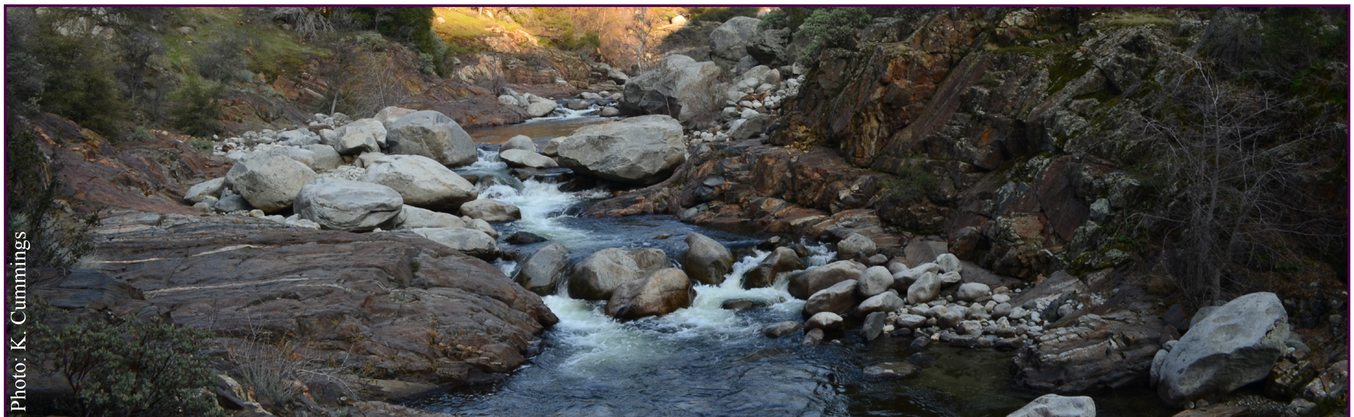

Watersheds, Rivers, and Lakes

A Southern Sierra Adaptation Workshop Information Brief

DISTRIBUTION

The Sierra Nevada serves as the headwaters for 24 major watersheds (Figure 1). These watersheds produce about 25 km^3 of water per year, about a third of the total water yield in California[1]. Despite being only 33% of the total yield, Sierra runoff accounts for nearly 65% of California's annual water supply for human use[2]. The high elevations in the southern Sierra are very important for providing water for agriculture and other human uses[3]. The direct value of Sierra Nevada water has been estimated to be $1.3 billion/year in California, not including recreational dollars from fishing, rafting, and more[4]. Additionally, much of Nevada is dependent on water from the eastern slopes of the Sierra[2]. Sierra Nevada water accounts for 60% of the total monetary value of all natural products/services produced by the region, which is more than forest or agricultural products, recreational services, or residential development[1].

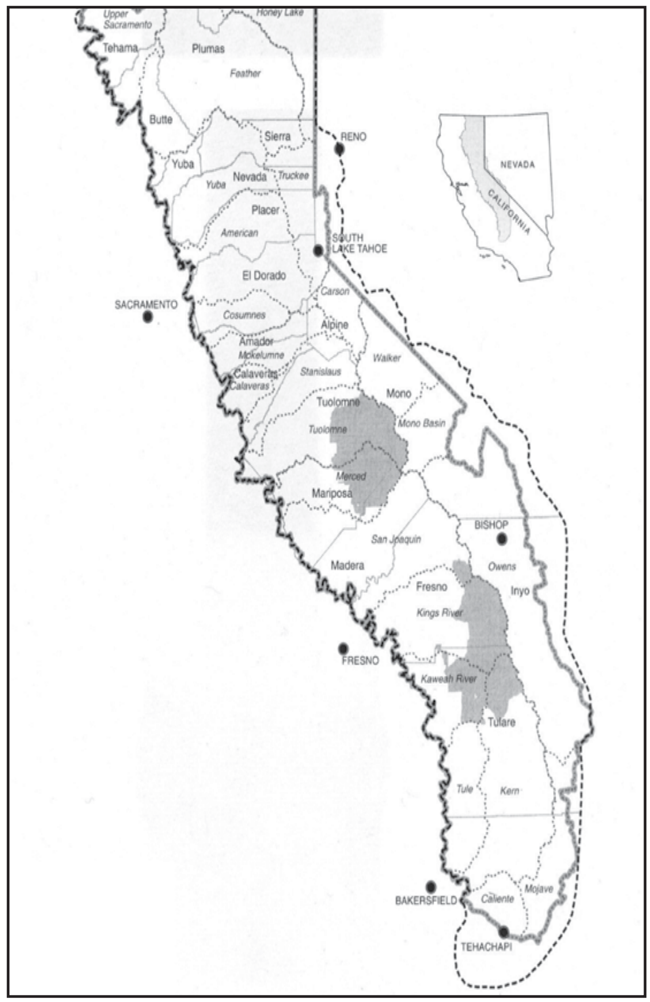

Figure 1: Names and locations of the 24 watersheds within the Sierra Nevada. The PACE includes all watersheds south of Calveras/Stanislaus/Walker Watersheds. Adapted from Timmer et al 2006.

CURRENT STATUS AND STRESSORS

Water Quality

A 1992 Water Quality Assessment characterized 21 streams on the western Sierra Nevada as having serious water quality problems due mainly to inadequate flow, but mine drainage and sedimentation were also causes[1]. On the eastern slope, almost all streams had water quality issues largely due to water diversion or overgrazing. Thirty streams throughout the Sierra Nevada were documented as having toxic contamination[1,5]. A substantial number of surveyed stream reaches were affected by pathogens, chemicals, and nutrients. Almost 80% of sampled watersheds within the Sierra contained fish with high concentrations of contaminants[4] and 75% of surveyed streams had reaches with reduced drinkability, defined as the ability of a water supply to yield enough potable

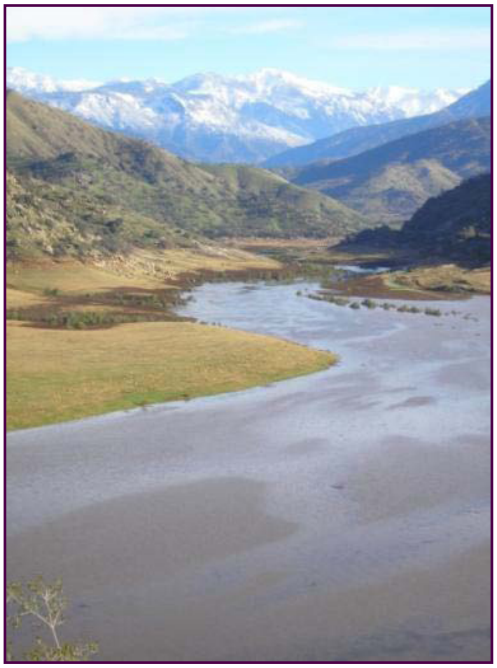

Figure 2: A river in the generally "unimpaired" areas within national forests and parks at higher elevations. Photo credit: NPS-SEKI

water after treatment[4,6]. Furthermore, 85% of Sierra Nevada watersheds are rated as having poor to fair aquatic biotic communities[7]. In terms of biotic integrity, dams at low to middle elevations and non-native fish introductions at higher elevations caused the greatest degradation[7]. See Table 1 for current stressors.

National forests and national parks mostly occur in the Sierra headwaters, however, and are often above the impaired portion of a river or stream(Figure 2)[8]. Generally, water quality within forested areas of watersheds throughout California is 80% unimpaired (i.e., meets requirements for its designated use), but as rivers and streams flow out of forests into agricultural and urban areas, only 20% of the monitored stream segments are unimpaired[9]. When a forest stream segment is impaired, it is most often due to nutrients, lack of habitat complexity, and riparian disturbance/ streambed stability[9]. In terms of mineral content, water quality above 300 m elevation has been called "excellent"[10], with increasing concentrations downstream.

Interactions between severe wildfires and intense storm events can have important repercussions for water quality, stream geomorphology, and biological communities in the Sierra[8]. Loss of vegetative cover after severe wildfires can increase erosion and sediment loading, especially if storms after the fire create debris flows[11]. Post-fire debris flows are a substantial concern in the S. Sierra. Recovery often is relatively rapid after fires, however. Within six years after a severe fire affected a northern Sierra stream, vegetation became reestablished, erosion returned to normal levels, and aquatic invertebrates recovered in terms of density and taxa richness, though significant differences remained in species composition[12]. A wide variety of management activities (notably roads, but also timber harvesting, site preparation, fuels reduction, and prescribed fire) can increase overland flow rates and sediment yields, potentially degrading water quality and aquatic habitat[8]. Prescribed fire had no or short-term impacts on streams and riparian zones in a northern Sierra Nevada stream, however[13].

Water Quantity

The hydrological cycle in the Sierra Nevada has been changed drastically by water management activities (Figure 3). No river reaches the Central Valley unaltered. Most have dams and reservoirs for flood control and to provide water for agriculture, cities, industry, and hydroelectric facilities[1]. Water management activities have profound effects on water quantity, temporal and spatial distribution of water, minimum flows, and flooding (Table 1). Forest management practices can alter water yield, but there is disagreement as to the degree of vegetation removal (via fire or mechanical thinning) required producing detectable increases in snowpack water storage and watershed runoff[8]. Already, warming over the past century is linked to earlier snowmelt and streamflow timing in the Sierra Nevada[14].

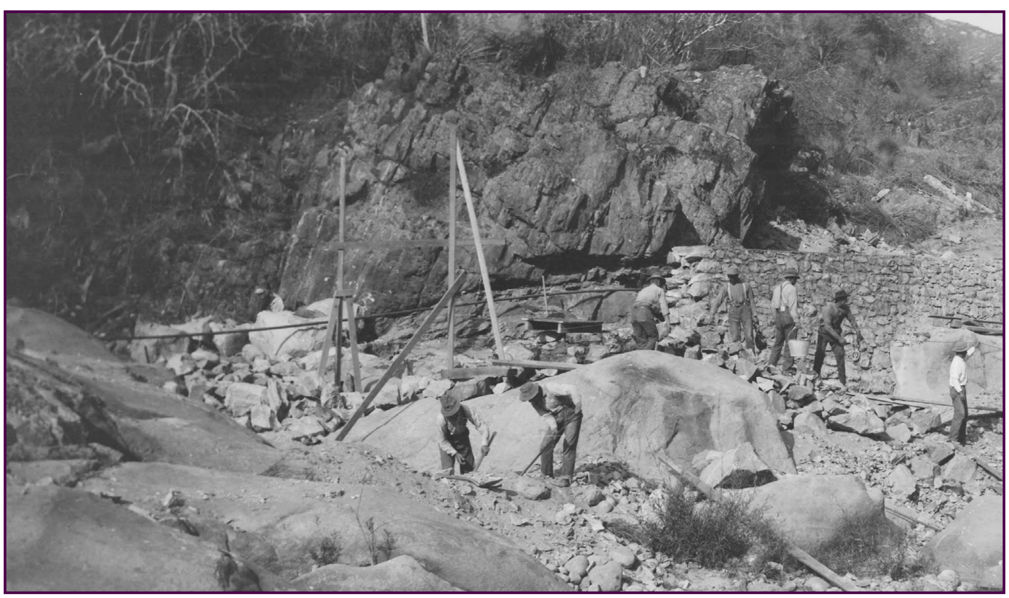

Figure 3: A construction crew working on the Middle Fork headworks of the Kaweah River, date unknown. Photo credit: NPS-SEKI

Native Aquatic Wildlife
As of 1994, there were 32 amphibian species found in the S. Sierra (Figure 4); of these, 11 were threatened or endangered and five were of special concern[15]. Since then, the southern mountain yellow-legged frog (*Rana muscosa*), Sierra Nevada yellow-legged frog (*R. sierrae*), and Yosemite toad (*Bufo canorus*) have been identified as candidates for listing under the Endangered Species Act[3]. Habitat alteration from a multitude of sources is partially to blame for the decline in amphibians[16], but their high sensitivity to pollutants, disease, and non-native fish introductions as well as life history traits, such as highly localized distributions and metapopulation dynamics, also contribute[17]. As of 1996, 40 fish species/subspecies were found in the Sierra Nevada, including six threatened or endangered, 12 of special concern, and four with declining populations[7,18]. Fish populations are most affected by dam construction, changes in aquatic habitat, and introduction of non-native species[18].

The introduction of non-native fish species for recreational purposes since the 1900s[19] is possibly the greatest major stressor affecting native aquatic wildlife. Introduced trout predate on native species including fish and frogs. In deep lakes important for overwintering and breeding for mountain yellow-legged frogs, predation can be especially severe and drive frog populations to extirpation[20,21,22,23]. Exotic trout can also cause top down effects in the food web via their influence on aquatic invertebrates[24,25,26], with consequences for the terrestrial food-web as well[27,28,29]. In the last decade, scientists and managers have removed non-native fish from a small subset of lakes and have observed very good recovery of native frog species[23,30,31,32]. Other stressors also affect amphibians, however. The amphibian chytrid fungus is a worldwide issue and has caused precipitous declines of mountain yellow-legged frogs throughout the Sierra[33,34,35]. This disease complicates the recovery efforts for the mountain yellow-legged frogs, but an anti-fungal treatment and natural beneficial skin bacteria are showing promise for disease intervention[81].

Exposure to pollution and pesticides from airborne deposition was hypothesized to cause population declines in amphibians in the Sierra, but a recent study found no correlation between frog population and pesticide concentration[36]. However, the interacting effects of these previously listed stressors can significantly decrease the fitness of the organisms and make them more susceptible to future changes. For example, fire negatively impacted plethodontid salamanders, with greater effects in fire-suppressed forests that burned with high severity[37,38].

Figure 4: One of the native amphibian species to the Sierra Nevada, a Sierra newt. Photo credit: K. Cummings

Table 1: Current stressors affecting Southern Sierra watersheds

Current Stressor		Mechanism	Potential Impact to Ecosystem
Wildfire Exclusion	Increased likelihood of very severe fires	Severe, stand-replacing fires kill large areas of vegetation	Increased soil moisture, water yield, overland flow[49], erosion[1,51], sediment yield[1,51,] flooding[50]; decreased infiltration; impermeable layer of volatilized organic matter forms in soil[48]; aquatic organisms effects; increased debris flows, scouring[51]
		Increased nitrate; other nutrients46	Eutrophication
	Loss of natural fire regime	Denser forests	Reduced water yields[1]
		Denser ground cover	Decreased surface erosion[1]
	Chemical Use	Fire retardants (sodium-calcium borate)	Sterilize soil; restrict plant growth; toxic to aquatic organisms[52]
Human Development	Sewage	Short term failures	Bacteriological contamination downstream; eutrophication
		Overloaded septic systems	
	Chemical use	Pesticides	Threat to water quality and aquatic organisms[53]
		Herbicides	Kills aquatic/riparian vegetation; reduces cover and shade benefits for fish; increased sedimentation; decreased DO via decomposing plant matter
		Insecticides	Kill aquatic insects; reduced food supplies for fish
	Roads and Structures	Destroy vegetation/surface organic matter; decreased infiltration; increase in overland flow; steepen adjacent cut/fill slopes; intercept subsurface flow	Increased erosion 100s X > natural rate; runoff collected and released as potentially erosive flows; increased sedimentation yields; increases in fine sediments that are harmful for some species of fish; declines in fish and amphibian populations[54]
		Stream crossings of roads	Disturbs beds, banks, floodplain, terraces; increased erosion/sedimentation
		Addition of pollutants - tires, fluid leaks, pet waste, exhaust, oils, pesticides, fertilizers, etc[47]	Detrimental effects on aquatic organisms; de-icing salt can affect plant growth
Water Management	Creation of dams	Blocked of stream flow; creation of reservoirs upstream; redistribution of water in space and time; decrease in peak flows; lower-than-normal flows	Sediment trapped upstream; channeling incision/narrowing downstream; impedes fish migrations; riverine habitat fragmentation; groundwater table below root zone for riparian vegetation; alters downstream water chemical/thermal characteristics, aquatic organisms effected; increases [pollutants], evaporation loss
		Catastrophic failure of dams[1]	Erosion; sediment deposition downstream; destruction of human structures
Air Pollution	Loading of acidity, sulfate, nitrate, and ammonia	Ions concentrate in snowpack, suddenly released during spring melt[55,68,69,70]	Lowers pH of water bodies in high-elevation areas - risk of acidification[55,56]; fertilization/eutrophication; airborne pesticides cause amphibian mortality[57,58]
Human Recreational Use	Fisheries enhancement	Stocking of non-native fish species	Introduces non-native predator; prey item mortality; decreased biodiversity[7]
	Recreational facilities	Snow compaction; fake snow creation; chemical use to improve skiing; tree removal	Snow remains on slopes longer[59]; water used to make snow returns to stream 5-8 mo. later; decreased water quality; increased soil moisture[1]
		Sewage issues	Eutrophication; increased plant growth on lake bottoms on heavily used trails[60]; degradation of habitat for aquatic organisms (esp. salmonoids/trout)
	Backcountry hiking	Human waste; bacteriological contamination	
	Packstock	Waste; nutrient and bacterial pollution	
Logging	Chemical use	Pesticides; insecticides; herbicides	See above
	Removal of trees	Less water loss from evapotranspiration; forest clearing creation; increased water	Increased water yield; increased sedimentation; increased peak flows; increased rate of snowmelt in clearings[65,66]; aquatic biota changes unknown[67]
	Post-fire salvaging	Generate revenue; disturb sensitive burned soils	Creates $ for watershed rehabilitation; replace culverts; slash used to physically protect soils; discourage erosion by retaining root mass in soil; erosion on sensitive soils; reduced critical snag & coarse woody debris habitat[1,61]
	Road creation	See above	See above
Grazing	Overgrazing of meadows	Vegetation defoliation; soil compaction; invasive plant & lodgepole pine spread	Increased erosion, gully formation, sediment loads; reduced open meadow area; loss of native wetland/meadow vegetation[1,62,63,64] (see meadow info brief)
	Waste production	Increased nutrient runoff	Alteration of nutrient cycle; euthrophication

Table 2: Potential climate change impacts and charactersitics affecting adaptive capacity for watersheds and associated organisms

Climate Change	Potential Results	Potential Impact to Watershed Hydrology	Potential Impact to Biota
"Much Warmer/ Much Drier" Scenario	Earlier snowpack melt[41,71,72]; decrease in snow pack[72,73]; changes in sub/surface hydrology; increased soil evaporation rate in summer; increased water deficit[74]	Decreased spring/summer flow, large basins will have 30% less spring flow; 45% less summer flow[77]; decreased relative contribution by snowmelt; increase in water temp 2-6 C; decreased DO, sediment[77]; earlier runoff; earlier soil moisture storage, subsurface flow, groundwater flow; shift in timing and vol of sediment transport[77]	For salmonoids: warmer temperatures could change migration timing, reduce growth rates & available oxygen, increase susceptibility to stress; reduced flows could further increase temps, impede migration; very high flows could wash away gravel at spawning sites[77,78]
			For humans: longer summers will increase growing season for crops, droughts will cause water stress, requiring more water that may not exist; other agriculture (livestock) will be effected; increased pop growth will require more water[50]
			For plants: drought conditions during growing season could lead to species shifts and die-offs
	Increase in fire probability at almost all elevations except foothills & alpine areas; increase burned area[75,76]; increase in frequency in SEKI & YOSE[72]	Increased soil moisture, overland flow[49],water yield, erosion, sediment yield; impermeable layer of volatilized organic matter forms in soil[48]; decreased infiltration	Potential impacts to flora and fauna, especially some salamander species[37,38]
"Moderately Warmer/Similar Precip" Scenario	Increased fire probability at almost all elevations except alpine areas[76]	See above	See above
Increased Extreme Precipitation Events	Increased large flood events; Increase in number, extent, and size of mass wasting movements and debris flows[1]	Greater volume of water being moved downstream in a short amount of time; increased erosion, scouring; sedimentation, turbidity; concentrated pulses of pollutants; decreased DO[50]	For biota: Lowered water quality; eutrophication; degraded habitat, but also increased complexity of habitat that may be beneficial[50]
			For humans: loss of life and property; may overcome dams, water loss for hydroelectricity, more difficult to treat for safe drinking water[50]

Future Vulnerabilities	Explanation	Potential Impact to Watershed Hydrology
Projected Increase in Human Water Use	Rapid human growth and development; inefficient water distribution systems; revenue base not large enough to sustain low water rates; limited funding sources; development of new water projects costly[79,80]	Increased water shortages in the future; recreational fisheries threatened; decreased habitat for aquatic organisms
Low Adaptive Capacity	Aquatic biota may not be able to migrate to new suitable habitat as climate warms and water levels drop. Non-native species may reduce dispersal ability.	Loss of native species that cannot disperse
Synergistic Effects	Already weakened ecosystems may become more vulnerable to new stressors and new combinations of stressors brought on by climate change	Watersheds that received low scores in terms of biotic integrity will be especially at risk. These include: 1) Low-middle elevation watersheds that have been dammed/diverted and are dominated by non-native fish and frogs and/or have greatly decreased native biodiversity; 2) High elevation watersheds dominated by non-native trout and have lost native frogs; 3) Small, low elevation watershed that have been highly altered by human activity (dams, agriculture, mining, urbanization, etc.)[7]

POSSIBLE FUTURE CHANGES AND WATERSHED/AQUATIC WILDLIFE ADAPTIVE CAPACITY

Although predicting future climates is extremely complex, the three main IPCC emission scenarios agree that temperature in the southern Sierra will warm, with predictions of +2.6 to 3.9°C by 2100[39]. Less certain is the change in precipitation – of the 18 general circulation models that include California, about half predict decreases and half predict increases for the Sierra region[39]. Even with no change in precipitation, increased temperatures still will increase evapotranspiration, cause more precipitation to fall as rain rather than snow, reduce snowpack water storage, cause shifts to earlier peak streamflow, alter wildfire regimes, and more[8] (Table 1, Figure 5). This is especially important for Sierra Nevada water yield, which depends heavily on snowpack to fuel water flows throughout the dry summer months[8]. Snowmelt is already occurring 15 days earlier than in 1960[40].

Under warming scenarios, the average annual flow is predicted to decline in all 24 major Sierra Nevada watersheds. The onset of snowmelt and streamflow centroid timing will occur earlier in the year, and low flow duration will lengthen over almost all the Sierra watersheds[41]. High elevation basins in the south-central Sierra are most susceptible to earlier runoff timing and those in central Sierra are most vulnerable to longer low flow durations[41]. Perhaps most importantly for human use of Sierra water, watersheds that have large capacity for hydropower generation, such as those in the San Joaquin, Stanislaus, and Tuolumne watersheds, are also the most vulnerable to shifts in streamflow timing[41]. These changes will overall result in increasing drought stress over the summer growing season for natural ecosystems, agriculture, and human consumption in the Central Valley.

Aquatic organisms will be affected directly by climate change via effects on water temperature and flow regimes and indirectly through a myriad of interactions, such as with wildfire severity, disease, non-native species, contaminants, and drying of aquatic habitat. Aquatic biota may have a hard time migrating to suitable habitat as climate changes due to lack of connectivity between aquatic/wetland ecosystems and the presence of non-native fish in many mountain lakes. Multiple stressors currently affecting some native aquatic organisms, including the mountain yellow-legged frog and California golden trout, will make it hard for these species to adapt to the multitude of potential changes brought on by climate change. Higher stream temperatures have been shown to be lethal for salmonids and also may affect growth, condition, and long-term survival[42]. Reduced hydroperiods will reduce available habitat for amphibians and possibly increase mortality of tadpoles and eggs through stranding[8]. The effects of chytrid fungus may also worsen under a warming climate[43,44].

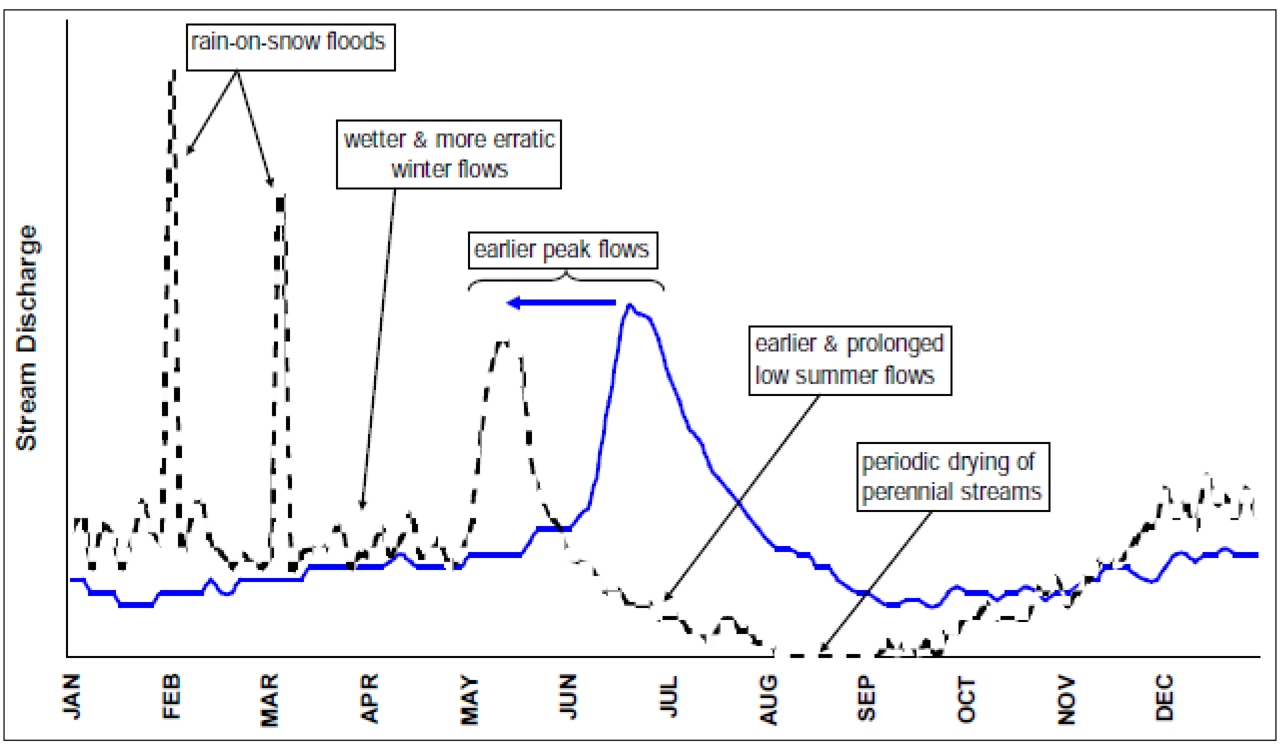

Figure 5: Conceptualization of climate-driven changes (dashed black line), some observed and some predicted, on the natural snowmelt-driven hydrograph (blue-line) of a Sierra Nevada Stream (Adapted from D. Herbst 2013[8])

POTENTIAL MANAGEMENT STRATEGIES (WORK IN PROGRESS)

- To manage for persistence (resist change and build resilience):
  - Suppress high severity fires in riparian areas
  - Install fuel breaks in strategic locations to limit fire spread
  - If pesticides need to sprayed, use ground application rather than aerial
  - Allow sediments to pass through dams during high flows
  - Restructure roads that are poorly designed, especially stream crossings.
  - Restore hydrological connectivity to riparian ecosystems
  - Utilize prescribed burning or mechanical thinning to reduce fuel loads
  - Remove invasive species, especially non-native stocked fish
  - Prioritize conservation of streams/riparian zones that are important wildlife migration corridors and/or hydrologic linkages
  - Significantly thin forests – reducing forest cover by 40% could increase water yields by 9%45
  - Conservation efforts should be focused on watersheds receiving high scores of biotic integrity
  - Restructure streams from shallow and wide to narrower and deeper, increase streamside vegetation to make more resilient to warming, especially for salmonoids and other thermally sensitive species.
  - Establish "freshwater protected areas" to increase resilience of streams – i.e. wilderness areas that eliminate or minimize activities such as grazing
  - Eradicate invasive species
  - Build more dams at higher elevations
  - Restore wet meadows to increase water quality
  - Develop and test feasible treatment options against chytridiomycosis for frogs

- To manage for change (facilitate transformation):
  - Use less water for human uses, because there is less water to use
  - Assist migration of riparian plants upslope
  - Plant dry areas with native upland species
  - Replant areas with species and genotypes for lower elevations
  - Assisted migration/captive breeding of fishes and amphibians
  - Focus assisted migration efforts on lake basins that have natural barriers to non-native fish

- Delay deciding (monitor and research):
  - Monitor species composition and changes
  - Monitor invasive species
  - Monitor stream discharge and surface water temperature
  - Monitor soil moisture
  - Monitor sediment loading and channel geomorphology
  - Map which streams have groundwater or high-elevation water sources to figure out which are more vulnerable to desiccation
  - Set up more comprehensive water health monitoring network with frequent and long-term sampling
  - Increased incorporation of bioassessment techniques using aquatic invertebrates

Authorship Note

This information brief was created by Katy Cummings (NPS) and Koren Nydick (NPS), with review and contributions from Don Seale (NPS). Additional thanks to Erika Williams (NPS) for graphic design assistance.

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