PARKS STEWARDSHIP FORUM
ADVANCES IN RESEARCH AND MANAGEMENT

Science and the evolving management of environmental hazards at Yosemite National Park

Jeffrey Jenkins, University of California, Merced

Department of Management of Complex Systems
University of California, Merced
Social Sciences and Management Building, 5400 N. Lake Rd.
Merced, CA 95340
jjenkins8@ucmerced.edu

Received for peer review 3 February 2022; revised 28 April 2022; accepted 11 May 2022; published 15 September 2022

Conflict of interest and funding declarations. The author declares no conflict of interest. This research did not rely on a funding source.

ABSTRACT

US national park managers must address a complex portfolio of foreseen and unforeseen challenges that arise in part from a dual mandate to preserve nature and facilitate visitation. To deal with resource management challenges, managers can identify potential pathways toward a solution through the use of science to inform policy and guide actions. The way science has been applied has evolved over the course of the National Park Service's history, in large part due to the prevailing societal context and ways of thinking about the environment, and relatedly as a necessity to mitigate the impact from development and anthropogenic climate change. Landscape-scale environmental hazards are a fitting proxy to recount the changing use of science and policy because biophysical processes become most hazardous at the interface of infrastructure and the natural environment, where people are most exposed. This paper synthesizes modern administrative and environmental histories of hazards in Yosemite National Park from the late 19th century to the early 21st century through archival records and long-term data, including significant events and trends in wildland fire, tree mortality (falls), extreme floods, and rockfalls and slides. Findings confirm increased severity and extent of wildland fire, correlations between periods of drought and high rates of tree mortality, warmer precipitation events lead to earlier annual peak streamflow, and connections between periods of prolonged cold with rockfalls, and prolonged precipitation with slides. These hazards exist as an interconnected system in the context of high seasonal visitation, and while there are averages of seasonal conditions over time, there are no "normal" years.

INTRODUCTION

This study is focused on landscape-scale environmental processes that have been exacerbated by climate change, past management regimes, and patterns of commercial development. Environmental hazards, including wildland fire, fall hazards from tree mortality, extreme flood events, and rockfalls and slides, can pose hazardous conditions for human life and property. The hazards analyzed here for Yosemite National Park (hereafter YOSE) aren't entirely natural, but rather created by humans: we have literally put ourselves in the position to be displaced as the result of past tourism promotion, engineering decisions, and management directives that have funneled visitation through corridors and to certain areas to access scenic vistas and other attractions.

To be clear, these environmental processes are natural biophysical phenomena but only become hazards when people and park resources are exposed to the potential risks. For hazards in national parks, consideration must be given to the different ways in which visitors may be exposed in terms of physical proximity to a potential hazard, as well as factors such as visitors' different cultural understandings of risk, communication barriers, and how risks may vary by time of year and severity (Adger 2006; Youngs 2020). Exposure to environmental hazards can be mitigated with adaptive management actions (e.g., prescribed burns, updates to infrastructure and relocation of facilities, seasonal use restrictions) that recognize the underlying drivers of risk through a double exposure to climatic and development vulnerabilities, and as spatial and structural processes over time (Iglesias et al. 2022). The "hazardscape," as it might be termed, has been produced through patterns of human settlement around utilitarian resources and scenic amenities and past forest management practices, both greatly magnified by climatic change.

Environmental hazards thus exist at the intersection of social, economic, and technical systems that have grown more interdependent over time, and these interdependencies can increase the impact of hazards through cascading effects (Yabe et al. 2022). For instance, a wildland fire may have more high-severity patches when standing dead trees are present, and the high rate of tree mortality is due to both drought-induced tree stress and the density of trees from historic suppression efforts, which have together led to increased bark beetle infestations and tree disease across the landscape. And there is greater potential for a landslide to be hazardous when it occurs near a road, especially when a heavy rain occurs after a recent fire leading to the potential for fallen tree snags and other debris to flow down a recently burned slope that is now more prone to runoff. Similarly, flood hazards are a product of siting buildings and roads near a river, subsequent channelization and bridge construction, and warmer-than-average rainfall's contribution to the rapid melt of nearby alpine snowpack.

In this study, hazard events and management actions are investigated through archival records, including annual park superintendent reports and historical data (National Park Service 2017), along with long-term environmental monitoring data, and a variety of public National Park Service (NPS) information and news sources. Owing to YOSE's long-standing protected area status, which has facilitated scientific inquiry and collection of long-term data, the park's archives are rich in historical data sources that have enabled novel longitudinal analysis of different management topics. These sources include: maps, to understand reductions in spatial extent and downgrading of protected area status (Kroner et al. 2016); photographic pairings, to reveal changes in forest composition and treeline (Vale 1987); and a survey of images and paintings, to document river channel conditions (Madej et al. 1994). Accompanying environmental monitoring data from YOSE from the early 1900s to the present, including snowpack, drought, peak streamflow, and rockfall and slide information, show hazard occurrence in the context of changing environmental processes and institutional approaches over time.

In the next section, background on the emergence and changing climatic conditions of environmental hazards is given as it relates to infrastructure in and visitation to YOSE. This is followed by a narrative results and discussion section that details the history of environmental hazards in YOSE through different eras of park management wherein scientific thought and data collection of hazards occurrence are contextualized through the prevailing social, economic, and technical conditions of American society. Per the NPS systemwide accounts of Sellars (2008), Dilsaver (2016), and others, this analysis of YOSE groups park management into successive eras that reflect common themes and evolving societal paradigms at the intersection of science and policy: early park management and commercialization (1890–1915); the Organic Act and agency priorities (1916–1932); the infrastructure workforce and control of nature (1933–1961); high visitation and the beginnings of the use of science to inform management (1962–1986); and environmental and political–legal complexity (1987–present). Taken together, the interdependencies between social, economic, and technical realities constitute a system, one which is variously trending toward more vulnerable or resilient outcomes, and dependent on the use of science to inform management actions and policies that respond and adapt to changing conditions.

BACKGROUND

High levels of visitation to YOSE are historically correlated with the period of April through October, with the summer months incurring the most use. The average total amount of visitation has increased from decade to decade (Jenkins et al. 2021). Snowfall, low temperatures, and the possibility of automobile tire chain requirements, icy conditions, and road closures are factors that contribute to decreased use in the winter season. With climate change extending the flood season from spring to warmer winters, the fire season from summer to nearly the year round, and the incidence of treefalls and rockfalls throughout the year, visitors are now exposed to risks from environmental hazards the and potential for parkwide closures at any month of the year (Figure 1). While there once was a reliable season for risk of high-severity wildland fire that overlapped with the height of visitation across the summer and fall months, it is effectively gone. Now that risk occurs nearly year round, especially as drought conditions persist and snowpack levels decline (Lutz et al. 2009). Floods typically occurred as part of the springtime runoff; now, annual peak streamflow levels are increasingly happening earlier in the water year as warmer temperatures contribute to precipitation in

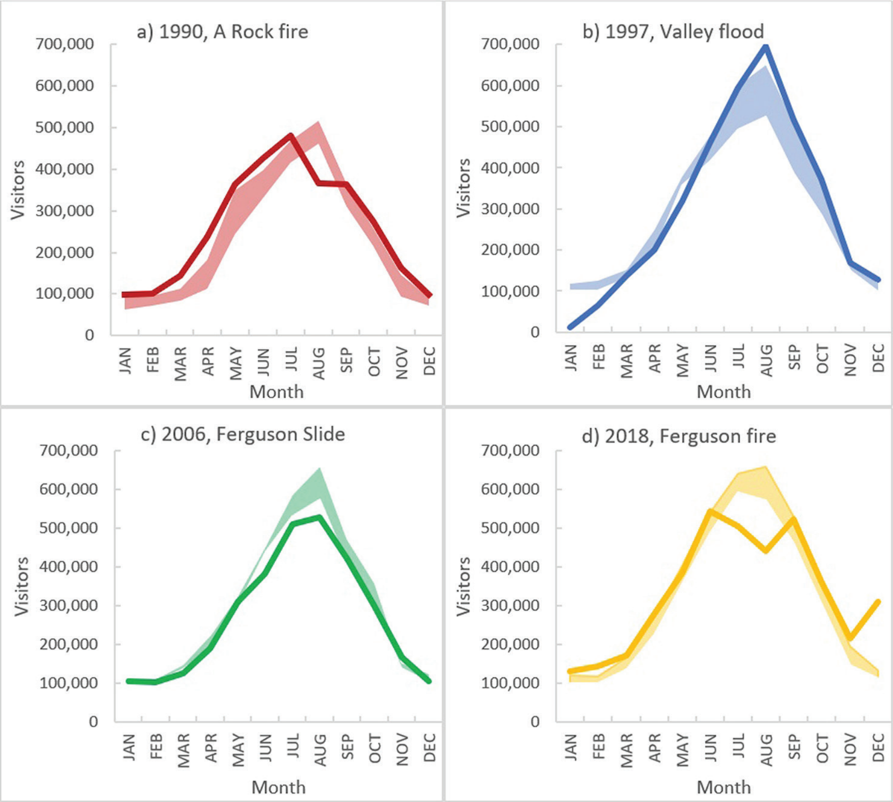


FIGURE 1. Visitation trends for Yosemite National Park compared with years when hazard events have occurred. Total visitors for each month during the year of a significant hazard event (solid line) are compared to the variation of visitation over the previous 10-year period of each event. The difference between a lower line value compared to a greater decadal range indicates reduced access or park closure from a hazard event, including (a) the A Rock Fire that started on August 7, 1990; (b) the 1997 Valley flood that occurred in January of that year; (c) the Ferguson Slide, outside YOSE, which first became inaccessible in May 2006; and (d) the Ferguson Fire, much of it outside YOSE, which began in July 2018. The decadal range for a "normal" year is defined as 50% of the data closest to the median (shaded area). Data source: National Park Service (2021).

lieu of snow and subsequent melt of existing snowpack (Booth et al. 2020). Tree mortality, standing dead wood, and eventual treefall poses an ongoing hazard as drought stress, insects, and disease contribute to longer periods of elevated mortality across the Sierra Nevada. Though dependent on a complex set of interactions, ultimately a tree can collapse as the result of heavy snowfall, high winds, or simply old age (Guarín and Taylor 2005). Rockfalls and rockslides have been occurring for millennia in the Yosemite Valley and throughout the area that is now the park. Landslides involving rock and debris can often follow a large precipitation event (e.g., heavy rainfalls or rapid snowmelts), while rockfalls are generally the result of granitic exfoliation triggered by either physical weathering from extreme temperature changes coupled with expanding water and ice inside fissures, or force from tree growth or an earthquake. Most rockfalls in Yosemite occur in the winter and early spring, during periods of intense rainfall, snowmelt, and below-freezing temperatures, but many large rockfalls have occurred in periods of warm and stable weather. While it is plausible that climate change-induced weather extremes are playing some role in the greater occurrence of rockfalls in recent decades in YOSE, geologists now have better technology at their disposal to regularly document these hazard events (Stock et al. 2014).

Many of the natural attractions in YOSE, including granitic domes, waterfalls, and the flood-prone Yosemite Valley itself, are the result of intense and prolonged biophysical processes, such as glaciation and erosion, while others, such as wildland fire and tree mortality, have co-evolved and serve as beneficial, regenerative forces for forest landscapes, though within a much different regime than seen today. Extensive areas of national parks are located in extreme environments, and spatial analyses of historical climate trends show that anthropogenic climate change has caused significant changes across units of the national park system, including increases in heat and aridity (decreases in precipitation), increases in wildland fire, and biome shifts (Gonzalez 2020). Moreover, the potential for resultant hazard events to occur and the magnitude of these events has been exacerbated by a combination of land management policy and climatic change, though more so the latter.

Before Yosemite became a government-protected area in 1864, Native Americans managed fire strategically, burning meadows and forests for resource harvests with the added benefit of supporting healthy ecological conditions. However, wildland fire came to be viewed as a threat to infrastructure and resources, and large-scale fire suppression became the norm for federal land agencies and private landholders by the early 20th century. The resultant dense forest stands have produced more numerous, but smaller, trees that exist under conditions of drought stress, and which are more vulnerable to high-severity fire, insects, and disease. Today, managers use tools to mimic fire's natural function in the ecosystem: prescribed fire, mechanical thinning, and wildland fire. Prescribed or managed ignition and mechanical thinning occur primarily in the frontcountry for community protection and ecosystem restoration, whereas YOSE maintains a policy to allow wildland fire to burn in the backcountry when it doesn't threaten park resources or human life. High-severity fires generate large amounts of smoke, which can make for hazardous health conditions hazardous in YOSE, regardless of how close to the actual fire perimeter one may be located. Fire-generated smoke and poor regional air quality can also impact scenery, and conditions can be especially difficult on a hot summer day when a pressure inversion suppresses particulate matter in the Valley and other topographic recessions, from where it doesn't easily escape (Figure 2). Heavy precipitation in a short amount of time coupled with snowmelt leads to spring floods, with the more extreme floods likely to happen earlier in the water year during a warmer winter; these events become a hazard where water features and drainages are close to developed areas, road corridors, or along trails. Standing dead trees and treefalls have increased in number as trees experience drought stress from a shift in their climatic envelope of necessary temperature and precipitation conditions, which makes them more susceptible to insects and disease.

RESULTS AND DISCUSSION

1890–1915: Early park management and commercialization

Early national park management emphasized the preservation of scenery and relatedly the protection of vast landscapes from utilitarian uses. The federal government ceded its role as developer to for-profit companies, and a tourism-oriented development approach to park management was seen in the construction of roads, trails, hotels, and campsites, and an emphasis on the number of visitors each year (Sellars 2008). Much of the early road and trail network in YOSE was constructed by the Army, with many of the main features and routes of today's system laid down by 1914. And, ostensibly under the mandate to preserve, but in fact to facilitate tourism, park management sought to enhance YOSE's natural appeal by manipulating resources that contributed to scenery for public enjoyment. In line with accepted policies on other public lands, fire was suppressed by Army personnel.

FIGURE 2. Scenic impact of smoke from the Ferguson Fire in July 2018 as seen from Half Dome. JEFFREY JENKINS

YOSE landscape architects had to balance preserving scenic integrity with impacts posed by the road and building infrastructure needed for visitor access. This involved extending development further into the wildlands, including one of the first planned residential developments on private land within a national park, Foresta, founded in 1913 (Bramwell 2015), and concealing infrastructure, such as by planting young pines within feet of buildings to screen them from public view (Colten and Dilsaver 2005).

The early infrastructural boom produced the initial spatial patterns of development that would funnel people toward scenic attractions, creating an initial set of conditions that would set the stage for potential exposure to environmental hazards. The development of villages and resorts in selected areas around tourist attractions, along with the roads and trails that connected these destinations, would have the unintended benefit of largely saving the remaining landscapes from intensive development and use. Although more a product of geography than being designated as purposeful sacrifice zones, park infrastructure, and thus areas of use and potential exposure to hazards, became spatially concentrated.

1916–1932: The Organic Act and agency priorities

Although the National Park Service Organic Act was passed in August 1916, it was not until the following spring that Congress appropriated funds for NPS. In the new bureau two groups of professionals became most prominent: landscape architects and engineers, who oversaw park development, and superintendents and rangers, who were in charge of day-to-day operations (Sellars 2008). They were often at odds over infrastructure and management actions, with the landscape architects and engineers emphasizing bureaucratic rationality and design standards, and the superintendents and rangers seeing management realities through lived experience and a hierarchal command structure. Where engineers and architects designed the roads and buildings, managers had to deal with and respond to the visitors using them.

For many years, NPS's interest was more in recreational tourism than in fostering innovative strategies in nature preservation. The emphasis the Organic Act placed on "unimpaired" scenic resources lent itself to a type of façade management, rather than understanding the biophysical processes that constitute the interconnected natural world. Early park managers did not advocate for scientific investigations to ensure preservation of flora and fauna. Nor was much emphasis placed on understanding the interaction of potential hazards across the landscape, such as how a period of low-precipitation years could lead to greater wildland fire risk, as in the drought years that occurred in 1924 and from 1928–1935. Rather, advice was sought from foresters and entomologists on how to prevent fire and insects from destroying the scenic integrity of forests. By the mid-1920s Congress was appropriating funds for the control of insects in parks, including the needle miner and bark beetle in Yosemite. Methods of insect control included chemical spraying, felling of trees, peeling the bark from trees, and burning infested trees. While NPS began to hire some foresters by the mid-1920s, their mission was largely duplicative of the approaches that the Army and US Forest Service took when it came to fire suppression (albeit for scenic preservation), and in 1927 NPS joined the Forest Protection Board, an inter-agency organization that fostered cooperative fire suppression.

The area of YOSE burned by wildland fire, and frequency of ignitions, have both increased over the decades since data collection began in 1930 following the NPS embrace of fire suppression policy (Figure 3a). Of the total ignitions for each decade, approximately 90–95% have been caused by lightning, and years of decreased spring snowpack exponentially increase the frequency. Lightning ignitions are expected to increase by 19.1% and area burned by high-severity fire by 21.9% between 2020 and 2049 (Lutz et al. 2009).

1933–1961: The infrastructure workforce and control of nature

Beginning in 1933, NPS used Civilian Conservation Corps (CCC) labor to develop the national parks, including construction of roads and trails, administrative and visitor facilities, and water and sewage systems. In addition, the CCC crews undertook natural resource management projects, such as fighting fire, removal of hazardous trees, and mosquito control. While much of the new road development in the 1930s was primitive and intended to provide access for firefighting, these roads penetrated deep into the backcountry and in doing so invited further development. Fire roads and lookout towers were among the infrastructure developed by the CCC in natural areas to combat wildland fire. In 1934 a CCC photographer was assigned to capture panoramic photos from existing and potential fire lookout locations across the western front of YOSE and bordering US Forest Service lands (Jenkins et al. 2019). These photographs show viewable areas that were used in conjunction with Osborne Fire Finder maps to identify ignition locations across the horizon. In addition to the photography, forestry technicians would also record the drive time that it took to access lookout locations, which informed wildland fire suppression efforts.

Aside from opening up large areas of formerly inaccessible wilderness, these roads and the removal of

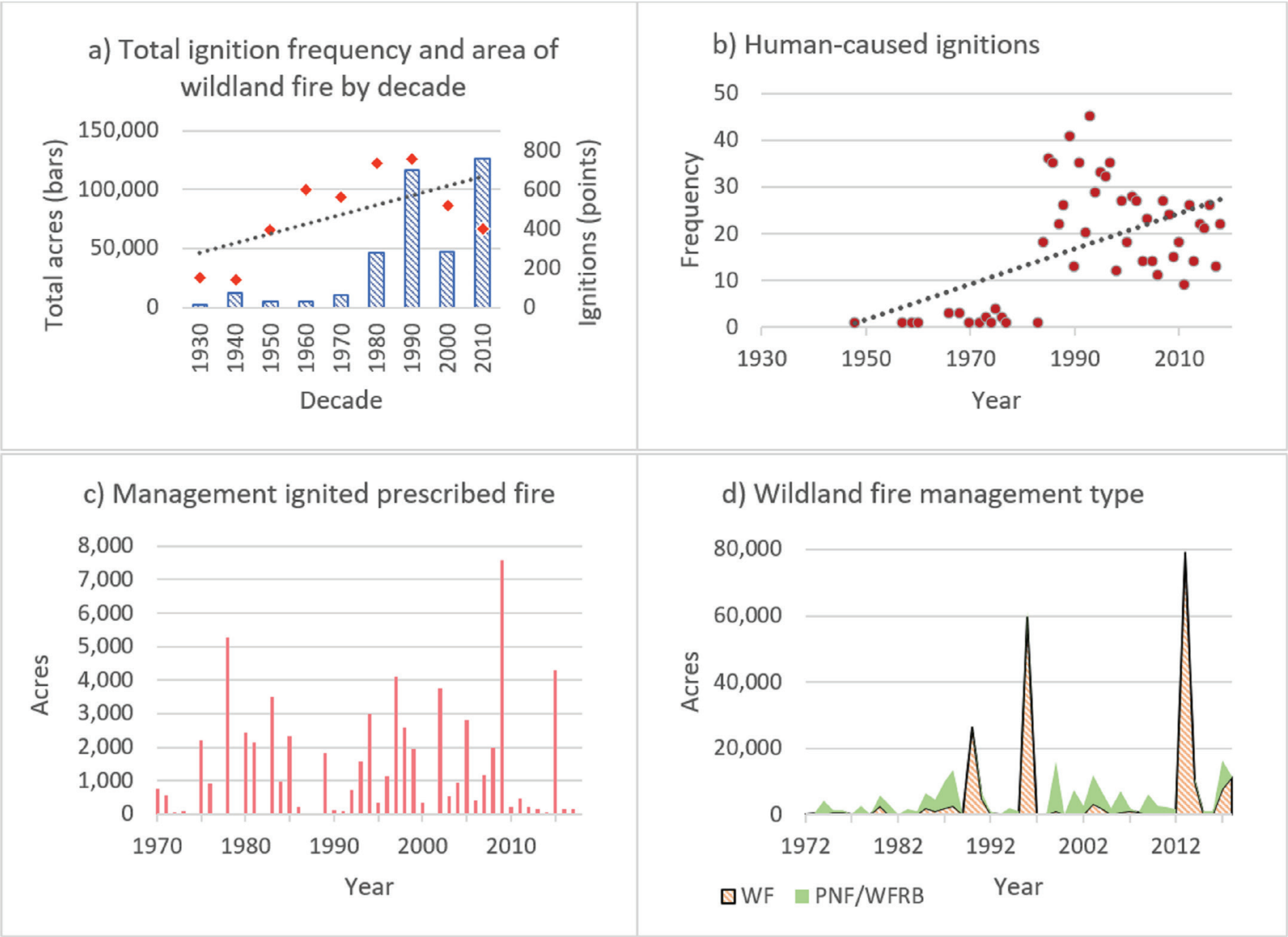


FIGURE 3. Wildland fire trends at Yosemite National Park including (a) total ignition frequency and area of wildland fire by decade; (b) frequency of human-caused ignitions; (c) total annual area of management-ignited prescribed fire; and (d) wildland fire management response, either wildfire (WF), or prescribed natural fire (PNF), which was later reclassified as wilderness fire resource benefit (WFRB). Data source: National Park Service (2019).

trees and snags would contribute to drying of the soil and increased erosion, effectively extending visitor exposure to potential hazards along the newly accessible routes and throughout the adjoining backcountry. Notable rockslides impacted road access in several instances, including in May 1935 along Big Oak Flat Road as a result of blasting to clear debris, which led to one fatality and two injuries. In March 1943, a very large slide damaged the powerhouse penstock and blocked the El Portal All-Year Highway and New Big Oak Flat Road,. In May 1945, a large slide occurred along Old Big Oak Flat Road that led to the closure of the Valley and ended use of the old route for good as it took out the switchback and its walls.

Due to gas rationing and rubber shortages during World War II, the number of visitors to YOSE plummeted from 598,000 in 1941 to 117,000 in 1943. NPS's management activity was reduced to protection and maintenance of the parks, rather than the expansion and development that had been the norm, and in YOSE control over nature was seen in continued fire suppression and spraying chemicals to eradicate forest insects and control disease. Years of fire suppression led to fuels build-up that produced high-severity conditions in the Rancheria Mountain Fire of 1948, the largest, most costly fire on record at the time. Human-caused ignitions in YOSE were first systematically reported in 1948 and have become more common in recent decades given more recreational users and a hotter, drier, denser forest (Figure 3b).

Spraying continued in the postwar years, with funds appropriated by the 1947 Forest Pest Control Act. Imprecise aerial spraying was employed across large wilderness areas of the park, including around Tenaya Lake and Tuolumne Meadows, where so-called ghost forests of dying trees (prevalent during the periods 1903–1921, 1933–1941, and 1947–1963 from infestations of the lodgepole needleminer moth) created dangerous "widow-making" gnarled branches that worried managers who wanted to provide recreational opportunities in these areas. DDT was sprayed via airplane in Yosemite in 1953 across 11,000 acres of the 47,500 acres affected by lodgepole needleminer and again in 1954 across an additional 500 acres. Despite fish population declines near areas where spraying occurred, similar treatments continued into the early 1960s using chemicals such as malathion and ethylene dibromide, as NPS's goal remained to preserve the scenic character of native vegetation.

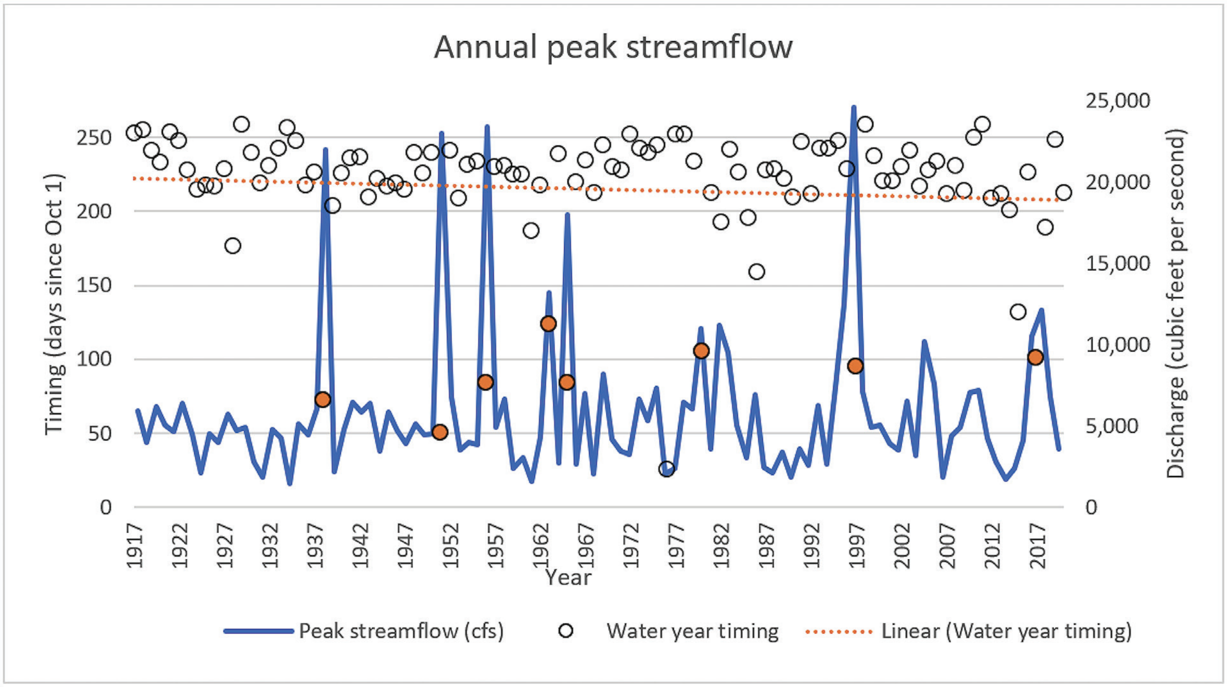
1962–1986: High visitation and the use of science to inform management

Visitation to YOSE first exceeded 1.5 million in 1962 and reached nearly 3 million annual visitors by the mid-1980s (National Park Service 2021). The Mission 66 program (1956–1966) created a new visitor center in the Valley; enlarged roads, parking areas, and campgrounds; and constructed new lodging. The biggest project during Mission 66 was the 21-mile rebuilding of the Tioga Road. Development was justified not just as a means of accommodating visitors, but also for controlling the record-setting crowds. Planning funneled use along roads and trails to designated sites, vistas, and other points, in an attempt to limit impact to specified areas.

In 1964, erosion along the riverbank, which had been observed since the 1930s, was linked to high levels of use at riparian-zone campgrounds. Bank protection devices were installed along the river in response to erosion, and by 1978 there was nearly three miles of revetment, which made the river more prone to flooding (Madej, Weaver, and Hagans 1994). Near-annual moderate floods can be hazardous for motorists and hikers who may not anticipate the magnitude of precipitation and snowmelt as it unfolds over a short period, especially in proximity to infrastructure such as bridges and roadways near slide-prone areas. Even modest precipitation events can lead to flash floods and associated debris flows, which can result in unsafe conditions for drivers that are especially hazardous when in the vicinity of a recently burned area (Staley 2013).

Peak streamflow and low-to-moderate levels of seasonal flooding usually occur in Yosemite Valley in the spring, and regularly lead park managers to close some campsites and trail segments, and issue warnings about fast-moving water. Major floods are declared when the gauge height at the Pohono Bridge—located at the downstream end of the Valley—exceeds 10 feet. This has happened 24 times since 1917. This location is used because vehicles must pass over the bridge or near it on the road next to the Merced River to access the Valley, and the gauge height at the bridge is an indicator of when a flood poses potentially unsafe conditions. The most extreme floods (1938, 1951, 1956, 1963, 1965, 1980, 1997, and 2017) generally occur early in the water year—which begins October —as the result of a high volume of precipitation in a relatively short amount of time, higher-than-normal temperatures, and rapid snowmelt (Figure 4). Notably, annual peak streamflow

FIGURE 4. Annual peak streamflow and timing of major floods from the October 1 start of the water year in Yosemite National Park (Merced River at Pohono Bridge, gage no. 11266500) shows that annual peak streamflow generally occurs later in the season as the result of snowmelt when the temperature is warmer in spring, but the most extreme floods have usually occurred early in the winter (marked as an orange shaded circle) when warmer precipitation and snowmelt lead to rapid runoff. Data source: United States Geological Survey (2021).



now occurs, on average, two weeks earlier than in 1917 (indicated by the linear trendline in Figure 4). Peak flows generally occur in the late afternoon for high-elevation streams. In Yosemite Valley these peak flows occur in late at night, many hours after the sun has melted snow at higher elevations, first in lower-lying valley floors then off slopes and peaks of the high country (Figure 5).

By the 1960s, areas of YOSE where fire had been suppressed had developed overly dense understory vegetation and altered wildlife habitat, thereby diminishing the visitor experience. NPS policy changed to allow natural and prescribed fires to burn, first with the recommendations of the Leopold Committee in 1963 and later formalized with the publication of the NPS Green Book in 1968. Prompted by the 1970 National Environmental Policy Act and building on tenets of the 1968 Wild and Scenic Rivers Act, a new Environmental Restoration Plan was put forward that emphasized science, with prescribed fire as a central strategy to help mitigate YOSE's ecological problems.

FIGURE 5. Yosemite Valley as seen from a plane in September 2017 shows the proximity of alpine snowpack. Snowpack on April 1, 2017 was 177% of average, and warmer-than-average temperatures contributed to an extreme flood in January of that year. JEFFREY JENKINS

In 1970, prescribed natural fire was first used in Foresta Village to reduce fuel loads around structures, and in Mariposa Grove to facilitate germination of and regenerate soils for fire-dependent giant sequoia. Selective mechanical thinning of trees was another approach formalized as part of a prescribed fire program. The use of managed burns, usually in the frontcountry, is dependent on winter and early-spring weather, the absence of drought conditions, and funding and staff limitations (Figure 3c). Building on the efforts in Sequoia and Kings Canyon National Parks in preceding years, in 1972 YOSE scientists began allowing lightning-strike fires to continue burning as "prescribed natural fire" in higher-elevation areas of the park's wilderness so long as they didn't threaten life or property. This type of fire was reclassified as "wilderness fire resource benefit" in 1998 (Figure 3d). The benefits have been significant. For instance, the return of a natural fire regime to Illilouette Creek Basin has increased biodiversity and soil moisture, and decreased tree mortality and overly dense forest cover, restoring the mosaic of vegetation essential for a functioning ecosystem (Stephens et al. 2021) (Figure 6).

Prior to 1970, most of the fire staff were trained foresters instead of ecologists, and the change to fire policy prompted departmental reorganization. Wildland and structural fire management were separated, given that the emergency response for structural fires differed greatly from the resource management approach to wildland fires. These early efforts culminated in the Natural, Conditional, and Prescribed Fire Management Plan of 1979, which became influential beyond YOSE. As part of the ecological shift in management of fire and other park resources, more systematic wilderness impact monitoring efforts began in the mid-1980s. They included an emphasis on surveying for informal

FIGURE 6. Illilouette Valley forest stand composition as seen in June 2020. JEFFREY JENKINS

campfire rings and. in many cases. removing them to prevent further proliferation of campsite impacts and to reduce the risk of human-caused ignitions (Jenkins, Fincher, and van Wagtendonk 2021).

The perception of rockfalls as hazards changed drastically after the 1980 rockfall onto the upper Yosemite Falls Trail, which caused three fatalities and 19 injuries, the largest mass casualty incident for in park history. This catalyzed a collaboration between the US Geological Survey and YOSE to establish a long-term scientific monitoring program to quantify rockfall hazards (Stock et al. 2014). Rockfalls and slides have also greatly impacted park infrastructure, including trails, roads, parking lots, tent cabins, wooden cabins, residences, and other structures in Yosemite Valley. A rockfall is an event where multiple independent rock fragments detach from the bedrock along fractures as the result of weathering processes (temperature and moisture differences) over time, which for granitic formations is referred to as "exfoliation."

When rockfalls, slides and other debris movement affect infrastructure and patterns of visitor use, they switch from being regarded as natural phenomena to being environmental hazards (Table 1). As such, evidence of past rockfalls (on talus slopes) provides an approximation of where hazards to life and property can occur again. However, there are no places within Yosemite Valley that are absolutely safe from large rockfalls (Stock et al. 2014).

1987-present: Environmental and political-legal complexity

Multi-year drought conditions re-emerged in 1987 after being largely absent during the previous two decades and conspired with fire to threaten giant sequoia and nearby structures in the August Heat Complex fire, which led to the closure of some portions of YOSE. The science of fire management became a political issue in 1988 when NPS declared a moratorium on prescribed burns as it bowed to public pressure in the aftermath of the Yellowstone fires. This policy was later revised to require NPS approval of park fire management plans. Then late in the summer

TABLE 1. Significant rockfall and slide hazard events occurring in Yosemite Valley in recent decades. Sources: Harp et al. (2008), Stock et al. (2013), and Wieczorek et al. (2000).

Date	Location	Magnitude	Impacts
November 16, 1980	Yosemite Falls rockfall	1,500 m^3 (4,500 tons) rockfall	Large slab from the western side of the upper fall destroyed or damaged 48 switchbacks leading to three fatalities, 19 injuries.
April 3, 1982	Merced River Gorge (Cookie Cliff) landslide	100,000 m^3 (300,000 tons) of rock and debris	Destroyed the Old Coulterville Road and wiped out the new road for a distance of approximately 150 m. Boulders of up to 20,000 tons came down, sewer and telephone lines were destroyed.
July 10, 1996	Yosemite Valley (Happy Isles) landslide	54,000 m^3 (162,000 tons) of rock and debris	Successive falls 14 seconds apart generated an air blast and dense sandy dust cloud that had velocities exceeding 110 m/s and toppled approximately 1,000 trees. One fatality and 14 injuries resulted, and a bridge, road, structures, trail, and utilities were destroyed.
April 29, 2006	Ferguson Slide (outside of YOSE)	800,000 m^3 (2,400,000 tons) of rock and debris	Massive landslide incrementally buried Highway 140, which was impassable by May 28 and closed for 92 days. This restricted access to YOSE from Mariposa County, which led to $4.8 million in losses for the tourism-dependent economy.
October 7 and 8, 2008	Glacier Point (above Curry Village)	1,133 m^3 (3,400 tons) / 4,530 m^3 (13,590 tons) rockfalls	The first rockfall and associated debris toppled trees and destroyed a cabin in Curry Village. The second rockfall further damaged structures and trails and led to three injuries.
September 27 and 28, 2017	El Capitan rockfall	450 m^3 (1,340 tons) / 10,250 m^3 (30,5000 tons) rockfalls	Seven rockfalls occurred during the first day, which led to one fatality and one injury, and a much larger rockfall the second day led to one additional injury.

of 1990, as drought conditions and the frequency of tree deaths peaked in YOSE (Guarín and Taylor 1995), several fires were ignited by lightning within the Park's suppression zone, none of which could be extinguished. These fires, which included the A Rock fire (17,769 acres), led to YOSE's full closure for the first time. In 1995, YOSE completed a revision of the Federal Wildland Fire Management Policy and Program Review Report, which led to a uniform approach and greater cooperation among federal agencies (National Park Service 2016). In 1996, severe fire conditions, lighting-caused ignitions, and limited resources led to the Ackerson Complex fire (59,153 acres), which necessitated a unified US Forest Service and NPS command. The response to these fires came on the heels of a catastrophic rockslide earlier that summer in July. At Happy Isles two rockslides, 14 seconds apart, led to an air blast that toppled approximately 1,000 trees, destroyed infrastructure, and resulted in one fatality and 14 injuries.

On New Year's Eve of 1996 and through January 5, 1997, a record flood inundate the Valley with the Merced River's peak flow in excess of 10,000 cubic feet per second, the result of unusually warm rainfall that contributed to rapid snowpack melt. Over 2,000 visitors were stranded in the Park for several days as roads were inundated by floodwaters. Nearly half of all accommodations and campsites were damaged or destroyed, and amenities like picnic tables, bear boxes, and trash cans floated down the river. The Park began to prepare the Yosemite Valley Plan in 2000 and relatedly the Merced River Plan, both of which addressed user capacity and restoration. While the plans enjoyed much public support, two environmental groups would litigate the proposed actions, and for nearly a decade this would restrict park manager's ability to do such things as relocate sewer lines under wet meadows that threatened natural resources or make repairs to flood-damaged roads.

Detailed documentation shows that between 2006 and 2011 approximately one rockfall occurred in Yosemite Valley each week on average, whereas historical data reveals that one larger rockfall of approximately 10,000 m^3 occurs each year in Yosemite Valley on average, and at least three rockfalls greater than 100,000 m^3 have occurred within the YOSE boundaries over its recorded history (Stock et al. 2013). While outside the boundary, the 2006 Ferguson slide led to a months-long closure of a portion of Highway 140 in what is an extension of the Merced River gorge emanating from the Valley; even today, traffic continues to be routed across the river by temporary bridges and one-way traffic control (Figure 7). The California state department of

FIGURE 7. The Ferguson slide and temporary bridge for Highway 140 crossing the Merced River. JEFFREY JENKINS

transportation plans to begin construction in late 2022 of a rock shed where the rockslide now rests, which will take five years to complete and allow for continuous two-way traffic to recommence. The project has been delayed for different reasons, though perhaps most prominently due to impacts on the habitat of limestone salamander, which is listed as a Threatened species by the California Department of Fish and Wildlife. An exception to allow some salamanders to be killed has been granted and nearby mitigation habitat purchased, which will allow the project to go forward. When complete, the "temporary" bridges will be removed after 20 years in accordance with the prohibition on new permanent structures imposed by the Merced's Wild and Scenic Rivers designation.

Additionally, the 2008 Glacier Point rockfalls led the NPS to permanently close more than 200 buildings within the Curry Village area as the result of severe damage from boulders, downed trees, and other debris (Stock et al. 2014). These closures highlight the difficulty that YOSE managers face in maintaining access and visitation given their limited ability to rebuild roads and buildings due to the legal constraints that arose in litigation after the 1997 Valley flood and, ultimately, the Wild and Scenic Rivers Act, which largely prohibits new and expanded infrastructure within the Merced River corridor. In 2013 the Rim Fire occurred, which was the largest wildland fire in the country that year, and the largest to ever occur in the YOSE (78,892 acres). The fire originated on the Stanislaus National Forest and burned a total of 257,314 acres. The fire burned through lower-elevation areas with high rates of tree mortality and historical fire suppression (Figure 8) and posed particularly hazardous conditions across slopes near roads and where debris, including downed dead trees, could flow during the rains of that following winter.

Thousands of trees have been removed in YOSE, particularly in locations within the 17% of the park classified as a fire suppression zone where potential treefalls threaten buildings, campgrounds, and roads (National Park Service 2016). High tree mortality is not simply the result of one severe dry year; rather, it is the result of extended periods of low moisture, such as the multi-year drought periods experienced in the region between 1987–1992 and 2012–2016. Many of the largest trees throughout YOSE established themselves between approximately 1650 and 1850 during the local manifestation of the Little Ice Age. This means they experienced a period of cool and dry temperatures during their rapid growth phase. When compared to current climatic conditions, these trees have increased water stress, which has been linked to tree mortality (Lutz, van Wagtendonk, and Franklin 2010). Following Guarín and Taylor (2005), Figure 9 compares the Palmer Drought Severity Index (PDSI) and April snowpack depth for YOSE to highlight drought periods that correspond with tree mortality. The PDSI and April snowpack depth are shown standardized with a Z-score for the five year running mean of annual data between 1930 and 2021. In the Mediterranean

FIGURE 8. Standing dead and burned trees in the Rim Fire burn scar show historic dense forest stand conditions that contributed to high-severity wildland fire.
JEFFREY JENKINS

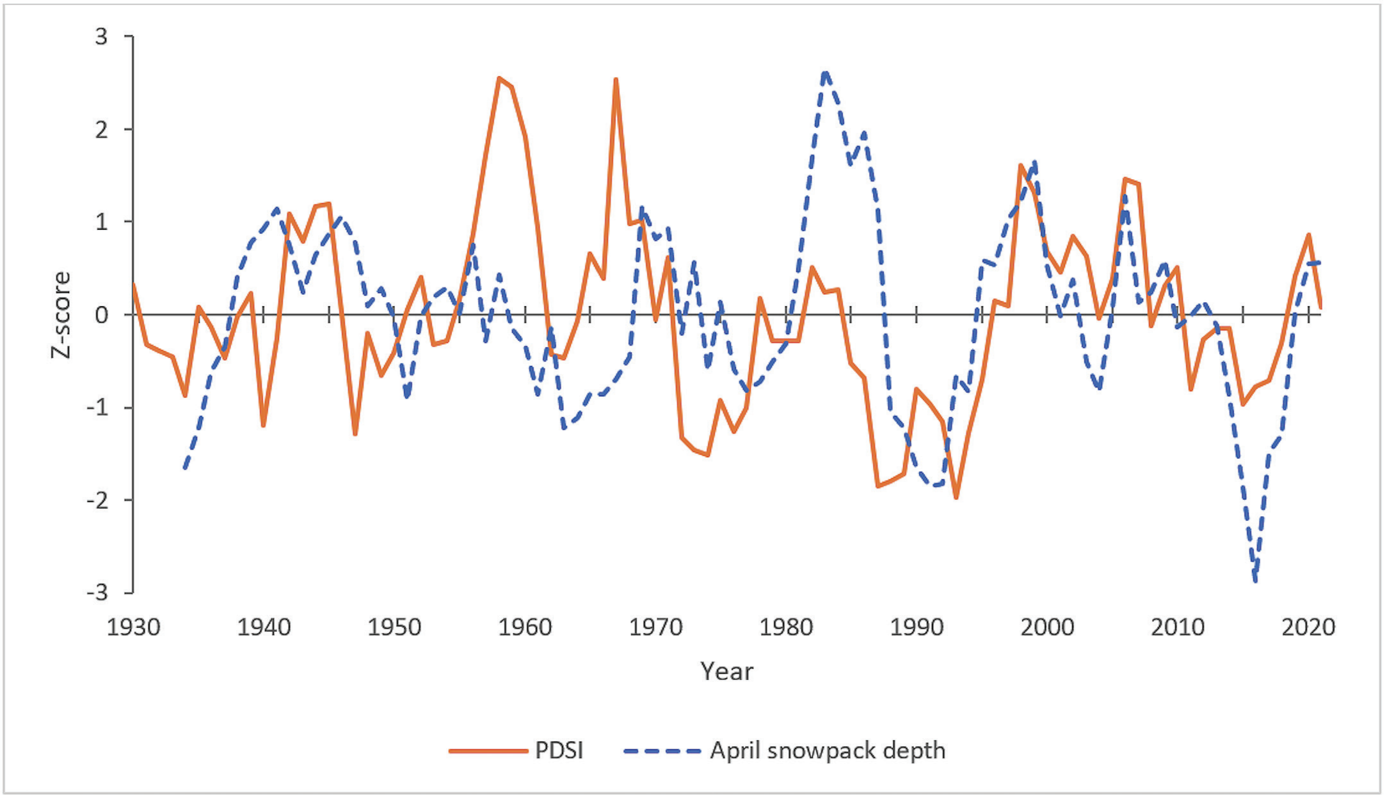


FIGURE 9. The Palmer Drought Severity Index (PDSI) (California Climate Division 5) and April snowpack depth for Yosemite National Park (Tuolumne Meadows) are compared to highlight drought periods that correspond with high rates of tree mortality. The PDSI and April snowpack depths are each standardized with a Z-score for the five-year running mean since tree stress (and therefore mortality) generally becomes compounded over longer periods of drought conditions. Data source: National Oceanic and Atmospheric Administration (2021) and California Department of Water Resources (2021).

climate of the Sierra Nevada, precipitation occurs mainly in winter. As such, April snowpack depth and spring temperatures are key determinants of annual water availability and the length and intensity of summer drought. The large-scale tree mortality that has unfolded has been amplified by dense forest stand conditions that are the result of fire suppression, and this density coupled with water stress from drought has made trees more susceptible to insect attack (Figure 10). By the end of 2017 it was estimated there were 2.4 million dead trees in an area of about 131,000 acres of YOSE, especially between 3,000- and 4,500-foot elevations. The Sierra Nevada lost 142 million trees between 2012 and 2018 due to the combined impacts of high temperatures, drought stress, fire suppression, and insects.

CONCLUSION

In YOSE, natural biophysical processes of low-intensity fire, spring floods, seasonal drought, and soil erosion and granitic exfoliation have come to be regarded as hazards. Early commercial development patterns in the latter half of the 19th century around recreational attractions and scenic features determined where people might generally be exposed to risk for generations to come. Prior to the conception of NPS through the Organic Act in 1916, later in the 1930s with CCC workers, and again in the 1960s with Mission 66, landscape architects and park developers would unknowingly create further vulnerabilities through riverbank channelization, stone bridges, and impervious roadways that didn't account for peak streamflow levels, contributing greatly to hazardous floods. Colocation of many people in overly dense and dry fire-suppressed forests has further magnified the risk of high-severity fire, particularly when peak visitation and wildland fire risk coincide in late summer. The number of reported human-caused ignitions per year has greatly increased since the mid-1980s, along with greater monitoring efforts and improved technical ability to locate sources, which often coincide areas of high use. The spatial extent in which treefalls and rockfalls or slides could possibly occur can be extensive, while the hazard to life or property is spatially concentrated along roadways and around buildings.

While we have chosen where we have placed our infrastructure and ourselves, climate change has led to greater likelihood of larger-magnitude and higher-severity events, along with uncertainty about the timing and duration of extremes away from average or expected conditions of seasons past. Prolonged periods of drought can mean that

FIGURE 10. Dense forest canopy and tree mortality as seen from Wawona in January 2017. JEFFREY JENKINS

hazard debt comes due in terms of the total rate of tree mortality. Antiquated thinking about preserving forests unimpaired from scenic blight helped to justify the chemical spraying of larger stands throughout YOSE that continued into the 1960s, and the idea of whether there is—or if there should even be—some ecological baseline to return to still dominates popular discussion about forest restoration outcomes. Instead, what might be considered is using substitutable species to establish functionally equivalent ecosystems.

Structural rigidities associated with NPS's hierarchical organizational structure, arcane and outdated legal guidelines, and the coupling of ecological and recreational outcomes with drawn-out litigation and regulatory processes have made determination of visitation capacity a particularly intractable management challenge over the years. The way knowledge has been utilized has also evolved throughout the history of YOSE, with rangers and professional engineers holding different opinions about the project design, either based on experiential or more technical or economic considerations. And as the case of the 1980 rockfall onto the upper Yosemite Falls Trail shows, it took an extremely impactful hazard event to catalyze a long-term collaboration between YOSE and the US Geological Survey to scientifically monitor and respond to rockfalls and slides. Relocation or removal of buildings has happened in YOSE's recent history, as with most buildings closest to the Merced River after the 1997 Valley flood or with the use of eminent domain to limit rebuilding of cabins in Foresta after the 1990 Arch Rock Fire.

The environmental hazards synthesized here can help us to think about management of YOSE as a system, where sustained perturbances from prolonged periods of drought and increased vulnerability to wildland fire can make visitors subject to additional, and potentially larger, hazards—a double exposure from current climate change and past development. The social, economic, and technical conditions for management of environmental hazards in YOSE continue to evolve through the use of science to inform management actions that address systemic impacts. YOSE is increasingly vulnerable to impacts from hazards exacerbated by higher levels of visitation and climate change. Social conditions for visitation have changed as people reassess their expectations about travel to YOSE as it relates to timing, scenery, and safety. So too have economic conditions changed, as repeated displacement of potential visitation means unrecoverable economic impacts for gateway communities.

However, YOSE may be trending toward a more resilient future. In response to COVID-19, YOSE has recently adopted an adaptive management approach to set visitor capacities through different tiers of use that equate with percentages of peak summer day-use levels (e.g., 50–90% of typical June use). This program allows managers to reduce overcrowding and traffic delays and has had the effect of distributing use evenly throughout the weekdays beyond the weekend peaks during the busy summer season. Managers also intend to deploy the day-use reservation permit system when environmental hazards pose risks to visitor safety or infrastructure by limiting access outright (Jenkins et al. 2021). While there are average patterns of visitor use across seasons, and averages of snowpack melt and stream runoff over time, there is no normal year in Yosemite. By understanding how the occurrence of hazards and use of science in management actions have evolved over time, we can develop a typology that links the timing and severity of hazards with expected visitation conditions and allows managers to adaptively manage for desired experiences.

REFERENCES

Adger, W. Neil. 2006. Vulnerability. *Global Environmental Change* 16(3): 268–281. http://doi:10.1016/j.gloenvcha.2006.02.006

Booth, Derek B., Katie Ross-Smith, Elizabeth K. Haddon, Thomas Dunne, Eric W. Larsen, James W. Roche, Greg M. Stock, and Virginia Mahacek. 2020 Opportunities and challenges for restoration of the Merced River through Yosemite Valley, Yosemite National Park, USA. *River Research and Applications* 36(9): 1803–1816. https://doi.org/10.1002/rra.3704

Bramwell, Lincoln. 2015. *Wilderburbs: Communities on Nature's Edge*. Seattle, WA: University of Washington Press.

California Department of Water Resources. 2021. California Data Exchange Center. Tuolumne Meadows (Snow depth, 1930–2021). https://cdec.water.ca.gov/dynamicapp/staMeta?station_id=TUM (accessed 3 January 2022).

Colten, Craig E., and Lary M. Dilsaver. 2005. The hidden landscape of Yosemite national park. *Journal of Cultural Geography* 22(2): 27–50. https://doi.org/10.1080/08873630509478238

Dilsaver, Lary M. 2016. *America's National Park System: The Critical Documents.* Lanham, MD: Rowman & Littlefield.

Gonzalez, Patrick. 2020. Human-caused climate change in United States national parks and solutions for the future. *Parks Stewardship Forum* 36(2): 188–210. https://doi.org/10.5070/p536248262

Guarín, Alejandro, and Alan H. Taylor. 2005. Drought triggered tree mortality in mixed conifer forests in Yosemite National Park, California, USA. *Forest Ecology and Management* 218(1–3): 229–244. https://doi.org/10.1016/j.foreco.2005.07.014

Harp, Edwin L., Mark E. Reid, Jonathan W. Godt, Jerome V. DeGraff, and Alan J. Gallegos. 2008. Ferguson rock slide buries California state highway near Yosemite National Park. *Landslides* 5(3): 331–337. https://doi.org/10.1007/s10346-008-0120-9

Iglesias, Virginia, Natasha Stavros, Jennifer K. Balch, Kimiko Barrett, Jeanette Cobian-Iñiguez, Cyrus Hester, Crystal A. Kolden, Stefan Leyk, R Chelsea Nagy, Colleen Reid, Christine Wiedinmyer, Elizabeth Woolner, and William Travis. 2022. Fires that matter: Reconceptualizing fire risk to include interactions between humans and the natural environment. *Environmental Research Letters* 17(4): 045014. https://doi.org/10.1088/1748-9326/ac5c0c

Jenkins, Jeffrey, Adam Fleenor, and Fisher Dietz. 2019. Moving beyond the frame: Geovisualization of landscape change along the southwestern edge of Yosemite National Park. *Journal of Geovisualization and Spatial Analysis* 3(2): 1–11. https://doi.org/10.1007/s41651-019-0032-3

Jenkins, Jeffrey, Felber Arroyave, Madeline Brown, Jullianna Chavez, Johnny Ly, Haania Origel, and Jacob Wetrosky. 2021. Assessing impacts to national park visitation from COVID-19: A new normal for Yosemite?. *Case Studies in the Environment* 5(1): 1–10. https://doi.org/10.1525/cse.2021.1434075

Jenkins, Jeffrey, Mark Fincher, and Jan van Wagtendonk. 2021. The evolution of management science to inform overnight visitor use carrying capacity in Yosemite Wilderness. *International Journal of Wilderness* 27(2): 22–39. https://ijw.org/evolution-management-science-carrying-capacity-overnight-visitors-yosemite-wilderness/

Kroner, Rachel E. Golden, Roopa Krithivasan, and Michael Mascia. 2016. Effects of protected area downsizing on habitat fragmentation in Yosemite National Park (USA), 1864–2014. *Ecology and Society* 21(3). https://www.jstor.org/stable/26269964

Lutz, James A., Jan W. van Wagtendonk, and Jerry F. Franklin. 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. *Journal of Biogeography* 37(5): 936–950. https://www.jstor.org/stable/25654310

Lutz, James A., Jan W. van Wagtendonk, Andrea E. Thode, Jay D. Miller, and Jerry F. Franklin. 2009. Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA. *International Journal of Wildland Fire* 18(7): 765–774. https://doi.org/10.1071/WF08117

Madej, Mary Ann, William E. Weaver, and Danny K. Hagans. 1994. Analysis of bank erosion on the Merced River, Yosemite Valley, Yosemite National Park, California, USA. *Environmental Management* 18(2): 235–250. https://doi.org/10.1007/bf02393764

Minear, J. Toby, and Scott A. Wright. 2013. *Hydraulic and Geomorphic Assessment of the Merced River and Historic Bridges in Eastern Yosemite Valley, Yosemite National Park, California.* Reston, VA: US Department of the Interior, US Geological Survey. https://pubs.usgs.gov/of/2013/1016/pdf/ofr2013-1016.pdf

National Oceanic and Atmospheric Administration. 2021. National Climatic Data Center "Climate at a Glance" (California Climate Division 5). https://www.ncdc.noaa.gov/cag/

divisional/time-series/405/pcp/2/5/1895-2021 (accessed 14 January 2022).

National Park Service. 2016. Fire Management Records. Online Archive of California. https://oac.cdlib.org/findaid/ark:/13030/c88s4vfm/entire_text/ (accessed 11 January 2022).

National Park Service. 2017. Records of the Office of the Superintendent. Online Archive of California. https://oac.cdlib.org/findaid/ark:/13030/c86114th/ (accessed 3 January 2022).

National Park Service. 2019. Yosemite National Park fire perimeters (1930–2019). ArcGIS Online open data: "yose_fire_perimeters_2019" (accessed 7 December 2021).

National Park Service. 2021. Yosemite NP: Recreation Visits By Month (1979–2021). Integrated Resource Management Applications. https://irma.nps.gov/STATS/Reports/Park/YOSE (accessed 20 January 2022).

Sellars, Richard W. 2008. *Preserving Nature in the National Parks.* 2nd ed. New Haven, CT: Yale University Press.

Staley, Dennis M. 2013. *Emergency Assessment of Post-fire Debris-flow Hazards for the 2013 Rim Fire, Stanislaus National Forest and Yosemite National Park, California.* US Geological Survey Open-File Report 1260, no. 11. Reston, VA: US Department of the Interior, US Geological Survey. https://pubs.usgs.gov/of/2013/1260/pdf/of2013-1260.pdf

Stephens, Scott L., Sally Thompson, Gabrielle Boisramé, Brandon M. Collins, Lauren C. Ponisio, Ekaterina Rakhmatulina, Zachary L. Steel, Jens T. Stevens, Jan W. van Wagtendonk, and Kate Wilkin. 2021. Fire, water, and biodiversity in the Sierra Nevada: A possible triple win. *Environmental Research Communications* 3(8). https://doi.org/10.1088/2515-7620/ac17e2

Stock, Greg M., Brian D. Collins, David J. Santaniello, Valerie L. Zimmer, Gerald F. Wieczorek, and James B. Snyder. 2013. *Historical Rockfalls in Yosemite National Park, California (1857–2011).* Reston, VA: US Department of the Interior, US Geological Survey. https://pubs.usgs.gov/ds/746/Yosemite_rock_fall_database_narratives_1857-2011.pdf

Stock, Greg M., Nicolas Luco, Brian D. Collins, Edwin L. Harp, Paola Reichenbach, and Kurt L. Frankel. 2014. *Quantitative Rock-fall Hazard and Risk Assessment for Yosemite Valley, Yosemite National Park, California.* US Geological Survey Scientific Investigations Report 2014-5129: 52. Reston, VA: US Department of the Interior, US Geological Survey. https://pubs.usgs.gov/sir/2014/5129/pdf/sir2014-5129.pdf

US Geological Survey. 2021. National Water Information System. Pohono Bridge (gage no. 11266500) peak streamflow (1917–2021). https://nwis.waterdata.usgs.gov/ca/nwis/peak/?site_no=11264500&agency_cd=USGS (accessed 17 December 2021).

Vale, Thomas. R. 1987. Vegetation change and park purposes in the high elevations of Yosemite National Park, California. *Annals of the Association of American Geographers* 77(1): 1–18. http://www.jstor.org/stable/2569198

Wieczorek, Gerald F., James B. Snyder, Richard B. Waitt, Meghan M. Morrissey, Robert A. Uhrhammer, Edwin L. Harp, Robert D. Norris, Marcus I. Bursik, and Lee G. Finewood. Unusual July 10, 1996, rockfall at Happy Isles, Yosemite National Park, California. 2000. *Geological Society of America Bulletin* 112(1): 75–85. https://doi.org/10.1130/0016-7606(2000)112%3C75:UJRFAH%3E2.0.CO;2

Yabe, Takahiro, P. Suresh C. Rao, Satish V. Ukkusuri, and Susan L. Cutter. 2022 Toward data-driven, dynamical complex systems approaches to disaster resilience. *Proceedings of the National Academy of Sciences* 119(8): e2111997119. https://doi.org/10.1073/pnas.2111997119

Youngs, Yolonda. 2020. Danger Beyond This Point: Visual representation, cultural landscapes, and the geography of environmental hazards in US national parks. *GeoHumanities* 6(2): 314–346. https://doi.org/10.1080/2373566X.2020.1784017

PSF
PARKS STEWARDSHIP FORUM

The Interdisciplinary Journal of Place-based Conservation

Co-published by the Institute for Parks, People, and Biodiversity, University of California, Berkeley and the George Wright Society. ISSN 2688-187X

Berkeley Institute for Parks, People, and Biodiversity

GEORGE WRIGHT SOCIETY

Citation for this article
Jenkins, Jeffrey. 2022. Science and the evolving management of environmental hazards at Yosemite National Park. *Parks Stewardship Forum* 38(3): 540–555.

Parks Stewardship Forum explores innovative thinking and offers enduring perspectives on critical issues of place-based heritage management and stewardship. Interdisciplinary in nature, the journal gathers insights from all fields related to parks, protected/conserved areas, cultural sites, and other place-based forms of conservation. The scope of the journal is international. It is dedicated to the legacy of George Meléndez Wright, a graduate of UC Berkeley and pioneer in conservation of national parks.

Parks Stewardship Forum is published online at https://escholarship.org/uc/psf through eScholarship, an open-access publishing platform subsidized by the University of California and managed by the California Digital Library. Open-access publishing serves the missions of the IPPB and GWS to share, freely and broadly, research and knowledge produced by and for those who manage parks, protected areas, and cultural sites throughout the world. A version of *Parks Stewardship Forum* designed for online reading is also available at https://parks.berkeley.edu/psf. For information about publishing in PSF, write to psf@georgewright.org.

The journal continues *The George Wright Forum*, published 1981–2018 by the George Wright Society.

PSF is designed by Laurie Frasier • lauriefrasier.com

On the cover of this issue
Climate change creates conditions conducive to larger, more frequent fires, particularly in the American West. As a result, historic structures and artifacts are at greater risk of fire damage. The Bent's Fort Fire started on the morning of April 12, 2022. Approximately 85% of the national historic site's 800 acres burned. Thanks to the efforts of fire crews, the reconstructed adobe fort was undamaged. | NATIONAL PARK SERVICE