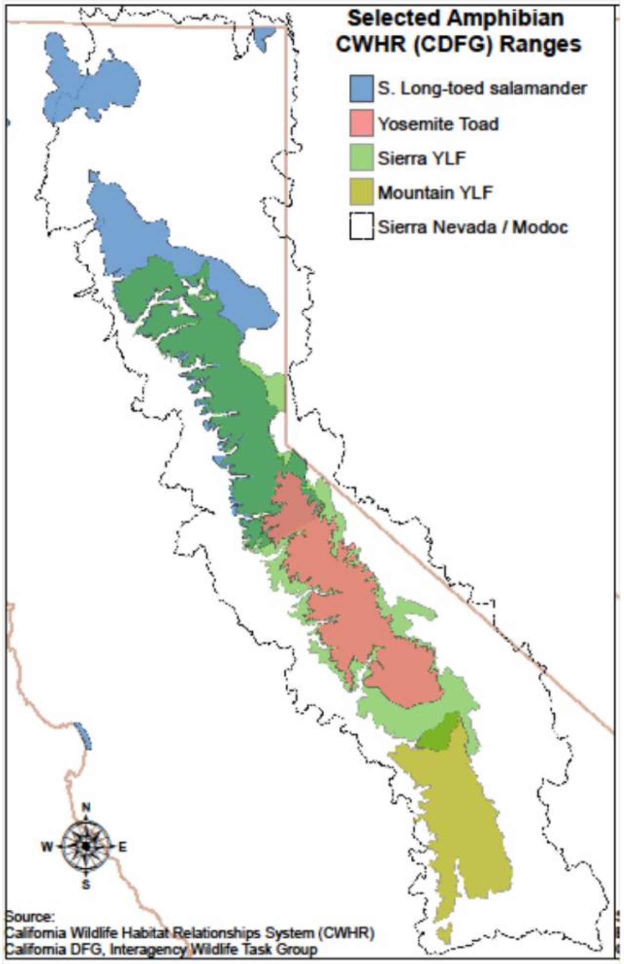
## A VULNERABILITY ASSESSMENT USING AMPHIBIAN INDICATOR SPECIES

We conducted a geographic vulnerability assessment of the Sierra Nevada using amphibian indicator species and meadow density as drivers for a predictive modeling effort.

### VULNERABILITY ASSESSMENT METHODS

For this portion of the vulnerability assessment we included the Sierra Nevada and Modoc Plateau (Figure 7). Drainage areas from the Watershed Boundary Dataset (WBD), which consisted of nested hydrologic unit codes (HUC) delineated within a hierarchical drainage system, were used as mapping units at the sub-watershed level, or 12-digit code (HUC12). A domain of 1,283 HUC12 watershed units was selected, with some HUCs in the eastern portion of the domain extending into Nevada. Mapping at the HUC12 scale provided a detailed landscape unit at a scale suitable for modeling both hydroclimatic variation and species distributions.

To assess potential changes in distributions of riparian-associated amphibians species were selected based on life history requirements associated with lentic montane meadow habitat, as well as high vulnerability to hydroclimatic change, with the exception of the Sierra chorus frog (Table 3) (Jennings *et al.* 1994; Thomson *et al.* 2012). Species distribution data were compiled from available electronic museum and field observation records for all species. In addition, Wildlife Habitat Relationship (WHR) range maps were used to code presence, by enveloping any HUC12 centroid that occurred within the species WHR range (Table 3). This likely overestimates the current range for these species, however, it provides a more conservative and useful estimate for resource management because ranges are inclusive of suitable areas that may have been historically occupied.



Source:
California Wildlife Habitat Relationships System (CWHR)
California DFG, Interagency Wildlife Task Group

**Figure . Study area for use of amphibian ranges to assess hydroclimatic alteration.**

**Table 3. Species selected for modeling ($^*$ adapted from ARSCC 2012).**

| Species Code | Species Name | Common Name | Range in the Sierra Nevada | Sensitivity (Score / total possible)$^*$ | Vulnerability to Climate Change$^*$ | HUC12 Observed Presence (Rangemap Presence) |
|---|---|---|---|---|---|---|
| AMMASI | *Ambystoma macrodactylum sigillatum* | Southern long-toed salamander | Moderate | 0.66 (73/110) | Highly Vulnerable (10) | 59 (251) |
| ANCA | *Anaxyrus canorus* | Yosemite toad | Limited | 0.79 (87/110) | 10 | 53 (111) |
| RAMU | *Rana muscosa* | Mountain yellow-legged frog | Limited | 0.97 (107/110) | 10 | 60 (92) |
| RASI | *Rana sierrae* | Sierra yellow-legged frog | Limited | 0.94 (103/110) | 10 | 169 (311) |
| PSSI | *Pseudacris sierra* | Sierra chorus frog | Expansive | n/a | n/a | 304 (1044) |

Modeling was conducted using boosted regression trees (BRT), a machine learning technique which utilizes a stage-wise additive regression model to handle different types of predictor variables, and ignores non-informative predictors when fitting trees (De'ath 2007; Elith *et al.* 2008) . Boosted regression tree modeling is suitable for ecological distribution modeling because it can reduce both bias and variance, handle sharp discontinuities common in sparsely sampled species or large study areas, and illustrate relationships between predictor and response variables (De'ath 2007; Elith *et al.* 2008). BRT techniques have been shown to outperform nearly all other competing models, particularly when sample sizes are not extremely small, and have been successfully applied across many taxa (Phillips *et al.* 2006; Guisan *et al.* 2007). Models were optimized by adjusting the model parameters for tree complexity, learning rate and bag-fraction (proportion of observations used to select variables). Parameters optimized for the meadow-associated amphibian models used 30-fold cross validation, a bag-fraction of 0.5, a learning rate of 0.005, and tree complexity of 3. All BRT modeling utilized the *gbm* package (Ridgeway 2007) in R (R Development Core Team 2012), and models were built using the *gbm.step* code (Elith *et al.* 2008).

## VULNERABILITY ASSESSMENT MODEL VARIABLES

A wide suite of environmental and hydroclimatic variables were used because BRT ignores on-informative predictors when fitting trees, and therefore irrelevant variables have a minimal effect on prediction (Elith *et al.* 2008). BRTs assess the relative impact of modeled variables by calculating the number of times a variable is selected for splitting a tree across all folds of the cross validation. As the focus was to identify the effects of hydroclimatic alteration on meadow associated amphibians, four meadow variables were included in all models. These meadow variables included total count of meadows within each HUC12, total percent of

HUC12 area that is meadow, the sum of meadow area per square km, and the average edge complexity across all meadows within each HUC12.

To evaluate the impacts of hydroclimatic alteration on sensitive lentic amphibians across a highly variable landscape, the Basin Characterization Model (BCM) was utilized because data were available at monthly time steps, and spans the full study area at a 270 m cell resolution (Flint *et al.* 2011). BCM data for runoff, snowpack, recharge, precipitation, and maximum and minimum temperature were aggregated for each HUC12 using majority zonal statistics as part of ArcGIS tools (ESRI 2012). The zonal data output was used to calculate a suite of hydrologic climate metrics in R (R Development Core Team 2012) and a sensitivity analysis using PCA was conducted to select meaningful metrics and reduce autocorrelation in the modeling. A total of 60 hydroclimatic variables were selected for the final models. In addition to the meadow variables described previously, twenty-four anthropogenic and environmental variables were also incorporated into the model using the best available data for a range of characteristics including slope, elevation, vegetation type and dominant percentage, stream density, road density, area burned, fire recurrence, recent fish stocking, etc.

## VULNERABILITY ASSESSMENT MODELING

Model training datasets for each species consisted of the coded WHR ranges (occupied if HUC12 centroid was within the species' range). Each model was trained using species WHR ranges and available environmental data, and validated using all available observation/museum records. Four different climate periods [recent (1980–2000), near (2020–2040), mid (2050–2070), and far (2080–2100)] were analyzed, future time series data was projected using Geophysical Fluid Dynamics Laboratory (GDFL) CM2.1 model based on the SRES-A2 scenario (Delworth *et al.* 2006). GFDL models have sufficient seasonal acuity to represent and predict climate simulations from continental to global scales (Stouffer *et al.* 2006). The GFDL-A2 scenario depicts a warmer and drier future climate when compared with other global climate models (Krawchuk and Moritz 2012), and is likely most representative for future climate in the Sierra Nevada. Data was aggregated for each time period and monthly, quarterly, and annual statistics were calculated for selected hydroclimatic BCM variables. Statistical evaluation of BRT model predictive performance utilized several metrics. Model performance was measured using cross validation (CV) deviance and standard error (calculated within each fold) to evaluate model predictions under the four climate periods. Threshold-independent receiver operating characteristic (ROC) analyses were conducted, and utilized the area under the ROC curves (AUC) to measure model discrimination of suitable and unsuitable areas for each species, following Phillips et al. (2006). Although there is much discussion regarding the use of ROC analysis and AUC (see (Hernandez *et al.* 2006; Phillips *et al.* 2006), particularly in regard to the use of presence-only data, BRT are insensitive to outliers and use a stochastic process to improve predictive performance by using a random subset of data to fit each new tree (Friedman 2002; Elith *et al.* 2008). Furthermore, the incorporation of cross-validation provides a suitable evaluation method for testing the model through comparisons of deviance reduction. Finally, probability surfaces of species occupancy within each HUC12 were generated for each climate period. Comparison of range shifts and changes in hydroclimatic variables between climate periods was mapped at a HUC12 scale.

## VULNERABILITY ASSESSMENT RESULTS

A total of 87 different variables were included in the final hydroclimatic species distribution models, and the range in boosted regression trees across species ranged from 1550 to 5100. Model predictive performance was comparable across species and climate periods, with the exception of Pacific chorus frogs, which had lower ROC scores compared with all other models and species (Table 4).

Overall, model performance was good and the predictors used in the dataset explained over seventy percent of the deviance in all species modeled.

**Table 4. Boosted regression tree model performance for five sensitive montane-amphibans. Area under the receiver operating characteristic curve score (AUC) was evaluated by climate period for each species used trained models.**

| BRT Model Results | AMMASI | ANCA | RASI | RAMU | PSSI |
|---|---|---|---|---|---|
| Total Number of Trees | 5100 | 1550 | 2450 | 3600 | 4800 |
| Mean Total Deviance | 0.984 | 0.589 | 1.106 | 0.516 | 0.962 |
| Cross-validation (CV) Deviance | 0.246 | 0.155 | 0.253 | 0.089 | 0.122 |
| CV standard error (SE) | 0.015 | 0.024 | 0.024 | 0.017 | 0.018 |
| Percent Deviance Explained (%) | 75 | 74 | 77 | 83 | 87 |
| AUC for Recent (1980–2000) | 0.913 | 0.909 | 0.966 | 0.913 | 0.682 |
| AUC for Near (2020–2040) | 0.912 | 0.853 | 0.958 | 0.896 | 0.670 |
| AUC for Mid (2050–2070) | 0.870 | 0.890 | 0.961 | 0.898 | 0.721 |
| AUC for Far (2080–2100) | 0.860 | 0.860 | 0.911 | 0.868 | 0.706 |

Hydroclimatic species distribution models predicted significant declines for all species except the Pacific chorus frog (Table 5, Figure 7). Modeled distributions contracted over 70% for the sensitive species between the recent and far models, and there were no HUCs with probabilities of occupancy greater than 0.50 by 2100 for Yosemite toads (far scenario). Mean occupancy probability and geographic range for Yosemite toad were the smallest of all the modeled species, while Pacific chorus frog occupancy remained relatively constant across climate periods (Figure 8).

**Table 5. HUC12s predicted to remain occupied (probability greater than 0.5) across climate model scenarios (x= mean probability of occupied HUCs) [Total HUC domain = 1,283].**

| Model Scenario | S. Long-toed salamander (AMMASI) | Yosemite toad (ANCA) | Mountain yellow-legged frog (RAMU) | Sierra yellow-legged frog (RASI) | Pacific chorus frog (PSSI) |
|---|---|---|---|---|---|
| Recent | 251 (x=0.932) | 108<br>(x=0.895) | 92<br>(x=0.971) | 304<br>(x=0.921) | 1044 |
| Near | 141 | 14 | 32 | 135 | 1023 |

| | | | | | |
|---|---|---|---|---|---|
| | (x=0.811) | (x=0.664) | (x=0.794) | (x=0.796) | |
| Mid | 53<br>(x=0.748) | 12<br>(x=0.692) | 67<br>(x=0.797) | 129<br>(x=0.876) | 1046 |
| Far | 14<br>(x=0.704) | 0 | 69<br>(x=0.819) | 57<br>(x=0.796) | 1023 |

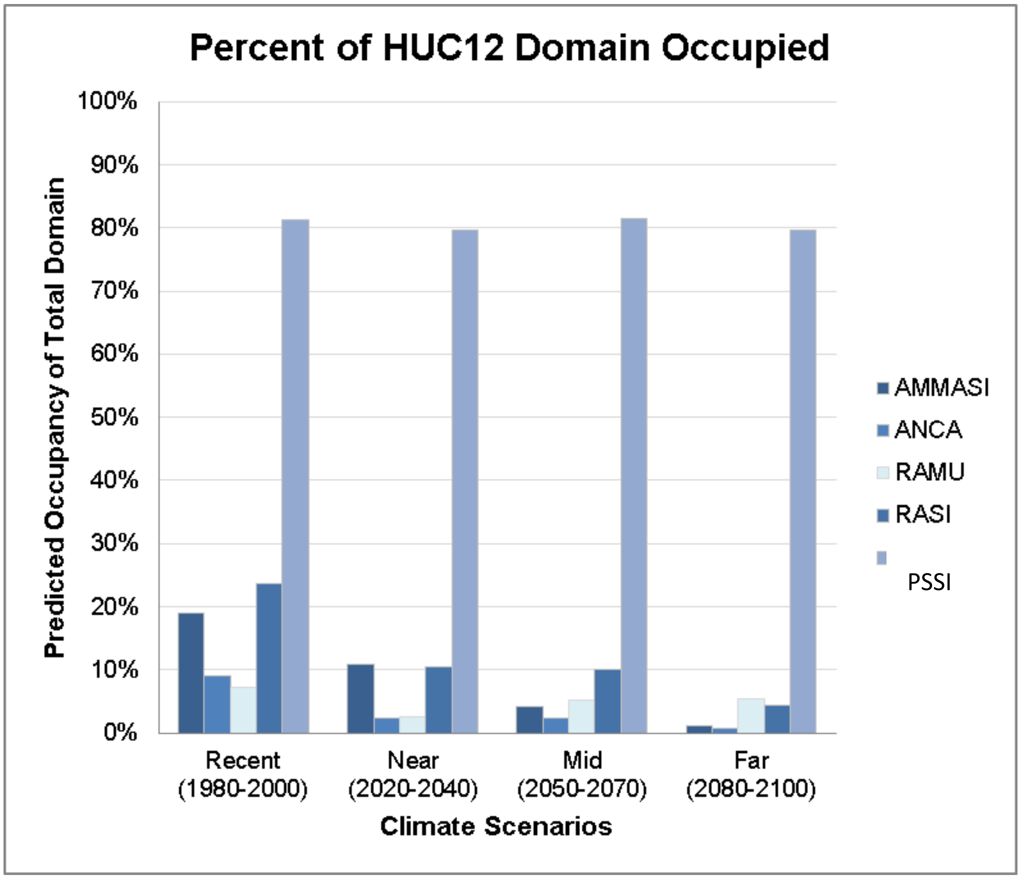


**Figure 8. Predicted occupancy over 4 different climate scenarios for riparian-montane associated amphibian species.**

Models of mountain yellow-legged frog occupancy showed a net reduction in the mean probability for occupied HUCs (HUCs with probabilities greater than 0.5) from recent to near climate periods, followed by net increases in mean probabilities from near to mid and mid to far climate periods (Figure 3). Increases largely occurred in the northern extent of the species' range, and probabilities were distributed more evenly through the near and mid scenarios (Figure 8). No other sensitive species exhibited similar trends between climate periods, however models of Pacific chorus frog distributions showed an increased probability of occupancy between climate periods. Sierra yellow-legged frogs and Yosemite toads showed similar stability in occupancy probabilities between the near and mid climate periods, followed by significant reductions between the mid and far model scenarios (Table 5).

At a HUC12 watershed scale, models showed net range contractions in all species except the Pacific chorus frog and mountain yellow-legged frog. Reductions in range (mapped as occupancy probabilities greater than 0.5), were greatest for the Yosemite toad and Southern long-toed salamander (Figure 9). Both of these species showed contractions in the central part of their predicted range of occupancy (although there is little range overlap between species), with the southern ranges of the modeled Yosemite toad and southern long-toed salamander ranges remaining most stable over each climate period. Sierra yellow-legged frog models showed similar contractions in range. In addition, southern long-toed salamander modeled distribution appeared more stable in several regions, including the vicinity of Mt. Lassen, and the eastern portion of Tahoe. Pacific chorus frog was not plotted because no appreciable shift in range was observed in the model.

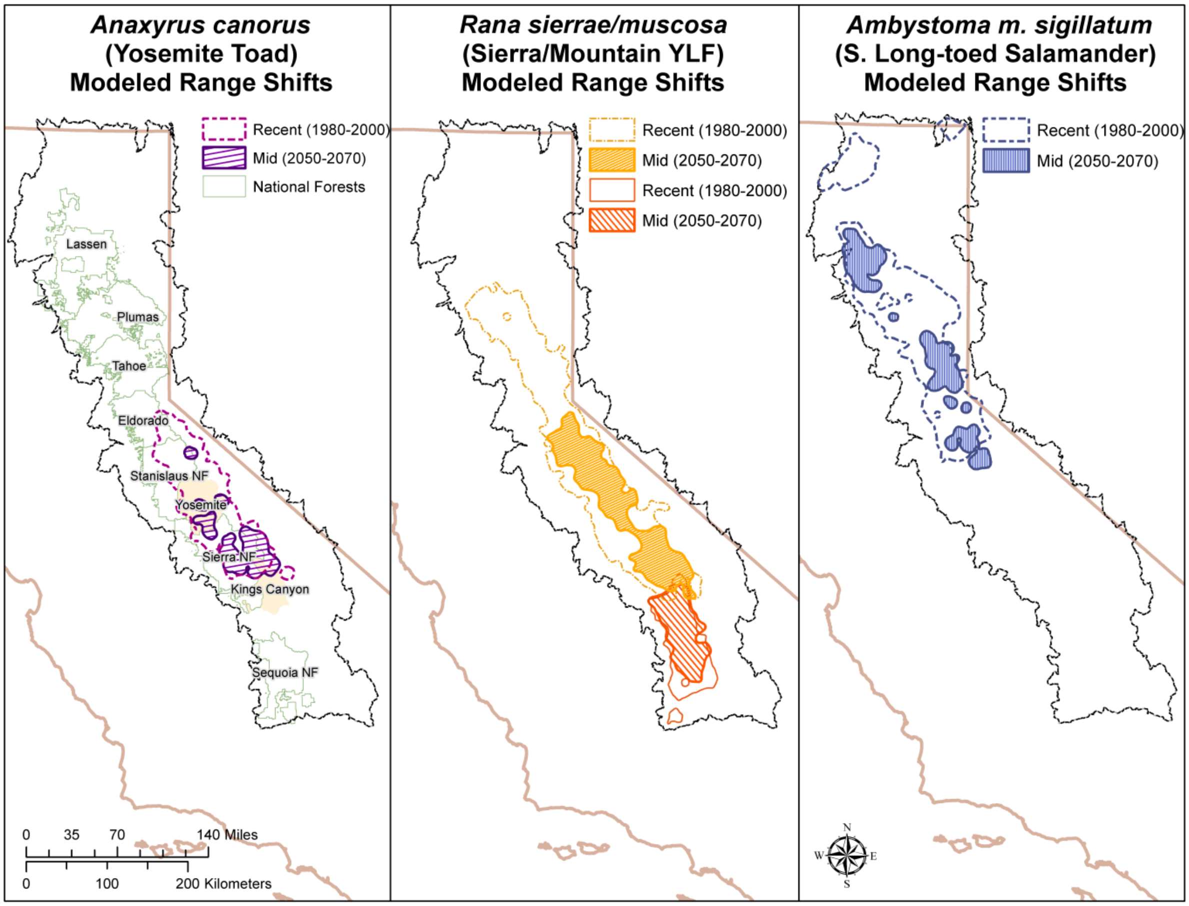


**Figure 9. Predicted range contraction from recent (1980-2000) to mid (2050-2070) time periods for four montane amphibian species.**

Although the relative influence of predictors varied across species, the most influential variables were largely hydroclimatic drivers relating to max temperature, snowpack, runoff, and precipitation. Mean snowpack for quarter one [Jan-Mar] was influential for both S. long-toed salamander and Sierra yellow-legged frog, while runoff (mean and percent of total annual runoff) was in the top five variables for Yosemite toad and Sierra/mountain yellow-legged frogs. The S. long-toed salamander, which had one of the largest current ranges of the species modeled and occurs in the northern half of the Sierra Nevada, was most strongly influenced by vegetation type and precipitation variables, while species that occurred in central and southern portion of the Sierra Nevada were most influenced by snow related variables (snowpack and runoff) (Table 6). Snow related variables (aside from mean snowpack in Q1) were strongly linked with the Sierra yellow-legged frog and Yosemite toad. Mean elevation and river density (using National Hydrology Dataset-NHD) were also generally informative predictors within models for a majority of the species.

Only one meadow variable, the total count of meadows within each HUC12 (MdwCnt_H12) was in the top ten most informative variables, and only for Pacific chorus frog and Yosemite toad. All other meadow variables were not influential factors in predicting occupancy (Table 6). However, mapping the spatial distribution of meadow counts by HUC12 showed the largest number of meadows occur in the central and southern Sierra Nevada, which correlated to the regions models identified as least likely to contract during climate warming for Sierra yellow-legged frog, southern long-toed salamander, and Yosemite toad (Figure 3 and Figure 4). Based on the most influential hydroclimatic variables for these sensitive amphibians, portions of several sub-basins (HUC8) were identified as more resilient to climate change, particularly in the southern Sierra Nevada (see circled areas in Figure 10). These areas, including those within the Crowley Lake, Upper San Joaquin, and Upper Kings drainages, coincided with the regions where ranges contracted for Yosemite toads and Sierra yellow-legged frogs. Within these sub-basins, specific sub-watersheds (HUC12) showed the least proportion of change between the recent and mid time periods for multiple hydroclimatic variables, including max quarterly temperatures and coefficient of variance of precipitation. Several sub-watersheds including Palisade Creek, Upper Middle Fork Kings River, Goddard Creek, Fleming Creek, Upper Mono Creek, Evolution Creek, Piute Creek, Goddard Canyon, Bear Creek, Pine Creek, McGee Creek, Horton Creek, Baker Creek, and South/Middle Fork Bishop Creek did show significant declines in snowpack and runoff between recent and mid/far time periods.

**Table 6. Relative influence score for selected variables from BRT models across species**

| AMMASI | ANCA | RAMU | RASI | PSSI |
|---|---|---|---|---|
| VegType (12.9) | tmxQ3mean (20.9) | tmxQ1sd (31.2) | pckQ1mean (15.8) | NFR (41.9) |
| pptQ2mean (11.1) | pptQ2cv (10.9) | River Density (11.1) | pptQ2cv (10.1) | domVegPrcnt (9.3) |
| pptQ3mean | runQ3mean (9.6) | pptQ2cv (9.2) | pckPrcntTotQ3 (9.9) | prcntBurned100yr (8.8) |
| pptPrcntTotQ1 (8.2) | tmxQ2sd (9.6) | pptPrcntTotQ1 (9.1) | runQ2mean (9.7) | VegTyp (8.3) |
| ElevMean (7.7) | MdwCnt_H12 (4.5) | runPrcntTotQ1 (4.9) | pckQ3mean (7.2) | meanFRID (4.4) |
| pckQ1mean (7.5) | pptAnnMean (3.9) | pptQ1cv (4.3) | VegType (6.3) | MdwCnt_H12 (3.1) |

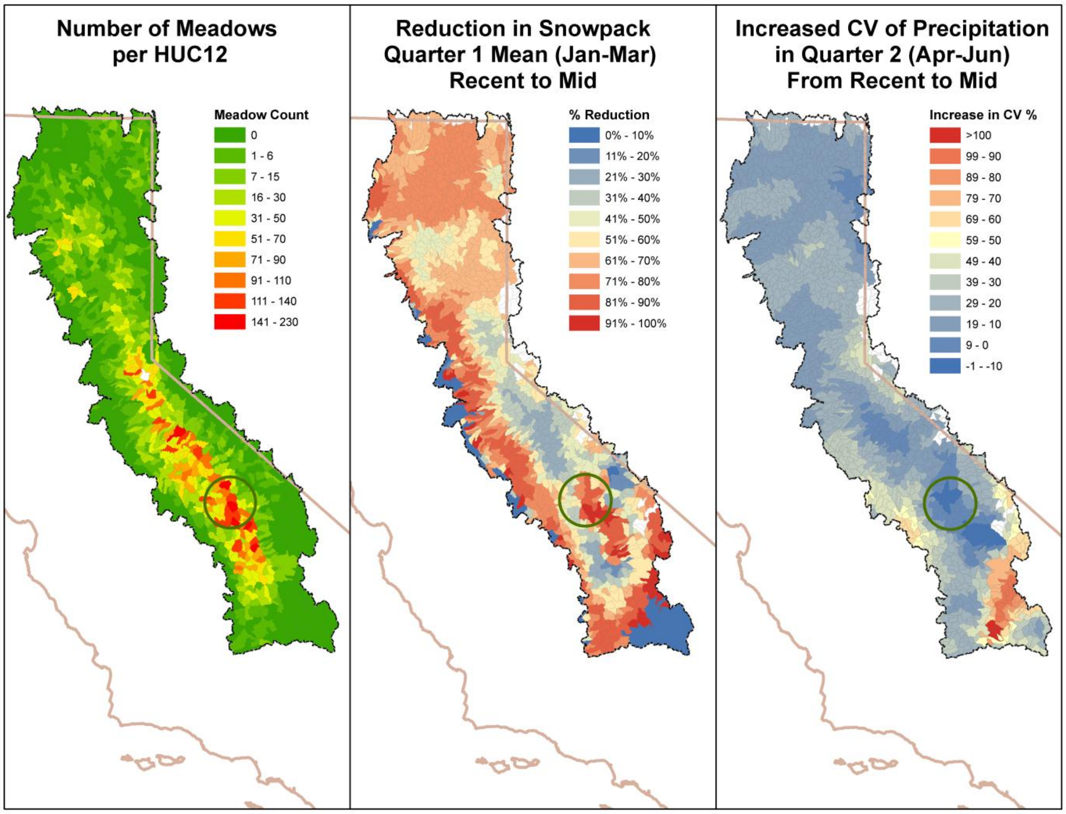
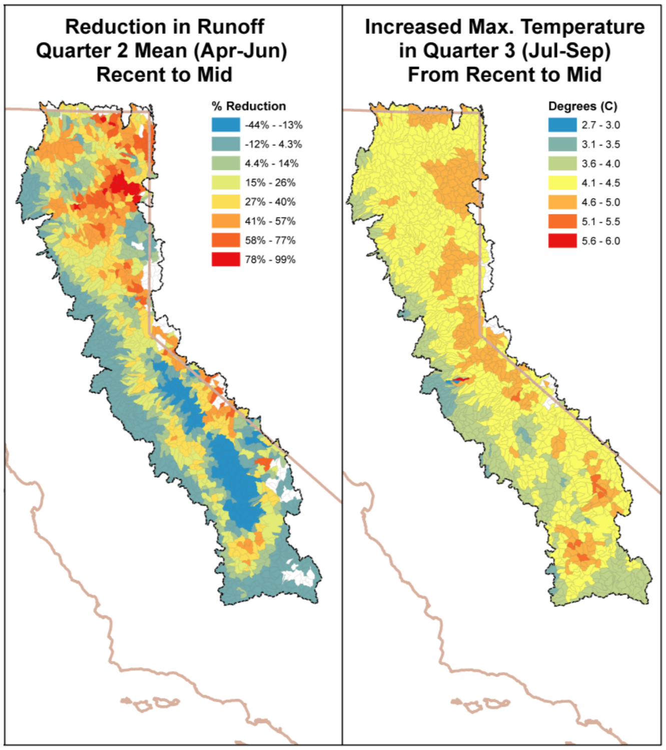


**Figure 10. Maps (above) of meadow count, reduction in snowpack in Q2, increase in coefficient of variability for precipitation Q2; and (below) of reduction in runoff Q2, increase in maximum air temperature Q3, circled area shows region where probabilities of occupancy for Yosemite toad and Sierra mountain yellow legged frogs remain above 0.5 after ranges contract between recent (1980-2000) and mid (2050-2070).**



## VULNERABILITY ASSESSMENT DISCUSSION

The ability to identify and quantify resilience to climate change for specific organisms or habitats is the ultimate goal of applied conservation management. With changing SDM techniques, annual revisions to global circulation models, and limited resources available to many conservation managers, it is often difficult to incorporate current research into actual management practice. This study documents an applicable method of combining BRT species distribution modeling with hydroclimatic data to identify shifts in species range and climatically resilient regions as a potential management tool for conservation. Effective conservation management requires detailed knowledge of a species' ecological and geographic distribution in order to prioritize areas with the greatest potential for successful outcomes (Elith *et al.* 2006). However, management decisions are often limited by sparse data; therefore the ability to utilize all available data in quantitative and effective ways is important. It may be particularly challenging to find sufficient life history data to support finer-scale species distribution models (which can be data-intensive) for many sensitive species. Paucity of fine-scale data should not be the limiting factor for successful integration of effective distribution modeling in conservation management. By using a combination of known species range data with available field observations and museum records, BRT modeling provided a unique and statistically quantifiable method to assess the distributional trends of indicator species using varying hydroclimatic and environmental conditions.

Although use of generalized range data as the training dataset may initially over-estimate presence for widely distributed species using current conditions, BRT models performed well in predicting species ranges using future environmental and climatic data. Species with smaller initial ranges such as the Yosemite Toad and Mountain yellow-legged frog had lower remaining mean deviance and cross validation deviance compared with wider ranging species, likely due to a wider range of hydroclimatic conditions across larger landscapes. Guisan *et al.* (2007) observed species with smaller ranges and narrower life history requirements were easier to model compared with widespread generalist species. The large number of variables included in these models did not significantly reduce the correlation or AUC scores across climate period or species. Relative influence of modeled variables did not change significantly between models, as BRT has been shown to effectively ignore non-relevant data (Elith *et al.* 2008).

Among many environmental and hydroclimatic variables used in the model, snowpack and snowmelt (runoff) variables were consistently among the most informative in predicting species occupancy across modeled species, which supports previous research indicating changes in snowpack and snowmelt due to climate warming will likely have the greatest impact on ecosystem structure and breeding phenology (Corn 2003; Stewart 2009). Snowpack was one of the most informative modeled variables for S. long-toed salamander and both Sierra/mountain yellow-legged frog, while runoff was more informative in Yosemite toad models. Among the species modeled, snowpack had the lowest relative influence on Pacific chorus frog range occupancy probabilities. The life history strategies for the species most influenced by snowpack are very different compared to faster developing species such as Yosemite toad and Pacific chorus frog. Snowpack was an important variable for the species which require multiple years to overwinter as larvae before metamorphosing, whereas Yosemite toad and Pacific chorus frogs have evolved much faster developmental strategies, and generally use much more ephemeral aquatic habitat for breeding and rearing.

Modeling indicates most montane amphibian species are strongly tied to hydroclimatic signals associated with snowpack, snowmelt and precipitation. As climate models show shifts towards earlier snowmelt, reduced snowpack, increased precipitation and air temperatures, it is unsurprising that modeled ranges show extreme contraction for amphibian species sensitive to climate change. However, the identification of specific areas which limit hydroclimatic variability in a changing climate is perhaps the most useful application these models provide. Future conservation management success may hinge on various factors, and there are many that remain too stochastic to quantify for some species (e.g., will population and species extirpation due to the fungal pathogen causing chytridiomycosis outstrip any deleterious impacts due to climate change). However, this should not prevent long-term conservation planning for vulnerable species. While complex ecological decisions should not solely be based on a model, this modeling approach provides a way to quantify and evaluate uncertainty for sensitive species, as well as assess how a given species or landscape may respond to climate change. A better understanding of which species are most sensitive to climate change, what variables are likely to be the best predictors for future range contraction, and where the most 'climate-resilient' regions within a species range may occur will help better inform conservation management.

For example, overwintering species require permanent bodies of water with sufficient persistence and stability to remain suitable for the duration of the rearing period before metamorphosis, and climate warming may increase the frequency of summer drying in small lakes and ponds (leading to complete mortality for larvae), as well as reducing fecundity in species dependent on above-average snowpack (Lacan *et al.* 2008a). BRT models show the predicted future reductions in snowpack in the Sierra Nevada will likely reduce the probability of occurrence and lead to much patchier distributions for these species, further isolating populations across the landscape. Changing snowpack has the potential to impact not only montane amphibian species which require deeper water for overwintering levels, but also species which use more ephemeral aquatic meadow habitat such as the Yosemite toad. Water levels are shallower during years with less snow, and studies have shown these differential depths can alter the amount of UV-B light to which eggs are exposed (because less water is present over the eggs to filter UV-B light), which can potentially make embryos more susceptible to disease and mortality (Blaustein et al. 1998, Kiesecker et al. 2004). In addition, changes in runoff duration and timing could have negative consequences for species such as the Yosemite toad, which have evolved life histories around stable and predictable melting periods during which larvae can develop and metamorphose.

For generalist species such as the Pacific chorus frog, which use ephemeral aquatic habitat similar to the Yosemite toad, hydroclimatic change does not appear to have perceptible effects on the probability of occupancy or population declines. Pacific chorus frogs are one of the most wide-spread amphibians in the western United States, and they have adapted to a wide range of habitats (Stebbins 2003). Certain adaptations may be advantageous in the face of hydroclimatic change, specifically short developmental time periods and the ability to utilize a wide variety of habitat for breeding. In addition, related factors such as resistance to UV-B light may increase reproductive success for species such as Pacific chorus frogs. Blaustein et al. (1998) found Pacific chorus frogs had the highest levels of photolyase (a UV-B protective enzyme) and lowest associated impact of UV-B of nine amphibians studied, and chorus frogs typically lay eggs in very shallow water.

The approach of using generalized range data as the training dataset inference of species occurrence is likely an over-estimation of a species presence, however it may be particularly challenging to find sufficient life history data to support finer-scale species distribution models (which can be data-intensive) for many sensitive species. Paucity of fine-scale data should not be the limiting factor for successful integration of climate change into distribution modeling in conservation management. Validation of the BRT models using a combination of available field observations and museum records provides a unique and statistically quantifiable method to assess the distributional trends of indicator species, while using the widest range possible to identify hydroclimatic change.

When integrating hydroclimatic change, BRT models may be more applicable for use in large landscape conservation management, and seem most useful for describing large changes in the landscape. Modeling at finer resolutions is possible, but application for species specific management would benefit from using different modeling methods to determine changes specific to a single species (i.e., Maxent). Models of sensitive species with large ranges (i.e., AMMASI and RASI) may provide more useful information for landscape level conservation action than models of species with smaller initial ranges, such as Yosemite toad and mountain yellow-legged frog. For example, the modeled effects of hydroclimatic change for Yosemite Toad show a stark decline in occupancy, with no expansion beyond the current range followed by complete extirpation by the far (2100) climate scenario. Compared with Yosemite toad, the Sierra yellow-legged frog BRT model shows significant declines, but not complete extirpation (based on hydroclimatic change). The initial range for Sierra yellow-legged frogs was over twice as large as the Yosemite toad range, and likely contains a much wider array of environmental conditions which may provide more areas with higher probabilities of occupancy throughout the climate scenarios. Quantifying these areas of habitat stability, or “resiliency” may ultimately be the most useful outcome of BRT modeling.

## VULNERABILITY ASSESSMENT CONCLUSIONS

Conservation management may occur at multiple spatial and time scales, however, long-term decisions should consider the effects of hydroclimatic change on both the landscape and the associated species within the landscape. BRT modeling can be used most effectively for species that have large geographic ranges, particularly when used with a wide array of environmental variables because sufficient variability across the landscape provides the model with greater predictive acuity. For hydroclimatic modeling, sensitive species with small geographic ranges, small sample sizes, and narrow life-history requirements may be more suited to fine scale species distribution models such as Maxent. Nonetheless, long term conservation management may be more successful if decisions are based on a broad suite of physical and biological characteristics centered on important ecological landscape features, instead of limited to the requirements of a single sensitive species at a fine scale.

There is no single conservation strategy that can prevent extinctions. Multi-foci management is required for any successful conservation action, particularly for species that are more sensitive to climate change (ARSCC, Sodhi et al. 2008). These native montane amphibian species are highly vulnerable because of existing declines associated anthropogenic factors such as fish stocking, grazing, and disease (chytridiomycosis) ((Pilliod & Peterson 2001; Briggs *et al.* 2005; Rachowicz *et al.* 2006). The current factors for amphibian declines combined with the unique life history requirements adapted over millennia within riparian meadow habitats that are highly sensitive to increased hydroclimatic variability resulting from global warming, place these montane species on the precipice of extinction. Ultimately managers need to consider both short term and long term conservation goals by identifying the species or communities of interest, evaluate the most important anthropogenic and climate factors associated with these species, and focusing resources on critical sensitive areas most resilient to climate change in occupied areas.

The vulnerability of Sierra Nevada meadow ecosystems to hydroclimatic alteration is best captured by changes in runoff across the range. Figure 11 depicts the difference in Q3 (Jul-Sep) runoff for a near-term (2020-2040) warming scenario as simulated by the Basin Characterization Model (BCM; Flint et al., 2011; USGS; GFDL GCM SRES A2) as a function of meadow density (meadow area per watershed area depicted as circle sizes with larger circles have a higher meadow density). Based on our analysis of amphibian indicator species, meadow density, and hydroclimatic alteration, the Central Sierra Nevada appears most vulnerable to anticipated future hydrological conditions (Figure 11) and the southern Sierra Nevada appears most resilient (Figure 10).

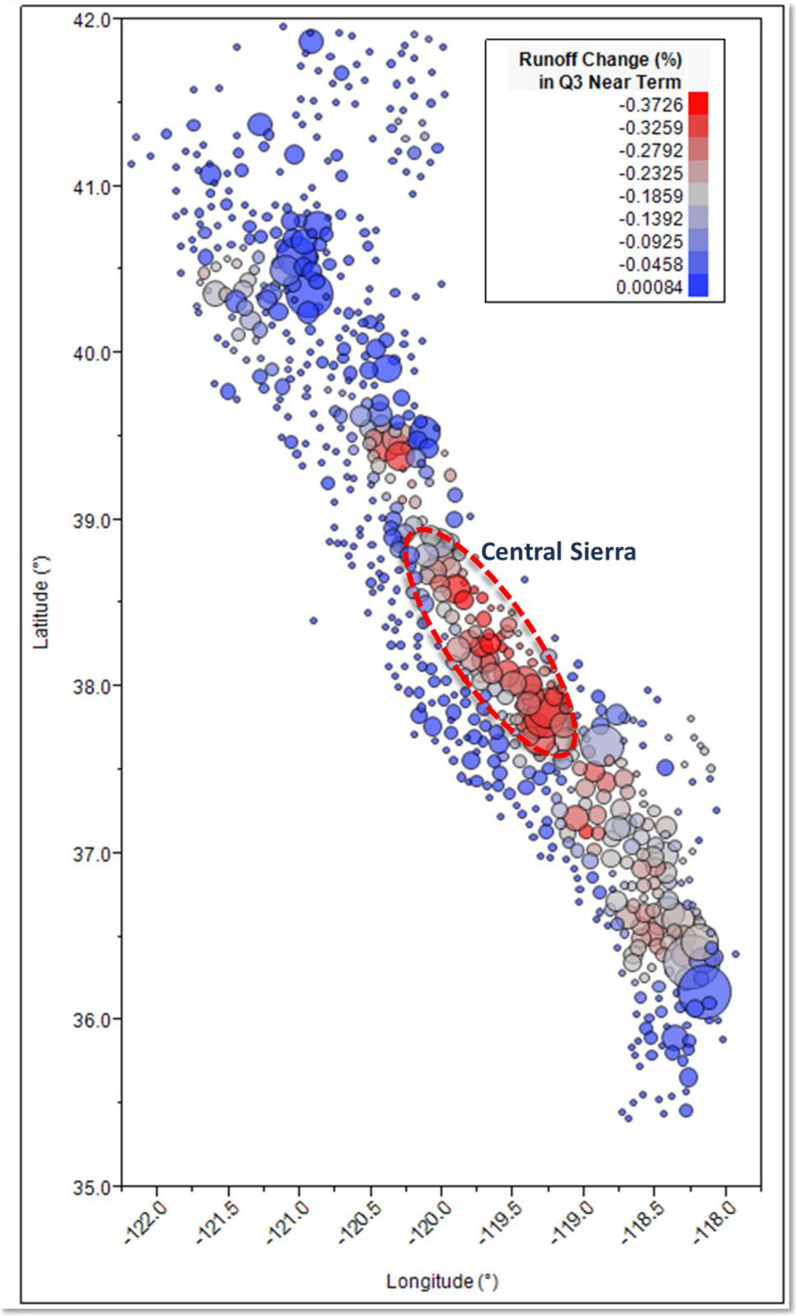


**Figure 11. Map of meadow density (area of circles with larger circles depicting higher density) as a function of changing runoff for a near-term GCM prediction of Jul-Sep for the period 2020-2040.**

Changes in late season discharge are likely to have detrimental effects on aquatic wildlife as habitat volume diminishes and indirect effects, such as stream heating, become more pronounced. Diminished water tables will likely stress hydric and mesic vegetation, promoting more xeric conditions. Coupled with greater magnitude stream flows due to extreme rainfall events, these conditions promote channel incision and ultimate state shift to non-meadow conditions. The biological effects of this type of hydroclimatic alteration, such as lower mean annual flow (Figure 11) and earlier timing, will result in an overall decrease in available habitat for aquatic species. Earlier timing and longer low flow duration will force aquatic biota to withstand more days at thermally challenging temperatures, potentially promoting non-native species. Decreased mean annual flow, less overall snow volume, and warmer daily air temperatures will potentially decrease the number of days of standing water available for amphibian reproduction.

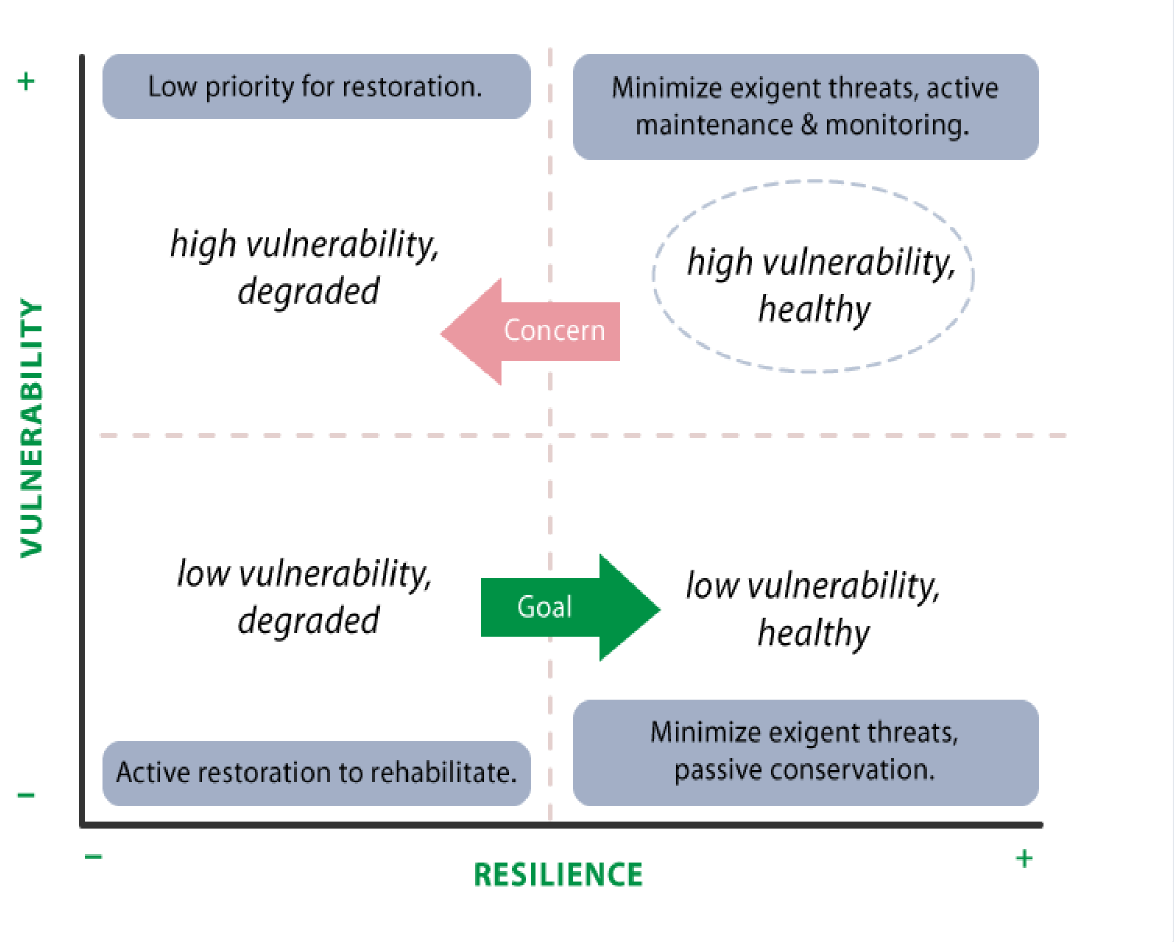


**Figure 12. Conceptual diagram of managing montane meadows for reducing vulnerability and increasing resilience.**

Despite the apparent geographic disparity in vulnerability and resilience depicted in Figures 10 and 11, it is important to recognize that each meadow has its own land use history and hydrogeomorpic context, thus focused vulnerability assessments (as presented in Appendices A & B) are also necessary. Placing such assessments within a conceptual model framework (Figure 12), will help guide future management strategies.

A core strategy for maintaining meadow ecosystems, ecosystem services, and dependent biodiversity is to reduce vulnerabilities, such as unstable stream banks that promote cycles of incision, and increase resilience to disturbance, such as actively removing encroaching vegetation that can overtap water tables and build up wildfire fuels. Reducing meadow vulnerability to hydroclimatic alteration and ensuring sustained ecosystem services will require active ecosystem management (i.e., managed for indicator species, but with focus on hydrological functioning) and coordinated hydrological management (i.e., conservation action and removal of stressors coordinated across all ownerships and management regimes) (Figure 12). Ultimately, the impacts of hydroclimatic alteration will be non-uniform in their spatial distribution and across time, and the true magnitude of impacts may lag behind specific events due to complex ecohydrological feedbacks. Thus, effective communication from managers to the general public and to ecosystem service recipients will be necessary to minimize human activities that degrade ecosystems and reduce resilience to alteration.

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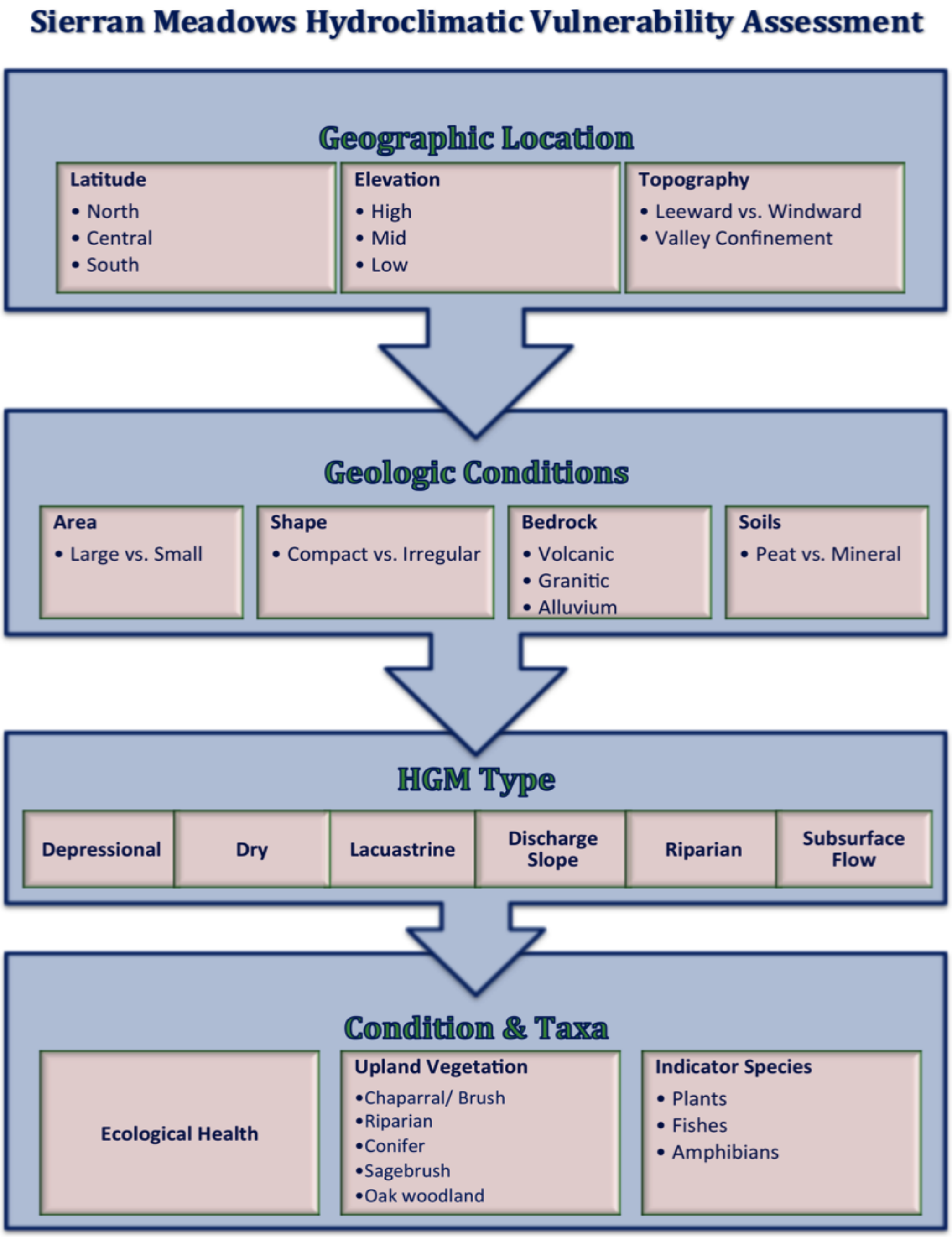
# APPENDICES

## APPENDIX A. MEADOW HYDROLOGIC ALTERATION VULNERABILITY ASSESSMENT

The following flow diagram (Appendix A; Figure 1) and accompanying discussion will aid resource managers in assessing the vulnerability to hydroclimatic alteration of individual meadows within their management area. Managers should follow the steps outlined below in four stages (I-IV, corresponding with each major box in Figure 1) to assess meadow context and vulnerability to hydroclimatic alteration.



**Appendix A; Figure 1. Flow Diagram for Hydroclimatic Vulnerability Assessment.**

# 1 LATITUDE

The latitudinal location of a given meadow will determine important dominant climatic regimes. Whether located in the northern, central or southern Sierra Nevada, there are common characteristics shared by most montane meadows in each respective region.

Note: geographical proximity is denoted by dominant west slope watersheds. Smaller watersheds of the eastern Sierra Nevada are similarly distributed, though with a pronounced rain-shadow effect (see section on Topography below). Projected hydrologic alterations described below are adapted from Null *et al.* (2010).

## NORTH

Meadows in the northern stretches of the Sierra Nevada, from the Yuba and Feather Rivers north, switch from snowfall dominant systems at Sierra Crest to rainfall dominant systems. Crests are generally at lower elevations, and parent material is predominantly volcanic, with considerable influence from groundwater inputs and spring systems. The greater capacity for deep soil moisture storage and infiltration buffers low flow duration (LFD). This region tends to consist of large area meadows or connected complexes of meadows, and has higher evapotranspiration rates due to the extensive forested land cover.

Despite a slightly smaller overall area and far lower elevations, the northern watersheds (e.g., greater Sacramento River) have a much higher absolute water yield than southern watersheds (e.g., greater San Joaquin River), which are roughly one third the yield of their northern counterparts.

## CENTRAL

Centrally-located meadows in the Sierra Nevada, roughly from the American River south to the Merced River, only retain snowfall at the highest elevations. Parent material is predominantly granitic, with shallow soils and a greater quantity of exposed bedrock, especially at high elevations. This contributes to both their low capacity for deep soil moisture storage and infiltration and their moderate evapotranspiration. The predicted low flow duration (LFD), the period in which water demands are highest relative to supply, undergoes the greatest increase in the Mokelumne, Merced, Tuolumne, American, and Stanislaus watersheds. The Stanislaus, Mokelumne, and Merced watersheds are predicted to have the greatest shift toward earlier centroid timing (CT).

## SOUTH

Meadows in the southern reaches of the Sierra Nevada, from the San Joaquin River to the Kern River, have the highest overall elevation at the Sierra Crest, and retain snowfall for a greater proportion of the watershed than northern or lower-elevation watersheds. This region exhibits areas of extensive glaciation, with granitic parent materials in the San Joaquin, Kings and Kaweah drainages. The Kern drainage is more dominated by unglaciated alluvium influenced by volcanic parent materials. These meadows have the lowest absolute water yield in the Sierra. Evapotranspiration rates are highly variable, based on elevation, land cover and soil moisture capacity. Low Flow Duration is buffered by the high elevation and unglaciated alluvial soils. A significant shift to earlier centroid timing (CT) is predicted for the San Joaquin and Kings Rivers, with a less pronounced shift for rivers at higher elevation (e.g., Kaweah, Kern) and rivers with headwaters below the crest or at lower elevations (e.g., Tule River).

# 2 ELEVATION

The elevation at which a meadow is located impacts many important factors, including precipitation type, soil depth, amount of exposed bedrock, and drainage area. High elevation meadow locations are likely to retain snow, though perhaps in reduced volume. Lower elevation meadows, which are currently predominantly rainfall driven, will likely see little change in CT. Mid-elevation meadows, however, are likely to experience increased variability in precipitation, in both amount and type (rain vs. snow), and are thus more prone to hydrologic alteration.

## HIGH

Meadows at high elevations (greater than 3000 m) currently receive the bulk of precipitation as snow. They are predicted to retain snow at upper elevations, but to decrease in mean annual flow (MAF) (1.1-12.2% decrease in MAF for the Kings, Kaweah, and Kern drainages at 2, 4, and 6˚ C of warming).

## MID

Meadows at mid elevations (between 2000 and 3000 m) currently receive the bulk of precipitation as snow, but are predicted to shift to rainfall dominated systems. A decrease in MAF (ranging from 1.3–8.2% decreases for the Stanislaus, Tuolumne, Merced, and San Joaquin drainages at 2, 4, and 6˚ C of warming) is also predicted, as well as a shift to earlier CT (approximately two weeks earlier for every 2˚ C of warming) in Central-South drainages.

## LOW

Meadows at low elevations (less than 2000 m) currently receive the bulk of precipitation as rain, thus little change in CT is predicted. The predicted decrease in mean annual flow (MAF) will be the dominant signal of hydrologic alteration, ranging from 3.1-14.0% decrease in MAF for the Bear, Cosumnes, and Calaveras basins, based on 2, 4, and 6˚ C of warming.

# 3 TOPOGRAPHY

### WINDWARD VS. LEEWARD

The Sierra Nevada, and to a lesser extent the California portion of the southern Cascade range, exhibits strong rain shadow effects. Thus, topographic position is an overarching consideration for determining the hydroclimatic context of meadows. In the Sierra Nevada western slope meadows are windward, and thus receive more precipitation. The eastern Sierra Nevada, including portions of the Modoc Plateau and the Feather/Pit River complexes, are generally leeward, and due to rain shadow effects receive less precipitation.

### VALLEY CONFINEMENT

Valley confinement is generally the measure of width between valley walls, but can also include valley bottom curvature, and is a primary driver of fluvial migration. Unconfined valley bottoms generally exhibit different geomorphic features (such as increased sinuosity) from confined valleys, and thus serve different roles in promoting a mosaic of habitat features. Valley confinement may have effects on sediment transport, grain size, and debris flow conveyance, which in turn serve as the formative basis for fluvial habitat and thus biological habitability.

## STAGE II: GEOLOGIC CONDITIONS

# 4 AREA

### LARGE VS. SMALL

Larger meadows (those with greater land area) are generally more buffered from hydrologic alteration than smaller meadows, due to:

- Increased absolute soil moisture capacity and infiltration,
- Smaller edge to surface area ratios where encroachment from upland plants occurs,
- Increased ability to buffer high flows and attenuate floods.

Alternately, smaller meadows (those with lesser land area) are more vulnerable to hydrologic alteration, due to:

- Larger edge to surface area ratios which encourage encroachment,
- Decreased absolute soil moisture capacity and infiltration, and
- Less ability to buffer high flows and attenuate floods.

Meadow Drainage Area is an important associated factor, as larger catchment size equates to greater variation in CT, the presence of higher-order streams, and increased sediment yields.

# 5 SHAPE

## COMPACT VS. IRREGULAR

Meadow shape is commonly defined as either compact or irregular.

***Compact meadows***, i.e., those without extensive arms and odd shapes, are better buffered against vegetation shifts from drying or lowered water tables. This is due to the increased soil moisture holding capacity in larger areas, and decreased opportunity for encroachment from upland plants associated with meadow edges.

***Irregularly-shaped meadows***, i.e., those with higher ratios of edge habitat to surface area, tend to be more vulnerable to hydrologic alteration and encroachment from upland plant communities associated with edge habitat.

# 6 Bedrock

The dominant underlying bedrock of meadows within the Sierra Nevada generally fall into three types, each with unique associated characteristics:

- **Volcanic fault block** geology generally indicates the presence of springs or other ground water inputs. These meadows have deeper soils and increased soil moisture holding capacity.
- **Granitic batholiths** have shallow soils, low infiltration, and lesser soil moisture holding capacity.
- **Unglaciated alluvium** is associated with deeper soils and increased infiltration but variable soil moisture holding capacity and groundwater inputs.

# 7 Soils

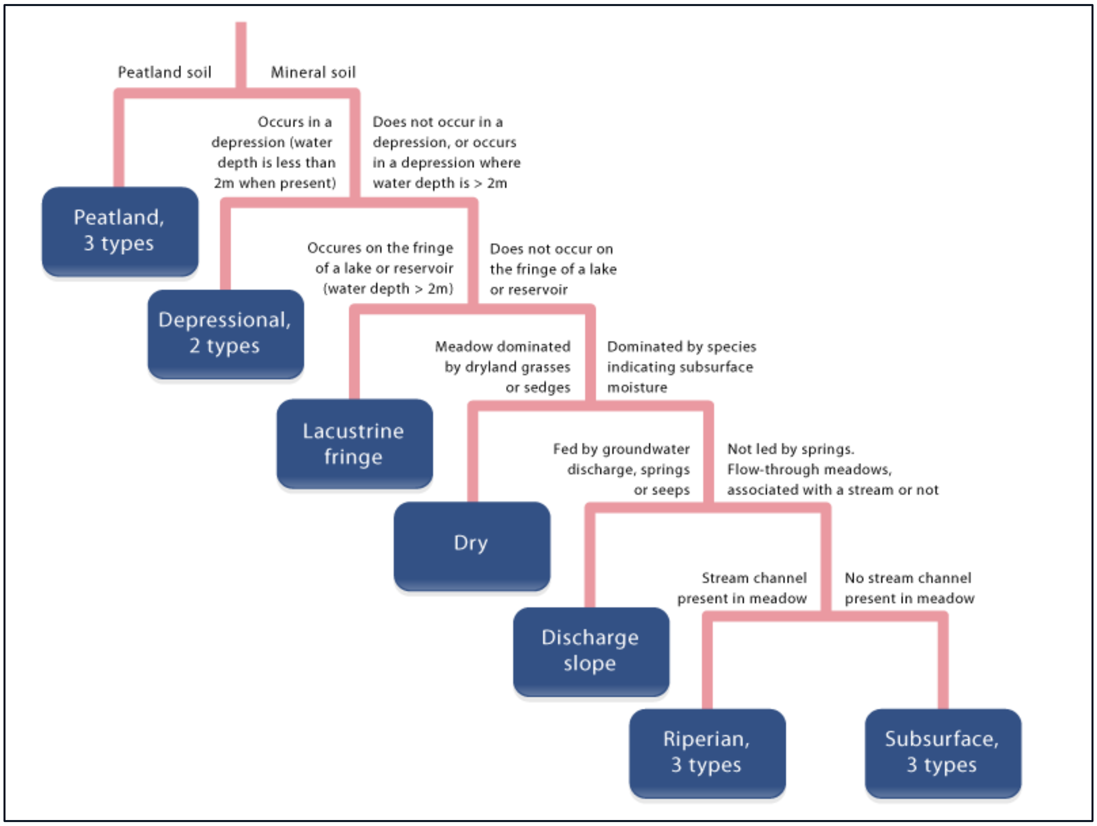
The dominant underlying soils of meadows within the Sierra Nevada generally fall into one of two unique categories:

- **Peat** Peat is formed by accumulation of organic matter (> 20 cm) and is often characterized by anaerobic conditions created by shallow water table (< 40 cm).
- **Mineral soils** Mineral soils are formed by the decomposition of surrounding geologic substrates, which in the Sierra Nevada are largely granodiorites and basalts, but can also include schists and gabbros.

# 8 HGM Type

We recommend using the field key of Weixelman *et al.* (2011), which defines seven major meadow hydrogeomorphic (HGM) types (and 14 associated subtypes). Using the tree diagram shown in Figure 1, one can systematically determine the hydrogeomorphic type of a meadow. By definition, using this approach will help define the hydrologic regime of the meadow. The following are the major HGMs:

- Peatland
- Depressional
- Lacustrine
- Dry
- Discharge slope
- Riparian
- Subsurface flow



Appendix A Figure 2. Dendrogram of Major Meadow Hydrogeomorphic Types (Weixelman 2011).

# 9 Ecological Health

Ultimately, evaluation of the current, overall ecological condition of the meadow and stream is necessary. The chief concern with respect to hydrological outcomes is bank stability. If a meadow is generally degraded—substantial evidence of erosion from grazing, off-road vehicles, etc.—the stream channel is likely to be very unstable. This will result in erratic stream behavior, such as down-cutting, incision, loss in water table, and potential outcomes from altered hydrologies that tend toward “flashy” or higher magnitude events driven by rain or rain-on-snow events.

Assessments of meadow condition often require benchmarking against a desired condition, or a reference site (Brinson & Rheinhardt 1996; Rheinhardt *et al.* 1999). While there are a number of methods to undertake a meadow condition assessment, the rapid assessment protocol developed by Hunt *et al.* (2012) can serve to compare condition across meadows, and also point to priority areas for restoration.

We also recommend including the approach of Henery *et al.* (2011), in using a stepwise approach to determining what, if any, limiting factors exist for target populations (e.g., breeding habitat for amphibians, or spawning habitat for fishes), determining whether actions mitigate against limiting factors, and determining if activity outside the immediate scope of the project is necessary to be successful.

Additional functional assessments can quantify absolute measures, such as rate of nutrient cycling, or relative to a reference standard, such as expected biodiversity values like plant species richness. For meadows, functional assessments are often hydrologic (e.g., water balance), biogeochemical (e.g., nutrient cycling), or ecologic (e.g., community composition). For the latter, indicator species assessments are the most robust in terms of information gained per unit effort.

# 10 UPLAND VEGETATION

It is important to consider the upland vegetation of a meadow, as its composition and status can largely define the functioning (or non-functioning) of meadows. The five main categories of dominant upland vegetation are:

- Chaparral/ Brush
- Riparian
- Conifer
- Sagebrush/ Juniper steppe
- Oak woodland

Surrounding dominant vegetation is the result of many factors, such as climate, elevation, soils, and land use history. Additionally, hydrology is an important factor, as it affects the overall suitability of a site, based on soil moisture, water availability, and potential seasonal deficit from evapotranspiration. Other considerations include the role of disturbance, such as flooding in riparian vegetation types, or fire in non-riparian types.

# 11 INDICATOR SPECIES

## PLANTS

Functional traits of a plant species can be used to assess ecosystem function and measure the impacts of ecosystem alterations. In meadow systems, plant species with specific functional traits, such as species height and life form, can be linked directly to the amount of disturbance or the hydrologic condition of a meadow. Weixelman (personal communication) established that there is a strong and predictable relationship between species functional traits and meadow condition in the Sierra Nevada. For example, annual species are associated with high disturbance and poor hydrologic condition, while perennial species are more often associated with low disturbance and good hydrological condition. By targeting species with specific functional traits, botanical field surveys can serve as a method to assess meadow condition and response to restoration. For further information about appropriate methods, please consult a vegetation ecologist with knowledge of local flora and meadow dependent species.

## FISH & AMPHIBIANS

In evaluating a meadow, determine whether native fish are currently or were historically present, and what the historical community structure was like in comparison to the current structure. This will guide a more thorough assessment of the potential impacts from hydrologic alteration, and how they may affect the current community structure. Use physiological tolerances, habitat preferences, and natural history strategies presented in Appendix B to further apply this assessment methodology.

# APPENDIX B. EFFECTS OF HYDROLOGIC ALTERATION ON KEY INDICATOR SPECIES

## FISHES

### SALMONIDS

- California Golden Trout (*Oncorhynchus mykiss aguabonita*)

Photo by Nicholas Buckmaster

California golden trout are native to the Kern River drainages in the southern Sierra Nevada. They are highly meadow associated throughout their range, and have been extensively introduced throughout the Sierra Nevada. Introductions of non-native rainbow trout has resulted in introgression in all but a very few populations. Stream impacts from livestock grazing and Off-Highway Vehicles (OHVs) use are of highest impact to habitat alteration. Although the Kern River is an area expected to retain precipitation as snow, centroid timing and low flow duration may impact golden trout in this locale.

- Eagle Lake Rainbow Trout (*Oncorhynchus mykiss aquilarum*)

Photo by Gerard Carmona-Catot

Endemic to only one watershed with a single spawning stream, Eagle Lake rainbow trout are highly vulnerable to climatic variation, especially periods of extremely high or low flows. There is currently no self-sustaining population of ELRT (all stocks are hatchery maintained), but habitat restoration efforts warrant at least a viable experimental population. The predicted shift from a predominantly snow-fed to predominantly rain-fed hydrograph may negatively affect the timing of spawning migrations and successful hatching and rearing. Long life and high fecundity may help buffer the negative impacts to Eagle Lake Rainbow Trout from these anticipated climatic changes.

- Redband Trout (*Oncorhynchus mykiss* spp.)

Photo by Nicholas Buckmaster

Found in the upper reaches of the Sacramento and Pit River drainages, the redband trout (McCloud River and Goose Lake subspecies) are highly dependent on spring-fed systems. They are frequently found in meadow streams as well as terminal alkali lakes (eg., Goose Lake), and have a high tolerance for alkalinity. Episodic drying events in Goose Lake have resulted in recolonizations from stream populations utilizing spring fed tributary streams as refuges. Climate change associated challenges may include stream temperatures exceeding thermal tolerances, drying of spring fed systems, and drying of lakes. The isolation of population groups will likely become more pronounced as suitable habitat becomes increasingly scarce.

- Lahontan Cutthroat (*Oncorhynchus clarki henshawi*)

Photo by Nicholas Buckmaster

A highly adaptable trout species, Lahontan cutthroat trout (LCT) are found in the Lahontan drainages of eastern California, Oregon and Nevada. Lahontan cutthroats occupy a variety of habitats, including: tiny alpine streams to large rivers, various lake ecosystems ranging from cold, clear Lake Tahoe to the terminal alkali desert lakes such as Pyramid and Walker. Consistent with other trout species in California, thermal tolerance is generally the cutthroat's most limiting trait. Predicted climate-associated changes to hydrology may have a pronounced impact on this specie. Many of their populations are fragmented and dependent upon already marginal habitats that may soon become inhospitable to trout species.

- Other Salmonid species of interest
    - Coastal Rainbow Trout (*Oncorhynchus mykiss*)
    - Paiute cutthroat (*Oncorhynchus clarki seleniris*)
    - Mountain whitefish (*Prosopium williamsoni*)
    - Chinook salmon (*Oncorhynchus tshawytscha*)

## CYPRINIDS

- Pikeminnow (*Ptychocheilus grandis*)

Photo by Nicholas Buckmaster

Pikeminnows are long-lived, highly fecund cyprinids that can grow to large sizes (potentially >1m), and are notably strong swimmers. They are large-mouthed, piscivorous fish found in habitats ranging from large low-gradient rivers in the Central Valley to headwater streams, and pools of small streams. Pikeminnows can be either sedentary or migratory (over large distances), determined by habitat needs and time of year, and readily colonize new areas when available. Due to their opportunistic nature and broad physiological tolerances, pikeminnows are a highly likely candidate to persist through the predicted thermal and hydrological in the Sierra Nevada.

- Speckled Dace (*Rhinichthys osculus*)

Photo by Joe Ferreira

Speckled dace are ubiquitous in meadow streams; no other species is as widely distributed throughout the western United States. They prefer open, shallow waters, and can thrive in disturbed meadow streams with eroding banks and shallow silty bottoms, inhospitable to other species. Dace play an important role in meadow foodwebs as forage fish for numerous species, and readily colonize new habitats (particularly in headwater streams). Dace are highly variable in morphology and habitat use, are broadly tolerant, and though short lived, are fairly fecund. They spawn multiple as eggs continuously ripen throughout the season. With their tolerance of disturbed conditions, high temperatures, and low dissolved oxygen levels, speckled dace will likely persist throughout much of their range where year-round water is maintained. Small streams will likely see periodic extirpations, but may be recolonized in high water years.

- Lahontan Redside (*Richardsonius egregius*)

*Photo by Peter B. Moyle*

Lahontan redsides are present in California only in waters connected to the Lahontan basin. They are a relatively small minnow, easily identified by their brilliant coloration during breeding season; a lateral red stripe on a background of bright yellow. Lahontan redsides prefer smaller headwater streams, and are also often found in the shallows of Lake Tahoe and Eagle Lake. Their abundance appears to be negatively affected by high flow events, and their population size in Lake Tahoe has been impacted by the presence of piscivorous brown trout. Lahontan Redsides are successful recolonizers of areas following localized extirpations.

- Tui Chub (*Siphateles bicolor spp.*)

*Photo by Joe Ferreria*

Heavy-bodied, long lived (30+ years) tui chubs exist in a wide range of habitats including isolated springs, meadow streams and large alkali lakes. There are six subspecies of tui chub (Lahontan, Eagle Lake, Goose Lake, Cowhead Lake, Pit River, and Owens Valley) in the Sierra Nevada, though taxonomic relationships remain somewhat unclear. Tui chubs succeed in a variety of environmental conditions, though they prefer low water velocities with plenty of available cover (especially aquatic macrophytes and emergent vegetation). They are highly tolerant of alkalinity and low dissolved oxygen levels, but have a lower threshold of thermal tolerance than typical desert fishes. Optimal temperatures range between 15 and 30˚ C. Tui chubs are opportunistic omnivores and are notably limited swimmers. Females are highly fecund, spawning multiple times in a season, generally over a bed of aquatic vegetation or algae-covered rocks and gravel. Flashy high flow events associated with hydrologic alteration will likely have a negative impact on all stages of tui chubs, but like other fishes will be particularly impactful to eggs and juveniles. Tui chub may have difficulty recolonizing once extirpated from streams by high flows.

## CATOSTOMIDS

- Mountain sucker (*Catostomus platyrhynchus*)

Photo by Peter B. Moyle

Though widely distributed throughout the western U.S., mountain suckers are found in California only within the Lahontan drainage river basins (Susan, Truckee, Carson, and Walker rivers), and occasionally small lakes and reservoirs. They are conspicuously absent from large lakes such as Tahoe, Eagle and Pyramid. An introduced population exists in Red Clover Creek, a tributary of the North Fork Feather River. Mountain suckers prefer small to medium mountain streams of moderate gradients. Though they normally segregate from other catostomids, in California, mountain suckers form mixed aggregations with Tahoe suckers, a species with very similar life history. Mountain suckers do not succeed in reservoirs, and much of their preferred habitat (lower reaches of mountain streams) is becoming inundated by dams. Mountain sucker populations are in steady decline throughout their entire Californian range. Unlike other Catostomids, they spawn at mid-summer (rather than spring), a trait that may not be sustainable under the predicted increase in low flow duration and lower mean annual flow expected for the central Sierra Nevada. Juveniles utilize smaller tributary streams that may become limited under future conditions. Protecting and maintaining currently-occupied habitats, particularly those with intact meadow systems (necessary for refuge from high velocity during spring runoff and as nursery for juveniles), may help preserve this species.

- Sacramento sucker (*Catostomus occidentalis*)

Photo by Dave Giordano

Sacramento suckers are the most ubiquitous of the California suckers, ranging throughout the Sacramento-San Joaquin system, and all of its tributaries. Sacramento suckers possess broad physiological tolerances, are quite long lived (30+ years), have high fecundity, and readily recolonize occupied habitats after localized extirpations. Like the related Cyprinid family, Sacramento suckers use floodplain habitats during the spring inundation, which provides a vastly productive foraging ground and relief from the stream channel's high flows. Suckers typically spawn in low velocity creeks, although there are observations of limited lake-shore spawning next to inlets as well. As one of the few native fishes to thrive despite significant anthropogenic alterations in California, Sacramento suckers will likely continue to persist throughout or even expand their currently occupied range. Suckers' resiliency is evidenced through their continued persistence despite concentrated eradication efforts from agencies favoring sportfish.

- Other Catostomids of interest
  - Tahoe sucker (*Catostomus tahoensis*)
  - Owens sucker (*Catostomus fumeiventris*)
  - Modoc sucker (*Catostomus microps*)

## COTTIDS

- Riffle sculpin (*Cottus gulosus*)

Photo by Lisa C. Thompson

Riffle sculpins, native to the Sacramento-San Joaquin drainages, are spottily distributed from the Kaweah River (southern range) to the upper Sacramento and McCloud Rivers (northern range). They prefer shallow riffle habitats with water velocities roughly 42–44 cm/sec. Riffle sculpin take refuge from the current in the substrate cobbles and boulders. Sculpins' major limiting characteristics are their lack of dispersal ability and intolerance of low dissolved oxygenlevels. Their preferred temperature range is less than 26˚C, reaching lethal levels around 30˚C. These narrow environmental tolerances will likely render riffle sculpins vulnerable to climate change induced hydrologic alteration. Conditions of low dissolved oxygen saturation stemming from decreased mean annual flow and increased low flow durations will have the greatest impact on the species. Recolonization may be possible in some areas, but riffle sculpins will likely be extirpated from at least a portion of their range, particularly in the northern Sierra Nevada. Sculpin are considerably less mobile than trout species, but with similar physiological constraints. Thus, they may be one of the most sensitive Sierran species to climate change.

- Other sculpin species of interest
    - Paiute sculpin (*Cottus beldingi*)
    - Pit River sculpin (*Cottus pitensis*)
    - Prickly sculpin (*Cottus asper*)

## AMPHIBIANS

- Mountain yellow-legged frog complex (*R. sierrae and R. muscosa*)

Photo by Ryan Peek

The mountain yellow-legged frog complex was recently split into two species based on genetic and morphological data (Vredenburg et al. 2007); the more widely distributed *Rana sierrae*, and the more limited, southern-ranging *Rana muscosa*. Both species have recently been listed under the California Endangered Species Act (CESA), and *R. muscosa* populations in the southern-most portion of the range are federally listed under the Endangered Species Act (ESA).

Mountain yellow-legged frogs are uniquely adapted to life at high elevations in montane aquatic habitats near meadows and lakes. The mountain yellow legged frog (*Rana muscosa* and *R. sierrae*), has a tadpole stage lasting 3–4 years (Knapp & Matthews 2000; Lacan *et al.* 2008b). They have largely been extirpated from their preferred habitats (deep alpine lakes) by the ubiquitous stocking of non-native trout into historically fishless lakes throughout the

Sierra Nevada. Further, the fungal pathogen *Batrachochytrium dendrobatidis* (chytrid), has decimated populations in historically fishless habitats (Rachowicz et al. 2006). Mountain yellow-legged frogs have declined from nearly 80% of their former range (Bradford et al. 1994, Vredenburg et al. 2007). Many remaining populations are found in more climatically marginal tarns and ponds, which may not remain suitable habitat in the future (Kupferberg 1996; Knapp *et al.* 2001a; Knapp *et al.* 2001b; Knapp 2005; Matthews & Miaud 2007; Lacan *et al.* 2008b; Matthews & Preisler 2010).

Based on the preliminary Amphibian and Reptile Species of Special Concern risk metrics used to evaluate and quantify declines for candidate taxa, both mountain yellow-legged frog species are highly vulnerable and changing hydrology and habitat in the Sierra Nevada will likely have drastic impacts on remaining populations.

- Yosemite Toad (*Anaxyrus canorus*)

*Photo by Rob Grasso*

Yosemite toads are endemic to the central Sierra Nevada, only found at elevations approximately between 2,000 m and 3,400 m (Lannoo 2005). This species has been extirpated from 50% of historically reported sites (Lannoo 2005), and lower elevation sites on the western edge of the range have experienced more disappearances (Davidson et al. 2002). Breeding takes place in shallow streams of meadow edges, with short emergent vegetation and loose silt substrates, in conjunction with the spring snowmelt (generally mid-May to mid-August) (Karlstrom 1962, Lannoo 2005). Eggs hatch in approximately 10–12 days and tadpoles metamorphose in roughly 2 months (Lannoo 2005). Predation on Yosemite toad tadpoles has been documented for mountain yellow-legged frogs and garter snakes, but the primary cause of larval mortality is desiccation of breeding pools (Kagarise Sherman 1980, Sherman and Morton 1993). This species is limited to alpine meadows in a relatively narrow elevational zone, and dependent upon ephemeral pools for breeding. Therefore, vulnerability to hydroclimatic alteration will likely be very high (Sherman and Morton 1993). Decreased mean annual flow, less overall snow volume, and warmer daily air temperatures will potentially decrease the number of days of standing water available for clutches to metamorphose from tadpoles to toadlets, likely increasing clutch mortality in an already declining species. Concurrently, continued or worsening channelization in montane meadows from flashy storms may worsen effects by increasing drops in the water table.

- Southern long-toed salamander (*Ambysoma macrodactylum sigillatum*)

Photo by Karen Leyse

Southern long-toed salamanders occur from near sea level to approximately 2700 m in elevation (Petranka 1998). In California, *long-toad salamanders* range into the Sierra Nevada as far south as Carson Pass (Lannoo 2005). Breeding habitat in the Sierra Nevada generally includes small to large permanent lakes and ponds, and adults may use a wide variety of habitat including alpine meadows, coniferous forests, and rocky shorelines of subalpine lakes (Petranka 1998, Lanoo 2005). At higher elevations, breeding does not occur until late spring or early summer, following snowmelt (as late as June–July) (Walls et al. 1993, Petranka 1998). Eggs are generally deposited in shallow water (<0.5 m) and can be attached to a wide range of substrates, but in the Sierra Nevada oviposition generally occurs on the undersides of logs or large branches in deeper water (Anderson 1967, Petranka 1998). Incubation may last as long as five weeks depending on water temperatures, and generally increases with elevation (Petranka 1998). Larvae feed on a wide variety of aquatic organisms, including Pacific chorus frog tadpoles (Petranka 1998). Similar to the mountain yellow-legged frog, the length of the larval period at higher elevations may be as long as 3 years in permanent lakes (Lanoo 2005). Adults are typically subterranean outside of the breeding season and will generally remain within 100 m of water (Lanoo 2005).

Stocking of non-native trout into deep, historically fishless breeding habitats has extirpated long-toed salamanders from some areas. Introduced trout prey on eggs and larvae, and can substantially reduce or extirpate long-toed salamanders from breeding sites (Petranka 1998, Pilliod and Peterson 2001, Stebbins 2003, Lanoo 2005). Additionally, demographic elasticity modeling for long-toed salamanders indicates environmental stressors may be more critical predictors of decline for post-metamorphic life stages (particularly juvenile survival) compared to embryos or larvae (Vonesh and De la Cruz 2002).

- Pacific chorus frog (*Pseudacris regilla*)

Photo by Ryan Peek

The ubiquitous Pacific chorus frog occurs across a wide range of aquatic habitat types and has been observed from sea level to approximately 3,600 m (Stebbins 2003). The pacific chorus frog is one of few amphibian species that does not appear to be declining, and has been identified as one of the most abundant amphibians in western North America (Brattstrom and Warren 1955). In the Sierra Nevada, chorus frogs are commonly found in sympatry with mountain yellow legged-frogs, in high elevation aquatic habitat (Matthews et al. 2001). This generalist species typically utilizes a wide range of high elevation lakes and ponds, breeding during spring and summer in the mountains (as late as July at 2000 m in the Sierra Nevada (Livezey 1953)). Eggs are laid on submerged aquatic vegetation, in either permanent or temporary waters (Lannoo 2005). Embryos develop and hatch in approximately 1–5 weeks (Lannoo 2005). In the Sierra Nevada, metamorphosis likely occurs after approximately 2–3 months, depending on altitude and latitude (Lannoo 2005). Pacific chorus frogs may be more resilient to hydroclimatic alteration, in comparison with other Sierra Nevada aquatic vertebrates, as they do not appear to have declined from their historical range, or they are not declining as precipitously as other aquatic species such as the Yosemite toad or mountain yellow-legged frog (Lannoo 2005).

- Other amphibian species of interest
    - California newt (*Taricha tarosa*)
    - Bullfrog (*Rana catesbeiana*), non-native

## REPTILES

- Garter snakes (*Thamnophis couchii, sirtalis, & elegans*)

*Photo by Ryan Peek*

Several garter snake species exist in the Sierra Nevada. Three species are of particular interest, as they prey primarily on native amphibian and fish species of aquatic montane meadow habitats. A subspecies of the common garter snake, the valley garter snake (*T. sirtalis fitchi*) is found at elevations up to about 2,000 m and tends to remain near water (Stebbins 2003). The Sierra garter snake (*T. couchi*) is found at elevations of approximately 2,000 m to 2,500 m and is primarily an aquatic snake, utilizing streams, rivers, meadows, ponds and lakes (Stebbins 2003). The mountain garter snake (*T. elegans elegans*) is found at elevations of 2,500–3,360 m and is highly dependent on mountain yellow-legged frogs as prey (Jennings et al. 1992). All of these garter snake species are live-bearing, generally occurring between July and September (Stebbins 2003). They will prey widely on aquatic vertebrate species at varying life history stages, including tadpoles, frogs, fish, toads, salamanders, and their larvae.

Changing hydroclimatic conditions, such as decreased mean annual flow, less overall snow volume, and warmer daily air temperatures, will potentially cause a decrease in populations of suitable prey items (i.e., *R.sierrae/muscosa, P. regilla*, and *A. canorus*), due to fewer days of standing water available for amphibian eggs to develop, hatch and metamorphose. Shifts in timing will also potentially alter breeding periods for both prey and predators. As prey species such as mountain yellow-legged frogs continue to decline precipitously, associated declines in predator species may be expected.

## Species of Interest as Indicators for "Ecology of Persistence in Sierra Nevada Montane Meadows"

| | | Life History | | | | | | Habitat | | | | | Flow Regime | | Temperature Preferences | | | | Sources |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Life Span (years) | Semalparous vs. Iteroparous | Spawning Time | Age at first spawning (years) | Lake Form | Stream Form | Preferred habitat | Spawning location | Spawning Substrate (mm)/Behavior | Spawning water Temperature (°C) | Hatching Period (Days)/Temp (c) | Velocity for Spawning | Water Depth Spawning (cm) | Preferred Temperature (°C) | Sublethal Negative effects/ Growth ceases (°C) | Lethal effects (°C) | Additional Notes | Literature |
| **Oncorhynchus spp.** | Golden trout (*Oncorynchus mykiss aguabonita*) | 9 | Iteroparous | spring (May/June) | 3-4 | | x | Pools/undercut banks | Gravel riffles in streams | 4-12 (small gravel) Typical spawning behavior of salmonids. Female builds a redd in gravels, is pursued by one or more males and fertilized eggs are deposited in redd and covered with a light layer of gravel. | 10-15 | 20/14 | 30-70 cm/sec | 5-20 | 10-21 | 24-25 | >25 | | Moyle 2002, Matthews 1995, Stephens et al. 2004 |
| | Redband trout (O.m. subsp) | 6-7 | Iteroparous | spring (May/June) | 2-3 | x | x | Boulder eddies, pools, undercut banks | Gravel riffles in streams | 10-130 (med/coarse gravel) Behavior similar to golden trout | 10-15 | 21-28/10-15 | 20-155 | 10-150 | 15-18 | <4, 23-24 | 25-27 | Alkaline tolerant, may tolerate higher temps than other trout | Moyle 2002 |
| | Eagle Lake rainbow (O.m. *aquilarum*) | <11, usually 8-9 | Iteroparous | Spring (March-May) | 2-3 | x | | Lake habitat except to spawn, seasonal and diurnal movements within lake | Gravel riffles in streams | 10-130 (med/coarse gravel) Behavior similar to golden trout | 10-15 | 21-28/10-16 | 20-155 | 10-150 | 15-19 | 23-24 | 25-27 | Alkaline tolerant, may tolerate higher temps than other trout | Moyle 2002 |
| | Lahontan cutthroat (O. *clarki henshawi*) | <5 (streams), 5-9 (Lakes) | Iteroparous, however High post-spawning mortality rates | Spring (April-July) | 2-3 (M) 3-4 (F) | x | x | Found in terminal alkaline lakes in Humboldt/Lahontan Basins as well as oligotrophic alpine lakes and small cold streams. Tend to stay on the bottom of lakes but feed pelagically | Natal Streams, gravel riffles | 20-102 (medium gravel) Behavior similar to golden trout | 5-16 | 42-56/8-16 | 30-90 | 10-150 | <17 | 25-27 for short periods | > 27 | Alkaline tolerant (pH 8.5-9.5, spawning in small streams can occur as very low flows in the range of 0.3-0.9 $m^3$/s | Moyle 2002, USFWS 1995 |
| | Paiute cutthroat (O. *clarki seleneris*) | 3 | Likely semalparous, with very high post-spawning mortality | Spring (June-July) | 2-3 | | x | Small montane meadow streams with overhanging riparian vegetation, undercut banks, and intermittent pools | Gravel riffles in streams | 20-102 (medium gravel) Behavior similar to golden trout | 5-16 | 42-56/8-16 | 30-90 | 10-150 | <17 | 23-24 | >25 | Extremely geographically limited in distribution. Several introduced populations exist outside of historical native range | Moyle 2002, USFWS 2004 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainbow trout (O. mykiss) | 6 | Iteroparous | Spring (Feb-June) | 2-3 |  |  | Wide variety of habitats ranging from large rivers to small alpine streams and lakes | Gravel riffles in streams | 10-130 (med/coarse gravel) Behavior similar to golden trout | 10-15 | 21-28/10-15 | 20-155 | 10-150 | 15-19 | 23-24 | >25 | Ubiquitously distributed as a mixture of wild steelhead stocks, wild resident fish, and hatchery-origin stocked fish from many sources | Moyle 2002 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Cyprinid spp.** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Sacramento Pikeminnow (*Ptychocheilus grandis*) | 12-16 | Iteroparous annual spawners | April-June | 3-4 |  | x | Low to mid-elevation west side streams with deep pools, slow runs, undercut banks, overhanging riparian vegetation | Gravel riffles in streams at night | Females release eggs in water column that are fertilized by persuing males. Eggs then drop to bottom and adhere to rocks and gravel | 15-20 | 4-7/18 | Low | Likely >100 | 18-28 | 26-37 | 38 | Predatory pikeminnows have been targeted as a cause of salmonid mortality though it is argued that this is only a problem in areas where anthropogenic activities have created situations that foster such opportunities. | Moyle 2002 |
| Speckled Dace (*Rhinicthys osculus*) | 3 | Iteroparous, can spawn multiple times over the course of the summer, but is usually sexually mature for only 1-2 seasons | June-July | 2 | x | x | Wide array of habitats including small creeks, streams and springs with deep cover from vegetation, undercut banks, boulders, as well as large lakes. Prefer moving water. Generally small, shallow stream specialists (<60 cm depth) | Riffle edges, lake inlets | Shallow gravels, female deposits a few eggs at a time under a rock or on gravel | 18-19 | 6/18-19 | very low | <60 | 18-24 | 28-34 | >34 | Tolerant of temperature extremes ranging from 95% anchor ice to temps as high as 31. They often thrive in distrubed, channelized and eroded streams because they have more of the preferred shallow riffle habitat | Moyle 2002, Moyle and Baltz 1985 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hardhead (*Mylopharodon conocephalus*) | 9-10, likely more | Iteroparous | April=May | 3 | x | x | Warm streams, and slow moving rivers. Prefer deep clear pools, runs with sand/gravel/boulder substrates and slow velocities. However, they are intolerant of low desolved oxygen. | tributary streams | Undocumented, though presumed similar to hitch and Pikeminnow | 16-20 | N/A | 0-30 | 40-140 | 24-28 | >28 | >34 | Can persist in reservoirs whose levels do not fluctuate greatly and are relatively free of introduced predatory fishes | Moyle 2002 |
| Roach (*Lavinia symmetricus*) | 3-6 | Iteroparous | March-July | 2-3 | | x | Mid-elevation foothill streams ranging from cold "trout" streams to warm intermittent streams | Fine gravels or aquatic macrophyte beds. | Spawning "swarms" conspicuously splash in shallow riffles clearing silt and sand from the gravel. Fertilized eggs adhere to gravel and rocks | >16 | 2-3/16 | low | shallow | 20-30 | 30-35 | >35 | Readily hybridizes with Hitch with fertile offspring | Moyle 2002 |
| Sacramento hitch (*Lavinia exilicauda*) | 4-6, maybe longer | Iteroparous | March-July | 1-3 | x | x | Warm, low elevation lakes, and sloughs. Slow moving rivers and low-gradient streams. Deep pools with heavy cover or beds of aquatic macrophytes | | Clean fine gravel in streams or the gravel along lake shores. Large congregations of Hitch come togeter with multiple males following females that drops eggs behind her to be fertilized. Non-adhesive eggs drop into interstices and swell to ~4x their original size. | 15-22 | 3-7/15-22 | very low | shallow | 27-29 | 34-38 | 38 | Can withstand moderate salinities (7-9ppt) | Moyle 2002 |
| Lahontan redside (*Richardsonius egregius*) | 4-5 | Iteroparous, can spawn multiple times over the course of the summer, but is usually sexually mature for only 1-2 seasons | May-August | 3-4 | x | x | Lakes and streams in the Lahontan basin. In small streams prefer deep pool habitat, though occupy | downstream edge of pools, shallow riffles and rocks | Sand/gravel in the shallows (<1m depth). Large groups of spawning fish swim together of which small groups drop to the bottom where eggs and milt are released to sink into the benthos adhering to rocks and gravel | 15-20 | 6/18-19* | NA | <100 | 18-24 | NA | NA | When water drops below 10˚C in the winter months, redsides disappear from shallows, presumably moving to deeper water for the winter. Lahontan redsides readily hybridize with speckled dace and tui chubs. | Moyle 2002, Evans 1966 |

# APPENDIX C. SPATIAL DATA DEVELOPMENT FOR MEADOW INVENTORY

## Sierra Nevada Multi-source Meadow Polygons Compilation v.1

**Resource Type:**

Geospatial Data

**Format:** ESRI ArcGIS 10 File Geodatabase

**Summary:**
Compiled meadows layer for the Sierra Nevada containing 17,039 meadow polygons (total area = 77,659 hectares, 191,900 acres).

**Citation:**
Fryjoff-Hung & Viers, 2012. Sierra Nevada Multi-Source Meadow Polygons Compilation (v 1.0), Center for Watershed Sciences, UC Davis. December 2012. http://meadows.ucdavis.edu/

**Data Available for Download:**

| Attachment | Size |
|---|---|
| Sierra Nevada Multi-source Meadow Polygons Compilation v.1, (ESRI File Geodatabase)<br>http://meadows.ucdavis.edu/sites/meadows.ucdavis.edu/files/SNMMPCv1.zip | 32.38 MB |

**Brief Data Development Methods**:

We compiled the “best available” meadow polygon layers into a single data layer. Data layers were collected from various agencies, individuals, and organizations. Data layer quality varied based on compilation methods and age; some layers were excluded due to poor data quality. A confidence rank (1 = low, 10 = high) was assigned to the remaining layers which were rasterized at a 10m resolution. The layers were combined and combined raster cells with a summed rank of 2 or less were excluded. Raster cells representing open water were also excluded. A majority filter was run on the resulting remaining cells to reduce boundary heterogeneity, which replaced cell values based on the majority of the eight neighboring cells. Individual meadow polygons were created through a raster to vector conversion that treated all contiguous cells as a single part meadow feature with boundaries smoothed using the Polynomial Approximation with Exponential Kernel (PAEK) method (20 m tolerance to reduce edge complexity). Polygons with an area less than 0.4 ha (< 1 acre) were removed from the final meadow composite. Original IDs and other attributes were attached to the meadow polygons. Please see data download resource for detailed metadata.

**Ownership Summary**:

The majority of meadows in the project area are located on public lands (71%), with the USDA Forest Service managing 46% of all meadows inventoried (~ 90,000 acres).

| Land Owner | Meadow Count | Area ($km^2$) | Area (acres) | Area (hectares) | Area (% Total) |
|---|---|---|---|---|---|
| USDA Forest Service | 8384 | 357 | 88113 | 35658 | 45.92 |
| Eldorado National Forest | 1162 | 25 | 6069 | 2456 | 3.16 |
| Inyo National Forest | 1107 | 103 | 25342 | 10255 | 13.21 |
| Lake Tahoe Basin Management Unit | 299 | 11 | 2614 | 1058 | 1.36 |
| Lassen National Forest | 552 | 42 | 10435 | 4223 | 5.44 |
| Modoc National Forest | 158 | 7 | 1654 | 669 | 0.86 |
| Plumas National Forest | 351 | 16 | 3980 | 1611 | 2.07 |
| Sequoia National Forest | 509 | 23 | 5568 | 2253 | 2.90 |
| Sierra National Forest | 2592 | 64 | 15805 | 6396 | 8.24 |
| Stanislaus National Forest | 1136 | 34 | 8507 | 3443 | 4.43 |
| Tahoe National Forest | 324 | 26 | 6519 | 2638 | 3.40 |
| Toiyabe National Forest | 194 | 7 | 1621 | 656 | 0.84 |
| National Park Service | 6368 | 169 | 41738 | 16891 | 21.75 |
| Devils Postpile National Monument | 1 | 0 | 15 | 6 | 0.01 |
| Kings Canyon National Park | 2253 | 39 | 9588 | 3880 | 5.00 |
| Lassen Volcanic National Park | 202 | 5 | 1119 | 453 | 0.58 |
| Sequoia National Park | 1490 | 40 | 9898 | 4006 | 5.16 |
| Yosemite National Park | 2422 | 85 | 21118 | 8546 | 11.00 |
| Other Public | 152 | 32 | 7788 | 3152 | 4.06 |
| Private | 2135 | 220 | 54261 | 21959 | 28.28 |
| Total | 17039 | 777 | 191900 | 77659 | 100 |