Chapter 4: Effects of Climate Change on Snowpack, Glaciers, and Water Resources in the Northern Rockies Region

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Introduction

Water is critical to life, and the effects of climate change on ecosystems are mediated through changes in hydrology. Changes in how snow accumulates and melts are one of the more consistently noted climate-induced changes to water in the western United States (Barnett et al. 2005; Service 2004), and these changes affect when water will be available for forests and fish alike. Changes in summer atmospheric circulation patterns may alter the ability of summer precipitation to allow midsummer respite from seasonal drought and dampening of wildfire spread (Intergovernmental Panel on Climate Change [IPCC] 2013; see chapter 8). Fish will be affected by both lower low flows with earlier snowmelt and higher midwinter floods caused by rain-on-snow events. Declining summer water supplies will likewise challenge municipal and agricultural water supplies. All of these meaningful effects can be traced to interactions between temperature and precipitation changes projected for the future and described in chapter 3. In this chapter, we describe mechanisms of hydrologic change, and provide maps illustrating variations in effects across the Forest Service, U.S. Department of Agriculture Northern Region and the Greater Yellowstone Area, hereafter called the Northern Rockies region. We also discuss some uncertainties relevant to these effects. Climate change effects on stream temperature in the region are discussed in chapter 5.

Warming temperatures are the most certain consequence of increased CO_2 in the atmosphere. The hydrologic consequences of warmer temperatures include less snowpack and greater evaporative demand from the atmosphere. Snowpack depth, extent, and duration are expected to decrease due to a combination of less precipitation falling as snow (Pierce et al. 2008), and slightly earlier melt (Luce et al. 2014). The degree of change expected as a result of warming varies dramatically over the landscape as a function of temperature (Luce et al. 2014). Places that are warm (near the melting point of snow) are expected to be more sensitive than places where temperatures remain subfreezing throughout much of the winter despite warming (Woods 2009). In the coldest locations, snowpack may increase with increasing winter precipitation under a changing climate (Hamlet et al. 2013).

The relationship of evapotranspiration to a warming climate is more complicated (Roderick et al. 2014). Warmer air can hold more water, which means that even if the relative humidity stays constant, the vapor pressure deficit, the difference between the actual water content of the air and the water content at saturation, increases. That difference drives a water vapor gradient between leaves and the atmosphere that can draw more moisture out of the leaves. This has led many to expect greater evaporation during climate change (e.g., Cook et al. 2014; Dai 2013) using potential evapotranspiration formulations dependent on temperature, reflecting the increased "demand."

Evaporation, however, is an energy-intensive process, and there is only so much additional energy that will be available for evaporation. In addition, both the water balance and the energy balance need to be considered under future warming (Roderick et al. 2015). The observation that temperatures are warmer during drought is more generally related to the lack of water to evaporate leading to warmer temperatures than to warmer temperatures causing faster evaporation (Yin et al. 2014). Unfortunately, when potential evapotranspiration models based on air temperature (including Penman-Monteith) are applied as post-processing to general circulation model (GCM) calculations, an overestimate of increased evapotranspiration is likely because the energy balance is no longer tracked (Milly 1992; Milly and Dunne 2011). The reality is that most of the increased energy from increased longwave radiation will result in warming rather than increased evaporation (Roderick et al. 2015).

Changing precipitation is less often discussed in climate change projections because it is more uncertain (Blöschl and Montanari 2010; IPCC 2013). Nevertheless, it has a much more direct impact on hydrologic process than temperature and cannot be ignored. On average, across many GCMs, precipitation is expected to increase very slightly in the Northern Rockies. The bounds are quite large, however, ranging from on the order of +30 percent to –20 percent (see chapter 3). Unfortunately, because many hydrologic processes are sensitive to precipitation (e.g., floods, hydrologic drought, snow accumulation), this represents a profoundly large uncertainty. As a consequence, the general approach in this and other analyses is to use an ensemble average (i.e., average across many GCMs) precipitation outcome. In this report, we discuss some of the uncertainty surrounding that mean estimate to illustrate which processes or hydrologic outcomes are most uncertain and where. Not all processes are sensitive to precipitation, and uncertainty in outcomes caused by uncertainty in precipitation is not the same everywhere for a given process. Acknowledging the substantial quantitative disagreement among models in projected precipitation behavior, we now turn to discussion of the general physical mechanisms behind precipitation change, on which there is some agreement.

Two primary concepts are applied for precipitation change: dynamic and thermodynamic (Seager et al. 2010). Dynamic drivers of precipitation change include changes in global circulation patterns (e.g., the Hadley cell extent) and changes in mid-latitude eddies. Changes in teleconnection patterns, for example the North American Monsoon System (NAMS), would also fall into this category. Thermodynamic changes refer to the fact that the atmosphere can hold more water (Held and Soden 2006) according to a nonlinear Clausius-Clapeyron relationship (saturation vapor pressure vs. temperature), leading to an expectation of roughly a 7-percent increase in precipitation per 1.8 °F of temperature change. There are, however, other physical limits on the disposition of energy driving the cycling of water in the atmosphere, leading to lesser estimates on the order of 1.6 percent per 1.8 °F at the global scale, with individual grid cells being less or potentially negative, particularly over land (Roderick et al. 2014). Different approaches to scaling the thermodynamic contribution is one of the reasons for differences among models, although the dynamic process modeling differences can be great as well.

When considering the impacts of precipitation change on streamflow, the seasonality of precipitation is important. One key outcome of the thermodynamically driven changes is that when precipitation happens, it is expected to fall with greater intensity. In turn, this is expected to result in longer dry spells between events. This process can be important in determining drought duration (and consequently severity) in locations where summer precipitation is an important component of the summer water budget (Luce et al. 2016), such as much of eastern Montana, and low elevation stations in western Montana (fig. 4.1). Locations with more exposure to

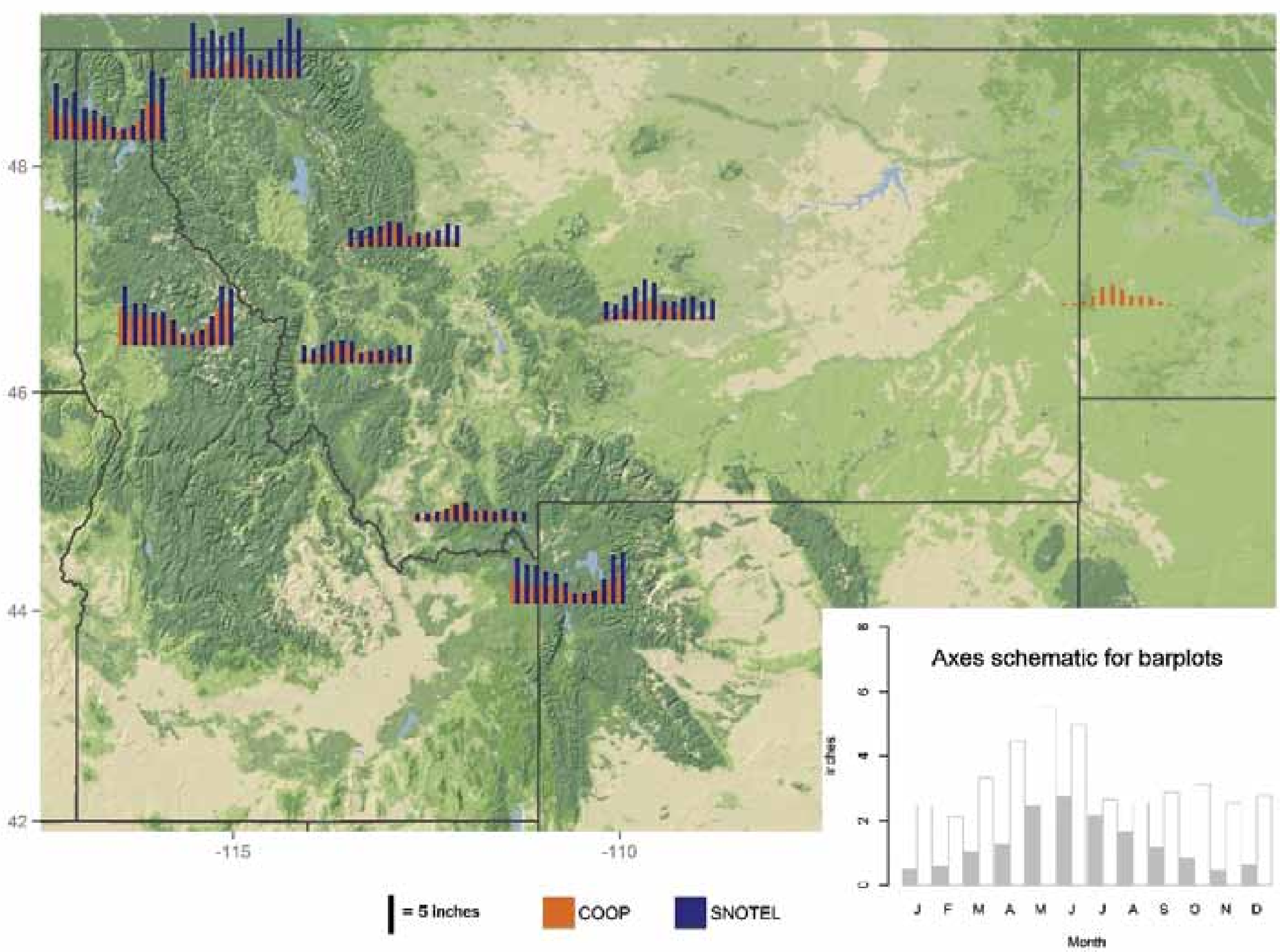

Figure 4.1—Bar graphs of annual precipitation amounts and distribution from several representative locations. More western and higher elevation sites tend to have stronger winter precipitation, with a pronounced lull in July and August. May and June precipitation is generally more pronounced than July and August precipitation and so is likely an important water source for vegetation during the summer drought.

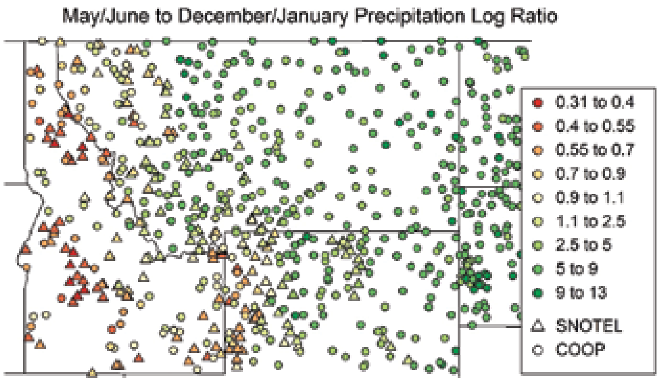

Figure 4.2—An index of precipitation seasonality in the Northern Rockies, a ratio of early summer (May–June) to winter (December–January) precipitation. Greener colors are wetter in May and June. July and August precipitation is low for most locations. Of note is the relative contribution of May through June precipitation in western Montana and central Idaho compared to mountains (SNOTEL sites) further south. There is also a notable difference in mountain versus local valley (COOP sites) seasonality.

westerly windflows (e.g., Idaho stations and the Yellowstone area), and high elevations in northern Montana, show a more pronounced winter-wet pattern, which is broadly more representative of high elevation stations than low elevation stations (figs. 4.1 and 4.2). Note that much of the region has a substantially wetter May and June than July and August, and in some cases, the May through June precipitation is on a par with or exceeds the winter snowpack contribution to the annual water budget (fig. 4.2). In these locations, the snowpack changes may have less consequence than any circulation changes driving summer precipitation, such as expected shifts in NAMS (IPCC 2013). The May through June precipitation contributions, for example, can be an important determination of the severity of summer drought and the fire season (Abatzoglou and Kolden 2013). Longer periods of precipitation deficit in summer paired with decreasing snowpack may be particularly challenging for vegetation and fishes.

Changes in orographic enhancement of precipitation over mountain areas in the Pacific Northwest is another effect within the class of dynamic effects. Historical changes in westerly windflows have led to a decrease in the enhancement of winter precipitation by orographic lifting over mountain ranges (Luce et al. 2013), raising the important question of whether such a pattern may continue into the future. Westerly winds across the Pacific Northwest are strongly correlated with precipitation in mountainous areas (fig. 4.3), but valley precipitation is not, nor is precipitation in much of eastern Montana. The historical trend in westerlies was driven by pressure and temperature changes spatially consistent with those expected under a changing climate, but were a consequence in part (~50 percent) of normal climate variability. Dynamic downscaling using a regional climate model (RCM) with small (~12.5 miles) cells provides a means to estimate orographically induced precipitation (fig. 4.4b), which cannot be simulated with the large cell size of GCMs (fig. 4.4a). Although the GCM shows general moistening over most of the area, the RCM shows a pattern of drying or no change on the upwind side of major mountain ranges, with moistening limited to valleys in the lee. Because precipitation falls mostly in mountain areas where streamflows originate, this is a potentially important aspect of future changes to consider. The variable infiltration capacity (VIC) model simulations detailed later in this chapter do not include this effect, so for purposes of general discussion, it can be lumped as an additional source of uncertainty for precipitation.

The range of potential changes in climate looks complex, particularly for such a varied landscape as the Northern

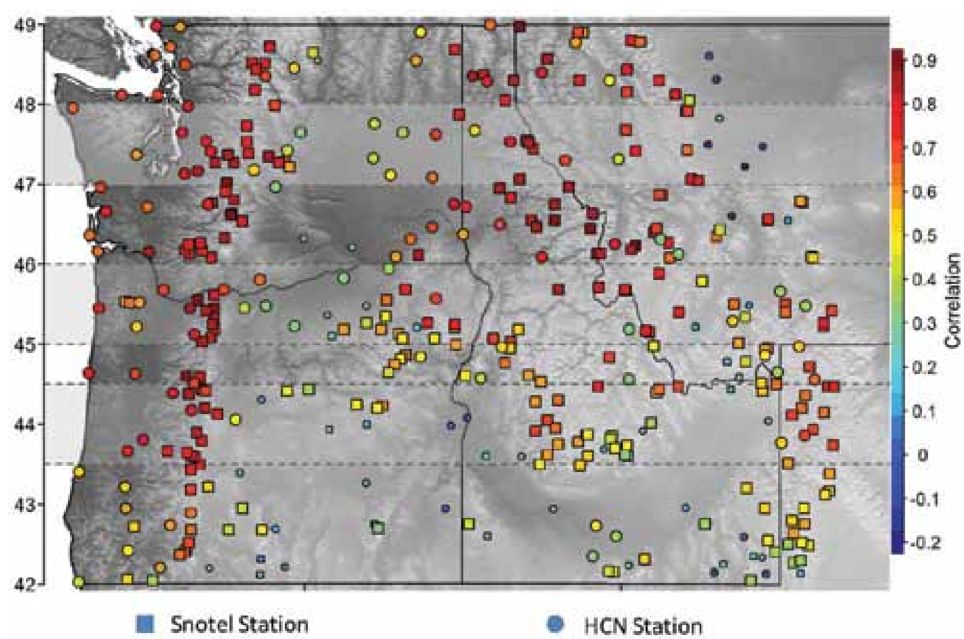

Figure 4.3—Correlation of winter precipitation to winter westerly wind speed across the Pacific Northwest (from Luce et al. 2013).

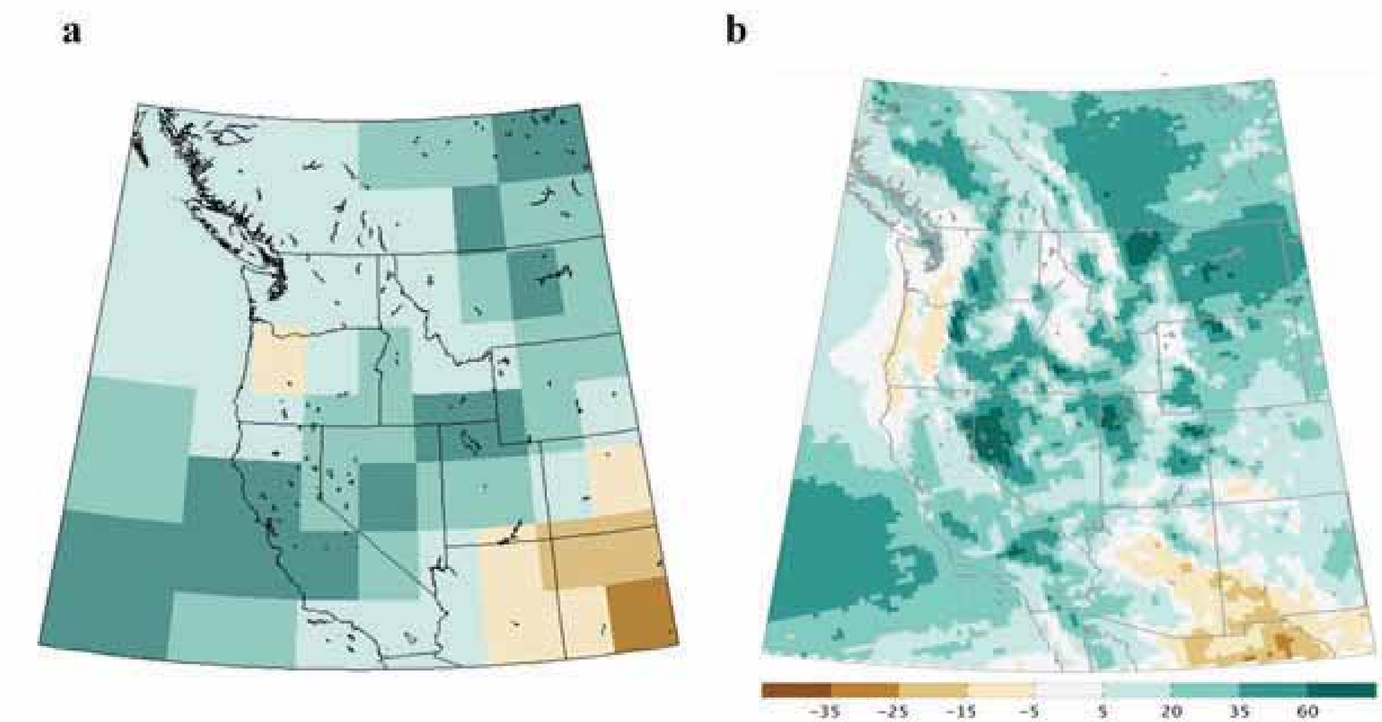

Figure 4.4—October through March precipitation change for 2041–2070 versus 1971–2000 as represented by (a) a global circulation model (CanESM2) and (b) a regional climate model with finer topographic detail.

Rockies. Perhaps the most important point to summarize from the previous discussion is that the current climatic settings vary over the landscape at both macroscales and fine scales. There are broad east-west changes in precipitation seasonality and amount, and local differences between nearby mountain and valley weather stations echo that pattern. Trends and drivers for climate variations will differ greatly from east to west. Fundamentally, topography is an important factor affecting seasonality, precipitation amount, and potential trends. Given that forests and much of the water supply generation are generally in mountain areas, it is important to recognize the role of topography in affecting the climate. Specific hydrologic outcomes of interest are changes to snowpacks and glaciers, streamflow, and drought.

Snowpack and Glaciers

Snowpack

Snowpack declines are among the most widely cited changes occurring with climate change, as warmer temperatures will reduce the fraction of precipitation falling as snow (Klos et al. 2014; Pierce et al. 2008). About 70 percent of the water supply in the western United States is tied to mountain snowpacks (Service 2004); thus, changes in snowpack are particularly relevant to municipal and agricultural water timing (Stewart et al. 2005).

Historical trends in snowpack accumulation have been negative across much of the Northern Rockies region (Mote et al. 2005; Regonda et al. 2005). Although earlier work has ascribed the changes primarily to warming temperatures, the interior parts of the Northern Rockies are cold enough to be relatively insensitive to warming and strongly sensitive to precipitation variation (Luce et al. 2014; Mote 2006). Consequently, decreased interior snowpacks are likely to be primarily a response to reduced precipitation (Luce et al. 2013). In contrast, the low elevation mountains of northern Idaho, the westernmost mountains in the region, are heavily influenced by a maritime snow climate (Armstrong and Armstrong 1987; Mock and Birkeland 2000; Roch 1949), and are still sensitive to temperature variability, particularly with respect to snow durability (Luce et al. 2014) (fig. 4.5).

Precipitation uncertainty can be substantial, but it does not translate into uncertainty in snowpack changes everywhere (fig. 4.6). An index of uncertainty can be calculated as a ratio of the effects of the likely range of precipitation values (about ±7.5 percent for one standard deviation across models) to the relatively certain temperature change (the timing is uncertain, but a change in temperature is certain as long as CO_2 concentrations continue to increase):

$$R_u = \frac{\Delta\,(+7.5\%)}{\Delta}$$

Figure 4.6 shows strong certainty of large changes in April 1 snow water equivalent for the Cascades, but substantial uncertainty in outcomes for the Greater Yellowstone

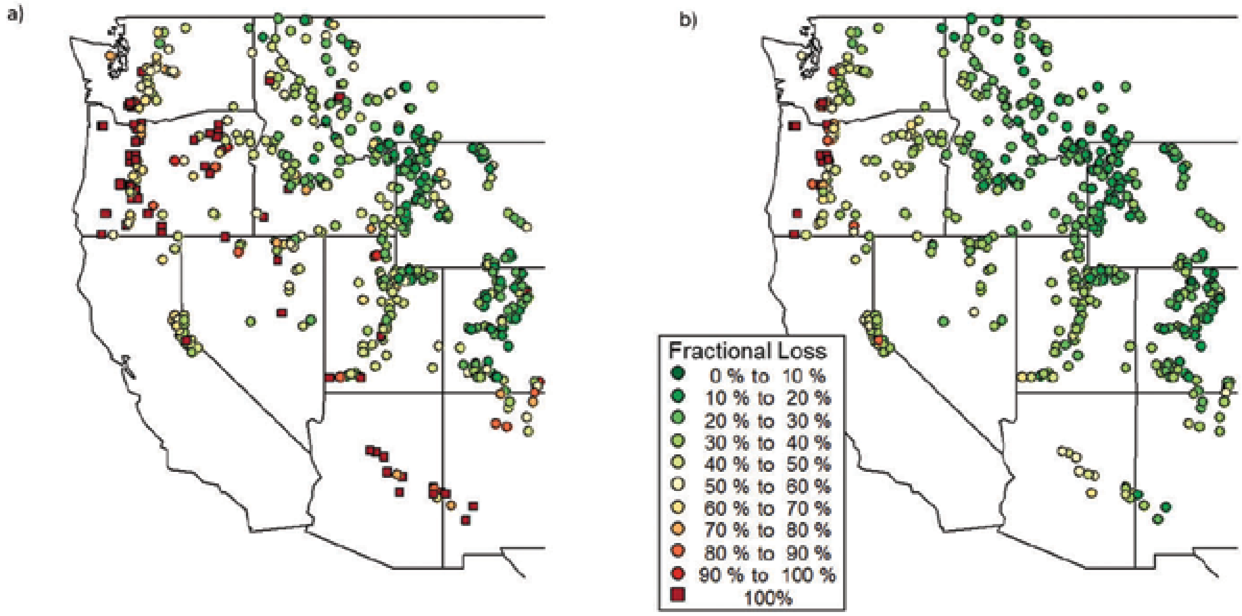

Figure 4.5—Estimated loss of (a) April 1 snow water equivalent and (b) mean snow residence time as related to warming of 5.4 °F (from Luce et al. 2014).

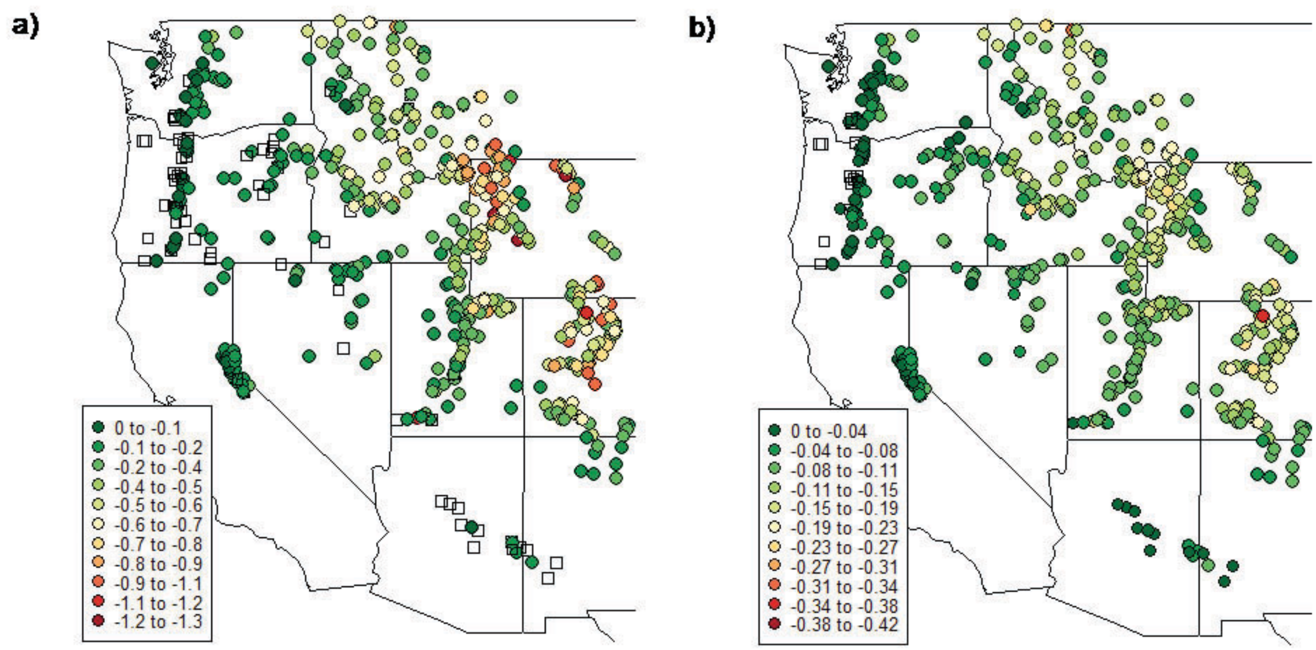

Figure 4.6—Uncertainty ratio for April 1 snow water equivalent. Orange to dark red sites are strongly influenced by precipitation in contrast to temperature. Thus, temperature-based projections in those sites may be inaccurate if precipitation changes are large. At dark green (and white) sites, temperature effects will predominate, and precipitation changes in either direction are inconsequential.

Area, where cold temperatures leave the snowpack more sensitive to precipitation than to temperature changes. The uncertainty ratio in these areas suggests that relatively large increases in precipitation could counter the effects of warming on snowpack loss.

Glaciers

Glaciers are well-known features in the Northern Rockies, with a large number located in and near Glacier National Park, on the northern edge of the region, and in the Wind River, Absaroka, and Beartooth Ranges in and near Yellowstone National Park, at the southern edge.

Figure 4.7—Oblique view of Grinnell Glacier taken from the summit of Mount Gould, Glacier National Park (after Fagre 2005).

They are also found in several other mountain ranges in Montana and Wyoming (see Portland State University [2009] for maps). Significant changes have been noted in the glaciers of Glacier National Park over the course of the 20th century (Fagre 2005), with the Grinnell Glacier having around 10 percent of the ice that it had at its peak in 1850 (fig. 4.7). Declines have also been seen in the Wind River Range over the 20th century (Marston et al. 1991).

Estimating future changes in glaciers is complex (Hall and Fagre 2003), but empirical relationships derived for the glaciers indicate a brief future for them, with many glaciers becoming fragmented or disappearing by the 2030s. Increasing temperatures yield a rising equilibrium line altitude, decreasing the effective contributing area for each glacier as warming progresses. A warming of 5.4 °F can translate into between 1,000 and 1,600 feet of elevation rise in snow-rain partitioning and summer temperatures. Unfortunately, for the sake of simplicity, those changes do not directly equate to shift in equilibrium line altitude, which depends on the geometry and topography of the contributing cirque. Temperate alpine glaciers are well known for being as, or more, sensitive to precipitation variations as they are to temperature changes (McCabe and Fountain 1995), which has probably contributed to changes in glaciers across the Pacific Northwest. Westerlies and their contribution to winter precipitation have changed over the Glacier National Park region since the 1940s (fig. 4.3) and April 1 snow water equivalent at these elevations and latitudes is relatively insensitive to temperature. However, this area receives significant spring and summer precipitation (fig. 4.1), and changing summer temperatures affect both the melt rate and additional summertime mass contributions (new snow) in these glaciers. Thus, summer temperature is a strong predictor of their behavior, and regardless of changes in precipitation, significant reduction in area of glaciers is expected by the end of the 21st century (Hall and Fagre 2003).

Streamflow

Streamflow changes of significance for aquatic species, water supply, and infrastructure include:

- Annual yield
- Summer low flows—average and extreme
- Peakflows—scouring floods
- Peakflow seasonality
- Center of runoff timing

Annual yield, summer low flows, and center of runoff timing are all important metrics with respect to water supply. Irrigation water for crops and urban landscapes is typically needed in summer months, and these metrics are most relevant to surface water supplies rather than groundwater supplies, although changes in long-term annual means could be informative for the latter. For summer low flows, two metrics are used, the mean summer yield (June through September), and the minimum weekly flow with a 10-year recurrence probability (7Q10). Center of runoff timing refers to the timing of water supply, and shifts in runoff earlier in the winter or spring disconnect streamflow timing from water supply needs. Center of timing can be redundant with other metrics that measure impact more directly, but with care in interpretation, it can help clarify different potential causal mechanisms: changing precipitation versus changing temperature.

Peakflows are important to fishes and infrastructure. Scouring flows can damage eggs in fish redds if they occur while the eggs are in the gravel or alevin are emerging (DeVries 1997; Goode et al. 2013; Montgomery et al. 1996; Tonina et al. 2008). Winter peakflows can affect fall-spawning fish: Chinook salmon (*Oncorhynchus tschawytscha*), bull trout (*Salvelinus confluentes*), and brook trout (*S. fontinalis*). Spring peakflows affect spring-spawning cutthroat trout (*O. clarkia*), steelhead (*O. mykiss*), and resident rainbow trout (*O. mykiss*) (Wenger et al. 2011a,b). Spring peakflows associated with the annual snowmelt pulse are typically muted in magnitude in comparison to winter rain-on-snow events. Scouring is less of a risk to spring-spawning fishes, whereas rain-on-snow events tend to affect much larger portions of a basin at a time. A shift to more midwinter events can yield greater peakflow magnitudes, which can threaten infrastructure such as roads, recreation sites, or water management facilities (diversions, dams).

Historical changes in some of these streamflow metrics have been examined in some of the western and southern basins in the Northern Rockies. For instance, earlier runoff timing was noted by Cayan et al. (2001) and Stewart et al. (2005), and declining annual streamflows were noted by Luce and Holden (2009) and Clark (2010). Declining low flows (7Q10) have also been seen in the western half of the Northern Rockies (Kormos et al. 2016) associated more with declining precipitation than warming temperature effects for the historical period. Projected changes in low flow and timing are generally associated with the expected changes in snowpack related to temperature (e.g., more melt or precipitation as rain in winter, yielding a longer summer dry period).

Streamflow Projections

Streamflow projections were produced from the VIC model (Liang et al. 1994) for the western United States (University of Washington, Climate Impacts Group n.d.). Climate projections are based on Coupled Model Intercomparison Project Phase 3 (CMIP3) GCM runs, the full details of which are discussed in Littell et al. (2011). Differences between the climate described by CMIP3 and CMIP5 are provided in Chapter 3. The gridded data were used to estimate streamflow by using area-weighted averages of runoff from each VIC grid cell within a given basin, following the methods of Wenger et al. (2010), to accumulate flow and validate. Streamflow metrics were calculated for stream segments in the NHD+ V2 stream segments (USDA FS n.d.).

Uncertainty in climate model inputs can be a significant factor in uncertainty for outcomes for natural resources (e.g., Wenger et al. 2013). Besides showing the projected change from the ensemble average, metrics were calculated for two additional climate scenarios; MIROC 3.2 and PCM GCMs were chosen to show warmer-drier and cooler-wetter summers than the ensemble mean, respectively (Littell et al. 2011). The difference between these two runs is shown in the second panel of the figures for each metric to give a sense of the certainty with which the change is projected in a given basin. Downscaling for these runs was done statistically, so GCM expectations for precipitation are implicit. No effects of change in orographic enhancement (e.g., fig. 4.4) are inherent in these images, so readers may wish to consider an additional degree of uncertainty (in a drier direction) on the windward side of mountain ranges.

Although calculations were made for all 6th-level hydrologic units in the Northern Rockies, only the western half of the region is shown in figures 4.8 through 4.13. Trimming the domain allows easier comparison of the uncertainty map to the ensemble mean projection, at the loss of display for eastern Montana and western North Dakota. Fortunately, the easternmost part of the maps that are shown indicate little change going east.

Mean annual flow (fig. 4.8) shows minor increases in the western and southern portions of the domain, with lesser changes across eastern Montana, whereas mean summer flow shows consistent decreases throughout the region (fig. 4.9). Higher mountains in northern Idaho and northwestern Montana show substantial uncertainty in the annual-scale water yield compared to the size of the change. Over much of the rest of the domain, the range of uncertainty is on par with the magnitude of the expected change in runoff. Changes in the ensemble mean are comparable to ensemble changes in precipitation.

Despite projections of increased annual flow, low flows are expected to decline (fig. 4.10). Uncertainty is low compared to the magnitude of changes, particularly in mountain areas. Patterns are nominally similar, with relatively uniform changes, though with somewhat more pronounced changes in mountain areas, particularly in wetter ranges. Those areas showing more pronounced change in low flows generally show a large shift in timing (on the order of 2 months; fig. 4.11), again with uncertainty mostly lower than magnitudes of change in mountain areas, and more substantial changes in mountains with greater precipitation. The primary mechanism expected to drive lower low flows is reduced snowpack in winter, leading to less stored water.

Summer wet portions of the region are more likely to have low flows affected by summer precipitation patterns. Shifts in circulation that affect how moisture flows from the Gulf of Mexico during summer months are expected to have a net negative effect on precipitation, and spacing between precipitation events is likely to increase (IPCC 2013; Luce et al. 2016). These summer wet areas are also more likely to see greater losses in precipitation with increased evaporation, but it is important to recognize the energy balance constraints when estimating the degree of loss (Roderick et al. 2014). This is not done in the VIC modeling, which uses only the temperature outputs from GCMs without reevaluating the change in energy balance from a different hydrologic formulation, which is known to potentially lead to overestimation of loss (Milly and Dunne 2011).

Changes to flood magnitude across the region are much more uncertain and spatially heterogeneous at fine scales (fig. 4.12). The second metric on flood timing shows changes in the number of days in winter that are in the top 5 percent of flows for the year (a maximum of 18.25 days on average; fig. 4.13). Bull trout are sensitive to this metric and tend to be rare when values exceed 5 percent (Wenger et al. 2011a,b). The shift to more midwinter rain and more

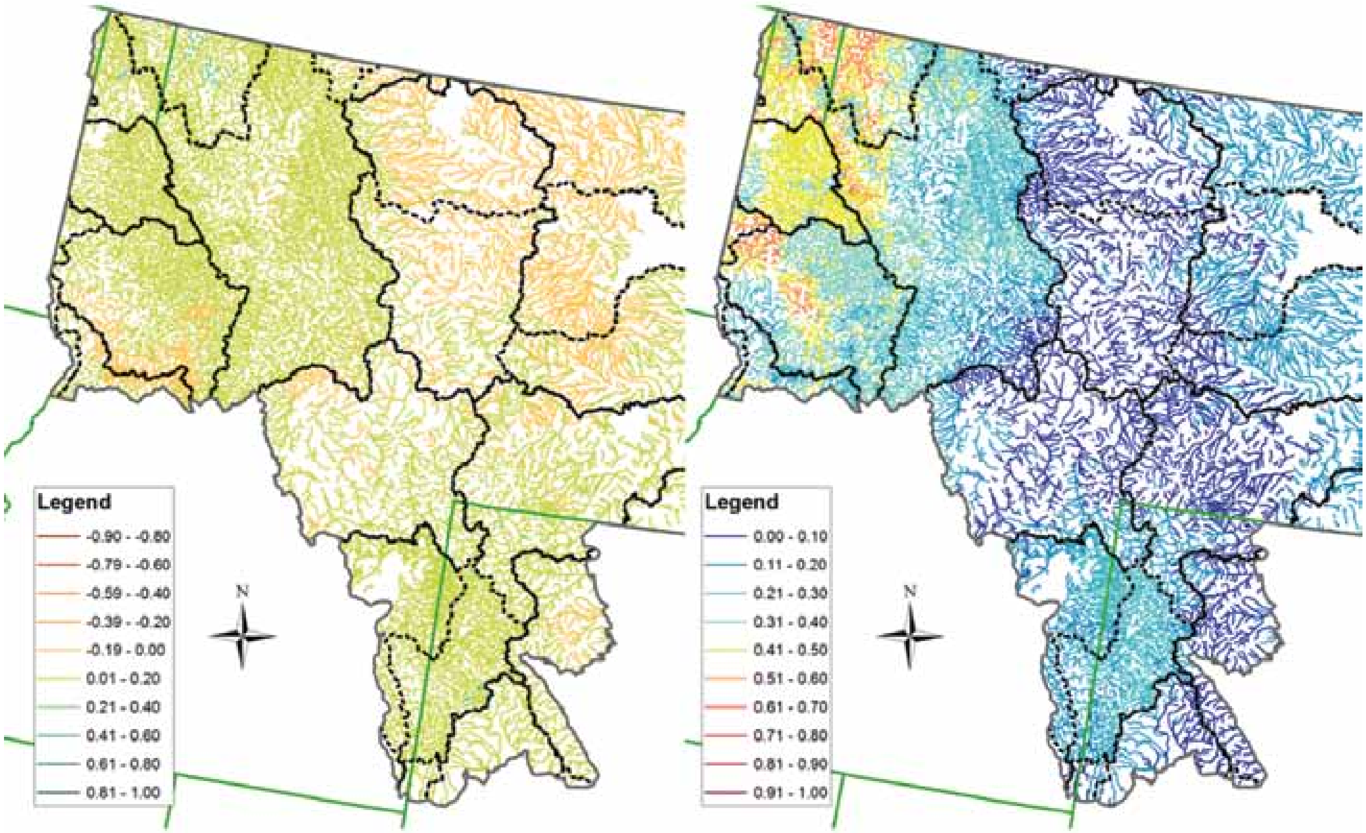

Figure 4.8—Projections for fractional change in mean annual flow for the 2080s compared to 1977–2006. The ensemble mean is on the left, and the range between two disagreeing projections is shown on the right.

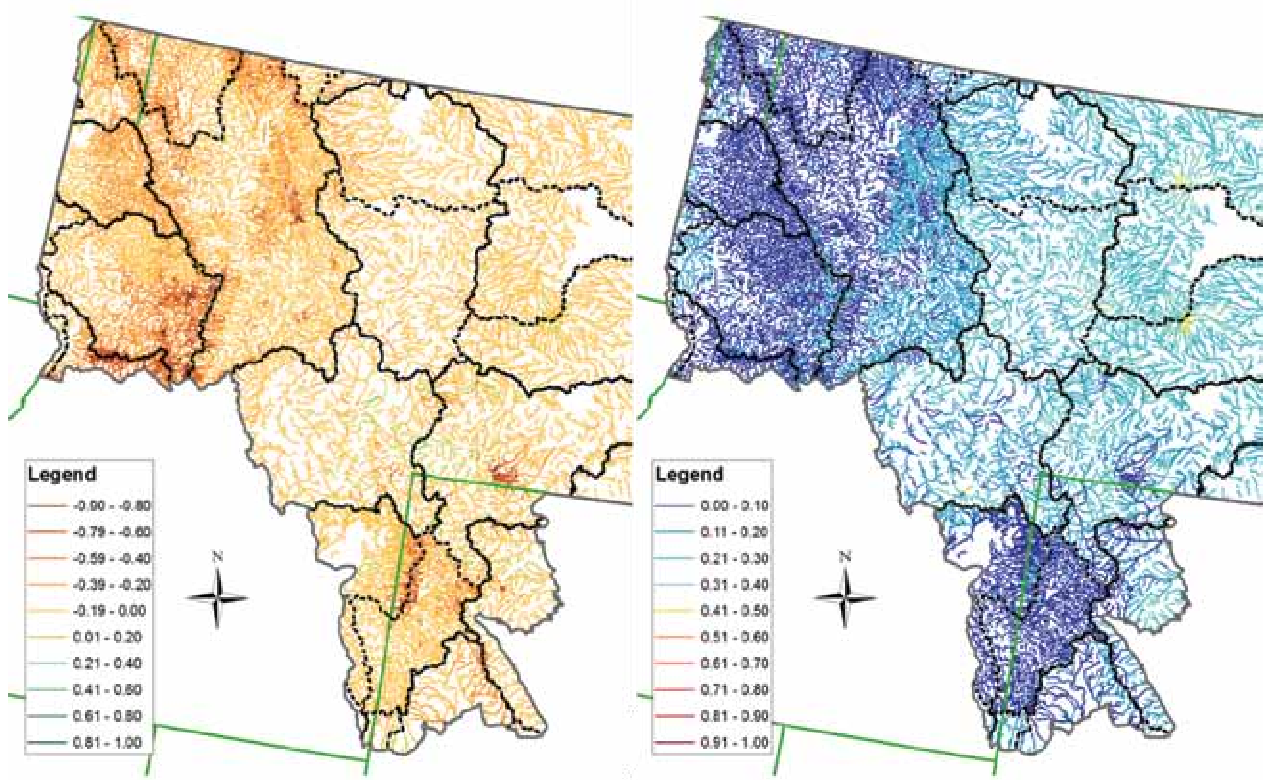

Figure 4.9—Projections for fractional change in mean summer flow (June–September) for the 2080s compared to 1977–2006. The ensemble mean is on the left, and the range between two disagreeing projections is shown on the right.

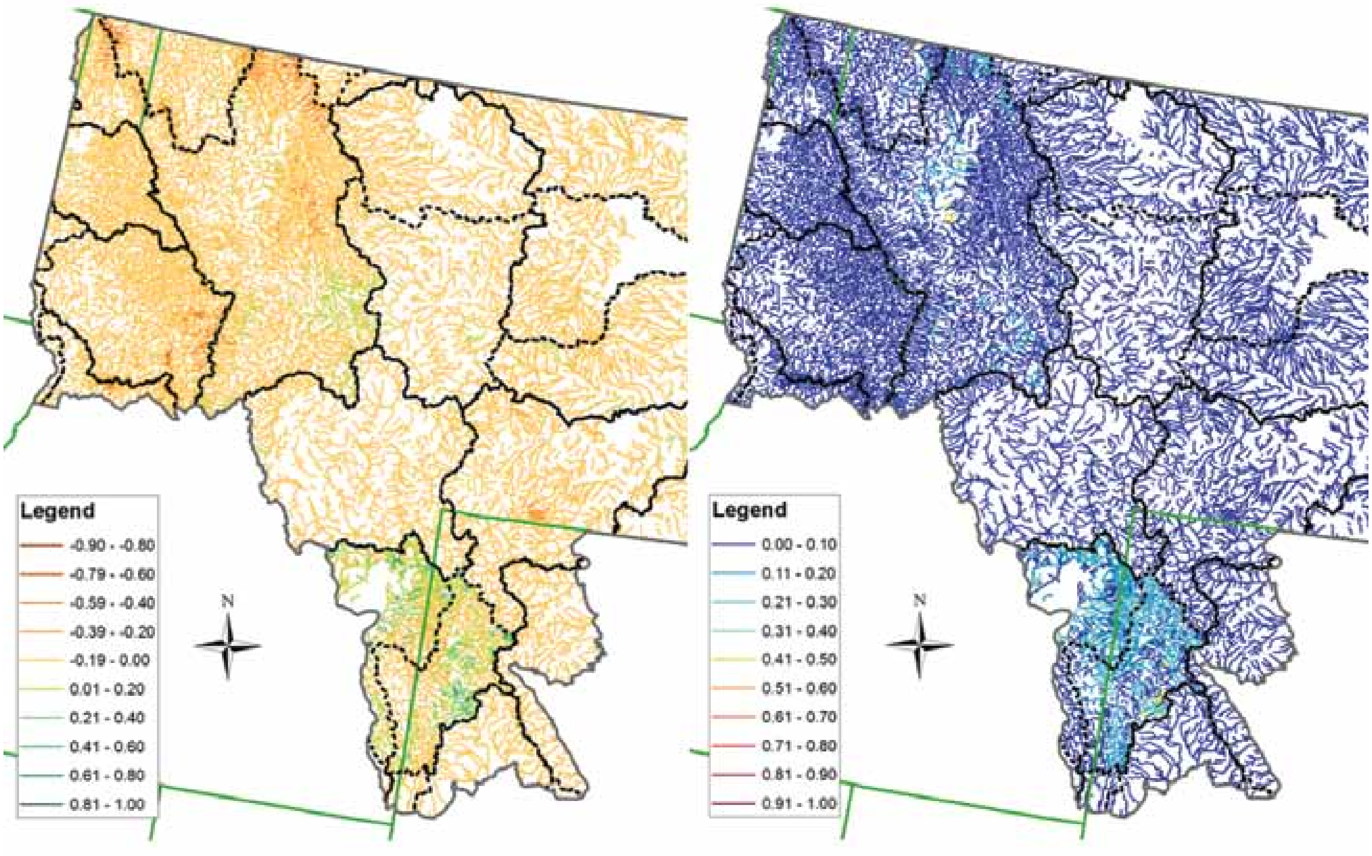

Figure 4.10—Projections for fractional change in minimum weekly flow with a 10-year return probability (7Q10) for the 2080s compared to 1977–2006. The ensemble mean is on the left, and the range between two disagreeing projections is shown on the right.

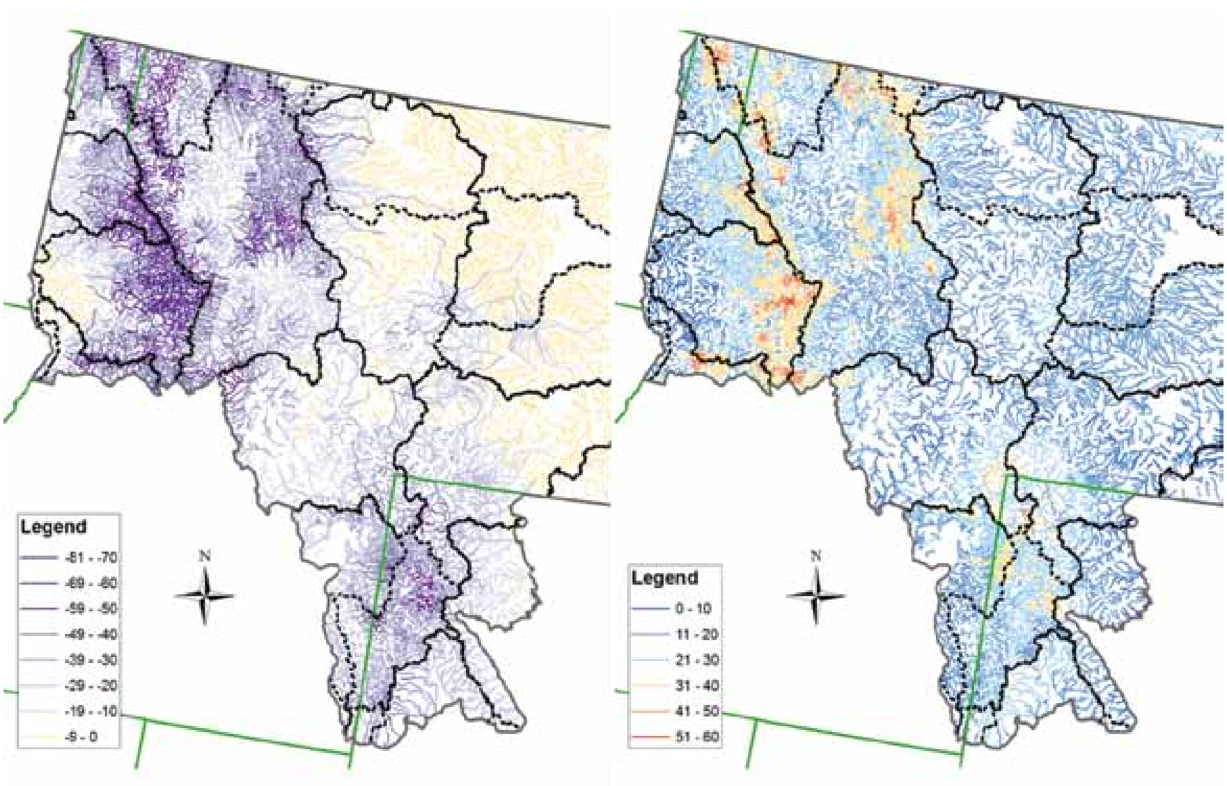

Figure 4.11—Projections for number of days of change in center of streamflow timing for the 2080s compared to 1977–2006. The ensemble mean is on the left, and the range between two disagreeing projections is shown on the right.

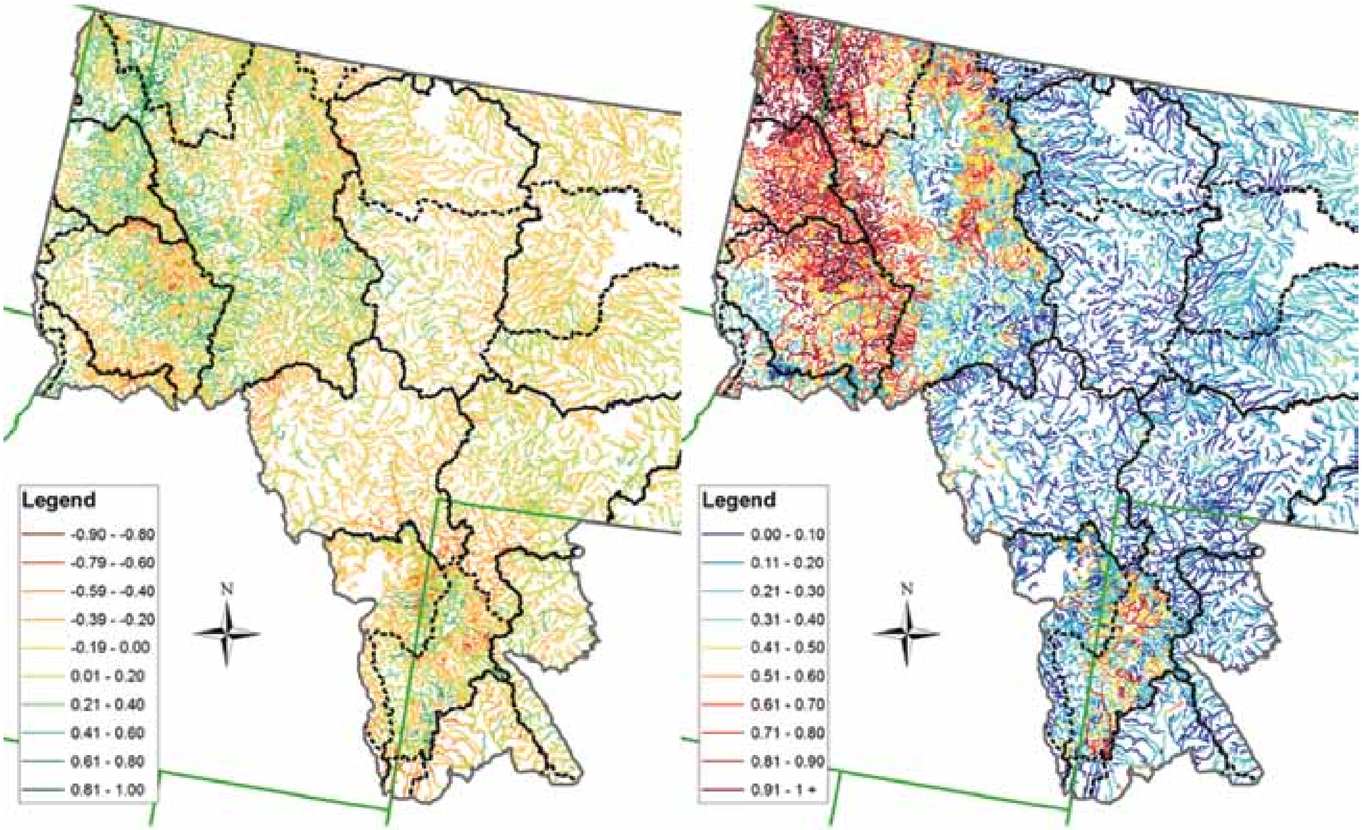

Figure 4.12—Projections for fractional change in 1.5-year flood magnitude (approximate "bankfull" flow) for the 2080s compared to 1977–2006. The ensemble mean is on the left, and the range between two disagreeing projections is shown on the right.

rain-on-snow flooding depends strongly on the elevation range of each given basin. Generally, the maps reflect large declines in flood magnitude in higher elevation basins near the crest of major mountain ranges, with large increases at mid-elevations and little change below that. This matches well with the information on number of midwinter events, which shows the greatest increases at mid-elevations and less pronounced changes at both higher and lower elevations. Although there is less snow and more rain at higher elevations, it is probably more a process of shifting shoulder seasons (Woods 2009) than more midwinter flood events, thus producing more rain or rain-on-spring snowmelt floods, which tend to be less severe (MacDonald and Hoffman 1995). With less snow accumulating, the annual snowmelt and rain events during snowmelt are likely to be smaller because less area will be snow-covered. At mid-elevations, temperatures will increase enough that rain is likely on snowpacks, even in midwinter. Uncertainty in peakflow magnitudes are generally as large as or larger than the expected magnitude of the change. There is less uncertainty in the amount of flooding occurring in midwinter.

Adapting Water Resources to Climatic Variability and Change in the Northern Rockies

With many potential changes in water resources, questions naturally arise about what we might be able to do to shift water and land management practices to reduce the impacts or consequences of a changing climate on water resources. Because the NRAP region includes diverse topography, geology, watershed configurations, and ecosystems, adaptation responses to climatic variability and change vary considerably across the region. However, several themes prevail across most of the region in response to dominant sensitivities to climate change (table 4.1). Many of these strategies and tactics may do little to alleviate some of the more direct consequences of shifting precipitation, snowpack timing, and temperature changes to forests during drought conditions (e.g.,Vose et al. 2016); they are largely directed toward affecting downstream water availability and consequences of drought.

Of greatest concern is reducing the vulnerability of roads and infrastructure to flooding, a phenomenon that is expected to increase considerably as snowpack declines and snow:rain ratios decrease. National forests in particular

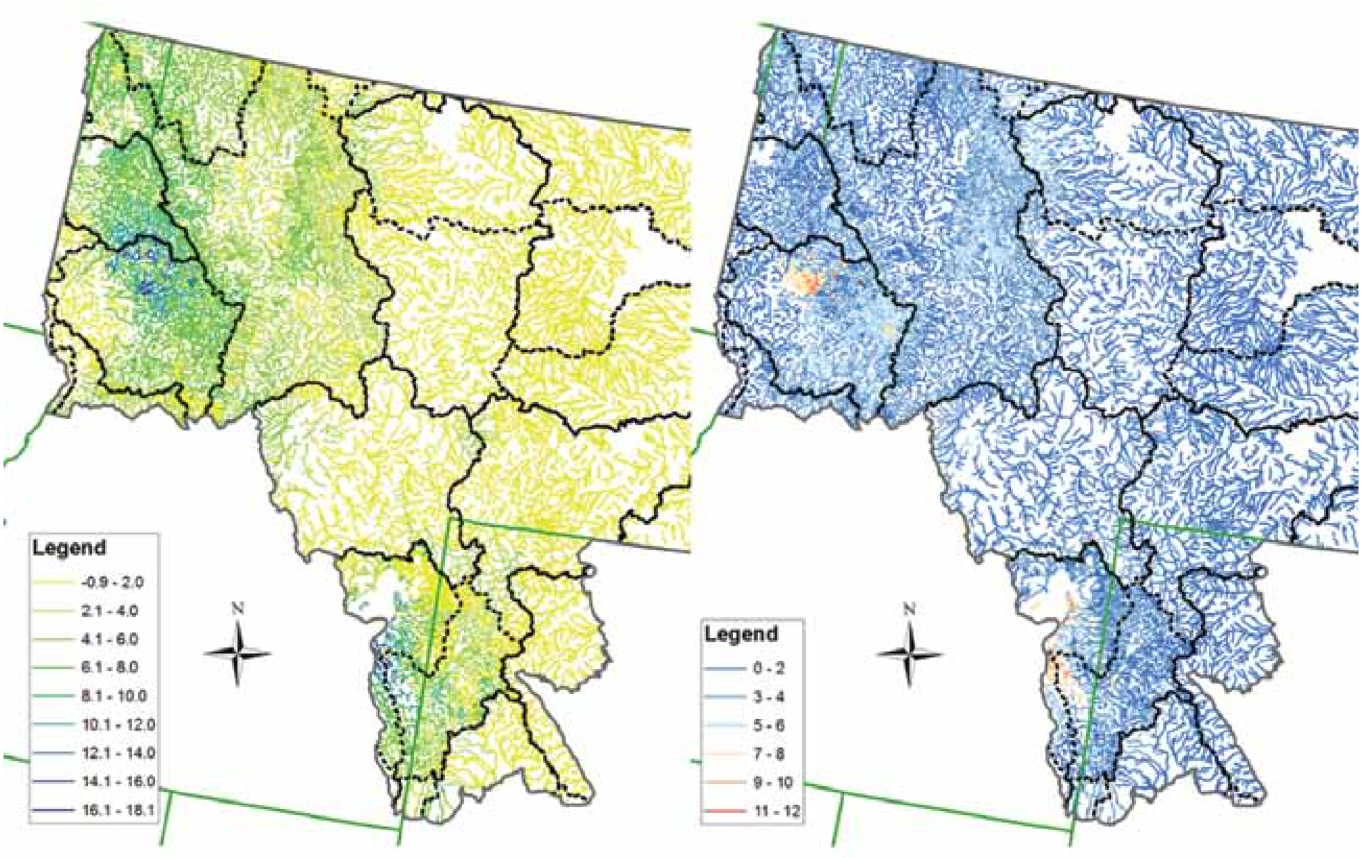

Figure 4.13—Projections for number of days in winter that exceed the 95th percentile flow in each year, an indicator of when floods are likely to happen, for the 2080s compared to 1977–2006. The value of this metric can take on values between 0 and 18.25, and the difference can take on the same range. The ensemble mean is on the, and while the range between two disagreeing projections is shown on the right.

contain thousands of miles of roads, mostly unpaved. Damage to those roads and associated drainage systems reduces access by users and is extremely expensive to repair. Road damage often has direct and deleterious effects on aquatic habitats as well, particularly when roads are adjacent to streams. Resilience to higher peakflows and frequency of flooding can be increased by maintaining the capability of floodplains and riparian areas to retain water, conducting a risk assessment of vulnerable roads and infrastructure, and modifying infrastructure where possible (e.g., increasing culvert size, improving road drainage, relocating vulnerable campgrounds or road segments).

Climate-induced occurrence of disturbances such as drought and flooding are expected to increase, thus reducing water quality. Building an information base on potential locations of and responses to disturbances will help ensure informed and timely decisionmaking when disturbances occur. Within this overall strategy, tactics include prioritizing data collection based on projections of future drought, collecting pre-disturbance data on water resources, and developing a clearinghouse for programs related to fire and other disturbance. All tactics are focused on Federal lands (table 4.1).

In contrast to the effects of winter peakflows, reduced overall base flows (especially in summer) are expected to reduce riparian habitat, water storage, and shallow aquifers. The primary adaptation strategies in this case are to increase natural storage and build storage where appropriate, as well as increase knowledge about groundwater. Specific tactics focus on (1) increasing storage with constructed wetlands, American beavers (*Castor canadensis*), and obliterated roads; and (2) considering small-scale storage in dams, retention ponds, and swales, where appropriate. In addition, it will be important to map aquifers and alluvial deposits, improve monitoring to provide feedback on water dynamics, and understand the physical and legal availability of water for aquifer recharge.

Public lands are a critical source of municipal water supplies, for which both quantity and quality are expected to decrease as snowpack declines. A critical adaptation strategy is to reduce erosion potential to protect water quality, as well as prioritize municipal water supplies. Water quality can be addressed by: (1) reducing hazardous fuels in dry forests to reduce the risk of crown fires, (2) reducing other types of disturbances (e.g., off-road vehicles, unregulated livestock grazing), and (3) using road management practices that reduce erosion. These tactics should be implemented primarily in high-value locations (near communities and reservoirs) on public and private lands.

Table 4.1—Adaptation options that address climate change effects on water resources in the Northern Rockies.

Sensitivity to climatic variability and change: Increased flooding will increase damage to roads and infrastructure.			
Adaptation strategy/approach: Identify and proactively decrease vulnerability of infrastructure to flooding.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Increase resilience of stream resources by identifying and restoring degraded riparian areas to reduce flooding and increase natural storage; add large woody debris, improve floodplain connectivity, increase riparian roughness, restore beavers.	Conduct a basin-wide risk assessment of hydrologic interactions with roads and other infrastructure where vulnerability of infrastructure is highest.	Increase resilience of infrastructure: culvert sizing, hardened fords, road drainage, etc.; remove or relocate infrastructure (e.g., roads, campgrounds).
Where can tactics be applied?	All lands	Federal and private lands	Mostly Federal lands
Sensitivity to climatic variability and change: Increased occurrence of disturbances such as drought and flooding will reduce water quality.			
Adaptation strategy/approach: Build an information base for a timely response to disturbance, thus ensuring that data are available to inform decisionmaking.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Prioritize data collection based on projections of future drought.	Collect pre-disturbance data on stream and riparian conditions, including high-quality values and habitat in need of protection.	Develop a clearinghouse for available funding and programs related to fire and other disturbances.
Where can tactics be applied?	Mostly Federal lands	Mostly Federal lands	Mostly Federal lands
Sensitivity to climatic variability and change: Reduced base flows will cause smaller riparian habitats and morphological changes, affecting groundwater, storage, and shallow alluvial aquifers.			
Adaptation strategy/approach: Increase knowledge about the groundwater resource.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Map aquifers and alluvial deposits	Determine legal availability and better understanding of physical availability of water for aquifer recharge.	Improve monitoring of streamflow and groundwater to improve understanding of surface water-groundwater interactions; obtain real-time data.
Where can tactics be applied?	All lands	All lands	All lands

Table 4.1 (cont.)—Adaptation options that address climate change effects on water resources in the Northern Rockies.

Sensitivity to climatic variability and change: Reduced base flows will cause smaller riparian habitats and morphological changes, affecting groundwater, storage, and shallow alluvial aquifers.			
Adaptation strategy Approach: Increase natural storage and build storage.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Increase natural water storage (mirroring natural processes) with constructed wetlands, beavers, and road obliteration.	Promote distributed small-scale water storage in small dams, retention ponds, and swales in stream channels and uplands.	Improve streamflow and groundwater monitoring to improve understanding of surface water-groundwater interactions and obtain real-time data.
Where can tactics be applied?	Multiple land ownerships	Agricultural lands, headwaters without native fish species	All lands
Sensitivity to climatic variability and change: Reduced snowpack will reduce the quantity and quality of municipal water supplies.			
Adaptation strategy/approach: Reduce erosion potential to protect municipal water supplies; prioritize municipal systems for protection.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Reduce hazardous fuels.	Reduce disturbances (off-road vehicles, grazing, etc.).	Use road management practices that reduce erosion.
Where can tactics be applied?	High-value locations	High value-locations on public and private lands	High value locations on public lands
Sensitivity to climatic variability and change: Higher temperatures and decreased snowpack will reduce water availability.			
Adaptation strategy/approach: Reduce water use and increase efficiency, demonstrate leadership in water efficiency, and create outreach opportunities.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Communicate water saving tactics and benefits.	Research successful water saving tactics and apply tactics where appropriate.	Install low-flow appliances at administrative sites; replace landscaping with drought tolerant plants.
Where can tactics be applied?	All lands, where appropriate	All lands, including administrative locations (campgrounds, visitor centers, etc.)	All lands, including administrative locations (campgrounds, visitor centers, etc.); use Internet, press releases, interpretive sign, etc.

Harvesting trees to increase water yield has been a practice of interest for some time (e.g., Bates and Henry 1928). Trees use water, so it is not surprising that water yields generally increase after canopy loss (Brown et al. 2005; Jones and Post 2004; Troendle and King 1987; Troendle et al. 2010). There are, however, certain caveats to be considered. For example, increases in water yield are generally greater in moister environments or years, with less increase in drier locations or years (e.g., Brown et al. 2005), and in some circumstances in drier climates, decreased yields may be seen (Adams et al. 2011; Guardiola-Claramonte et al. 2011). In broad terms, the general places and times one would want to see increases in water yield are the places and times when forest harvest is least effective (Troendle et al. 2010; Vose et al. 2012). Furthermore, thinning has proven to be ineffective in increasing water yield (Lesch and Scott 1997; Wilm and Dunford 1948). But it can be useful in augmenting snow accumulation depths, for example for wildlife or recreation benefit (Sankey et al. 2015; Wilm 1944).

Consequences of canopy removal for streamflow augmentation are likewise not all positive. A negative effect of canopy reduction treatments is that they advance the timing of runoff (Luce et al. 2012). An example of large-scale canopy loss in an area with similar vegetation and climate is the Boise River Basin, where about 45 percent of one basin burned while the other was left relatively unchanged after 46 years of calibration. Water yield from the 494,211-acre basin increased 5 percent, providing an average of an additional 50,000 acre-feet each year. However, the average timing of release advanced by 2 weeks because the exposed snowpack melted faster, and most of the additional runoff was available before April, when it would be of little use in bolstering low flows. In warmer regions of the Northern Rockies, such large-scale canopy removal could increase the magnitude of midwinter rain-on-snow floods (Marks et al. 1998; Tonina et al. 2008). There are also water quality consequences to large-scale canopy treatments, such as warming stream temperatures (Isaak et al. 2010) or sediment from increased road construction and use (Black et al. 2012; Luce and Black 1999).

Conceptually, replacing snowpack storage with storage in constructed reservoirs to carry over water from the winter wet season into the summer could be beneficial to irrigators in regions with significant irrigated agriculture. But the degree of potential benefit varies substantially with context of existing water right regulations, reservoir operating rules, snowpack sensitivity to temperature and precipitation, expectations for future precipitation, and the role and future of summer precipitation. The benefits of replacing snowpack storage with reservoir storage are somewhat built around the notion that the only factor changing is timing and that total volumes are unchanged. If, for instance, precipitation rises, temperature-induced changes could be compensated for in relatively cold regions (Luce et al. 2014), such as those found across most of the Northern Rockies. If, on the other hand, precipitation declines, total flow volume will be reduced, and it will be harder to fill reservoir storage because of other rights for water farther downstream that might not be fulfilled. Ironically, this would be most difficult in dry years when the timing would be most strongly shifted because of the effect of snow water equivalence on duration of the melt period (Luce and Holden 2009). Given the large expenses, both financial and ecological, of dam construction, and the considerable uncertainties about precipitation, it would be worthwhile to perform a detailed economic and ecological analysis before dam construction is seriously considered.

Shifting dam operation is another possibility, which would cost significantly less, but still requires some infrastructure investment in monitoring upstream snowpack, soil, and weather. Streamflow forecasting allows more informed management of the tension between water storage for irrigation and maintaining empty reservoirs to buffer potential flooding (e.g., Wood and Lettenmaier 2006). Information on current state of the snowpack is a great boon to runoff forecasting in basins with substantial snowmelt contributions (Wood et al. 2015), even more so than climate and weather forecasting. Under such circumstances, it is reasonable to taper reservoir filling in such a way as to bring the reservoir to operational levels without undue flood risks; later in the season, snowpack area is substantially reduced and rain-on-snow during the spring is generally less severe (or variable) than midwinter events, when snowpack coverage over the basin is greater (MacDonald and Hoffman 1995). Predictability is declining in some regions as we lose snowpack, but the Northern Rockies region will still retain significant snowpack, making improved forecasting through investment in instrumentation a viable alternative. Note that besides informing reservoir operation, improved forecasting can be used to better determine downstream financial investments in crops and community choices in how to invest water (Broad et al. 2007).

A final strategy for addressing water availability is to reduce water use by increasing efficiency, an important connection between the source of water on public lands and use of water downstream on public and private lands. First, it will be helpful to identify effective water-saving tactics and where they can be successfully implemented. Second, low water-use appliances can be installed at administrative sites (e.g., restrooms), and drought-tolerant plants can be used for landscaping (e.g., adjacent to management unit buildings). Third, the benefit of water conservation can be communicated to users of public lands (e.g., in campgrounds). These tactics demonstrate leadership in water conservation as an agency, providing outreach and public relations that extend to local communities.

More-specific details on adaptation strategies and tactics that address climate change effects on water resources in each NRAP subregion are in Appendix 4A.

Conclusions

Changes in climate over the Northern Rockies are likely to have substantial impacts on hydrology. A primary change will be shifts in snowpack storage, although other changes in precipitation and atmospheric circulation could have significant consequences for forests, grasslands, streams, fishes, and agriculture in the region. Information is still the best tool for adaptation to a changing climate, and summaries provided here give a sense of both the general expectation for change as well as uncertainties that need to be considered in adaptation planning.

A range of adaptation options exists for the future of water resources, and although there is a bias in human nature toward taking action, information may yet be one of our better choices for future adaptation to an uncertain and varying climate. If we continue to invest in monitoring to track changing climate and outcomes, we can be better prepared, as what are now challenges of the future become current challenges. Armed with better knowledge of how shifting temperatures and circulation have played out on our landscapes, snowpacks, and streams, we can make better decisions.

This effort illustrated that adapting to climate change does not necessarily entail management actions drastically different from those that are currently implemented. Many of the current Federal agency management actions to improve and restore watersheds and riparian areas are consistent with the adaptation strategies and tactics identified here, as fully functional watersheds and riparian areas are more resilient to change. Thus, in many cases, adaptation to climate change involves increasing restoration activities and reprioritizing actions, and agencies are well prepared for these types of shifts in management.

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Appendix 4A—Adaptation Options for Water Resources in the Northern Rockies.

The following tables describe climate change sensitivities and adaptation strategies and tactics for water resources, developed in a series of workshops as a part of the Northern Rockies Adaptation Partnership. Tables are organized by subregion within the Northern Rockies. See Chapter 4 for summary tables and discussion of adaptation options for water resources.

Table 4A.1—Adaptation options that address climate change effects on water resources in the Central Rockies subregion.

Sensitivity to climatic variability and change: Increased flooding will increase damage to roads and infrastructure.

Adaptation strategy/approach: Identify and proactively decrease vulnerability of infrastructure to flooding.

Strategy objective: Increase resilience.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Identify and restore degraded riparian areas in order to reduce flooding and increase natural storage. Reduce the amount of infrastructure in the floodplain.	Conduct a basin-wide risk assessment of hydrologic interactions with roads and other infrastructure where vulnerability of infrastructure is highest.	Educate private landowners, county managers, and recreational users to increase knowledge on benefits of riparian vegetation, water storage, and effects of floodplain development.
Tactic effectiveness (risks)	High	High	Moderate
Implementation urgency	Near term and ongoing	Near term	Near term and ongoing
Where can tactics be applied? (geographic)	All lands	Federal and private lands	Partnerships with State agencies, county and municipal governments, and private property owners
Opportunities for implementation	Partnerships with other Federal and State agencies, and county and municipal governments	Partnerships with other Federal and State agencies, and county and municipal governments	Partnerships with other Federal and State agencies, and county and municipal governments
Cost	Moderate	Inexpensive, mostly employee time required	Low
Barriers to implementation	Property rights issues	Social resistance to change (e.g., property rights)	Social resistance to change (e.g., property rights)

Table 4A.2—Adaptation options that address climate change effects on water resources in the Central Rockies subregion.

Sensitivity to climatic variability and change: Reduced base flows will shrink riparian habitats and alter morphology, affecting groundwater, storage, and shallow alluvial aquifers.			
Adaptation strategy/approach: Increase natural storage and built storage.			
Strategy objective: Increase resilience.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Increase natural water storage (mirroring natural processes) with constructed wetlands, beavers, and road obliteration.	Promote distributed small-scale water storage, using small dams, retention ponds, and swales in stream channels and uplands.	Use groundwater injection wells and sills to retain water upstream in alluvial deposits (and retain higher water table).
Tactic effectiveness (risks)	Highly effective at small scales	Dams – high Swales – low to unknown	Variable
Implementation urgency	Near term	Mid term to long term	Near term to long term
Where can tactics be applied? (geographic)	Multiple land ownerships	Agricultural lands, headwaters without native fish species	Injection wells, large aquifers, sills
Opportunities for implementation	Collaboration with other land management activities (timber sales, road decommissioning)	Collaboration with Bureau of Reclamation and NGOs, combined with hydropower projects	Areas near high-value water supplies
Cost	Moderate to high	High	High
Barriers to implementation	Lack of available sites, plans for future land use, social acceptance	For dams—significant environmental effects, safety risks, cost, access	Lack of available sites

Table 4A.3—Adaptation options that address climate change effects on water resources in the Central Rockies subregion.

Sensitivity to climatic variability and change: Reduced base flows will shrink riparian habitats and alter morphology, affecting groundwater, storage, and shallow alluvial aquifers.			
Adaptation strategy/approach: Increase knowledge about the groundwater resource.			
Strategy objective: Increase knowledge.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Map aquifers and alluvial deposits.	Determine legal availability and better understanding of physical availability of water for aquifer recharge.	Improve monitoring of streamflow and groundwater to improve understanding of surface water-groundwater interactions; obtain real-time data.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Near term—information needed for both water and fisheries	Near term—information needed for both water and fisheries	Near term—information needed for both water and fisheries
Where can tactics be applied? (geographic)	All lands and locations	All lands and locations	All lands and locations
Opportunities for implementation	Collaboration with USFS Rocky Mountain Research Station	Collaboration with state of Montana Water Court and Dept. of Natural Resources and Conservation	Collaboration with USGS; state and research partnerships
Cost	Low to moderate	Moderate	High
Barriers to implementation	Availability of staff and funding	Availability of staff and funding	Availability of staff and funding

Table 4A.4—Adaptation options that address climate change effects on water resources in the Central Rockies subregion.

Sensitivity to climatic variability and change: Reduced base flows will shrink riparian habitats and alter morphology, affecting groundwater, storage, and shallow alluvial aquifers.

Adaptation strategy/approach: Reduce evaporation and transpiration losses.

Strategy objective: Increase resilience.

	Specific tactic – A	Specific tactic – B
Tactic	Evaluate how increasing western larch cover would decrease evapotranspiration.	Selectively use forest harvest (patch clearcuts) to increase water yield.
Tactic effectiveness (risks)	Unknown	Low
Implementation urgency	Near term	Long term
Where can tactics be applied? (geographic	Areas where western larch is currently present	Areas with moderate to high precipitation
Opportunities for implementation	Projects where western larch is planted	Minimal opportunities
Cost	Moderate for study	Moderate for treatment, high for maintenance
Barriers to implementation	Cost	Environmental consequences (loss of forested habitat, more edge, less interior species, more roads); political and social acceptance

Table 4A.5—Adaptation options that address climate change effects on water resources in the Central Rockies subregion.

Sensitivity to climatic variability and change: Reduced snowpack will reduce the quantity and quality of municipal water supplies.		
Adaptation strategy/approach: Reduce erosion potential to protect municipal water supplies; prioritize municipal systems for protection.		
Strategy objective: Increase resilience.		
	Specific tactic – A	**Specific tactic – B**
Tactic	Evaluate how increasing western larch cover would decrease evapotranspiration.	Selectively use forest harvest (patch clearcuts) to increase water yield.
Tactic effectiveness (risks)	Unknown	Low
Implementation urgency	Near term	Long term
Where can tactics be applied? (geographic)	Areas where western larch is currently present	Areas with moderate to high precipitation
Opportunities for implementation	Projects where western larch is planted	Minimal opportunities
Cost	Moderate for study	Moderate for treatment, high for maintenance
Barriers to implementation	Cost	Environmental consequences (loss of forested habitat, more edge, less interior species, more roads); political and social acceptance

Table 4A.6—Adaptation options that address climate change effects on water resources in the Central Rockies subregion.

Sensitivity to climatic variability and change: Increased occurrence of disturbances such as drought and flooding will reduce water quality.			
Adaptation strategy/approach: Build an information base for a timely response to disturbance, thus ensuring that data are available to inform decision making.			
Strategy objective: Increase knowledge.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Prioritize data collection based on projections of future drought.	Collect pre-disturbance data on stream and riparian conditions, including high-quality values and habitat in need of protection.	Develop a clearinghouse for available funding and programs related to fire and other disturbances.
Tactic effectiveness (risks)	Moderate	High	Moderate
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Mostly Federal lands	Mostly Federal lands	Mostly Federal lands
Opportunities for implementation	NEPA, USFWS	NEPA, ESA, USFWS	Emergency Relief for Federally Owned Roads; BAER implementation; NRCS, Federal Highway Administration
Cost	Low	Low	Low
Barriers to implementation	Agency culture, staffing, budget	Agency culture, staffing, budget	Agency requirements and time to manage clearinghouse

Table 4A.7—Adaptation options that address climate change effects on water resources in the Eastern Rockies subregion.

Sensitivity to climatic variability and change: Large riverine systems are susceptible to a change in timing and quantity of peak flows as well as lower low flows associated with warming temperatures. Lower low flows and flashier flow regimes could lead to bank instability due to loss of vegetation. Changes in precipitation and/or temperature may reduce base flows.

Adaptation strategy/approach: Determine how climate change will alter lakes and reservoirs.

Strategy objective: Increase resilience; reduce stressors.

	Specific tactic – A	Specific tactic – B	Specific tactic – C
Tactic	Optimize grazing management practices to enhance riparian health and stream channel stability, soil water holding capacity, and shallow groundwater storage.	Promote beaver recolonization and maintenance of beavers where appropriate.	Promote cottonwood, willow, and aspen to improve riparian health and support beaver recolonization.
Tactic effectiveness (risks)	High for riparian health and baseflows	High	Moderate
Implementation urgency	Near term—information needed for water, fisheries, and amphibians	Near term—information needed for water, fisheries, and amphibians	Near term—information needed for water, fisheries, and amphibians
Where can tactics be applied? (geographic)	Forest wide, especially priority watersheds and allotments	Where appropriate, based on local knowledge and inventory and monitoring data	Where appropriate, based on local knowledge and inventory and monitoring data
Opportunities for implementation	Collaboration with private partners, local ranchers, permittees, non-governmental organizations (NGOs), and Montana Fish, Wildlife and Parks; Clean Water Act, Endangered Species Act, grass banking	Collaboration with private partners, local ranchers, permittees, NGOs, and Montana Fish, Wildlife and Parks; Clean Water Act, Endangered Species Act, grass banking	Collaboration with USFS wildlife program, NGOs, and Montana Fish, Wildlife and Parks
Cost	Inexpensive	Inexpensive	Moderate
Barriers to implementation	Political and social opposition, concern about offsite water use; education and perhaps incentives needed	Social opposition; need education and identification of appropriate locations	Funding, staff availability, competing priorities

Table 4A.8—Adaptation options that address climate change effects on water resources in the Grassland subregion.

Sensitivity to climatic variability and change: Decreased snowpack will lead to increased frequency of high peak flows.

Adaptation strategy/approach: Maintain hydrological and ecological function of watersheds.

Strategy objective: Promote resilience, reduce stressors, engage coordination

	Specific tactic – A	Specific tactic – B	Specific tactic – C
Tactic	Implement 17 Indicators of rangeland health, and maintain or restore forest vegetation resilience.	Promote/maintain proper functioning condition of riparian areas and wetlands, including: ensure adequate grazing regimes, adequate riparian buffers, beaver colonization, and restoration of riparian vegetation.	Maintain/improve streamflow continuity by optimizing hydrologic connectivity, including: reduce sediment loading, properly design in-channel infrastructure, ensure adequate culvert size, promote beaver colonization, and procure in-stream flow water rights.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All Federal lands	All Federal lands	Where watersheds have been heavily fragmented, prioritizing intact habitat where native guilds exist
Opportunities for implementation	State wildlife action plans, grassland/forest plan direction, interdisciplinary approach to management	Coordination with tribes. Watershed Condition Framework documents where this is an issue at the 6^{th} code scale	Opportunities exist, but need work to be identified; coordination with federal and state agencies, tribes, counties, and watershed restoration plans
Cost	Inexpensive to moderately expensive	Inexpensive to expensive, depending on treatments	Inexpensive to expensive, depending on treatments
Barriers to implementation	Personnel availability, litigation barriers with vegetation management projects, common understanding of purpose	Social barriers—lack of understanding, not valued by some.	Funding, coordination, data gaps

able 4A.8 (cont.)—Adaptation options that address climate change effects on water resources in the Grassland Subregion

Sensitivity to climatic variability and change: Decreased snowpack will lead to increased frequency of high peak flows.

Adaptation Strategy / Approach: Maintain hydrological and ecological function of watersheds.

Strategy Objective: Promote resilience, reduce stressors, engage coordination

	Specific Tactic – D	**Specific Tactic – E**	**Specific Tactic – F**
Tactic	Minimize expansion of drainage network by disconnecting road system from stream system, including improved road drainage and road decommissioning.	Develop off-channel watering strategies; minimize in-stream dewatering (e.g., horizontal wells), for both livestock and other water uses.	Move infrastructure out of floodplains, and encourage use of best management practices throughout watershed to protect and restore water quality.
Tactic effectiveness (risks)	High	Low	High
Implementation urgency	Near term	Near term	Near to mid term
Where can tactics be applied? (geographic)	Prioritize by value of downstream water and associated biota	Priority watersheds	Where assets exist on floodplains
Opportunities for implementation	Prioritize by value of downstream water and associated biota	Coordination with tribes, federal and state agencies, and counties	Prioritize by values at risk associated with assets; public education opportunity
Cost	Inexpensive to expensive	Inexpensive to moderate	Moderate to expensive
Barriers to implementation	Funding, legal authority (including NEPA), social opposition (road access, changing traditional land-use practices)	Water rights, social opposition	Social opposition (effects on recreation sites, public perception), cultural resource concerns

Table 4A.9—Adaptation options that address climate change effects on water resources in the Grassland subregion.

Sensitivity to climatic variability and change: Higher temperatures will lead to lower low stream flows in the summer.			
Adaptation strategy/approach: Maintain hydrological and ecological function of watersheds.			
Strategy objective: Promote resilience, reduce stressors, engage coordination			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Implement 17 Indicators of rangeland health, and maintain or restore forest vegetation resilience.	Promote/maintain proper functioning condition of riparian areas and wetlands, including: ensure adequate grazing regimes, adequate riparian buffers, beaver colonization, and restoration of riparian vegetation.	Maintain/improve streamflow continuity by optimizing hydrologic connectivity, including: reduce sediment loading, properly design in-channel infrastructure, ensure adequate culvert size, promote beaver colonization, and procure in-stream flow water rights.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All Federal lands	All Federal lands	Where watersheds have been heavily fragmented, prioritizing intact habitat where native guilds exist
Opportunities for implementation	State wildlife action plans, grassland/forest plan direction, interdisciplinary approach to management	Coordination with tribes. Watershed Condition Framework documents where this is an issue at the 6th code scale	Opportunities exist, but need work to be identified; coordination with federal and state agencies, tribes, counties, and watershed restoration plans
Cost	Inexpensive to moderate	Inexpensive to expensive, depending on treatments	Inexpensive to expensive, depending on treatments
Barriers to implementation	Personnel availability, litigation barriers with vegetation management projects, common understanding of purpose	Social barriers – lack of understanding, not valued by some.	Funding, coordination, data gaps

Table 4A.10—Adaptation options that address climate change effects on water resources in the Grassland subregion.

Sensitivity to climatic variability and change: Increasing air temperature will lead to increased stream temperature, changes in the hydrograph, and changes in land use, affecting water quality.

Adaptation strategy/approach: Ensure riparian function and resilience, including groundwater-surface water interactions

Strategy objective: Promote resilience, reduce stressors, engage coordination

	Specific tactic – A	Specific tactic – B	Specific tactic – C
Tactic	Promote/maintain proper functioning condition of riparian areas and wetlands: ensure adequate grazing regimes and adequate riparian buffers, promote beaver colonization, and restore riparian vegetation.	Develop adequate inventory and promote protection of spring sources and shallow aquifers.	Promote and educate regarding best management practices for agricultural runoff; form/participate in task forces and working groups.
Tactic effectiveness (risks)	Moderate to high, depending on degree of implementation	Moderate to high	Low to moderate, depending on social factors
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All lands	Priority watersheds	Mostly non-Federal lands
Opportunities for implementation	Coordination with tribes; Watershed Condition Framework documents where this is an issue at the 6th HUC scale	Work with botanists, soil scientists, hydrologists to compile existing information	Partnerships with NRCS, Prairie Potholes Landscape Conservation Cooperative
Cost	Inexpensive to expensive, depending on treatments	Inexpensive to moderate, depending on scale	Inexpensive to moderate
Barriers to implementation	Social opposition—lack of understanding and not valued by some	Lack of funding and staff time	Social opposition, lack of staff time, crop values

Table 4A.11—Adaptation options that address climate change effects on water resources in the Greater Yellowstone Area subregion.

Sensitivity to climatic variability and change: Higher temperatures and decreased snowpack will reduce water availability.

Adaptation strategy/approach: Reduce water use and increase efficiency, demonstrate leadership in water efficiency, and create outreach opportunities.

Strategy Objective: Reduce stressors, facilitate transition, increase knowledge.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Research successful water saving tactics and apply tactics where appropriate.	Install low-flow appliances at administrative sites; replace landscaping with drought tolerant plants.	Communicate water saving tactics and benefits.
Tactic effectiveness (risks)	High	High	Variable—difficult to measure effects
Implementation urgency	Near term	Mid term	Near term
Where can tactics be applied? (geographic)	All lands, where appropriate	All lands, including administrative locations (campgrounds, visitor centers, etc.)	All lands, including administrative locations (campgrounds, visitor centers, etc.); use Internet, press releases, interpretive signing, etc.
Opportunities for implementation	Collaboration with GYCC	Collaboration with GYCC	Collaboration with GYCC
Cost	Inexpensive	Inexpensive	Inexpensive
Barriers to implementation	None	Resistance to xeriscaping, low-flow toilets	None

Table 4A.12—Adaptation options that address climate change effects on water resources in the Greater Yellowstone Area subregion.

Sensitivity to climatic variability and change: Discharge from natural springs and seeps may be reduced, affecting water quantity and quality, wetland plant species, wildlife habitat, and water for livestock.

Adaptation strategy/approach: Protect natural springs and seeps from potential degradation and development.

Strategy objective: Reduce stressors.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Develop map/inventory of springs and seeps locations (6th code level).	Instrument (piezometer) prioritized representative springs to get detailed flow information.	Develop local protection strategies such as fencing, stock fencing; develop alternative water sources; moratoriums on wells where appropriate.
Tactic effectiveness (risks)	High	High	Variable depending on strategy and stakeholder support
Implementation urgency	Near term	Near to mid term	Near to mid term
Where can tactics be applied? (geographic)	All lands	Priority areas with springs and seeps	Priority areas with springs and seeps
Opportunities for implementation	Collaborations with USGS, State agencies that manage water, NOAA, USFS remote sensing center	Collaborations with USGS, State agencies that manage water, NOAA	Collaborations with Federal and State agencies, private landowners, range permittees
Cost	Moderate	Inexpensive to moderate	Inexpensive to moderate
Barriers to implementation	Information may be sensitive	None	Social and legal opposition, especially based on water rights

Table 4A.13—Adaptation options that address climate change effects on water resources in the Greater Yellowstone Area subregion.

Sensitivity to climatic variability and change: Higher flows may lead to flooding of valuable infrastructure (roads, buildings, campgrounds, etc.).

Adaptation strategy/approach: Reduce risk of damage to infrastructure.

Strategy objective: Promote resilience.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Map and prioritize areas with higher peak flows to determine high-risk locations.	Implement tactic A—replace, remove, adjust, and resize as necessary; implement early warning systems.	Communicate risk with all stakeholders, including affected public and private entities.
Tactic effectiveness (risks)	High	Variable, depending on tactic/location. Low—replacing culverts, due to variable nature of stream types and unknown changes in climate affecting flows High—removal of campgrounds from floodplains, installation of bridges, removal of culverts	Variable, depending on reception of information, severity of risk, and ability to implement changes
Implementation urgency	Near term – need this information to take further steps toward adaptation	Near to long term, depending on model predictions and expected flows	Near term, especially where human safety is a concern
Where can tactics be applied? (geographic)	All lands	Priority areas	All locations where stakeholders are at risk
Opportunities for implementation	Collaboration with USGS, FEMA, county emergency management, NOAA	Collaboration with State and local, USGS, FEMA, county emergency management, NOAA	Collaboration with State and local, USGS, FEMA, county emergency management, NOAA
Cost	Inexpensive	Inexpensive to moderate	Inexpensive
Barriers to implementation	None	Legal—NEPA, Social—removal of favorite recreation spots	None

Table 4A.14—Adaptation options that address climate change effects on water resources in the Greater Yellowstone Area subregion.

Sensitivity to climatic variability and change: Higher temperatures, higher evapotranspiration rates, and earlier runoff may reduce recharge to shallow aquifers, reducing downstream domestic water yields.

Adaptation strategy/approach: Identify and protect shallow aquifer recharge zones by communicating and partnering with stakeholders.

Strategy objective: Reduce stressors, facilitate transition, engage coordination.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Map/inventory recharge zones, especially in areas where water is heavily utilized (municipal watersheds).	Form watershed user groups—coordinated resource management groups (CRM—Federal, State, stakeholders) to identify concerns and solutions.	Improve diversion efficiencies (install headgatess, convert from ditch to pipeline, install weirs as needed, etc.).
Tactic effectiveness (risks)	High	High to moderate	High
Implementation urgency	Near term	Near to mid term	Near to mid term
Where can tactics be applied? (geographic)	Recharge zones and identified CRMs	Identified CRMs, identified watersheds with stakeholders	Site specific within affected watersheds
Opportunities for implementation	GYA partners. USGS, university, GYCC	Conservation districts, NRCS, state agencies that regulate water, advisory groups, landscape conservation cooperatives, Trout Unlimited	Conservation districts, NRCS, state agencies that regulate water, advisory groups, landscape conservation cooperatives, Trout Unlimited
Cost	Moderate	Inexpensive	Inexpensive to moderate
Barriers to implementation	None	Social opposition; need communication to work through barrier	Variable legal and social opposition; concerns about listed fish species and downstream users.

Table 4A.15—Adaptation options that address climate change effects on water resources in the Greater Yellowstone Area subregion.

Sensitivity to climatic variability and change: Higher temperatures and evapotranspiration rates may lead to increased loss of lower elevation, isolated wetlands.			
Adaptation strategy/approach: Increase understanding of location and risk for all wetland types and apply appropriate management actions to reduce loss.			
Strategy objective: Reduce stressors, promote resilience.			
	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Update National Wetland Inventory maps for all wetlands, including hydrologic regime and type.	Assess vulnerability of all wetlands.	Increase connectivity of wetlands (e.g., prevent road bisections); avoid degradation of wetlands by new structures; protect beaver dams; consider artificial wetland construction/augmentation of natural wetlands in vulnerable watersheds.
Tactic effectiveness (risks)	High	High	Variable, depending on action
Implementation urgency	Near term	Near term	Mid to long term
Where can tactics be applied? (geographic)	All lands	All lands	Mostly Federal lands
Opportunities for implementation	Collaborations with GYCC, Ducks Unlimited, National Academy of Sciences, National Science Foundation, USFWS, National Wildlife Federation	Collaborations with GYCC, Ducks Unlimited, National Academy of Sciences, National Science Foundation, USFWS, National Wildlife Federation	Collaborations with State and Federal agencies, private land owners
Cost	Inexpensive	Inexpensive	Moderate
Barriers to implementation	None	None	Social and legal opposition (road removal, augmenting wetlands)

Table 4A.16—Adaptation options that address climate change effects on water resources in the Western Rockies subregion.

Sensitivity to climatic variability and change: Decreased snowpack will increase flooding and damage to roads and infrastructure.

Adaptation strategy/approach: Identify and proactively decrease vulnerability of roads and infrastructure to flooding.

Strategy objective: Increase resilience.

	Specific tactic – A	Specific tactic – B	Specific tactic – C
Tactic	Identify and restore degraded riparian areas in order to reduce flooding and increase natural storage; reduce the amount of infrastructure in the floodplain.	Increase resilience of infrastructure: culvert sizing, hardened fords, road drainage; remove and relocate infrastructure (e.g., roads, campgrounds).	Increase resilience of stream resources by identifying and restoring degraded riparian areas to reduce flooding and increase natural storage; add large woody debris, improve floodplain connectivity, increase riparian roughness, restore beavers.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Near term and ongoing	Near term and ongoing	Near term and ongoing
Where can tactics be applied? (geographic)	Across the Western Rockies subregion	Across the Western Rockies subregion	Across the Western Rockies subregion
Opportunities for implementation	Partnerships with Federal and State agencies, county and municipal governments, NGOs, private landowners	Partnerships with Federal and State agencies, NGOs, Avista, U.S. Army Corps of Engineers, Idaho Power	Partnerships with Federal and State agencies, NGOs, Avista, U.S. Army Corps of Engineers, Idaho Power
Cost	Moderate to expensive	Expensive	Inexpensive to expensive
Barriers to implementation	Property rights advocates	Public acceptance; depends on location, scale of project, and partnerships.	Public acceptance; depends on location, scale of project, and partnerships.

Table 4A.17—Adaptation options that address climate change effects on water resources in the Western Rockies subregion.

Sensitivity to climatic variability and change: Decreased snowpack will reduce base flows and shrink riparian habitats, altering groundwater, storage, and shallow alluvial aquifers.

Adaptation strategy/approach: Increase knowledge of the groundwater resource.

Strategy objective: Increase knowledge.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Map aquifers and alluvial deposits; identify groundwater influenced streams.	Determine legal availability and better understanding of physical availability of water for aquifer recharge.	Improve streamflow and groundwater monitoring information to improve understanding of surface water-groundwater interactions; obtain real-time data.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Near term—Information is needed for both water and fisheries	Near term—Information is needed for both water and fisheries	Near term—Information is needed for both water and fisheries
Where can tactics be applied? (geographic)	All lands	All lands	All lands
Opportunities for implementation	USFS Rocky Mountain Research Station, universities, Montana Bureau of Mines	State agencies	USGS, State and research partnerships
Cost	Moderate	Moderate	High
Barriers to implementation	Availability of staff and funding	Availability of staff and funding	Availability of staff and funding

Table 4A.18—Adaptation options that address climate change effects on water resources in the Western Rockies subregion.

Sensitivity to climatic variability and change: Decreased snowpack and increased disturbance will reduce municipal water supply and quality.

Adaptation strategy/approach: Reduce erosion potential to protect municipal water supplies; prioritize municipal systems for protection.

Strategy objective: Increase resilience.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Reduce hazardous fuels.	Reduce disturbance (e.g., off-road vehicles, grazing, riparian roads).	Manage roads to reduce erosion.
Tactic effectiveness (risks)	Moderate	High	High, although detecting improvements can be difficult and site dependent
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	High-value locations	High-value locations on public and private lands	High value locations on public lands
Opportunities for implementation	Partnerships with municipalities, counties, NGOs, tribes, private landowners.	Partnerships with municipalities, counties, NGOs, tribes, private landowners.	Partnerships with municipalities, counties, NGOs, tribes, private landowners.
Cost	Expensive	Inexpensive to moderate	Moderate to high
Barriers to implementation	Public acceptance, cost	Public acceptance, cost	Public acceptance, cost, some user groups

Table 4A.19—Adaptation options that address climate change effects on water resources in the Western Rockies subregion.

Sensitivity to climatic variability and change: Increased droughts and flooding will reduce water quality.

Adaptation strategy/approach: Build an information base for a timely response to disturbance, thus ensuring data are available to inform decision making.

Strategy objective: Increase knowledge.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Prioritize data collection based on forecasted drought.	Collect pre-disturbance data on stream and riparian conditions (high-quality values, habitat most in need of protection).	Develop a directory/checklist for sites where disturbance has a direct effect on water quality (metals).
Tactic effectiveness (risks)	Moderate	High	Moderate
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Mostly Federal lands	Mostly Federal lands	All lands
Opportunities for implementation	Collaboration with other agencies, universities	Collaboration with other agencies, universities	Collaborate with USEPA (TMDL, CERCLA, Natural Resource Damage Assessment)
Cost	Moderate	Moderate	Expensive
Barriers to implementation	Staffing, budget	Staffing, budget	Agency requirements, time to staff and manage the clearinghouse

Table 4A.20—Adaptation options that address climate change effects on water resources in the Western Rockies subregion.

Sensitivity to climatic variability and change: Decreased snowpack and increased disturbance will alter water quantity and quality of lakes and reservoirs (including dam operations).

Adaptation strategy/approach: Determine how climate change will alter lakes and reservoirs.

Strategy objective: Increase knowledge.

	Specific tactic – A	**Specific tactic – B**	**Specific tactic – C**
Tactic	Develop a clearinghouse of information on the effects of climate change from all available sources.	Increase coordination between all partners (Federal, State, tribal, private).	Improve understanding about connectivity and interaction of streams and lakes (temperature, nutrient sinks, sources, etc.).
Tactic effectiveness (risks)	High	High	Moderate
Implementation urgency	Near term—Information needed for water, fisheries, and amphibians	Near term—Information needed for water, fisheries, and amphibians	Near term—Information needed for water and fisheries
Where can tactics be applied? (geographic)	All lands	All lands	All lands
Opportunities for implementation	Forest or regional level for identified sources of data	Forest or regional level for identified sources of data	Collaborations with USGS, State, and research institutions
Cost	Moderate	Moderate	Expensive
Barriers to implementation	Availability of staff and funding	Availability of staff and funding	Availability of staff and funding