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Assessing the Vulnerability of Watersheds to Climate Change

Results of National Forest Watershed Vulnerability Pilot Assessments

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Cover Photograph

North Pole Basin, Sopris Ranger District, White River National Forest, by Cindy Dean.

Abstract

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Existing models and predictions project serious changes to worldwide hydrologic processes as a result of global climate change. Projections indicate that significant change may threaten National Forest System watersheds that are an important source of water used to support people, economies, and ecosystems.

Wildland managers are expected to anticipate and respond to these threats, adjusting management priorities and actions. Because watersheds differ greatly in: (1) the values they support, (2) their exposure to climatic changes, and (3) their sensitivity to climatic changes, understanding these differences will help inform the setting of priorities and selection of management approaches. Drawing distinctions in climate change vulnerability among watersheds on a national forest or grassland allows more efficient and effective allocation of resources and better land and watershed stewardship.

Eleven national forests from throughout the United States, representing each of the nine Forest Service regions, conducted assessments of potential hydrologic change resulting from ongoing and expected climate warming. A pilot assessment approach was developed and implemented. Each national forest identified water resources important in that area, assessed climate change exposure and watershed sensitivity, and evaluated the relative vulnerabilities of watersheds to climate change. The assessments provided management recommendations to anticipate and respond to projected climate-hydrologic changes.

Completed assessments differed in level of detail, but all assessments identified priority areas and management actions to maintain or improve watershed resilience in response to a changing climate. The pilot efforts also identified key principles important to conducting future vulnerability assessments.

Keywords: Watersheds, hydrology, climate change, vulnerability, restoration, national forests.

Contents

Pilot reports are available online only at
http:/www.fs.fed.us/pnw/pubs/pnw-gtr884_appendix.pdf

The Challenge

> *Water and its availability and quality will be the main pressures on, and issues for, societies and the environment under climate change.*
>
> —Intergovernmental Panel on Climate Change

Climate change poses important challenges to the U.S. Department of Agriculture Forest Service, the agency charged with management of more than 193 million acres of public forests and grasslands. Current and projected trends in global warming present risks to a wide range of ecosystem values and services, and the impacts are most closely associated with water resources, including changes in their volume, timing, and quality.

In response, initial priorities of the Forest Service climate change strategy are to build knowledge, skills, and expertise, and to develop experience and partnerships. These initial steps build toward planning and designing management actions to improve ecosystem resilience (Furniss et al. 2010). (In this report, "resilience" means both the resistance to adverse changes and the ability of a watershed to recover following adverse changes.)

Maintaining or improving resilience is widely accepted as the best means to adapt to climate change (Williams et al. 2007). Forest Service managers have extensive experience in implementing practices that improve watershed health and resilience, such as restoring connectivity to aquatic habitats, restoring degraded wetlands, and using prescribed burning to restore fire regimes.

Although much is known about the hydrologic impacts of climate change and the means to improve watershed resilience, linkages to integrate this knowledge into existing programs and priorities are needed. The capacity of national forests and grasslands to implement effective management measures is constrained by available resources (budgets and staffing). Priorities that integrate the impacts of climate change are needed to effectively allocate resources and focus management activities.

Climatic changes are not expressed uniformly across the landscape. Not all watersheds are equally vulnerable. Some support more water resource values, and some are inherently more sensitive to change. Identifying these important differences is critical to setting priorities and identifying responses for management.

Clean and abundant water is often considered the most valuable ecosystem service provided by the national forests and grasslands, and most climate changes affect hydrologic processes. Water from these lands is important for domestic, agricultural, and industrial uses, and for hydropower generation. It supports recreational uses and provides crucial habitat for threatened, endangered, and sensitive aquatic species.

Despite these challenges, Forest Service managers are being directed to act. The agency's climate change strategy has been launched, and efforts to adapt to climate change are now a reporting requirement for forest supervisors. A Climate Change Scorecard measures progress made by each national forest and grassland in four areas, including assessment of resource vulnerabilities.

Currently, there are few examples of assessments that inform managers about the vulnerability of watersheds to climate change. Existing assessments are limited to analyses of vulnerability of particular species or habitats (e.g., Gardali 2012). Likewise, existing protocols for vulnerability assessments (e.g., Glick et al. 2011) focus primarily on single species or specific biological communities. Not widely available are informative examples of place-based assessments that provide relative ratings of vulnerability of watersheds to climate change.

In response to this information gap, the Forest Service Stream Systems Technology Center funded the Watershed Vulnerability Assessment (WVA) pilot project to determine if watershed-focused climate change assessments could be prepared by national forest staff, using existing data sources. The goal of the pilot project was to provide land managers with assessments of the relative vulnerability of watersheds to climate change. The project involved substantial collaboration between National Forest System (NFS) and Forest Service Research and Development staff; the task group included representation from two research stations and each of the nine Forest Service regions.

This report summarizes the pilot effort. Because each NFS unit has different levels of staffing and data availability, the results represent a diversity of approaches on how to conduct a vulnerability assessment. We provide an overview of core assessment components, and highlight similarities and differences of the 11 pilot assessments. We also share important concepts that emerged during completion of the assessments. These "Assessment Principles" could be applied in assessments in other national forests and grasslands, and are described in boxes located throughout the report.

Each individual pilot assessment is locally based and has relevance at local scales. We do not attempt to summarize all of the findings of these assessments. The assessments represent a broad range of conditions similar to those found on national forests and grasslands across the country, and provide examples of approaches for a wide variety of environmental contexts. Readers are encouraged to review the individual pilot reports for details on methods used and results produced. These reports are available online at http:/www.fs.fed.us/pnw/pubs/pnw_gtr884_appendix.pdf.

Watershed Condition, Health, and Resilience...What's the Difference?

For the purposes of this report, two frequently used terms—watershed condition and health—are considered interchangeable. Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change and still retain the same functions, structure, identity, and feedbacks (Walker et al. 2004). Because the term "resilience" is used most frequently in the climate change literature, we have used this term throughout this project and report. Watershed resilience can be described as a subset or synthesis of "watershed health" or "watershed condition" (Furniss et al. 2010).

The Forest Service has recently published a methodology to assess watershed condition (defined in box below), and has conducted baseline assessments across the entire 193-million-acre NFS (USDA FS 2011a). This national program was initiated concurrent with the pilot WVAs.

Principles of Vulnerability Assessment Derived from WVA Pilot Forests

1. Use resource values to focus the analysis.
2. The HUC-6 (hydrologic unit code level 6) subwatershed is currently the best scale for analysis and reporting.
3. Local climate data provides context.
4. Analyze exposure before sensitivity.
5. Don't get lost in exposure data.
6. Keep the end product in mind.

Watershed condition is the state of the physical and biological characteristics and processes within a watershed that affect the soil and hydrologic functions supporting aquatic ecosystems…. When watersheds are functioning properly, they create and sustain functional terrestrial, riparian, aquatic, and wetland habitats that are capable of supporting diverse populations of native aquatic- and riparian-dependent species. In general, the greater the departure from the natural pristine state, the more impaired the watershed condition is likely to be… .

Watersheds that are functioning properly have five important characteristics (Williams et al. 1997):

1. They provide for high biotic integrity, which includes habitats that support adaptive animal and plant communities that reflect natural processes.
2. They are resilient and recover rapidly from natural and human disturbances.
3. They exhibit a high degree of connectivity longitudinally along the stream, laterally across the floodplain and valley bottom, and vertically between surface and subsurface flows.
4. They provide important ecosystem services, such as high quality water, the recharge of streams and aquifers, the maintenance of riparian communities, and the moderation of climate variability and change.
5. They maintain long-term soil productivity.

—From the *USFS Watershed Condition Framework* (USDA FS 2011b)

The Pilot Assessment Approach

> *The scientist is not a person who gives the right answers; he's the one who asks the right questions.*
>
> —Claude Levi-Strauss

The WVA pilot team was composed of watershed and aquatic specialists from each Forest Service region, stationed on 11 national forests (see fig. 1). The group was supported by a steering committee composed of representatives from two research stations and two regional offices. Pilot national forests were selected to provide a range of water resource issues and environmental factors, and each national forest brought different levels of staffing, expertise, and existing information to the project. A few pilot forests had taken initial steps to consider how climate change might affect management priorities, though most had not. The goal was to conduct pilot assessments with a range of analytical rigor, in different geographic settings and organizational structures, with varying subject-matter focus.

The pilot team and steering committee met to develop a methodology to guide the assessments. The initial step was to define the purpose of the assessments, which was to identify (for each unit) areas with the highest priority for implementing actions to maintain or improve watershed resilience. This approach is based on two assumptions. The first is that there is a strong correlation between the condition and resilience of watersheds, with watersheds in better condition displaying more resilience than comparable watersheds in poor condition. The second assumption is that climate change is one of many factors, both natural and anthropogenic, that affect hydrology and watershed condition. A conceptual model illustrating these factors and linkages is displayed in figure 2.

The objective of the pilot assessments stemmed from the need to prioritize where to concentrate management activities to improve or maintain resilience. Comparing analysis options against this objective helped national forest staff focus their efforts.

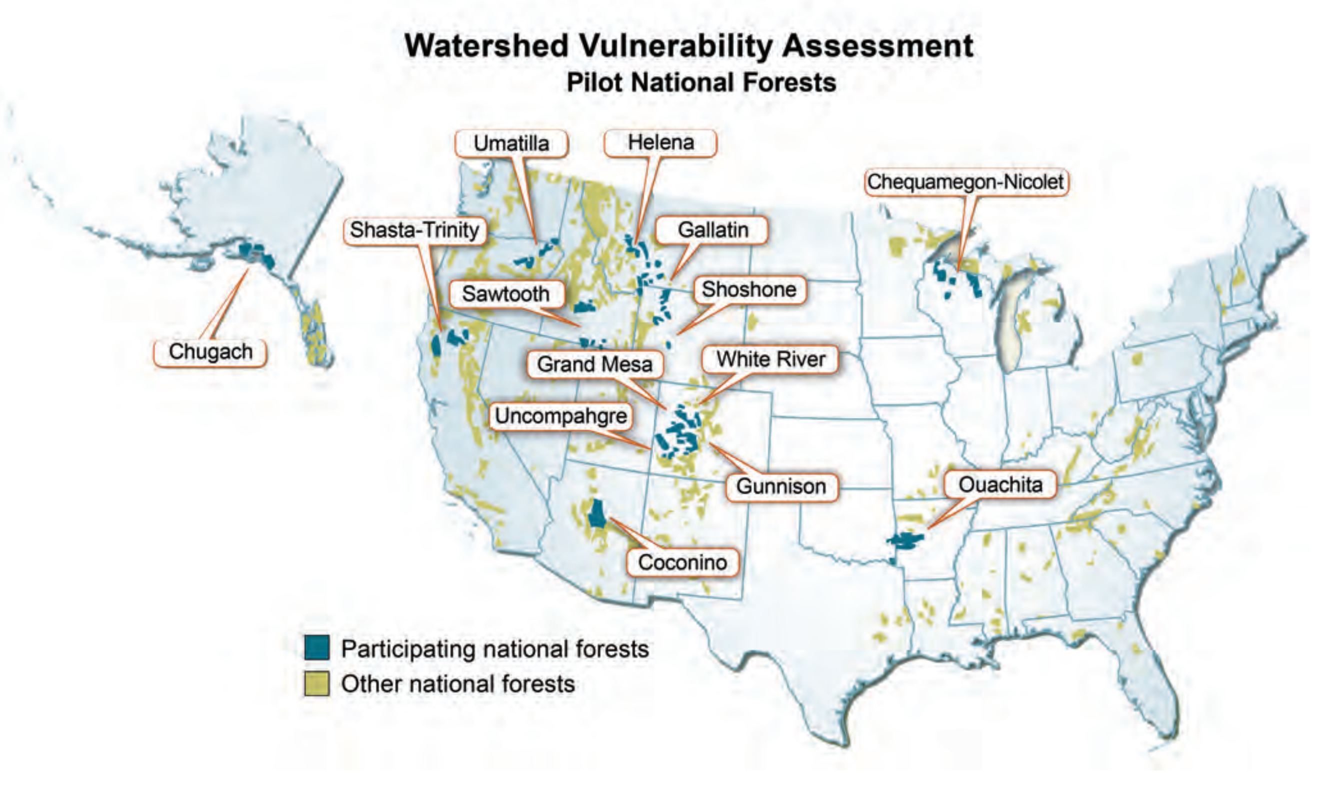


Figure 1—Location of national forests participating in the pilot Watershed Vulnerability Assessments (WVA). Coordination was provided by representatives from regional staffs in Regions 2 and 6, and the Pacific Northwest and Rocky Mountain Research Stations. A parallel WVA was conducted on the Shoshone National Forest (Rice et al. 2012) and coordinated with the core WVA group of 11 pilot forests.

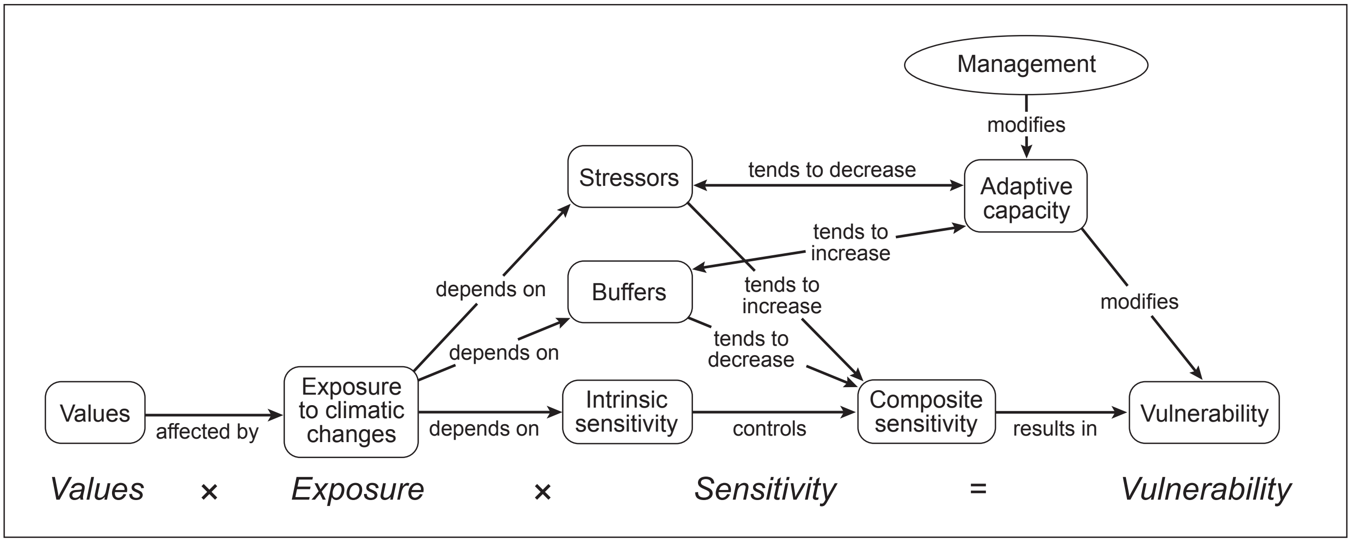


Figure 2—Conceptual model for assessing vulnerability, showing linkages between exposure, resource values, and system condition (sensitivity). We found utility in separating three components of sensitivity. "Buffers" and "stressors" are human-induced, whereas intrinsic sensitivity is based on inherent characteristics independent of human influence.

The process was intended to produce useful results with differing levels of data availability and resource investment. Given the variety of watershed types, water resource issues, experience, and data availability on the pilot forests, a flexible assessment method was needed. The team developed an analysis method that relied heavily on previous experience with watershed analysis (USDA FS 1995) and the basic model of vulnerability (fig. 2). The assessment steps are summarized below.

Steps in the Watershed Vulnerability Assessments

1. Identify water resource values and scales of analysis.
2. Assess exposure.
3. Evaluate watershed sensitivity.
4. Evaluate and categorize vulnerability.
5. Identify adaptive management responses.
6. Critique the assessment.

The pilot assessments benefited from having leaders identified at the outset of the project. Leaders coordinated the assessment on their units, and at times acted as a one-person analysis team. A defined project leader was important to making key decisions on what to include in the assessment, identifying available data, determining how to analyze the information, and making adjustments when necessary.

Each pilot forest took a slightly different approach, depending on the resources selected for analysis, the type and amount of data available, and the staff time that could be devoted to analysis. After the assessments were initiated, the pilot team met monthly via video conference to discuss progress and share ideas and approaches. These discussions led to changes in the stepwise process and to the methods used in individual assessments.

For the WVA, vulnerability was defined as the interaction of climatic exposure with values at risk and watershed sensitivity. In the framework model, management actions are intended to increase the resilience or buffering capacity of watersheds by modifying the effect of stressors that decrease resilience. Each of the primary components of the assessment: values, exposure, sensitivity, vulnerability, and application and lessons learned from applying the conceptual model, are further described in the following section.

Identify Water Resource Values and Scales of Analysis

> *Ecosystem management is most successful when it considers and connects all spatial and temporal scales. For collaborative analysis, a specific scale and unit of land must be chosen, but this does not imply that only the collaborative analysis scale matters: they all matter.*
>
> —The authors

Water Resource Values

Identifying the water resources to be included is vital to the overall assessment. Water resources are the prism through which all the other assessment steps are viewed and focused. For example, factors used to characterize sensitivity and exposure are selected because they have strong linkages or they most directly affect the selected water resources.

Each pilot forest considered including at least three designated water resource values in their assessments. These were aquatic species, water uses (diversions and improvements), and infrastructure. The rationale was that climate change would influence these resources in different ways, and that including them in the pilot analysis would broaden the range of analytical methods and approaches.

Given this objective, each pilot forest selected water resource values based on their importance and perceived susceptibility to climate changes. All pilot forests included aquatic species (or habitat for selected aquatic species) and infrastructure in their analyses. Eight of the 11 pilot forests included the vulnerability of water uses in their assessments. The water resource issues addressed by each pilot forest, and the reporting scale, are listed in table 1.

The species (and aquatic habitats) selected for analysis represent the range of aquatic habitats found on the pilot forests. Anadromous fishes were a focus on each national forest where they occurred. Other salmonids included in the analyses were red-band trout, bull trout, brook trout, and three species of cutthroat trout. Brook trout are of note: they were a resource of concern within their historical habitat on the Chequamegon-Nicolet National Forest (NF), and a stressor (invasive species) on several of the Western pilot forests. Other fishes included as resource issues were warm water species on the Ouachita and Coconino NFs. Amphibian species and habitat were included in three analyses.

The evaluation of water resources resulted in maps and descriptions displaying the location and relative importance by subwatersheds for each resource or combination of resources. For example, the Shasta-Trinity NF analyzed the density of springs and small lakes at three watershed scales (fig. 3). The Sawtooth NF displayed the relative importance of infrastructure (road crossings and near-stream recreation facilities) by subwatershed in the Sawtooth National Recreation Area (fig. 4). The characterization of watersheds in terms of the resources they support is an important step in any watershed planning effort and a first step in informing managers where limited resources might be invested. The assessment goal was to identify the most important places, categorize their relative value (high, moderate, low), and map the individual and composite values.

Assessment Principle One

Use resource values to focus the analysis

One of the major challenges in conducting a broad-scale analysis is deciding what to address. The land areas under consideration are large and ecosystems and social systems are extremely complex. Narrowing the focus of the pilot assessments was considered essential and was achieved by identifying key water resource issues using iterative analyses.

One aspect of the approach instrumental in focussing the pilot efforts was using water resource values, identified at the outset, to drive the assessment. Once resources of concern are identified, assessment questions are narrowed. The question then is not what exposure attributes to use, but what exposure attributes have the strongest effect on the resource value. Likewise, the question “What elements influence watershed sensitivity?” narrows to “What watershed sensitivity elements most strongly influence the water resource?”

Using a specific set of resource values as the prism through which exposure and sensitivity were evaluated also provided for comparison of responses between resource values. Often, analysts found commonality among resources and were able to combine resources and methods to streamline the assessment.

Table 1—Water resource issues, scope of analysis, and reporting scales included in pilot assessments

Region	National forest	Scale of analysis	Reporting scale	Water resource issues
1	Gallatin	National forest	HUC-6 (subwatershed)	West-slope cutthroat trout, Yellowstone cutthroat trout, water uses, infrastructure
1	Helena	National forest	HUC-6 (subwatershed)	West-slope cutthroat trout, bull trout, recreational fisheries, infrastructure
2	Grand Mesa, Uncompahgre, and Gunnison (GMUG)	National forest	HUC-6 (subwatershed)	Aquatic habitats and species, water uses, infrastructure
2	White River	National forest	HUC-6 (subwatershed)	Boreal toad and cutthroat trout habitat, water uses, infrastructure
3	Coconino	Five HUC-5 watersheds	HUC-6 (subwatershed)	Amphibians, stream and riparian habitat, water uses, infrastructure
4	Sawtooth	Recreation area	HUC-6 (subwatershed)	Salmon, bull trout, water uses, infrastructure
5	Shasta-Trinity	National forest	HUC-6 (subwatershed)	Springs, salmon, redband trout, water uses, infrastructure
6	Umatilla	National forest	HUC-6 (subwatershed)	Springs, salmon, bull trout, water uses, infrastructure
8	Ouachita	National forest	HUC-6 (subwatershed)	Warm-water fishes, infrastructure
9	Chequamegon-Nicolet	National forest	HUC-6 (subwatershed)	Wetlands; cold-, cool-, and warm-water fishes; ground water; infrastructure
10	Chugach	Eyak Lake and Resurrection Creek watersheds	HUC-6 (subwatershed)	Salmon, hydropower, infrastructure

HUC = hydrologic unit code.

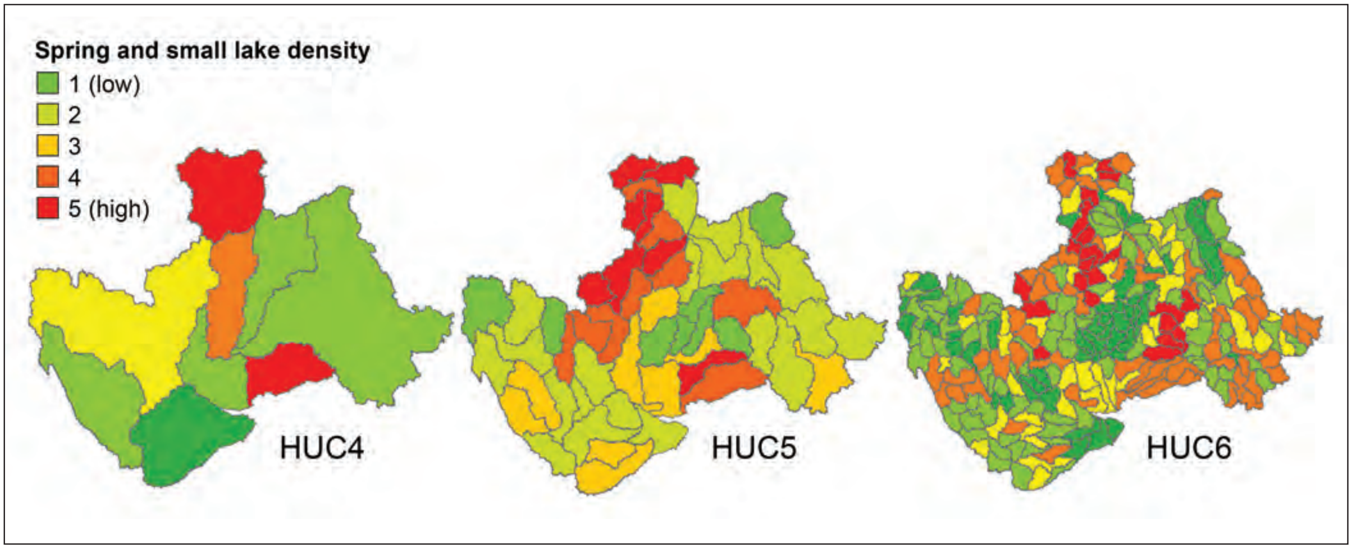


Figure 3—Density of springs and small lakes on the Shasta-Trinity National Forest. Results are shown at the scales of HUC-4 (hydrologic unit code level 4) (left), HUC-5 (middle), and HUC-6 (right). The Shasta-Trinity assessment evaluated resource value, sensitivity, and vulnerability at the three scales, all showing that identifying priority locations for management actions was best done by using HUC-6.

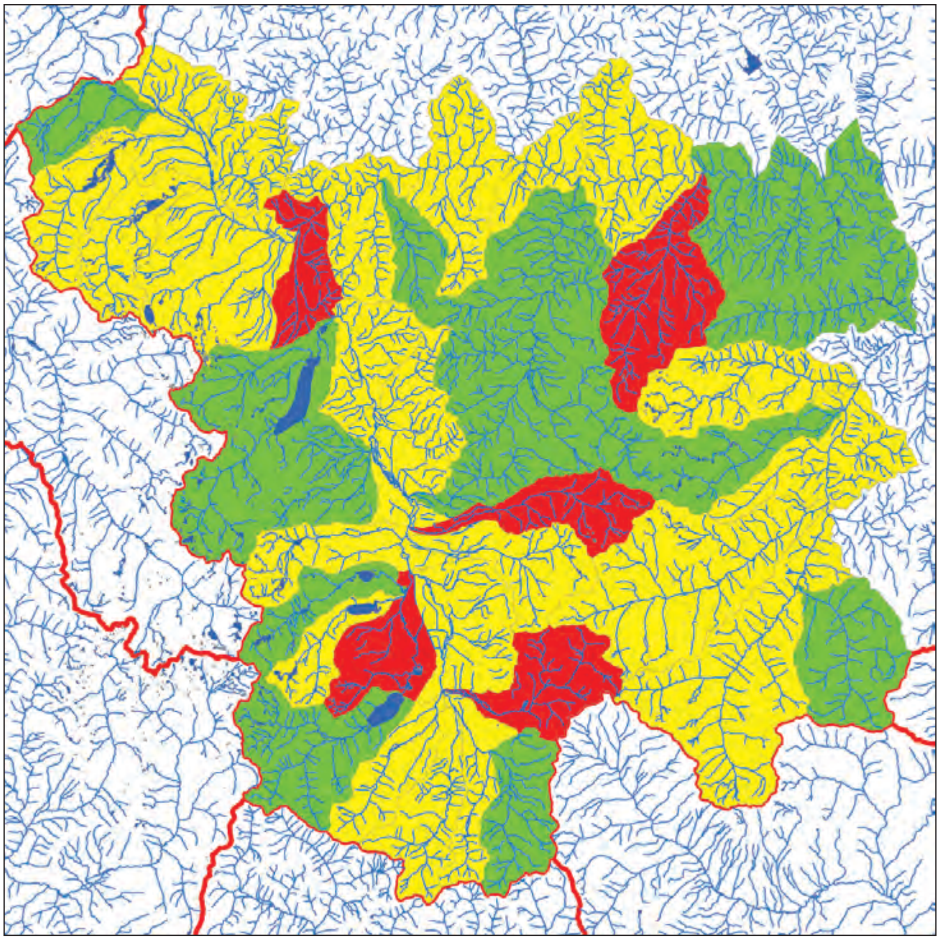


Figure 4—Amount of infrastructure (roads and developed recreation facilities) within the Sawtooth National Recreation Area. Red-shaded subwatersheds have the highest density of infrastructure, yellow show moderate density, and green show the lowest density. Red lines are HUC-4 (hydrologic unit code level 4) boundaries.

Important Considerations in Assessing Water Resources

- Identify partners who can improve the assessment and engage with them.
- Identify the most important places (if possible), categorize their relative values (high, moderate, low), and map them.
- Determine what relevant broad-scale evaluations, assessments, and plans are available.
- Consider all downstream uses (such as species and diversions).
- Identify any ecological thresholds or risk levels (flow requirements, temperatures, and so on) associated with specific resource values.
- As the assessment progresses, look for similarities (and differences) in response of resource values and consider grouping resource values where appropriate.

Scale(s) of Analysis and Reporting

The pilot assessments were conducted over relatively large geographic areas, typically (8 of the 11 pilots) an entire national forest. Three forests analyzed smaller areas for specific reasons. The Chugach NF (Region 10) focused on subwatersheds where management activities would be most influenced by the results of the assessment. The Coconino NF (Region 3) included five watersheds (at the HUC-5 scale) that support the majority of aquatic resources on the forest. The Sawtooth NF limited its evaluation to the Sawtooth National Recreation Area because it supports remaining strongholds for steelhead, bull trout, and Chinook and sockeye salmon listed under the Endangered Species Act, and significant data were available for this area of the forest.

All of the pilot forests used the subwatershed (HUC-6) scale for analysis and reporting. This arose from the shared conclusion that subwatersheds provide a logical unit and scale for setting priorities and implementing management activities on NFS lands.

The Shasta-Trinity NF also used the HUC-6 as the scale to apply results of the vulnerability assessment, and, in addition, evaluated water resource values, watershed sensitivity, and vulnerability at two broader scales (HUC-4 and

Assessment Principle Two

The HUC-6 (hydrologic unit code level 6) is currently the best scale for analysis and reporting

The scale for the pilot assessments was not prescribed, but all pilot forests elected to use the HUC-6 (subwatershed) scale to characterize and map results. Climatic exposure data was often available, displayed, and assessed at scales larger than HUC-6; the work by the Shasta-Trinity National Forest demonstrated that HUC-4 and HUC-5 scales are usually too large to effectively manage for water values, sensitivity, adaptive capacity, and resilience. The HUC-6 is the appropriate size for planning and implementing management strategies to sustain or improve watershed condition. In addition, HUC-6 is also the scale used to assess and report conditions for the Classification portion of the Watershed Condition Framework.

HUC-5). The results from the Shasta-Trinity suggest that general trends can be expressed at broader scales, but as might be expected, detail shown at the HUC-6 scale is lost at each higher level (fig. 3).

Although HUC-6 was determined to be the best reporting unit for displaying water resource values, sensitivity, and vulnerability, exposure information is generally available and appropriately used only at broader scales. As a result, most pilot forests evaluated exposure at the HUC-5 scale.

Assess Exposure

> *So why worry about global warming, which is just one more scale of climate change? The problem is that global warming is essentially off the scale of normal in two ways: the rate at which this climate change is taking place, and how different the "new" climate is compared to what came before.*
>
> —Anthony D. Barnosky

The consideration of climate change exposure data is the primary difference between the WVA and evaluations that Forest Service professionals have previously produced. Past assessments have been conducted for watershed analysis, restoration planning, and watershed condition. Pilot team members built upon this experience but few team members had used or were familiar with climate change projections.

Analysis of exposure included four components: (1) review and evaluation of pertinent local historical climatic data, (2) selection and use of one or two modeled projections of future climate conditions, (3) analyses of historical and projected changes to hydrologic processes that might affect water resources, and (4) selection of metrics to analyze and display differences in exposure across each analysis area.

Using Historical Data

One finding consistent to all the pilots was the value of local historical data in providing local context and understanding of climate change. Display of historical changes with strong connection to local water resource values is typically easier to understand and appreciate than projections of future conditions. Projections are uncertain because they are associated with future emission scenarios and modeling assumptions. Differences between models increase because they are projected multiple decades into the future and display high variability that may be unsettling to managers. Historical data help both analysts and decisionmakers by providing local context and trends in climatic conditions.

Two examples from the pilot assessments are included here. The first shows changes to ice cover on Lake Mendota in southern Wisconsin (fig. 5). This historical trend was obtained from the Wisconsin Initiative on Climate Change Impacts (WICCI) by the Chequamegon-Nicolet NF during the assessment process. The second example shows changes in snow depth from the Trinity and Sacramento River basins in the Shasta-Trinity NF (fig. 6).

Climate Change Projections

Evaluation of climate exposure was the most difficult component of the assessment for several pilot forests, owing primarily to lack of experience with downscaled global climate modeling data. There were two basic challenges: deciding which climate change projections to use, and selecting the climate metrics.

Assessment Principle Three

Local climate data provides context

Local or regional examples of historical changes in climate and to valued resources should be incorporated as components of the assessment. Such information (e.g., historical trends in temperature and precipitation, changes in ice duration, or species phenology) can readily illustrate current influences on water resources. These data are local, and usually of high confidence. Use of local and regional climatological data, field observations, and local knowledge helps to frame the importance of climate change in terms that are better understood and appreciated than relying only on model-based projections of future climate.

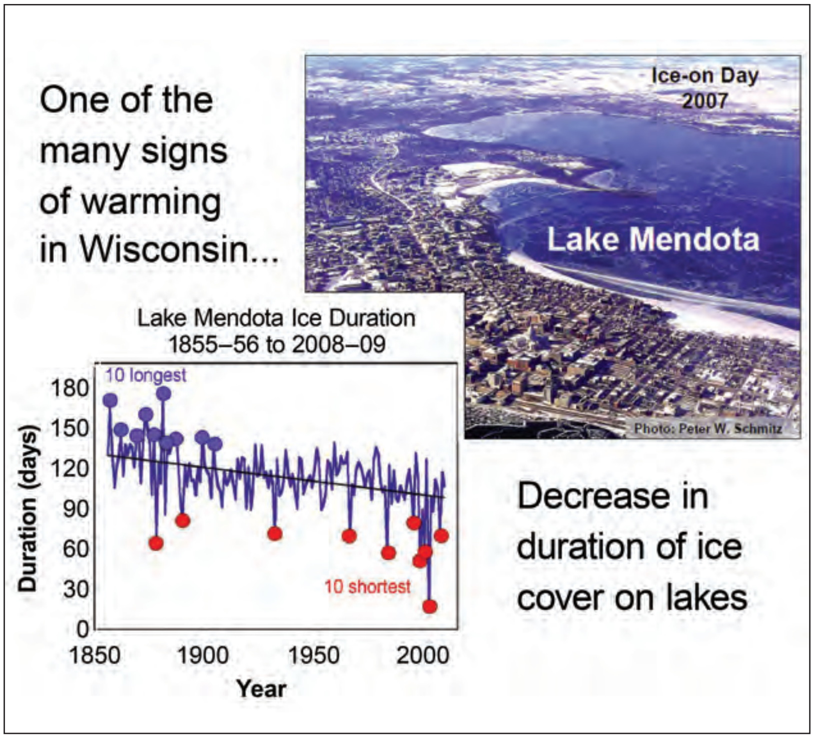


Figure 5—Duration of ice cover (days) on Lake Mendota in Wisconsin, 1855–2009. Source: J. Magnuson, University of Wisconsin-Madison.

The availability of downscaled climate model data has increased substantially since the WVA pilot project was initiated. Of particular note are data now available from the Climate Impacts Group (CIG) at the University of Washington. The CIG has evaluated available Global Circulation Models (GCMs), and determined which models and ensembles of models produce the best fit with historical data, for the major river basins of the Western United States. Data provided by CIG were used for evaluations conducted in Regions 1, 2, 3, 4, and 6. The Grand Mesa, Uncompahgre,

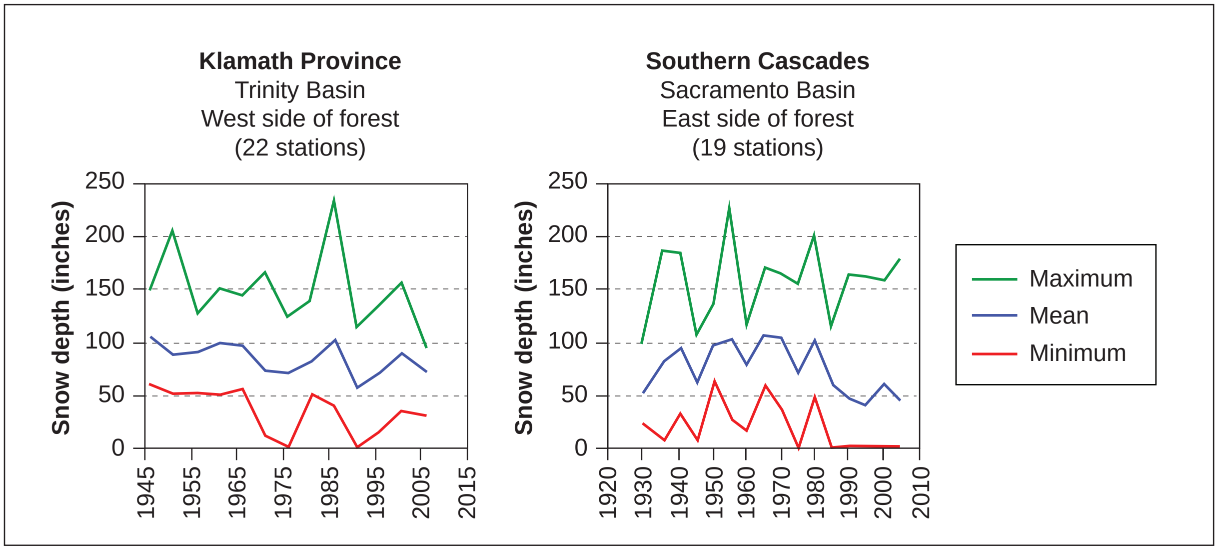


Figure 6—Changes in average snow depths from snow courses located in the Trinity River basin (1945–2009) and Sacramento River basin (1930–2009).

and Gunnison (GMUG) NFs used projections from CIG, and additional projections for the Upper Gunnison River (Barsugli and Mearns 2010). In retrospect, providing data available from CIG at the outset would have expedited some analyses and greatly assisted the process.

In Region 2, the White River NF used projections supplied by the Colorado Water Conservation Boards (Ray et al. 2008, Spears et al. 2009). The Shasta-Trinity NF (Region 5) used the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. This is a downscaled global temperature modeling output available from the University of California, Santa Barbara. The Ouachita NF (Region 8) relied on information from The Nature Conservancy's Climate Change Wizard (table 2). The Chequamegon-Nicolet NF (Region 9) employed data from WICCI, and the Chugach NF (Region 10) used projections provided by the University of Alaska, Fairbanks Scenarios Network for Alaska Planning Project (fig. 7).

All the pilot assessments used air temperature change projections in their analyses and most pilots included projected changes to precipitation. These projections were obtained from the variety of publically available state or regional climate sources listed above. All projections of future climate are based on GCMs. These models are mathematical representations of atmospheric and oceanic motion, physics, and chemistry, and employ different emission scenarios to yield predictions of temperature and precipitation change. The global-scale model outputs are very coarse, so data are often downscaled and used as inputs to macro-scale hydrologic models for use in regional and finer scale analysis, such as the WVA pilots. The accuracy of the data becomes more uncertain with each subsequent layer of modeling. The greatest certainty is associated with air temperature projections. Precipitation projections are highly variable, with even less certainty for derived attributes like snowmelt, runoff, and stream baseflows. Precise changes in hydrologic extremes, such as flood and drought frequency, cannot be credibly modeled at the stream-reach scale at present.

The WVA pilot experience points to the value of broader scale (e.g., regional) vulnerability analyses in providing exposure data and recommending future climate scenarios to national forests. Interpreting exposure data at a broad scale would be useful for several reasons. First, exposure data are not available at finer scales. Second, consistency among national forests in selected emissions scenarios and modeling assumptions would allow comparisons of expected climate changes across national forests.

Table 2—Modeled exposure data from the Ouachita National Forest assessment showing monthly and annual changes in temperature and precipitation derived from the B1 and A1B climate scenarios

	Increases in temperature (°F)				Percent change in precipitation			
	B1 2050	**B1 2080**	**A1B 2050**	**A1B 2080**	**B1 2050**	**B1 2080**	**A1B 2050**	**A1B 2080**
January	2.70	4.42	4.38	6.00	(0.69)	8.85	5.98	1.68
February	3.50	4.01	4.46	5.19	(0.97)	(4.50)	(2.54)	(1.24)
March	3.46	4.25	4.70	5.74	(0.75)	(4.30)	0.63	(5.17)
April	2.99	4.46	4.49	5.93	5.42	2.45	(1.19)	0.67
May	3.68	4.48	5.02	7.16	(8.46)	(1.28)	(6.26)	(10.68)
June	3.90	4.64	5.34	7.04	(5.87)	(7.17)	(8.76)	(12.37)
July	4.14	4.98	5.40	7.28	(8.34)	(2.70)	(7.39)	(12.84)
August	4.13	5.04	5.21	6.84	1.20	6.97	1.52	2.61
September	4.23	5.49	5.35	7.45	(0.49)	1.10	(3.47)	1.32
October	4.12	5.46	5.29	7.15	(13.81)	(8.17)	(9.75)	(8.17)
November	3.52	4.36	4.93	6.15	0.91	(5.08)	(7.93)	(8.75)
December	3.18	4.40	4.11	5.97	5.20	(9.39)	(1.69)	(1.68)
Annual	3.63	4.67	4.89	6.49	(2.22)	(1.93)	(3.40)	(4.55)

Note: Decreases in precipitation are in parentheses.

Source: The Nature Conservancy Climate Change Wizard.

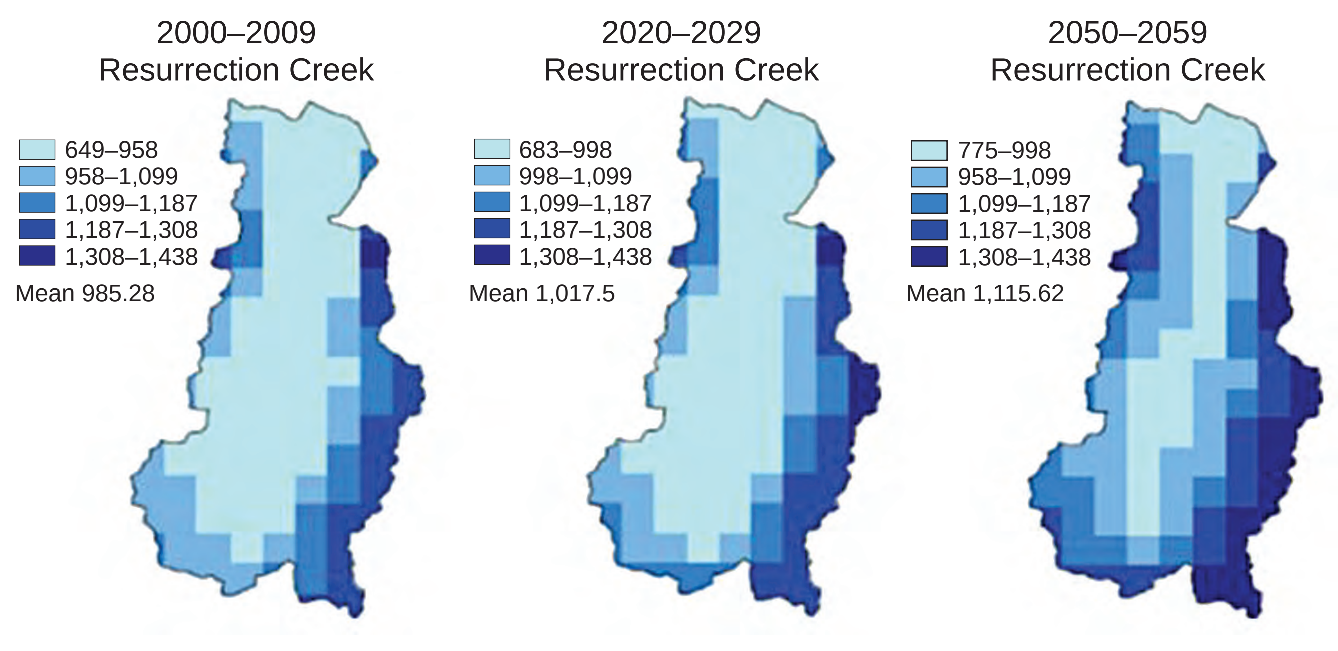


Figure 7—An example of a downscaled, gridded projection of future climate conditions. The maps display projected precipitation (mm). The projections are based on the A1B model. The figure is from the Chugach National Forest watershed vulnerability assessment.

Evaluating Hydrologic Changes

Using projections of future temperatures and other climatic changes, most pilot forests then considered what specific hydrologic changes would result from projected climate changes, and how water resource values would be affected by these changes. This step was integrative. In addition to the obvious connection between exposure and water resources, the evaluation served to stimulate thinking about which watershed characteristics might influence (either moderate or exacerbate) the hydrologic response to climate change, providing a segue to evaluating watershed sensitivity. An example of this type of analysis, which tracks climate changes through hydrologic responses to potential impacts on water resources from the Helena NF, is provided in table 3.

Applying Exposure Projections

Once the hydrologic processes important to selected water resource values were established, exposure metrics closely linked to those processes were identified. The list of metrics used to characterize exposure was limited because of the commonality in water resources in the assessments (table 4). The selection of exposure metrics differed among national forests for three reasons. The first is the water resources themselves. The Chequamegon-Nicolet was the only pilot forest to include assessment of changes to ground-water recharge, and the only forest to use soil-water balance as an exposure metric. The second difference in selecting metrics was data availability. Both the Sawtooth and Umatilla assessments included finer scaled analysis of

Assessment Principle Four

Analyze exposure before sensitivity

The first iteration of the watershed vulnerability assessment process used in the pilot project called for assessment of sensitivity before evaluating exposure. The result was development of rather generic sensitivity factors that did not have the strongest links to hydrologic processes most likely to be affected by climate.

Exposure is considered first in order to produce a list of the most important hydrologic changes affecting each water resource. Sensitivity elements that strongly modify these hydrologic changes are then selected.

Table 3—Projected hydrologic changes relative to identified values (Helena National Forest)

Projected climatic changes	Anticipated hydrologic response	Potential consequences to watershed resources
Warmer air temperatures	Warmer water temperature in streams	Decrease in coldwater aquatic habitats
Changes in precipitation amounts and timing	Altered timing and volume of runoff Altered erosion rates	Increases or decreases in availability of water supplies Complex changes in water quality related to flow and sediment changes
Less snowfall, earlier snowmelt, increased snowpack density	Higher winter flows Lower summer flows Earlier and smaller peak flows in spring	Changes in the amounts, quality, and distribution of aquatic and riparian habitats and biota
Intensified storms, greater extremes of precipitation and wind	Greater likelihood of flooding Increased erosion rates and sediment yields	Changes in aquatic and riparian habitats Increased damage to roads, campgrounds, and other facilities

Adapted from Furniss et al. 2010.

Table 4—National forests and metrics included to evaluate exposure effects in water vulnerability assessments

National forest	Exposure metrics
Gallatin	Combined flow, snowpack vulnerability
Helena	Winter water temps, summer air temps, snow water equivalent (SWE), precipitation
Grand Mesa, Uncompahgre and Gunnison (GMUG)	Seasonal temperature, aridity index
Ouachita	Monthly precipitation and temperature
White River	Snowpack vulnerability
Sawtooth	Winter peak flows, summer stream temperature, summer flows
Coconino	Snowpack vulnerability
Shasta-Trinity	Air temperature, stream aspect, snowpack vulnerability
Umatilla	Winter and summer temperatures, SWE
Chequamegon-Nicolet	Air temperature, precipitation, soil water balance, rainstorm frequency and intensity
Chugach	Air temperature, precipitation, freeze and thaw days

potential changes to water temperature in evaluating change to bull trout habitat. These analyses were possible because of the availability of stream temperature data and predictive models, and the support of the Rocky Mountain Research Station (RMRS). The third difference in exposure metrics was the level of analysis. Differences in the depth of analysis were partly the result of data availability, as in the example described above. But the amount of time team leads could devote to the assessment was also a factor. Available time and perceived need for detailed analysis were practical matters in the exposure analysis. Some pilots chose to make use of more detailed information that was available, and provided metrics with closer links to the subject water resources. Baseflow, for example, may be more closely linked with trout habitat than snowpack vulnerability, but the decision to conduct more detailed analysis was largely driven by the anticipated need for adequate detail to rate watersheds and set priorities. Some analysts thought that more detailed analysis would further discriminate areas at risk. Others thought the objective of rating watersheds could be met adequately with coarser evaluation of exposure.

There are advantages and limitations to both the coarser and more detailed approaches to characterizing exposure. The common factor in cases where the most detailed analyses were conducted is that they evaluated effects on species which, because of population status and trend, were already the focal point of restoration strategies and management emphasis. In such cases, additional detail may be warranted. At the same time, exposure is the assessment component with the greatest level of uncertainty. Though there may be uncertainty in characterizing resource value, especially when ratings comprise more than one resource (e.g., frog plus fish species), descriptions of resource locations generally have little error. Likewise, assessments of sensitivity, as we will see in the next section, are composites of both intrinsic and anthropogenic factors. Schemes to combine or weigh the factors contain error, relative to how these factors are expressed in nature. Nevertheless, these assessment components are likely to be more accurate than projections of future temperature and snowpack, especially regarding what will actually occur decades from now.

On the White River, Gallatin, and Coconino NFs, changes to snowmelt hydrology were determined to be the primary hydrologic change affecting selected resources. In both the White River and Coconino assessments, changes to the existing snow line resulting from projected temperature increases were anticipated. The watershed area within zones of predicted snow elevation change was used to characterize relative exposure of subwatersheds. The Gallatin NF assessment used projected changes in snowpack from the CIG (fig. 8). The Gallatin also included assessments of changes to summer and winter flow (from the variable infiltration capacity [VIC] model) in its assessment. A similar approach was taken on the Shasta-Trinity NF.

The impact of climate change on stream temperatures and habitat for salmonids was the focus on four national

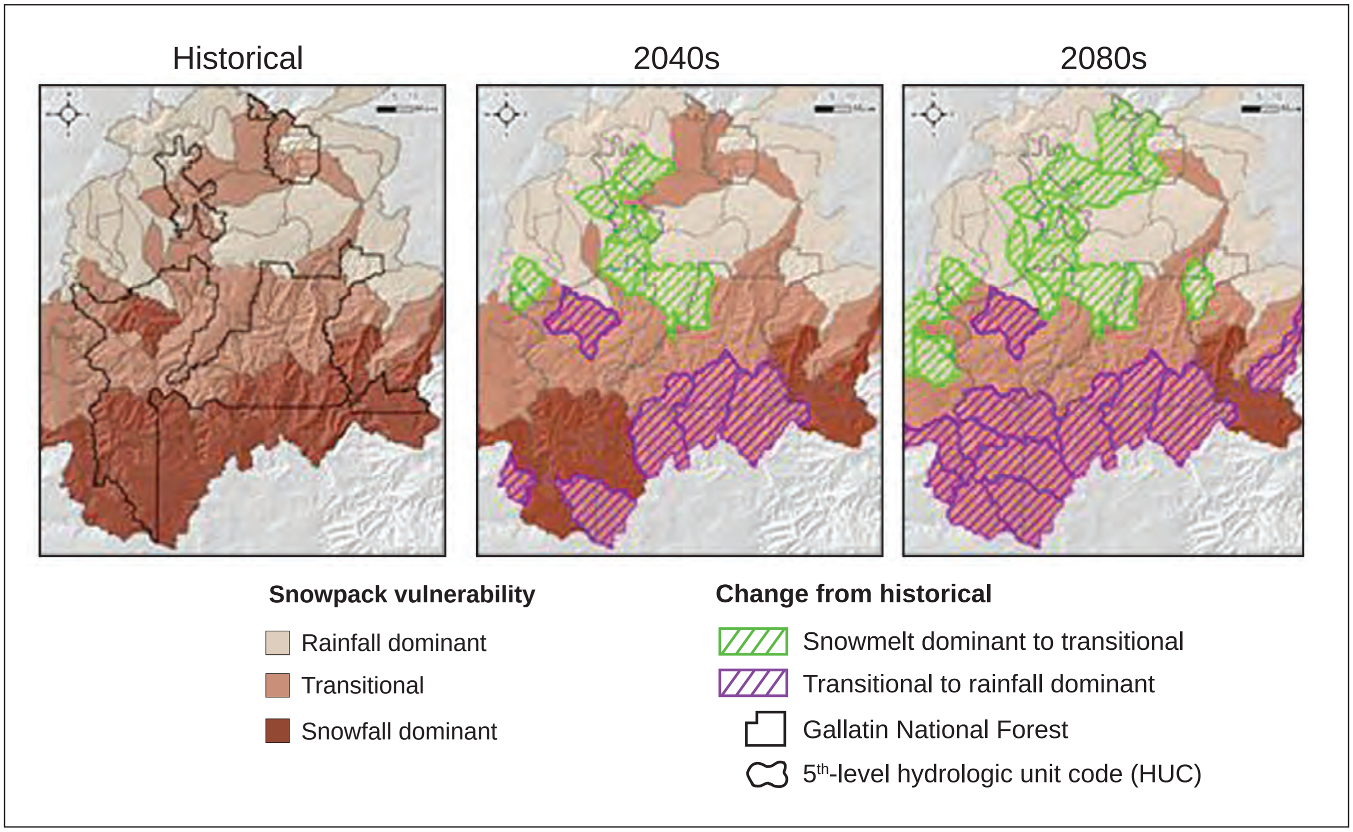


Figure 8—Projected changes in snowpack vulnerability between historical and two future scenarios, Gallatin National Forest. Data are from the Climate Impacts Group (CIG) at the University of Washington, using the CIG composite model.

Assessment Principle Five

Don't get lost in exposure data

Pilot forests used exposure data of different specificity and detail (e.g., in one case, only air temperature change; in another, predicted stream temperatures). The level of detail influenced the analysis, but the take-home message is that all levels of exposure projections produced useable vulnerability assessments. Detailed projections at management-relevant scales are not necessary to gauge relative vulnerability of watersheds. It is more productive to move forward with the analysis than to get lost in the details of refining exposure data.

forests (Umatilla, Sawtooth, Helena, and Shasta-Trinity). These pilots employed data that looked deeper at potential hydrologic changes than other assessments. The Chequamegon-Nicolet NF included a salmonid (brook trout) in their assessment of potential impacts of stream temperature increases on 16 species of cold-, cool-, and warm-water fishes. In addition to stream temperature, the Sawtooth NF evaluated potential changes to frequency of flood flows critical to bull trout habitat condition. This evaluation was possible because of support from RMRS, a leader in assessing potential climate change impacts on aquatic ecosystems.

The Ouachita NF selected aquatic communities as the resource of concern, and identified increased sediment production as the most likely adverse effect to that resource. Changes in precipitation and temperature from The Nature Conservancy's Climate Wizard (see table 2) were captured by month from the composite climate change models. The predicted changes in climate were then used to modify the climate generator in the Watershed Erosion Prediction Project (WEPP) model (Elliot et al. 1995), which were then used to estimate sediment production under different climatic scenarios.

The Chequamegon-Nicolet NF's assessment considered how climate change might affect important aquatic habitats, including lakes and wetlands. A soil water balance model was used to assess how potential ground-water recharge might change in the future and whether any change will differ by soil type. A ground water flow model will eventually be used to determine changes in ground water levels and flow rates to lakes, streams, and wetlands.

The analysis on the GMUG NFs differed from other assessments, in that results were displayed at a large scale. Six large geographic areas, stratified by climatic regime and elevation, were used for graphical analysis. Projected changes to maximum and minimum air temperatures and an index of aridity were factors used to rate exposure in each of these geographical areas. This analysis technique was at least partially driven by the resolution of the downscaled exposure data, which is typically on a grid of 6 km^2 (fig. 7). This fairly gross resolution results in as few as two or three data points for an HUC-6, making discrimination at this scale inappropriate. As a result, pilots typically used HUC-6 for distinguishing differences in resource densities and sensitivity, overlaid with a larger scale rating of exposure.

Climate models typically provide predictions of temperature and precipitation. These data are then combined with characterizations of watershed characteristics and vegetation in modeling of other hydrologic variables. The CIG has also developed predictions of hydrologic change based on the VIC model (Gao et al., n.d.). The CIG was extremely helpful in releasing data for use during the pilot study, and in explaining its utility and limitations. Variable Infiltration Capacity is a distributed, largely physically based macro-scale model that balances water and energy fluxes at the land surface and takes into account soil moisture, infiltration, runoff, and baseflow processes within vegetation classes. It has been widely used in the Western United States to study past and potential future changes to water flow regimes (e.g., Hamlet et al. 2009), snowpacks (Hamlet et al. 2005), and droughts (Luo and Wood 2007). Several pilot forests (Helena, GMUG, Coconino, and Sawtooth) made use of the VIC model outputs to evaluate exposure; VIC attributes evaluated by pilots included runoff, baseflow, and snow water equivalent.

Several pilot forests employed projections of changes to flow characteristics. These were selected because of their important influence on habitat for species of concern. Flow metrics were also useful in describing relative exposure of water uses. In contrast, predictions of peak- and low-flow responses to climate change are limited and consist primarily of generalized predictions of higher peaks and more severe droughts with warming climate (Casola et al. 2005). Only the Sawtooth NF applied a tool useful in describing exposure relative to increased peak flows and infrastructure. This analysis used the VIC-generated "Winter 95" metric. Winter 95 represents the number of days during winter that are among the highest 5 percent of flows for the year. Winter was defined as Dec. 1–Feb. 28. Changes in Winter 95 were determined by comparing the increase in the number of days with the highest 5 percent of flows between current and predicted conditions (2040 and 2080). Subwatersheds with less than a 0.5-day increase were considered low risk, those with 0.5- to 2-day increases were considered moderate risk, and subwatersheds with increases greater than 2 days were considered high risk. Results of this analysis for 2040 are depicted in figure 9.

At first glance, the difference in metrics and the level of detail might suggest that pilot forests took very different paths in their characterization of exposure. In fact, all took very similar approaches. All used review of historical data to display the trend in local climatic conditions. All pilot forests also first looked at projected temperature and precipitation changes. Sometimes this information had been compiled for states, sometimes for river basins or larger geographical areas. The commonality is that the analysis was broad scale. Next, pilot forests considered what impacts the climatic changes would have on hydrologic processes, and then how the hydrologic changes would affect water resources. Differences in pilot outputs resulted from decisions made at this point, primarily influencing the level of detail used to characterize the hydrologic changes. Perhaps the most valuable lesson learned by pilot forests in assessing exposure was that you do not have to become a climate scientist to do a climate change vulnerability assessment.

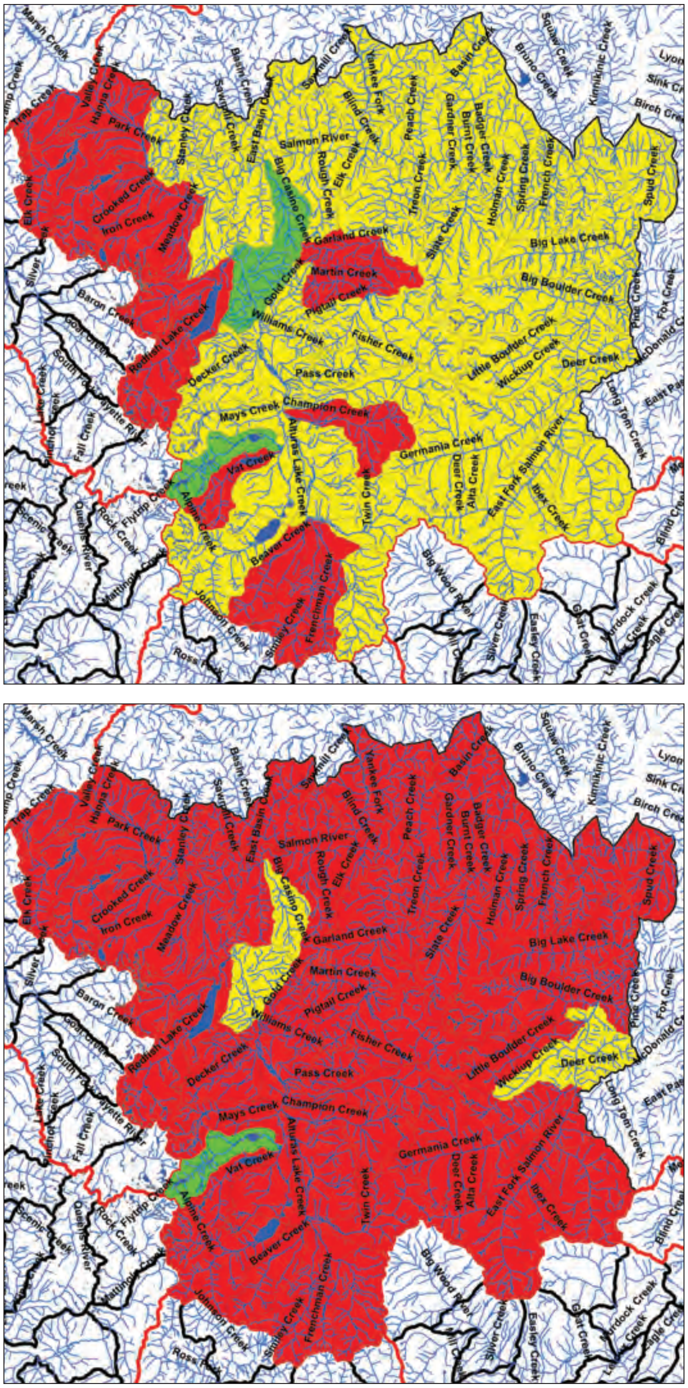


Figure 9—Winter peak flow risk from the Sawtooth National Forest watershed vulnerability assessment; showing current data (top) and projected data for 2040 (bottom). Ratings for subwatersheds are highest risk (red), moderate risk (yellow), and lowest risk (green). Ratings were developed by assessing change to frequency of highest streamflows occurring during the winter. Red lines are hydrologic unit code level 4 (HUC-4) boundaries.

Important Considerations in Evaluating Exposure

- Quantify trends in available, relevant, historical climate datasets. Local and regional data that display significant changes demonstrate the likelihood that changes will continue into the future. Observed changes and trends in ecosystem traits, such as ice duration, species phenology, and species composition, are of great value.
- Use best available climate change projections. Focus on near-term timeframes.
- Identify the effects of a changing climate on watershed processes to inform iterations of exposure data acquisition and assessment.
- Identify hydrologic processes important to the identified resource value.
- Determine how projected changes in hydrologic processes might affect each resource value.
- Quantify the relative magnitude of differences in effects, including spatial and temporal variability.
- Include disturbance regimes in the analysis and quantify disturbance-related effects.
- Document critical data gaps, rationale, and assumptions for inferences, references for data sources, and confidence associated with assessment outputs.

Evaluate Watershed Sensitivity

> *Models are tools for thinkers, not crutches for the thoughtless.*
>
> —Michael Soulé

The goal of assessing sensitivity was to place areas (subwatersheds) into categories based on how they would respond to the expected climate-induced changes to hydrologic processes. The sensitivity of watersheds to any change is partially a function of parent geology, soils, typical climate, topography, and vegetation. Human influences also affect watershed resilience, depending on the extent and location of management-related activities.

The Forest Service often evaluates watershed condition; watershed specialists routinely describe watershed condition in National Environmental Policy Act (NEPA) analyses, and many national forests have watershed or aquatic species restoration plans in place that weigh heavily on assessments of watershed condition. Several pilot forests were able to take advantage of existing watershed condition ratings and apply them to their WVA. This included use of the Blue Mountains Forest Plan Revision watershed condition (Umatilla NF) and "Matrix of Pathways and Indicators" determination of watershed condition factors in conjunction with Endangered Species Act compliance for several salmonid species (Helena, Gallatin, and Sawtooth NFs).

Sensitivity indicators were selected that most influenced the hydrologic process and water resource value in question. Some indicators tend to dampen effects (buffers) and others to amplify effects (stressors). For example, road density may amplify peak flow response and the potential for flood damage to vulnerable infrastructure near streams. In contrast, investment in road improvements such as disconnection of road surfaces from streams would tend to buffer effects.

Attributes selected by pilot forests to characterize sensitivity included both intrinsic factors and anthropogenic or management-related factors (table 5). In some cases, pilot forests termed the "natural" factors as sensitivity, and the anthropogenic factors as risks, combining the two types of indicators to derive a measure of sensitivity. Most pilots included both types of indicators (intrinsic and anthropogenic), although two pilots (Chequamegon-Nicolet and Ouachita NFs) employed only intrinsic factors, and the Coconino NF selected only factors that related to management activities. A sample output (relative erosion

Table 5—Attributes most commonly used in assessing sensitivity by the pilot forests

Intrinsic	Anthropogenic
Geology	Road density
Soil types	Road-stream proximity
Risk of mass wasting	Road crossings
Ground water baseflow	Range condition
Slope	Water diverted
Aspect	Vegetation condition

sensitivity of subwatersheds on the GMUG NFs) is shown in figure 10. Soil hydrologic groups used to classify watershed sensitivity on the Chequamegon-Nicolet NF are shown in figure 11.

The Chugach NF assessment used many of the same sensitivity attributes as the other pilot forests, but the approach differed in that the analysis consisted of comparing two watersheds with significant management activity (primarily undeveloped watersheds or those in wilderness were not included).

Ratings from National Watershed Condition Classification were used in the sensitivity evaluation by the Coconino and Gallatin NFs. The Coconino was completing the condition classification at the same time the WVA was underway, and staff realized the utility that data developed would have in both efforts. The Coconino used few intrinsic factors to characterize watershed sensitivity. Most were derived from the Watershed Condition Classification (fig. 12). The Gallatin NF characterization of sensitivity had two components: one included intrinsic watershed attributes, the other included levels of disturbance. The Watershed Condition Classification ratings of “functioning,” “functioning at risk,” and “nonfunctioning” were used to characterize disturbance. Because national forests and grasslands now have completed the Watershed Condition Classification, these data would be useful in conducting future WVAs.

Pilot forests that took advantage of existing condition ratings tended to apply them to all resource issues. Several pilots, however, identified different indicators for each resource value. Although many indicators are important influences on multiple water resources, some are not. For instance, the most important factors affecting peak

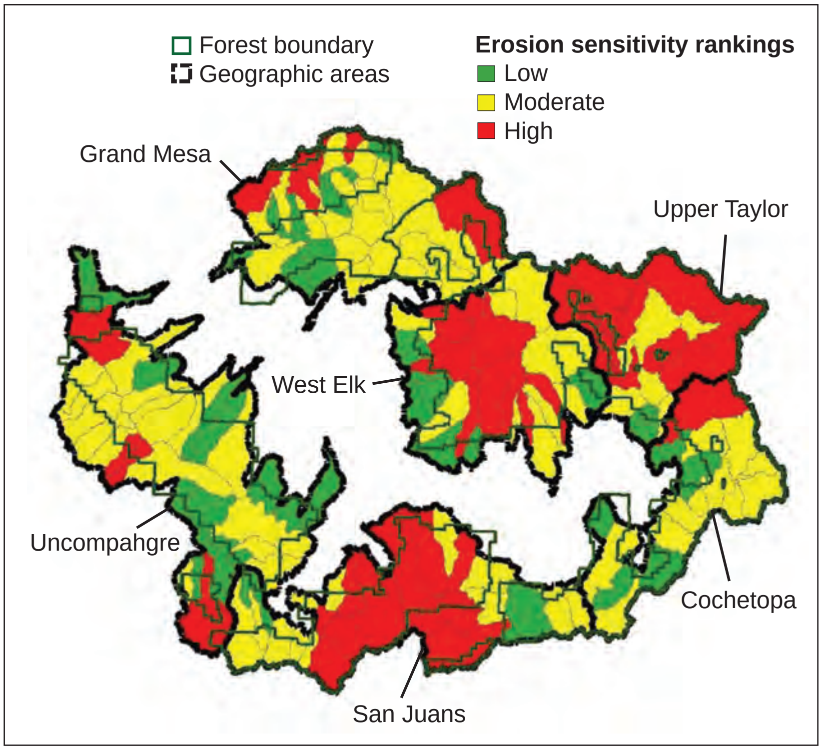


Figure 10—Erosion sensitivity rating from the Grand Mesa, Uncompahgre, and Gunnison National Forests watershed vulnerability assessment. This rating was derived from subwatershed characterizations of runoff potential, rainfall intensity, stream density, density of response channels, and mass wasting potential.

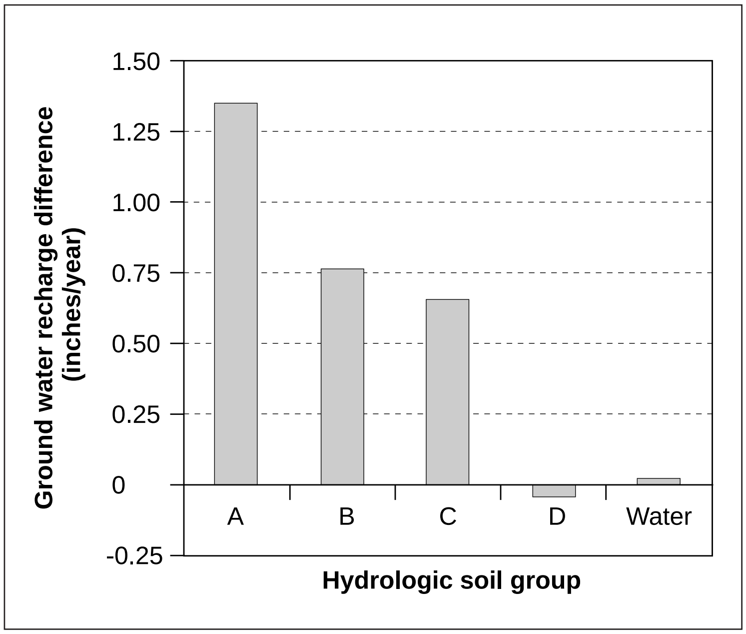


Figure 11—Average annual difference in potential ground water recharge by hydrologic soil group (HSG) (2046–2065 minus 1971–1990). HSG was one of two sensitivity attributes applied to the ground water resource issue in the Chequamegon-Nicolet National Forest watershed vulnerability assessment.

Aquatic biological
- Life form presence
- Native species
- Exotic and/or invasive species
- (Riparian) vegetation condition

Terrestrial physical
- Density
- Road maintenance
- Proximity to water
- Mass wasting
- Soil productivity
- Soil erosion
- Soil contamination

Terrestrial biological
- Fire condition class
- Wildfire effects
- Loss of forest cover
- (Rangeland) vegetation condition
- (Riparian) invasive condition
- (Forest) insects and disease

Figure 12—Watershed condition factors from the Forest Service Watershed Condition Classification. Aquatic-physical attributes are not included. Factors shown in blue are those used as sensitivity indicators in the Coconino National Forest watershed vulnerability assessment.

flows and infrastructure may differ from those that most influence springs and other aquatic habitats.

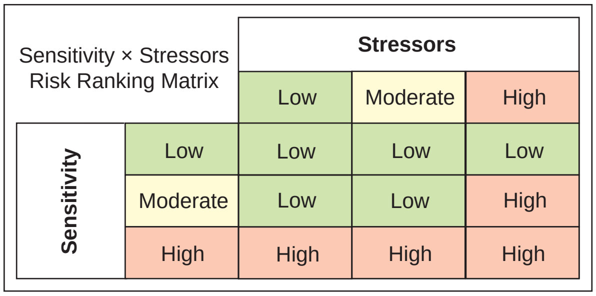
Pilot forests took several approaches to developing ratings of watershed sensitivity. In the simplest applications (Ouachita and Chequamegon-Nicolet NFs), sensitivity indicators (e.g., basin slope, peat land type) were used to place watersheds into different categories. Other pilot forests produced sensitivity ratings based on numerous indicators. When multiple indicators were used, pilots developed methods of weighting and rating the relative influence of the attributes. For example, when considering influences on stream habitat, the amount of water withdrawn from a subwatershed is likely more important than the condition of terrestrial vegetation, and would therefore be given greater weight in calculating a sensitivity score. One approach to weighting sensitivity indicators, from the White River NF assessment, is shown in table 6. In several cases, pilot forests distinguished intrinsic and anthropogenic factors, and used a categorical matrix approach to combining and categorizing sensitivity, into a single rating. An example of such an approach (from the GMUG NFs) is displayed in figure 13.

On the Sawtooth NF, assessment of watershed condition was aided by use of Bayesian belief networks (Lee and Rieman 1997). The networks were used to evaluate relative differences in predicted physical baseline outcomes. The basic structure employs a box-and-arrow diagram depicting hypothesized causes, effects, and ecological interactions (see fig. 14). The system was used to weight the relative importance of, and connections between, a comprehensive list of intrinsic and management attributes, and watershed and habitat elements. As with the other pilot assessments, results from this process were used to rate watershed condition as high, moderate, or low.

Although there was no detailed comparison of the products developed from these varied approaches, they

Table 6—Summary of attribute types affecting subwatershed resilience to climate change (White River National Forest)

Subwatershed attribute	Type of attribute	Relative weight	Net effect relative to climate change
Geochemistry of parent geology	Inherent to watershed	0.25	Buffer
Extent of glaciation	Inherent to watershed	0.75	Buffer
Aspect	Inherent to watershed	0.50	Additive
Hydroclimatic regime	Inherent to watershed	1.0	Additive
Weighted precipitation	Inherent to watershed	1.0	Buffer
Extent of surface water features	Inherent to watershed	1.0	Buffer
Extent of large-scale pine beetle mortality	Inherent to watershed	0.5	Buffer (short term)
Water uses	Anthropogenic	1.0	Additive
Development (primarily roads)	Anthropogenic	0.5	Additive
Extent of beetle salvage	Anthropogenic	0.5	Additive (short term)



Sensitivity × Stressors Risk Ranking Matrix		Stressors		
		Low	Moderate	High
Sensitivity	Low	Low	Low	Low
	Moderate	Low	Low	High
	High	High	High	High

Figure 13—Scheme used to rate watershed sensitivity on the Grand Mesa, Uncompahgre, and Gunnison National Forests. The matrix combines ratings for watershed stressors and sensitivity. Ratings of erosion sensitivity (six elements) and runoff sensitivity (seven elements) were combined to produce the sensitivity rating. The stressor rating was derived by combining ratings of past management (two elements), roads (three elements), vegetation treatments, private land, and mining.

had one thing in common: they all made use of available information to the greatest degree possible. By using existing condition or sensitivity ratings or developing them from scratch, each pilot forest produced useful ratings of watershed vulnerability. It is very important to determine what intrinsic and management-related attributes are important influences on watershed condition, as they strongly affect the selected water resources. If available data, analyses, or assessments include attributes that match those identified in the WVA process or may serve as surrogates, it makes sense to use them.

Important Considerations in Evaluating Sensitivity

- Determine the intrinsic factors (such as geology, soils, and topography) affecting the hydrologic processes of concern—those that can most affect the resource values.
- Determine the management factors (such as roads and reservoirs) affecting the hydrologic processes of concern.
- Determine if management activities will serve as buffers or stressors.
- Consider weighing the relative importance of the buffers and stressors in influencing condition and response.
- Evaluate trends or expected trends in stressors, and how management actions and restoration could affect them.

The sensitivity evaluation typically resulted in maps showing relative sensitivities of subwatersheds. Two examples of this type of product are displayed. Figure 15 shows the sensitivity rating from the Umatilla NF, where (like the GMUG example) a matrix was used to produce a combined rating of intrinsic and anthropogenic factors. A combined sensitivity rating was applied to a composite of resource values. The Coconino NF developed different sensitivity ratings for each water resource issue (fig. 16).

Recent trends and projected future trends in resource conditions should also be included. For example, increased water diversion could exacerbate effects on a resource, whereas anticipated road improvements could improve condition and reduce effects that might otherwise occur.

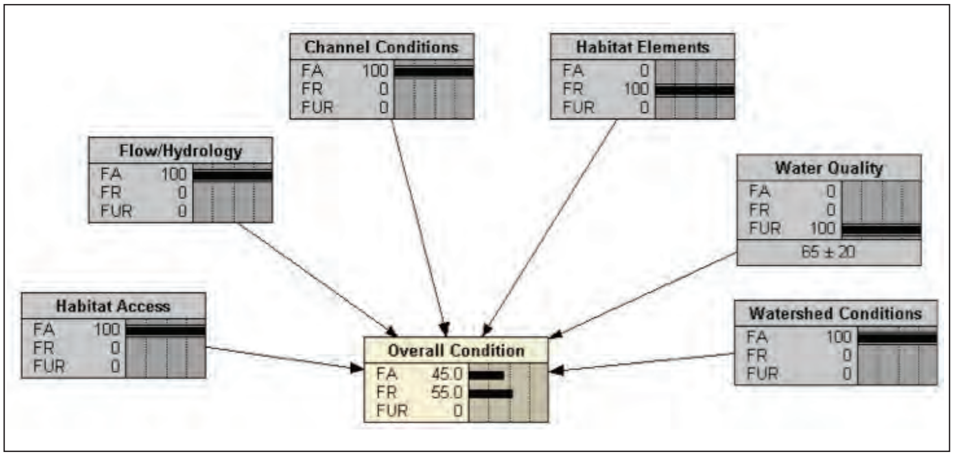


Figure 14—Bayesian belief network for determining overall physical condition, from the Sawtooth National Forest watershed vulnerability assessment. Contributing factors included habitat access, flow, channel condition, habitat elements, water quality, and watershed conditions.

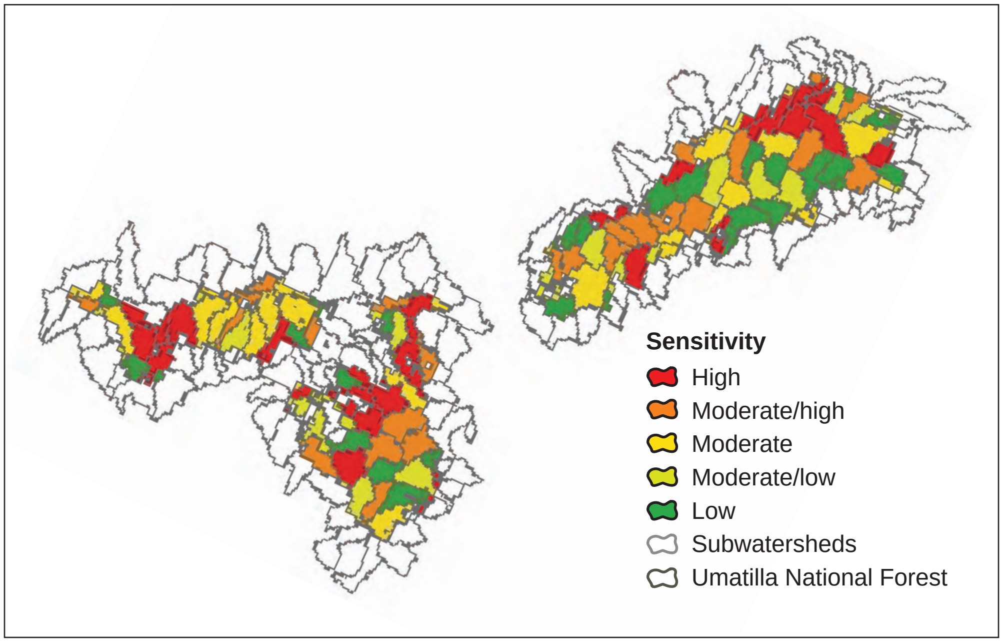


Figure 15—Composite rating of watershed sensitivity from the Umatilla National Forest. Factors used in the rating include ground-water dependence, watershed restoration investment category, road density, near stream road length, road grade, range condition, forest vegetation condition, and aquatic habitat condition. White areas have no National Forest System ownership.

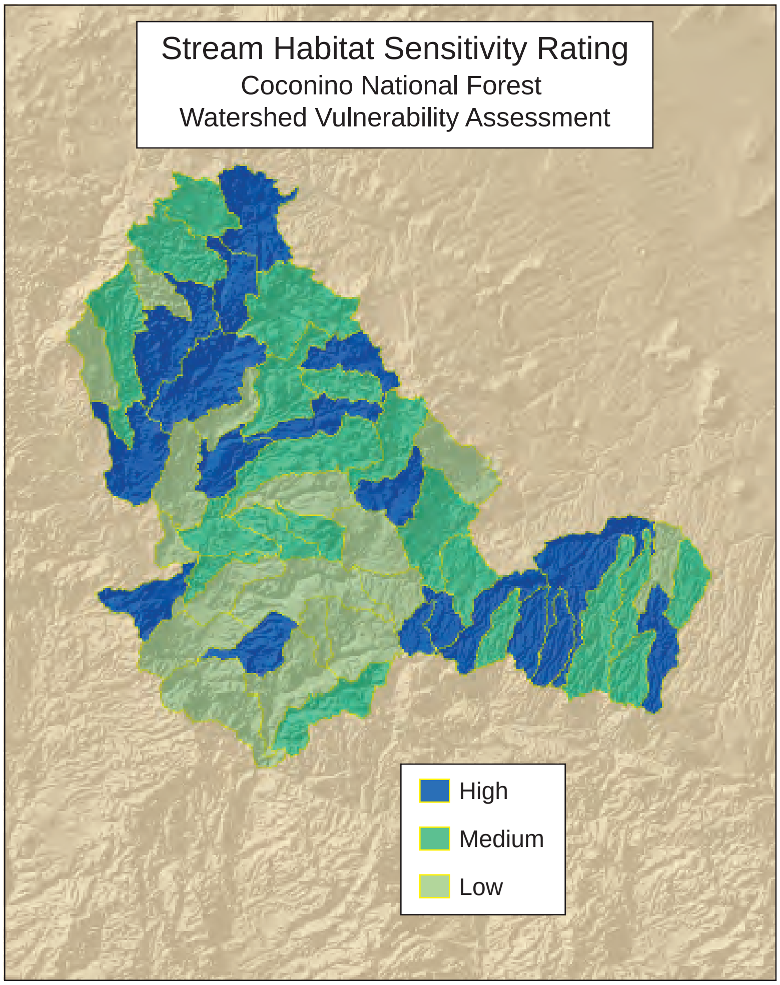


Figure 16—Watershed sensitivity for stream habitats, Coconino National Forest. Attributes contributing to this rating were derived from the forest's watershed condition classification. Stressors included water diversions, terrestrial vegetation condition, riparian vegetation condition and invasive species, road proximity to streams, and wildfire. Buffers included holding instream water rights and degree of implementation of regional ground-water policy.

Evaluate and Categorize Vulnerability

> *Climate change is a risk-multiplier… any decline in the ecological resilience of one resource base or ecosystem increases the fragility of the whole.*
>
> —Charles, Prince of Wales, addressing
> United Nations climate conference COP15
> in Copenhagen (December 2009)

A relative rating of vulnerability of water resources to climate change was produced by combining information from the evaluation of resource values, exposure, and sensitivity. Pilot forests used a variety of approaches to complete this step. Primary determinants were the number of water resources selected for analysis, and the way that values, sensitivities, and responses had been described. Some pilot forests classified vulnerability based on a threshold or ecological value (such as the amount of wetland area in each watershed, as shown in the Chequamegon-Nicolet example in fig. 17). The most common approach used by pilot forests was to merge the location of values with ratings of watershed sensitivity, and then overlay that summary rating with differences in exposure. The result of combining these elements is a classification, typically by subwatershed (HUC-6), that displays the relative vulnerability of the identified values. All pilot forests provided a narrative and mapped their results. Some pilots combined resource values in the analysis (see fig. 18), and others displayed resource values separately (figs. 17 and 19). The GMUG NFs' summary rating of vulnerability was presented in tabular format (table 7). The GMUG assessed exposure and rated vulnerability at the watershed scale. The GMUG's adjusted vulnerability ranking combines the ratings of values, sensitivity, and exposure.

Based on its strong partnership with RMRS and its access to considerable habitat condition data (including stream temperature data), the Sawtooth NF conducted the most detailed evaluation. The Sawtooth analysis included assessing the effects of potential changes to stream temperature and flow on bull trout. Potential temperature effects were analyzed by summarizing the available stream miles that were within or exceeded 15 °C within each bull trout patch for 2008, 2040, and 2080 timeframes. Impacts on both low flow and winter flows were also assessed. Change

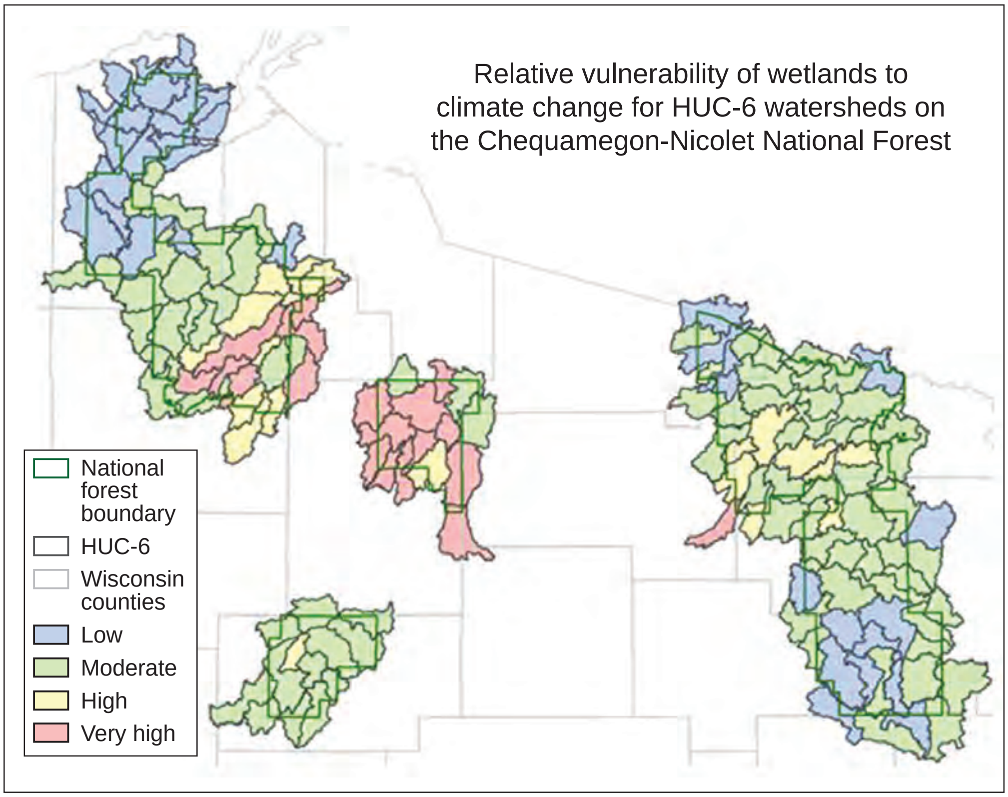


Figure 17—Classification of climate-change risk to wetlands on the Chequamegon-Nicolet National Forest. The rating is based on the proportion of total wetland and acid wetland within the national forest boundary in each HUC-6 subwatershed. Total wetland area ranged from 0 to 55.8 percent of the area for all HUC-6 watersheds. The HUC-6s with less than 10 percent were rated "low," those with 10 to 30 percent were rated "moderate," and those with greater than 30 percent were rated "high." The HUC-6s with less than 5 percent acid wetland area were rated "low," those with 5 to 15 percent were rated "moderate," and those with greater than 15 percent were rated "high," and above that value were "very high." These two risk classes were combined to form one vulnerability classification for each watershed.

in mean summer flow was evaluated by looking at the percentage of change in flow from current to 2040 and 2080. Changes of less than 20 percent of baseflow were considered low risk, 20 to 40 percent were considered moderate, and greater than 40 percent were considered high risk. Winter flow analysis compared how the number of days with the highest 5 percent flows increased from current to 2040 and 2080. Subwatersheds with less than a 0.5-day increase from current conditions were considered at low risk, 0.5- to 2-day increase were considered at moderate risk, and greater than 2-day increase from current conditions were considered at high risk. Once the individual elements were analyzed, a Bayesian Belief Network was used to rate the impact of the change on bull trout population persistence. The vulnerability rating resulting from this process (the extinction risk for bull trout) is shown in figure 20.

On the Ouachita NF, predicted changes to precipitation were applied to WEPP:Road modeling of road sediment production and compared to modeled estimates of existing condition. Changes in future conditions were then compared to existing correlations between aquatic assemblages and sediment production, which include high, moderate, and low risk categories. In this case, the assessment illustrates the differences in risk categories that exist presently, and those projected to result from climate change.

As with some other aspects of the WVA, the Chugach NF took a different approach to assessing vulnerability, owing to the fact that they analyzed only the two subwatersheds in their analysis area that are subject to management activities. Their objective was to look at those two subwatersheds and identify specific vulnerabilities and possible mitigations. The Chugach assessment focused on potential changes to salmonid habitat. The creeks and tributaries in the two subwatersheds are currently cold enough that the projected increase in water temperatures would not exceed optimal temperatures. The key concern was the unknown response of other organisms (including aquatic invertebrates). Of specific interest was whether increased water temperatures would alter the life cycles of prey species currently synchronous with newly emerged salmon fry.

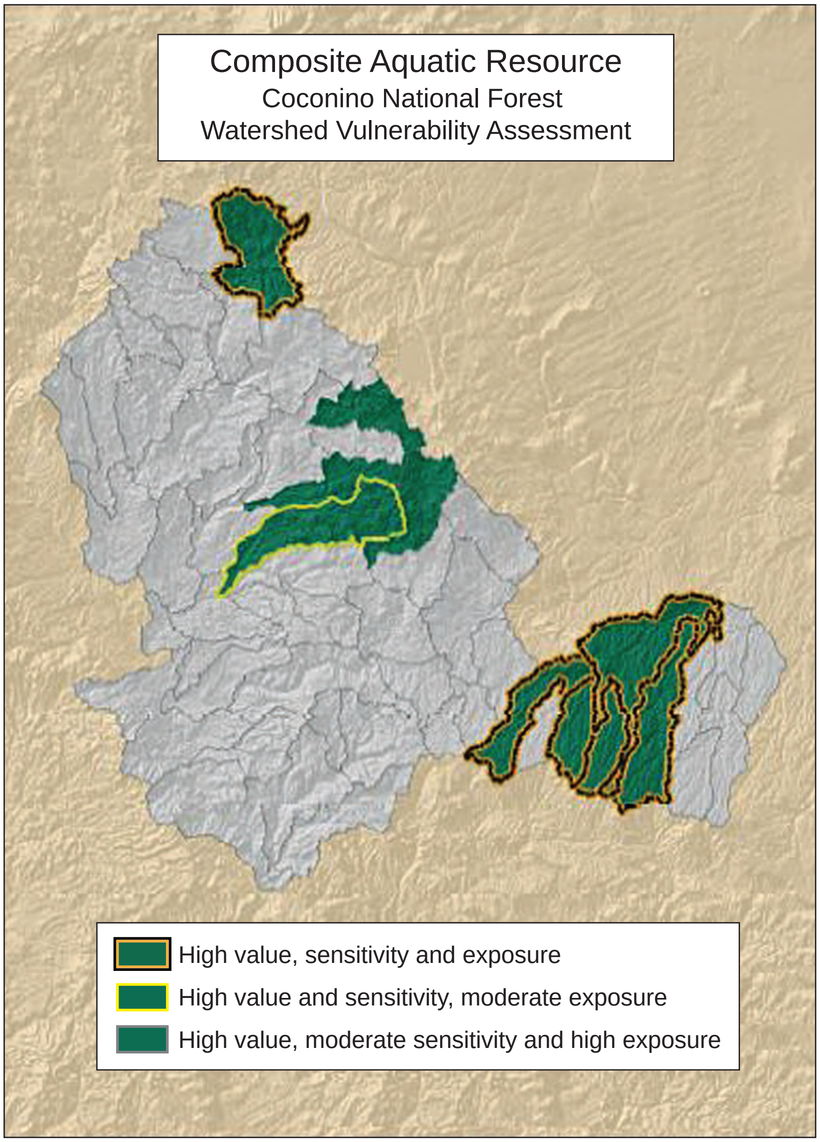


Figure 18—Vulnerability ratings from the Coconino National Forest. The map displays the subwatersheds with the highest density of water resource values (native fishes, amphibians, water uses, stream habitat, riparian and spring habitat, and infrastructure) that also have high or moderate sensitivity and high or moderate exposure.

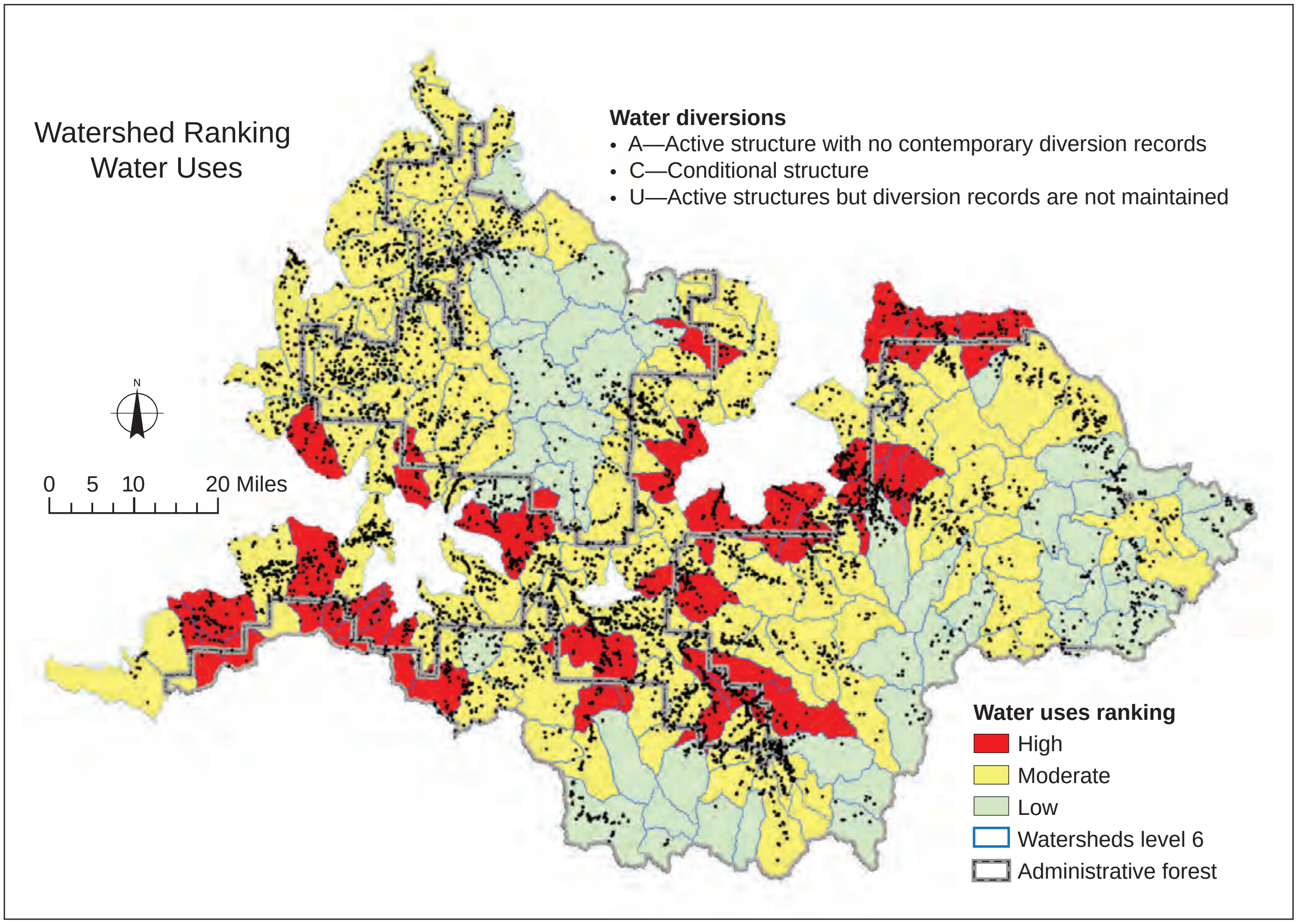


Figure 19—Climate change vulnerability rating for the water uses resource value, White River National Forest. Red shading depicts subwatersheds with the highest vulnerability. Points of diversion for water uses are shown as black dots.

Table 7—Vulnerability ratings from the Grand Mesa, Uncompahgre, and Gunnison National Forests[a]

Geographic areas	Exposure ranking	Value risk ranking (weighted average)	Vulnerability ranking[b]	Adjusted vulnerability ranking[c]
Uncompahgre	6	1	7/12 =	0.583
Grand Mesa	5	2	7/12 =	0.584
San Juans	4	6	10/12 =	0.836
West Elk	3	3	6/12 =	0.502
Upper Taylor	2	5	7/12 =	0.585
Cochetopa	1	4	5/12 =	0.411

[a] Exposure was ranked for the six landscape units (a composite of HUC-6 subwatersheds) on the forest (1 is the lowest), based on biggest change in annual average maximum temperature, annual average minimum temperature, and percentage of change in annual aridity index. Value risk ranking is the highest risk to values based on weighted average of acres × count of high rankings for each subwatershed.

[b] Exposure ranking + value risk ranking)/12.

[c] Upper Taylor adjusted > Grand Mesa and Uncompahgre (area in high risk); Grand Mesa adjusted > Uncompahgre (higher concentration of values).

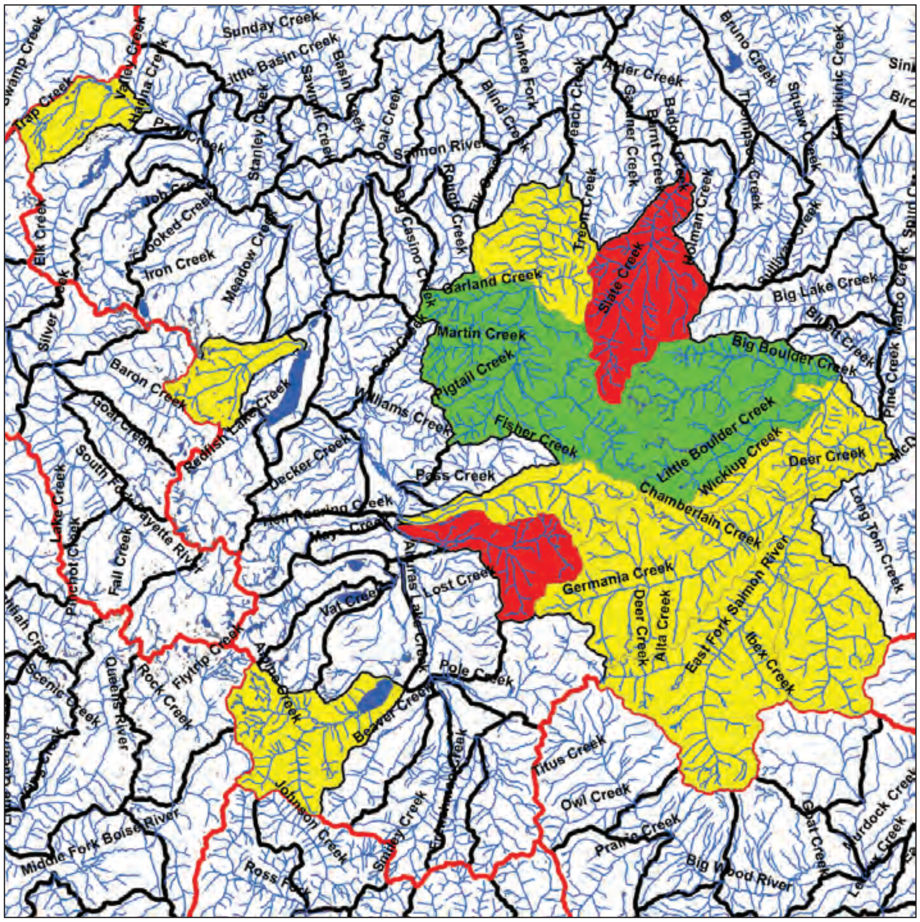


Figure 20—Predicted bull trout persistence in 2040 for subwatersheds in the Sawtooth National Recreation Area. Red-shaded subwatersheds are at high extinction risk, yellow-shaded are at moderate risk, and green are at low risk (subwatersheds without bull trout are not colored). Red lines are HUC-4 boundaries.

Pilot forest staff brought a variety of skills and backgrounds to their assessments. Some assessments were prepared by teams, some primarily by one person. In addition, there was great variation in the types and amount of available information. Despite these differences, each pilot forest was able to conduct an assessment and report the results in an effective way. There were many differences in how the individual steps were approached, and the results reflect these differences. All the vulnerability ratings were derived by combining values, sensitivity, and exposure. We believe that the performance of the pilots in completing meaningful assessments using the basic process should encourage other units desiring to conduct vulnerability assessments.

Important Considerations in Evaluating Vulnerability

- Identify where the location of water resource values overlaps with highest sensitivity and greatest exposure.
- Determine how changes in hydrologic processes affect water resource values.
- Determine the relative vulnerabilities of watersheds across the assessment area (e.g.: low, moderate, high) to inform priorities for adaptive response to predicted climate change.

Identify Adaptive Management Responses

> *Nobody made a greater mistake than he who did nothing because he could only do a little.*
>
> —Edmund Burke

Each pilot forest produced an assessment that effectively displays the location of water resources of concern, key climate change metrics, and watershed sensitivities of the resources to the projected changes. The combination of these elements yielded relative ratings of watershed vulnerability to climate change. As such, the assessments met the objective of providing managers with information necessary to identify priority areas to undertake management actions.

Management priorities should focus on maintaining or improving watershed resilience. Resilience is the capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly (Holling 1973). By definition, resilient watersheds are better able to continue delivery of ecosystem services when subjected to ecological change, including changes that might result from a warming climate. A related assumption is that watershed resilience is closely tied to watershed sensitivity. Watershed resilience is a product of both inherent sensitivity and anthropogenic influences on watershed condition.

Assessment Principle Six

Keep the end product in mind

A plethora of climate change exposure data are now available. Models are continually refined. The number, types, and detail of climate projections can be confusing and overwhelming. Managers and analysts should realize that projections have substantial uncertainty and that uncertainty grows with down-scaling and time.

Most pilot forests structured their analyses such that actual values for temperature changes, runoff changes, etc., were not critical. The focus was, instead, on the ranges and direction of projected changes.

This approach was appropriate, because the objective was to produce a relative vulnerability rating to inform decisions about priority areas for management.

Periodically reflecting on the goal—what decisions need to be informed—helps put the need for data and precision in perspective. The necessary depth of analysis is that which will produce these relative ratings.

The results of the WVAs will be useful in development of management options and strategies. This includes discussion of which vulnerability classes should be highest priority for management actions. If, for instance, a highly valued water resource has a very limited distribution, management options are limited. If the value is more widely dispersed, managers must decide if the most vulnerable areas should be highest priority, or if they should focus their efforts on sustaining the values in areas with lower vulnerability. Scale must be considered in this discussion. Naturally, for resources (especially species) whose range is greater than the analysis area, discussion of results with other land managers will be necessary.

The greatest value of WVA results is in identifying geographical areas that are priorities for actions designed to maintain or improve watershed resilience. Several pilot forests are already using the results to this end. The recently completed Watershed Condition Classification (fig. 21) led to the designation of priority subwatersheds for improvement actions. The connection of the WVA to setting these priorities is clear. One pilot forest (Coconino NF) applied WVA findings during this priority-setting process. On many national forests and grasslands, strategic plans have been developed to guide restoration and management efforts. In these cases, the vulnerability assessment process will be used to reassess existing priorities and to determine if changes are warranted. None of the pilot forests was engaged in land management planning during the WVA, but results have clear application to that effort in helping to identify priority areas for management.

One pilot forest (Ouachita NF) incorporated potential management actions in its sensitivity ratings. A tabular result from the Ouachita (table 8) displays the number of subwatersheds in different watershed risk classes. These ratings were derived from estimates of current and future sediment production. In this assessment, future changes to

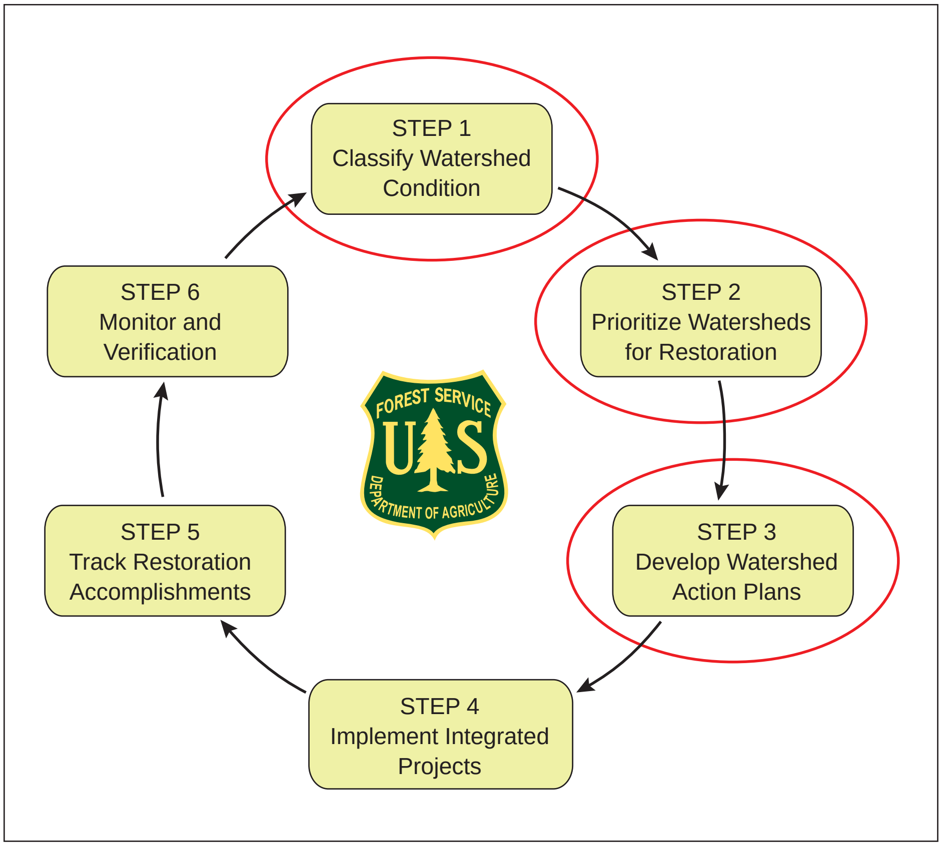


Figure 21—U.S. Department of Agriculture Forest Service Watershed Condition Framework. Watershed vulnerability assessments contribute directly to steps 1, 2, and 3.

Table 8—Vulnerability ratings (by risk class) of subwatersheds on the Ouachita National Forest, as influenced by climate change scenarios and application of road management actions (maintenance to standard and closure of user-created trails)

	Climate change scenarios					
Risk	2010 current	2010 with road management	2050 B1	2050 B1 with road management	2080 B1	2080 B1 with road management
High	88	82	93	85	93	85
Moderate	46	40	42	43	42	43
Low	56	68	55	62	55	62

	2050 A1B	2050 A1B with road management	2080 A1B	2080 A1B with road management
High	105	96	105	96
Moderate	44	43	45	43
Low	41	51	40	51

precipitation were predicted to increase sediment production, with subsequent impacts on aquatic communities. Shown are the projected change in watershed condition class caused by climate changes from conditions in 2010 to those projected for 2050 and 2080, and potential modifications to the response from road management activities. The analysis demonstrates that implementation of road management activities could reduce the number of subwatersheds with high risk ratings. In terms of setting priorities for management, subwatersheds where implementation of road improvements would reduce vulnerability should be considered for high priority.

Road improvements were identified as a key action to improve condition and resilience of watersheds on all the pilot forests. In addition to treatments that reduce erosion, road improvements can reduce the delivery of runoff from road segments to channels, prevent diversion of flow during large events, and restore aquatic habitat connectivity by providing for passage of aquatic organisms.

As stated previously, watershed sensitivity is determined by both inherent and management-related factors. Managers have no control over the inherent factors, so to improve resilience, efforts must be directed at anthropogenic influences such as instream flows, roads, rangeland, and vegetation management.

In subwatersheds with the highest vulnerability, any activity that maintains or increases water quantity or quality would ultimately be beneficial. In addition to roadwork, management actions to maintain or improve resilience could include contesting new water rights proposals, exploring ways to convert existing water rights into instream flows, improving conditions in grazing allotments, restoring natural function in meadows, and implementing silvicultural treatments aimed at moving toward more natural fire regimes.

Results from WVA can also help guide implementation of travel management planning by informing priority setting for decommissioning roads and road reconstruction/maintenance. As with the Ouachita NF example, disconnecting roads from the stream network is a key objective of such work. Similarly, WVA analysis could also help prioritize aquatic organism passage projects at road-stream crossings to allow migration by aquatic residents to suitable habitat as streamflow and temperatures change.

Pilot forests in the Rocky Mountains recognized the utility of WVA results in selecting the subset of high-vulnerability watersheds in areas with high pine beetle mortality. These areas are of high priority for upgrades of road-stream crossings to protect them from floods and debris flows. The same watersheds are also priorities for vegetation management to enhance natural reproduction, hydrologic recovery, stream shading, and future large woody debris recruitment. Both sets of actions would improve watershed condition and resilience.

Not all the findings in the vulnerability assessments are good news. In some cases, projected changes may indicate that maintaining certain water resources (especially aquatic species) may be extremely difficult, even with restoration or improved management. In such cases, results from the vulnerability assessment may be used to rethink local or broad-scale improvement or protection strategies to prioritize limited management resources.

The rating of vulnerability is based almost entirely on ecological considerations. Management activities are a key component in assessing watershed sensitivity, but only in terms of how they influence water resource values through hydrologic processes. Although such characteristics are significant, social, economic, and administrative factors may be more important in determining where management activities can be effectively undertaken. Such factors include availability of expertise, land ownership, the presence of willing partners, land and resource management planning guidance, and opportunities for internal or external funding. These factors need to be considered when determining where management activities should be focused.

Almost all the pilot forests encountered data gaps, and all encountered uncertainties during their analyses. Such data gaps (e.g., distribution of key species and uncertainty on road condition in key watersheds) can be used to identify inventory or monitoring priorities. Results from these efforts can, in turn, improve the utility of management and restoration plans.

It is noteworthy that the specific management activities discussed above, including road improvements, improving aquatic organism passage, thinning forests to improve stand resilience, and improving range condition, are not new treatments designed to address climate change. Rather, they are activities for which wildland resource managers have a long record of accomplishment. In land management and statutory jargon, they are established Best Management Practices (USDA FS 2012). Climate change increases the need for application of these practices nearly everywhere.

Important Considerations in Applying the Assessment Results

- Consider whether additional information, analysis, or consultation is needed before setting priorities.
- Identify approaches that can enhance resilience sufficiently to protect resource values.
- Consider which effects of climate change might be irreversible, and how that can inform priority setting.
- In places where vulnerabilities are high, can resource values be sustained?
- Determine how management actions from watershed vulnerability assessment can be integrated into existing programs and priorities.
- Identify management practices that would enhance resilience in both the short and long term, and assess the magnitude of treatment that would be required to meet improvement objectives.
- Determine if land ownership patterns and administrative status of National Forest System lands are conducive to planning and implementing treatments.
- Identify areas where partnerships would improve the likelihood of success.
- Determine if sufficient technical and financial capacity is available to implement treatments.

Critique the Assessment

Test fast, fail fast, adjust fast.

—Tom Peters

The purpose of the WVA pilot was to determine if worthwhile assessments could be conducted with available information and expertise. Within a relatively short period of time and despite limited funding and other pressing business, watershed and aquatic specialists from the pilot forests were able to develop a watershed-vulnerability approach and complete useful assessments. Four pilot forests were able to complete the process within 8 months, and an additional five were completed within a year.

With an eye toward sharing approaches and experiences, each pilot forest was asked to critique its assessment. These reviews are key in applying the principles of adaptive management to the vulnerability assessments. In this final section, we discuss how access to information affected the assessments and share additional lessons learned by the pilots.

Data Gaps and Uncertainty

Assessing the sensitivity and vulnerability of watersheds to climate change is complex. At each step of the assessment process, pilot forests encountered data gaps and uncertainty. Uncertainty was prevalent in estimates of exposure, but each analytical step contained some uncertainty (e.g., the expected response of hydrologic processes to climate change, and the response of aquatic resources to the hydrologic change).

Lack of information also contributes to uncertainty; at the least, it limits the detail of the assessment. Every pilot forest identified data needs, and each made assumptions about system responses and interactions. These were captured in the pilot reports as monitoring needs and included validating assumptions made in the assessment, tracking trends in key resource values, and providing data to inform key adaptive responses.

Acquiring and applying data to improve the analysis would produce assessments with a higher level of confidence, but lack of data should not be used as a reason for not conducting an assessment. Some pilot forests were datarich, in terms of water resource, watershed sensitivity, and exposure information, and some were data-poor. Despite these differences, all were able to apply the available information and complete a vulnerability assessment. Again, the objective of producing a relative rating of vulnerability (rather than a more rigorous, quantitative description of vulnerability) explains the favorable outcome.

Other Lessons Learned

The pilot assessment effort was successful in that it demonstrated that vulnerability assessments could be completed by national forest staff using existing information and tools. Some of the primary reasons for this success have already been discussed; a few others are worth noting.

Although we have discussed how availability of data influenced the results, we have not articulated the importance of the data format. National forests with digital data progressed much faster than those that had to convert paper summaries to digital formats. In some cases, lack of useable data caused elements of the assessment (e.g., sensitivity factors) to be deferred. Ideally, necessary data would be gathered and prepared in anticipation of assessments. A credible expectation that watershed vulnerability assessments will occur could help make this happen.

Connection of the pilot forests with ongoing climate change research and experienced scientists resulted in a more detailed analysis. The partnership between the Sawtooth NF and RMRS yielded the most detailed pilot assessment. Collaborative work in downscaling climate change projections to assess potential changes in stream temperature was underway, and was well utilized by the Sawtooth. Connection to sources of exposure data (especially CIG) also aided pilot forests.

As with most endeavors, the resulting products were strongly influenced by the experience and expertise of those participating. Participants with the greatest localized knowledge of forest resources and interactions tended to have the easiest time with the process. Use of the pilot participants as trainers or facilitators for future assessments would streamline and focus those efforts.

At the outset of the pilot project, several national forests declined to participate, owing to other priorities. The reality is that all participating national forests managed to work on the WVA despite heavy workloads. Agreeing to participate in the WVA process reflected recognition of the potential value of conducting WVAs. Pilot forests where line and staff were more engaged with the assessments made resources (interdisciplinary team members and geographic information system expertise) available to project leads, generally completed assessments sooner, and produced assessments of greater depth and detail.

Recently available electronic communication tools that facilitate information exchange proved extremely useful to the pilot effort. The pilot project applied both a collaborative Web space (a wiki bulletin board and a file repository) and videoconferencing to great advantage. Pilot leads were located across the country; monthly videoconferencing facilitated sharing of information and approaches, and helped cultivate a community of practice. The collaborative Web space proved a very effective means of sharing written information, publications, announcements, and Web links. The exchange of information enabled team members to learn from each other about processes and approaches that were working, and those that were posing difficulties. As a result, individual pilot efforts were strongly influenced

The Forest Service
Climate Change Resource Center

The Climate Change Resource Center (CCRC) (http://www.fs.fed.us/ccrc) provides land managers with an online portal to science-based information and tools concerning climate change and ecosystem management options. The CCRC’s objectives are to

- Synthesize scientific literature on ecosystem response, adaptation, and mitigation;
- Highlight recent scientific research that has practical applications for practitioners on public and private lands;
- Support communication of information through a user-friendly interface and appropriate use of multimedia; and
- Work with scientists to develop educational resources.

by each other. Readers who anticipate conducting an assessment are encouraged to contact members of the pilot assessment team, who can provide advice and counsel.

Finally, it is clear that establishing an analytical methodology was of great value. As the WVA pilots evolved, participants made modifications to meet their needs, but the basic approach provided a consistent framework for pilot forests to apply. The success of the pilots, which encompass a wide range of geographies, uses, and sensitivities, demonstrates that the conceptual basis of the approach is sound and likely applicable across the entire NFS. It will probably be applicable for all types of climate vulnerability assessments, not just water resources. Also of note is that we defined the component vulnerability terms at the outset, as this can be a source of confusion and unproductive debate; consistently sticking to and applying the terminology throughout the process assisted in moving the assessments forward.

Summary

Observations clearly demonstrate that the Earth's climate is warming and ecosystems are changing in response. Climate models predict substantial additional changes to worldwide temperatures and hydrologic processes throughout the 21st century. These changes will have complex and variable effects on the Nation's watersheds and affect their ability to sustain the ecosystem services upon which people depend. These effects pose significant challenges to the Forest Service and other land management agencies. To date, limited resources have been directed specifically towards planning for or responding to these changes on national forests and grasslands. This is largely because managers have limited experience applying global- or regional-scale climate change information at the local scale. This has led to uncertainties about likely impacts and appropriate responses for individual national forests or grasslands.

To address this need, we implemented a Pilot Watershed Vulnerability Assessment Project that developed and tested a process that national forest personnel can use to complete useful, locally based assessments of water resource vulnerability to climate change. These evaluations followed a process patterned after watershed analysis on federal lands in the Pacific Northwest (USDA FS 1995). The assessments covered relatively large areas (e.g., entire national forests) with modest investments of time and effort. Regional climate projections, local historical data, and the Watershed Condition Classification recently completed by all national forests in the United States (http://www.fs.fed.us/publications/watershed) provided a solid base of information to support the assessments.

In conducting the vulnerability assessments, forest staff became familiar with available historical climate data and climate projections for their geographic areas. Sorting through this information and learning how to use it was an important step in the process. Many forests found that partners had already compiled climate data and projections that could be used for the forest-level assessments. Knowing future climates precisely or accurately is not possible, but this was not a barrier to producing effective, efficient, informative assessments.

In addition to climate data, the pilot assessments used existing information on watershed sensitivity and water resource values, data with which land managers are familiar and rely upon in many resource decisionmaking processes. The resulting assessments provided place-based identification of priority areas, with discernment of the watersheds most vulnerable and most resilient to climate change.

Assessing vulnerability is the essential first step in adapting to climate change, and this information provides a basis for managers to target investment of limited resources to sustain or improve watershed resilience. The good news is that the knowledge and tools to maintain and improve watershed resilience are already in place, while the National Watershed Condition Framework (USDA 2011a) serves as a foundation for setting priorities and restoring watersheds and watershed services. Other Forest Service programs to improve watersheds, meadows, and streams include diverse partners and programs across the country (Furniss et al. 2010). Implementation of this wide array of management activities is supported by decades of technical experience in planning, analysis, and collaboration. These existing core strengths can be effectively applied to address the growing challenge to public natural resources posed by our changing climate.

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Appendix: Pilot National Forest Reports

The 11 pilot reports discussed in this report are available online only at http:/www.fs.fed.us/pnw/pubs/pnw_gtr884_appendix.pdf.

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