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Natural Resource Stewardship and Science

A Natural Resource Condition Assessment for Sequoia and Kings Canyon National Parks

Appendix 3 – Erosion and Mass Wasting

Natural Resource Report NPS/SEKI/ NRR—2013/665.3

ON THE COVER
Giant Forest, Sequoia National Park
Photography by: Brent Paull

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This document contains subject matter expert interpretation of the data. The authors of this document are responsible for the technical accuracy of the information provided. The parks refrained from providing substantive administrative review to encourage the experts to offer their opinions and ideas on management implications based on their assessments of conditions. Some authors accepted the offer to cross the science/management divide while others preferred to stay firmly grounded in the presentation of only science-based results. While the authors' interpretations of the data and ideas/opinions on management implications were desired, the results and opinions provided do not represent the policies or positions of the parks, the NPS, or the U.S. Government.

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Introduction

Erosion and mass wasting is important to Sequoia and Kings Canyon National Parks (SEKI) for a number of reasons.

- It shapes the landscape.
- It is a dynamic force that influences the composition and successional direction of vegetation.
- It influences the distribution and abundance of aquatic resources, particularly benthic invertebrates and fish.
- It impacts infrastructure and puts lives at risk.

This report contains many examples of storms, landslides, debris flows, etc. Because of space limitations, those events are presented here in summary form without details. Fuller descriptions of the events are presented in the document, *Floods and Droughts of the Tulare Lake Basin* (Austin 2012), complete with citations. Many other examples are also included in that document.

When describing various geomorphic processes, this report relies on the best available literature. Because relatively little geomorphic research has been conducted in SEKI, that results in the discussion of those processes being somewhat general in nature, as opposed to specific to SEKI. However, an understanding of these processes is necessary prior to describing the geodynamics that have been researched specifically in SEKI.

Anthropogenic Stressors

Anthropogenic stressors that affect erosion and mass wasting are primarily related to landscape use, altered fire regimes, and climate change.

Landscape use stressors include various types of erosional impacts to meadows as well as erosional impacts caused by infrastructure, especially roads. These stressors are addressed in various sections of this report.

Altered fire regimes contribute to somewhat greater erosion. They can also result in increased risk of shallow landslides and similar debris flows, depending on site factors. This is occurring now and is expected to continue into the foreseeable future. This stressor is addressed in various sections of this report (e.g., Fire and Surface Erosion and Fire as a Trigger of Debris Flows).

Climate change is currently resulting in a higher tree mortality rate and this is expected to increase in the future (van Mantgem and Stephenson 2007, van Mantgem et al. 2009). This loss of large trees could contribute to increased erosion and an increased risk of shallow landslides and similar debris flows, depending on site factors.

Climate change will also result in more precipitation falling as rain rather than snow. This may result in greater erosion. This change in the form of precipitation combined with the change in temperature will likely alter the risk of various mass wasting processes. However, there are no reliable models to predict specifically where and how different processes are likely to respond. Some mass wasting processes might become less frequent in one area while some might become more frequent in another area.

Erosion

Erosion is the movement of soil, rock, and other particles from one location to another. The transport force is usually water, ice, wind, or gravity. Erosion can take several forms, but the two most common forms in the Southern Sierra Nevada are:

- surface erosion such as rill erosion, gully erosion, and valley erosion (terms defined later)
- mass wasting such as rock falls, landslides, rock slides, and debris flows (terms defined later)

Processes

Water

A review of the literature suggests that the four most important forms of water erosion in the Southern Sierra Nevada are:

- **Rill erosion.** The removal of soil by concentrated surface runoff whereby numerous small channels are formed.
- **Gully erosion.** Rill erosion evolves into gully erosion either over time or with intensity of runoff. A gully is commonly defined as a rill too big to drive a tractor across.
- **Valley or stream erosion.** Stream erosion digs valleys deeper and wider. It also makes them longer by eating farther and farther into the uplands where they begin. By far the most erosion occurs during times of flood, when more and faster-moving water is available to carry a larger sediment load.
- **Bank erosion.** This is the wearing away of the banks of a stream or river. Bank erosion is distinguished from changes on the bed of the watercourse, which is referred to as scour.

Ice

Ice erosion can take one of two forms. It can be caused by the movement of ice, typically as glaciers, in a process called glacial erosion. It can also be due to freeze-thaw processes in which water inside pores and fractures in rock can expand causing further cracking.

Glaciers erode predominantly by three different processes: abrasion/scouring, plucking, and ice thrusting. In an abrasion process, debris in the basal ice scrapes along the bed, polishing and gouging the underlying rocks, similar to sandpaper on wood. Glaciers can also cause pieces of bedrock to crack off in the process of plucking. Plucking produced many of the lake basins that dot the High Sierra. These processes, combined with erosion and transport by the water network beneath the glacier, left moraines and glacial erratics in their wake during glacier retreat.

In some places, water seeps into rocks during the daytime, then freezes at night. Ice expands, thus creating a wedge in the rock. Over time, the repetition in the forming and melting of the ice causes a fissure which eventually breaks the rock down. Because of this freeze-thaw process, rocks often drop onto the roadway overnight when a road is adjacent to a rocky outcropping.

Gravity

Gravity influences two significant geomorphic processes: dry ravel and mass wasting. The process of dry ravel typically occurs after fire and is discussed in a later section of this report on Fire and Surface Erosion. Mass wasting is the geomorphic process by which soil and rock move downslope under the force of gravity. Mass wasting processes occur continuously on all slopes. Some mass wasting processes act very slowly; others occur very suddenly, sometimes with disastrous results. Any perceptible downslope movement of rock or soil is often referred to in general terms as a landslide. However, mass wasting can be classified in a much more detailed way that reflects the mechanisms responsible for the movement. Mass wasting processes are discussed in detail in a later section of this report.

Causes of Erosion

General

The rate of erosion depends on many climatic, geologic, and biologic factors. The factor that is most subject to natural environment change is the amount and type of ground cover. In an undisturbed forest, the mineral soil is protected by the tree canopy, by an organic layer (i.e., the topmost soil layer, the A horizon) and a litter layer (aka ground cover). These three layers protect the soil by absorbing the impact of raindrops. These layers and the underlying soil in a forest are usually porous and highly permeable to rainfall. They reduce overland flow and reduce surface erosion.

Any disturbance that removes these layers will decrease infiltration rates and increase the speed and amount of surface runoff. Examples of anthropogenically driven disturbances are buildings, parking lots, livestock grazing, roads, and trails. Roads are especially likely to cause an increased rate of erosion. In addition to reducing infiltration, roads often concentrate runoff and create channels in their course or at waterbreaks (e.g., culvert outfalls). Depending on placement, roads can also intercept shallow groundwater.

Fire and Surface Erosion

The presence of tree canopy, litter, and ground cover minimizes surface erosion. High-, and sometimes moderate-burn severity usually reduce litter and ground cover. When this occurs, infiltration rates can decrease, the amount and the speed of surface runoff increase, and surface erosion can temporarily increase. The amount of litter and ground cover required to prevent increased rates of erosion varies depending on the steepness of the slope.

Waxes in the surface layer of the soil can form a hydrophobic layer that temporarily resists moisture infiltration. High-, and sometimes moderate-burn severity can somewhat increase the thickness of that layer. However, that hydrophobic layer provides only a temporary moisture barrier. After a period of soaking, water penetrates the hydrophobic layer.

Dry ravel is the movement of soil and debris downhill between the time of a fire and the first rains. Where fire consumes the vegetative cover, the mechanical resistance to gravitational forces decreases, and the soils become more susceptible to this type of surface erosion. The sediment accumulates in stream channels at the base of the hillslopes. Dry ravel is caused by gravitational forces and is a major erosional process in postfire conditions in areas with steep slopes.

Accelerated levels of surface erosion (dry ravel and rill formation) generally do not occur if fire occurs as a mosaic of relatively small, low-burn severity fires scattered across the landscape. When fire occurs as a moderate- and high-burn severity, landscape-wide fire, then surface erosion can increase significantly above normal levels.

Soils are critical to the functioning of hydrological processes. Within a watershed, sediment and water responses to fire are often a function of soil burn severity and the occurrence of hydrologic events. For a wide range of soil burn severities, the impacts on hydrology and sediment loss can be minimal in the absence of precipitation. However, when a significant storm follows a large fire, impacts can be substantial. Increased runoff, peak flows, and sediment delivery to streams can affect fish populations and their habitat as well as creating other adverse effects (Rinne 1997).

Accelerated surface erosion commonly occurs after fire on forested lands. As burned areas recover, erosion returns towards pre-fire rates depending on many site-specific characteristics, including soil burn severity, vegetation type, soil type, and climate. In some areas, surface erosion recovery can be rapid, particularly where revegetation is quick.

Research in Sequoia National Forest suggests that after low- to high-burn severity wildfire, rilling is seldom evident more than four years after fire. That research also looked at the association of erosion with a variety of fuel reduction techniques and found that there was little difference (Berg and Azuma 2010).

In Southern California, erosion rates can increase dramatically after a high-burn severity fire. In the Southern Sierra Nevada, the increase appears to be fairly modest after a low- or even high-burn severity fire. Dave Graber, the NPS regional chief scientist, says that is because the soil and underlying geology types are very different (personal communication, August 2012). No example has yet been found in SEKI where erosion rates increased significantly after fire.

Major Geomorphological Factors Affecting Erosion

The Sierra Nevada has at least two key geomorphological factors that affect erosion:

- The hillslopes below the conifer zone are generally steep, and the canyons are deep. Because of this, the streams and rivers that flow off these hills have a lot of energy.
- The soils on these hillslopes are loosely attached to the underlying bedrock. Many of these soils occur on colluvial debris slopes and are easily eroded.

Steep Rivers in the U.S.

One way to compare the steepness of different rivers is to evaluate them over their entire length (Tweed 2011). Measured over its entire length, the Kaweah is the steepest river in the United States. As shown in **Table 1**, only a dozen or so river systems in the U.S. have descents approaching or exceeding 10,000 feet. The six steepest rivers relative to total length occur in the Southern Sierra Nevada.

There are a number of rivers in the Southern Sierra Nevada that start at very high altitudes and have roughly the same drop as the Kaweah. However, those rivers are about twice as long as the Kaweah, meaning that their overall gradients are lower. The Kaweah is the only river in the U.S. that drops 10,000 feet in less than 100 miles. As shown in **Table 1**, that gives the Kaweah a gradient nearly twice as great as any other river in its category in the U.S.

Table 1. Gradient of U.S. rivers with large elevation drops.

Mountain System	River	Length (miles)	Drop (feet)	Gradient (feet/mile)
Rocky Mountains	Arkansas	1,469	9,620	7
	Missouri	2,619	8,405	3
	Snake	1,078	9,642	9
	Colorado	1,450	10,184	7
Sierra Nevada	Tuolumne	148.7	8,557	58
	Merced	150	11,255	75
	San Joaquin	366	9,839	27
	Kings	170	11,420	67
	Kaweah	76.5	10,826	142
	Kern	164	11,701	71

Based on this metric (average gradient), SEKI contains three of the steepest rivers in the U.S.: the Kings, Kaweah, and Kern. The gradients shown in Table 1 are for the entire river. However, individual reaches of those rivers can be much steeper. For example, the Marble Fork of the Kaweah has a gradient of 559 feet per mile, dropping 8,549 feet in just 15.3 miles.

As shown in **Table 1**, the rivers in the Rocky Mountains have a low average gradient. That is because those mountains are a long distance from the ocean. However, even the sections of those rivers that drop most steeply have a smaller drop than the Kaweah.

From a geomorphic standpoint, a key metric is the drop from the headwaters to the range front. By that metric, the Kaweah and Merced are the steepest rivers in the U.S. When measured from its headwaters to the range front at Terminus Dam, the Kaweah drops 10,505 feet in 37.5 miles, a gradient of 280 feet per mile. When measured from its headwaters to the range front at El Portal, the Merced drops 9,611 feet in 40 miles, a gradient of 240 feet per mile.

The steep, high-energy rivers of the Southern Sierra Nevada have eroded very deep canyons. For example, a line drawn across the canyon of the Middle Fork of the Kaweah between Panther Peak and Paradise Peak discloses that the canyon at that point is nearly a mile deep. Panther Peak’s elevation is 9,047 feet and Paradise Peak’s elevation is 9,368 feet. The river in between is 3,877 feet in elevation, making that canyon 5,331 feet deep at its deepest point. It would probably be 400–500 feet deeper if measured between some higher, unnamed peaks further upstream. The canyon of the Middle Fork of the Kaweah between Panther Peak and Paradise Peak is 7.4 miles wide. For comparison, the Grand Canyon of the Colorado is a slightly deeper but much broader canyon. That canyon attains a maximum depth of 6,000 feet and is up to 18 miles wide. Kings Canyon and Kern Canyon are also quite impressive erosive features.

The combination of high-energy rivers, deep canyons, and unstable hillslopes sets the stage for the type of erosion and mass wasting that characterize SEKI.

Floods and Erosion

SEKI's rivers do most of their active sediment transport during flood flows. Austin (2012) contains a detailed account of those floods and the storms that caused them. A sample of those floods follow:

- The heaviest 24-hour rainfall ever recorded in the entire Central Valley up until that time, 17.0 inches, occurred on December 6, 1966 at Hockett Meadows. This record precipitation on the Hockett Plateau generated unprecedented runoff. Cahoon Meadow was predisposed for erosion by years of intense livestock grazing. It is possible that this was the event that caused the majority of the gullying that we see today in that meadow.
- The December 1966 storm also caused considerable erosion on the Sequoia National Forest. Large sections of the Kernville Road (Highway 155) were badly damaged by erosion. Sections up to 2½ miles long were washed away.
- A cloudburst occurred above Silver City on or about July 20, 2006. The resulting flash flood damaged some of the cabins in Cabin Cove (just west of Silver City) and washed out portions of the Mineral King Road. The flood eroded low-gradient stream channels down nearly to bedrock. That level of erosion implies a very high stream discharge far from the statistical norm; an event that would occur only rarely.

Anthropogenically Driven Erosion of Meadows

Many park meadows have been impacted by anthropogenically driven erosion (Neuman 1990). This has most typically taken the form of intense livestock grazing followed by surface erosion, resulting in gullying, cut stream banks, and lowered water tables. Cahoon Meadow in the East Fork Kaweah drainage is a good example of this category. That meadow has not yet been restored and is still seriously degraded. Most of the meadows in this category, however, were restored to a significant degree. The CCC performed fairly major erosion control work, especially in Williams and Sugarloaf Meadows (Neuman 1990). SEKI's soil and moisture crews added smaller check dams in these meadows in the 1950s.

Another form of backcountry erosion that affected meadows was a result of packstock eroding a trail tread, followed by running water eroding the trail further. This typically resulted in gullies up to about 18 inches deep. There was a lot of this type of gullying in the 1960s and 1970s. There were virtually no drift fences in the backcountry prior to that time. SEKI's soil and moisture crews treated this type of erosion by constructing check dams and drift fences.

Until 2007, one of the most impacted meadows in SEKI was Halstead Meadow. Halstead Meadow is a 21-acre wetland bisected by the Generals Highway. As a result of historical livestock grazing, road construction and maintenance, and water channelization through culverts, that meadow developed severe erosion gullies up to 18 feet deep and 85 feet wide with loss of at least 24,000 cubic yards of sediment. These impacts resulted in a lowered water table, dried wetland soils, and wetland plant dieback.

SEKI is currently restoring Halstead Meadow. The lost sediment was replaced with 8,000 cubic yards of fill above the road in 2007 and 16,000 yards below the road in 2012. That replacement sediment was used to fill the gullies, level the topography, and restore the natural sheet flow. Native wetland plants are being planted. The Federal Lands Highway Administration replaced the filled roadway with a raised bridge that allows sheet flow to pass under the road from the upper to the lower meadow. (Athena Demetry, personal communication, September 2012)

Sediment Loads

Stream Gradients and Delta Fans

When rivers flow west out of the Sierra Nevada onto the valley floor, they lose energy. This causes them to lose their ability to carry sediment, and they usually form fan-shaped deltas. For the bigger rivers, these deltas can be quite large, covering many square miles in area and stretch far out across the valley floor. The Kings River Delta begins about Kingsburg. Visalia sits atop the Kaweah Delta.

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Kaweah Sediment Loads

There is no sediment gage on the Kaweah River, but Lake Kaweah serves essentially the same purpose. On a typical river, most sediment transport work is done by 1– or 2–year flood events. Such small flood events also prime the system for major events sediment-wise. Big floods are spectacular but infrequent.

However, there are indications that the majority of the sediment transport work on the Kaweah River is not done by these relatively small 1– or 2–year events. In Lake Kaweah's first 17 years, it received an average of 474 acre-feet a year of sediment. That high rate was primarily the result of having two big storm events in those 17 years: 1966 and 1969. Significant additional sediment was delivered in subsequent floods, especially in the 1997 flood. There are no data on what sediment transport has been like since 1978.

SEKI's rivers vary quite dramatically in their flow levels. Most of their active erosion and sediment transport takes place in brief moments of high energy flows. The parks' rivers move relatively little material most of the time, then go into high gear for a few hours or days before they settle down again.

Huge sediment bars appear seemingly overnight after a big flood. Where that sediment comes from is not precisely known. No sediment budget has been worked out for SEKI's watersheds. Many of the hillslopes are unstable colluvial debris slopes. Typically landslides dominate sediment budgets in steep mountain watersheds. Whether that is the case in SEKI is unknown.

One of the lessons learned from preparing the document, *Floods and Droughts of the Tulare Lake Basin,* was that the Kaweah River has been relatively quiet of late. It hasn't seen any 20-year or larger floods during the last 40 years. This is just a quiet interlude. The Kaweah is certain to have big floods in its future, and these will bring big sediment loads, similar to what occurred in 1966 and 1969.

The watershed drainage area for Lake Kaweah is about 561 square miles. A rate of 474 acre-feet a year of sediment over that size watershed is equivalent to 1,840 tons/mi^2-yr. A review of the published sediment yields for drainage basins throughout the Sierra Nevada (Andrews 2012) found that those basins vary from less than 10 to more than 430 tons/mi^2-yr. The observed sediment rate on the Kaweah drainage basin (1,840 tons/mi^2-yr) is 4.3 times greater than any of those.

This can be explained in large part because the Kaweah is such a steep river, giving it a lot of energy. But that is only part of the story. Natural sediment yields are affected by a number of factors including precipitation, vegetation, topography, rock type, and soil development. It's instructive to compare the sediment load of the Kaweah River with that of the Merced River in Yosemite National Park. The two drainage basins are relatively undisturbed in the portions that flow through NPS administered lands, and the rivers have similar gradients. However, the sediment loads of these two rivers are dramatically different.

Merced River Sediment Loads

The sediment yield from the Merced River drainage basin above the Happy Isles Bridge is one of the lowest in the Sierra Nevada, only 13 tons/mi^2-yr. That seems surprising enough, but the contrast is even more dramatic when compared to the sediment yield of 1,840 tons/mi^2-yr for the Kaweah River. That is 142 times greater than the sediment load carried by the Merced.

Four explanations have been given for this large difference:

1. There are several sediment traps or sinks upstream of the Happy Isles gaging station in the mainstem basin including Little Yosemite Valley, Merced Lake, and Washburn Lake. Jim Roche, the Yosemite hydrologist, says (personal communication, July 2012) that the Illilouette basin may be the dominant source of sediment for Yosemite Valley given the lack of sediment traps along its length.
2. The gradient on the Merced isn't steady, it is stepped. The Illilouette and mainstem basins both drop about 3,000 feet into Yosemite Valley over a very short distance, so that the upper parts of both basins are relatively low-gradient compared to the Kaweah. The beautiful waterfalls that the Merced is famed for don't contribute much toward erosion. In contrast, the Kaweah has little in the way of big waterfalls; it just keeps on steadily dropping.
3. As calculated above the sediment measurement point, a much higher percent of the Merced basin was glaciated during the Tioga glaciation than in the Kaweah. That glaciation removed much of the readily erodible material.
4. The sediment load on the Kaweah is measured at Lake Kaweah, elevation about 694 feet. The sediment load on the Merced is measured at the Happy Isles gaging station at the head of Yosemite Valley, elevation 4,016. Lower elevation soils are more erodible than higher elevation soils. Compared to the Merced, the various tributaries of the Kaweah have many more miles in which to erode these lower elevation soils. In addition, the geology of the lower elevation of the Kaweah's basin consists of sedimentary or metamorphic rock that is far more erodible than the granite of the Merced basin above the Happy Isles gaging station.

Mass Wasting

Mass wasting (aka mass erosion) is a form of erosion. It is the geomorphic process by which soil and rock move downslope under the force of gravity. Types of mass wasting include creeps, slides, flows, topples, and falls; each with its own characteristic features, and taking place over timescales from seconds to years.

When the gravitational force acting on a slope exceeds its resisting force, slope movement (mass wasting) occurs. The strength of the soil and rock underlying a slope helps maintain the slope's stability. For soil, two components, cohesion and internal friction collectively provide the slope's shear strength. Cohesion is an attractive force between fine particles in the clay and silt size range. Internal friction refers to the friction between adjacent particles. It differs depending on factors such as the range of particle sizes present and how smooth or rough their surfaces may be. A soil with its shear strength derived from both cohesion and internal friction (e.g., many foothill soils) is a cohesive soil. One that only has strength due to internal friction between particles (e.g., high elevation granular soils) is a non-cohesive soil.

Rock strength is derived from the type of rock and any discontinuities in the rock mass. Discontinuities are joints, faults and other fractures along which part of the rock mass may move.

Factors that change the potential of mass wasting include: change in slope angle, weakening of material by weathering, increased water content, changes in vegetation cover, overloading, and ground acceleration due to earthquakes. Next to shear strength, water is the second most important factor in slope stability.

Mass wasting may occur at a very slow rate in areas where vegetation has stabilized the surface (deep-seated landslides). It may also occur at very high speed, such as in landslides or rock slides. This can result in disastrous consequences, both immediate and delayed (e.g., the formation of landslide dams followed by dam failure and flood).

Rock Falls

A rock fall is a fragment of rock (a detached block or series of blocks) that falls along a vertical or near-vertical cliff and proceeds downslope by bouncing, rolling, or sliding. The pieces of rock collect at the bottom of the slope and are collectively known as talus or scree.

In the opinion of Joel Despain, the parks' former geologist (personal communication, July 2012), many of the very large boulders in foothill canyons (e.g., Tunnel Rock and Hospital Rock) are not the result of rock falls. Such boulders probably came down in a massive landslide and were later exposed by erosion.

Little formal research or even documentation has been conducted for the rock falls in SEKI. However, considerable research and documentation has been conducted for the rock falls in Yosemite National Park, especially in Yosemite Valley. Much of the following discussion benefits from what has been learned in Yosemite (National Park Service, n.d.). The lessons learned in Yosemite are particularly applicable to SEKI's vertical-walled canyons. But in the opinion of Joel Despain (personal communication, July 2012), many of the basic processes are also applicable in SEKI's less steep canyons.

Falls are promoted in rocks which are characterized by the presence of vertical cracks. They usually occur at very steep slopes such as a cliff face. The rock material may be loosened by earthquakes, rain, plant-root wedging, or expanding ice, among other things.

A number of geologic processes set the stage for rock fall. Glaciation, weathering, and bedrock fractures all play a role in causing rock fall. Tectonic stresses and erosion cause rock to fracture. Rock falls later occur along those fractures. Fractures that develop parallel to the surface are called sheet joints. Sheet joints create large slabs of rock that ultimately fall away in a process known as exfoliation. Over long periods, water flowing through fractures weathers the bedrock, loosening bonds that hold rocks in place.

Triggering mechanisms such as water, ice, earthquakes, and vegetation create the final forces that cause unstable rocks to fall. Water may seep into fractures in the bedrock and freeze, causing the fractures in the rock to expand. This process is called “frost wedging” or “freeze-thaw” and can incrementally lever loose rocks away from cliff faces. Ground shaking during earthquakes can also trigger rock falls. Additionally, a variety of vegetation — most notably firs, pines, and canyon live oaks — grow into the sheer rock faces where their roots expand and pry apart joints in the rock. There is still uncertainty about exactly what triggers rock fall; less than half of all documented rock falls in Yosemite have been associated with a recognizable trigger.

Many rock falls in Yosemite occur in the winter and early spring, during periods of intense rainfall, snowmelt, and/or subfreezing temperatures, but large rock falls have also occurred during periods of warm, stable weather.

The primary triggering variables that change from year to year seem to be some combination of moisture and temperature. It isn’t clear just what combination of variables results in years of big rock fall. However, the impression of SEKI’s trail foremen is that those conditions are parkwide. It seems like there are light years for rock fall and very big years for rock fall, but not much in between. Whether that is really the case or not is uncertain. Without documentation, it is hard to draw any reliable conclusions. Storms are important in triggering rock falls, so years with more storm activity should theoretically generate more rock falls.

The rock falls above timberline are little noticed, as there boulders are falling onto existing boulder fields. The boulder fields are constantly moving and changing terrain, but do not change much in appearance. (David Karplus, personal communication, July 2011)

According to Tyler Johnson and David Karplus, SEKI’s trail foremen (personal communication, July 2012), there are many chutes that cross trails which dump tons of debris onto the trails essentially every year. Most of that activity is believed to occur during snowmelt. Examples are the chute just below Mist Falls, the top of the Bubbs switchbacks, down-canyon of Grouse Meadow, between Middle and Upper Paradise, Hamilton Gorge, and Angel Wing Gorge below Hamilton Falls.

We tend to think of rock falls as discrete events, but they can be fairly continuous. An example of a somewhat continuous rock fall is the Black Kaweah in the high country of SEKI. Corie Cann, one of the parks' biological science technicians, reports (personal communication, July 2012) that there the freeze-thaw cycle seems to work on the schist to make the falls virtually continuous, especially at night.

Table 2 lists some of the recent rock falls on SEKI's roads that have required blasting to remove. SEKI does not have a rock fall documentation system. Therefore, when such rock falls occur, they are not routinely documented nor do they make it into the parks' records management system. Instead, they are managed as individual incidents rather than as part of a hazard management program. That makes it difficult for the park to know when or how often such rock falls occur.

Table 2. Selected recent rock falls on roads in SEKI.

Location	Date	Size (cubic feet)
Generals Highway between Wuksachi and Red Fir	2/21/1995	4
Generals Highway at Granite Springs	11/13/1998	50
Generals Highway below Big Fern Springs	11/19/2002	6.5
Generals Highway about a mile below Tunnel Rock	1/28/2005	18
Oriole Lake Road just above Squirrel Creek	2/9/2006	30–35
Generals Highway just north of the Red Fir gate	3/8/2007	3 large rocks
Generals Highway near the Ash Mountain entrance	3/2011	1.5

We notice individual big rocks more when they come down in the frontcountry. For example, the rock that fell on the Generals Highway in 2005 was big enough to block the entire road all by itself.

Figure 1. Rock fall about a mile below Tunnel Rock, January 28 2005.

Rock falls can be high energy events. The most spectacular one in recent years occurred in 1998. In that event, a rock broke loose from a point near Hanging Rock on the west slope of Moro Rock. After a very long roll, it landed on the Generals Highway at Granite Springs. Despite its massive weight (about 110 tons), it was moving so fast that it became airborne; it last touched the ground more than a hundred feet before it landed on the highway. When it struck the road, the force of the impact drove the rock some six feet into the roadbed and melted the pavement for several inches out from the rock.

Rocks fall off of cliffs a lot. These are primarily noticed when they come to rest in on or near a road, trail, or development. For example, in 1986 some very big rocks landed near the Bailey Bridge two miles from Roads End.

Rock falls can also make their presence known by the scar that they leave behind. The scar from the 1998 Granite Springs rock fall event described above is particularly visible; it can be seen from Visalia. A lesser known rock fall occurred on the Sierra National Forest in the winter of 2006–07. In that event, some large flakes fell off a marble cliff, leaving a prominent white scar high on the wall of Kings Canyon. That scar can be seen as you drive down Highway 180 into Kings Canyon.

According to SEKI's fatality database, no park visitors or employees have been killed by rock falls. The park does not track rock fall near-misses, but there have probably been several. Two that we are aware of occurred on the section of Highway 180 leading down into Kings Canyon:

- In the summer of 1979, a visitor had a rock roughly 6 inches in diameter strike the hood of his car while he was driving in the vicinity of the half bridge.
- A SEKI employee had a very close call when a boulder fell in the bed of his government truck when he was driving somewhere along the cliff section.

Landslides

A landslide is the movement of a mass of rock, debris, and/or soil down a slope. This includes rock slides and debris flows.

Solid landslide debris can add volume and density to otherwise normal streamflow or cause channel blockages (aka landslide dams) and diversions, creating flood conditions or localized erosion. When a large landslide dam fails rapidly, it can result in downstream flooding. See the section below that discusses Landslide Dams. Landslides can also cause overtopping of reservoirs and/or reduced capacity of reservoirs to store water. These can be features of debris flows as well.

Rock Slides

A rock slide is a type of landslide caused by rock failure in which part of the plane of failure passes through intact rock and where material moves *en masse* as opposed to in individual blocks. A well-known example is the massive Ferguson Rock Slide in the Merced River Canyon that buried Highway 140 near Yosemite in 2006. There the highway had to be relocated to the other side of the river to bypass the slide. There was fear that the slide would create a landslide dam (Harp et al. 2008).

Rock slides are relatively rare events in and near SEKI; we know of only two rock slides in historic times. The Mammoth Lakes Earthquake occurred on May 25, 1980. A particularly strong aftershock occurred at 7:50 a.m. on May 27, the first workday after the Memorial Day Weekend. It struck as SEKI's forestry crew was driving down into Kings Canyon, in the general vicinity of Horseshoe Bend. It caused a moderately large rock slide to peel off the cliff just as the crew approached. The driver of the lead pickup tried to take evasive action, but there is little room to maneuver on that narrow cliff-side. Approximately one cubic yard of rock landed in the bed of his pickup, pushing the vehicle to the very edge of the cliff. This is one of only two near-misses with a rock slide or rock fall to occur with a park employee. Refer to the section above on Rock Falls for a brief description of the other such incident.

Figure 2. Cliff-side road in Kings Canyon.

The second rock slide to be recorded in SEKI also occurred about 1980 and may have been caused by this same earthquake. It occurred on the cliffs near Cliff Creek and the Timber Gap Trail. That event generated so much dust that it was originally mistaken for a wildfire.

The discussion in the following sections is about landslides that involve a large soil component rather than those that involve intact rock and generate rock slides.

Causes of Landslides

Landslides, debris flows, and floods are closely allied because all are related to precipitation, runoff, and the saturation of ground by water.

Slope saturation by water is a primary cause of landslides (U.S. Geological Survey, n.d.). This effect can occur in the form of intense rainfall, snowmelt, changes in groundwater levels, or water level changes along the banks of lakes, reservoirs, and rivers.

Small landslides are relatively common where hillslopes are undercut by roads, trails, and similar developments. Elsewhere, landslides are relatively rare in the Southern Sierra Nevada; both rock falls and debris flows are much more frequent than landslides.

Landslide Dams

Landslides can form dams that block stream channels. In the Sierra Nevada, such natural dams are occasionally formed by large-scale debris flows and rock slides. Landslide dams are localized events and therefore often go unrecorded. Some of the ones that we know of occurred in 1861–62, 1867, 1983, and 2002. When the landslide dams and the blocked streams are both small (such as in the 1983 and 2002 floods) there is relatively little damage. But when a large dam blocks a large river and then fails rapidly, downstream flooding can be highly destructive.

The largest historic dam failures in the Southern Sierra Nevada that we know of occurred during a nine-day period in December 1867 and resulted in spectacular floods on several widely separated rivers. Large dam failures that may have occurred prehistorically are the Little Kern Lake dam and the series of slides on the west slope of Moro Rock. One enormous slide on the north side of Dennison Peak put boulders into the North Fork of the Tule River that averaged up to roughly 50 feet on a side. The local canyons of the Kaweah show geologic evidence of dozens of massive landslides. Some of those undoubtedly produced severe flooding downstream similar to what occurred in December 1867 (Moore 2000).

The 1861–62 flood was a huge flood in the Tulare Lake Basin. The force of the flood was so great that all four of our major rivers (Kings, Kaweah, Tule, and Kern) relocated and cut new channels. The USGS predicts that a flood as big as the 1861–62 flood could return in the foreseeable future (U.S. Geological Survey 2011).

The Tulare Lake Basin experienced a flood even bigger than the 1861–62 flood just six years later: the 1867–68 flood. It was a bigger flood on all four of our major rivers (U.S. Army Corps of Engineers 1999). In addition to being a major flood, the storm that brought on that flood was a deep soaking rain that lasted for approximately six weeks. Hillslopes in the middle elevations of the Sierra Nevada are typically quite steep. Some are weathered in place, but many consist of unconsolidated colluvial debris slopes. When these hillslopes are soaked to depth, huge landslides can be triggered.

In a short intense event like the December 2010 storm, SEKI experiences many relatively small landslides and debris flows. But in an extended event like the 1867–68 storm, the mid-elevation zone can experience cataclysmic landslides. In the past, some of those have formed landslide dams across our major rivers that were up to 400 feet high. When dams such as those fail, the results downstream can be catastrophic. For example, the residents of Bakersfield woke on New Year's Day 1868 to a 200-foot-high flood coming out of the Kern Canyon.

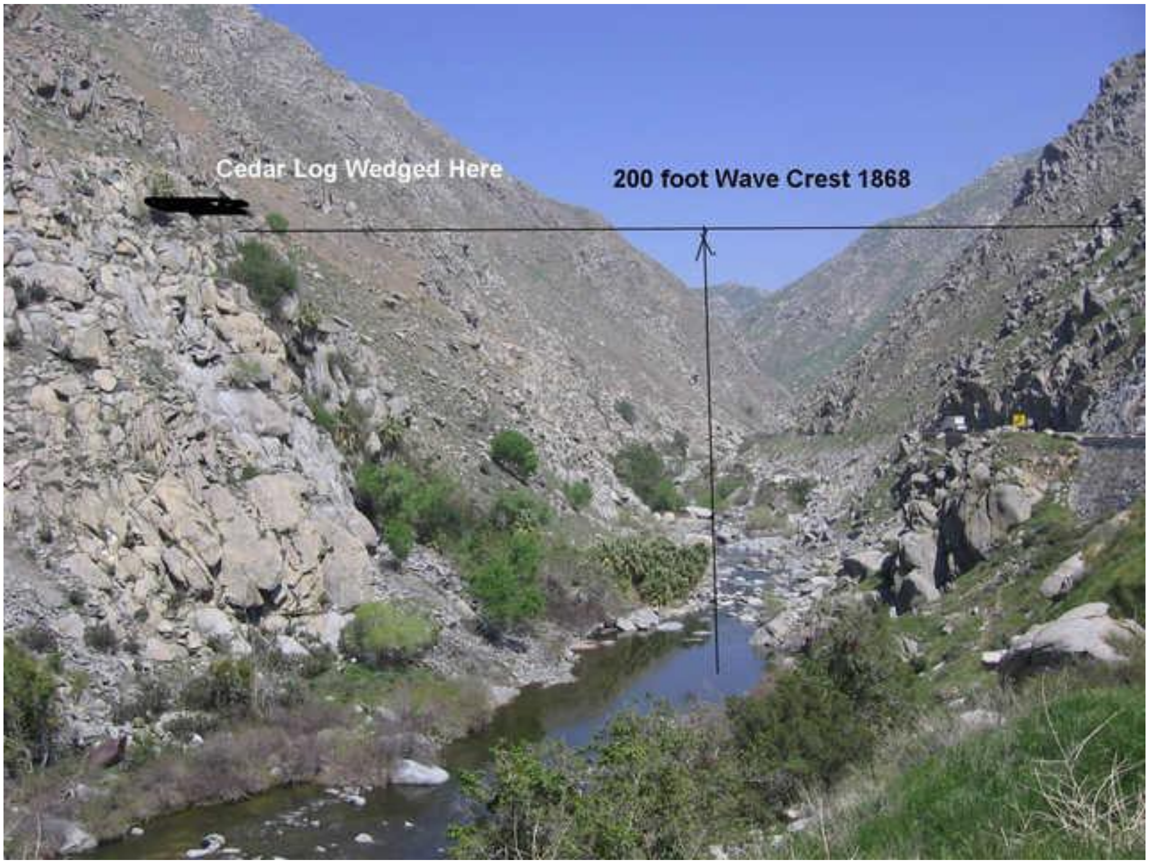

Figure 3. Height of wave crest at Bakersfield after landslide dam failed, New Year's Day, 1868.

We have a partial record of the landslides that occurred during the 1867–68 storm. We have a sense of what areas are at risk for landslides and landslide dams.

In the 1867–68 storm, the landslide dams on the Kaweah and Kern held the flooding rivers back long enough for the residents downstream to react and get out of the floodplain. In contrast, the dams on the San Joaquin River and Mill Flat Creek presented a less clear signal downstream, partly because those events happened at night.

The residents of Old Kernville and Weldon had about 24-hours' notice because the Kern River stopped running. They were able to evacuate their towns before the returning river submerged them under about 50 feet of water. The residents of Millerton, the county seat of Fresno at the time, weren't aware of what was happening. The disintegrating remnants of one or more landslide dams hit their town just before midnight on Christmas Eve 1867, destroying it. That’s why Fresno is now the county seat of Fresno County.

Debris Flows

General

A debris flow is a type of landslide. It is a moving mass of loose soil, rock, debris, and water that travels down a slope under the influence of gravity. It can carry material ranging in size from clay to exceptionally large boulders, and may contain a large amount of woody debris such as logs. A debris flow is differentiated from a mudflow by having at least 50% of the material being sand-size particles or larger. To the best of the parks’ knowledge, SEKI has never experienced a mudflow.

Debris flows are among the most numerous and dangerous types of landslides in the world. They are particularly dangerous to life and property because of their high speeds and the sheer destructive force of their flow. These flows are capable of destroying buildings, washing out roads and bridges, sweeping away vehicles, knocking down trees, and obstructing streams and roadways with thick deposits of sand and rocks. They are the most erosive type of landslide and are notable because they can bulk by thousands of percent in volume. Debris flows are much more common in the Southern Sierra Nevada than other types of landslides. They have caused considerable property damage in our area. Although there have been many near-misses, there have apparently not been any fatalities from these events in the Southern Sierra Nevada. That is partly a matter of luck; that has not been the experience elsewhere.

Debris flows are a particular problem in steep mountainous areas subject to intense rainstorms. They are typically associated with periods of heavy rainfall or rapid snowmelt and tend to worsen the effects of flooding that often accompany these events. However, prolonged rainfall is not necessary to trigger large-scale debris flows. The two largest debris flows ever recorded in the Sierra Nevada (the July 12, 2008 Oak Creek and Erskine Creek Debris Flows) resulted from brief, intense, summer thunderstorms (DeGraff 1994).

There appear to be two categories of debris flows. The first category consists of relatively small debris flows that run a few hundred yards or so. This category occurs in both the frontcountry and backcountry of SEKI. These usually do little scouring. SEKI experiences many of these. This category receives scant attention in the literature. However, this is the category of debris flow that causes the most economic damage to SEKI’s infrastructure. That is because this category of debris flow is so common and because the road and trail infrastructure is often built on colluvial debris slopes or at the bottom of hillslopes.

When these small-scale debris flows occur in SEKI, they are not routinely documented, nor do they make it into the parks’ records management system. That makes it difficult for the park to know how often they occur. Austin (2012) documents some of the most significant of these debris flows. For example, the Generals Highway, Mineral King Road, Crystal Cave Road, and the Shepherd’s Saddle Road all sustained significant damage from debris flows during a November 8, 2002 storm event. Combined damage from flows on that day required 1.49 million dollars to repair, the most property damage that SEKI has ever sustained from a debris flow event.

The second category is large-scale debris flows. Because of geography, this category of debris flow typically begins in the backcountry. However, if there is enough water, such flows will continue into the frontcountry. An example is the July 14, 2008 Lewis Creek Debris Flow that had a total length of about 11 miles and an elevational drop of 6,100 feet. Debris flows in this category often scour down to bedrock and can pull out old-growth trees.

When this category of debris flows occurs in SEKI, they are not routinely documented nor do they make it into the parks' records management system. That makes it difficult to know how often such debris flows occur. Austin (2012) documents some of the largest such debris flows. Large-scale debris flows in the Sierra Nevada have an average peak velocity of 12.4 mph (DeGraff 1994). Debris flows in this category have the greatest potential for causing property damage and deaths, but so far SEKI has been very lucky. The largest property damage sustained so far in the parks was $80,000 in the July 2008 Lewis Creek Debris Flow. Large-scale debris flows have the potential to kill employees, visitors, and others because they can catch them before they have time to react and get out of the way. They have caused no deaths to date in the parks, although one park employee almost died when he was caught up in one of these debris flows on May 27, 1983.

Based on the experience of Tyler Johnson and David Karplus, SEKI's trail foremen (personal communications, July 2012), it appears that large-scale debris flows may occur roughly twice as often in the Kings Canyon portion of the wilderness as in the Sequoia portion. That might reflect that the spring storm track more often moves east or northeast across the San Joaquin Valley, aimed more at Kings Canyon northward. It might also be that the difference is caused by a possible relationship between precipitation and the elevation that the debris flows occur. It seems like the heaviest precipitation in the Kaweah and Kern drainages most frequently occurs at the highest elevation where there isn't any soil to cause a debris flow. While precipitation in the Kings drainage is also a high elevation event, it seems that it occurs more frequently at lower elevations (that is, further west) as well.

The July 2008 Lewis Creek Debris Flow is the largest and most recent that we are aware of on the Kings Canyon side of SEKI. The October 2009 Hamilton Gorge debris flow is the most recent on the Sequoia side of the parks (Austin 2012).

To the best of the parks' knowledge, no formal research has been conducted on the debris flows that have occurred in SEKI. However, considerable documentation and research has been conducted for the large-scale debris flows that occur in the national forests that surround SEKI. Much of the following discussion benefits from what has been learned on those national forests.

We are aware of only a dozen or so examples of these large-scale debris flows occurring within SEKI in the last 30 years. There are a number of additional examples from the nearby national forests. Some of those have been very large with a length and drop equal to that of the July 2008 Lewis Creek Debris Flow (Austin 2012).

In addition to being dangerous, large-scale debris flows have the potential to significantly alter hydrological conditions. They can add volume and density to the pre-existing streamflow and cause channel blockages and diversions, creating flood conditions or localized erosion. Since debris flows in the

Sierra Nevada can be up to two million cubic yards in size, they can result in stream channel morphology changes that last for years. Such changes occurred in both the May 1983 Lewis Creek Debris Flow and in the July 2008 Lewis Creek Debris Flow.

Large-scale debris flows can also reduce the capacity of reservoirs to store water. This is best illustrated by the January 1, 1997 Sourgrass Debris Flow on the Stanislaus National Forest (DeGraff 2001).

Large-scale debris flows usually occur in small, steep stream channels and are often mistaken for floods. In fact, debris flows and flash floods often occur simultaneously in the same area.

Debris flows typically start on a hillslope and then flow down into a drainage. Once they reach that drainage, they turn and follow it downslope. Large-scale debris flows often start fairly high up on a hillslope. They characteristically bulk up, gaining up to at least 100 cubic feet of volume for every foot of movement downstream (Santi 2008).

Causes of Debris Flows

Except as noted otherwise, this section is based largely on consultation with Jerry DeGraff (personal communications 2012).

Small-scale and large-scale debris flows have similar triggers. Water is the most critical factor. The soil has to be saturated to initiate a debris flow. But unlike a large landslide, debris flows do not require a prolonged period of heavy rain to reach this condition.

Higher elevation soils in SEKI are generally granular and non-cohesive. Such soils depend on grain-to-grain friction for soil strength. Rapid rainfall can exceed the infiltration capacity of these soils (i.e., the ability of the soil to pass the water downward in the soil profile.) This usually results in a temporary perched water table above a point where the infiltration capacity deep in the soil slows the rate. The soil is essentially saturated above this point.

This results in water filling the pore spaces of the soil and reducing the contact between individual grains. The decreased frictional contact temporarily reduces soil strength at which point the soil mass can begin to move downslope as a flowing mass. Debris flows in the Sierra Nevada are initiated when these conditions arise from intense rainfall, rain-on-snow events, or rapid snowmelt (DeGraff 1994). A large debris flow can be triggered in as little as one hour from the onset of an intense rainfall event. On occasion, a debris flow can even be triggered by ground water movement (DeGraff 1994).

Debris flows start on moderately steep or steeper slopes. Once started, however, a debris flow can travel over even gently sloping ground. Debris flows in the Sierra Nevada have been observed starting on slopes as low as 30%. Steeper slopes are more prone to debris flows; and the more dangerous, faster moving flows are more likely to develop on steeper slopes. Many debris flows start on slopes of 40% or more. The type of bedrock and the thickness of the soil that has weathered from it mean that the optimum slope steepness for debris flow occurrence will vary. On very steep slopes, soil thickness tends to be so thin that debris flows are less likely to occur (Campbell 1975). Few debris flows in the Sierra Nevada seem to start on slopes steeper than 65% (DeGraff 1994).

Debris flows typically start in an area that is sparsely vegetated (e.g., brushy, alpine, burned). But if there is enough water present (as in the July 5, 1983 Calvin Crest Debris Flow), the ground can still become unstable and flow (DeGraff 1994).

Large-scale debris flows in the Sierra Nevada are initiated primarily in one of three ways:

1. The majority are landslide-initiated debris flows. The initial failure is on a discreet surface with movement as a debris slide with a very rapid transformation into a debris flow, often into a nearby channel. The January 1, 1997 Sourgrass Debris Flow is a good example.
2. Many are initiated by intense summer thunderstorms on bare ground. This can apparently occur on burned areas, although no examples of this are known from the Tulare Lake Basin. Many others have been triggered by storms on generally bare granular soils in the higher elevations of the Sierra Nevada. The July 14, 2008 Lewis Creek Debris Flow is an example of this type of debris flow.
3. Intense storms mobilizing sediments that have accumulated in stream channels following fires. This is the most common form of debris flows following fires.

Fire as a Trigger of Debris Flows

Except as noted otherwise, this section is based largely on consultation with Jerry DeGraff and Jon Keeley (personal communications 2012).

Because of their roots, trees and shrubs increase the ability of soil to resist debris flow occurrence through the mechanical strengthening of the soil. Shallow landslides and similar debris flows increase when trees are killed and sufficient time has passed for roots to decay without revegetation.

Areas that have recently burned are vulnerable to debris flows. But this is commonly due to sediment laden water eroding material stored in stream channels rather than from erosion occurring on the slopes themselves. Channel erosion and scour are the dominant sources of debris in burned areas. Side channels are much more important sources of debris than hillslope rilling. Rills contribute an average of only 3% of the total debris in a postfire debris flow (Santi et al. 2008).

The sediment in the stream channels will typically have accumulated from dry ravel if there has been sufficient time since the fire. If the storm comes shortly after the fire, that same debris may wash off the hillslope without resulting in significant rilling.

Although recently burned areas are vulnerable to debris flows, there are few examples of this occurring in the Tulare Lake Basin. Based on reports from the time, the July 16, 1984 Goat Ranch Canyon and Long Canyon Debris Flow apparently falls in this category (California State University San Bernardino, n.d.).

That debris flow was initiated by a high-intensity storm that occurred just one week after ignition of a large wildfire. In that case, the fire created a large amount of debris that the storm then washed down the canyons. Fire was apparently a principal factor in this debris flow. However, this seems to be the exception in the Tulare Lake Basin.

Whenever a debris flow occurs after a fire, there is a tendency to assume that the debris flow was caused primarily by the fire. That is, to assume the fire was necessary to create the conditions for the debris flow to occur. Examples of debris flows in and near SEKI that were initially attributed to a fire include:

- May 27, 1983 Lewis Creek Debris Flow (Austin 2012)
- July 12, 2008 Erskine Creek Debris Flow (DeGraff et al. 2011)
- July 14, 2008 Lewis Creek Debris Flow (Austin 2012)
- July 30, 2011 Canyon View Debris Flow (Austin 2012)

In each of the above examples, the primary trigger was an intense cloudburst. Investigation showed that the presence of an active fire or a fire that had occurred at some previous time was incidental to the debris flow. In none of the above four situations had fire been a principal factor in the debris flow. The fires that were associated with these debris flows had contributed little to creating the conditions necessary for the debris flow. Other than the 1984 Goat Ranch Canyon and Long Canyon Debris Flow, there are very few examples in the Tulare Lake Basin where fire has clearly been a principal factor in the creation of a debris flow.

Debris Flow Hazard Areas

One way to predict major debris flow hazard areas is to identify where they have occurred in the past. In the Tulare Lake Basin, areas of moderate debris flow susceptibility appear to exist in the Lewis Creek Watershed, on the west slope of Black Rock Pass, and in the Kern Canyon area south of Lake Isabella. If we had a better record of past debris flows, we could probably identify more such areas in SEKI and elsewhere in the Tulare Lake Basin. However, most large-scale debris flows in the Southern Sierra Nevada appear to occur in areas that haven’t experienced a debris flow in a very long time; they have a long recurrence interval.

In a powerful cloudburst, multiple debris flows that start high in canyons commonly funnel into channels. There they merge, gain volume, and travel long distances from their sources. That was the case with the July 2008 Lewis Creek, Oak Creek, and Erskine Creek Debris Flows (Austin 2012).

The most hazardous areas for debris flows are canyon bottoms, areas near the outlets of canyons, and slopes excavated for buildings. In the Sierra Nevada foothill and montane zones, those are the areas where roads, campgrounds, houses, and administrative areas are typically built.

In the opinion of Sean Foley, SEKI’s former water systems supervisor (personal communication September 2011), all six of the parks’ surface water collection systems are considered potentially vulnerable to debris flows. The three systems considered most at risk are Sheep Creek, Wolverton, and Lodgepole. A maintenance employee was caught and almost killed at the Lewis Creek surface water collection system by the May 27, 1983 Lewis Creek Debris Flow. That water collection system has since been replaced by the Sheep Creek system.

Because many of SEKI’s roads are built on — and often cut into — colluvial debris slopes, they are particularly susceptible to small landslides and small-scale debris flows. The resulting slides and debris flows not only block the roadway itself, they tend to clog the drainage systems. Because the roads contribute to destabilizing the slope, small landslides and small-scale debris flows often occur during milder rainfall conditions than those needed for debris flows on natural slopes. This is just one example of how roads result in anthropogenically driven mass wasting. Areas where surface runoff is channeled, such as along roadways and below culverts, are common sites of small landslides and small-scale debris flows.

Generals Highway and Colony Mill Road

One of the challenges faced by SEKI is the building and maintaining of roads across colluvial debris slopes. The most extreme case is the section of the Generals Highway on the hill (i.e., the debris slope) between Hospital Rock and Giant Forest. That section of road opened in 1925. It gradually replaced the Colony Mill Road which was also built on an unstable slope.

In subsequent years, that section of road has experienced:

- Frequent rock falls involving rocks of all size, including single rocks capable of closing the highway all by themselves.
- Debris flows that routinely overwhelm the highway's drainage system. The problem is particularly challenging when a very intense rain occurs. Because these hillslopes are colluvial debris slopes, the drainage channels are easy to mobilize. SEKI has upsized some of the culverts in response to past flooding and debris flow events such as those of November 2002. However, this only reduces the frequency of culverts being plugged. It is considered infeasible to build culverts large enough to handle the runoff generated by intense storms with all the associated debris. There is only so much space under the roadbed to install a big culvert, the geometry of the debris contributes to plugging, plus larger culverts and bridges cost more to build.
- Hundreds of landslides of various sizes. Some of these have undermined the highway and swept the roadbed away. Others have buried the highway under as much as several thousand cubic yards of debris. Austin (2012) documents major landslide damage to the highways that occurred in November 1924, February 1937, 1943, November 1950, January 1952, December 1955, 1958 or 1959, and December 1966.

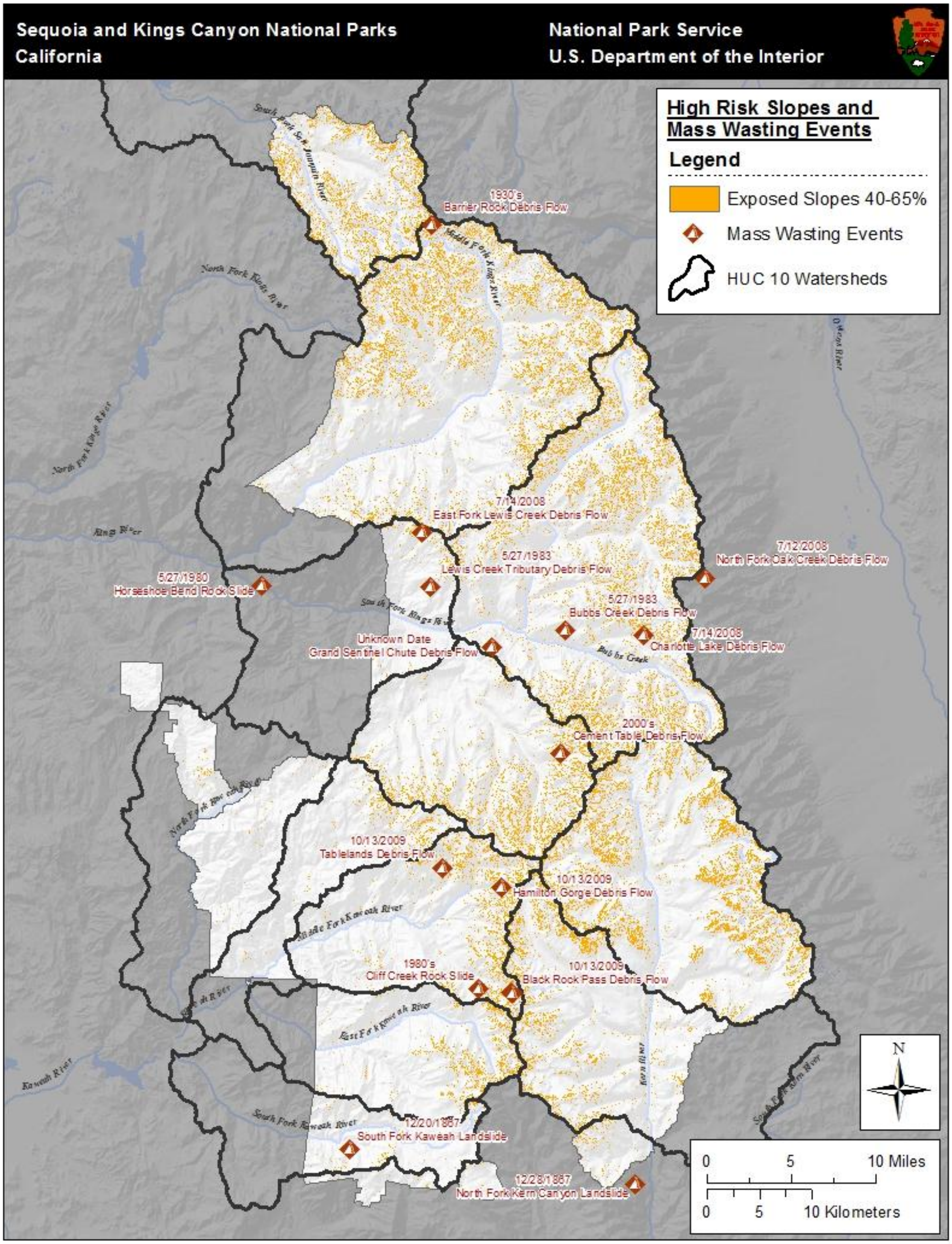

Figure 4. Map of areas most at risk for large landslides and large-scale debris flows (see the text for an explanation of how to interpret this map).

Map of High Risk Slopes and Mass Wasting Events

Figure 4 illustrates, to the extent data allow, where large landslides and large-scale debris flows are more likely to initiate. For details on what triggers these events, see the sections of this report that address Landslides and Debris Flows.

In general, the map illustrates the zone where slopes are between 40% and 65% and the land is sparsely vegetated (aka exposed). Most, but not all large landslides and large-scale debris flows start within this zone. Once started, landslides and debris flows can travel over even gently sloping ground. Such mass wasting events can be thought of as having two zones: a narrow zone high up on the hillslope where they initiate, and a broader zone lower down where the event plays out.

The map also shows 15 or so known large landslides and large-scale debris flows in and near SEKI as examples. Many more such events have surely occurred during historic times, but these are the only ones that have been documented.

Suggestions for Management Consideration

The suggestions expressed in this section are generally those of federal agency geologists and geomorphologists. They are not from the published literature and have not been peer-reviewed.

Assessment of Erosion

Erosion is a major process in SEKI that affects both natural processes and infrastructure. Based on available data, the observed sediment rate in the Kaweah drainage basin appears to be more than four times greater than has been reported for any drainage basin in the Sierra Nevada. It also appears that the majority of this sediment is transported in major flood events rather than during small flooding events as would generally be expected. Preparing a sediment budget for the Kaweah drainage basin would provide a much better understanding of what is going on with erosion in SEKI. Such an analysis might be prepared cooperatively with the Army Corps of Engineers since sedimentation significantly affects the operation of Lake Kaweah.

Risk Mitigation

Assessment of risk is a complex and difficult analysis. Even when probability and magnitude are known values, combining them to calculate risk is not straightforward, let alone how much risk management is willing to assume — which is a policy/values issue, not a technical one. Some of the mass wasting events discussed in this report pose a significant risk to infrastructure, employees, or the public. The following sections discuss actions that managers could consider taking to mitigate those risks.

Rock Falls

Rock falls such as the examples cited in Table 2 could be viewed as near-misses. SEKI could establish a rock fall documentation system and manage rock falls as part of a hazard management program rather than as individual incidents. SEKI could use its records management system to track rock falls so that it has a sense of when they occur and under what conditions. In establishing such a program, SEKI could review the lessons learned from Yosemite’s rock fall documentation system.

Landslides and Landslide Dams

As illustrated by Figure 4 and the text explanations, much of SEKI is susceptible to very infrequent large landslides, primarily in the wilderness. A few of these have the potential to result in large landslide dams and catastrophic dam failures. This is a relatively low-probability risk that might be addressed in consultation with downstream risk-management agencies.

Debris Flows

As illustrated by Figure 4 and the text explanations, much of SEKI is susceptible to large-scale debris flows. SEKI could use its records management system to track large-scale debris flows so that it has a sense of when these events occur and under what conditions. These events are much more frequent than large landslides and generally travel much greater distances. They have the potential to cause significant damage to frontcountry infrastructure and place lives at risk. This is probably the most dangerous and most expensive mass wasting process in the parks. Evaluation of this risk requires an on-site review by a subject matter expert. The park probably has less than a dozen high risk targets that merit such an on-site review.

Mass Wasting Spatial Model

Figure 4 provides only a general idea of the areas of the park that are at risk from mass wasting events. A mass wasting spatial model could be constructed to provide management with much more accurate information. Identifying high risk areas would require the assemblage and analysis of the following spatial layers: slope, watershed boundaries, vegetation, land use, and rainfall isohyets; all of which currently exist for the park. These would be analyzed in combination with geology and the derived products of weathering rate and structure; soils and the derived information of permeability and porosity, soil depth, stability and texture; and hydrologic drainage grid, none of which currently exist for the entire park.

The characteristics of each spatial layer would be weighted based on its individual attributes as well as the overall contribution towards its potential for mass wasting. Once appropriately weighted the spatial layers would be combined to produce an overall score as to an area’s potential to experience a mass wasting event. Ideally, this information would be compared to information collected on known and future mass wasting events to further refine the model.

Disclaimer

All conclusions made in this document are from the author’s perspective only and not necessarily representative of the NPS.

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