SCOTT RIVER WATER YIELD ENHANCEMENT STUDY

PHASE I REPORT

Roger Bales and Robert York

Report to:

Scott River Watershed Cooperative Planning Group
P.O. Box 342, Ft. Jones, CA 96032

April 5, 2014

Table of contents

1. Executive summary

The goal of this study is to provide information to support evaluation of the potential to enhance water supply in the Scott River by managing upslope forest vegetation. The scope of this study involves investigating relationships between stream water yield and upland forest densities in the Sugar Creek sub-watershed of the Scott River, and estimating any potential to enhance water yield in the Scott River by managing upslope forest vegetation. This report covers Task 1 of the study, which is to develop a study plan for a more in-depth investigation.

Sugar Creek and other forested headwater basins provide the year-round flow in the Scott River, plus water for multiple consumptive uses in the area. Water diversions from headwater streams provide the water for irrigation and stock-water beneficial uses in the valley below. Sugar Creek was chosen for this analysis in part because its apparent high-density forests, topography and soils are representative of the main runoff-producing Scott River basin headwaters. The upper part of the 32.7 km^2 (8080 ac) Sugar Creek basin has dense but patchy stands of trees; the middle part is very dense, continuous canopy cover; and the lower part of the basin has dense vegetation near Sugar Creek and on north-facing slopes, but sparser vegetation on south-facing slopes.

Winter precipitation is rain dominated at the lower elevations, below about 1200 m (4000 ft), transitioning to snow dominated above about 1500 m (5000 ft). The higher elevations, especially above about 1800 m (6000 ft), have short summers and relatively long winters with deep snowpacks. Thus vegetation growth in the lower part of the Sugar Creek basin may be in part water limited, especially in areas with shallow or fast-draining soils; and the upper part of the basin may be cold limited part of the year. Although most precipitation falls winter through spring, there may be short periods of locally intense rainfall from summer thunderstorms.

Understanding past forest structure and the disturbance regime that sustained this structure is critical for prioritizing management that seeks to build forest resilience to future stressors. Prior to the current era of active fire suppression, forests of the Klamath Mountains were defined by periodic and variable-severity fires. This landscape looked much different than it does today in three primary ways: 1) Overall density was kept much lower by frequent fires; 2) Structural heterogeneity (i.e. canopy gaps) was much higher from fires of variable severity; 3) Ponderosa pine was much more abundant in both the over- and understory. This information, coupled with site-specific information about current forest structure, can guide the development of prescriptions for areas such as the Sugar Creek watershed. Treatments can be designed to meet the mutually beneficial objectives of reducing fire severity, building resilience to drought stress, and increasing water yield, while maintaining other ecosystem services.

Generalizations from reviews of paired-catchment studies suggest that the Klamath conifer forest has ecological attributes with a high potential for water-yield gains. Using a simple estimation procedure that is based on observation from paired catchment studies around the world, we estimated that on average, treatments that reduce forest cover from 90 to 30% canopy cover across a watershed were projected to increase runoff by 38 mm (1.5 in), 128 mm (5 in), 207 mm (8 in) and 261 mm (10 in) for precipitation amounts of 500, 1000, 1500 and 2000 mm (20, 39, 59, 79 in) respectively. Thus the additional water amount would be higher with higher precipitation, and lower if there was less vegetation removal.

While there are limited hydrologic and meteorological measurements in the Sugar Creek basin, there are many stations in the vicinity that can be used to develop time-series temperature and precipitation data for use in the modeling. There are few streamflow measurements, and those that are reported are heavily affected by diversions. There is no available continuous, long-term record of diversions, and considerable effort will be needed to develop estimates. It is will be necessary to carry out the modeling without accurate stream-discharge data, though the available data can inform parameter estimation, particularly during seasons when diversions are either known or small. It is proposed to use satellite-snowcover data as an additional constraint on the hydrologic modeling, plus transfer some parameterization from Sierra Nevada basins with similar vegetation densities and climate patterns. A field measurement program is proposed to develop vegetation data for both thinning prescriptions and hydrologic modeling.

It is proposed to use the RHESSys modeling package for the next phase of this work, to integrate data and make estimates of evapotranspiration and streamflow for the various historical and future climate and vegetation scenarios. RHESSys is a spatially explicit, daily time step model, and is being extensively used for similar purposes across the mountains of the Western United States.

2. Introduction

2.1. Regional setting

The Klamath Mountains are the headwaters for several tributaries of the Klamath River, including the 97-km (60-mi) long Scott River, in Siskyou County (Figure 2.1). The Scott River and its tributaries support several species of anadromous fish, including Chinook salmon, coho salmon, and steelhead trout. Coho Salmon in the Klamath Basin are listed as threatened under both the State and Federal Endangered Species Acts. The Scott River is also listed as impaired under section 303(d) of the Clean Water Act for violation of water-quality standards for stream temperature and sediment. It has been reported that low water levels in Scott River tributaries can limit suitable over-summering habitat for juvenile coho and steelhead during the late summer and prevent adult Chinook and coho salmon from getting upriver to prime spawning areas in the Scott Valley during the fall months. There are both temperature and other water-quality issues associated with low flows. Low flows from headwater streams can affect riparian features important for habitats, as well as in-stream water levels, pools and other features. In dry years the main stem of the Scott River completely dries up, and the only available habitat is located in the smaller tributaries. Stream flows are often too low for the fall migration of coho salmon, which are blocked from passing the lower reaches. The U.S. Forest Service holds adjudicated water rights to in-stream flows in the Scott River that are considered the minimum subsistence-level flows needed for fish survival. Historical streamflow records show that in most years, summer and fall flows are not adequate to fully meet the Forest Service allotment (CA DWR, 1991). A review of recent records shows that flow was below the Forest Service allotment in at least one month in 17 of the past 20 years. Thus there is interest in improving stream flow for salmon and steelhead at critical periods of their life cycles in the Scott River stream system while economically protecting Scott Valley's family farms and ranches.

The climate of the area is referred to as montane Mediterranean, with cold wet winters and hot dry summers. Average annual precipitation is estimated to range from below 50 cm (20 in) at the lowest elevations along the Scott River to greater than 150 cm (60 in) at the highest elevations. The Scott Valley lies in the rain shadow of several mountain ranges between it and the Pacific Ocean. While the eastern slopes of the Scott, Salmon, and Marble Mountains receive large amounts of precipitation, the Scott Bar Mountains, Scott Valley, and the surrounding foothills to the east receive noticeably less. Historically, low stream flows in the Scott River have been attributed partly to climate change, and partly to increased consumptive irrigation use and groundwater pumping (Van Kirk and Naman, 2008; Drake et al. 2000). Only in recent years has the influence of vegetation density in headwater areas on runoff and thus on streamflow been considered.

The northerly flowing Scott River in the 2100 km^2 (815 mi^2) Scott River watershed begins in the Scott Mountains. Its east fork originates on the slopes of China Mountain (2600 m, 8540 ft), just north of Mount Eddy. Its south fork starts at South Fork Lakes near the convergence of the Scott and Salmon mountains and Trinity Alps. This ridge crest is the divide between the Scott and Trinity rivers. The northern slopes are dotted with subalpine lakes and open forests. Mountainsides are moderately steep, with about half exceeding a 15 percent slope. The north-facing drainages present many glacial features, including a rock glacier on the north side of Cory Peak (2350 m, 7700 ft.) (Sawyer 2006). Figure 2.2 shows the watersheds in the vicinity of the Scott River basin.

The Salmon and Marble mountains form the western boundary of the Scott Valley. In contrast to the Scott Mountains, which contains serpentine substrates, the Salmons are mainly granites of the Russian Peak batholith, and beautiful subalpine lakes are concentrated near Russian Peak (2500 m, 8190 ft).

The Scott Bar Mountains form the northeastern boundary of the Scott River watershed. Peaks, such as Deadwood Baldy Peak (1840 m, 6045 ft) and Indian Peak Baldy (1735 m, 5695 ft), are sufficiently low that these mountains show little effect of glaciation. The still-lower Greenhorn Mountains, with Paleozoic and Mesozoic rocks, represent the eastern boundary of the Scott Valley country. Duzel Rock (1840 m, 6040 ft.), a noticeable capstone of limestone, is prominent on the eastern ridgeline (Sawyer, 2006).

The Scott Valley supports both grazing and irrigated cropland, and includes the towns of Callahan, Fort Jones, Etna and Greenview. Gold-recovery operations in the area started with the Gold Rush and continued well into the Twentieth century, including substantial dredging for gold along the Scott River. Until the 1990s Scott Valley's economy relied heavily on logging, though more recently the industry has been more limited (KARE, 2014).

Sugar Creek and other headwater basins provide the year-round flow in the Scott River, plus water for multiple consumptive uses in the area. Water diversions from headwater streams provide the water for irrigation and stock-water beneficial uses in the valley below.

The Klamath Mountains, including the western and southern Scott River headwaters, support a dense and diverse conifer forest, much of which is managed by the Klamath National Forest. Fire suppression/prevention policies began in the region in the 1920s, although effectiveness of suppression efforts came later. Before this, American Indians and early settlers regularly set fires and let natural wildfires burn. The last large fire in the Callahan watershed (>40 ha, or 100 acres) occurred in 1957 (USDA, 1997). The Callahan watershed includes southern and western tributaries to the Scott River, from Boulder Creek in the south to Etna Willow Creek in the west. Fire suppression in this area, and across much of the region, has altered vegetative succession and the spatial arrangement of vegetative types. Natural fuels buildup, increased densities of forested stands, activity fuels from timber harvest, a warmer climate and an increased wildland-urban interface have increased the likelihood of catastrophic fire.

Prior to fire suppression, forest structure was dominated by open stands of large conifers. Meadows, shrub fields, and patches of small trees were found throughout the watershed (USDA, 1997). Differences in forest density in the Klamath National forest can be seen in repeat photos taken in 1934 from fire lookout towers, and 1991 from the same locations. While not quantitative measures, they support reconstruction studies done in this area and illustrate increases in tree density on some slopes between these two times (Figure 2.3a-d).

2.2. Ecosystem Services

Mountain forests deliver important benefits to the citizens of California and the rest of the world. With the extensive exploitation that began with the 1849 gold rush, these forests provided considerable timber, feed for grazing animals, and irrigation water for local agriculture. Other benefits, or “ecosystem services” derived from these forests include clean air, fresh water, wildlife habitats, nutrient cycling, carbon storage, and recreational opportunities. The concept of valuing ecosystem services has recently received considerable attention as a means to ensure investment and management of sustainable ecosystems (e.g., Millennium Ecosystem Assessment 2003, Collins and Larry 2007, Daily and Matson 2008, Smail and Lewis 2009).

One of the most valuable services provided by forests in the Scott River headwaters is the clean water that flows downhill to fuel the region’s economy and support freshwater and terrestrial ecosystems. At the higher elevations much of the winter precipitation falls as snow. The slow melting of snow in the spring and storage of water in the subsurface provide the water necessary for vegetation to grow as well as the flows of water for downstream use. Snowpack retention is a valuable ecosystem service, but the forest landowners who provide this service derive no economic return from this service.

The Klamath National Forest has received multiple requests from the public to use harvest activity to meet multiple goals, including increasing water yields in the Scott River. It is generally believed that the low flows in the Scott River are due to an increase in evapotranspiration caused by an increase in forest density, with species shifts from pine to fir also playing a role. Fire suppression over the past century has caused local forests to change from low-density ponderosa pine-dominated stands to high-density fir-dominated stands. The public has demanded that forest treatments be designed to simultaneously restore stream flows for coho salmon, reduce the threat of high-severity wildfires, and produce commercial timber products (personal communication, Ray Haupt).

The Forest Service has targeted the Scott River as part of a nationwide initiative to pursue opportunities for ecological restoration. This restoration project aims to initiate and accelerate ecosystem recovery through active management, including commercial thinning. The overall goal is increased ecosystem resilience, and preparing natural systems to better absorb future stressors while maintaining function.

A challenge to planning any water-yield enhancement project on National Forest lands is meeting agency policy which states in part:

> “Where Forest plans indicate a need for both increased water and available storage to recover the increased yield, evaluate opportunities to enhance existing water supplies. Implement enhancement practices only if cost-effective, environmentally and scientifically feasible, and consistent with other resource uses and values” (FSM 2522.12.a).

2.3. Climate change and the mountain water cycle

California’s water supply is particularly vulnerable to the forces of climate change. This vulnerability is due to both the supply of water and the infrastructure built to manage this water

(Department of Water Resources 2010). General-circulation models project generally drier conditions in California, particularly with regard to water supply (Vicuna 2006). Specifically, they project that critical water shortages will become more common compared to the historical record. It is worth noting that the projections of reduced precipitation are less certain and less severe than the predicted temperature increases (Miller et al. 2009). By 2050, snowpack storage is expected to decline by 25% because of a warming climate (Department of Water Resources 2008). Warmer temperatures lead to more precipitation falling as rain and an earlier snowmelt (Kapnick and Hall 2010). Less precipitation falling as snow means less storage and a greater potential for high peak flows followed by drier periods. This change will lead to the loss of considerable economic value as less water will be available for irrigating crops and in some areas less hydroelectric power will be available to match high summer electricity demands. The warming, drying climate will have direct negative effects on supply of water from and storage of water within mountain forests.

One of the few ways that California can address the negative impacts of climate change on water yield and storage is through changes to the forest vegetation. At the most basic level, trees move water from the soil to the atmosphere, reducing surface flow and downstream yield. In the winter, a portion of the snow caught in branches evaporates or sublimates and reenters the atmosphere without ever melting. Reducing the total amount of evapotranspiration from vegetation could potentially increase the amount of water flowing downstream. Reducing the current forest canopy cover and related evapotranspiration could also bring forest stands closer to historic conditions where regular fires across the landscape resulted in much lower levels of forest canopy cover than we have today (Collins 2011). Further, these treatments can be designed to reduce fire hazard, build resilience to drought stress by improving tree vigor, and supply commercial timber. Regional water budgets suggest that around 70 percent of total precipitation is evapotranspired by native vegetation in the Sierra Nevada and other inland mountains of Northern California (Department of Water Resources 2005). The density of trees can also affect the storage of snow in a forest. In general, overly dense forest stand structures result in a higher proportion of snowpack in tree canopies rather than on the forest floor, where it is more protected from solar radiation. Therefore, a relatively open stand structure consisting of fewer, larger trees where understory vegetation is controlled could enhance snowpack retention. The impacts of specific forest-management prescriptions on water yield and snowpack involve multiple factors. The need for site-specific analysis of the link between forests and water is the key motivation for this project.

2.4. Scope of report

The goal of this study is to provide information to support evaluation of the potential to enhance water supply in the Scott River by managing upslope forest vegetation. Specific questions that motivated this study follow.

1. Has past forest management and fire suppression caused a reduction in streamflow that is detrimental to fisheries?
2. Will fuels treatments typically used to reduce the threat of wildfire also restore and maintain in-stream flows that are beneficial to fisheries?

3. Can restoration projects be designed to maintain maximum streamflow for fisheries while meeting Forest Plan standards for other resources and uses
4. Can the vegetation treatments be designed to provide a supply of commercial timber?

The scope of this study involves investigating relationships between stream water yield and upland forest densities in the Sugar Creek sub-watershed of the Scott River, and estimating any potential to enhance water yield in the Scott River by managing upslope forest vegetation.

This report covers Task 1 of the study, which is to develop a study plan for a more in-depth investigation. This plan includes:

1. A study design, schedule, and proposed budget. This will included compiling relevant, readily available data and information, and identifying additional information needs.
2. A review of the literature and its relevance to conditions in the Scott River. It will include a review of conditions in the Scott River basin, as reflected in ground-based and satellite data, in order to develop hypotheses regarding the impact of forest management actions on the forest water balance.
3. Data and information about past and current vegetation structure, as well as Forest Plan standards for future treatments will be provided to the contractor in the early phases of this task in order to incorporate this information into the study plan.

Task 1 also includes a site visit to assess local conditions, assess data availability, and meet with USFS staff to help define scope of study. The deliverable is this report.

Task 2 involves presentation of the project plan to stakeholders in the Scott Valley, and revision based on comments received:

1. Present project plans, along with supporting data and information, in an online format, via the www.
2. Present the project plan in a public meeting to be organized by the USFS and the Advisory Committee. Conduct a question and answer session to identify issues to include in the final study plan.
3. Provide written answers to written questions, provided by the Advisory Committee.

References

CA DWR, 1991. Scott River Flow Augmentation Study, California Department of Water Resources, Northern District, 137 pp.

USDA, 1997. Callahan Ecosystem Analysis. Scott River Ranger District, Klamath National Forest.148 pp.

Drake, Daniel., Tate, Kenneth., Carlson, Harry. (2000) “Analysis shows climate-caused decreases in Scott River Fall Flows” *California Agriculture*, Vol 54 n6, pp46-49

van Kirk, R.W. and Naman, S.W. (2008) Relative effects of climate and water use on base-flow trends in the lower Klamath basin, J. American Water Resources Association 44:4:1035-1052.

Sawyer, J.O. (2006) Northwest California: A Natural History. University of California Press, Berkeley, CA.264 pp.

KARE (2014) Timber Harvest Levels on the Major National Forests in Siskiyou County, http://www.klamathalliance.org/education/HarvestLevels.php, accessed February 1, 2014.

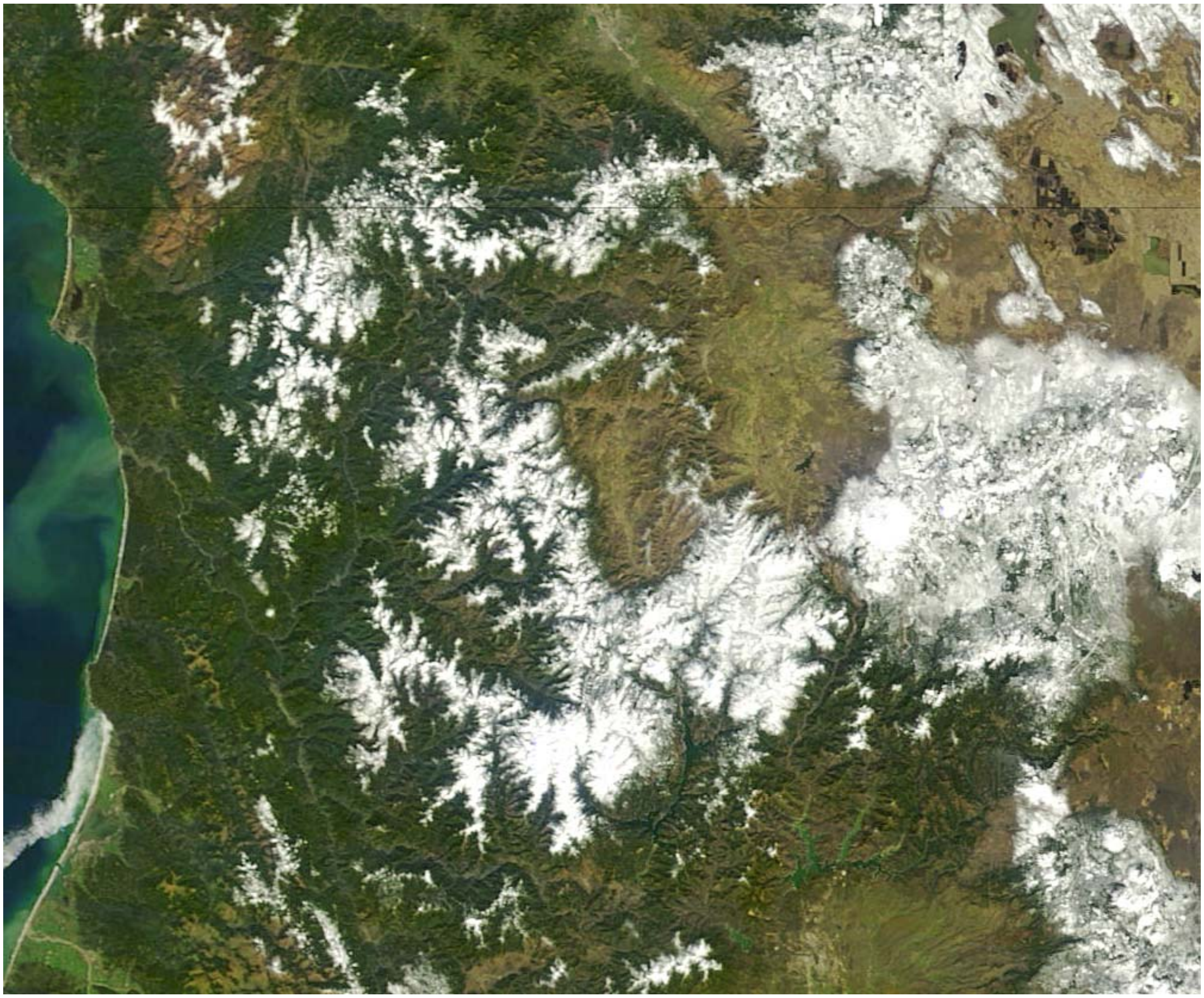

Figure 2.1. MODIS false-color image of Klamath Mountains and surrounding area, March 7, 2004. Image was acquired following heavy rain and snow in late February 2004. The Scott Valley is visible in the center of the image.

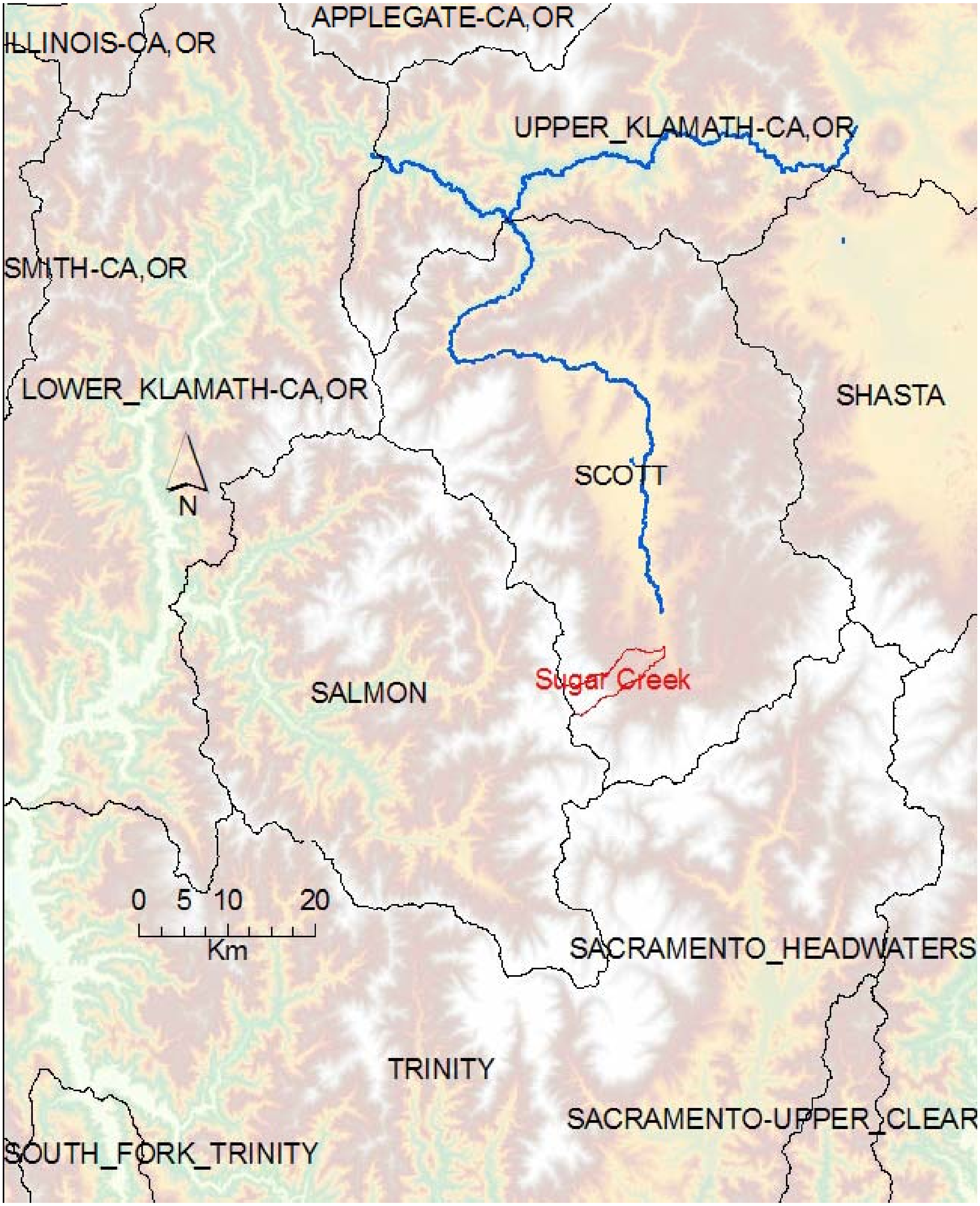

Figure 2.2. HUC-8 watersheds in the vicinity, plus outline for Sugar Creek. Background shows topography. A portion of the Scot River and Klamath Rive r are also shown. Background colors indicate elevation, going from low (green) to mid (yellow and brown) to high (white) elevation.

Figure2.3a. Repeat photos from Quartz Hill lookout.

Figure 2.3b. Repeat photos from Duzel Rock Fire lookout.

Figure 2.3c. Repeat photos from Marble Mountain lookout.

Figure 2.3d. Repeat photos from Deadwood lookout.

3. Study area description

3.1. Geographic setting

The Sugar Creek watershed (41.31 N, 122.88 W) is a 32.7 km^2 (8080 ac) hydrologic drainage in the headwaters of the Scott River basin (Figure 3-1). It was chosen for this analysis in part because its apparent high-density forests, topography and soils are representative of the main runoff-producing Scott River basin headwaters. Much of the following information on the geographic setting is taken from a Klamath National Forest report (USDA, 1997).

The watershed contains rocky peaks and steep, forested slopes below its western divide with the Upper South Fork Salmon River basin. Elevations range from 2460 m (8200 ft) at the highest point on this divide, to 907 m (3020 ft) at its confluence with the Scott River near Callahan (Figure 3-2). California State Highway 3, which connects the towns of Etna and Callahan, provides access to this confluence. Unpaved roads, including Siskyou County Road 2G001 and Klamath National Forest road 40N09, provide access to the lower half of the Sugar Creek basin.

The upper part of the Sugar Creek basin has dense but patchy stands of trees; the middle part is very dense, continuous canopy cover; and the lower part of the basin has dense vegetation near Sugar Creek and on north-facing slopes, but sparser vegetation on south-facing slopes (Figures 3-3 and 3-4).

The upper part of the Sugar Creek basin is in the Russian Wilderness, Klamath National Forest; the middle part is a mix of national forest and Timbervest ownership; and the lower part includes other private landowners and one small BLM parcel. The Sugar Creek Research Natural Area (RNA) is also in the upper part of the basin, lying almost entirely in the Russian Wilderness. This RNA designation stems from the occurrence of a unique and rich diversity of conifer species. The RNA is for research concerning the conifer species mix, with heavy recreational use being discouraged.

3.2. Geology and soils

The Klamath Mountains region consists of numerous oceanic terranes representing fragments of crustal material that were embedded into the western margin of North America since Early Paleozoic time. A succession of terranes moved eastward on the ancient Farallon plate and collided with the North American plate between 260 and about 130 million years ago. Each accretion left a terrane of rock of a single age. The fragments include metamorphosed volcanic and sedimentary rocks that represent volcanic island arcs, submarine plateaus, reeflike bodies of limestone, and deep ocean sediments that were intensely deformed during accretion. During the accretion, subduction of the plate metamorphosed the overlying rock and produced magma that intruded the overlying rock as plutons. Serpentinite, produced by the metamorphism of basaltic oceanic rocks, and intrusive rocks of gabbroic to granodiorite composition are common rocks within the Klamath terranes. Its mix of granitic, sedimentary, metamorphic, and extrusive rocks contrasts with the predominantly volcanic rocks of the Cascades to the northeast.

The region has extensive exposures of mafics and ophiolites, sequences of igneous rocks thought to represent disrupted oceanic lithosphere. Ophiolites consist of upper mantle peridotite overlain by layered and massive gabbro, sheeted basalt dikes, and basaltic pillow lavas. The bedrock of the Klamath Mountains province has strong similarities with the Sierra Nevada to the south, and can be considered as a northwest continuation of the geologic patterns of the later. In both areas, metamorphic bedrock comprising multiple terranes is intruded by Mesozoic granite plutons and overlain by Cenozoic-age sedimentary and volcanic rocks. The rocks comprising some of the Klamath Mountains terranes are almost identical in type, age, and origin to those of the northern Sierra Nevada.

Landforms at higher elevations have been shaped by glaciers in the last ice age. Glacial-scoured bowls of exposed bedrock, lush valleys, and high mountain lakes are common in the region. Mid-slope areas are composed of mountain side slopes, dormant earth flows, and inner gorges. The large, nearly level Scott Valley below the mouth of Sugar Creek consists of mixed alluvium washed down from slopes above. The geology of the area is a complex of several geologic terranes and many identified formations and rock types. The upper part of the Sugar Creek basin is granitic. The other two major rock types in the region, ultramafic, and metamorphic, are found in the lower part of the basin (Figure 3-5).

Soils of the Klamath Mountains range from very shallow to very deep and are well drained to excessively drained and have medium textured to moderately course textures. Soils derived from granitic parent material are noncohesive and usually highly erodible. Extensive granitic soils are found in the Scott River watershed, mainly on the south and west sides of Scott Valley (Harter and Hines, 2008).

Soils reflect the geologic parent material. Mid-slope unglaciated areas contain shallow to deeply weathered soils on steep to gentle side slopes. Vegetation types reflect underlying soils, with conifers preferring moister sites with deeper soils. Ponderosa pine mixed conifer is more prevalent on drier south and west aspects within the zone. Jeffrey pine mixed conifer is found on harsher sites primarily the ultramafic and serpentine soils, with incense cedar also found on these soils. Douglas-fir and white fir mixed conifer communities are found on moister sites north and east aspects and often at higher elevations than the pine mixed conifers.

3.3. Forests, land use & management

Vegetation varies with elevation, rainfall, exposure, and soils. The highest-elevation sites, above 1800 m (6000 ft), are dominated by red and white fir with a rich diversity of associated tree species including Engelmann spruce, brewer spruce, fox tail pine, subalpine fir, western white pine, and mountain hemlock (Figure 3-6). Alpine meadows and sparsely vegetated rocky areas are also found at the higher elevations (Figures 3-2 and 3-3). Mid elevations contain mixed-conifer stands dominated by white fir and Douglas fir above 1200 m (4000 ft) and Douglas fir/ponderosa pine down to about 1200 m (3000 ft). Jeffery pine and incense cedar are the primary species on the ultramafic soils.

Winter precipitation is rain dominated at the lower elevations, below about 1200 m (4000 ft), transitioning to snow dominated above about 1500 m (5000 ft). The higher elevations, especially above about 1800 m (6000 ft), have short summers and relatively long winters with deep snowpacks. Thus vegetation growth in the lower part of the Sugar Creek basin may be in part water limited, especially in areas with shallow or fast-draining soils; and the upper part of the basin may be cold limited part of the year. Although most precipitation falls winter through spring, there may be short periods of locally intense rainfall from summer thunderstorms. Streamflows are reported to be highest during warm winter rains and rain-on-snow events, generally between November and March. Flooding is often associated with these events. Although Sugar Creek is perennial, streams on the east side of the river may be dry by late summer or early fall.

References

USDA, 1997. Callahan Ecosystem Analysis. Scott River Ranger District, Klamath National Forest.148 pp.

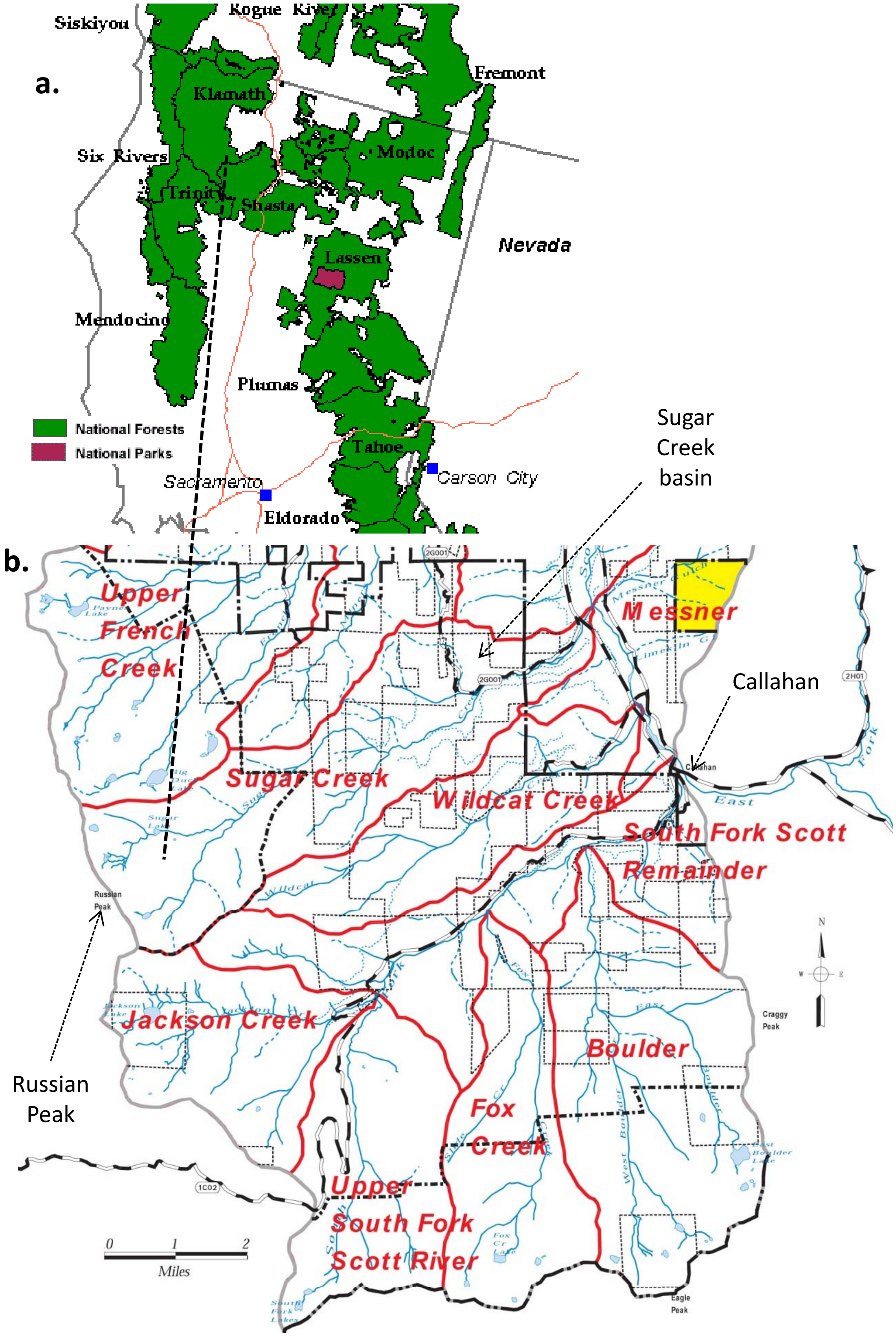

Figure 3.1. Sugar Creek basin location map: a) Northern California, b) Southwest portion of Upper Scott River basin. Adapted from USDA (2007).

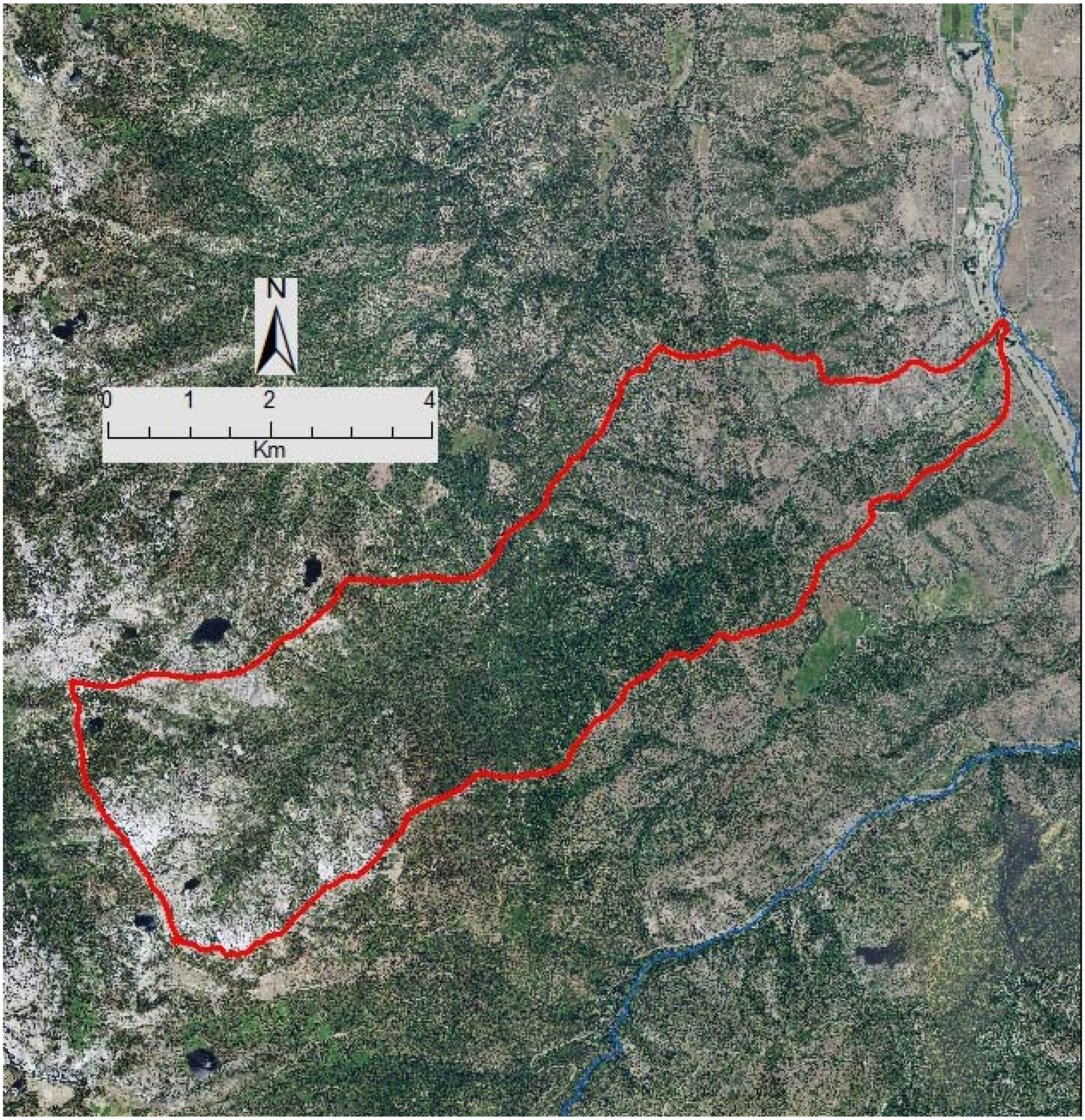

Figure 3.2. Digital ortho quarter quad (DOQQ) showing outline of Sugar Creek basin

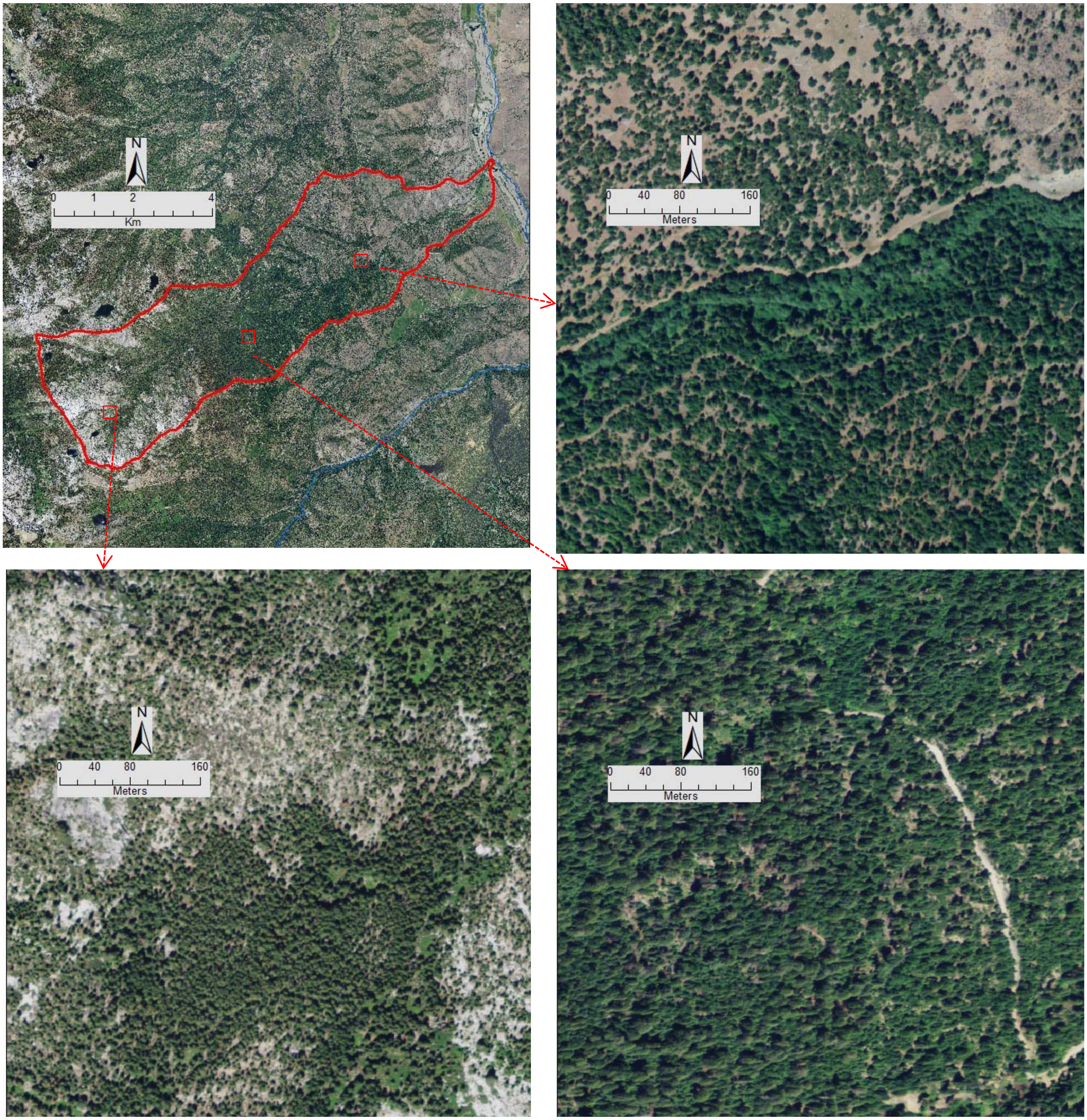

Figure 3.3. Digital ortho quarter quad (DOQQ) showing: a) Sugar Creek basin, b) zoom of dense but patchy upper-elevation forest, c) dense mid elevation forest, and d) lower elevation with sparse vegetation on south-facing and dense on north-facing slope.

Figure 3.4. Summer 2013 photos showing: a) dense mid-elevation forest in Sugar Creek area, b) dense mid-elevation forest within Sugar Creek basin, c) dense mid elevation forest along Sugar Creek, and d) lower elevation south-facing forest with less-dense vegetation.

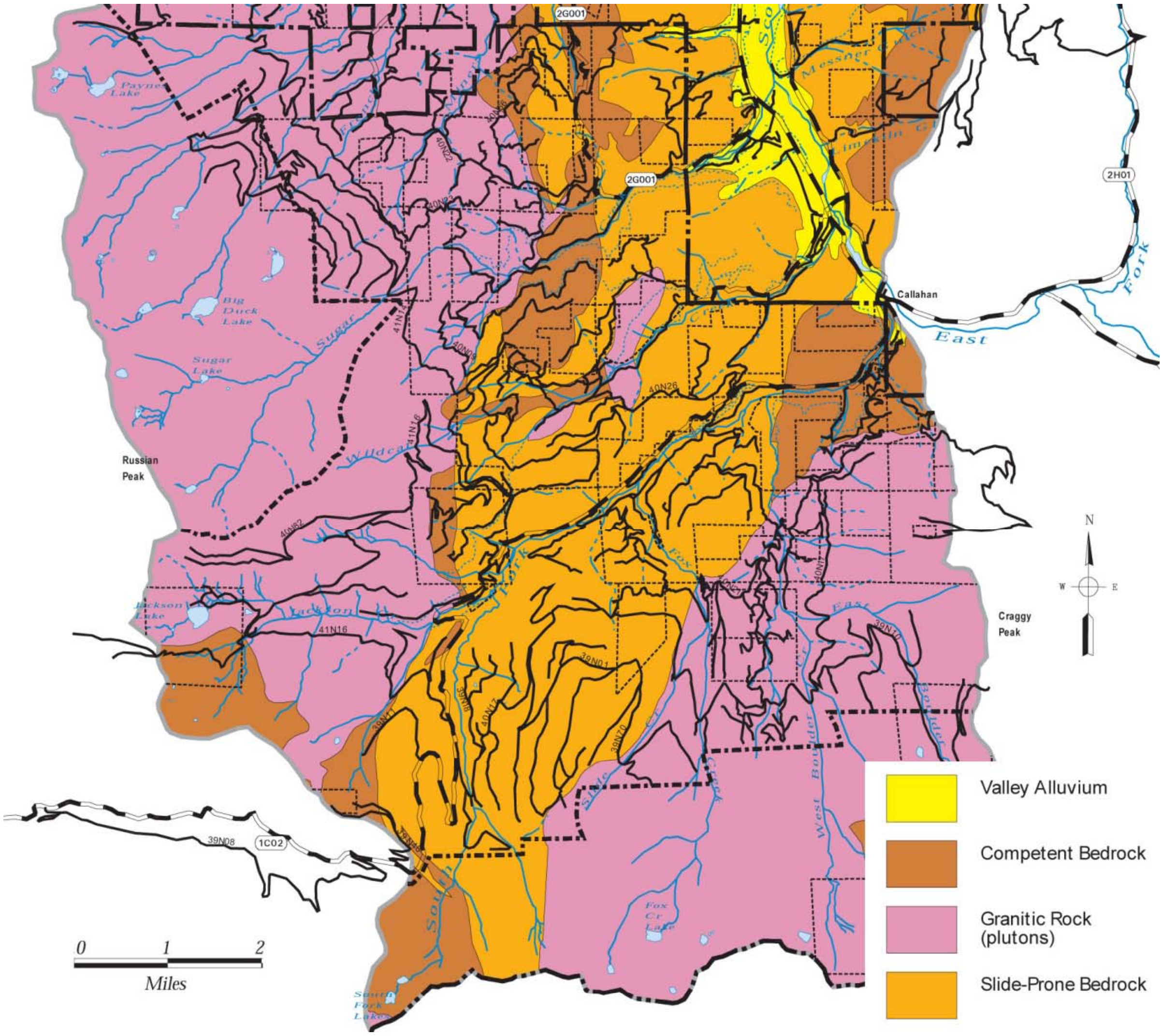

Figure 3.5. Simplified lithology of Sugar Creek area. Adapted from USDA (2007).

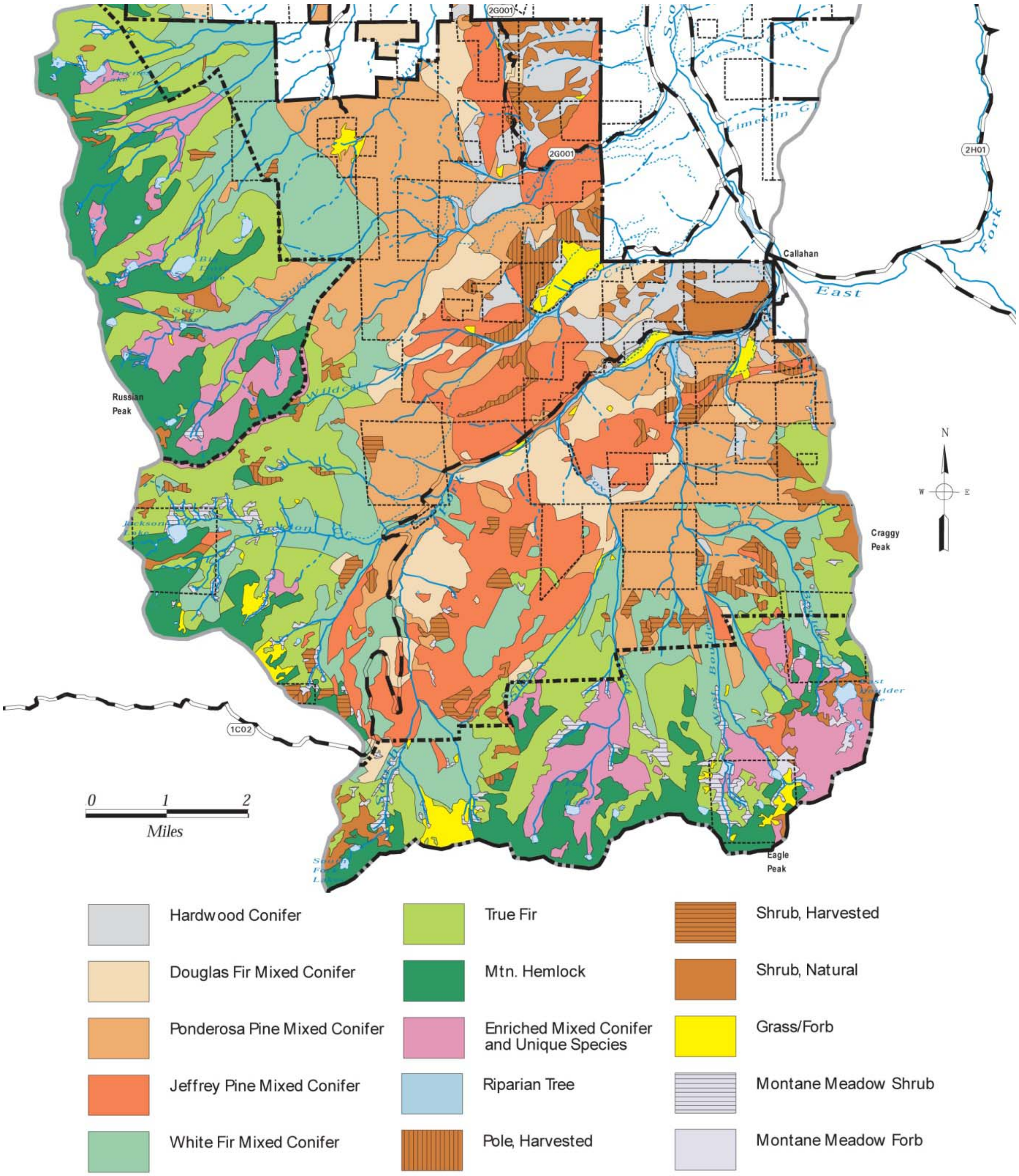

Figure 3.6. Current vegetation of Sugar Creek area. Adapted from USDA (2007).

4. Forest conditions

4.1. Forest-management context

This section reviews recent literature that is of primary relevance to the goal of building resilience while increasing water yield within the Sugar Creek watershed of the Klamath National Forest. It provides the conceptual framework for how active management can meet both objectives of building resilience to future stressors while also enhancing water yield for habitat restoration. The overall aim is to investigate applying historic fire regimes and structures as a guide for building resilience and enhancing water yield in the Scott River watershed of the Klamath Mountains.

The Sugar Creek watershed is of particular value as a case study, because it encompasses the wide gradient of vegetation and physiographic conditions that exist throughout the Klamath range. Further, it is of high priority for management and conservation, as it contains an area of extremely high conifer diversity on its upper slopes**.** Resilience, in this case, is defined as the capacity to withstand reasonably projected future stressors while maintaining basic ecological processes and services. Stressors include those that have or are currently occurring within dry western forests, including mortality from prolonged drought (Breshears et al. 2009; van Mantgem et al. 2009), large insect outbreaks (Fettig et al. 2007), and increasingly severe and extensive wildfires (Westerling et al. 2006; Miller et al. 2009). As climatic change interacts with these and future stressors, uncertain yet profound consequences will require active adaptive management approaches that emphasize a wide variety of proactive management alternatives to actively test (Chmura et al. 2011; Millar et al. 2007).

Of primary importance is management that builds the general resilience of forests to drought stress (van Mantgem et al. 2009). Treatments designed to build resilience to drought stress are, fortunately, also consistent with basic conventional objectives of restoring forest to their pre-fire-suppression structures (Franklin and Johnson 2012) and for increasing water yield (Bales et al. 2011). Actively maintaining forests with silvicultural decisions that are generally guided by the forest's defining disturbance regime (e.g. Seymour et al. 2002), which in the case of western forests is the fire regime (i.e. frequency, severity, seasonality) are also in line with sustaining advances in resilience and water yield. Modern proposed restoration treatments in western forests ubiquitously aim for the basic objectives of reducing density, favoring large tree retention of fire tolerant species, and increasing spatial heterogeneity (e.g. Franklin and Johnson 2012; North et al. 2009; Covington 2000). Such treatments will build the basic physiological capacity to be resilient to stressors in the future (Chmura et al. 2011). The challenge at local levels such as the Sugar Creek watershed, then, is defining treatment alternatives in a way that incorporates local knowledge and studies so that treatments are designed to accommodate local conditions.

The sections that follow describe what is known about the fire regime and forest structure prior to fire suppression in the Klamath Mountain area. From fire history studies, the fire regime is relatively well understood, and basic inferences about the forest structure that was sustained by the fire regime can be applied. Reconstruction studies as well as studies that use extensive pre-fire-suppression measurements can also be applied to define pre-suppression structure. Basic alternatives for meeting the dual objectives of resilience in the face of climate change (especially drought stress and increased fire severity) and increased water yield are identified for the Sugar Creek watershed.

4.2. Geographic scope and time frame of relevant studies

Studies used for defining pre-fire suppression conditions are from the Klamath and Siskiyou mountain ranges. While studies from the Sierra Nevada range are arguably relevant for describing the general conditions of the Klamath Mountains (Skinner and Chang 1996), there have been several recent studies from locations closer to the Sugar Creek watershed, which allow a more locally informed description.

Fire suppression as a policy officially began in 1905 when forests of the Klamath mountain region became part of the National Forest system. Effective suppression in this area, however, did not occur until later. This is documented by fire-history studies, which show an abrupt decline in fire activity beginning in the 1940's (Wills 1991; Wills and Stuart 1994; Taylor and Skinner 1998; Skinner 2003). Early descriptions of fire activity in the area also support this assertion of a delay in effective fire suppression (Ogle 1920). The onset of settlement activity in California's mountain areas beginning 1849 is commonly observed to be associated with an alteration in the fire regime associated with grazing (Savage and Swetnam 1990). Comparisons of fire frequency between the settlement period and the time immediately prior to settlement, however, suggest that the settlement era did not alter the fire regime in the Klamath region substantially (Wills and Stuart 1994; Taylor and Skinner 1998). The pre-fire-suppression era for the Sugar Creek watershed is therefore assumed to be prior to the 1940's, extending back to the mid 1700's, which is the earliest that the majority of fire-history studies encompass.

4.3. Pre-fire-suppression fire regime

The Klamath region is similar to other western dry forests in that the fire regime was characterized by frequent fires of low to mixed severity, with primary local factors being aspect and elevation. The fire regime is somewhat similar to the giant sequoia-mixed conifer forests of the southern Sierra Nevada (Kilgore and Taylor 1979), where similar but steeper gradients in fire frequency and severity occur across similar physiographic and climatic gradients. Sugar Creek is an east-west running watershed with a wide elevational gradient that spans oak-mixed conifer, ponderosa pine-mixed conifer, upper-slope mixed conifer with higher Douglas-fir and white fir importance, and higher elevation stands of diverse conifer assemblages. The fire-return interval in the lower oak-mixed conifer forests of the Klamath region at the point scale was relatively low, approximately 13 years with maximum intervals of 39 years (Skinner and Chang 1996). Ponderosa pine-mixed conifer stands, which occur over a large portion of the Sugar Creek watershed, especially on the south-facing aspects, had a similar fire frequency of approximately 13 years and may have had a slightly longer maximum return interval in the range of 50 to 60 years (Skinner and Chang 1996; Fry and Stephens 2006). The mixed-conifer stands occurring on north-facing slopes and above ponderosa pine-dominated stands tended to have fairly similar fire-return intervals, with studies ranging from 12 to 16 years at the point scale (Agee 1991; Wills and Stuart 1994; Skinner and Chang 1996; Taylor and Skinner 1998; Taylor and Skinner 2003). Taylor and Skinner (1998) found small differences related to aspect within mixed-conifer stands, where southern aspects (8 years) tended to have greater frequency compared to northern aspects (15 years).

While some subtle elevation and aspect trends are apparent, the collection of fire-history studies suggest that fire-return intervals across the vegetation types occurring within the Sugar Creek watershed are mostly similar. Observations of substantially longer return intervals within the environments of Sugar Creek do not occur until the topographical extremes are reached. Specifically, riparian areas (31 years; Skinner and Chang 1996) and high elevation forests (25-75 years; Skinner 2003) have evidence to suggest they had longer return intervals. Even in these areas of longer return intervals, however, maximum intervals have been skipped during the current era of fire suppression.

Nearly all fire-history studies from the Klamath region make the inference that fires were of “low to moderate” or “mixed” severity and that the diversity of severity (i.e. “pyrodiversity”) contributed to structural diversity of pre-fire-suppression forests (Agee 1991; Wills and Stuart 1994; Skinner and Chang 1996; Taylor and Skinner 1998; Taylor and Skinner 2003; Fry and Stephens 2006). Using early aerial photos from the 1940’s, Skinner (1995) measured the canopy-gap regime, describing it as dominated by canopy gaps ranging in size from 0.3 to 1.2 hectares (0.74 to 3.0 acres) and concluded that a low-moderate severity fire regime sustained this diverse type of structure. Using age structures and the spatial clumping of cohorts, Taylor and Skinner (1998) made the inference that new cohort establishment occurred following fires that had localized higher severities that created canopy gaps large enough to regenerate shade-intolerant species. The exception to the prevalence of a low-moderate severity regime is in the highest-elevation forests, where fires were common but primarily restricted to low severity because of fuel discontinuity (Skinner 2003).

While none of the studies that describe the fire regime of the Klamath Mountains were done within the Sugar Creek watershed, there is nothing particular about the lower- and mid-elevation stands of Sugar Creek that would suggest it was vastly different with respect to fire regime. While it has not had a large fire in over 100 years, lightning strikes occur approximately once per year (McDaniel and Isbell 2010) and Native American ignitions very likely augmented ignition frequencies (Fry and Stephens 2006). Ample evidence suggests that fires were in general frequent (11 to 16 years) and of low severity, with some localized areas of moderate severity that created small yet distinct canopy gaps. The south-facing slopes along the north side of the watershed likely had return intervals of slightly higher frequency compared to the north-facing slopes, and the riparian area surrounding Sugar Creek likely had longer periods between fires and sustained slightly higher basal area and canopy densities. The higher-elevation stands near the headwaters of Sugar Creek have long been noted for their extremely high conifer diversity (Sawyer and Thornburgh 1970). These stands are indeed an outlier compared to the region in general. The high diversity, however, only supports the inference that fires were of low to moderate severity in this area. Mixed fire severity, coupled with edaphic factors, likely sustained areas of high diversity in the Klamath region (Whitlock et al. 2008; Briles et al. 2011).

4.4. Pre-fire-suppression forest structure

Often, much more is known about the components of past disturbance processes compared to the components that made up forest structure (Stephenson 1999). This is because the methods used to reconstruct past forest structures often include uncertainties or involve subjective interpretations. The recovery of data from past forest inventories, however, are of particular value if the inventories were comprehensive and extensive over large areas so that past forest structure can be accurately described with straightforward descriptive statistics. Fortunately, a vast dataset that describes pre-fire-suppression forest structure and composition in ponderosa pine and mixed conifer forests of south-central Oregon has recently been published (Hagmann et al. 2013). This is a unique dataset in that it is extensive (nearly 15,000 acres), intensive (10-20% sampling intensity), and covers both ponderosa-pine and mixed-conifer community types from a time prior to fire suppression. When coupled with existing knowledge about the past fire regime, the utility of this dataset as a source for reference conditions in the Klamath-Siskiyou region is extremely high when compared to other possible sources for reference conditions.

The study is consistent with the large majority of reconstruction studies in Western dry forests in the general conclusion that forests prior to effective suppression efforts were of lower density, had higher structural diversity, and a had a higher dominance of fire-tolerant species. The change in forest structure as a result of fire suppression is also consistent with other pre-fire-suppression databases that have recently been discovered and re-measured in the Sierra Nevada range (Collins et al. 2011; Knapp et al. 2013). As with these other studies that have used extensive inventories from the past, the magnitude of the difference between conventional and past structures is striking. Prior to fire suppression, average basal area was only 16 m^2 ha^{-1} (70 ft^2 ac^{-1}), with the 95^{th} percentile of basal area at 24 m^2 ha^{-1} (105 ft^2 ac^{-1}). Overall stem density was roughly a third of what exists currently in the study area. The forests were clearly dominated by large ponderosa pine, and smaller trees were of much lower density and also dominant to ponderosa pine. White fir only became as much as co-dominant with ponderosa pine in the moistest sites. Compared to present forest structure and composition, the landscape described in this study was one of variable canopy density (including distinct gaps), low overall stocking (i.e. basal area or leaf area), and a dominance of large-diameter ponderosa pine as the primary structural feature. This type of structure is consistent with the fire regime that has been described by the various fire-history studies in this region. Frequent fires maintained overall stocking at levels well below maximum levels given local site productivity. The occasional occurrence of moderate-severity fires created areas of distinct high resource availability at local levels, creating canopy gaps large enough to regenerate the dominant species, i.e. ponderosa pine. Recruitment of large ponderosa pine was facilitated by additional lower-severity fires that periodically reduced competition by thinning of smaller trees of lower fire tolerance.

4.5. Implications for increasing resilience and water yield

In the forested areas of the Klamath Mountains there is high certainty in the basic parameters that made up the defining disturbance regime prior to effective fire suppression. Periodic and variable-severity fires defined a forested landscape that looks much different than today. There is also high certainty in the understanding of at least three primary effects that this past fire regime had on forest structure and composition:

1. Overall density was kept low by frequent fires
2. Structural heterogeneity was high from spatially complex fires (i.e. low to moderate severity)
3. Ponderosa pine was abundant both in the over- and understory

Parameterizing this structure so that treatments can be carried out in a way that is consistent with modern objectives of building resilience and increasing water yield can be done with an active adaptive-management framework that considers the uncertainty in the magnitude and patterns of future climate changes and the effects of forest-management decisions on water yield. Enough is known, however, about the mechanisms involved in resilient and water-efficient forests to move forward with active management. Decisions about precise targets such as residual basal area, entry interval, and rotation ages will be guided at the local level. At Sugar Creek, for example, we do not know the current structure because of a lack of recent inventory data. Such data are important, especially for Sugar Creek, where a wide range of physiographic conditions exist. Following collection of such data, a treatment that varies by topographic position and elevation and regenerates ponderosa pine can be developed similar to those proposed by North et al. (2009) and York et al. (2011) for meeting these objectives (Figure 4-1). It should be noted that the basal-area density ranges in Figure 1 are given as an example of how relative density may change following treatments done across the watershed. While these ranges can be used for modeling purposes, implemented ranges would more likely be made relative to site maximums for the area (i.e. Bales et al. 2011). Because it correlates well with leaf area for conifer species in this area (Gersonde 2003) it is beneficial to use residual basal area as the primary metric for defining forest density from a water-yield perspective. Basal area is also a metric easily measured in the field.

Maintaining low density, whether it is done with prescribed fire, wildfire or mechanical methods, can be achieved with active applications of disturbances that remove stems from the lower and middle size classes. Density reductions can improve individual tree vigor (Chmura et al. 2011), increase water yield (Bales et al. 2011), and facilitate the recruitment of large ponderosa pine into upper-canopy strata (Franklin and Johnson 2012). Residual density needs to be low enough to be in line with pre-fire-suppression structures and to make a difference for meeting these three objectives, however. As a rough target guided by the reference of pre-fire-suppression forest structure, a basal area range of 11-40 m^2 ha^{-1} (50-175 ft^2 ac^{-1}), depending on topographical position, are described in Figure 4-1. Although it may not actually be very common at any given location, an average basal area of 17 m^2 ha^{-1} (75 ft^2 ac^{-1}) across the mid-elevation stands of the watershed would be roughly equivalent to what was found by Hageman et al (2013). Precise ranges would be modified depending on current or projected maximum stand-density levels for the given area (i.e. to a large degree a factor of site productivity). An important outcome of any thinning treatment is the simultaneous reduction of shrub stems along with tree stems because of the high capacity for certain shrub species to compete with trees for water (Royce and Barbour 2001). It is likely, however, that the shrub strata of pre-fire-suppression forests were significant (Knapp et. al. 2013). The interaction of shrub density management and water yield may be an area of uncertainty that can be tested further with an active adaptive-management approach.

Reintroducing structural heterogeneity and regenerating ponderosa pine can come from either wildland-fire-use or gap-based-silvicultural methods (York et al. 2004; York et al. 2011). The key outcome is the creation of distinct canopy gaps that create enough resource availability for regenerating and recruiting ponderosa pine. These gaps are also an important structure to have from a water-yield perspective as sweet spots for snow accumulation and storage (Figure 4-2; Bales et al. 2011). Using what is known about the past gap regime as a guide (Skinner 2003), gaps ranging in size from 0.1 to 2.0 acres (Figure 4-1) should provide adequate growing space for ponderosa pine (York et al. 2003) while reversing some of the homogenization of forest structure that has resulted from fire suppression. On the smaller end of this range, however, reductions in light availability from encroaching and releasing edge trees would likely require future expansions of gap sizes (York, unpublished data). Precise gap-size ranges, again, would be based on the local structure. In the case of Sugar Creek, an important determinant would be canopy height. For example, gap size could range from 1 to 2 times the height of the surrounding canopy of low density, largest trees (Figure 4-2).

Treatment return intervals should be guided by both the disturbance regime and how long treatments last in terms of meeting objectives (i.e. increasing water yield and resiliency). The removal of competition from thinning is well known to increase growth rates and photosynthetic capacity of remaining trees (e.g. York et al. 2004; Renninger et al. 2007). Even the largest and oldest trees have recently been shown to retain a strong physiologic capacity to release from competition (McDowell et al. 2003; York et al. 2010). Thinning treatments will reduce leaf area and begin a period of leaf area expansion until maximum levels are again reached. The intensity of thinning, therefore, an important factor in guiding treatment-return interval (i.e. higher intensity things will require a longer time until reentry). Using fire-return interval as a guide, treatments would occur roughly every 13 years. This should be adjusted based on site specific productivity and treatment schedule alternatives can be modeled with growth simulation software such as Forest Visualization Software once site specific data are collected.

By thinning from below and removing white fir preferentially, the thinning treatments described above would result in a shift in species composition from the current overabundance of white fir toward ponderosa pine. The gap-based approach of regenerating ponderosa pine would further *sustain* a significant population of ponderosa pine in the future. Such a species composition shift would not only meet the objective of guiding the forest to be similar in composition to what it was prior to fire suppression, it should also have beneficial effects from a drought stress and water yield perspective. Climatic drought stress is thought to currently be the primary factor in increased mortality rates in western forests (van Mantgem et al. 2009). Pine species are well known to have a drought avoidance physiological strategy. Specifically, they close stomata as a response to drought and maintain relatively constant water potential (i.e. “isohydric” regulation). This more-conservative water-use strategy helps explain why *Pinus* species tended to maintain higher vigor during droughts under moderate levels of density in the few studies that have been done (McDowell et al. 2006, D’Amato et al. 2013). These same studies, however, also suggest that older pine trees may be sensitive to drought even when density is low. Taking the restoration approach to a logical extreme and only managing for large pine at low densities, therefore, is not necessarily the best approach given a future climate of elevated drought stress. This emphasizes the need for not only favoring ponderosa pine as a species, but also favoring a wide diversity of structure and age classes as a means for building resilience.

4.6. Steps needed for further development of treatments

In order to develop precise prescriptions that can be tested for building resilience and increasing water yield in the Sugar Creek watershed, the current forest structure will need to be measured. From visual observations of current forest structure, treatments may reduce density (in terms of leaf area) by roughly 30 to 60%. For planning out gap-based silvicultural treatments, measurements of site productivity, species composition, and some idea of current age structure would also be necessary (or at the least, maximum ages of ponderosa pine in this area).

References

Bales, R.C., Battles, J.J., Chen, Y., Conklin, M., Holst, E., O’Hara, K.L., Saksa, P., and Stewart W. 2011. Forest and Water in the Sierra Nevada: Sierra Nevada Watershed Ecosystem Enhancement Project. Sierra Nevada Research Institute report number 11.1

Breshears, D.D., Myers, O.B., Meyer, C.W., Barnes, F.J., Zou, C.B., Allen, C.D., McDowell, N.G., Pockman, W.T., 2009. Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. Front. Ecol. Environ. 7, 185–189

Chmura, D.J., Anderson, P.D., Howe, G.T., Harrington, C.A., Halofsky, J.E., Peterson, D.L., Shaw, D.C., St Clair, J. Brad, 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. For. Ecol. Manage. 261, 1121–1142

Covington, W.W. 2000. Helping western forests heal. Nature 408: 135-136

Briles, C.E., Whitlock, C., and Skinner, C.N. 2011. Holocene forest development and maintenance on different substrates in the Klamath Mountains, northern California, USA. Ecology 92(3): 590-601

Collins, B.M., Everett, R.G., and Stephens, S.L. 2011. Impacts of fire exclusion and recent managed fire on structure in old growth Sierra Nevada mixed-conifer forests. Ecosphere 2(4): 1-14.

D'Amato, A.W., Bradford, J.B., Fraver, S., Palic, B.J. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecological Applications 23(8): 1735-1742.

Fettig, C.J., Klepzig, K.D., Billings, R.F., Munson, A.S., Nebeker, T.E., Negrón, J.F., Nowak, J.T., 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. For. Ecol. Manage. 238, 24–53.

Franklin, J.F., Johnson, K.N., 2012. A restoration framework for federal forests in the Pacific Northwest. J. For. 110, 429–439.

Fry, D.L. and Stephens, S.L. Influence of humans and climate on the fire history of a ponderosa pine mixed conifer forest in the southeastern Klamath Mountains, California. Forest Ecology and Management 223: 428-438.

Hagmann, R.K., Franklin, J.F., and Johnson, K.N. 2013. Historical structure and composition of ponderosa pine and mixed-conifer forests in south-central Oregon. Forest Ecology and Management 304: 492-504

Kilgore, B.M., and Taylor, D. 1979. Fire history of a sequoia-mixed conifer forest. Ecology 60(1): 129-142.

Knapp, E.E., Skinner, C.N., North, M.P., and Estes, B.L. 2013. Long-term overstory and understory change following logging and fire exclusion in a Sierra Nevada mixed-conifer forest. Forest Ecology and Management 310: 903-914.

McDaniel, V. and Isbell, C. 2010. Fuel loading threatens most diverse assemblage of conifers in the world. Presentation at Klamath Fire Ecology Symposium. Orleans, CA.

McDowell, N., Brooks, J.R., Fitzgerals, S.A. & Bond, B.J. 2003. Carbon isotope discrimination and growth response of old Pinus ponderosa trees to stand density reductions. *Plant, Cell and Environment* 26: 631-644.

McDowell, N.G., Adams, H.D., Bailey, J.D., Mess, M., Kolb, T.E. 2006. Homeostatic maintenance of ponderosa pine gas exchange in response to stand density changes. Ecological Applications 16(3): 1164-1182.

Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. Appl. 17, 2145–2151

Miller, J., Safford, H., Crimmins, M., Thode, A., 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12, 16–32.

North, M., Stine, P., O'Hara, K., Zielinski, W., Stephens, S., 2009. An Ecosystem Management Strategy for Sierran Mixed-Conifer Forest. PSW-GTR-220. Pacific Southwest Research Station, Albany, CA.

North, M., Collins, B.M., and Stephens, S.L. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. Journal of Forestry 110(7): 392-401

Ogle, C.E. 1920. Light Burning. The Timberman 21(9): 106-108

Renninger, H.J., Meinzer, F.C., and Gartner, B.L. 2007. Hydraulic architecture and photosynthetic capacity as constraints on release from suppression in Douglas-fir and western hemlock. Tree Physiology 27: 33-42.

Royce, E.B., and Barbour, M.G. 2001. Mediterranean climate effects I: Conifer water use across a Sierra Nevada ecotone. American Journal of Botany 88(5): 911-918

Savage, M., Swetnam, T.W., 1990. Early 19th-century fire decline following sheep pasturing in a Navajo ponderosa pine forest. Ecology 71, 2374–2378

Sawyer, J. O.; Thornburgh, D. A. 1970. The ecology of relict conifers in the Klamath region, California. Report to Pacific Southwest Forest and Range Experiment Station, Berkeley, California. PSW COOP-AID Grant #9. Unpublished report on file, Pacific Southwest Research Station, Albany, Calif.

Seymour, R.S., White, A.S. and deMaynadier, P.G. (2002). Natural disturbance regimes in northeastern North America - evaluating silvicultural systems using natural scales and frequencies. *Forest Ecology and Management,* **155,** 357-367.

Skinner CN, Chang C (1996) Fire regimes, past and present. In 'Sierra Nevada Ecosystem Project: Final Report to Congress, Vol. II, Assessments and Scientific Basis for Management Options'. pp. 1041–1069.

Skinner, C.N. 2003. Fire history of upper montane and subalpine glacial basins in the Klamath Mountains of Northern California. Tall Timbers Research Station Miscellaneous Publication No. 13: 145-151

Stephenson, N. L. 1999. Reference conditions for giant sequoia forest restoration: Structure, process, and precision. *Ecological Applications* 9:1253-1265.

Taylor, A.H., and Skinner, C.N. 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA. 1998. Forest Ecology and Management 111: 285-301.

Taylor, A.H., and Skinner, C.H. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications 13(3): 704-719.

van Mantgem, P.J., Stephenson, N.L., Byrne, J.C., Daniels, L.D., Franklin, J.F., Fulé, P.F., Harmon, M.E., Larson, A.J., Smith, J.M., Taylor, A.H., Veblen, T.T. 2009. Widespread Increase of Tree Mortality Rates in the Western United States. Science 323: 521-524.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313, 940.

Whitlock, C., Marlon, J., Briles, C., Brunelle, A., Long, C., and Bartlein, P. 2008. Long-term relations among fire, fuel, and climate in the north-western US based on lake-sediment studies. International Journal of Wildland Fire 17(1): 72-83.

M.S. Thesis, Humboldt State University, Arcata,

Wills, R.D., 1991. Fire history and stand development of Douglas-fir/hardwood forests in northern California. M.S. Thesis, Humboldt State University, Arcata, CA.

Wills, R.D., Stuart, J.D., 1994. Fire history and stand development of a Douglas-fir hardwood forest in northern California. Northwest Science 68, 205-212.

York, R.A., J.J. Battles, and R.C. Heald 2003. Edge effects in mixed conifer group selection openings: tree height response to resource gradients. Forest Ecology and Management 179: 107-121.

York, R.A. Heald, R.C., Battles, J.J., and York, J.D. 2004. Group selection management in conifer forests: Relationships between opening size and tree growth. Canadian Journal of Forestry 34: 630-641.

York, R.A., Fuchs, D., Battles, J.J., and Stephens, S.L. 2010. Radial growth response to gap creation in large, old Sequoiadendron giganteum. 13: 498-509

York, R.A., Battles, J.J., Wenk, R.C., and Saah, D. 2012. A gap-based approach for regenerating pine species and reducing surface fuels in multi-aged mixed conifer stands in the Sierra Nevada, California. Forestry 85(2): 203-213.

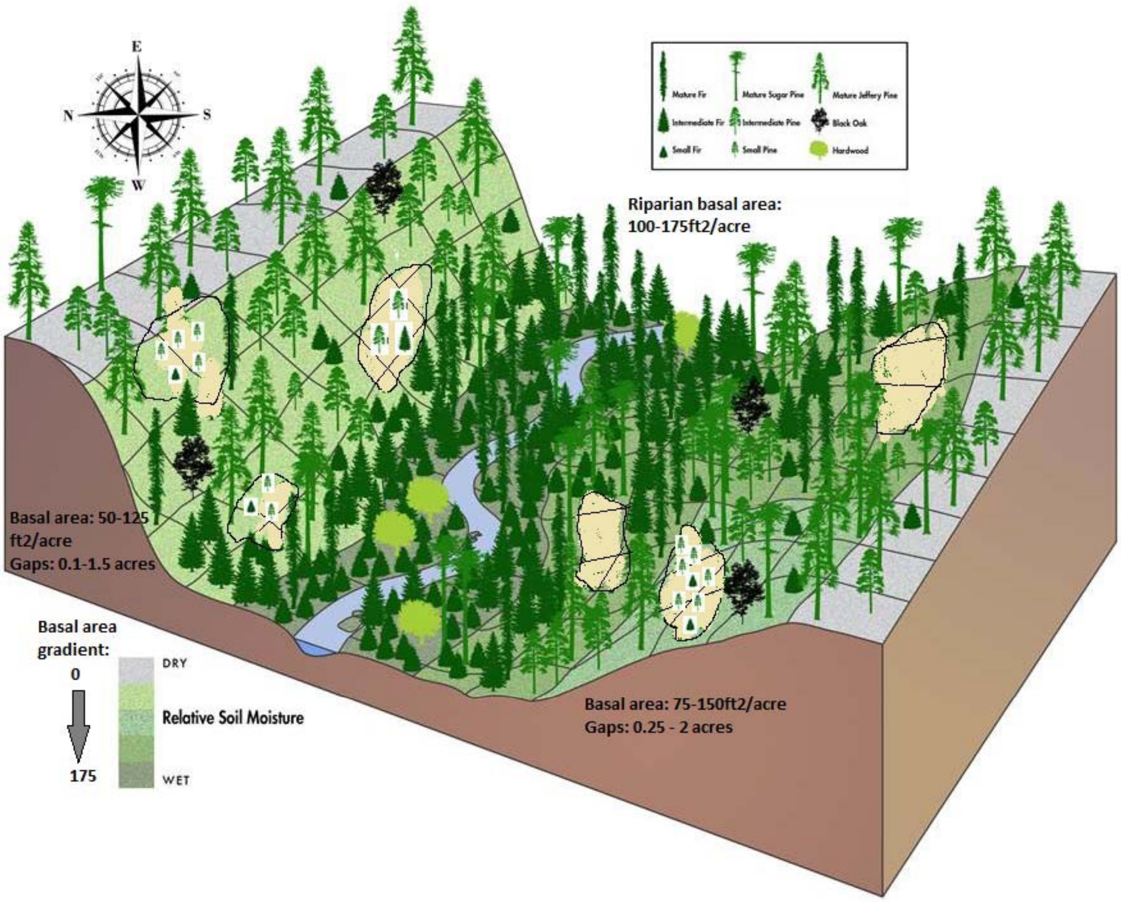

Figure 4.1. Example of forest structure following treatments guided by pre-fire suppression processes and structures, adapted to meet objectives of resilience and water yield enhancement. The treatment involves periodic thinning using basal area ranges and creating canopy gaps for ponderosa pine regeneration. Adapted from North et al. 2012.

Figure 4.2. A 0.45 ha (1.1-ac) gap retaining snow much longer than surrounding mature forest in the Central Sierra Nevada. The long axis of the gap is oriented East-West. The short North-West axis is 37 m (122 ft) wide, roughly equivalent to the height of the surrounding canopy.

5. Climate features

Historically the Scott Valley region experiences hot dry summers and cold wet winters, with significant variability both seasonally and inter-annually. The 1500-m (5000 ft) elevation difference within the Sugar Creek watershed results in significant differences in temperature and precipitation across the landscape.

5.1. Temperature patterns

Temperature is measured at elevations ranging from 2145 m (7150 ft) to 123 m (410 ft) in the broader area in and around the Scott Valley. Figure 5-1 shows locations of 29 stations that were assessed for establishing temperature patterns in the area, with further station information shown in Table 5-1. Data and metadata for these stations were downloaded from two sources, the California Data Exchange Center (http://cdec.water.ca.gov/), which is part of the California Department of Water Resources, and the Western Regional Climate Center (http://www.wrcc.dri.edu/), which is operated by the Desert Research Institute.

The longest records are generally associated with NOAA's Cooperative (Co-op) network, which are at lower elevations. Lower to mid-elevation temperatures are reported at stations in the Remote Automatic Weather Station (RAWS) network. The RAWS stations form the basis for fire weather and other operational uses by government agencies. Higher-elevation temperatures are associated with snow-pillow and meteorological stations operated by the Bureau of Reclamation in support of hydrologic operations.

Fifteen of the current stations have reasonably continuous daily records over the past 20 years (Figure 5-2). Some also report hourly data, and several report daily minimum and maximum temperature. The current analysis used only daily average temperature, as all data that were downloaded will need cleaning to remove outliers and fill missing-data gaps. This is especially true of the stations that only report hourly data, which were not averaged for use in this analysis. However, they can be used to extend the analysis after cleaning. Other data problems apparent in some of the daily data include periodic switching of daily minimum and maximum temperatures.

Annual-average temperatures at the stations shown on Figure 5-2 ranged from about 4.5 to 13.3 ^{o}C, representing an elevation range of 2145 to 276 m elevation. These average temperatures generally decrease with elevation, with an average slope of -7.5 ^{o}C per 1000 m elevation (Figure 5-3). This ground-based lapse rate varies seasonally (data not shown), though some data cleaning is needed to calculate seasonal values. Some of the variability of points around the straight line on Figure 5-3 reflects local topographic differences in station locations, e.g. differences in night-time cold-air drainage and thus minimum daily temperatures.

Applying the -7.5 ^{o}C per 1000 m ground-based lapse rate to the data on Figure 5-2, an average temperature is calculated for an index elevation of 1500 m (5000 ft) (Figure 5-4). The same calculation could be done for any index elevation. The relatively low spread (standard deviation) of values around the mean indicates that this averaging approach provides representative values that can be used across the elevation range of the Sugar Creek basin for hydrologic modeling. The temperature data are also of sufficient quality to enable establishing daily minimum and maximum temperatures.

5.2. Precipitation patterns

Precipitation as rain and/or snow is measured at most of the same stations as is temperature (Figure 5-1). Some report monthly and some daily values. Because of frequent missing data and values out of range, data from essentially any of these stations requires significant cleaning in order to establish inputs for hydrologic modeling. It will be especially important to evaluate the higher-elevation stations, owing to the often poor correlations between precipitation at valley versus mountain stations in California.

Perhaps the most-relevant station for Sugar Creek is at Scott Mountain, which has daily precipitation for the period 1988-present (Figure 5-5). This station exhibits the typical wet/dry seasons characteristic of the region. It also shows considerable interannual variability in both timing and amount of precipitation. Annual amounts range from a low of 87 cm in 1992 to 274 cm in 1998. Note also that in some years much of the annual precipitation occurs by January (1988), versus March in many other years. Annual values for this station are shown on Figure 5-6, with a 15-year median value of 186 cm.

Figure 5-7 shows annual precipitation values for the 5 Co-op stations with the longest record. These stations had data that could be presented with only a small amount of cleaning. These still contain some missing values and possible outliers, and further rigorous station-to-station comparisons are needed before using the data for hydrologic modeling. Two stations, Happy Camp and Orleans, have higher precipitation than apparent at the Ft. Jones and Callahan stations in the Scott Valley. Cecilville has intermediate precipitation amounts. At least Orleans and Cecilville should have higher precipitation by virtue of being nearer the coast, i.e. less rain-shadow effect. However, local siting issues with Cecilville may be responsible for its lower value. Four of the five stations show some correlation between annual precipitation amounts, but Happy Camp does not correlate well with the other four stations (Figure 5-8). We expect that after cleaning there will be sufficient correlation between several of the stations on shorter time scales to allow for establishing daily precipitation for modeling inputs. Significantly, Scott Mountain (1770 m elevation) also shows some correlation with precipitation at Callahan, which is about 800 m lower. It is also significant that Scott Mountain has over three times the precipitation as does Callahan.

With variable rain-shadow effects, the detailed data from these precipitation stations will be used for indicators of precipitation amount, and for timing of precipitation. Snow-course and snow-pillow sites will provide further indexing for precipitation, timing, and separating rain versus snow. Finally, regional gridded model estimates of monthly precipitation will be evaluated relative to these station values to establish model inputs (http://www.prism.oregonstate.edu/).

5.3. Snow accumulation and melt

Snow depth and water equivalent are measured by two networks: i) 18 monthly, manually measured snow courses (Table 5-2, Figure 5-9), and ii) 9 daily or hourly snow-pillow sites, which telemeter data to CDEC daily (Table 5-3, Figure 5-9).

Data for 6 of the nearby snow courses with more-complete records show April 1 snow accumulation values, which is taken by water managers as being near the data of annual peak accumulation (Figures 5-10 and 5-11). Four of the sites also have March 1 snow measurements, which in most years have less accumulation than on April 1. Normalizing annual April 1values by the 30-year mean at each site shows considerable inter-site variability (Figure 5-12). The multi-site average values shown on this figure do illustrate that there have been few multi-year dry periods over 2 years in duration in the 1945-present period. The 6 sites also show variability when plotted versus elevation, reflecting local topographic controls other than elevation on snow accumulation (Figure 5-13). In particular, the differences between Swampy John versus nearby Etna may reflect in part a rain-shadow effect. Similarly, the higher values for a group of 4 sites further south, e.g. Wolford Cabin versus Middle Boulder, Middle Boulder 3 and Dynamite Meadows may also reflect in part a rain-shadow effect.

The snow-pillow sites will provide estimates of snowmelt rates, and together with meteorological data will help to evaluate modeled snowmelt. However, data will need significant cleaning, in some cases day-by-day. This is illustrated on Figure 5-14, which shows data for the Middle Boulder 3 snow pillow. Data will be cleaned using other temperature, precipitation and snow-course data.

5.4. Relative humidity, wind and radiation

Additional meteorological data needed for hydrologic modeling are available at 10 stations in the region, including both snow-pillow and valley stations. Essentially all of these data need cleaning and additional processing.

5.5. Satellite snowcover

Fractional snow-covered from the MODIS satellite provides an additional index of snow accumulation and melt. MODIS has daily global coverage, and during winter/spring in the Sierra Nevada provides typically 1-5 cloud-free scenes per week that can be used to update snowcover estimates (Rice et al., 2011). Additional adjustments are made for canopy cover, as the satellite only images snow in canopy gaps. Figures 5-15a-d show snowcover detected near April 1 for 4 years, 2008-2011. Note that the upper half of the Sugar Creek basin has detectable snowcover, and the lower half does not. These scenes are not yet adjusted for canopy cover. The snowcover fractions range from 0.15 (detection limit) to 1.0, with values binned into 4 shades of black and white for ease of viewing. These data, available through NASA-JPL for 2000 to present, will provide an additional constraint on the hydrologic modeling.

References

Robert, R., Bales, R.C., Painter, T.H. & Dozier, J. (2011) Snow water equivalent along elevation gradients in the Merced and Tuolumne River basins of the Sierra Nevada, *Water Resources Research,W08515, doi:10.1029/2010WR009278.*

Table 5-1. Temperature and precipitation measurements near Scott River basin

ID	Name	Type	Operator	Elev, m	Lat/Lon	Period
PET	Peterson Flat	CCSS	USBR	2145	41.302/122.528	1985-
SCT	Scott Mountain	CCSS	USBR	1770	41.272/122.718	1985-
MB3[a]	Middle Boulder 3	CCSS	USBR	1860	41.225/122.811	1986-
MUM	Mumbo Basin	CCSS	USBR	1695	41.197/122.523	1984-
HIG	Highland Lakes	CCSS	USBR	1809	41.093/122.483	1987-
BNK	Bonanza King	CCSS	USBR	1935	41.083/122.628	1989-
CFR	Coffee Ridge	CCSS	USBR	912	41.083/122.717	1998-
BFL	Big Flat	CCSS	USBR	1530	41.080/122.942	1985-
RRM[a]	Red Rock Mtn.	CCSS	USBR	2010	41.023/122.885	1986-
SHM[a]	Shimmy Lake	CCSS	USBR	1920	41.008/122.800	1985-
SRB	Slater Butte	RAWS	USFS	1401	41.858/123.354	1990-
CLB	Collins Baldy	RAWS	USFS	1648	41.775/122.950	1991-
–	Brazie Ranch	RAWS	S&PF	900	41.685/123.594	1990-
–	Dutch-Indy	RAWS	USFS	693	41.644/123.444	2010-
QTZ	Quartz Hill	RAWS	Cal Fire	1271	41.600/122.929	1984-
WED	Weed Airport	RAWS	Cal Fire	879	41.479/122.455	1984-
–	Slate Creek	RAWS	USFS	1251	41.341/123.659	2012-
SSB	Somes Bar	RAWS	USFS	276	41.333/123.500	1995-
CHA	Callahan USFS	RAWS	USFS	941	41.333/122.833	1989-
SYB[b]	Sawyers Bar	RAWS	USFS	1350	41.300/123.117	1991-
–	Blue Ridge	RAWS	USFS	1787	41.269/123.188	2001-
SCP	Scorpion	RAWS	USFS	1320	41.112/122.697	2000-
CFF	Coffee Creek RS	RAWS	DWR	751	41.089/122.709	1960-
043761/HAP	Happy Camp RS	Coop	USFS	336	41.800/122.367	1913-
043182/FJN	Ft Jones RS	Coop	USFS	818	41.600/122.850	1935-
043614	Greenview	Coop	–	846	41.550/122.900	1948-1989
041316/CAL	Callahan NWS	Coop	–	956	41.317/122.800	1943-
046508	Orleans	Coop	–	123	41.300/123.533	1903-
041606	Cecilville1SE	Coop	–	888	41.133/123.133	1954-

[a]Temperature only.

[b]Too many missing data to use.

Table 5-2. Snow courses near Scott River basin

ID	Name	Operator	Elev, m	Lat/Lon	Period
BXC	Box Camp	Salmon/Scott R RD	1935	41.597/123.165	1979-
MBV	Marble Valley	Not specified	1770	41.567/123.198	1951-82
LOG	Log Lake	Not specified	1590	41.547/123.100	1951-78
ETN	Etna Mountain	Salmon/Scott R RD	1770	41.400/123.001	1951-
SWJ	Swampy John	Salmon/Scott R RD	1650	41.397/122.993	1951-
SWT	Sweetwater	Mt Shasta RD	1755	41.382/122.535	1936-
PRK	Parks Creek	Mt Shasta RD	2010	41.367/122.550	1936-
DDF	Deadfall Lakes	Mt Shasta RD	2160	41.318/122.503	1946-
NFS	North Fork Sacramento R	Mt Shasta RD	2070	41.305/122.493	1936-
DYM	Dynamite Meadow	Salmon/Scott R RD	1710	41.233/122.817	1955-
MB3	Middle Boulder 3	USBR	1860	41.225/122.811	1948-
MBL	Middle Boulder 1	Salmon/Scott R RD	1980	41.217/122.807	1946-
WLC	Wolford Cabin	Salmon/Scott R RD	1845	41.200/122.833	1949-
MUM	Mumbo Basin	USBR	1695	41.197/122.523	1947-
HIG	Highland Lakes	USBR	1809	41.093/122.483	1947-
BFT	Big Flat Course	Weaverville RD	1530	41.077/122.938	1946-
RRM	Red Rock Mountain	USBR	2010	41.023/122.885	1946-
SHM	Shimmy Lake	USBR	1920	41.008/122.800	1947-

Table 5-3. Snow-pillow sites near the Scott River basin

ID	Name	Operator	Elev, m	Lat/Lon	Period
PET	Peterson Flat	USBR	2145	41.302/122.528	1985-
SCT	Scott Mountain	USBR	1770	41.272/122.718	1985-
MB3	Middle Boulder 3	USBR	1860	41.225/122.811	1986-
MUM	Mumbo Basin	USBR	1695	41.197/122.523	1984-
HIG	Highland Lakes	USBR	1809	41.093/122.483	1987-
BNK	Bonanza King	USBR	1935	41.083/122.628	1989-
BFL	Big Flat	USBR	1530	41.080/122.942	1985-
RRM	Red Rock Mountain	USBR	2010	41.023/122.885	1986-
SHM	Shimmy Lake	USBR	1920	41.008/122.800	1985-

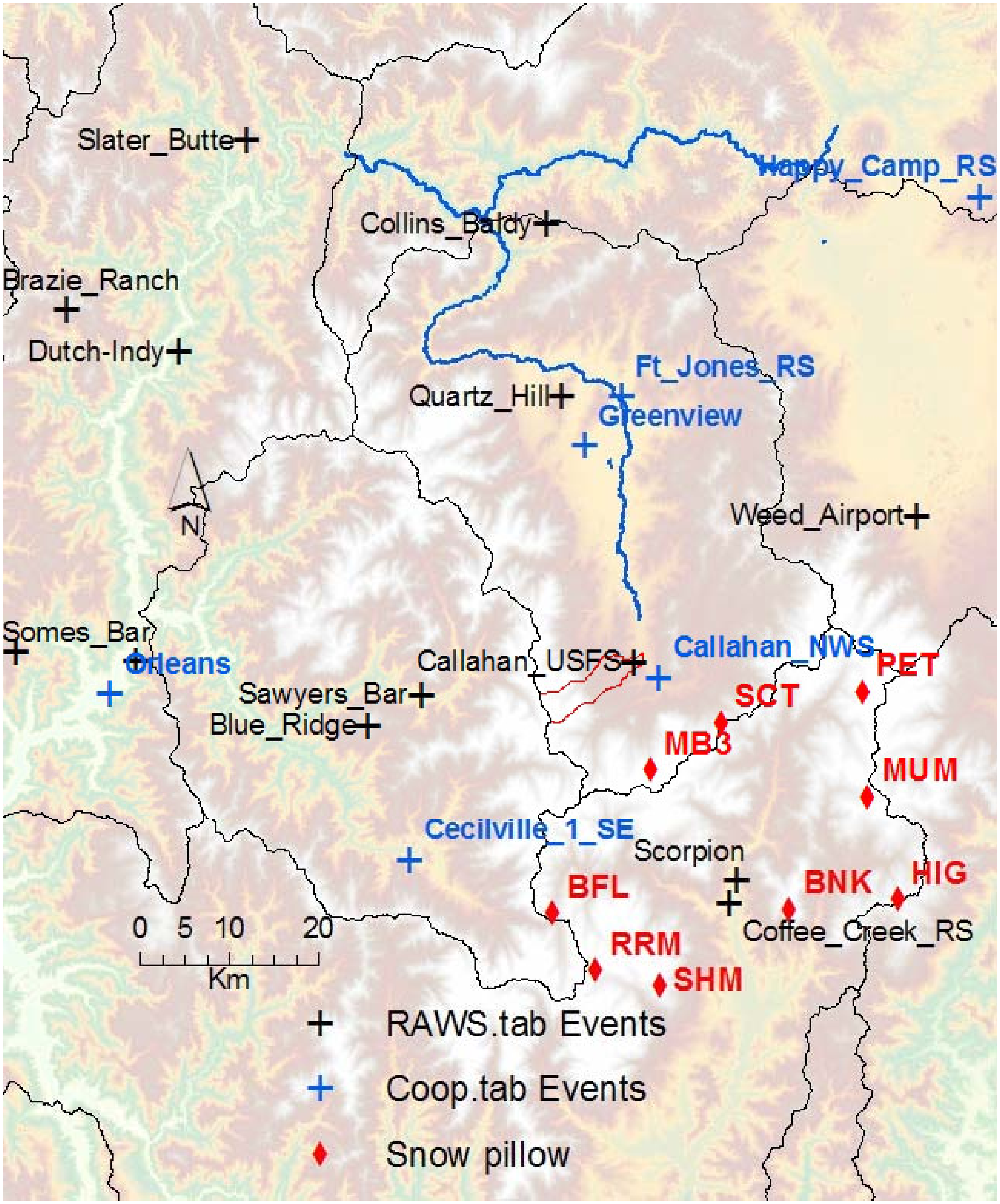

Figure 5.1. Temperature and precipitation stations evaluated in this analysis.

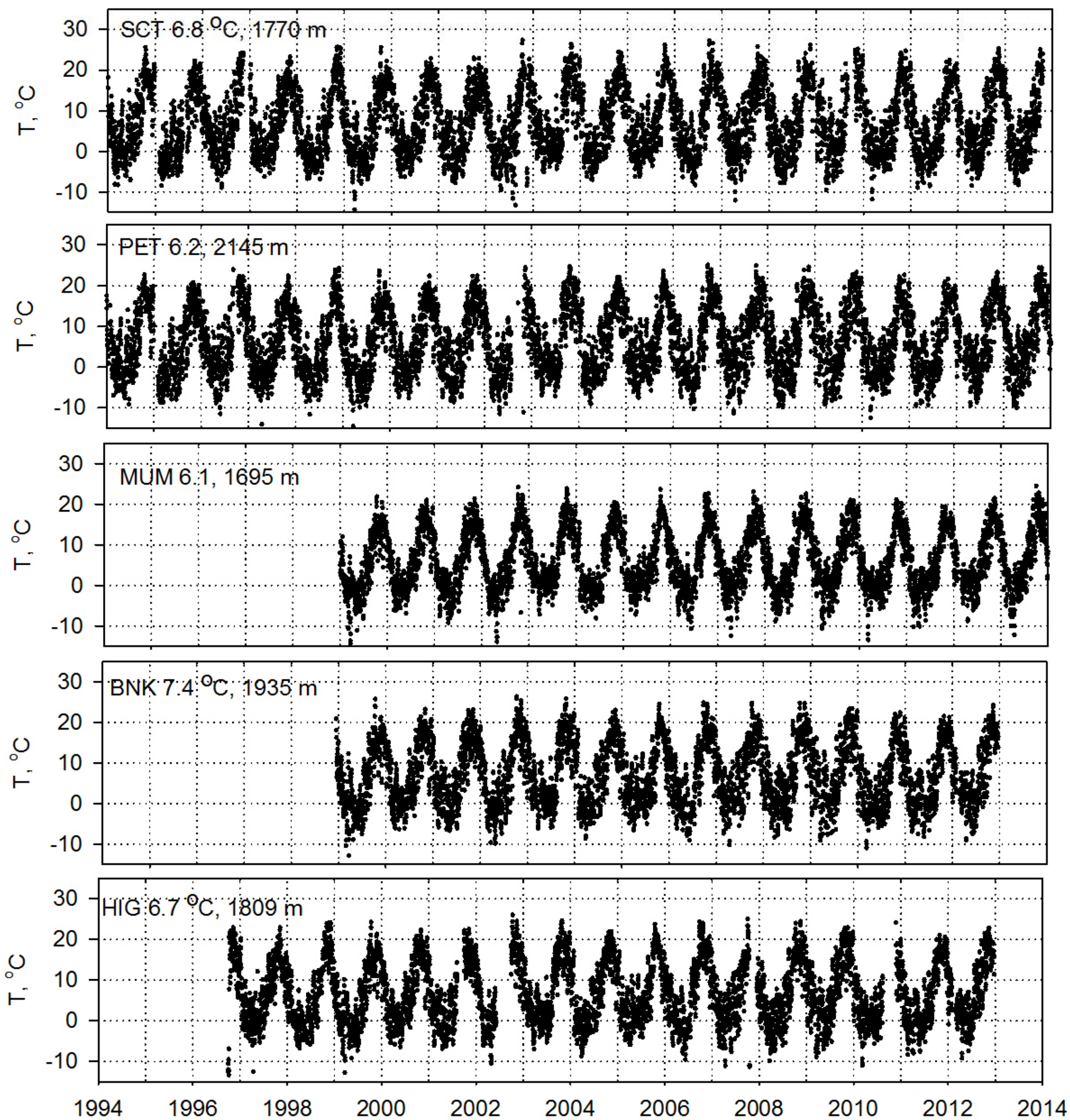

Figure 5.2. Temperature data from 15 stations with reasonably complete 20-year records of daily average temperature. Data are plotted by water year (October 1 through September 30). Each point is a daily average temperature. See Table 1 for station information. Elevation and average temperature are given in each panel.

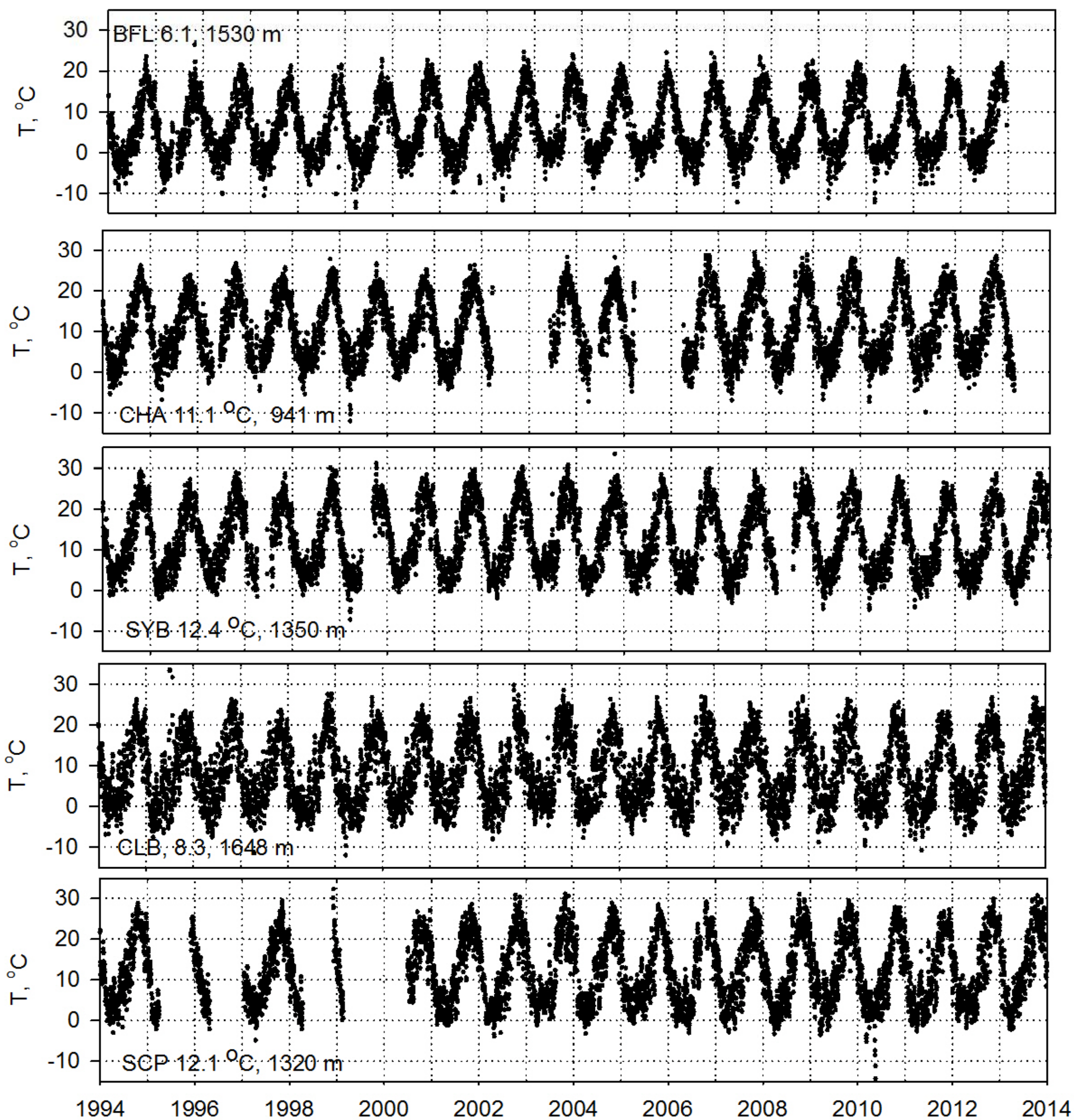

Figure 5.2 (cont.). Temperature data from 15 stations with reasonably complete 20-year records of daily average temperature. Data are plotted by water year (October 1 through September 30). Each point is a daily average temperature. See Table 1 for station information. Elevation and average temperature are given in each panel.

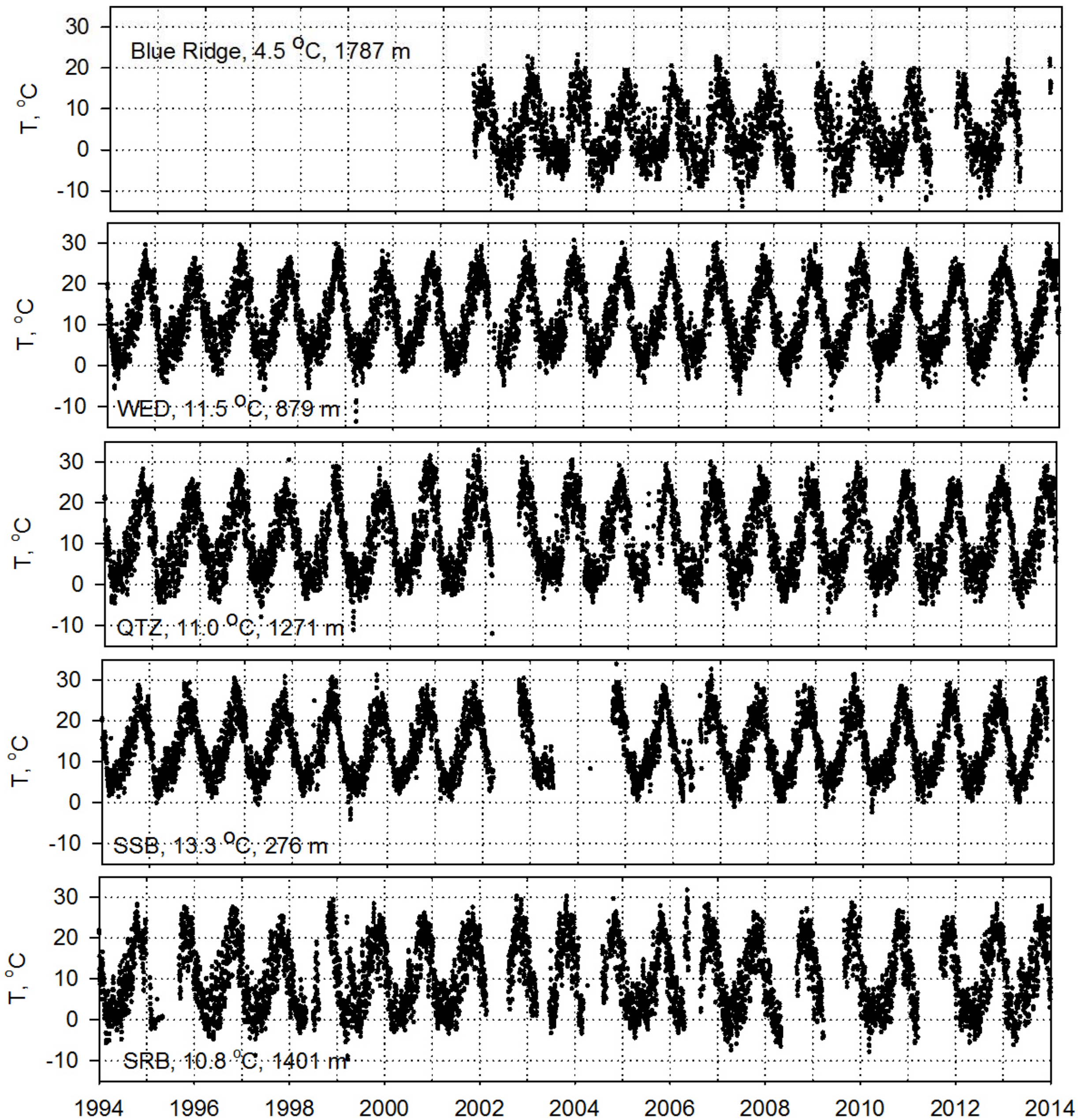

Figure 5.2 (cont.). Temperature data from 15 stations with reasonably complete 20-year records of daily average temperature. Data are plotted by water year (October 1 through September 30). Each point is a daily average temperature. See Table 1 for station information. Elevation and average temperature are given in each panel.

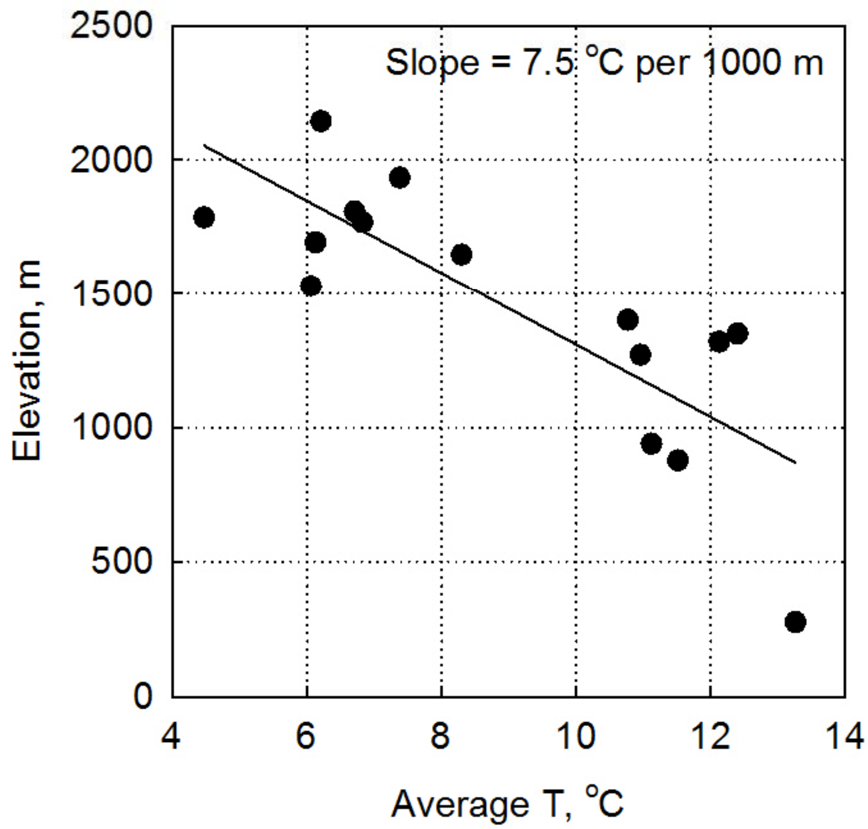

Figure 5.3. Average temperature versus elevation for the 15 stations shown on Figure 2..

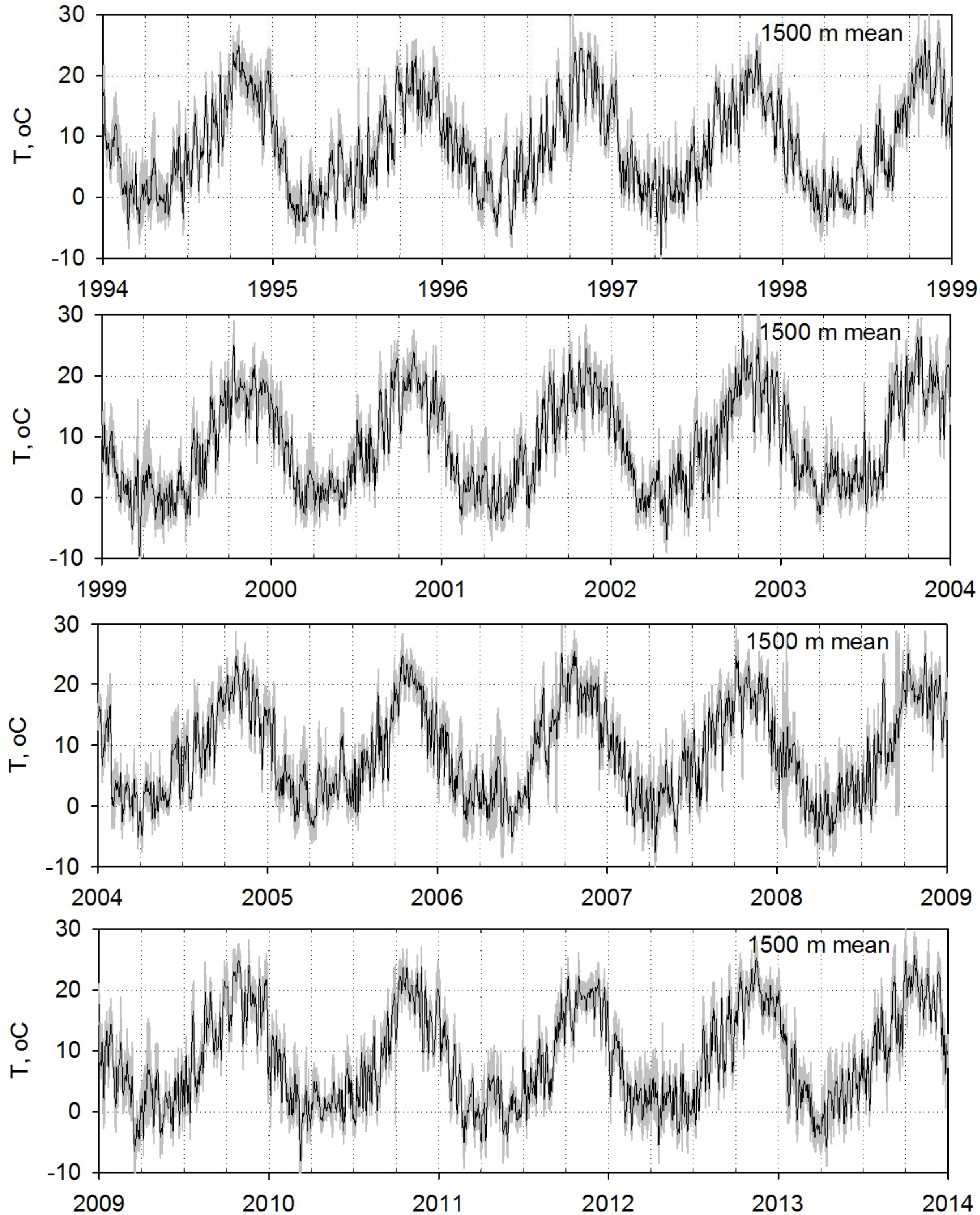

Figure 5.4. Average temperature for an index elevation of 1500 m, based on the 15 stations shown in Figure 2 and the average ground-based lapse rate on Figure 3. The grey shaded area represents the standard deviation across the 15 stations.

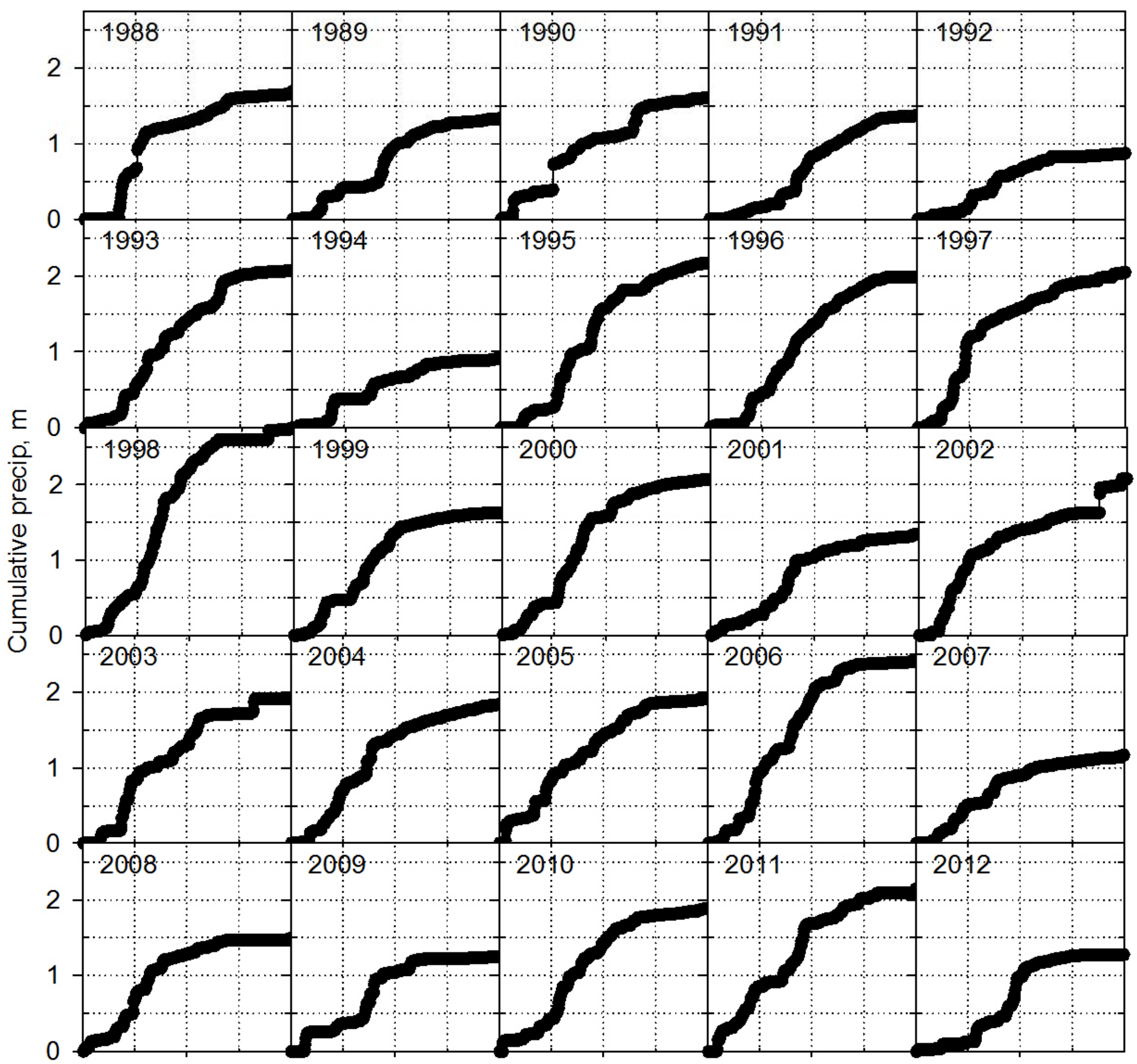

Figure 5.5. Cumulative daily precipitation for water years 1988 5through 2012, Scott Mountain station.

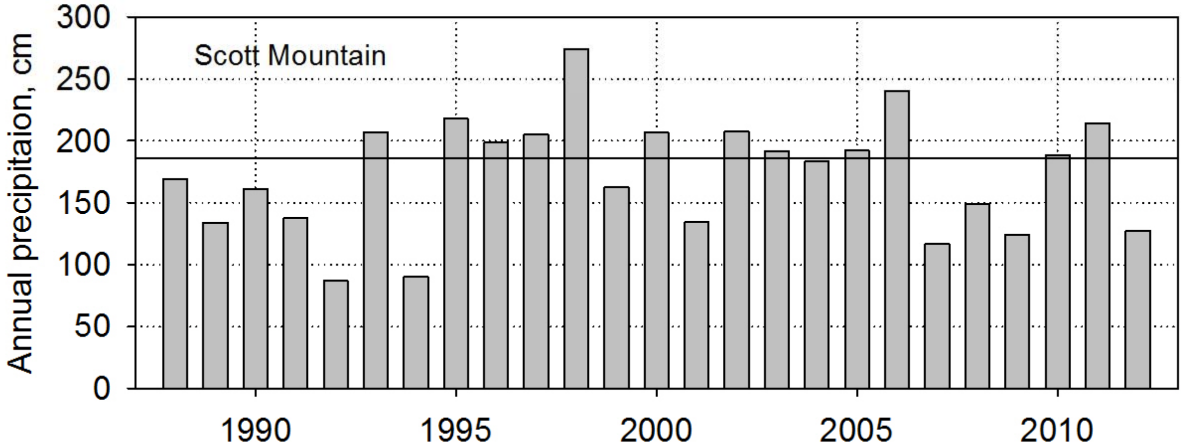

Figure 5-6. Annual precipitation for water years 1988 through 2012, Scott Mountain station. Median value is 186 cm.

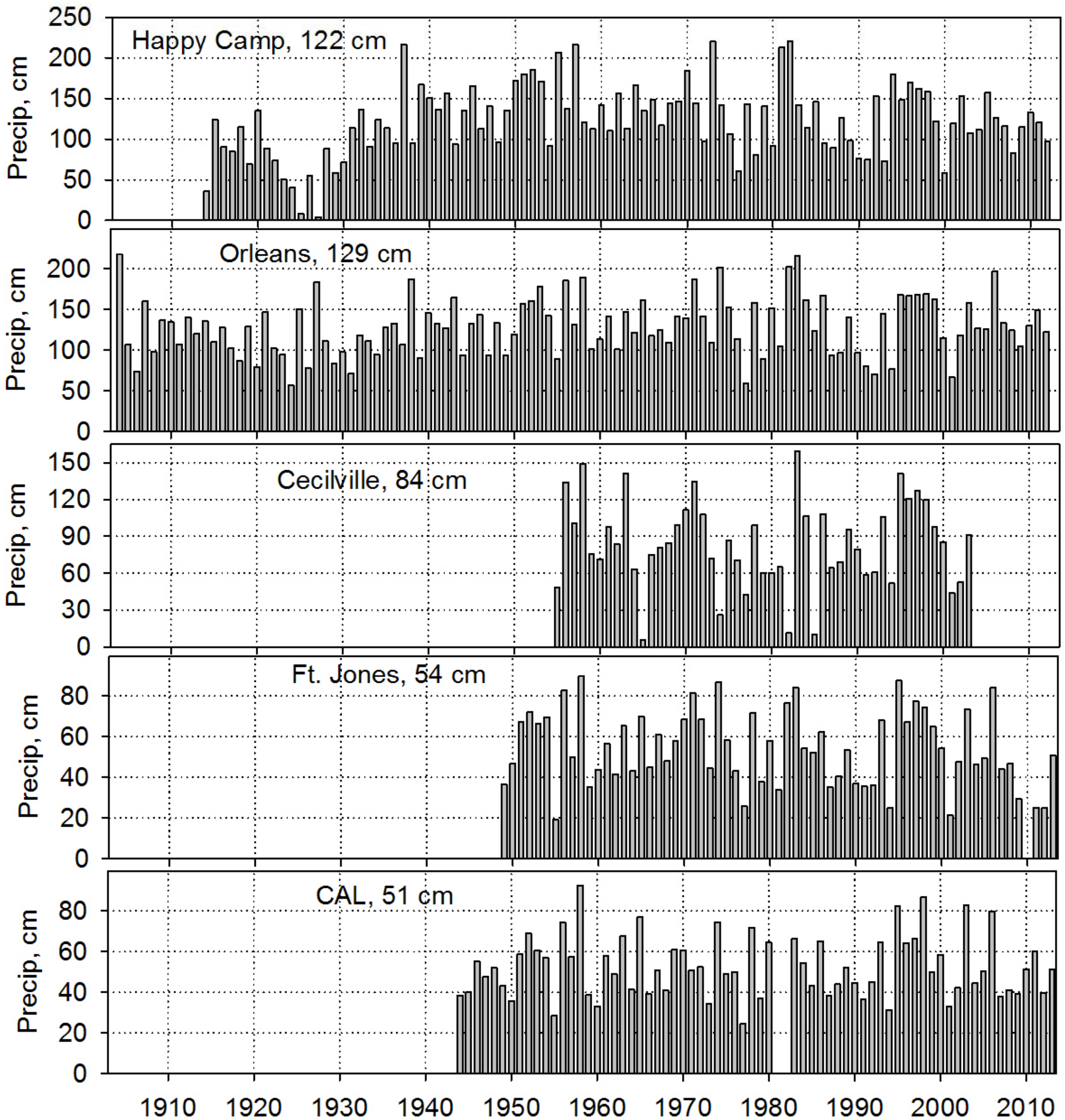

Figure 5.7. Precipitation stations evaluated in this analysis.

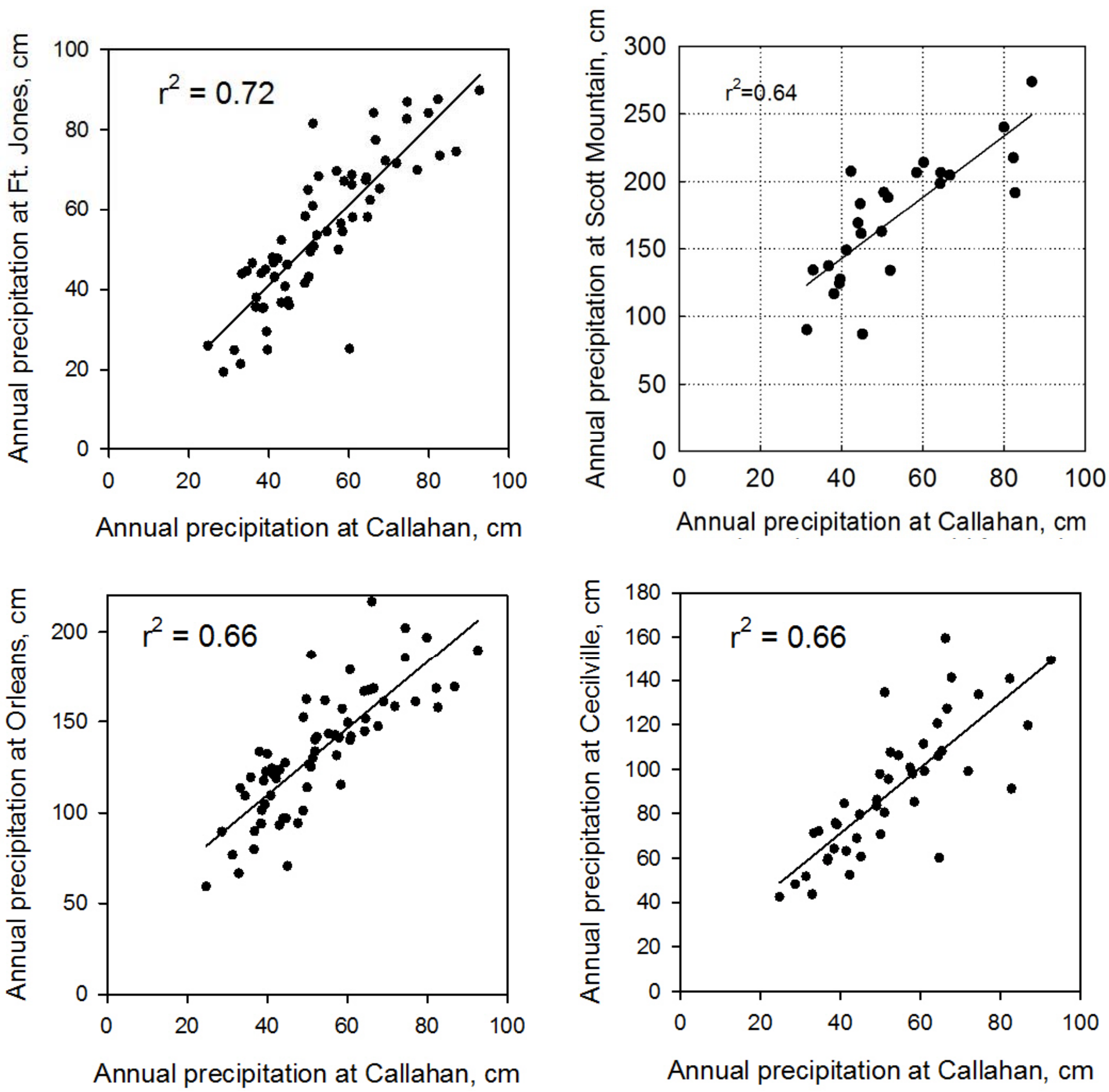

Figure 5.8. Correlation between annual precipitation amounts at stations shown on Figure 5.7. Obvious outliers, i.e. zero or near zero precipitation values, were removed for these plots.

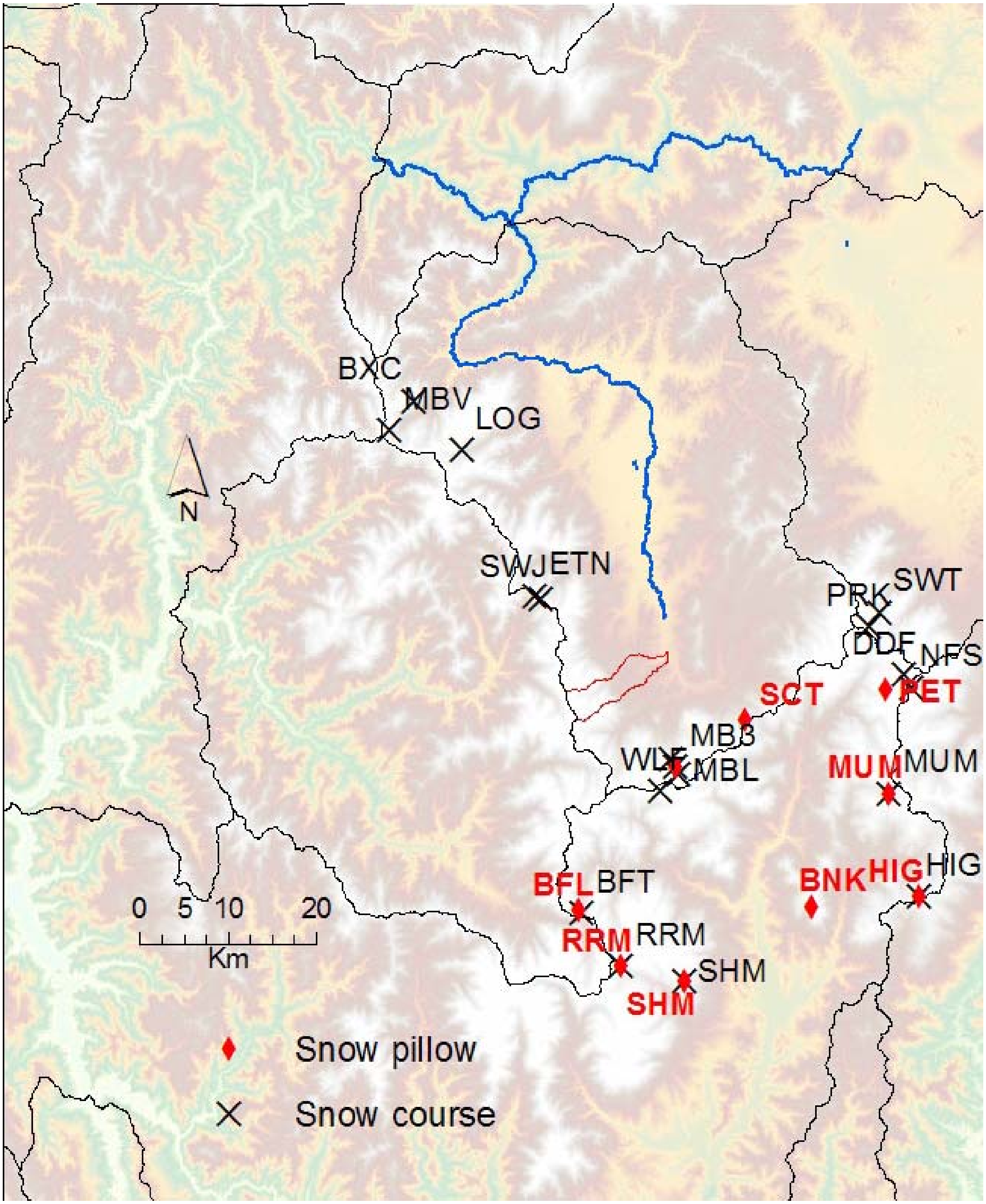

Figure 5.9. Snow courses and snow pillows evaluated in this analysis.

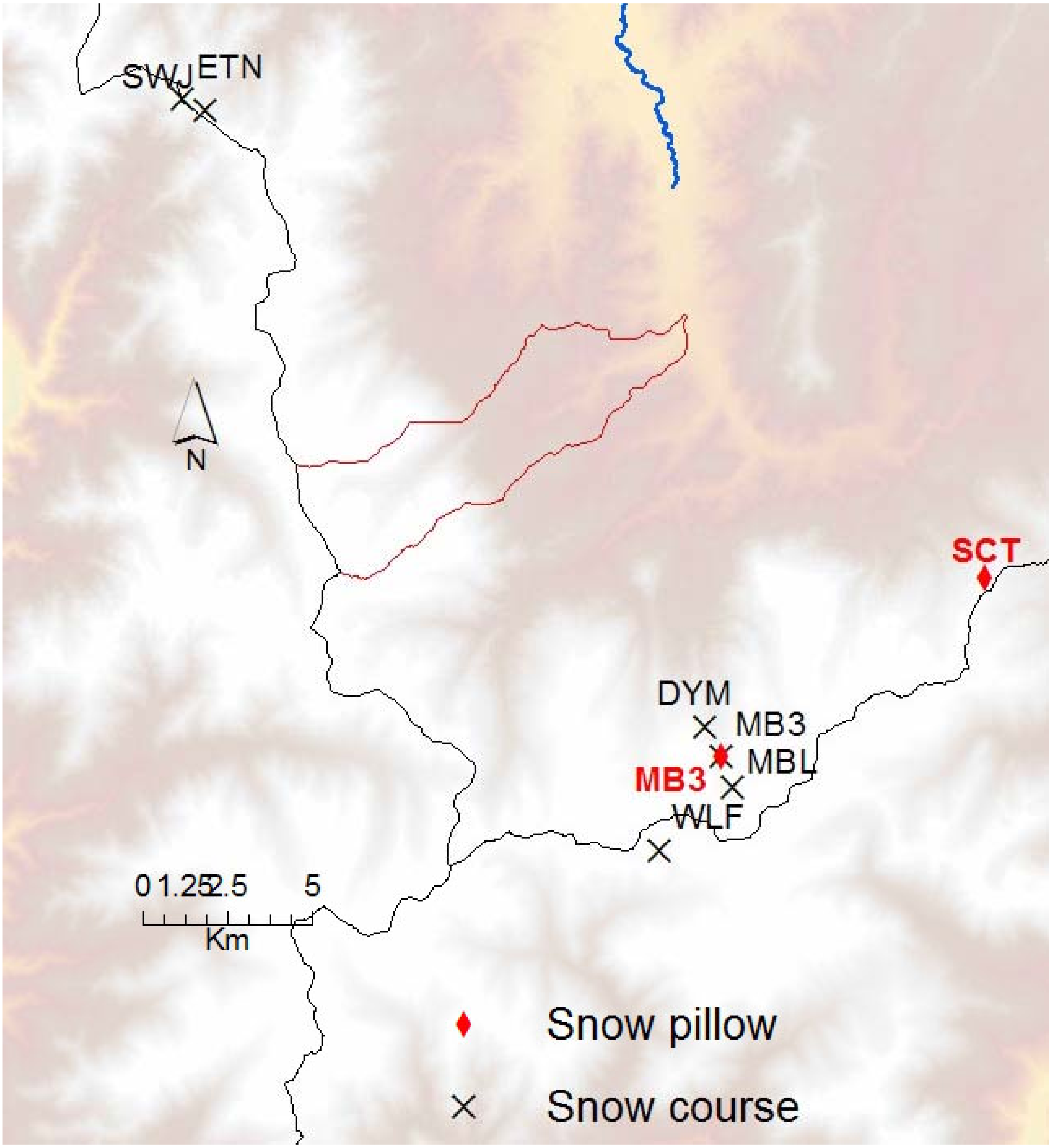

Figure 5.10. Closer view of locations of snow courses and snow-pillow sites close to Sugar Creek.

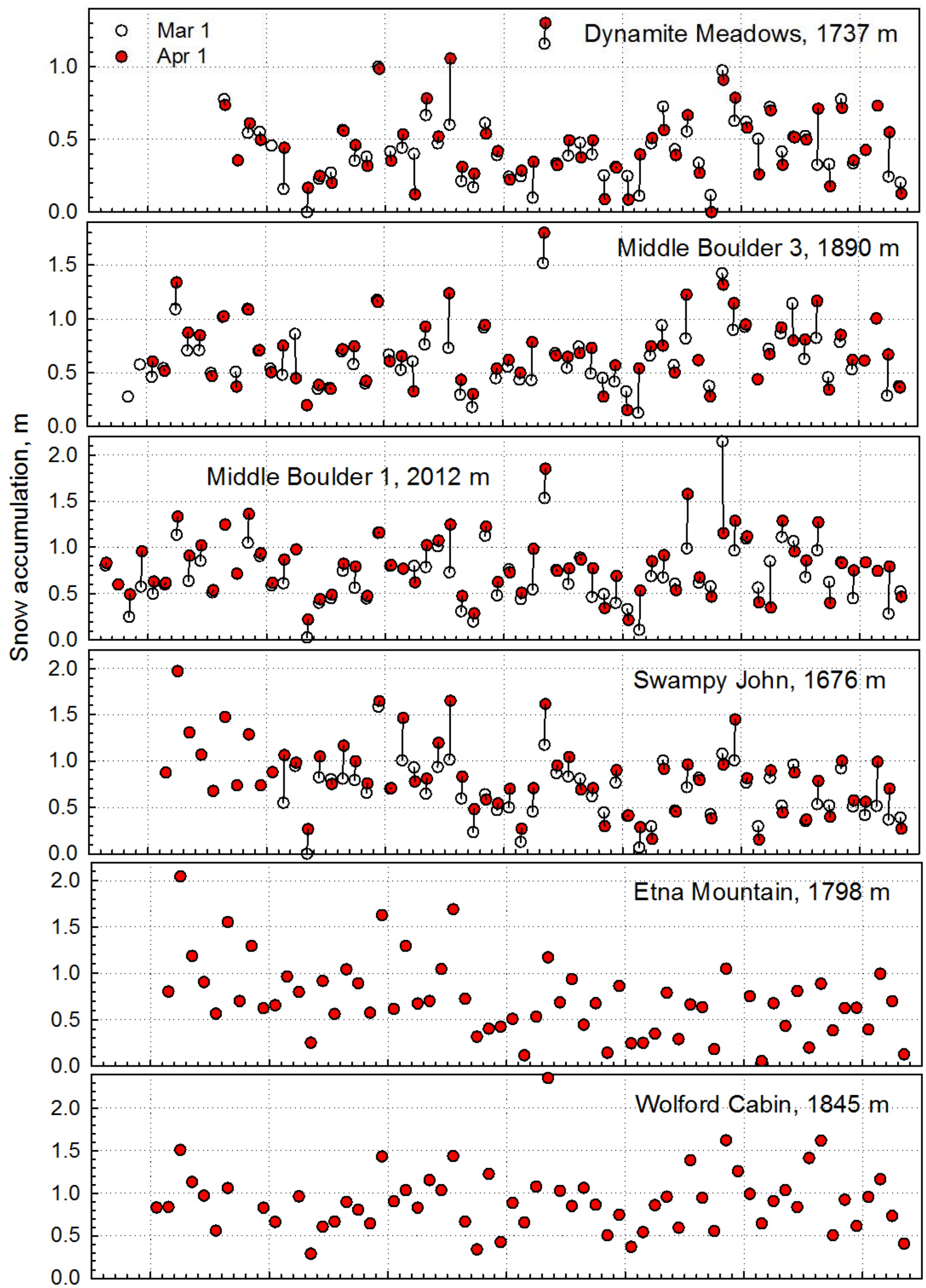

Figure 5.11. Snow-course April 1 accumulation, and March 1 at sites reporting that month.

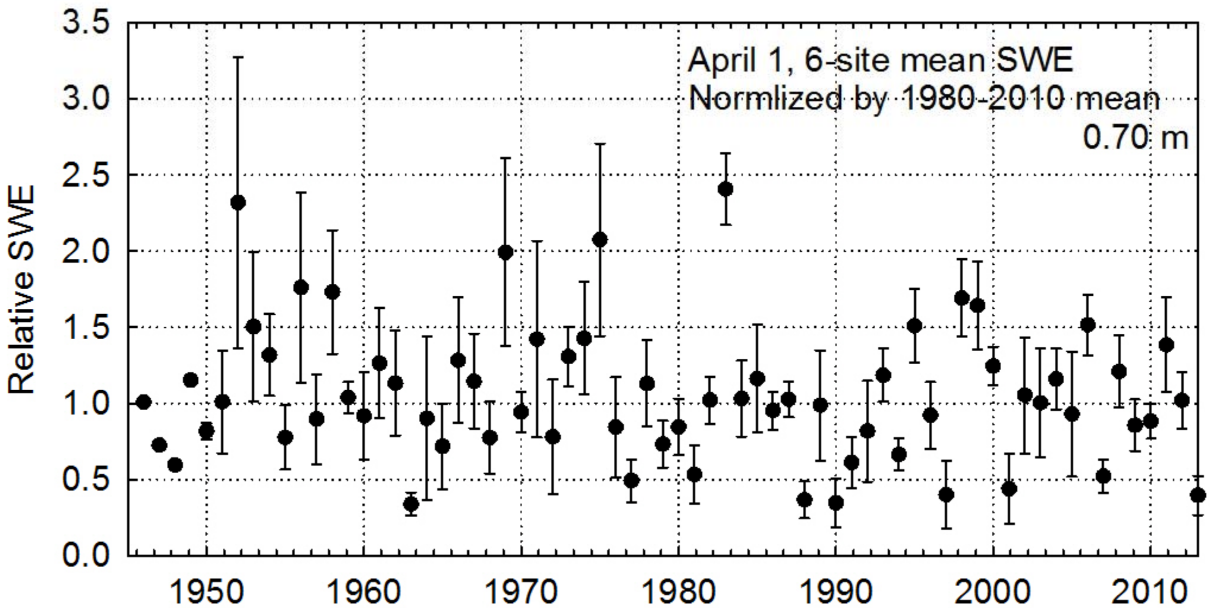

Figure 5.12. Mean and standard deviation of April 1 snow-course values, from Figure 5.11, normalized by the 1980-2010 mean at each site. The overall snow-course average April1 SWE was 0.7 m..

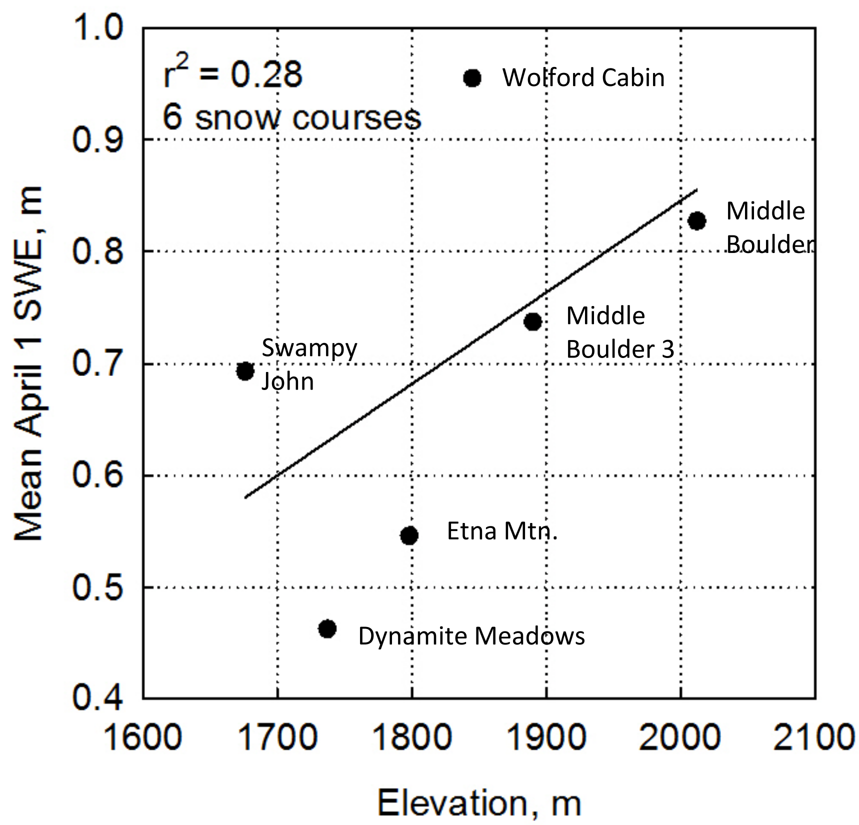

Figure 5.13. Average snow water equivalent (SWE) for the 6 sites on Figure 11, versus elevation of the snow course...

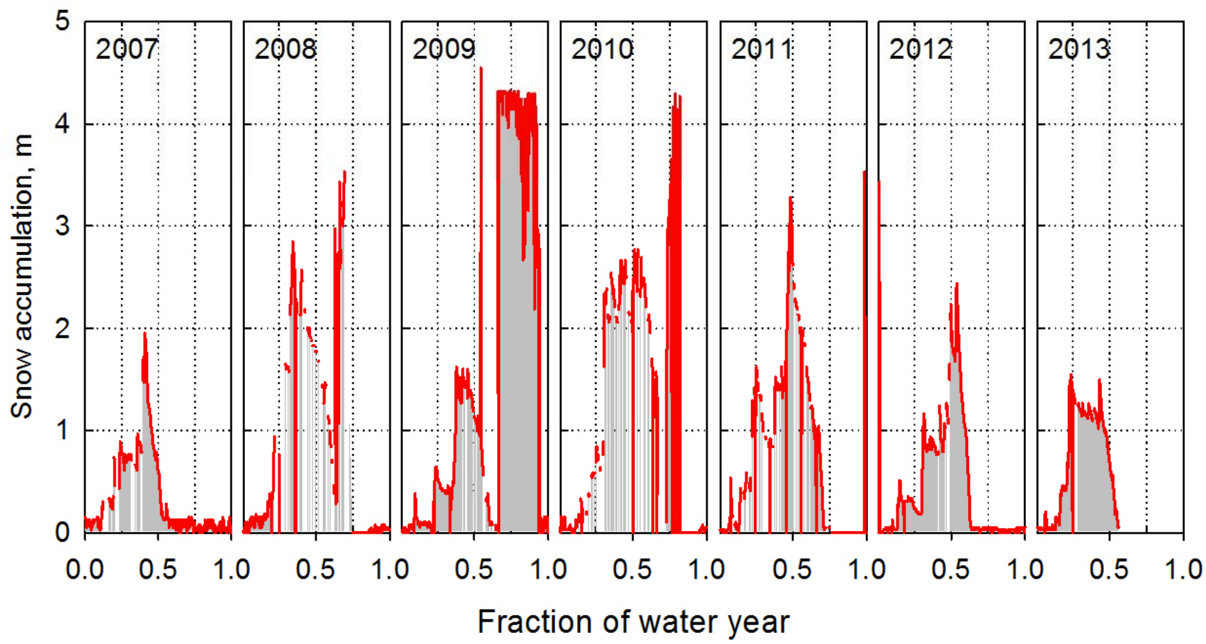

Figure 5.14. Snow water equivalent for the Middle Boulder 3 (MB3) snow pillow.

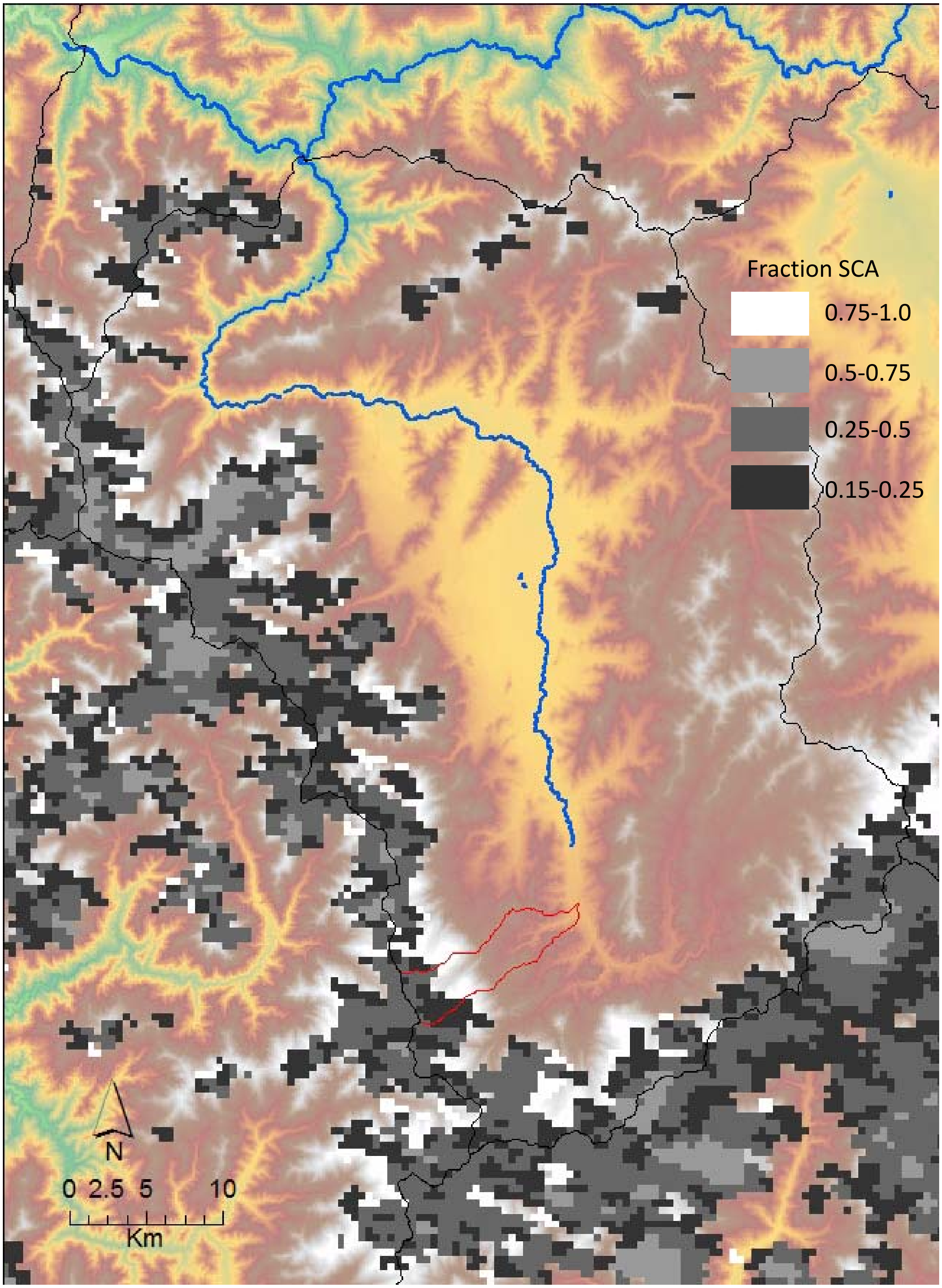

Figure 5.15a. Snow-covered area (SCA) for Scott River basin area, April 3, 2008. Areas with mapped snowcover are shades of black and white, with white being the most and black the least detected snowcover. Pixel size is 500 m. Outline of Sugar Creek basin shown in red, and Scott River basin in black.

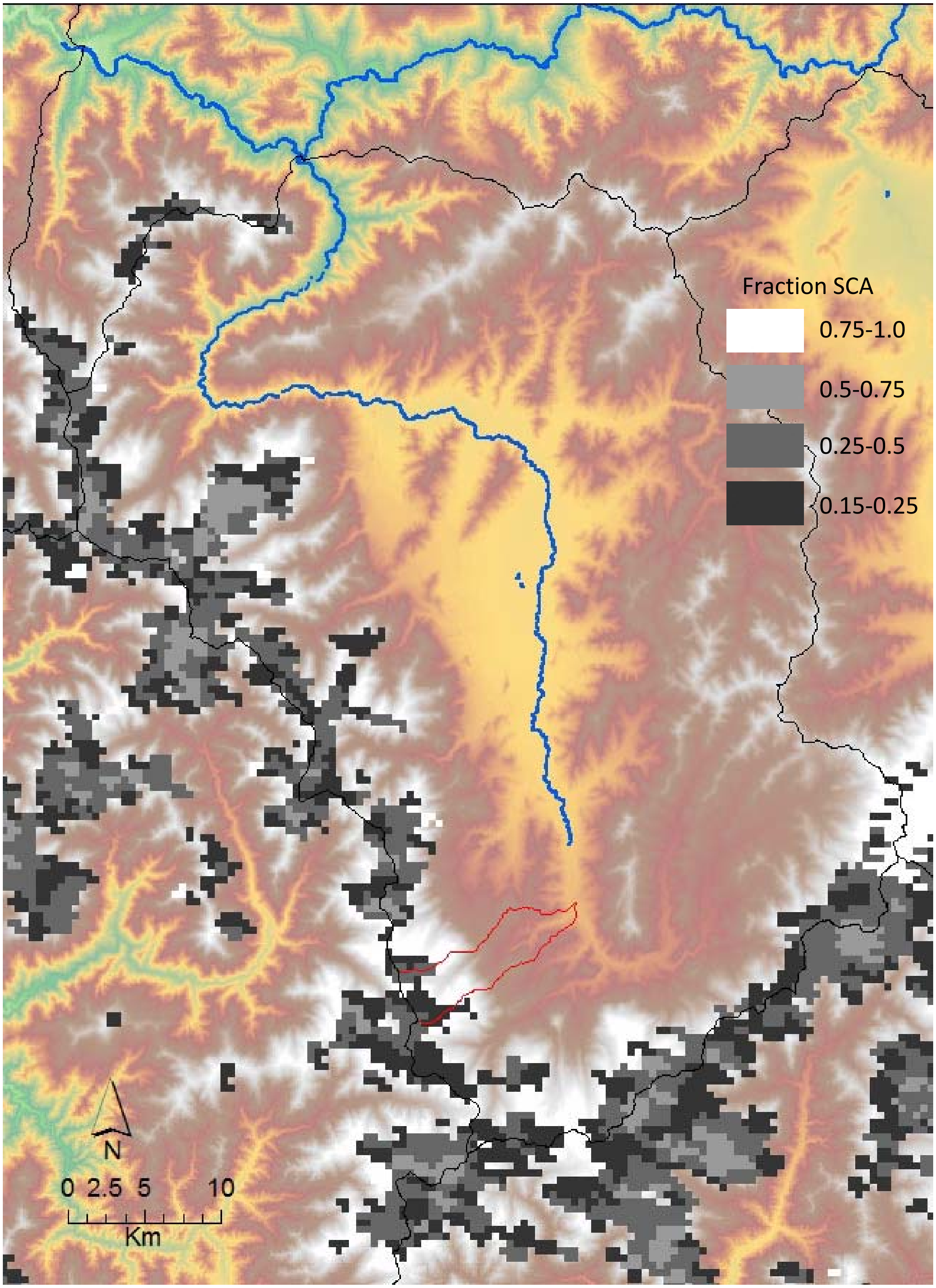

Figure 5.15b. Snow-covered area (SCA) for Scott River basin area, April 5, 2009. Areas with mapped snowcover are shades of black and white, with white being the most and black the least detected snowcover. Pixel size is 500 m. Outline of Sugar Creek basin shown in red, and Scott River basin in black.

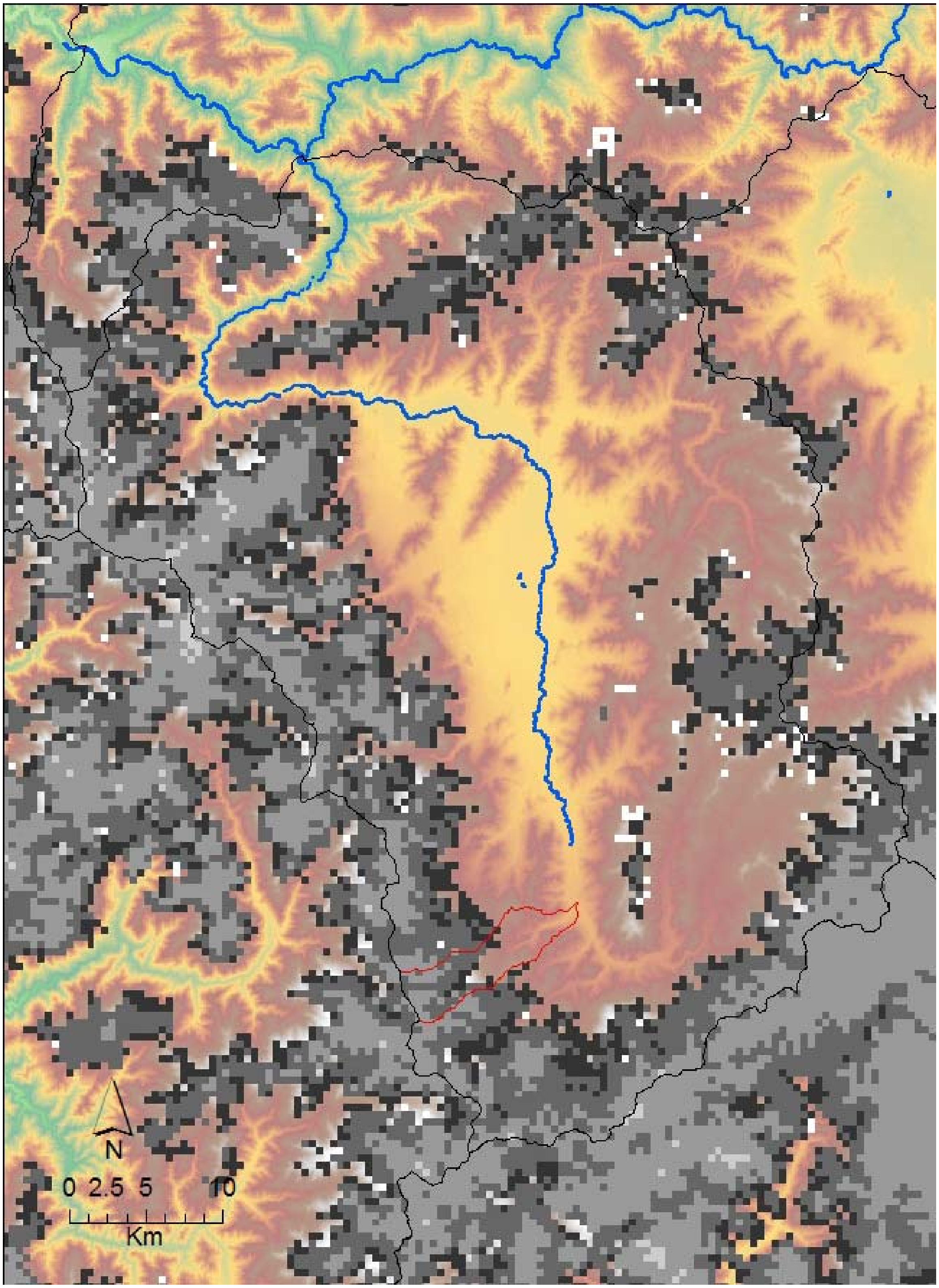

Figure 5.15c. Snow-covered area (SCA) for Scott River basin area, April 7, 2010. Areas with mapped snowcover are shades of black and white, with white being the most and black the least detected snowcover. Pixel size is 500 m. Outline of Sugar Creek basin shown in red, and Scott River basin in black.

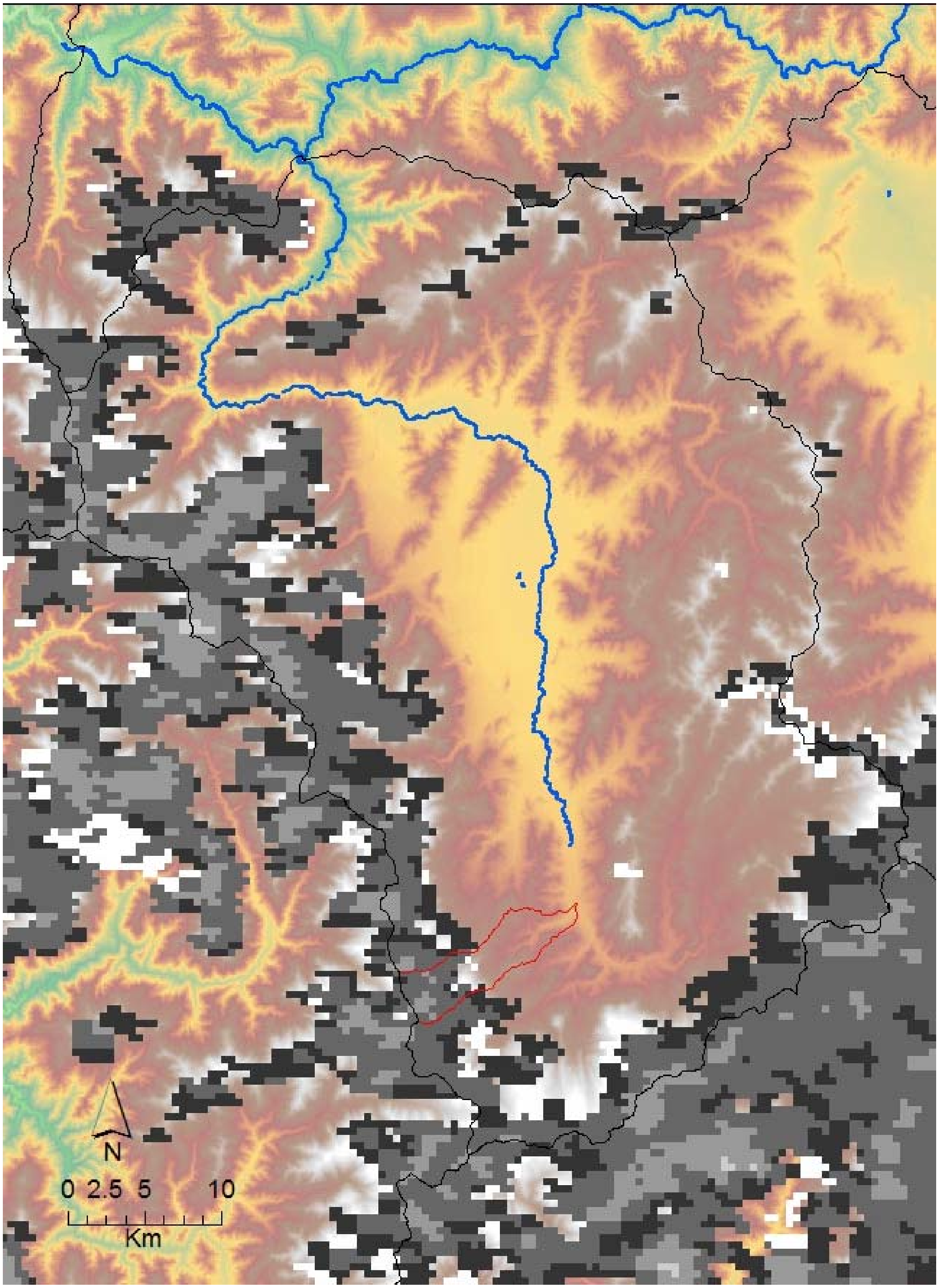

Figure 5.15d. Snow-covered area (SCA) for Scott River basin area March 31, 2011. Areas with mapped snowcover are shades of black and white, with white being the most and black the least detected snowcover. Pixel size is 500 m. Outline of Sugar Creek basin shown in red, and Scott River basin in black.

6. Hydrologic features

6.1. Streamflow

Two primary stream gauges that will be used to inform the hydrologic modeling are those on Sugar Creek near Callahan and the Scott River near Ft. Jones (Figure 6-1, Table 6-1). The Sugar Creek gauge has 3 years of streamflow in the late 1950s, including both above average (1958) and below average (1959 and 1960) precipitation years (Figure 6-2). Note the greater total discharge in WY 1958, and the much later hydrograph recession to baseflow in 1958 versus the two later years (Figures 6-2 and 6-3). Baseflow is similar in all 3 years, but it is not known the extent to which diversions affect baseflow. It was reported that Sugar Creek has 6 stream diversions, totaling 0.722 $m^3 s^{-1}$ (25.5 cfs) (Figure 6-4) (USDA, 1997). This is a large amount relative to the total streamflow, and a record of the magnitude of only one diversion is available, beginning in 2010. Gauge data are available for 3 additional locations: i) Darby Ditch, ii) Sugar Creek below Darby Ditch, and iii) Sugar Creek near Callahan. Only stage data, not discharge are currently available publically (Figure 6-5). However, the data look reasonably good and should be readily converted to discharge provided the operator (DWR) can provide a rating curve.

The USGS record for the Scott River at Ft. Jones is perhaps the most-complete data set evaluated. The daily values on Figure 6-6 illustrate the sensitivity of the stream gauge to rain events, spring snowmelt and dry periods. However, this site is also affected by many diversions, the magnitude of which are not known on a day-to-day or month-to-month basis.

Two additional tributary streams have active gauges, and will help establish the timing of streamflow in Sugar Creek. These are French Creek and Shackelford Creek. Data will require some cleaning in order to use. Finally, the short-term historical records noted in Table 6-1 will provide additional constraints on Sugar Creek streamflow timing and amount.

6.2. Annual discharge and variability

The discharge records shows wet and dry periods more distinctly than do the precipitation records at this point, though it is expected that with cleaning the snow and precipitation records will also show multi-year wet and dry periods. For hydrologic modeling it will be necessary to set up a time series of precipitation and temperature inputs, using both historical records and expected shifts to historical records.

Annual values for the Scott River discharge at Ft. Jones show considerable interannual variability (Figure 6-7). Note that these records do not account for diversions. While information on allowable diversions is available, actual records of diversions in the basin would be helpful to improve the accuracy of the hydrologic simulations. Some distinct features that stand out include the very dry water year 1977, and the six-year dry period beginning in 1987. Note also that 8 of the past 10 years have been below the median discharge.

The average discharge of the Scott River at Ft. Jones corresponds to a water yield of about 28 cm, with a range of 2-62 cm. Again, this does not account for diversions. Similarly, the water yield based on the gauge for Sugar Creek is about 10 cm for 2010-13.

Longer records for scenario planning can be developed from paleoclimate data. Cook et al. (1999) have developed a gridded data set for the continental United States for the past 2000 yr, based largely on tree-ring chronologies. That record shows that the 1940 to present period is relatively wet, and that each prior century had a multi-decadal drier period (Figure 6-8). This plot shows Palmer Drought Severity Index (PDSI), which reflects a combination of precipitation and soil water storage.

Diversions

Discharge and thus measured streamflow in the Scott River and its tributaries, including Sugar Creek, are heavily influenced by diversions. Surface-water rights are adjudicated by three decrees: the Shackleford Creek Decree (1950), the French Creek Decree (1958), and the Scott River Decree (1980). The latter applies to Sugar Creek, and provides for diversions totaling 25.58 cfs (CADFG, 2009). The decrees, as explained by Scott River Watershed Council (SRWC) (2006), have defined: 1) the amount of water each user is entitled to divert from surface streams or to pump from the interconnected groundwater supplies near the river; 2) the area where such water may be used; 3) the priority of each water right as it relates to other water rights on the same source; 4) the purpose for which the water is used (e.g., irrigation, municipal, domestic, stock-water); and 5) the diversion season. The decrees sum to an allotment that is greater than the average monthly flow of the Scott River from June through December (CADFG, 2009).The Scott River and most of its tributaries do not have appointed watermasters and, consequently, there is no way to verify whether water diversions are in compliance with existing water rights (DWR, 1991).

Whereas USBR has done a natural-flow study for parts of the Upper Klamath River, the Scott River was not included (NRC, 2007; USBR, 2005). That approach estimated monthly crop consumptive uses, adding the values to measured streamflow to get naturalized flow. That assumes that diversions correspond to actual evapotranspiration, which was not verified. It is further limited by the coarse time step. A similar approach could be taken for the Scott River Valley, even using daily data. While not definitive, it could provide a valuable check on modeled values of streamflow.

References

USDA (1997). Callahan Ecosystem Analysis. Scott River Ranger District, Klamath National Forest.148 pp.

Cook, E.R., Meko, D.M., Stahle, D.W. and Cleaveland, M.K. (1999) Drought reconstructions for the continental United States. *Journal of Climate*, 12:1145-1162.

NRC. (2008) Hydrology, Ecology, and Fishes of the Klamath River Basin National Academies Press, Washington, D.C. 272 pages

USBR (2005) Natural Flow of the Upper Klamath River—Phase I. 115 pages.

CADFG (2009) Scott River Watershed-Wide Permitting Program, Final Environmental Impact Report. Chapter 3.2, Geomorphology, Hydrology, and Water Quality, 65 pages.

DWR (1991) State of California, Department of Water Resources (DWR), *Scott River Flow Augmentation Study*.

Table 6-1. Streamflow stations in and near the Scott Valley

ID	Name	Operator	Elev, m	Area, km^2	Lat/Lon	Period
11519500 SFJ	Scott R nr Ft. Jones	USGS	787	1691	41.6407/123.01504	1941-
11518300 SGR	Sugar Creek nr Callahan	USGS, DWR	939	31.1	41.3286/122.8434	1957-60 2005-
DDC	Darby Ditch	DWR	1020		41.316/122.8686	2010-
SDA	Sugar C bl Darbee D nr Callahan	DWR	1020		41.3157/122.8694	2010-
FCC	French Creek	DWR	852		41.4117/122.8588	2004-
11519000 SCK	Shackelford Cr nr Mugginsville	USGS, DWR	807	45.8	41.6248/122.9657	1956-60 2004-
11518310	Cedar Gulch nr Callahan	USGS	939	2.6	41.3444/122.8292	1966-73
11518000	EF Scott R nr Callahan	USGS	977	149	41.3217/122.7217	1910-11
11518050	EF Scott R Callahan	USGS	977	285		1959-74
11517900	EF Scott R bl Houston C nr Callahan	USGS	1189	51	41.4017/122.6522	1970-73
11517950	EF Scott R ab Kangaroo C nr Callahan	USGS	1110	128	41.3394/122.7186	1970-73
11518600	Moffett C nr Fort Jones	USGS	890	181	41.6333/122.7466	1958-67
11520000	Scott R nr Scott Bar	USGS	473	2082	41.7750/123.0333	1911-13
11518200	SF Scott R nr Callahan	USGS	981	981	41.2958/122.8089	1958-60

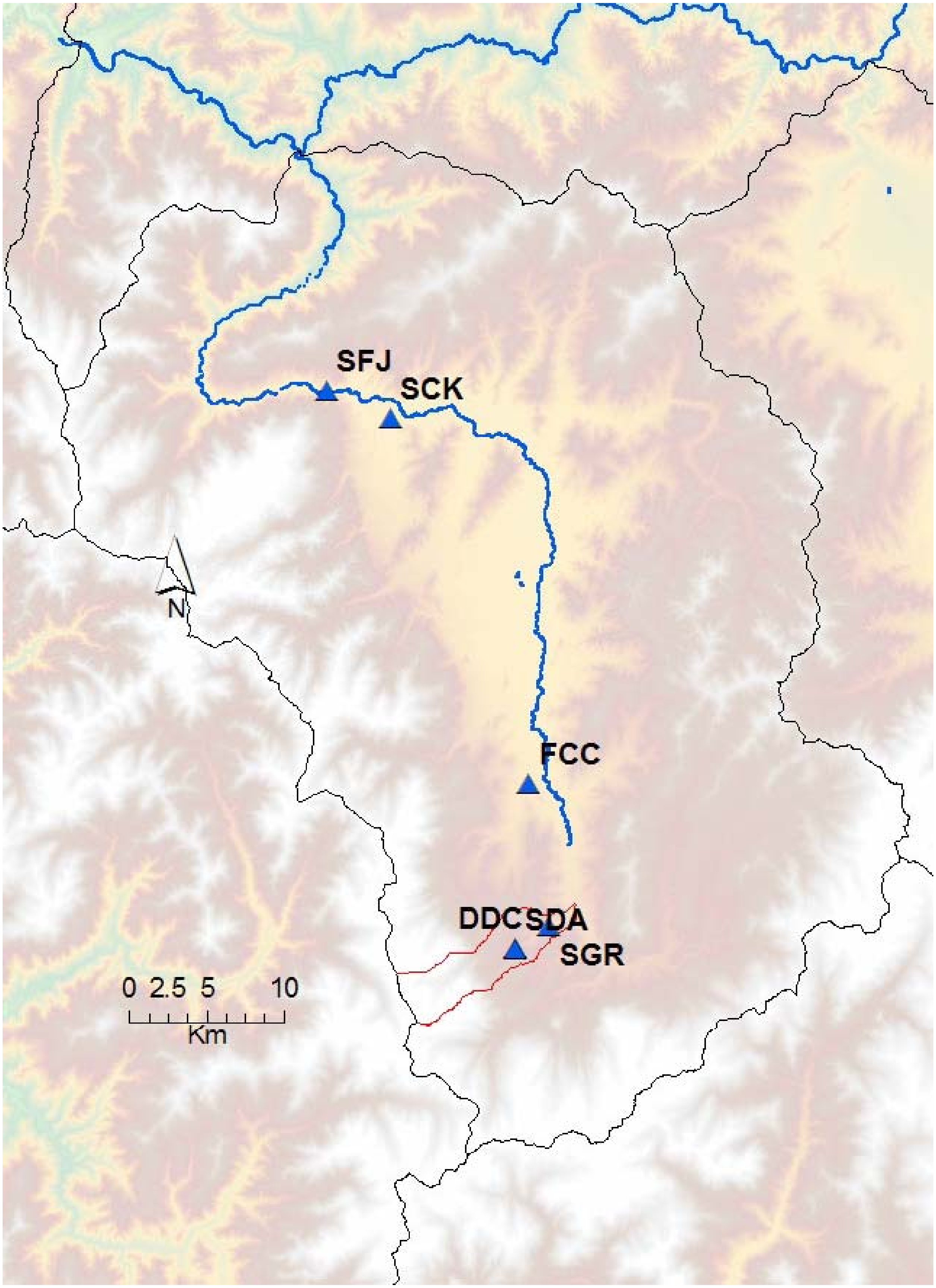

Figure 6.1. Streamflow stations in and near the Scott Valley.

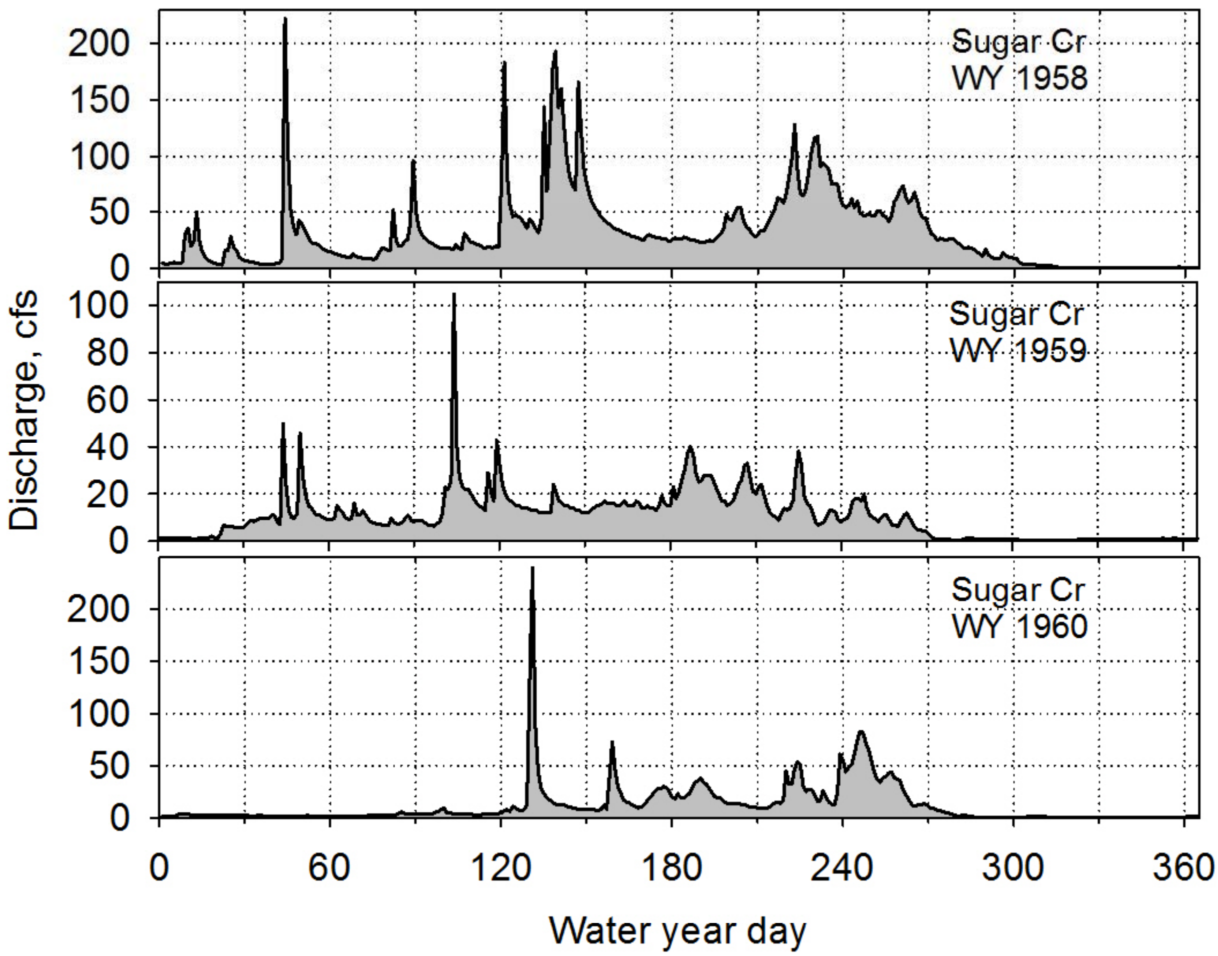

Figure 6.2. Sugar Creek discharge for 3 water years (Water year is Oct 1 through Sept 30).

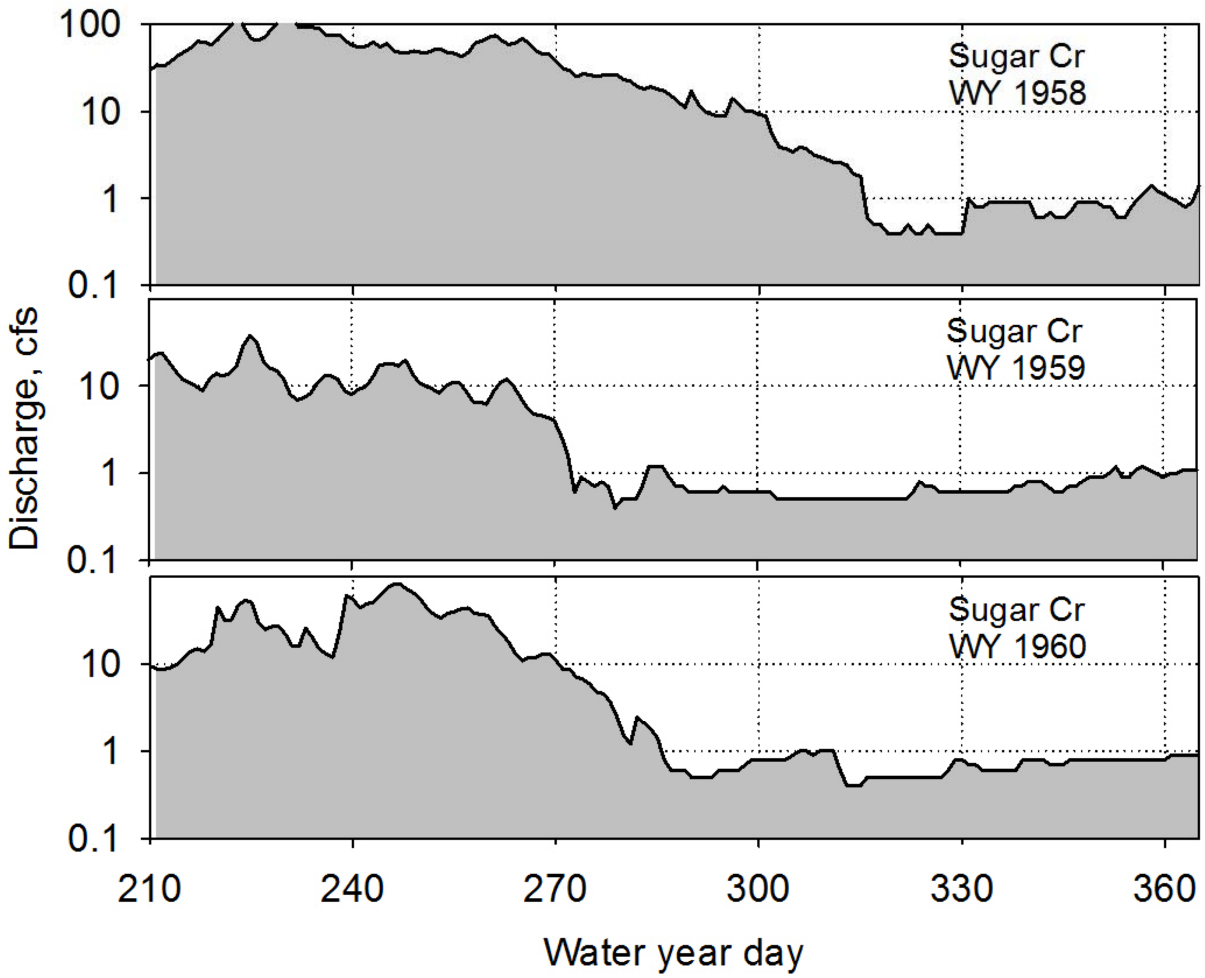

Figure 6.3. Semi-log plot of Sugar Creek discharge for 3 water years illustrating hydrograph recession and baseflow,.

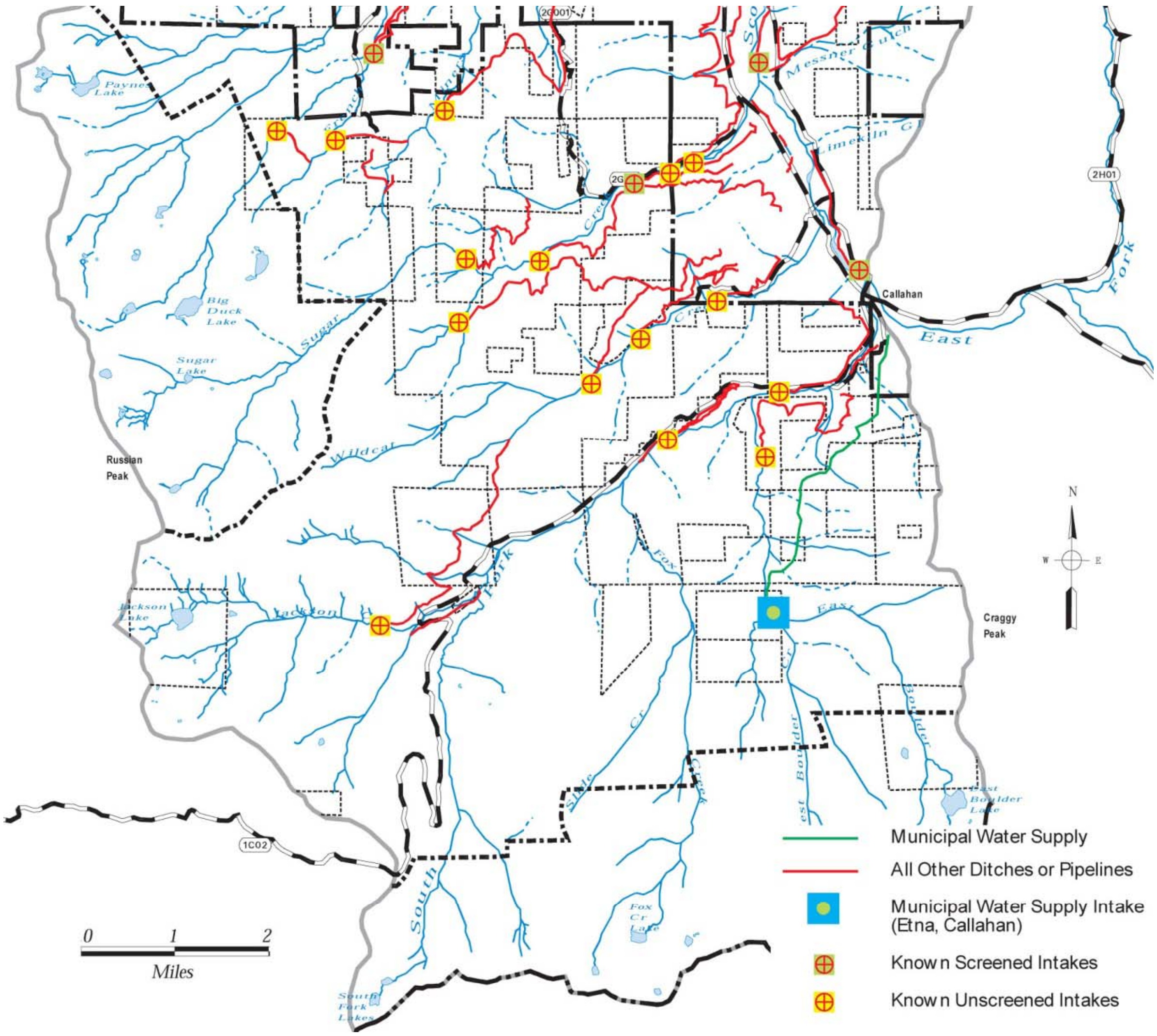

Figure 6.4. Sugar Creek water diversions. Adapted from USDA (2007).

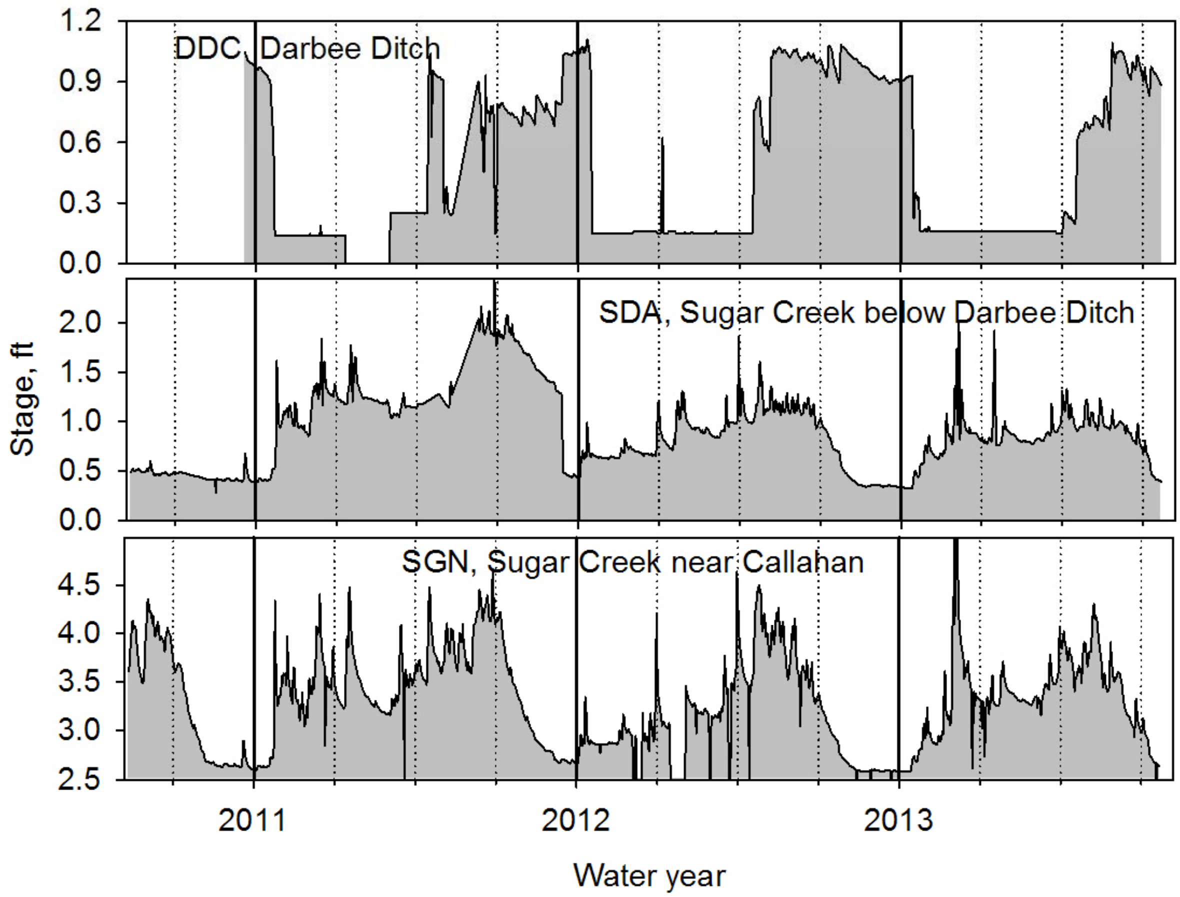

Figure 6.5. Stage records for 2 locations on Sugar Creek, and one diversion from Sugar Creek (Darbee Ditch).

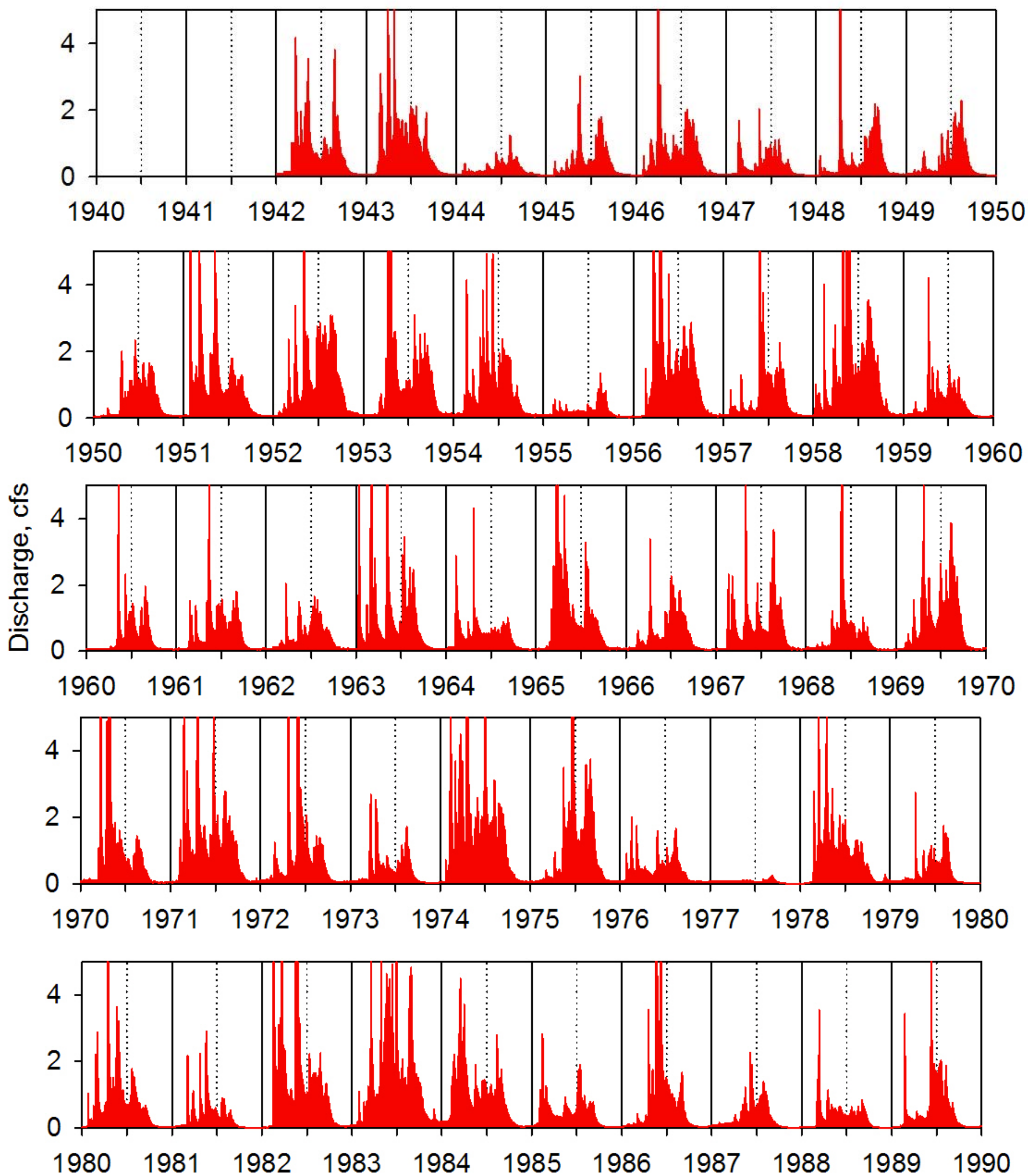

Figure 6.6. Discharge record for Scott River at Ft. Jones. Discharge is thousand cfs. Peaks over 5000 cfs are not shown.

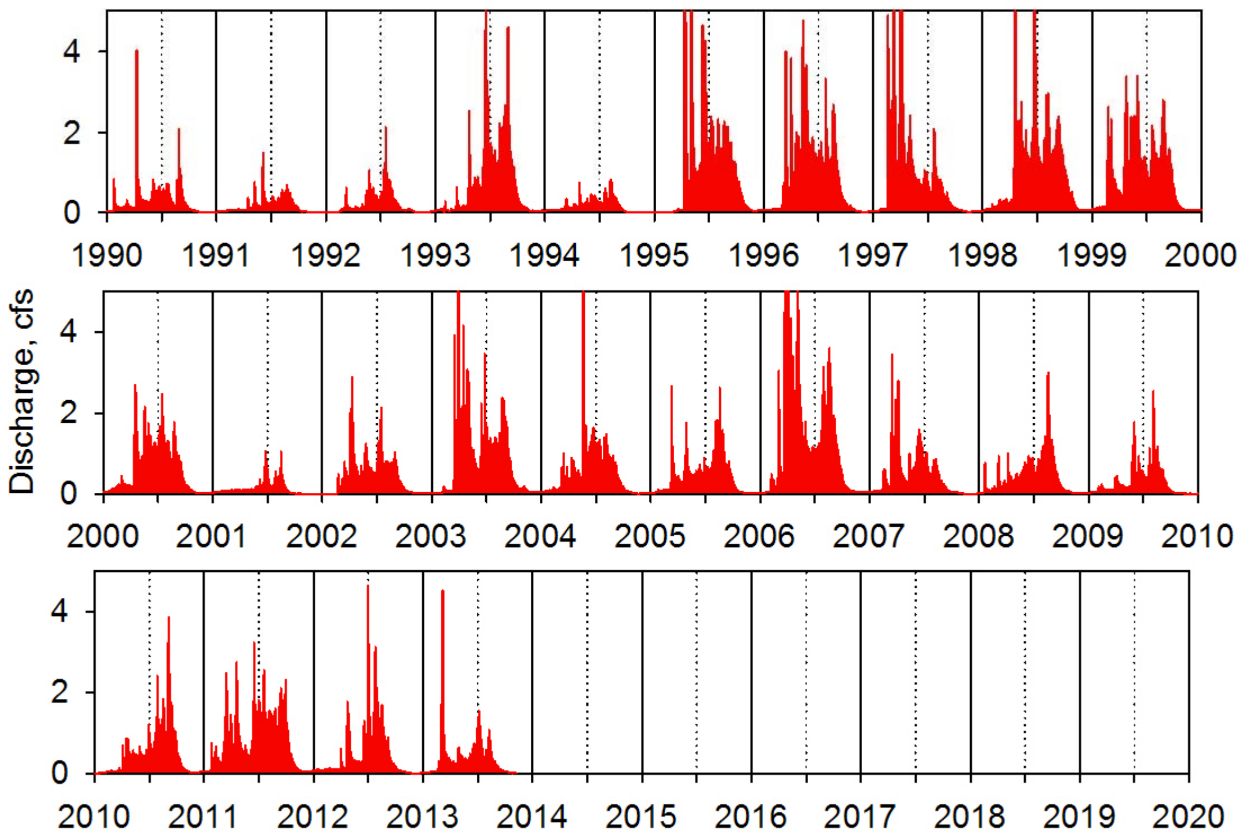

Figure 6.6 (cont.). Discharge record for Scott River at Ft. Jones. Discharge is thousand cfs. Peaks over 5000 cfs are not shown.

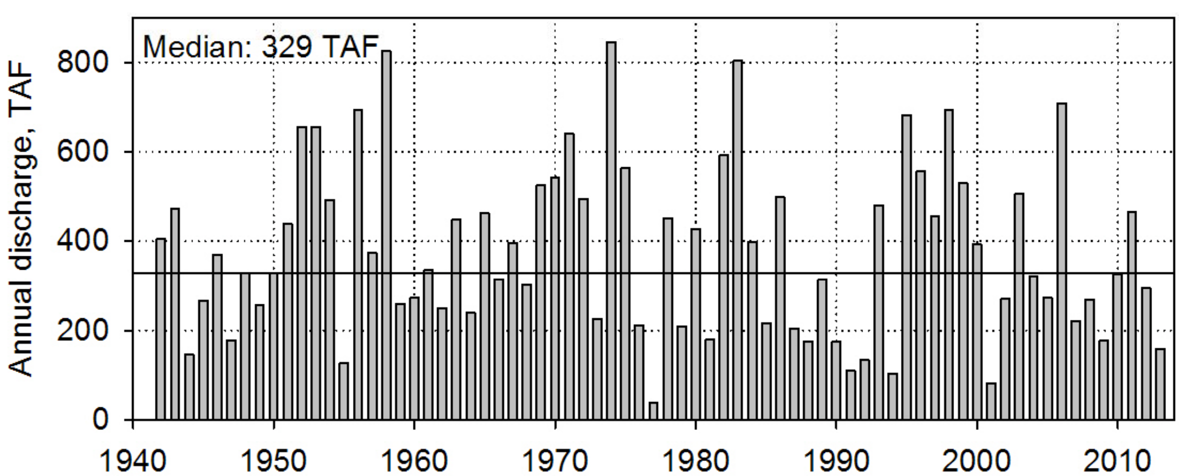

Figure 6.7. Annual discharge measured on the Scott River at Ft. Jones.

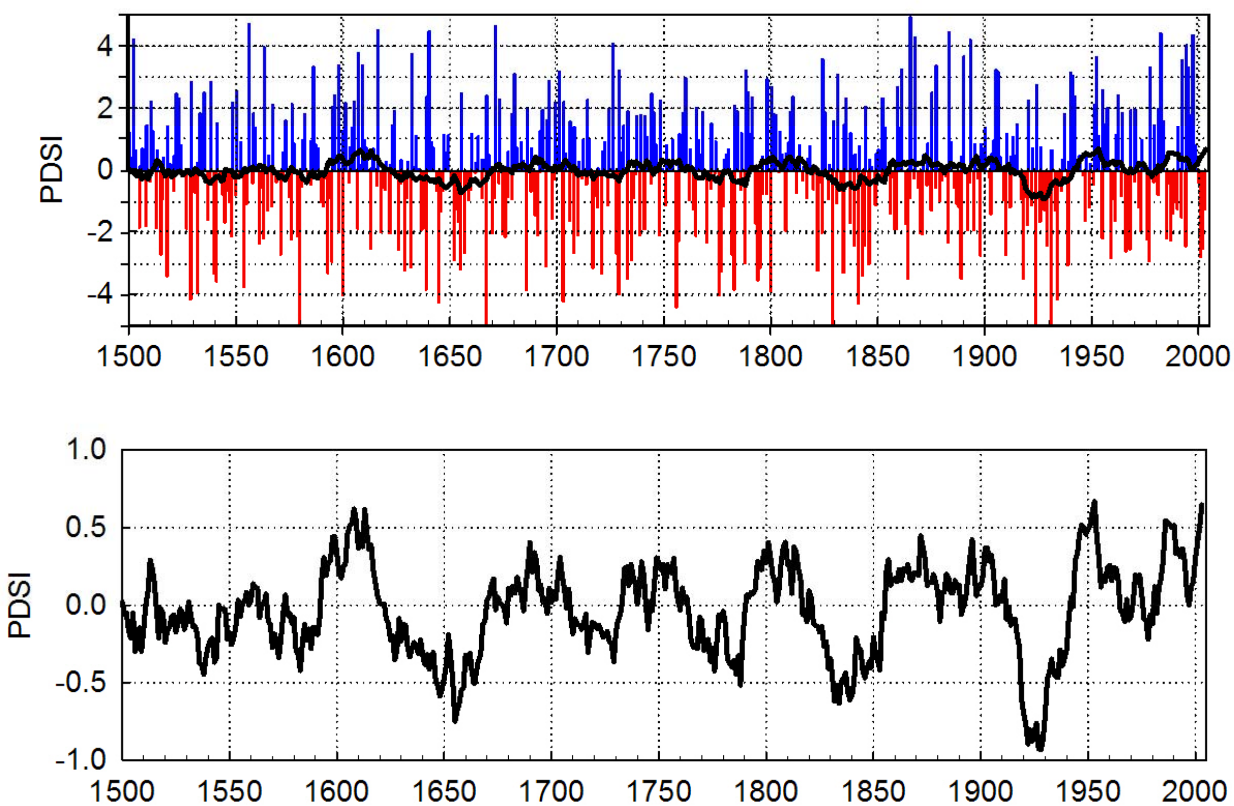

Figure 6.8. Palmer Drought Severity Index (PDSI) for a 2.5 x 2.5° grid point centered at 41.25 N latitude and 122.5 W. Panel a) shows annual values (positive in blue, negative in red) and 25-yr running mean (black line); panel b) shows an expanded view of the 25-yr mean.

7. Projecting hydrologic change

Some of the following is taken from the report *Forests and Water in the Sierra Nevada: Sierra Nevada Watershed Ecosystem Enhancement Project* (Bales et al., 2011). Updates have been made to reflect published results since then, or relevant to the Klamath Mountains.

7.1. Forest hydrology

Wet winters and dry summers distinguish the mountain water cycle in the Klamath Mountains. The seasonal snowpack is a critical component of this water balance. At lower elevations, the snowpack melts shortly after being deposited by a cold storm, but at higher elevations the snowpack typically accumulates from November or December until March or April, and then melts from April through June or July. The elevation at which precipitation falls as snow versus rain varies from storm to storm and often varies during an individual storm.

In a forest, the water balance for the near surface, or zone of interest for trees and other components of the ecosystem, can be written as precipitation (P) being equal to the sum of evapotranspiration (ET) plus runoff (R), measured as streamflow, plus groundwater recharge (D) plus the change is soil water storage (ΔS):

$$P = ET + R + D + \Delta S \qquad (1)$$

In forest catchments, precipitation, runoff, and evapotranspiration typically dominate the water balance. Groundwater recharge is often the smallest term in the water-balance equation; soil-water storage is expected to balance over the long term (5-10 years), if not annually. Thus for an analysis of Sugar Creek, groundwater recharge will be assumed to be small and the net change in soil water storage assumed to equal 0. Therefore mean annual water yield is defined as:

$$R = P - ET \qquad (2)$$

7.2. Forest management and water

In principle, vegetation can be managed to meet water-resource goals, particularly in forests where trees create dense canopies. As net primary productivity (i.e., plant growth) increases, evapotranspiration (the primary cause of water loss) also increases. Any manipulation that reduces the productivity (e.g., removes trees, shrubs or grasses) reduces evapotranspiration and thus may increase water availability.

This well-established link between water and forests suggests that forest ecosystems can be managed to meet water resource priorities. Indeed, there is a long history of research in forest hydrology in which the impacts of various natural and anthropogenic disturbances are evaluated with regard to water quantity and quality (Bosch and Hewlett 1982, Hornbeck et al. 1993, Sahin and Hall 1996, Stednick 1996, Brown et al. 2005).

Paired-watershed experiments provide the bulk of the evidence informing conclusions regarding the effects of vegetation management on forest hydrology. In a paired-watershed study, stream gages are built at the mouth of two or more watersheds. Ideally the watersheds are similar in size, soils, vegetation, and land-use history. Streamflow is monitored for several years to define baseline conditions. Then watersheds are manipulated (e.g., trees cut, shrubs removed, fire introduced). At least one watershed is left untreated to provide a reference. The differences in water yield between experimental watersheds and the reference is the measure of the impact of the treatments. It is an expensive but potentially rigorous approach to watershed science. During the past 60 years, literally hundreds of experiments have been conducted worldwide, and the results have been summarized in a sequence of reviews (e.g., Bosch and Hewlett 1982, Hornbeck et al. 1993, Sahin and Hall 1996, Stednick 1996, Brown et al. 2005). However, no paired-watershed studies have been conducted in the conifer forest that dominates the Klamath Mountains, or the Sierra Nevada. Thus, when assessing the potential of forest management to influence hydrology in the Sugar Creek area, inferences must be drawn from an appropriate subset of the literature.

Perhaps the most significant consideration is that most of the paired-watershed studies impose a treatment once and then allow the forest to regrow (Hornbeck et al. 1997). In reporting yield effects, runoff is typically measured for five years following the treatment and the effect reported as the mean during those five years (Brown et al. 2005). However, the recovery of forest vegetation can be rapid. For example, following a whole-tree harvest in a northern hardwood forest in New Hampshire, canopy cover returned to preharvest levels in three years, as did evapotranspiration and stream runoff (Hornbeck et al. 1997). A recent review of 25 afforestation studies showed a clear relationship between forest age and reduction in water yield (Wang et al., 2012). Maintenance of treatment effects is a key consideration and long-recognized issue in forest management for water (Hibbert, 1967).

Generally, paired-catchment studies show immediate on-site increases in water yield, but to propagate the effect far enough downstream to be meaningful for end users requires a large portion of the watershed to be treated. Applying this idea to Coon Creek, a 1659 ha (4100-acre) watershed in Wyoming, Troendle and others (2001) found that removing 24% of vegetation led to a significant water yield increase of 8 cm (3 in). Yield increases have been shown to be minimal or negligible during years with drier-than-normal precipitation and maximized during wet years.

A comprehensive project (based at the Fraser Experimental Forest in Colorado) used the Fool Creek Watershed to evaluate the effects of harvesting on water yield, timing, peak discharge, and peak water equivalent over 28 years (Troendle and King 1985). Initial studies following harvest (Hoover and Leaf 1967; Leaf 1975) suggested no change in water balance, attributing changes in water yield to reduced transpiration, with increases in SWE in forest clearings attributed to aerodynamic redistribution of the snowpack. However, when Troendle and King (1985) revisited the issue, analyzing 28 years of data, they were led to the conclusion that increases in water yield (+40%), peak discharge (+23%), and peak water equivalent (+9%) do exist, along with earlier peak flows (-7.5 days). This study highlights the need for long-term monitoring of hydrologic research sites, few of which exist in California or areas that can directly inform management in the Klamath Mountains or the Sierra Nevada.

While most of the attention regarding changes in water yield focuses on removal of the trees themselves, additional factors may also affect the water balance. In measurements at sites in the Kern plateau over one snow accumulation/melt season, Royce and Barbour (2001) found that per unit of biomass, understory shrubs depleted soil moisture faster and consumed more shallow soil moisture than did conifers. While this research was focused on competition and recruitment, is also highlights potential implications of understory management in modifying transpiration and thus water yield.

Generalizations from reviews of paired-catchment studies suggest that the Klamath and Sierran conifers forest have ecological attributes with a high potential for water-yield gains. First, forest catchments dominated by evergreen, needle-leaved trees consistently show greater per capita gains in water yield relative to fraction of forest cover removed) than any other forest type. For example, Bosch and Hewlett (1982) found per capita water yield in temperate conifer forests to be on average 60% greater than in temperate deciduous forests. Changes in water yields depend on the amount of precipitation (Zhang et al. 2001).

An indication of the potential water impacts of forest management can be developed using data from the Klamath Mountains and models established in the literature (equation 8 in Zhang et al. 2001). Using a range of annual precipitation for the region, we compared 90% forest cover (i.e., untreated baseline) to 60% and 30% forest cover. Water-yield gain was calculated using a simplified water-balance approach, i.e., the difference in evapotranspiration between treated areas and the untreated baseline for a given precipitation input. There is a steady increase in evapotranspiration with increasing precipitation for the range of inputs considered (500-2000 mm; 20-79 in) (Figure 7-1). However, increases do begin to taper around 1400 mm (55 in) of precipitation, suggesting that in the wettest catchments there is an upper limit to absolute yield gains. These amounts will also vary within a watershed. In general, higher elevations that are colder, snow dominated and have a shorter growing season, yield more water that lower elevations that are warmer, rain dominated, have a longer growing season (Hunsaker et al., 2012).

On average, treatments that reduce forest cover from 90 to 30% canopy cover across a watershed were projected to increase runoff by 38 mm (1.5 in), 128 mm (5 in), 207 mm (8 in) and 261 mm (10 in) for precipitation amounts of 500, 1000, 1500 and 2000 mm (20, 39, 59, 79 in) respectively (Figure 7-2). Thus the additional water amount would be higher with higher precipitation, and lower if there was less vegetation removal.

Thus both the qualitative and quantitative evidence support the assumption that vegetation management can meaningfully modify forest hydrology in Klamath Mountains, and the Scott River basin. The cumulative impact depends on area treated, the extent of treatment, and climate.

7.3. Snow accumulation, sublimation and melt

The energy balance in the forest determines when snow melts. Snowmelt is driven by temperature and vapor-density gradients within the snow caused by heat exchange at the snow surface and at the snow–soil interface (Marks et al. 1999; Pomeroy et al. 1998). Forest cover reduces the energy from the sun and the influence of wind on snowmelt. The energy balance on sub-canopy snow is dominated by radiation, with incoming shortwave irradiance modified by the canopy shading and longwave irradiance increasing from canopy thermal emissions (Link et al., 2004; Sicart et al., 2004; Pomeroy et al., 2009). Forest cover may also affect sub-canopy shortwave radiation by altering snow-surface albedo (the fraction of incident sunlight that is reflected) through deposition of forest litter on snow (Hardy et al., 2000; Melloh et al., 2002).

That is, trees and litter are dark, and absorb more solar radiation than does snow, re-emitting it as longwave to snow. The atmosphere also emits longwave, to the snow surface, but less than does vegetation per unit area. Snow melts in response to both absorbed shortwave (solar) and longwave radiation.

The energy balance of a snowcover can be expressed as:

$$\Delta Q = R_n + H + L_v E + G + M \qquad (3)$$

where ΔQ is change in snowcover energy, and R_n, H, L_vE, G and M are net radiative, sensible, latent, conductive, and advective energy fluxes (all terms are in W m^2), respectively; L_v is the latent heat of vaporization, or sublimation (J kg^{-1}) and E is the mass flux by sublimation from or condensation to the snow surface (kg m^2 s^{-1}). In this context, advected energy M is heat lost or gained when mass (precipitation) of a specified temperature is added to the snow cover. In thermal equilibrium $\Delta Q = 0.0$; whereas a negative energy balance will cool the snow cover, increasing its cold content, while a positive energy balance will warm the snowcover. The snow cover cannot be warmer than the melting temperature T_{melt} (0°C) and melt cannot occur until the snow, or a layer within the snow cover, has reached this temperature. Once the snow is isothermal at 0°C, positive values of ΔQ must result in melt. While the tools are readily available to calculate energy balance both above and beneath the canopy, the necessary data are not widely available. Thus in some cases a simpler temperature-index approach is used, with coefficients developed from snow-index sites in the area. In this approach, daily snowmelt is a linear function of degree days (degrees daily average temperature is above zero) times a degree-day coefficient (T_{index}):

$$Melt = D_{day} \times T_{index} \qquad (4)$$

Typically T_{index} increases as the season melt season progresses, reflecting the generally greater net radiation for snowmelt later in the year. While this simpler approach indicates the average snowmelt with warmer temperature, a more-explicit energy-balance approach is needed to describe the effect of forest thinning on snowmelt.

Snowmelt rates are higher in open areas in near-freezing temperatures, but when the air warms (i.e., temperatures well above freezing) melt rates are higher under the canopy (Lopez-Moreno and Latron 2008). This switch in melt rates during warm periods is in part due to sensible heat exchange and latent heat of evaporation becoming melt drivers, such that the blocking of incoming solar radiation becomes relatively minor. Additional longwave radiation emitted by the dense vegetation during the warmer periods also amplifies this effect.

Conifer canopies intercept a portion of snowfall, and snow caught in canopies sublimates at higher rates than ground-level snow (Essery et al. 2003). Sublimation rates in areas that have been studied range from 15% to 60% of annual snowfall (Hood et al. 1999, Parviainen and Pomeroy 2000, Montesi et al. 2004, Troendle and King, 1985; Schmidt et al., 1988; Pomeroy and Schmidt, 1993; Lundberg and Halldin, 1994; Storck et al., 2002). Higher temperatures, lower humidity, and greater wind speeds can all increase sublimation rates (Montesi et al. 2004). Following the 2011 Las Conchas fire in northern New Mexico, it was observed that canopy interception and associated sublimation losses from a 15-cm snowfall dropped from 36% to 5% of snowfall, with much of the intercepted snow sublimating (Harpold et al., 2013). However, sublimation of snow on the ground experienced even more sublimation owing to the change in solar radiation reaching the snow. This reinforces the point that in between a closed canopy and a denuded landscape there is an optimal gap size for snow retention (Seyednasrollah et al., 2013).

Data to evaluate differences in sublimation losses in forests similar to those in the Klamath Mountains are few; however, Ellis et al. (2010) compared accumulation at 4 locations, two of which have trees over 25 m tall (82 ft) and may be somewhat relevant. Both showed significantly more snow water equivalent (SWE) in the open versus under the canopy, though no differences in melt rates were apparent; differences in melt out date were also inconclusive. However, in the warmer mountains of California, canopy snow unloading should be higher and thus canopy sublimation loss lower than in their Canadian locations.

7.4. Forest management and snow

One of the most-important impacts that forest management has on water yield is related to snow accumulation and melt. For example, in a recent study that included sites analogous to the conifer forests of inland California there was significantly more snow in open areas compared to beneath intact canopies (Ellis et al., 2010). This accumulation and persistence of snow in forested openings is a common observation beneath small canopy gaps created by harvests (Section 4, Figure 4-2). Golding and Swanson (1978) found greatest snow storage in clearing sizes of one tree height compared to either smaller or larger openings in Alberta, Canada. Larger openings had greater exposure to sunlight, leading to a faster rate of melt. In the Storck and others (2002) study on snowpack in the maritime climate of Oregon, a simple relationship between under-canopy and open SWE was not possible, but in general more snow accumulated in the open areas and snow melted out of open areas one month later compared to snow accumulation and retention under the canopy. The spatial arrangement of trees also affects snow accumulation, through both interception in denser canopies and energy balance both in the canopy and at the snow surface on the ground (Woods et al. 2006). Recent simulations illustrate that minumum energy for melt occurs in between an open versus closed canopy, and the dependence of net energy on slope, aspect, tree height and canopy closure can be simulated Seyednasrollah et al., 2013).

Studies of forest-management impacts on snow properties in the Sierra Nevada date from the early 1900s (Church 1913, Church 1933). Since that time, the issue has been of interest to the U.S. Forest Service (USFS) and California Department of Water Resources (Kittredge 1953, Colman 1955, Anderson 1963, McGurk and Berg 1987, MacDonald 1987), though forest management for snow retention has never been implemented on a large scale. Church (1913) suggested a honeycomb pattern of forest clearings, stating, “The ideal forest seems to be one filled with glades whose width bears such proportion to the height of the tress that the wind and the sun cannot reach the bottom.” McGurk and Berg (1987) presumed that this pattern of forest treatments would not be as economical as strip-cuts (i.e., cutting a line of trees), which were also recommended by Kittredge (1953). More recent desires to increase forest landscape heterogeneity may actually result in Church’s idealized gap approach being more feasible than uniform strip cuts. Independent work with gap creation from 0.04 to 1 hectares in size (0.1 – 2.5 ac) are increasingly used to increase the regeneration of pines in the Sierra Nevada (York et al. 2004; York et al. 2011) and could potentially replicate patterns roughly similar to the idealized honeycomb pattern originally suggested by Church. Ultimately, the effectiveness of any treatment depends upon individual stand tree height, slope, and aspect to obtain the right mixture of openings large enough to accumulate additional snow, yet with enough shading to block direct solar radiation for prolonging ablation (the removal of snow by evaporation, sublimation, or wind). Data from sites in the southern Sierra Nevada also show significant differences in snow accumulation between open areas and forest. However, it must be recognized that because openings were small, some of the snow falling from the canopy may have added to that in the open areas (Bales et al. 2011). Clearly, gap sizes are an important factor in the analysis, not only for snow, snowmelt and soil moisture, but also for forest health and habitat.

Within the Sierra Nevada, the Central Sierra Snow Lab (CSSL), Onion Creek Experimental Forest, Yuba Pass, and Swain Experimental Forests have all reported on the outcomes of efforts to study forest-treatment impacts on snow accumulation. The CSSL found the lowest increases in snow accumulation from selective cutting of red fir that reduced crown cover to 50%; this resulted in a 5% increase in SWE (Anderson et al., 1976). The highest percentage increase of SWE, approximately 50%, resulted from strip cuts implemented in Swain Experimental Forest and Yuba Pass. Results from all other types of forest harvesting (block cutting, commercial selection, selective cutting, and clearcutting) increased SWE in the treated areas between 14 and 34% The effects of forest management on snow accumulation can have a lasting impact.

McGurk and Berg (1987) revisited the strip-cuts at Yuba Pass 20 years after harvest and found sustained increases in SWE of 25 to 45%.

Increasing temperatures from climate change may actually lead to a decrease in vegetation water use, as snowmelt occurs earlier and less late-summer moisture is available (Tague et al. 2009). Additionally, not removing slash post harvest has been shown to hasten snow ablation in the spring (Anderson and Gleason 1960), which also affects snowmelt timing.

In large forest openings, direct solar radiation reaches the ground, causing earlier snowmelt, and water passes through the soil prior to peak transpiration use by vegetation (Troendle and Leaf 1980). This both increases water yield at high flows and augments flow during the period when water resources' economic and ecosystem values are lowest. Therefore, a treatment pattern to not only increase water yield but also extend snow storage by creating small forest openings would be best. Modifying the implementation of treatments towards this goal would be beneficial for water management and would also provide a direct complement to fire treatments. Reducing the period of the dry season, when vegetation is extremely susceptible to ignition, is desirable for protecting both property and timberland from devastating fires. With the advent of climate change, this process may be more important to help offset earlier snowmelt (Stewart et al. 2004), as opposed to advancing historical melt-out dates.

7.5. Watershed-scale studies of thinning & hydrologic response

A number of recent modeling studies have added to the scenarios for forest thinning and changes in the forest water balance. Carr et al. (2013) demonstrated at Caspar Creek that a detailed hydrologic model could simulate observed increases and decreases, respectively, for throughfall and potential evapotranspiration related to clear-cutting; as both had quantifiable impacts on the simulated hydrologic response at both the catchment and watershed scales. Green and Alila (2012) observed that moderate tree harvesting increased both the magnitude and frequency of flood events as various catchments in the Western United States. Significantly, Ellis et al. (2014) showed that prescribed forest gap-thinning treatments in mountain regions may substantially alter the timing and magnitude of snowmelt runoff from headwater areas. The snowmelt period in mountain headwater basins may be advanced, delayed, or expanded through forest gap-thinning treatments depending on the slope and aspect of where they occur. Changes in snowmelt timing from forest gap-thinning treatments are caused by shifts in radiation to snow, which is generally increased on south-facing slopes due to shortwave gains and generally decreased on north-facing slopes due to longwave losses.

A recent review by the National Research Council (2008) noted that "Forest hydrology studies show that changes in forest structure and composition, and associated changes in forest soils and hillslopes, can alter the storage and flowpaths of water through soil and subsoil, which modifies water yield, peak flows, low flows, water chemistry, and water quality." The report then concluded that "Although in principle forest harvest can increase water yield, in practice a number of factors make it impractical to manage forests for increased water." This review, which covered forests nationwide, brought up practical considerations such as "…timber harvest to augment water yield may diminish water quality. Increases in water yield tend to occur at wet, not dry, times of the year, and tend to be much smaller in relatively dry years. In addition, harvesting enough area to achieve a sustainable increase in water yield will have potential effects on wildlife fisheries and aquatic ecosystems." That is, the report reaffirmed the potential for increases in water yield through vegetation management, but cautioned that many practical issues may limit its implementation.

Similarly, a USFS policy analysis echoed this caution in evaluating the potentials and limitations of augmenting water yield on forested lands (Sedell et al. 2008): "For a variety of reasons, water yield increases are likely to be undetectable." This conclusion was based in part on work in the Sierra Nevada where Kattelmann et al. (1983) estimated that only a 2 to 6% increase in streamflow could be attained if "National Forest lands were managed almost exclusively for water production while meeting the minimum standards of all applicable laws." The implicit assumption is that limitations on the removal of vegetation due to wildlife habitat and floral-retention standards will severely restrict any government action. The perspective that forest management for water supply is not worth the trouble is ingrained in both upstream and downstream resource managers.

Various forest managers have also pointed out the multiple barriers to successful implementation of vegetation treatments at a sufficiently large scale to make an impact on downstream water, including: i) costs, ii) lack of verification of impacts, iii) water rights issues, iv) potential restrictions on vegetation management in wilderness or other habitat-sensitive areas, and v) other legal issues (e.g. Ziemer, 1986). Thus both institutional/legal as well as scientific issues bear investigation in parallel when considering large-scale vegetation management.

7.6. Hydrologic modeling

It is proposed to use the Regional Hydro-Ecologic Simulation System (RHESSys) to develop estimates of the hydrologic response to forest vegetation management (Tague and Band, 2004). RHESSys is a process-based, spatially explicit model of coupled terrestrial hydrologic and biogeochemical cycles, including snow accumulation and melt, vegetation, and surface-subsurface exchange. For simulations in Sugar Creek the suggested approach is to leverage and extend existing baseline simulations from other sites in California and the Western United States, especially those from the rain-snow transition region of the Sierra Nevada. Being spatially explicit RHESSys can describe in some detail the physiographic and ecological heterogeneity present in the basin. It is recommended to use it at a daily time step, and to carry out multi-year simulations using historical data, plus historical data with warmer temperatures imposed.\

As additional users apply the RHESSys model, improvements in process description, parameter estimation and model evaluation are emerging. A small number of similar models are also being used, which also provide modeling insight, e.g. DHSVM. This is an absolutely critical component of the assessment of water-balance changes resulting from vegetation management, as modeled runoff versus evapotranspiration will reflect the assumptions going into the modeling. Those assumptions must be firmly founded and defensible, reflecting current scientific knowledge. For example, it has been found that transpiration response to vapor pressure deficit (humidity) and soil moisture differ depending on subsurface moisture sources, and the amount of vegetation. There are also feedbacks between soil moisture, transpiration amount and vapor-pressure deficit that are often not well captured by models.

RHESSys can include fine-scale heterogeneity within spatial patches that are typically 30-90 m in extent, using spatial distributions of coupled vegetation-soil subpatches within these spatial patches. This is a significant modeling advance and it bridges the gap between plot-scale heterogeneity and coarser-scale watershed models. This will allow: i) representing heterogeneity within a watershed-scale model; ii) developing parameterizations based upon the varying scales of observations; and iii) testing the implications for watershed-scale fluxes. If needed, RHESSys can simulate vegetation disturbance scenarios that incorporate feedbacks among fire, climate and drought, as is currently being done under the Western Mountain Initiative, which compares RHESSYs estimates of vegetation mortality patterns with observations (van Mantgem and Stephenson. 2007).

This approach differs from the traditional estimation tools used by forest practitioners to make climatological estimates of the impact of vegetation management on water yield, e.g. the WRENSS Hydrologic Model (Troendle et al., 2007; Swanson, 1991; Swanson, 2004), or the Zhang approach described above. Whereas WRENSS is an empirical calculation procedure for applying results of past vegetation management experiments to different landscapes, RHESSys includes equations and parameters explicitly describing processes affecting water and nutrients. The WRENSS calculations can account for spatial variability in canopy cover. However, it does not include the internal processes associated with mapping precipitation onto runoff, other than vegetation amount. The simple estimation procedure on Figure 5-1, is a lumped estimation procedure, which is also based on past field studies. Either the Zhang approach or WRENSS can be applied to spatial data, but they still assume that Klamath forests respond similar to average conditions in other regions.

As it does account for a wide range of variables, RHESSys will also have utility as a verification tool after forest treatments, and for estimating responses under a wide range of climate scenarios.

References

Anderson, HW (1963). Managing California's Snow Zone Lands for Water. US Forest Service Research Paper, PSW-6. USDA Forest Service Pacific Southwest Forest and Range Experiment Station; Berkeley, CA, 28p.

Anderson, HW and Gleason CH (1960). Effects of logging and brush removal on snow water runoff. Int. Assoc. Sci. Hydrol. Publ. 51: 478-489.

Anderson, H.W., M.D. Hoover and K.G. Reinhart, 1976. Forests and Water: Effects of Forest Management on Floods, Sedimentation, and Water Supply. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, *Cali*fomia, USDA Forest Service General Technical Report PSW 18/1976, 115 pp.

Bales, R.C., Battles, J.J., Chen, Y., Conklin, M., Holst, E., O'Hara, K.L., Saksa, P., and Stewart W. 2011. Forest and Water in the Sierra Nevada: Sierra Nevada Watershed Ecosystem Enhancement Project. Sierra Nevada Research Institute report number 11.1

Bosch, J. M., and J. D. Hewlett. 1982. A review of catchment studies to determine the effect of vegetative changes on water yield and evapotranspiration. *Journal of Hydrology* 55:3-23.

Brown, A.E., L. Zhang, T.A. McMahon, A.W. Western, and R.A. Vertessy. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* 310: 28-61.

Carr, A.E. Loague, K. VanderKwaak, J.E.. 2014. Hydrologic-response simulations for the North Fork of Caspar Creek: Second-growth, clear-cut, new-growth, and CWE scenarios, *Hydrological Processes*, 28, 1476–1494.

Church, JE (1912). The conservation of snow: its dependence on forest and mountains. Scientific American Supplement 74: 152-155.

Church, JE (1933). Snow Surveying: its principles and possibilities. Geog. Rev. 23(4): 529-63.

Colman, EA (1955). Operation wet blanket: proposed research in snowpack management in California.

Ellis C. R.; Pomeroy J. W.; Brown T., MacDonald, J. 2010. Simulation of snow accumulation and melt in needleleaf forest environments, *Hydrology and Earth System Sciences*, 14:925-940, DOI: 10.5194/hess-14-925-2010.

Ellis C.R., Pomeroy J.W., Link, T.E. 2014. Modeling increases in snowmelt yield and desynchronization resulting from forest gap thinning treatments in a northern mountain headwater basin, *Water Resources Research*, in press.

Essery, R., J. Pomeroy, J. Parviainen, and P. Storck. 2003. Sublimation of Snow from Coniferous Forests in a Climate Model. *Journal of Climate* 16(11):1855-1864.

Golding, D.L.; Swanson, R.H. 1978. Snow Accumulation And Melt In Small Forest Openings In Alberta, Canadian Journal Of Forest Research, 8:380-388, DOI: 10.1139/x78-057.

Green, K.C., Alila, Y. 2012. A paradigm shift in understanding and quantifying the effects of forest harvesting on floods in snow environments, *Water Resources Research* 48:W10503, doi:10.1029/2012WR012449.

Hardy, J. P., R. A. Melloh, P. Robinson, and R. Jordan, 2000: Incorporating effects of forest litter in a snow process model. *Hydrol. Processes*, **14,** 3227–3237.

Harpold,A.A., Biederman, J.A., Condon,K., Merino,M., Korgaonkar,Y., Nan,T., Sloat,L., Ross, M., & Brooks, P.D. 2013. Changes in snow accumulation and ablation following the Las Conchas Forest Fire, New Mexico, USA. Ecohydrology. DOI: 10.1002/eco.1363

Hood, E., M. Williams, and D. Cline. 1999. Sublimation from a seasonal snowpack at a continental, mid-latitude alpine site. Hydrological Processes 13(12-13):1781-1797.

Hibbert, A. R. 1967. Forest treatment effects on water yield. In: W. E. Sopper and H. W. Lull (eds.), Forest Hydrology. Pergamon, New York, NY. 527-543.

Troendle, C.A., King, R.M., 1985. The Fool Creek watershed—30 years later. *Water Resour. Res.* 2112, 1915-1922.

Hoover, M. D. and C. F. Leaf, 1967. Process and Significance of Interception in Colorado Subalpine Forest. ***In:*** Forest Hydrology, W. E. Sopper and H. W. Lull (Editors). International Symposium Forest Hydrology, University Park, Pennsylvania, August-September, 1967), Pergamon Press, New York, New York, 813 pp.

Hornbeck, J.W., Adams, M.B., Corbett, E.S., Verry, E.S.,Lynch, J.A., 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. J*ournal of Hydrology* 150: 323–344.

Hornbeck, J. W., C.W. Martin, and C. Eager. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. *Canadian Journal of Forest Research* 27: 2043-2052.

Hunsaker, C., T. Whitaker and R. C. Bales. Submited. Snowmelt runoff and water yield along elevation and temperature gradients in California's southern Sierra Nevada.

Kattelmann, R. C., Berg, N. H., and Rector, J. 1983. The potential for increasing streamflow from Sierra Nevada watersheds. *Water Resources Bulletin* 19(3):395-402.

Kittredge (1953). Influence of forests on snow in the ponderosa-sugar pine-fir zone of the central Sierra Nevada. Hilgardia 22:1-96.

Leaf, Charles F., 1975. Watershed Management in the Rocky Mountain Subalpine Zone: The Status of Our Knowledge. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, USDA Forest Service Research Paper RM-137, 31 pp.

Link T.E. D. Marks, J.P. Hardy. 2004. A deterministic method to characterize canopy radiative transfer properties, *Hydrological Processes*, 18:3583-3594, DOI: 10.1002/hyp.5793.

Lopez-Moreno, JI and J Latron (2008). Spatial heterogeneity in snow water equivalent induced by forest canopy in a mixed beech-fir stand in the Pyrenees. Annals of Glaciology 49: 83-90.

Lundberg A, S. Halldin 1994, Evaporation of Intercepted Snow - Analysis of Governing Factors, Water Resources Research, 30:2587-2598, DOI: 10.1029/94WR00873.

Marks, D., J. Domingo, D. Susong, T. Link, and D. Garen, 1999: A spatially distributed energy balance snowmelt model for application in mountain basins. *Hydrol. Processes,* **13,** 1935–1959.

MacDonald, LH (1987). Forest harvest, snowmelt and streamflow in the central Sierra Nevada. Forest Hydrology and Watershed Management, Proceedings of the Vancouver Symposium, August 1987: 273-283.

McGurk, BJ and NH Berg (1987). Snow redistribution: strip cuts at Yuba Pass, California. Forest Hydrology and Watershed Management, Proceedings of the Vancouver Symposium, August 1987: 273-283.

Melloh RA, Hardy JP, Bailey RN, Hall TJ. 2002. An efficient snow albedo model for the open and sub-canopy. *Hydrol. Process.* **16**:3571–3584.

Montesi, J., K. Elder, R. A. Schmidt, and R. E. Davis. 2004. Sublimation of Intercepted Snow within a Subalpine Forest Canopy at Two Elevations. *Journal of Hydrometeorology* 5(5):763-773.

National Research Council. 2008. Hydrologic Effects of a Changing Forest Landscape. Committee on Hydrologic Impacts of Forest Management. The National Academies Press. Washington, D.C.

North, M., P. Stine, K. O'Hara, W. Zielinski, and S. Stephens. 2009. An ecosystem management strategy for Sierran mixed-conifer forests. PSW-GTR-220, US Forest Service, Pacific Southwest Research Station, Albany, CA.

Parviainen, J., and J. W. Pomeroy. 2000. Multiple-scale modelling of forest snow sublimation: initial findings. *Hydrological Processes* 14(15):2669-2681.

Pomeroy, J.W, Parviainen, J, Hedstrom, N and DM Gray (1998). Coupled modeling of forest snow interception and sublimation. Hydrological Processes 12: 2317-2337.

Pomeroy, J. W. *and* Schmidt, R. A. 1993. *'The use of fractal geometry in modelling intercepted snow accumulation and sublimation', Proceedings of the 50th Annual Eastern Snow Conference, pp.* 1–10.

Pomeroy, J., Rowlands, A., Hardy, J., Link, T., Marks, D., Essery, R. Sicart, J.E., Ellis, C. 2009. Spatial Variability of Shortwave Irradiance for Snowmelt in Forests. Journal Of Hydrometeorology, DOI: 10.1175/2008JHM867.1

Royce, EB and MG Barbour (2001). Mediterranean climate effects I. Conifer water use across a Sierra Nevada ecotone. American Journal of Botany 88(5): 911-918.

Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. *Journal of Hydrology* 178: 293–309.

Schmidt, R.A., R. A. Jairella, J.W. Pomeroy, 1988. Measuring snow Interception and loss from an artificial conifer, in Proceedings 5 6th Western Snow Conference, pp. 166-169 Colo. State Univ., Fort Collins, 1988.

Sedell, J., M. Sharpe, D. D. Apple, M. Copenhagen, and M. Furniss, 2008. *Water and the Forest Service*. USDA Forest Service, Policy Analysis. Washington, DC 20090-6090. http://www.stream.fs.fed.us/publications/PDFs/Water_and_FS.pdf

Seyednasrollah, B., Kumar, M., Link, T.E. 2013. On the role of vegetation density on net snow cover radiation at the forest floor. Journal Of Geophysical Research-Atmospheres, 118: 15, 8359-8374, DOI: 10.1002/jgrd.50575

Sicart, J.E., Pomeroy, J.W., Essery, R.L.H. Hardy, J., Link, T. 2004. A sensitivity study of daytime net radiation during snowmelt to forest canopy and atmospheric conditions, Journal Of Hydrometeorology 5:774-784, DOI: 10.1175/1525-7541(2004)005<0774:ASSODN>2.0.CO;2

Stednick, J.D. 1996. Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* 176 (1/4):79–95.

Stewart, IT, Cayan, DR, and MD Dettinger (2004). Changes in snowmelt runoff timing in western North America under a "business as usual' climate change scenario. Climatic Change 62: 217-232.

Storck, P, Lettenmaier, DP and SM Bolton (2002). Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. Water Resources Research 38 (11): 1223.

Swanson, R. H. 1991. WRNSHYD-The WRENSS hydrologic procedures programmed for an IBM PC. Computer program and associated files. Available from P.O. Box 1431, Canmore, Alberta, Canada T0L 0M0.

Swanson, R. H. 2004. The complete WRENSS hydrologic model. Proceedings of the 72nd Western Snow Conference. Richmond, BC.

Tague, C. L. and L. E. Band. 2004. RHESSys: regional hydro-ecologic simulation system – an object- oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. *Earth Interactions* 19: 1-42.

Tague, C. L., and G. E. Grant. 2009. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions, *Water Resource Research*. 45, W07421, doi: 10.1029/2008WR007179.

Troendle, C.A., King, R.M., 1985. The Fool Creek watershed—30 years later. *Water Resour. Res.* 2112, 1915-1922.

Troendle, CA, Wilcox, MS, Bevenger, GS, and LS Porth (2001). The Coon Creek Water Yield Augmentation Project: implementation of timber harvesting technology to increase streamflow. Forest Ecology and Management 143: 179-187.

Troendle, C. A. and C. F. Leaf. 1980. Hydrology. In: An approach to water resource evaluation of non-point silvicultural sources. EPA 60018-80-012. Envir Res. Lab., Athens, GA. pp. III-1 - III-173.

Troendle, C.A., Nankervis, J.M., Peavy, A. 2007. Final Report The Herger-Feinstein Quincy Library Group Project — Impacts of Vegetation Management on Water Yield.

van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fule, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor, T.T. Veblen. Widespread Increase of Tree Mortality Rates in the Western United States. *Science* **323**, 521-524 (2009).

Wang, Y. Bredemeier, M. Bonell, M., Yu. P. Felger, K.-H., Xiong, W. and Xu, L. 2012. Comparison between a statistical approach and paired catchment study in estimating water-yield response to afforestation. In Revisiting Experimental Catchment Studies in forest Hydrology (Proceedings of a Workshop held during the XXV IUGG General Assembly in Melbourne, June-July 2011. IAHS pub. 353.

Woods, S. W., R. Ahl, J. Sappington, and W. McCaughey. 2006. Snow accumulation in thinned lodgepole pine stands, Montana, USA. *Forest Ecology and Management* 235(1-3):202-211.

York, R. A., R. C. Heald, J. J. Battles, and J. D. York. 2004. Group selection management in conifer forests: relationships between opening size and tree growth. Canadian Journal of Forest Research **34**:630-641.

York, R.A., Battles, J.J., Eschtruth, A.K., Schurr, F.G. 2011. Giant Sequoia (Sequoiadendron giganteum) Regeneration in Experimental Canopy Gaps. Restoration Ecology 19:1 , 14-23.

Ziemer, R.R. 1986. Water Yields from Forests: An Agnostic View. Presented at the California Watershed Management Conference, November 18-20, 1986, West Sacramento, California.

Zhang, L., W.R. Dawes, and G.R. Walker. 2001. Responses of mean annual temperature to vegetation changes at catchment scale. Water Resources Research 37: 701-708.

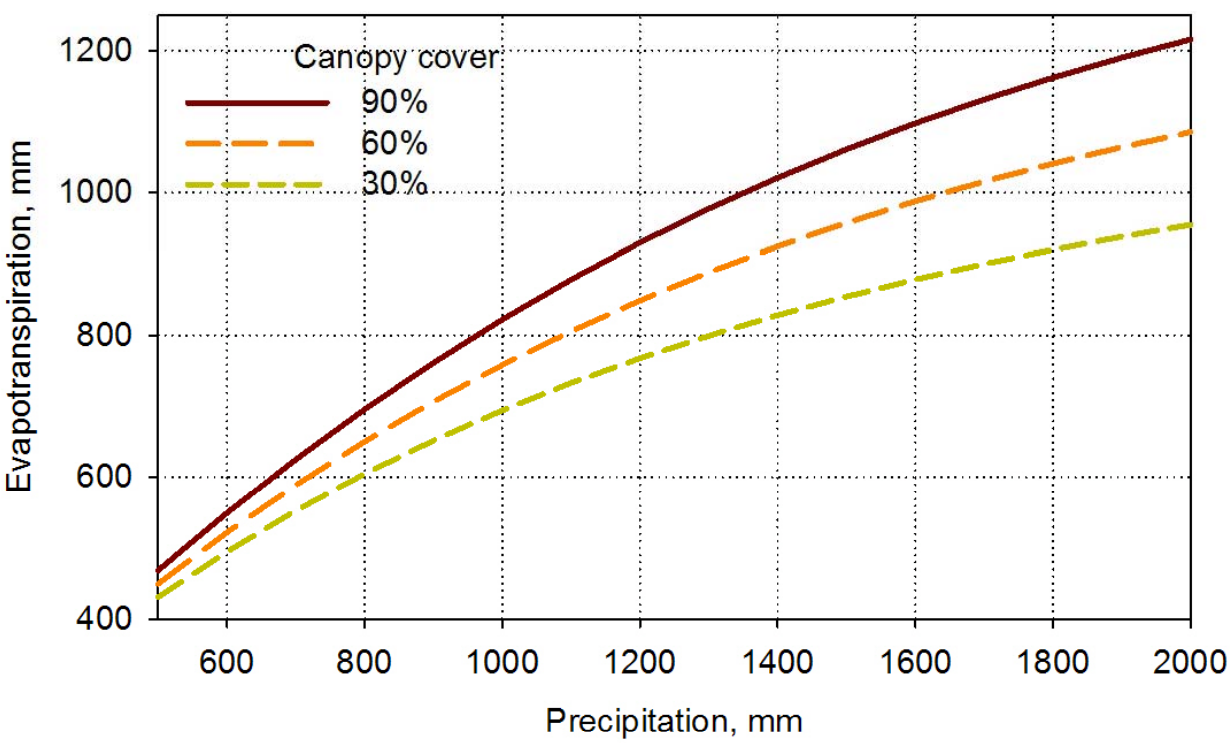

Figure 7.1. Predicted changes in evapotranspiration for forested watersheds is a function of precipitation inputs and reductions in forest cover. Based on Zhang et al. (2001).

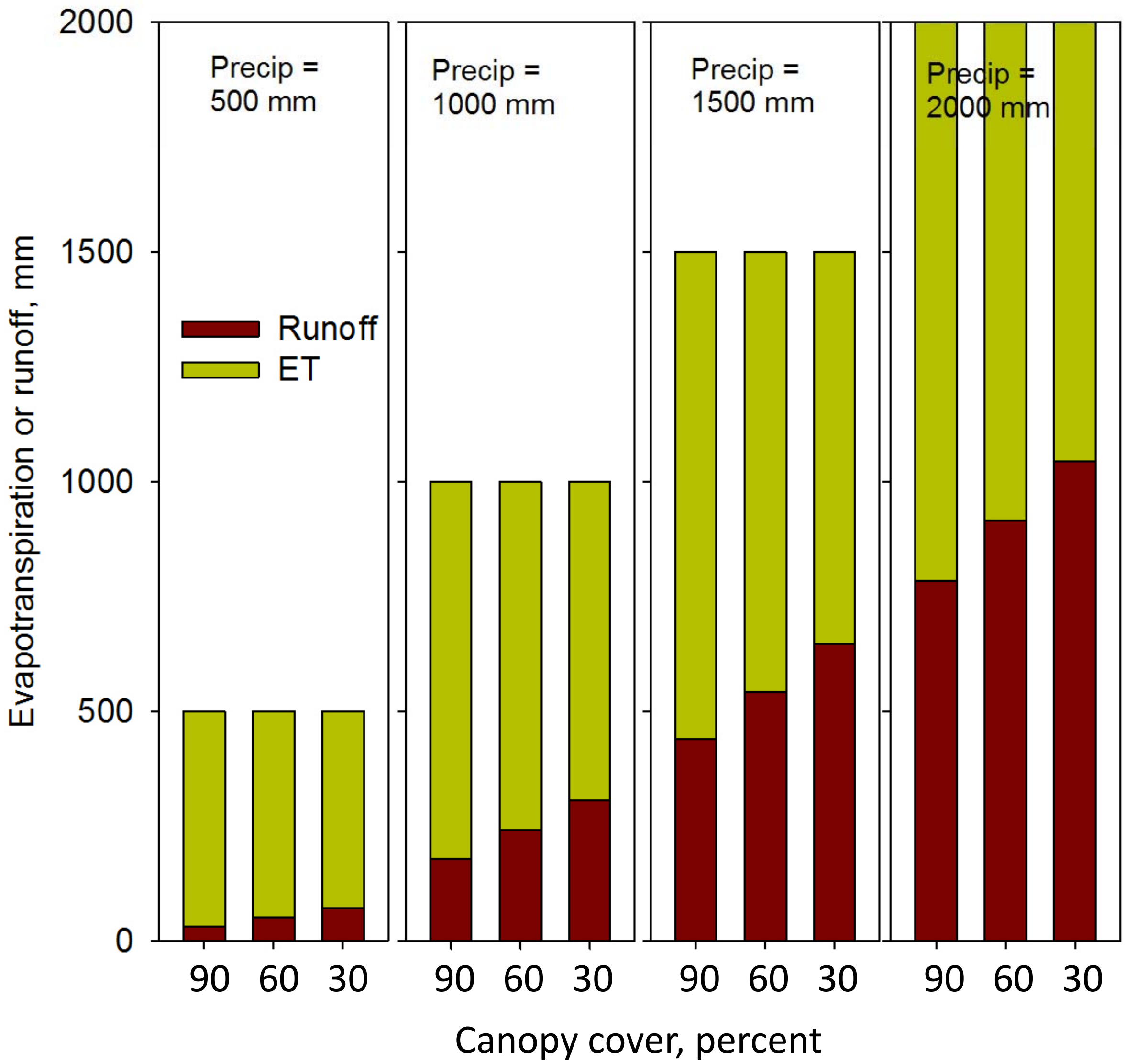

Figure 7.2. Partitioning of precipitation between evapotranspiration and runoff for 4 different precipitation amounts and 3 different canopy cover densities. Calculations based on Figure 1.

8. Recommendations and study plan

The recommendations outlined below are based on an assessment of: i) conditions in the Sugar Creek basin, ii) available data to inform and constrain hydrologic modeling, and iii) results of relevant past studies. The study plan for Phase 3 should be built around 4 tasks:

1. Field measurements of forest conditions and analysis of those data
2. Analysis of meteorological, hydrologic and landscape data for hydrologic modeling
3. Hydrologic modeling and assessment
4. Reporting and presentation of findings

8.1. Field measurements and analysis

In order to develop precise prescriptions that can be tested for building resilience and increasing water yield in the Sugar Creek watershed, the current forest structure will need to be measured. This assessment will have two primary objectives: i) measure forest structure and composition, and ii) develop canopy metrics.

Of primary interest for forest structure and composition are the parameters stem density and basal area by species. To improve efficiency, this can be captured with variable-radius plots with nested fixed-radius (1/100th acres) plots for smaller trees. A roughly 120 × 120 m (400 × 400 ft) sampling grid should provide adequate sampling intensity. Sampling can be stratified by vegetation type, as indicated by aerial photos. It will be important to capture variability within the mid-elevation mixed conifer, ponderosa pine, and riparian vegetation types. The sampling may be restricted to these types because of the assumption that *commercial* thins will be a primary component of prescriptions. Lower- and higher-elevation types can be included if desired or if they are determined to be feasible locations for non-commercial treatments such as prescribed fire or pre commercial thins.

Canopy metrics needed or modeling can be developed using a grid of hemispherical photos on the same sampling grid described above, and ground observations. Variables of interest include Leaf Area Index, canopy-cover fraction and canopy density. This will require approximately 2 weeks of field work and a week of lab work. Tree age, site index and litter-depth data can be collected simultaneously.

8.2. Analysis of data for hydrologic modeling

The most time-intensive step in detailed hydrologic modeling is preparation of the data inputs. It is proposed to develop a historical data set covering at least 20 years. This analysis will have as its objective developing accurate time-series data for six main attributes, plus additional site information needed for modeling.

1. ***Temperature***. Station data for the region will be cleaned to remove outliers and fill gaps. Data only reported as hourly values will be averaged to get daily average, maximum and minimum temperatures. Measurements for the region will then be assessed to develop a

composite data set for the Sugar Creek basin, across its elevation range. Our analysis of station data will also be compared with available results from the PRISM model, and any inconsistencies resolved. Temperature data for the region are relatively good.

2. ***Precipitation***. Station data for the region will be cleaned to remove outliers and fill gaps. Data only reported as hourly values will be averaged to get daily totals. Data will be compared with temperature and snow-pillow data to separate precipitation into rain versus snow, by elevation, by day. Measurements for the region will then be assessed to develop a composite data set for the Sugar Creek basin, across its elevation range. Our analysis of station data will also be compared with available results from the PRISM model, and any inconsistencies resolved. Precipitation data for the broader region are relatively good. Owing to the complex regional topography, the main challenge will be to provide confident estimates for the Sugar Creek basin, which lacks any precipitation measurements.

3. ***Snow accumulation and depletion***. Snow-pillow data for the region will be cleaned to remove outliers and fill gaps. Many data are already reported by day. Values will be assessed for consistency with precipitation measurements, and adjustments made to either data set as needed. During the snowmelt period, daily snow-depletion amounts will be assessed for consistency with temperature and streamflow data. Daily satellite snowcover data from MODIS will be analyzed to develop canopy-adjusted snowcover-depletion time series. These data will be compared with snow-pillow and snow-course data for consistency, and adjustments made as warranted. We will also assess by-weekly to monthly snow-covered area from LANDSAT, which is a higher spatial resolution than is MODIS, to aid in the canopy adjustments. Snow-pillow and snow-course data will also be analyzed to provide time series estimates of snow density. Snow-pillow data will be further analyzed, together with co-located daily temperature measurements, to develop seasonally adjusted melt factors that can be applied across the study area.

4. ***Meteorological data***. Additional data for wind, relative humidity and solar radiation will be cleaned to remove outliers and fill gaps. Data only reported as hourly values will be averaged to get daily totals. Values will be compared across stations to develop a composite data set for the Sugar Creek basin, across its elevation range. We will also model clear-sky and cloud-adjusted radiation for comparison. We will then develop a canopy-adjusted time series of radiation. Meteorological data for the region are adequate, though there are no data in the Sugar Creek basin.

5. ***Streamflow***. These data are important for hydrologic modeling, and are largely lacking for the Sugar Creek basin. The limited data that are available are incomplete, as data for stream diversions were not available for the current assessment. Two approaches are available for the Phase 3 work: i) focus the hydrologic modeling on estimating evapotranspiration as much as streamflow, without long-term verification of either, or ii) reconstruct streamflow using estimates of crop consumptive uses, plus further interviews with persons responsible for making and overseeing diversions to establish what, if any information is available as to the

historical timing and amount of actual diversions. Recent stream-stage data the Darbee Ditch diversion, together with follow-up contacts with the responsible parties, will provide some information and should be pursued in either case. Consideration should be given to adding stage recorders on any additional active diversions from Sugar Creek.

6. ***Vegetation characteristics and scenarios***. Data from the field surveys, plus available remotely sensed data, will be used to develop the vegetation inputs for modeling. Scenarios for vegetation changes will be developed in consultation with stakeholders in the area. Consideration should also be given to acquiring LiDAR data to better define vegetation across the full watershed, following what the USFS and others have done in the Sierra Nevada.
7. ***Watershed characteristics***. Data for soils will be based on available data from broad surveys, plus prior modeling in mountain watersheds. Topographic data will be from the USGS 10-m dataset.

8.3. Hydrologic modeling

It is proposed to use the RHESSys modeling package to integrate data and make estimates of evapotranspiration and streamflow for the various historical and future climate and vegetation scenarios (Tague and Band, 2004). RHESSys is a spatially explicit, daily time step model, and is being extensively used for similar purposes across the mountains of the Western United States (Tague and Hui, 2013). Documentation for the model can be found at http://fiesta.bren.ucsb.edu/~rhessys/. This model is well suited to develop scenarios for forest vegetation management. Some important features include: i) separation of evaporation and sublimation from transpiration, ii) separate treatment of transpiration from overstory versus understory, iii) consideration of evaporation from litter versus soil, iv) estimation of snowmelt energy balance under different canopy conditions, v) ability to include regrowth following vegetation thinning, including a complete carbon balance (optional), and vi) calibration using a variety of measurements. This latter point is important, and RHESSys can been successfully calibrated in the absence of streamflow data (Tague et al., 2013). Time series snowcover data will be used to assist in model calibration, plus potentially reconstructed estimates of snowmelt and streamflow in the upper part of the basin. It is also proposed to use RHESSys with a range of optimal parameter sets to develop uncertainty estimates and bound the scenarios simulated.

8.4. Schedule

It is proposed to initiate all tasks 1 and 2 in parallel, with task 3 to begin about 1 month before completion of those tasks, in order to provide some feedback on model parameter estimation. Overall, the project can be completed in about one year to 15 month, depending on when data become available. This assumes that data for task 1 are collected during the field season of 2014, with data analysis and integration taking place during the fall of 2014, with results by the spring of 2015.

8.3. Proposed budget

A preliminary budget was provided in summer 2013, which will be updated pending discussion of alternative approaches and verification of costs during review of this report.

References

Tague, C. and Band, L. 2004. RHESSys: Regional Hydro-ecologic simulation system: An object-oriented approach to spatially distributed modeling of carbon, water and nutrient cycling. *Earth Interactions*, 8:19, 1-42

Tague, C. and Hui, P. 2013. The sensitivity of forest water use to the timing of precipitation and snowmelt recharge in the California Sierra: Implications for a warming climate, Journal of Geophysical Research: Biogeosciences, 118:2:875-887, DOI: 10.1002/jgrg.20073.

Tague, C. L., Choate, J. S., and Grant, G.: Parameterizing sub-surface drainage with geology to improve modeling streamflow responses to climate in data limited environments, Hydrol. Earth Syst. Sci., 17, 341-354, doi:10.5194/hess-17-341-2013, 2013.