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The role of wildfires in the recovery strategy for the endangered southern California steelhead

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ABSTRACT

Southern California steelhead (*Oncorhynchus mykiss*) occupy wildfire-prone watersheds from the Santa Maria River in Santa Barbara County to the Tijuana River at the U.S.-Mexico border. This tectonically active landscape is characterized by a Mediterranean climate, highly erosive soils, and a fire-dependent chaparral/coastal sage scrub-dominated plant community. These features create an unstable landscape to which the southernmost steelhead populations have adapted over the past 20 m.y. Wildfires help to create and maintain essential features of the species' freshwater habitats, including boulder-forced and step pools, which provide oversummering rearing habitat, and spawning gravels, which are essential for reproduction. Disturbance events can also periodically render steelhead spawning and rearing habitat locally inaccessible or unsuitable for the freshwater reproductive phase of their life-history.

The episodic nature of wildfires, floods, and droughts characteristic of southern California is reflected in river and stream evolution as a cyclical rather than a linear process. These disturbance events have become more frequent, intense, and extensive as a result of anthropogenic climate change and the increased extent of the urban-wildland human interface with chaparral/coastal sage scrub and forested lands, including the four U.S. national forests in southern California.

The long-term viability of southern California steelhead populations requires that they be able to persist under the foreseeable natural disturbance regime characteristic of southern California. The recovery strategy pursued by the National Marine Fisheries Service (NMFS) for the listed endangered southern California steelhead has recognized the essential role of wildfire in the species' life-history and its role as one of the major natural disturbances that pose a risk to the listed species. Using a wildfire-frequency analysis, NMFS has adopted a recovery strategy consisting of population redundancy and spatial separation to maximize the persistence of the species in the face of wildfire and associated geomorphic processes and facilitate the species' ability to evolve adaptations in response to changing environmental conditions.

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INTRODUCTION

Steelhead are the anadromous, or ocean-going, form of the species *Oncorhynchus mykiss* (Walbaum, 1792). Historically, these fish were the only anadromous salmonid species that regularly occurred within the coast ranges of southern California (Jordan and Gilbert, 1881; Jordan and Evermann, 1896, 1923; Behnke, 1992, 2002). Other species of anadromous salmonids are found off the coast of southern California, but they do not currently enter freshwater to spawn (Hubbs, 1946). However, as Spence (2019, p. 35), observed, "given the highly migratory nature of the Pacific salmon, and salmonids generally, a fixed freshwater spawning range for the species over geologic periods of time, or in response to shorter climate changes, should not be expected, further compounding questions of the reproductive range of these species."

Following the dramatic rise in southern California's human population after World War II and the associated land and water development within coastal watersheds (particularly major dams, water diversions, and flood-control facilities), steelhead runs rapidly declined, leading to the extirpation of populations in many watersheds and leaving only sporadic and remnant runs in the remainder (Busby et al., 1996; Boughton et al., 2005; Good et al., 2005; Helmbrecht and Boughton, 2005). Whereas steelhead populations have declined sharply throughout southern California, the upstream headwater reaches of most watersheds within the four U.S. national forests in southern California (Los Padres, Angeles, San Gabriel, and Cleveland) have retained populations of the non-anadromous life-history form of the species—commonly known as resident rainbow trout. However, many of the southernmost steelhead populations have experienced substantial genetic introgression through stocking of non-endemic strains of *O. mykiss* or other nonnative trout species (Girman and Garza, 2006; Garza et al., 2014; Abadía-Cardoso et al., 2016).

Numerous factors have contributed to declines in steelhead populations, including: (1) loss or degradation of freshwater and estuarine habitat as result of anthropogenic activities such as water-supply and flood-control developments; (2) urban and agricultural land-use practices that encroach on floodplain, riparian, and estuarine areas; (3) overfishing and hatchery practices; and, more recently, (4) climate-related changes (Busby et al., 1996; Stouder et al., 1997; Good et al., 2005; Capelli, 2007; Araki et al., 2008, 2009; Crozier et al., 2008; Beamish et al., 2010; Cooper et al., 2013; Williams et al., 2015; Garfin et al., 2018; Intergovernmental Panel on Climate Change, 2021, 2023; Kocik et al., 2022; National Oceanic and Atmospheric Administration [NOAA] Fisheries Southwest Fisheries Science Center, 2022). Poor ocean conditions in response to large-scale changes in the North Pacific Gyre Oscillation or the Pacific Decadal Oscillation and longer-term climate change can affect the growth and survival of ocean-maturing steelhead (and other West Coast Pacific salmon), and therefore the size of returning spawning runs (Mantua et al., 1997; Mantua and Hare, 2002; Mantua et al., 2010; Mantua, 2011; Johnstone and Mantua, 2014; Intergovernmental Panel on Climate Change, 2021, 2023; NOAA Fisheries Southwest Fisheries Science Center, 2022).

In 1997, in response to the sharp decline of southern California steelhead populations, the National Marine Fisheries Service (NMFS) listed the populations from the Santa Maria River south to Topanga Creek as an endangered Evolutionary Significant Unit (ESU) under the U.S. Endangered Species Act (ESA) (Federal Register, 1997); in 2002, NMFS extended the listing to cover the populations southward from the Santa Monica Mountains to the U.S.-Mexico border (Federal Register, 2002). Critical habitat was designated for steelhead and other Pacific anadromous salmonids in 2005 (Federal Register, 2005). In 2006, NMFS reaffirmed the species listing as endangered under the Distinct Population Segment (DPS) policy (Federal Register, 2006). The listing included only the anadromous form of the southern California *O. mykiss* populations and therefore applied only to the sub-reaches of streams and rivers downstream of dams or other barriers to upstream-migrating steelhead (Fig. 1).

In 2012, NMFS published a Southern California Steelhead Recovery Plan (NMFS, 2012) to guide the recovery of this federally listed endangered species. NMFS's recovery plan recognized the prevalence of natural disturbances such as wildfire and post-wildfire geomorphic processes, including floods and debris flows, which have the potential to extirpate an entire steelhead population in a watershed. NMFS adopted a recovery strategy of population redundancy and spatial distribution (and natural recolonization) to maximize the long-term viability of southern California steelhead. Multiple recovered populations distributed across the steelhead recovery planning area are intended to ensure the survival of at least one viable population, in each of five Biogeographic Population Groups (BPG) comprising the recovery planning area, in the aftermath of a worst-case natural catastrophic event such as a large wildfire or debris flow (Fig. 2). The assumption is that this population would then serve as a source population that would recolonize extirpated watersheds after the habitat had recovered from a catastrophic disturbance event. This chapter reviews how knowledge about the wildfire regime in southern California was used to inform the recovery strategy for the southern California steelhead, and the viability criteria that will be used to determine when the species has recovered and would therefore become a candidate for removal from the federal list of threatened and endangered species, consistent with the requirements of the ESA.

Environmental Setting

Southern California steelhead occur in chaparral/coastal sage scrub landscapes that differs in significant ways from steelhead habitats found in snow-fed and/or conifer-dominated ecosystems in the more northerly Pacific Coast mountain ranges and the western Sierra Nevada (Stephenson and Calcarone, 1999; Mooney and Dawson, 2016; Millar and Rundel, 2016; North et al., 2016). Chaparral consists of woody shrubs from sea level

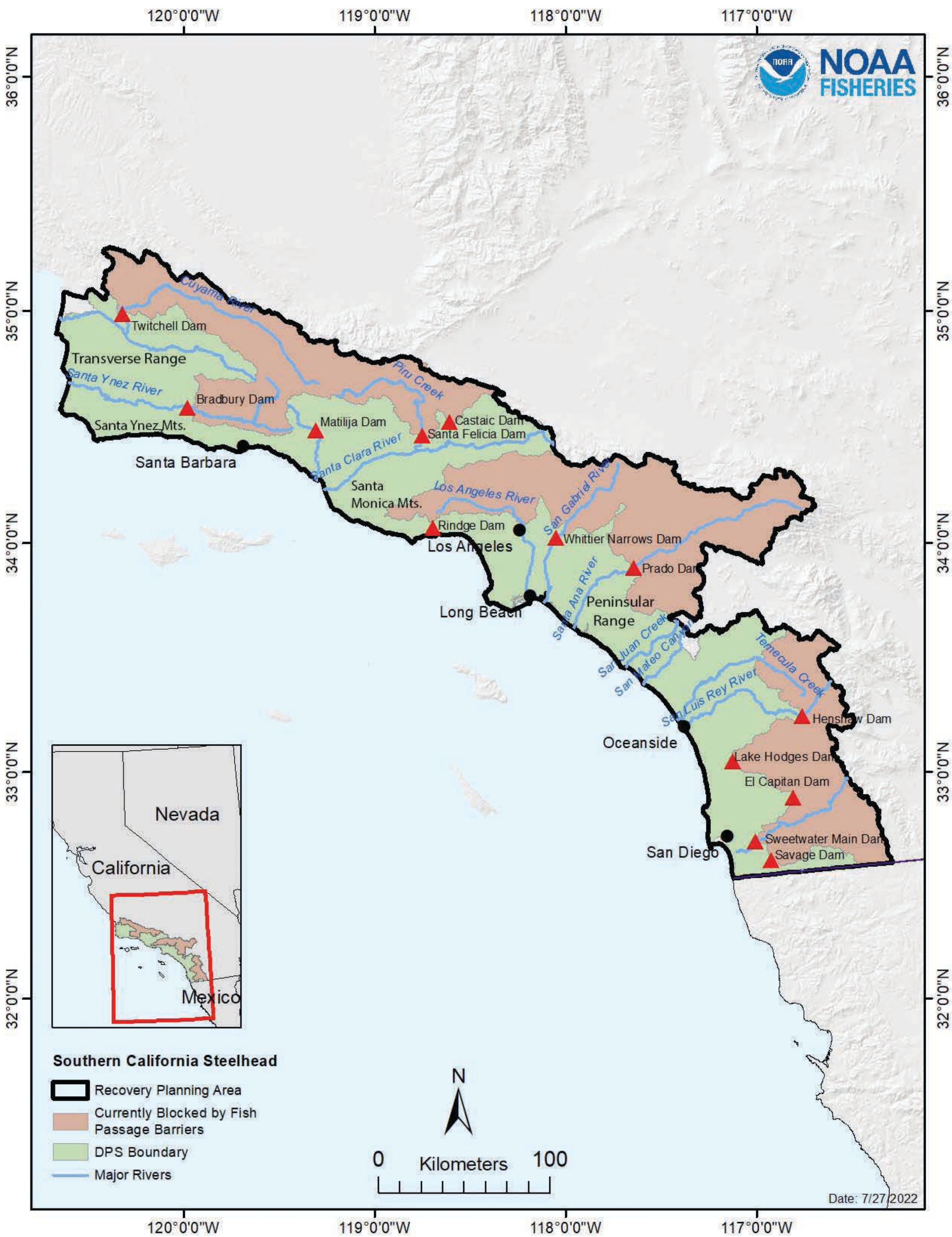

Figure 1. Southern California Steelhead Recovery Planning Area and Southern California Distinct Population Segment (DPS), a sub-area of the recovery planning area delimited by the presence of dams (red triangles) or other barriers to upstream-migrating steelhead.

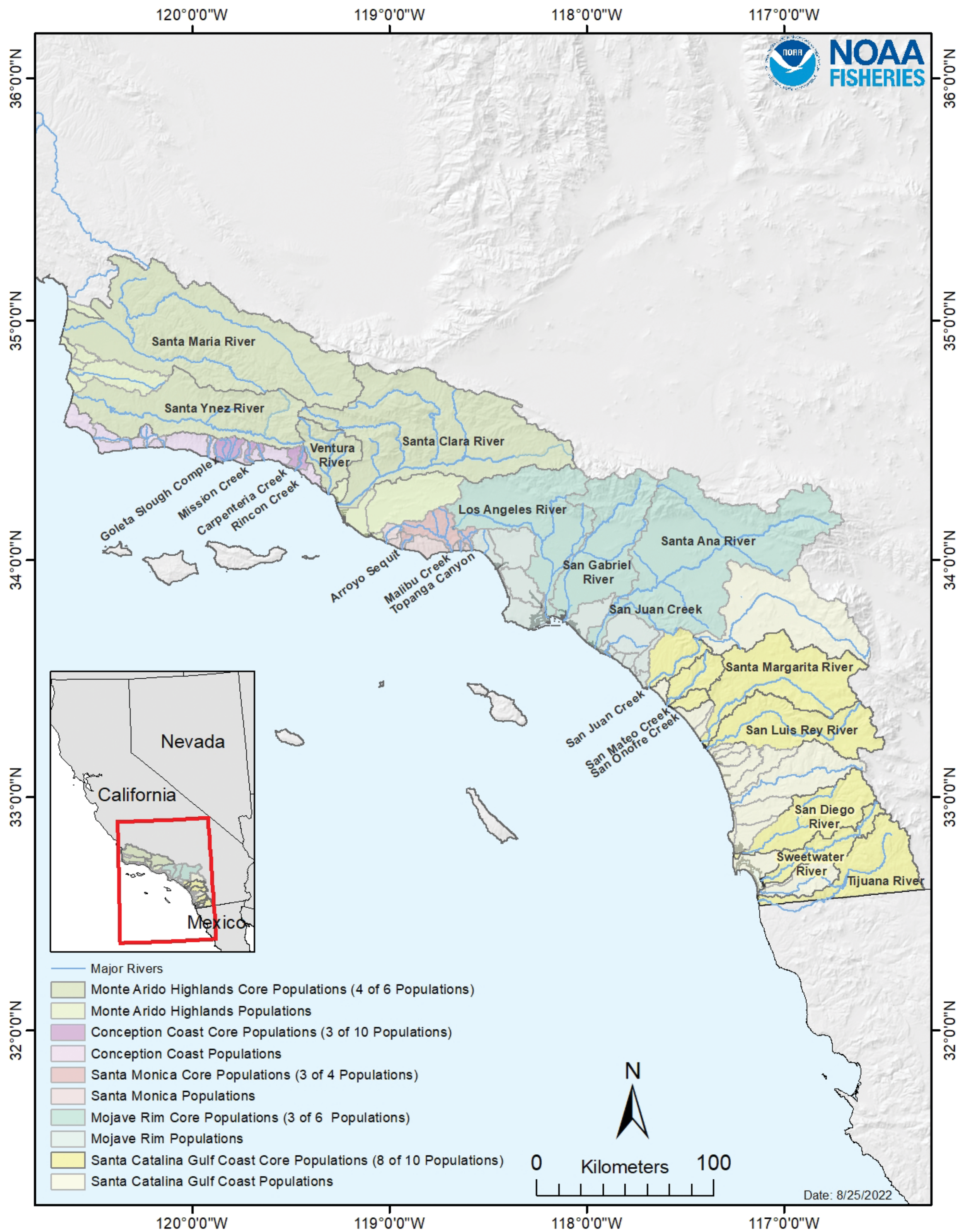

Figure 2. Biogeographic Population Groups (BPGs) within the Southern California Steelhead Recovery Planning Area. The number of populations in parentheses are the minimum number of core recovery populations out of the total number of steelhead-bearing watersheds in each BPG necessary to meet the DPS-wide viability criteria for redundancy and spatial separation and distribution within the Southern California Steelhead Recovery Planning Area.

to ~1500 m, which can form dense stands (>10 yr old) when mature (Keeley and Davis, 2007; Keeley and Syphard, 2018; Parker et al., 2018; Underwood et al., 2018). Coastal sage scrub (often referred to as "soft chaparral") consists of low-growing, less woody shrubs from sea level to ~900 m, which form more open stands (Westman, 1982; O'Leary, 1990; Rundel, 2007; Underwood et al., 2018). Both plant communities contain species with aromatic oils and, when mature, abundant dead branch material, which contributes to their high flammability. Both plant communities are fire-dependent and exhibit a number of phenological features that have adapted them to repeated burning. The pre-European settlement fire return intervals associated with these plant communities varied greatly: chaparral, 30–90 yr; coastal sage scrub, 20–120 yr (Van de Water and Safford, 2011). However, fire frequency has increased in southern California as a result of anthropogenic activities, including climate change (Zedler, 1995; Keeley and Syphard, 2016, 2018; Parker et al., 2018; Underwood et al., 2018). Southern California shares with other Mediterranean regions a climate characterized by long dry summers and short, sometimes intense cyclonic winter storms (Keeley et al., 2012; Ester et al., 2018). Rainfall is restricted almost exclusively to the fall, winter, and spring months (October through April), though the southernmost portion of the region is subject to occasional summer storms originating from the Gulf of California (U.S. Weather Bureau, 1961; Weaver, 1962; Bailey, 1966; Potter, 2014).

The region is also subject to an El Niño/La Niña–Southern Oscillation weather cycle, which can significantly affect winter precipitation, causing highly variable rainfall among water years (Schonher and Nicholson, 1989; Philander, 1990, 2004; Andrews et al., 2004; Davis, 2022). Additionally, there is a wide disparity in annual winter rainfall along the coast, as well as between coastal plains and inland mountainous areas. Mean annual precipitation along the coast (west to east) ranges from 32 to 24 cm/yr, with larger variations (24–90 cm/yr) from the coast to inland areas (south to north) due to the orographic effects of the Transverse Ranges (Santa Ynez, Santa Monica, San Gabriel, and San Bernardino Mountains) and the Peninsular Ranges (Santa Ana, San Jacinto, Sana Rosa, and Laguna Mountains) within southern California (Neiman et al., 2002, 2004; Conil and Hall, 2006; Hughes et al., 2009). Fog along the coastal areas is typical in late spring and summer, extending inland along coastal reaches with valleys extending into the interior (Coffin, 1961; Leipper, 1994). Fog can moderate conditions for rearing *O. mykiss* in these lower, coastal reaches. The region also experiences seasonally high downslope winds (e.g., Santa Ana or "sundowner" winds). These seasonal hot, dry winds occur primarily during the fall and winter, and they are driven by large-scale atmospheric circulation resulting from high pressure over the Great Basin coupled with low pressure off the southern California coast (Ryan and Burch, 1992; Raphael, 2003; Westerling et al., 2004). These winds can reach 60 km/h, or more, and can increase the burn severity and size of chaparral/coastal sage scrub or forest wildfires, especially under drought conditions (Miller and Schlegel, 2006; Mastrandrea et al., 2009; Mastrandrea and Luers, 2012; Keeley et al., 2012; Jin et al., 2015; Dong et al., 2019).

The geologic setting of southern California is complex and characterized by extensive Cenozoic (Tertiary and Quaternary) sedimentary rock formations (both marine and terrestrial) in the Transverse Ranges, which are highly fractured by active faults, and subject to high rates of erosion (Hornbeck and Kane, 1983; Norris and Webb, 1990; Harden, 2004; Warrick and Mertes, 2010; Keller and DeVecchio, 2013). The Peninsular Ranges are dominated by Mesozoic (Triassic, Jurassic, Cretaceous) granitic rocks, with exposed formations that are often decomposed as a result of weathering processes and subject to erosion (Morton and Miller, 2014). Both ranges are characterized by rapid and continuing uplift ranging from 0.1 to 1.5 m/k.y. (Graham and O'Geen, 2016). On steep hillslopes, these formations are subject to high rates of erosion and episodic debris flows (Starkel, 1976; Scott and Williams, 1978; Brownlie and Taylor, 1981; Taylor, 1981; Inman and Jenkins, 1999; Lavé and Burbank, 2004; Kean et al., 2011, 2019; DiBiase and Lamb, 2013, 2019; Kean and Staley, 2021). Debris flows are water-laden masses of soil, sand, and large rocks and boulders that have a high bulk density but that can flow with the fluidity of water, and can reach speeds greater than 36 km/h. Debris flows differ from mudslides and other types of mass earth movements by containing a high percentage (>50%) of sediment larger than sand-sized material (Costa and Wieczorek, 1987; Keller and DeVecchio, 2019). Debris flows can occur in response to intense winter storms, particularly storms immediately following wildfires, as well as land-use changes resulting from development or vegetation type conversion (Hanes, 1971; Wells, 1981, 1985, 1987; Gabet and Dunne, 2003; Kean et al., 2011, 2019; Warrick et al., 2012, 2015; Gartner et al., 2014; Alessio et al., 2021; Khand and Senay, 2021; Kean and Staley, 2021).

Short but intense rainfall events can cause debris flows that can have catastrophic effects on steelhead populations (Boughton et al., 2007a). Keller et al. (1997) identified large debris flows as the most severe type of sediment transport event, moving large amounts of sediment of various sizes, from fine grains to large boulders. Keller et al. (1997, 2020) hypothesized that large debris flows in southern California are usually produced by the convergence of three conditions: (1) a preexisting large geomorphic instability somewhere in the stream network that provides a sediment source; (2) a large wildfire that removes vegetation and exposes the ground surface to the impact of precipitation; and (3) an exceptionally intense winter rainstorm within one or two years following a wildfire. Because of the rapid recovery rate of chaparral/coastal sage scrub vegetation following a wildfire, the potential for large debris flows related to a wildfire subsides relatively quickly to the background levels associated with unburned conditions (Warrick et al., 2012; Kean and Staley, 2021).

The frequency of wildfires is greater than that of large debris flows (Keller, 2011; Keller and DeVecchio, 2019). Thus, if a group of recovered of steelhead populations has sufficient redundancy and spatial separation to be protected against wildfire risk, the populations will also likely be able to persist in the face of large debris flows (Boughton et al., 2007a).

Chaparral/coastal sage scrub ecosystems can be divided into two basic categories for the purposes of steelhead recovery planning: small coastal watersheds with relatively short stream lengths draining directly into the ocean (e.g., those draining the coastal Santa Ynez and Santa Monica Mountains), and large watersheds extending inland and separated from the coast by ridges within the Transverse and Peninsular Mountain ranges (e.g., Santa Ynez, Ventura, Santa Clara, Los Angeles, San Gabriel, Santa Ana, San Luis Rey, and San Dieguito rivers). The more numerous coastal watersheds tend to be small, relatively wet, and heavily influenced by the marine climate, with significant fog in the summer months; the larger watersheds extending inland are relatively few and have a hotter, terrestrial-influenced climate (Figs. 1 and 2; Coffin, 1961; U.S. Weather Bureau, 1961; Felton, 1965; Leipper, 1994; Boughton et al., 2006).

Within the Southern California Steelhead Recovery Planning Area, coastal and inland watersheds were stratified into five BPGs (Fig. 2). These groups are composed of geographically contiguous watersheds with broadly similar physical geography and hydrology (Boughton et al., 2006, 2007a; NMFS, 2012). The combinations of these physical characteristics present differing natural selective regimes for steelhead populations utilizing groups of watersheds among the five BPGs. These differing physical characteristics have led to diverse life-history adaptations that enable the populations to persist in the varying habitat conditions represented by the five BPGs. From north to south, these BPGs are: (1) Monte Arido Highlands, (2) Conception Coast, (3) Santa Monica Mountains, (4) Mojave Rim, and (5) Santa Catalina Gulf Coast (Boughton et al., 2006). The basic biologic goal adopted by NMFS for the recovery of southern California steelhead is the protection and perpetuation (by continued evolutionary adaptations) of the natural genotypic, phenotypic, and behavioral biodiversity of steelhead populations—through the restoration and protection of the diverse steelhead habitats within the five BPGs (Fig. 2).

Wildfires and Sedimentation in Southern California Watersheds

The historical record provides glimpses of the future environmental variability of southern California—prolonged droughts, large wildfires, and longer-term climate changes, exacerbated by anthropogenic disturbances—and implications for the persistence of steelhead in southern California (Byrne et al., 1977; Haston and Michaelsen, 1997; Mensing et al., 1999; Battin et al., 2007; Everett, 2008; Andrews and Antweiler, 2012; Griffin and Anchukaitis, 2014; He and Gautam, 2016; Mosase et al., 2019; Davis, 2022). There is also evidence that indigenous peoples employed fire management in chaparral/coastal sage scrub plant communities to maintain different vegetation ages and size classes to meet food and other material needs, thus creating a mosaic of chaparral and native grasslands (Aschmann, 1959; Lewis, 1993; Timbrook et al., 1993; Keeley, 2002; Stewart et al., 2009; Anderson, 2006, 2013, 2018; Lightfoot et al., 2015; Anderson and Keeley, 2018). The pattern and spatial extent of intentional burning remains an active area of investigation, with some estimates as high as 25% of the landscape altered by indigenous fire-driven type conversion of chaparral/coastal sage scrub plant communities to grasslands (Anderson and Keeley, 2018). For a longer view of paleo-environmental changes (including climate change, vegetation and fauna composition) concurrent with indigenous colonization of southern California, and North and South America generally, during the later Pleistocene, see Pinter et al. (2011); Kelly et al. (2020); O'Keefe et al. (2023).

Next to water, fire may be the most distinguishing physical feature on Earth's surface. Viewed globally, a significant portion of Earth's land surface is on fire year-round (Scott et al., 2014; Scott, 2018; Pyne, 2021). While the occurrence of wildfire is pervasive across the globe, some regions are naturally more prone to frequent burning, and areas with a Mediterranean climate (with a pattern of intense rainfall, which fuels the growth of vegetation, and long dry seasons that reduce moisture) are particularly vulnerable to naturally or anthropogenically initiated wildfires (Keeley et al., 2012; Underwood et al., 2018).

Wildfires are a pervasive phenomenon in southern California and are an integral part of a complex suite of natural physical processes that create and serve to maintain both the terrestrial and aquatic habitats in the Mediterranean climate and the chaparral/coastal sage scrub-dominated landscape characteristic of the recovery planning area (Swanson, 1981; Keeley and Zedler, 2009; Keeley et al., 2012; Scott et al., 2014; Keeley and Syphard, 2016, 2017, 2018; McLauchlan et al., 2020; Florsheim and Chin, 2022; Syphard et al., 2022). Wildfire and related hillslope erosion and sediment transport to and deposition in stream channels play critical roles in recruiting suitably sized spawning gravels (with a medium diameter between 15 and 45 mm) that are necessary to maintain steelhead spawning habitat (Kondolf and Wolman, 1993; Schuett-Hames et al., 1996; Kondolf, 2000; Boughton et al., 2006; Morell et al., 2021). Wildfire can burn vegetation that is then transported to a stream channel by hillslope and fluvial processes, where downed wood material can alter channel morphology (Keller and Swanson, 1979; Thompson et al., 2008). Geomorphic processes associated with significant rainfall events and elevated streamflows erode and deposit sediment and wood material in stream channels, contributing to stream channel complexity in steelhead habitats. This complexity creates high-quality habitat for steelhead, and it also provides habitat for other aquatic species, including invertebrates, which are an important food source for rearing juvenile steelhead (Bond and Bradley, 2003; Thompson et al., 2008, 2012; Bendix and Cowell, 2010a, 2010b; Lassettre and Kondolf, 2011; Harrison et al., 2017). Other effects of wildfire important to the creation and maintenance of steelhead habitat include (Figs. 3 and 4): (1) increased runoff in response to rainfall on burned slopes and hydrophobic soils (DeBano et al., 1967; DeBano, 2000; Ice et al., 2004; Goforth et al., 2005; Larsen et al., 2009; Moody et al., 2013; Chen et

Figure 3. Ventura River watershed, looking south toward the North Fork Matilija Creek, 7 January 2018. The extensive loss of chaparral vegetative cover was caused by the 2017 Thomas Fire, which burned ~90% of the Ventura River watershed. Photo: Mark H. Capelli, National Marine Fisheries Service.

al., 2013; Neumann, 2016; Saxe et al., 2018; Wilder et al., 2020; Movasat and Tomac, 2021); (2) increased groundwater support for summer base flows (Tague et al., 2009; Bart and Tague, 2017; Tsinnajinnie et al., 2021); (3) modification of the composition of terrestrial and riparian vegetation (Davis et al., 1988; Faber et al., 1989; Bendix and Hupp, 2000; Loáiciga et al., 2001; Bendix and Cowell, 2010a, 2010b; Cooper et al., 2015; Bendix and Commons, 2017); and (4) alteration of water quality, including inputs of nutrients such as nitrogen and carbon that control instream plant growth and affect pH and dissolved oxygen levels (Knicker,

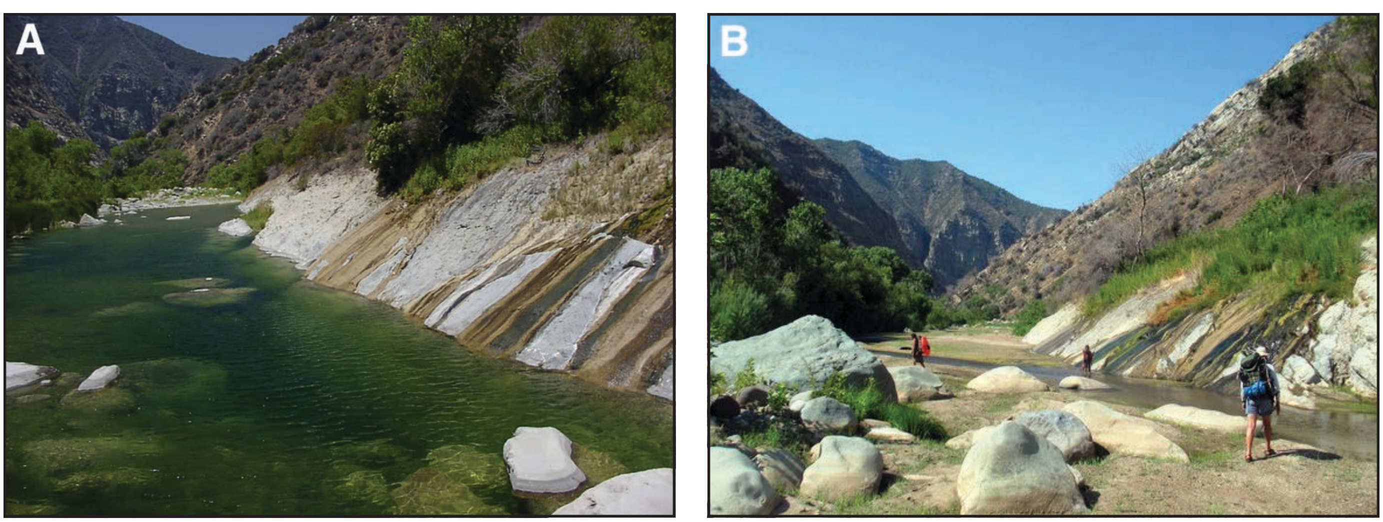

Figure 4. (A) Sespe Creek prefire pool, 2002. (B) Sespe Creek postfire pool, 2008. Photos: Mark H. Capelli, National Marine Fisheries Service.

2007; Bodí et al., 2014; Aguilera and Melack, 2018; Goodridge et al., 2018).

Natural patterns of wildfire (i.e., timing, intensity, frequency, geographic extent, etc.) have been modified by short- and longer-term climatic changes (particularly droughts), and by anthropogenic interventions, including ignitions and firefighting methods and strategies. Wildfires are likely to increase in frequency, intensity, and extent as a result of these and a variety of other factors, including increased human-caused ignitions, vegetation type conversions, and anthropogenic climatic changes (Hanes, 1971; Cook et al., 2004; Diffenbaugh et al., 2008; Westerling and Bryant, 2008; Westerling et al., 2009; Bryant and Westerling, 2009; Seager et al., 2015; Westerling, 2016; Abatzoglou and Williams, 2016; Garfin et al., 2018; Keyser and Westerling, 2019; Radeloff et al., 2018; Parks and Abatzoglou, 2020; Li and Banerjee, 2021; Brown et al., 2023). Wildfire is an active area of research, and monthly updates on wildfire-related publications are compiled by the Fire Research Institute: www.firerearchinstitute.org.

Recurring droughts are a fundamental characteristic of southern California's Mediterranean climate, and they strongly influence wildfire occurrence and behavior. The most recent series of droughts (2012–2022), coupled with extensive wildfires, illustrates the threat posed by these environmental perturbations to southern California steelhead. No adult steelhead have been observed in most southern California rivers and streams over the past 10 yr (2012–2022). In watersheds where adult steelhead were observed, the fish counts have been in the single digits (Alagona et al., 2012; Dagit et al., 2017, 2019, 2020; Redman, 2021; St. George and Horgan, 2022; NMFS, 2023). Thus, during the most recent extended drought, expression of the steelhead's anadromous life history has nearly disappeared. The risk of permanently losing the anadromous phenotype (and related haplotypes) of *O. mykiss* over the long term is high and increasing due to the lack of unobstructed migration corridors between the Pacific Ocean and upstream spawning, rearing, and oversummering drought refugia habitats (Deitch et al., 2018; NMFS, 2023). Droughts can also affect the rate of recovery of watersheds affected by wildfire (Florsheim et al., 2017; Florsheim and Chin, 2022). By delaying the revegetation of denuded slopes, or prolonging the transport of elevated levels of sediment, which then accumulates—either through dry ravel processes or other hillslope erosion processes—in the stream channel network, steelhead habitats can be rendered unsuitable for spawning, rearing, or oversummering refugia for extended periods. Figures 4A and 4B illustrate the long-term effects of wildfire coupled with an extended drought on sedimentation in steelhead rearing and refugia habitat of Sespe Creek—an important steelhead spawning tributary to the Santa Clara River, and a core recovery watershed identified in NMFS' recovery plan (NMFS, 2012). The watershed experienced a series of extensive wildfires between 2002 and 2006: Wolf Fire (2002), Piru Fire (2003), and Day Fire (2006). These fires burned a total of 421 km^2 (28%) of the Sespe Creek watershed (U.S. Fish and Wildlife Service, 2003; Clark et al., 2003; U.S. Forest Service, 2006a, 2006b, 2007; Stillwater Sciences, 2010). The elevated rates of erosion and sedimentation during subsequent small storms (in combination with ongoing rock weathering and dry raveling processes) filled in many of the deep pools that typically maintain water year-round. These deep pools are also fed by cool groundwater seeps that provide water with suitable temperatures for rearing juvenile steelhead. Twenty years after this series of wildfires, the large pools in the lower Sespe Creek had not completely reestablished their prefire depth; the long recovery has been exacerbated by the prolonged drought beginning in 2012 and extending through 2022 (Swain et al., 2014; Williams et al., 2015; Mount et al., 2021). Three post–Day Fire sediment production estimates produced a range of postfire sediment production and delivery predictions for the main stem of Sespe Creek (from 3 to 20 times above background levels), depending on antecedent sediment and storage and rainfall conditions, the magnitude of the first postfire rainfall event, and routing of the sediment through Sespe Creek. In the lower reaches of Sespe Creek (Figs. 4A and 4B), pools were filled with as much as 5 m of sandy sediments; this likely occurred during high flows in 2005 and moderately high flows in early 2008, which eroded substantial amounts of material from the steep, denuded hillslopes; however, the storm events were not sufficient to transport the elevated level of sediment through the stream network into the lower main stem of the Santa Clara River (Stillwater Sciences, 2010).

Multiple wildfires have occurred over the past 70 yr throughout the recovery planning area, in each of the five BPGs, affecting most of the core recovery watersheds identified in NMFS' recovery plan (Dressler et al., 2020; NMFS, 2023). The incidence of recorded wildfires in southern California from 1950 to 2019 is generally highest in the inland mountainous areas dominated by chaparral. A notable exception is the coastal Santa Monica Mountains, where the urban-wildland interface is extensive on both the inland and coastal sides of the chaparral/coastal sage scrub plant communities (Fig. 5).

Wildfires that occur in mountainous areas with steep slopes composed of highly erodible sedimentary or other weathered rock types have the potential to promote debris flows or otherwise accelerate the natural processes of erosion, transportation, and sediment delivery to the stream networks associated with these wildfires. Small postfire debris flows are also frequent in headwater tributaries, but because of their limited extent, they do not generally affect the entire burned area (Florsheim et al., 2017; Kean et al., 2011; Kean and Staley, 2021), and therefore the entire *O. mykiss* population in the affected watershed.

The episodic nature of wildfires, floods, and droughts characteristic of southern California is also reflected in river and stream channel (and floodplain) evolution as a cyclical rather than a linear phenomenon (Waananen and Crippen, 1977; Chin, 1998, 1999, 2002; Dunham et al., 2007; Cluer and Thorne, 2014; Keller et al., 2015). Rivers and streams naturally receive, store, and exchange inputs of sediment and nutrients generated by hillslope disturbances triggered by seismic, wildfire, and/or intense rainfall events. While the ongoing processes of hillslope evolution, channel

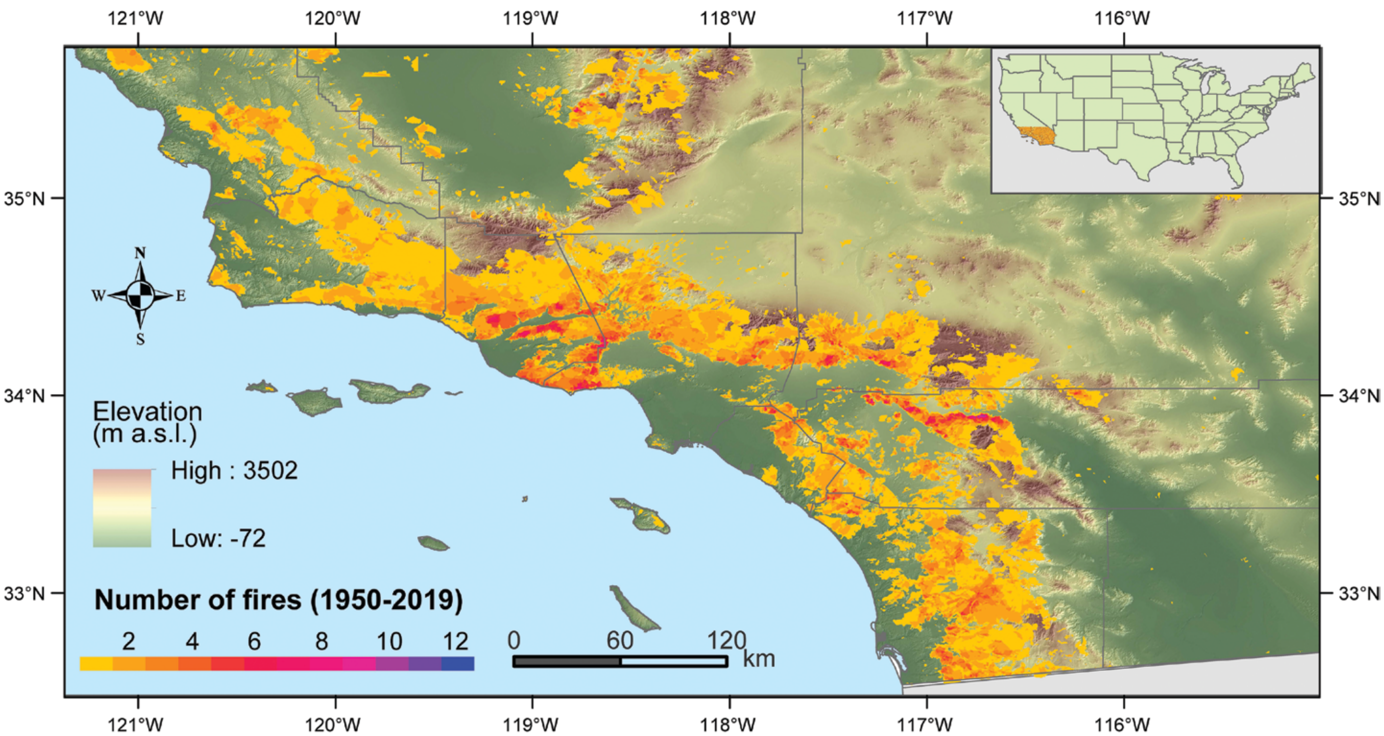

Figure 5. Total number of recorded wildfires in southern California from 1950 to 2019. Figure is courtesy of Chunyu Dong, Sun Yat-sen University and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China. Elevation: m above sea level (m a.s.l.).

deposition, and scour are essential habitat-forming and maintenance processes, these disturbance events can also temporarily degrade steelhead spawning and rearing habitats by: (1) smothering suitable spawning gravels with fine sediments that prevent or retard the incubation of eggs by reducing the hyporheic flow and dissolved oxygen through spawning gravels (Cordone and Kelley, 1961; Waters, 1995; Kondolf, 2000; Verkaik et al., 2013); (2) filling in deep pools, which provide oversummering and drought refugia habitat for rearing juvenile steelhead (Spina and Tormey, 2000; Verkaik et al., 2013; Isaak et al., 2015; Florsheim et al., 2017); (3) altering water-temperature regimes by reducing pool depths and cold groundwater inputs (Dunham et al., 2007; Isaak et al., 2016, 2020; Verkaik et al., 2013); and (4) promoting the spread of invasive, nonnative species (Bell et al., 2009; Coffman et al., 2010; Verkaik et al., 2013). Large wildfires with significant debris flow potential have occurred in all five BPGs within the recovery planning area within the most recent 10 yr period (2012–2022).

In 2014, the U.S. Geological Survey (USGS) initiated a program to provide debris-flow projection maps for areas affected by wildfire where there was a significant potential for a debris-flow event in response to a wildfire followed by intense rainfall. The post-wildfire debris-flow maps are based on geospatial data related to basin morphometry, particularly the degree of slope, burn severity, soil properties, and historic rainfall patterns within the watersheds; these parameters were used in conjunction with a logistic model to estimate the likelihood and volume of debris flows for selected watersheds in response to a post-wildfire design storm (Staley et al., 2016; Kean and Staley, 2021). A design storm is a rainfall event with an intensity of 24 mm/h for 15 min (equivalent to 6 mm of rainfall accumulation over a 15 min interval). For many parts of California, the 24 mm/h–15 min scenario is roughly equivalent to a 1 yr rainfall storm recurrence interval (Staley et al., 2020; see also Cannon et al., 2008). Additional rainstorm scenarios from 12 mm/h to 40 mm/h in 4 mm/h increments were provided in the USGS geodatabase for each wildfire. Rainfall recurrence intervals can also be estimated for a specific location from the NOAA Atlas 14: https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html. Details on the methodology used by the USGS to determine debris-flow potential can be found at: https://www.usgs.gov/programs/landslide-hazards/science/scientific-background.

While the USGS debris-flow potential maps were developed primarily to project and manage post-wildfire debris-flow hazards, they were based in part on identification of steep slopes where post-wildfire sediment erosion from other hillslope processes is also possible. The maps can therefore also be used as a proxy to identify potential impacts to steelhead habitats from elevated rates of hillslope erosion and sediment transport to instream habitats. Elevated levels of sedimentation are particularly significant because they can degrade or destroy steelhead habitats by burying spawning gravels with fine sediment and reduce the flow depths of stream riffles, which are important rearing/feeding habitat for juvenile *O mykiss*, as well as other aquatic species. Sedimentation similarly fills in refugia pools that provide important oversummering habitat for rearing steelhead (Cordone and Kelley, 1961; Florsheim et al., 1991; Waters, 1995; Spina and Tormey, 2000). Sediment from large debris flows and other erosion processes has the potential to radically modify stream morphology and extirpate entire steelhead populations (Boughton et al., 2007a).

Debris flow potential maps of selected recent wildfires in each of the five BPGs illustrate the prevalence of potential debris flows with the ability to adversely affect stream habitats within the recovery planning area (Figs. 6–11). Each map depicts the areas providing potential source material for debris flows (and also potential elevated hillslope erosion and dry ravel processes) in core steelhead recovery watersheds utilized by southern California steelhead within each BPG. The maps also depict the relative potential initiation of a debris-flow event within individual sub-watersheds associated with the respective wildfire; however, they do not depict the downslope course or the distribution of debris-flow material through the stream network, which may vary considerably depending on the amount of available sediment and the intensity and duration of a triggering rainfall event.

Habitat Impacts of Recent Southern California Wildfires

The 2017 Thomas Fire affected steelhead habitats in three of the four core recovery populations in the Monte Arido Highlands BPG: Santa Ynez River, Ventura River, and Santa Clara River. The wildfire also affected several core recovery populations in the adjacent Conception Coast BPG, including Rincon Creek, Carpinteria Creek, Montecito Creek, San Ysidro Creek, and Sycamore Creek (Figs. 2 and 6).

Within the perimeter of the Thomas Fire, the highest debris-flow potential was located in the headwater reaches of the burned watersheds with steep slopes dominated by chaparral vegetation. A significant portion of the steelhead spawning, rearing, and oversummering drought refugia habitat is located in these debris-flow–prone areas; additionally, elevated hillslope erosion of fine

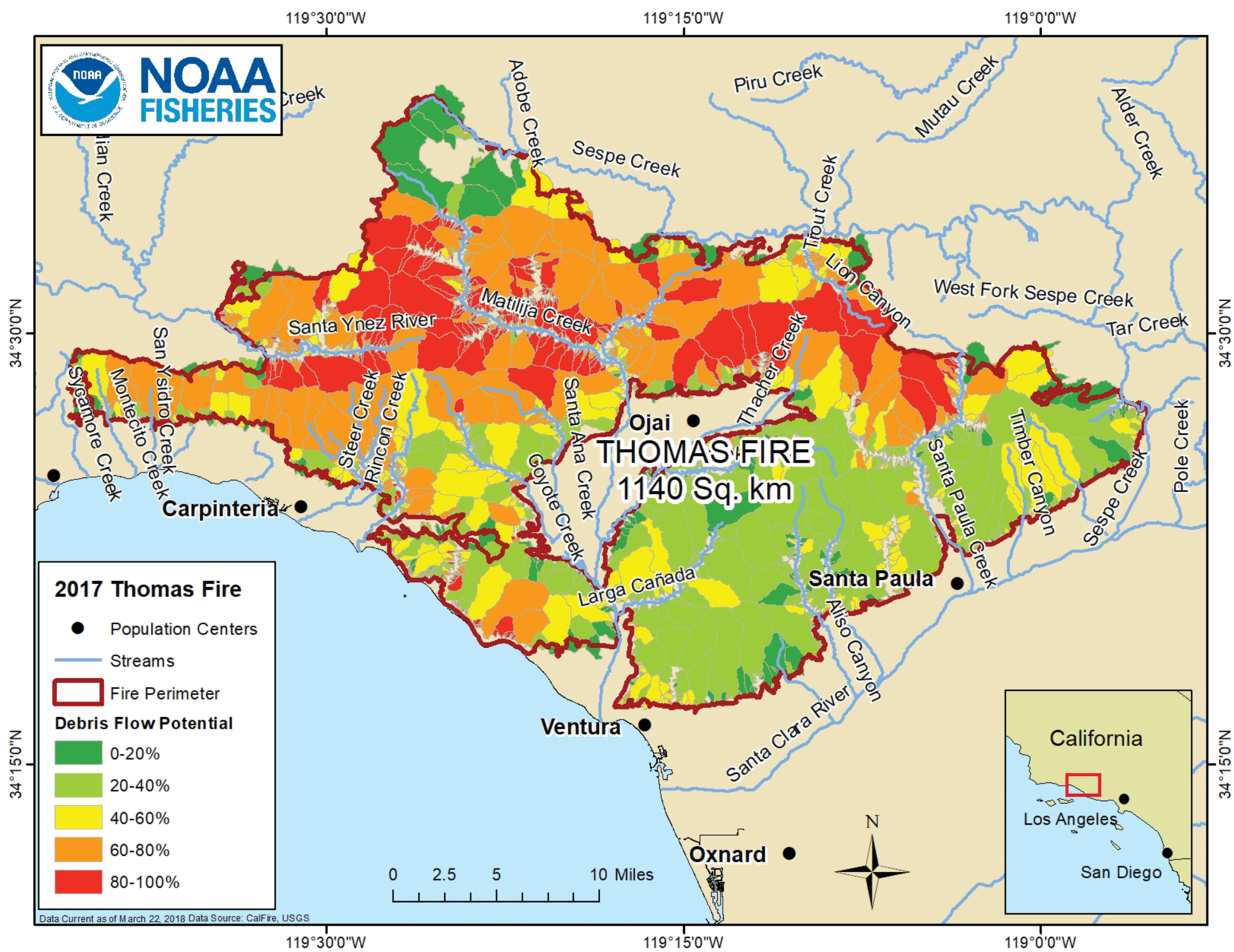

Figure 6. Thomas Fire and debris-flow potential within the Monte Arido BPG. Source: USGS Landslide Hazards Program (USGS, 2022).

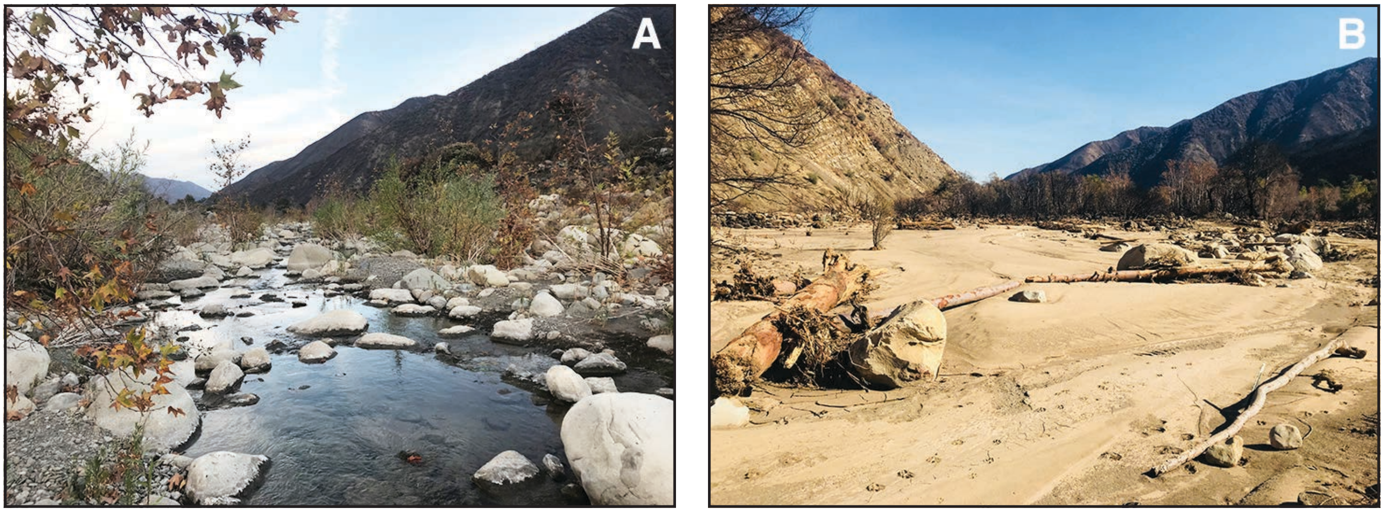

Figure 7. (A) Matilija Creek post–Thomas Fire, 7 January 2017. (B) Matilija Creek post–debris flow, 9 February 2018. Photos: Mark H. Capelli, National Marine Fisheries Service.

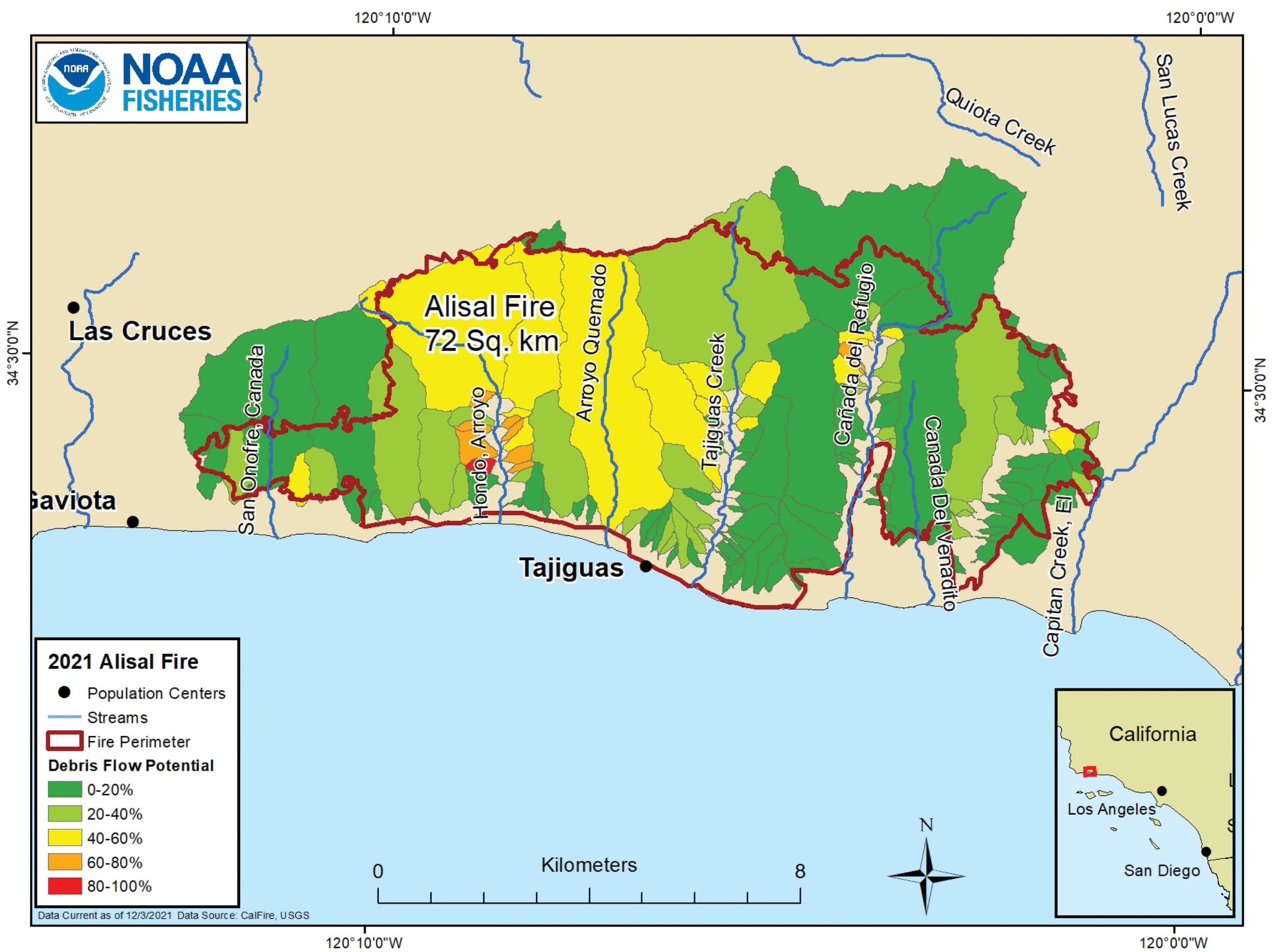

Figure 8. Alisal Fire and debris-flow potential within the Conception Coast BPG. Source: USGS Landslide Hazards Program (USGS, 2022).

sediments generated by smaller postfire rainfall events has the potential to degrade steelhead spawning and rearing habitats in downstream reaches (Klose, 2018). In addition to the large debris flow that impacted the community of Montecito, Santa Barbara County (Serra-Llobet et al., 2023), the Thomas Fire and subsequent rainfall event of 8–9 January 2017 triggered a debris flow in the upper Matilija Creek watershed (a tributary to the Ventura River) and resulted in elevated levels of suspended sediments (Jumps et al., 2022). This debris flow eroded large amounts sediment from the steep slopes of the upper Matilija Canyon, transported material downstream, and filled in pools that had provided productive spawning and rearing habitat. *O. mykiss* populations were reportedly extirpated from the main stem of the Matilija Creek and the North Fork Matilija Creek; however, small numbers of *O. mykiss* were subsequently identified in two of its tributaries, Muirietta Creek and Upper North Fork Matilija Creek (Figs. 7A and 7B; Klose, 2018; Redman et al., 2018; Carmody, 2009; Evans, 2019; Evans and St. George, 2020). Other major recent fires that have affected steelhead habitat within the Monte Arido Highlands BPG include the Hill Fire (2018) and Maria Fire (2019).

The 2021 Alisal Fire affected a majority of the steelhead habitats in three of the 17 core recovery populations in the Conception Coast BPG: San Onofre, Arroyo Hondo, and Canada del Refugio (Figs. 2 and 8). The previous 2017 Whittier Fire immediately downcoast affected four additional core recovery populations in the Conception Coast BPG and three tributaries to the lower Santa Ynez River in the Monte Arido Highlands BPG.

Within the perimeter of the Alisal Fire, the highest debris-flow potential is in the upper reaches of the watersheds with steep slopes dominated by chaparral vegetation, and in the lower reaches, which have a combination of chaparral/coastal sage scrub vegetation. Arroyo Hondo is one of the few watersheds within this BPG where adult spawning steelhead have been recently documented (Fischer and Haverland, 2014; Meeuwen, 2014; Dressler, 2015; Capelli, 2017; Pelletier et al., 2018); significantly, no *O. mykiss* individuals have been observed in Arroyo Hondo since the Alisal Fire, due in part to

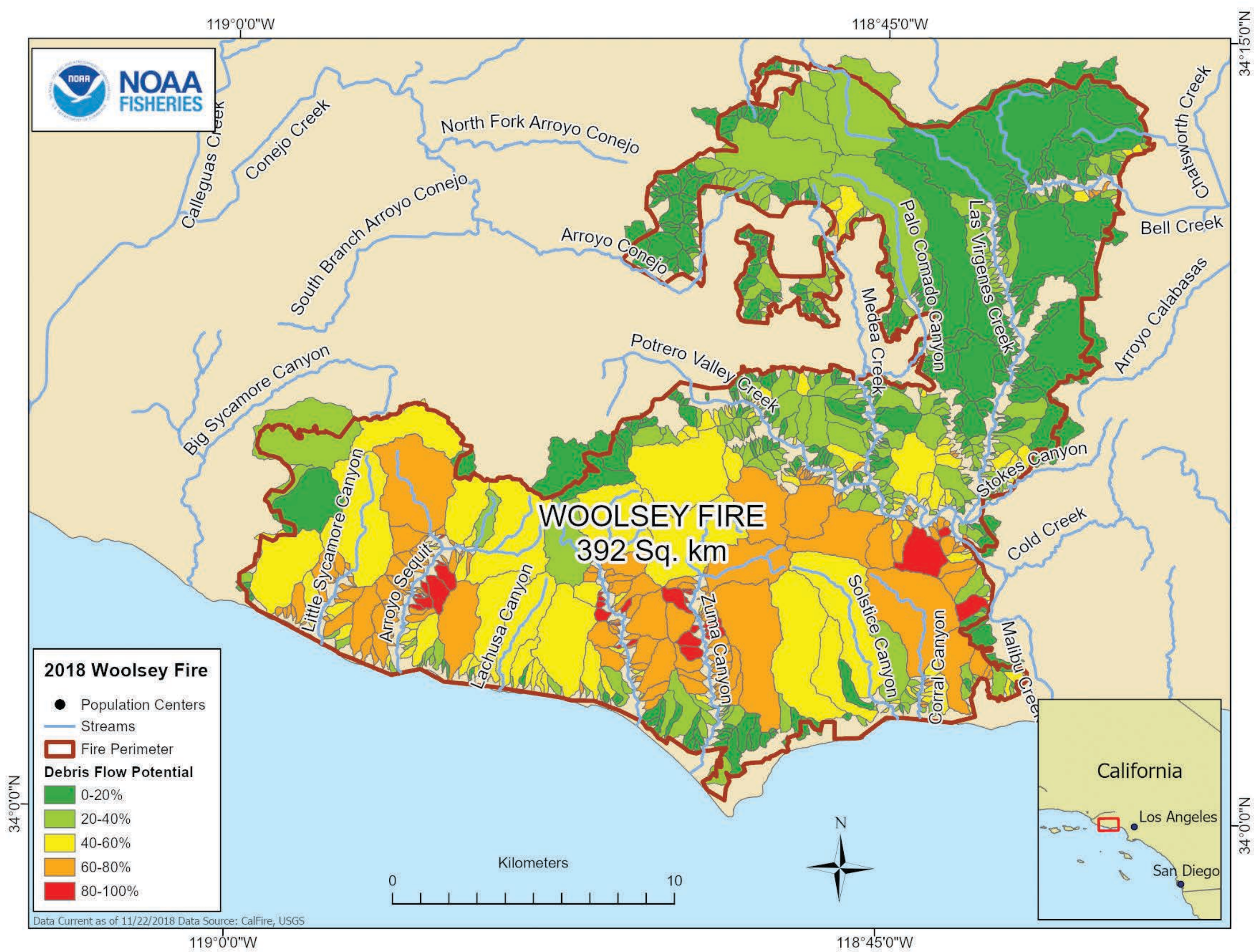

Figure 9. Woolsey Fire and debris-flow potential within the Santa Monica Mountains BPG. Source: USGS Landslide Hazards Program (USGS, 2022).

an extended drought, but also to oversummering rearing conditions degraded by the Alisal Fire. Other major recent fires that have affected steelhead habitat within the Conception Coast BPG include the Sherpa Fire (2016), Canyon Fire (2016), and Cave Fire (2019).

The 2018 Woolsey Fire affected steelhead habitats in three of the five core recovery populations in the Santa Monica BPG: Big Sycamore Canyon, Solstice Canyon, and Malibu Creek (Figs. 2 and 9). The Woolsey Fire burned over 90% of these watersheds, denuding the hillslopes of chaparral/coastal sage scrub vegetation, and impacting riparian vegetation (Watershed Emergency Response Team, 2018); previously, the 2013 Springs Fire burnt 85% of Big Sycamore Canyon to the immediate west of the Woolsey Fire (Staley, 2014; Florsheim et al., 2017). Currently, only the Topanga Creek watershed within this BPG retains a remnant population of *O. mykis*s, though no returning adult steelhead have been recorded since 2017, and this population is threatened by the ongoing drought in southern California (Dagit et al., 2017, 2019, 2020; Hunter, 2022). Other major recent fires that have affected steelhead habitat within the Santa Monica Mountains BPG include the Hill Fire (2018).

The 2020 Bobcat Fire affected significant portions of the steelhead habitats in two of the three core recovery populations in the Mojave Rim BPG: Big Tujunga Creek (a tributary of the Los Angeles River) and the San Gabriel River (Figs. 2 and 10). Within the perimeter of the Bobcat Fire, the highest debris-flow potential is in the middle reaches of the watersheds where steep slopes are dominated by chaparral vegetation.

The Bobcat Fire has had a major impact on the San Gabriel River watershed, burning 93% of the lower West Fork San Gabriel River watershed and 81% of the Bear Creek watershed (tributary to the East Fork San Gabriel River). This fire triggered debris flows and ongoing elevated sedimentation of streams within the San Gabriel River watershed (U.S. Forest Service, 2020; see also Warrick and Rubin, 2007). As a consequence, the California Department of Fish and Wildlife (CDFW) relocated rearing *O. mykiss* to several nearby watersheds with suitable rearing habitat conditions: East Fork San Gabriel River, Coldwater

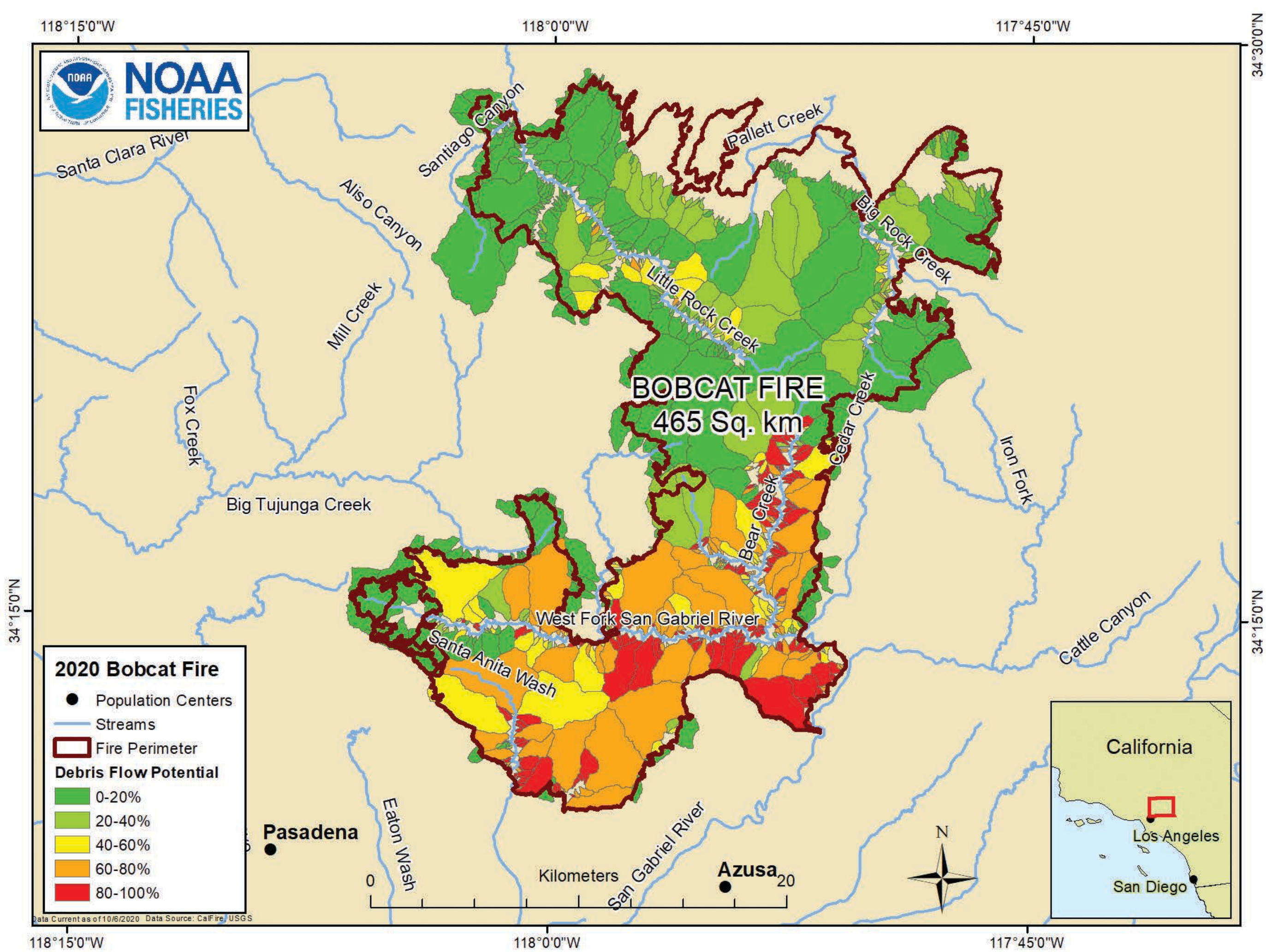

Figure 10. Bobcat Fire and debris-flow potential within the Mojave Rim BPG. Source: USGS Landslide Hazards Program (USGS, 2022).

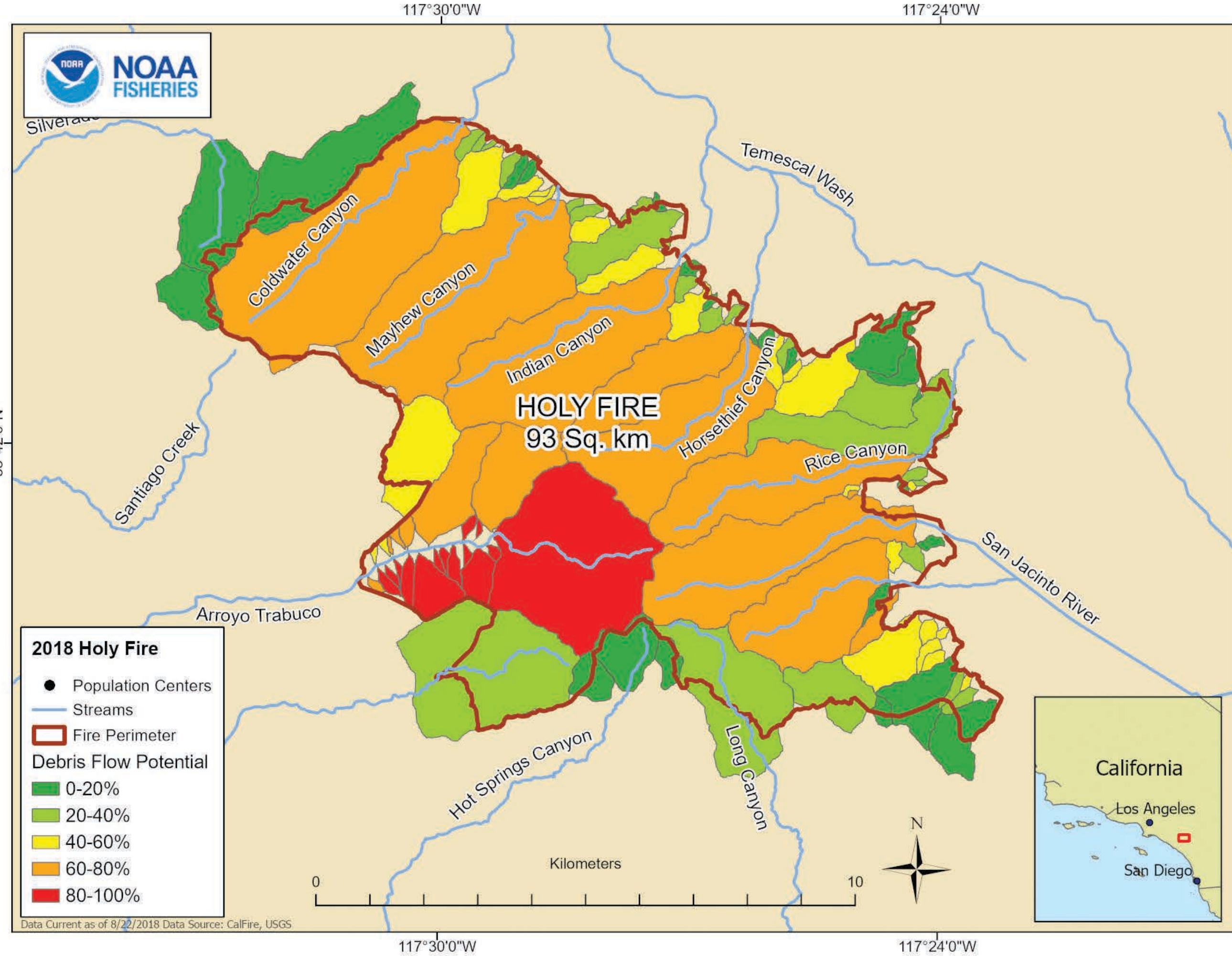

Figure 11. Holy Fire and debris-flow potential within the Santa Catalina Gulf Coast BPG. Source: USGS Landslide Hazards Program (USGS, 2022).

Canyon (tributary to the Santa Ana River), and the Arroyo Seco (tributary to the Los Angeles River); see O'Brien et al. (2011); Pareti (2020a, 2020b, 2021); O'Brien and Stanovich (2022); and Stanovich (2022) for details. Other major recent fires that have affected steelhead habitat within the Mojave Rim BPG include: San Gabriel Complex Fire (2016), Pilot Fire (2016), Sand Fire (2016), Ranch 2 Fire (2020), Eldorado Fire (2020), and Apple Fire (2020).

The 2018 Holy Fire affected the steelhead habitats in one of the eight core recovery populations in the Santa Catalina Gulf Coast BPG: Arroyo Trabuco Creek (a tributary to San Juan Creek); the Holy Fire also impacted Coldwater Canyon (tributary to the Santa Ana River) in the adjacent Mojave Rim BPG (Figs. 2 and 11). As a result, *O. mykiss* were rescued from the Santa Ana River watershed prior to the first major winter storm, which subsequently triggered a debris flow and heavy sedimentation that degraded or destroyed *O. mykiss* rearing habitat in Coldwater Canyon. The rescued fish were moved to the CDFW's Mojave Hatchery and then to Marion Creek, before being returned to Coldwater Canyon (Hemmert, 2018, 2020).

Within the perimeter of the Holy Fire, the highest debris-flow potential is in the middle reaches of the watersheds with steep slopes dominated by chaparral vegetation (Schwartz and Stempniewicz, 2018). Other major recent fires that have adversely affect steelhead habitat within the Santa Catalina Gulf Coast BPG include: Canyon Fire (2017), Canyon 2 Fire (2017), Valley Fire (2021), and Sierra Fire (2021). The Sierra Fire impacted a portion of the Santa Margarita River watershed as a result of the fire and the application of fire retardant, which reached the Santa Margarita River (U.S. Department of Defense, 2018, 2021). Several dead *O. mykiss* individuals were subsequently observed downstream of the Sierra Fire, though the cause of the mortalities was not determined (Larson, 2021).

For southern California steelhead recovery planning, individual wildfires are viewed in a broader context, temporally and spatially. A recent analysis of the wildfire season in southern

California found that the area burned annually had not significantly changed in recent decades (Dong et al., 2022). Longer-term wildfire records show an increasing incidence of anthropogenically initiated wildfire ignitions in California and the western United States (Keeley, 1982; Westerling, 2016; Bryant and Westerling, 2009; Saffarod and Van de Water, 2014; Radeloff et al., 2018); however, Andela et al. (2017) found a contrary global trend. Under some climate change projections driven by moderate to high greenhouse gas emission scenarios, the wildfire season in southern California is projected to be more intense and have an earlier onset and a delayed end. A recent study projected a 38% increase in the number of days that exhibit a suite of variables (e.g., vapor pressure, fuel moisture, wind speed, etc.) that favor wildfire ignitions under a moderate greenhouse gas emission scenario—from 36 days/yr during the period 1970–1999 to 58 days/yr by 2070–2099 (Dong et al., 2022). Santa Ana winds play an important role in the fire regime in the southern California chaparral/coastal sage scrub landscape. One general climate model showed a shift in the seasonal cycle, with fewer Santa Ana wind events occurring in September and more occurring in December (Miller and Schlegel, 2006). The potential implications of this shift for the fire regime are unclear, but it may contribute to the delayed end of the fire season in southern California (Keeley, 1981, 2001, 2006; Keeley and Fotheringham, 2001; McKenzie et al., 2004; Dennison et al., 2014; Keeley and Syphard, 2016; Keeley and Syphard, 2018; Williams et al., 2019).

STEELHEAD RECOVERY PLANNING

Following the listing of the southern California steelhead as endangered, NMFS appointed a Technical Recovery Team (TRT) led by NOAA Fisheries' Southwest Fisheries Science Center–Santa Cruz Laboratory, and comprised of scientists with expertise in a variety of relevant scientific disciplines, including biological and earth sciences. The TRT was tasked with developing a scientific framework for recovery of the species. The two principal responsibilities of the TRT were: (1) to characterize the prehistorical versus current population structure of *O. mykiss* in the recovery planning area, and (2) to develop a set of scientifically based viability criteria (for both individual populations and the DPS as a whole) based on NMFS' Viable Salmonid Population (VSP) concept (McElhany et al., 2000). The TRT recognized the important role of wildfire in the evolution and maintenance of steelhead and steelhead habitats, and it incorporated projected future wildfires into the development of viability criteria for southern California steelhead (Boughton and Goslin, 2006; Boughton et al., 2006, 2007a).

The VSP concept uses four quantitative criteria—abundance, productivity, spatial structure, and diversity—to assess species viability. These factors serve as the viability recovery metrics for both individual populations and the whole DPS. A viable population should meet quantitative metrics for each of the four criteria: mean annual run size, population density, persistence over varying ocean conditions, and anadromous fraction of the mean annual run size (see table 1 in Boughton et al., 2007a). A viable salmonid population is a population of Pacific salmon or steelhead (genus *Oncorhynchus* spp.) that has a negligible risk of extinction (<5%) due to threats from demographic variation (random or directional), local environmental variation, and changes in genetic diversity (random or directional) over a 100 yr time frame (McElhany et al., 2000). The 100 yr time frame for the viability of individual populations was chosen because it is long enough to encompass many long-term ecological processes but short enough to feasibly model or evaluate, and it is similar to quantitative and qualitative conservation assessments and extinction risk evaluations used for other species (Gilpin and Soulé, 1986; Lande, 1993; Caughley, 1994; Beissinger and Westphal, 1998; Dunham et al., 1999; Morris et al., 1999; McElhany et al., 2000).

The viability criteria for the DPS as a whole includes the number and spatial distribution of individual viable populations across the landscape of the recovery planning area, and the diversity of life-history types (anadromous, lagoon anadromous, and resident) within each of the five BPGs over a 1000 yr time frame (Boughton et al., 2007a; NMFS, 2012; Kendall et al. 2014). The longer 1000 yr time frame for the DPS-wide viability was selected to promote the evolutionary potential of the species by ensuring its persistence over the long term in the face of the environmental variation that is characteristic of southern California—prolonged droughts, large wildfires, and profound anthropogenic disturbance (McElhany et al., 2000; Hunt & Associates Biological Consulting Services, 2008; Beechie et al., 2012; NMFS, 2012).

As part of the recovery planning process, the TRT undertook a number of investigations and published a series of Technical Memoranda that provided the scientific foundation upon which NMFS developed the Southern California Steelhead Recovery Plan (Boughton et al., 2005, 2006, 2007a; Boughton and Goslin, 2006; Boughton, 2010a, 2010b; NMFS, 2012). NOAA Fisheries' Southwest Fisheries Science Center–Santa Cruz Laboratory also conducted genetic investigations in an attempt to identify the population structure of the southern California steelhead populations (Girman and Garza, 2006; Pearse and Garza, 2008; Clemento et al., 2009; Garza et al., 2014; Abadía-Cardoso et al., 2016). More recent research has shed additional light on the relationship between the anadromous and nonanadromous forms of *O. mykiss*, which bears on several elements of the population viability criteria for the Southern California Steelhead DPS—particularly the mean annual run size and the anadromous fraction (Boughton, 2022; NMFS, 2023). This work indicates that the tendency to out-migrate to the ocean (versus maturing in freshwater) is associated with particular juvenile body sizes, gender, the presence of a particular haplotype on chromosome Omy5, and interactions between these and potentially other environmental factors (Martínez et al., 2011; Pearse et al., 2014; Pearse, 2016; Pearse et al., 2019; Campbell et al., 2021; Rundio et al., 2021). The two basic variants of the tightly linked Omy5 gene occur in most populations, but one variant tends to predominate in sites with connectivity to the ocean, and the other is predominant in populations without connectivity. The resident and anadromous forms of *O. mykiss* that interbreed are closely integrated at the population level, and each can play an important role in the perpetuation of the other life-history form. These findings may warrant a reevaluation of two elements of the population viability criteria (i.e., the mean annual run size and the anadromous fraction of the total spawning population in a watershed); however, a reevaluation would require additional data from monitoring and a quantitative analysis before the population viability criteria could be modified (Boughton et al., 2022; Boughton, 2022).

Recent work has also documented dispersal of anadromous *O. mykiss* from their natal watersheds to non-natal watersheds (Donohoe et al., 2021). The study documented the dispersal of steelhead over considerable distances (680 km) from their natal to non-natal watersheds, including the dispersal of anadromous progeny from a non-anadromous female, thus providing some genetic connectivity among fish from widely separated watersheds, and potentially an additional source of anadromous fishes for extirpated watersheds. These behavioral and genetic characteristics provide a potentially important mechanism for naturally recolonizing steelhead habitats that have been depopulated as a result of anthropogenic modifications (e.g., construction of artificial barriers such as dams or road crossings) or natural environmental disturbances (e.g., wildfire, debris flows, droughts, or catastrophic floods). These findings offer further support for the recovery strategy that NMFS has developed for southern California steelhead.

Viability Criteria

The TRT developed viability criteria for two levels of biological organization: individual steelhead populations and DPS-wide criteria. The population-level viability criteria apply to individual populations or watersheds where one population is associated with one watershed. The DPS-wide viability criteria—which is the focus of the wildfire analysis presented here—identify the overall population structure of the DPS, including the number and distribution of recovered (viable) populations subject to potential natural disturbances, such as wildfires and post-wildfire debris flows.

DPS-wide criteria address issues of: (1) biogeographic diversity, as reflected in the range of landscape diversity in the five BPGs; (2) life-history diversity (fluvial anadromous, lagoon anadromous, and non-anadromous forms); and (3) population redundancy and spatial distribution within BPGs as a hedge against wildfire-related and other natural disturbances. The DPS-wide viability criteria also address recurring drought conditions by including large inland watersheds where the upper reaches include steelhead rearing and oversummering drought refugia habitat that maintains surface water during dry summer months or during prolonged droughts. The recovery of the southern California steelhead will require recovery of a sufficient number of individually viable populations distributed within each of the five BPGs (or sets of interacting watersheds that support adult spawning steelhead derived from multiple, nearby watersheds; Fig. 2).

Biogeographic Diversity

The long-term persistence of the species requires that a minimum number of viable populations must be distributed through each of the five distinctive BPGs. The survival of at least one viable steelhead population from each of the five BPGs following wildfire-related or other natural disturbances would ensure that a variety of habitat types and conditions are represented in the steelhead recovery planning area. Restoration and persistence of inland and coastal watersheds, with a natural range of selective pressures, would continue to drive the adaption and evolution of the species (Stouder et al., 1997; McPhail, 1996; Montgomery, 2000; Hendry and Stearns, 2004; Boughton et al., 2007a).

Life-History Diversity

An essential factor in the recovery and long-term viability of southern California steelhead is the preservation and/or restoration of the life-history forms and strategies steelhead (and their resident cohorts) have evolved to exploit the diversity of environmental conditions that are characteristic of the recovery planning area. This adaptive life-history diversity includes differences in age at smolting and spawning, the time of year of spawning, as well as tolerance for higher water temperatures, migration through waters with high suspended sediment loads, etc. (Boughton et al., 2007b; Spina, 2007, 2020; Satterthwaite et al., 2012; Sloat and Osterback, 2013; Capelli, 2020; Dressler et al., 2023). The three general strategies that native populations of *O. mykiss* exhibit most commonly to complete their life cycle are: fluvial anadromous (sea-run fish that rear in freshwater and mature in the ocean before returning to spawn in freshwater), lagoon anadromous (fish that rear in the lagoon before emigrating to the ocean to mature and returning to spawn in freshwater), and non-anadromous (fish that rear, mature, and reproduce entirely in freshwater). These three life-history strategies should all be expressed in each recovered BPG. This assumes that other aspects of life-history diversity (diversity in age of smolting, spawning, etc.) will also be conserved by environmental conditions that promote the three fundamental forms of life-history diversity. However, future research may indicate that not all life-history forms have to be present in all viable populations on a continuous basis, but only expressed periodically (Boughton, 2010b, 2022; Boughton et al., 2022)

Redundancy and Spatial Distribution within BPGs

The redundancy and spatial distribution criteria are designed to safeguard the DPS from the loss of all steelhead populations in a BPG due to natural disturbance events. Occasional losses of individual populations resulting from wildfires, droughts, catastrophic floods, and debris flows in the recovery planning area are part of the evolutionary process. However, the preservation of biogeographic and life-history diversity of *O. mykiss* requires that not all viable populations in a BPG are extirpated as a result of one catastrophic event, or a series of events, which in turn requires both a redundancy of populations and an effective geographic separation of core recovery populations within each of the five BPGs.

To ensure the survival of at least one viable population per BPG during a catastrophic wildfire/debris-flow event, two criteria must be met: (1) The number of viable populations in each BPG should exceed the number of wildfires expected in a catastrophic wildfire season; and (2) wherever possible, those populations should be spatially separated by a distance sufficient to prevent a wildfire or post-wildfire disturbance event from extirpating more than one viable population in a BPG.

To determine the level of redundancy and spatial separation of populations necessary to withstand wildfire and associated post-wildfire disturbances, the TRT estimated the expected geographic extent of a wildfire (or a series of wildfires within a single year) with a 1000 yr recurrence interval, based on historical wildfire data (from 1910 through 2003) from the California Department of Forestry fire database (ttp://frap.cdf.ca.gov/projects/fire_data/fire_perimeters/). Because the footprint of wildfires within southern California tends to aggregate in time due to climatic conditions such as the hot, dry Santa Ana winds out of the Mojave Desert, the fire analysis used the total area burned in a year rather than the area of the single largest fire (Moritz, 1997; Raphael, 2003; Westerling et al., 2004; Boughton et al., 2007a; Moritz et al., 2010).

Fire return times were estimated using standard methods: An exponential distribution was found to fit the data (parameter λ = 0.0025084; fit: $\chi^2 = 2.32$ [df = 3]; $p = 0.51$), which predicted a 1000 yr burned area of ~2750 km^2. The 1000 yr interval refers to the median return time expected for an event; however, actual return times are distributed around the median; so the parametric and empirical results are consistent. The number of wildfires that might be expected to affect each BPG was then estimated from the number of wildfire ignitions per square kilometer in each BPG using the data for the 2003 fire season, which closely matched a 1000 yr wildfire scenario for the size of the burn area described above (Fig. 12).

From this analysis, the TRT determined the criterion of redundancy for each BPG to be one viable steelhead population plus the maximum number of wildfire ignitions expected for the BPG, or the number of historic viable populations in the BPG, whichever was less. The spatial separation criterion (i.e., the minimum distance between individual viable populations) was estimated to be 68 km, based on the maximum width of the largest fire recorded (i.e., the 2003 Cedar Fire; City of San Diego, 2004) during the 94 yr period of record. If meeting the spatial separation criterion is geographically impossible within a BPG, then the viable core recovery populations should be as widely spaced as possible. Using this analysis, a minimum number of watersheds was identified in each BPG that would meet this criterion. From the suite of potential steelhead-bearing watersheds in each BPG, a group of core recovery watersheds/populations was then identified on which to focus recovery efforts. See Table 1 and Figures 13–17 for the results of this analysis.

These selected core recovery watersheds exhibit the physical and hydrological characteristics (e.g., large spatial area, perennial and reliable winter streamflow, stream network complexity extending inland, etc.) that are most likely to sustain independently viable steelhead populations, and they are therefore critical for achieving viability of the DPS (Fig. 1). To focus recovery efforts further, recovery populations/watersheds were classified as core 1, core 2, or core 3. This classification was based on: (1) the intrinsic potential of the populations to be viable in an unimpaired condition (e.g., free of anthropogenic fish-passage impediments, a natural pattern of streamflow and sediment transport, an undisturbed riparian/floodplain corridor, and functional estuarine habitat, etc.); (2) the role of the population/watershed in meeting the spatial and/or redundancy DPS-wide viability criteria; (3) the current condition of the population/watershed; (4) the severity of the threats facing the population/watershed; (5) the potential ecological or genetic diversity the population/watershed could provide to the listed species; and (6) the capacity of the population/watershed to respond to the recovery actions intended to abate those threats (NMFS, 2012).

NMFS identified and ranked intrinsic potential steelhead spawning and oversummering habitat within core recovery watersheds using the "envelope method" (Boughton and Goslin,

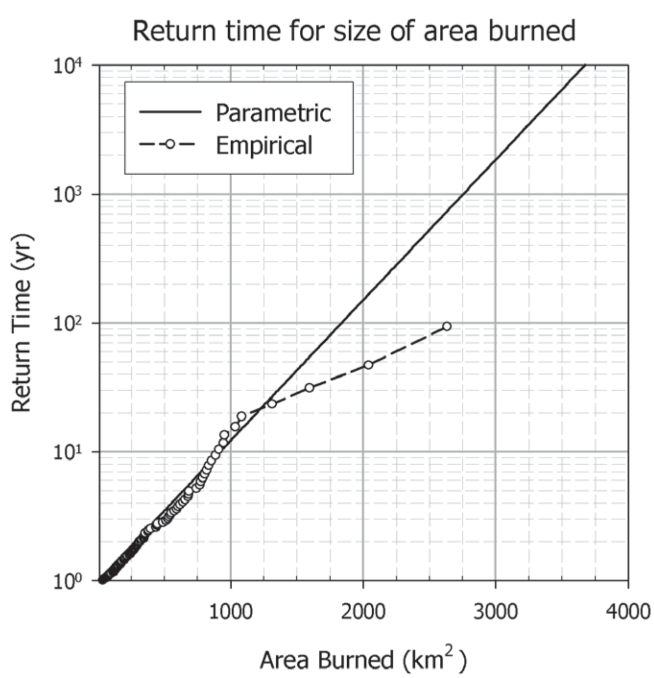

Figure 12. Return times for wildfire seasons in the steelhead recovery planning area. Based on a 94 yr record (1910–2003). The dashed line (with circles) plots the actual recorded wildfires. The last data point on the empirical curve is the 2003 fire season. The solid line is the modeled parametric line derived from the available fire record examined (Boughton et al., 2007a).

TABLE 1. NUMBER OF WILDFIRES IN EACH POPULATION GROUP DURING A 1000 YR FIRE EVENT SIMILAR TO THE EVENTS OF 2003, AND NUMBER OF VIABLE POPULATIONS NECESSARY TO ACHIEVE VIABILITY FOR THE SOUTHERN CALIFORNIA STEELHEAD DISTINCT POPULATION SEGMENT (ADAPTED FROM BOUGHTON ET AL., 2007a)

Biogeographic Population Group (BPG)	Expected number of wildfires	Maximum number of wildfires		Number of populations*
		95% confidence	99% confidence	
Monte Arido Highlands	5.624	10	12	4
Conception Coast	0.327	1	2	3
Mojave Rim	3.209	6	8	3[†]
Santa Monica Mountains	0.210	1	2	3[†§]
Santa Catalina Gulf Coast	2.563	5	7	8[†§]

*Viable and spatially separated from other viable populations by >68 km. Estimated as 1 + the number of wildfires at 99% confidence, or the number of historic populations, whichever is less.

[†]Anadromy may not be consistently expressed in *Oncorhynchus mykiss* populations in these southernmost BPGs. The freshwater-resident form has been a persistent feature of these populations, and the anadromous life history has been periodically expressed.

[§]The number of historically viable populations may be smaller than the table entry, since some historical populations may have been ephemeral and required recurrent colonization.

2006; see figure 31 in Boughton et al., 2006). Synoptic maps of this habitat were based on observed associations between fish distributions and the values of environmental conditions such as stream gradient, summer mean discharge and air temperature, ratio of valley width to mean discharge, and the presence of alluvial deposits, which are essential to successful steelhead spawning and rearing; for details, see Boughton and Goslin (2006). The current condition of the populations, severity of threats, potential ecological or genetic diversity, and the recovery potential of watersheds and populations were determined by NMFS staff and consultants (Hunt & Associates Biological Consulting Services, 2008; Kier Associates and National Marine Fisheries Service, 2008a, 2008b; NMFS, 2012).

Core 1 populations are those populations identified as the highest priority for recovery actions, including the removal of impediments to fish passage, the restoration of flows to support their freshwater life-history stages, including adult migration and spawning, and juvenile incubation and rearing, as well as rigorous monitoring of the populations (NMFS, 2012; Boughton et al., 2022).

Core 2 populations also form part of the recovery implementation strategy and contribute to the set of populations necessary to achieve recovery criteria such as the minimum number of viable populations needed within a BPG, but generally are either smaller, or may have lower intrinsic potential, or in some cases, are less impacted, and therefore require comparatively fewer or less extensive recovery actions.

While recovery actions for core 3 populations are not assigned as high an implementation priority as core 1 and 2 populations, these populations can be important in promoting genetic diversity and connectivity between populations across the recovery planning area. Promoting connectivity between populations/watersheds within BPGs, and between BPGs, serves to promote dispersal and natural recolonization of watersheds that may experience a local extirpation of steelhead as a result of disturbances such wildfire, debris flows, or reoccurring droughts. Core 3 populations are therefore an integral part of the overall biological recovery strategy. The TRT concluded that this level of redundancy was necessary to protect against wildfires and post-wildfire disturbances such as debris flows (Boughton et al., 2007a).

The following series of maps (Figs. 13–17) depict the suite of potential steelhead-bearing watersheds in the five BPGs and the core recovery watersheds/populations that were identified by the TRT. These populations/watersheds are the focus of recovery actions identified in the Southern California Steelhead Recovery Plan (NMFS, 2012). Core 1 and core 2 recovery populations must meet the four population-level viability criteria (i.e., mean annual run size, population density, persistence over varying ocean conditions, and anadromous fraction) as either single populations or a group of interacting trans-watershed populations. Core 3 recovery populations may not meet all four population-level viability criteria but are still important in promoting connectivity between populations and genetic diversity within the five BPGs.

The Monte Arido Highlands BPG (Fig. 13) includes four large inland watersheds with a total area of 11,914 km^2, ~50% of which is in public ownership, including portions of the Los Padres National Forest. Approximately 87% of this BPG is covered by various forms of undeveloped open space. Urban development is concentrated along the coast, and has encroached on coastal estuaries, reducing their size and habitat complexity; there is extensive agricultural development along some of the major interior valleys (Capelli, 2007; Hunt & Associates Biological Consulting Services, 2008; Kier Associates and National Marine Fisheries Service, 2008b). Because of their large size and variable habitat conditions (including steelhead rearing and oversummering drought refugia habitat), these four watersheds have high intrinsic potential rankings and therefore the highest potential to support viable populations in unimpaired conditions. However,

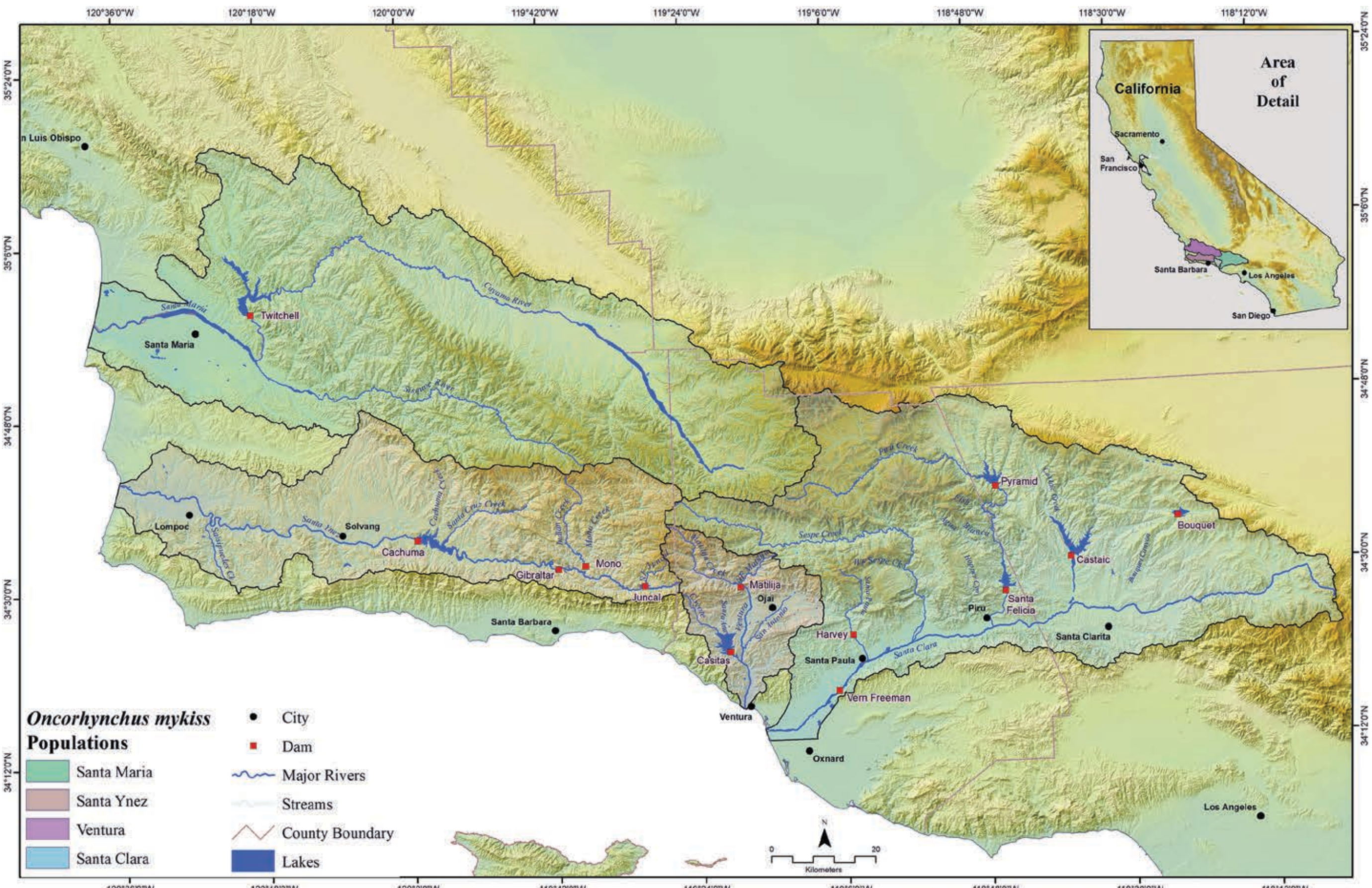

Figure 13. Monte Arido Highlands BPG. The following core 1 recovery population must meet the four population-level viability criteria as either single populations or a group of interacting trans-watershed populations: Santa Maria River, Santa Ynez River, Ventura River, and Santa Clara River.

much of this spawning, rearing, and oversummering drought refugia habitat is currently above impassable fish-passage barriers (Fig. 1; NMFS, 2012). These watersheds are dominated by fire-prone chaparral vegetation in the interior (Keeley and Davis, 2007; Parker et al., 2018) and an oak woodland and grassland complex in the lower elevations (Bartolome et al., 2007; Allen-Diaz et al., 2007; Davis et al., 2018; Eviner, 2018; see also Smith, 1998). Consequently, these watersheds are highly vulnerable to wildfire and postfire disturbances (Figs. 6 and 7; NMFS, 2012), which pose a significant risk to important oversummering and drought refugia habitat that is critical to the successful rearing of juvenile steelhead within the Monte Arido Highlands BPG.

The Conception Coast BPG (Fig. 14) includes numerous small coastal watersheds with a total area of 862 km^2, ~50% of which is in public ownership, including state and local parks and portions of the Los Padres National Forest. Approximately 74% of this BPG is covered by various forms of undeveloped open space. Urban development is concentrated along the eastern most portion of the coast and has encroached on coastal estuaries, reducing their size and habitat complexity (Capelli, 2007; Hunt & Associates Biological Consulting Services, 2008; Kier Associates and National Marine Fisheries Service, 2008b). These watersheds are dominated by chaparral in the interiors (Keeley and Davis, 2007; Parker et al., 2018), with oak woodlands in the lower elevations (Allen-Diaz et al., 2007; Lentz, 2013; Davis et al., 2018), and California Department of Fish and Wildlife are vulnerable to episodic wildfires and postfire disturbances (Fig. 8; NMFS, 2012), as well as anthropogenic disturbances (e.g., diversions, flood-control activities, fish-passage impediments, etc.), particularly in their lower reaches (NMFS, 2012). These watersheds include interacting trans-watershed populations of fish that may function as a metapopulation (i.e., a group of populations utilizing multiple watersheds, with some larger watersheds with more regular flows and appropriate spawning and rearing habitat serving as "source" populations, and other smaller watersheds with less reliable flow or limited spawning and rearing habitat functioning as "sink" populations). The potential natural recolonization of these watersheds, following episodic extirpations of *O. mykiss* populations as a result of postfire disturbances or drought conditions, through dispersal of fish from other watersheds is one of many adaptations to the naturally dynamic freshwater environments of southern California. However, numerous

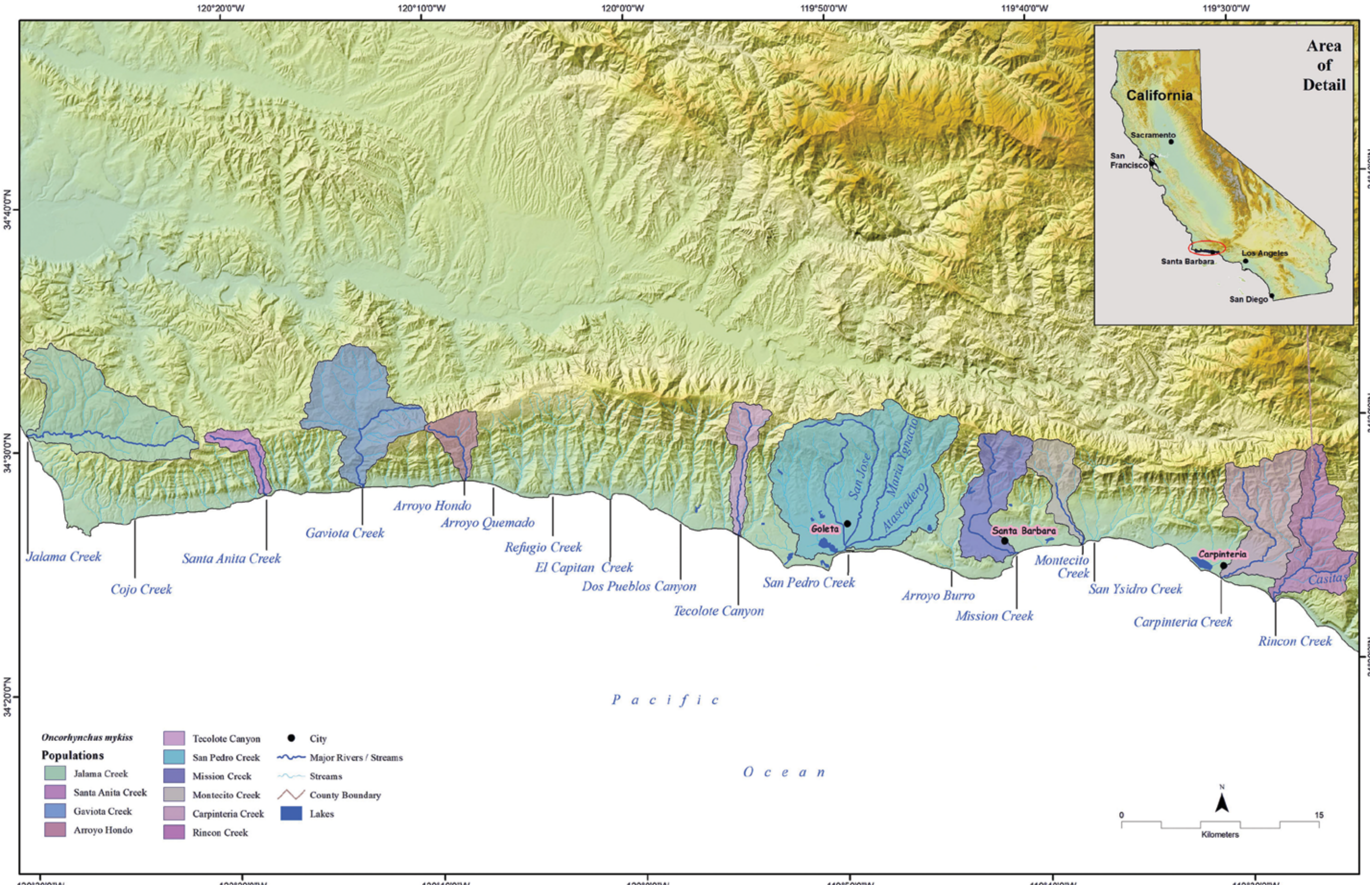

Figure 14. Conception Coast BPG. The following core 1 recovery populations must meet the four population-level viability criteria as either single populations or a group of interacting trans-watershed populations: Goleta Slough Complex (San Pedro, San Jose, Maria Ygnacio, Atascadero), Mission Creek, Carpinteria Creek, and Rincon Creek, and the core 2 recovery population, Gaviota Creek. BPG viability would be further bolstered if the following core 3 recovery populations promote connectivity between populations and genetic diversity across the BPG: Jalama Creek, Cañada de Santa Anita, Agua Caliente, Cañada San Onofre, Arroyo Hondo, Arroyo Quemado, Tajiguas Creek, Cañada del Refugio, Cañada del Venadito, Cañada del Corral, Cañada del Capitan, Gato Canyon, Dos Pueblos Canyon, Eagle Canyon, Tecolote Canyon, Bell Canyon, Arroyo Burro, Montecito Creek, Oak Creek, San Ysidro Creek, Romero Creek, Toro Canyon Creek, and Arroyo Paredon.

fish-passage impediments (e.g., flood and debris flow control structures such as debris dams and ring-nets, road crossings, pipelines, etc.) have restricted access to a significant portion of the steelhead spawning, rearing, and oversummering drought refugia habitat within the Conception Coast BPG.

The Santa Monica Mountains BPG (Fig. 15) includes several small coastal watersheds with a total area of 435 km^2, ~50% of which is in public ownership, such as state and local parks, including Point Mugu State Park, Malibu State Park, Topanga State Park, and portions of the Santa Monica Mountains National Recreation Area. Approximately 81% of this BPG is covered by various forms of undeveloped open space. Urban development is concentrated along the coast and has encroached on coastal estuaries, reducing their size and habitat complexity (Capelli, 2007; Hunt & Associates Biological Consulting Services, 2008; Kier Associates and National Marine Fisheries Service, 2008b). Dams on Malibu Creek, historically the most productive steelhead-bearing watershed in this BPG, have blocked over 90% of the steelhead spawning, rearing, and oversummering drought refugia habitat within this watershed (Fig. 1; NMFS, 2012). As with the watersheds in the Conception Coast BPG, they are relatively small and vulnerable to periodic extirpations as a result of natural environmental perturbations. These watersheds are dominated by an oak woodland and grassland complex in the higher elevation (Raven et al., 1986; Allen-Diaz et al., 2007; Bartolome et al., 2007; Keeley and Davis, 2007; Davis et al., 2018) and coastal sage scrub in the lower elevations adjacent to the coastline (Raven et al., 1986; Rundel, 2007; Cleland et al., 2018), and they are therefore highly vulnerable to wildfire and postfire disturbances (Fig. 9; NMFS, 2012). Watersheds in this BPG also include interacting trans-watershed populations of fish that may function as a metapopulation, which rely on potential recolonizations following episodic extirpations, either as a result of postfire disturbances or drought conditions. However, dams

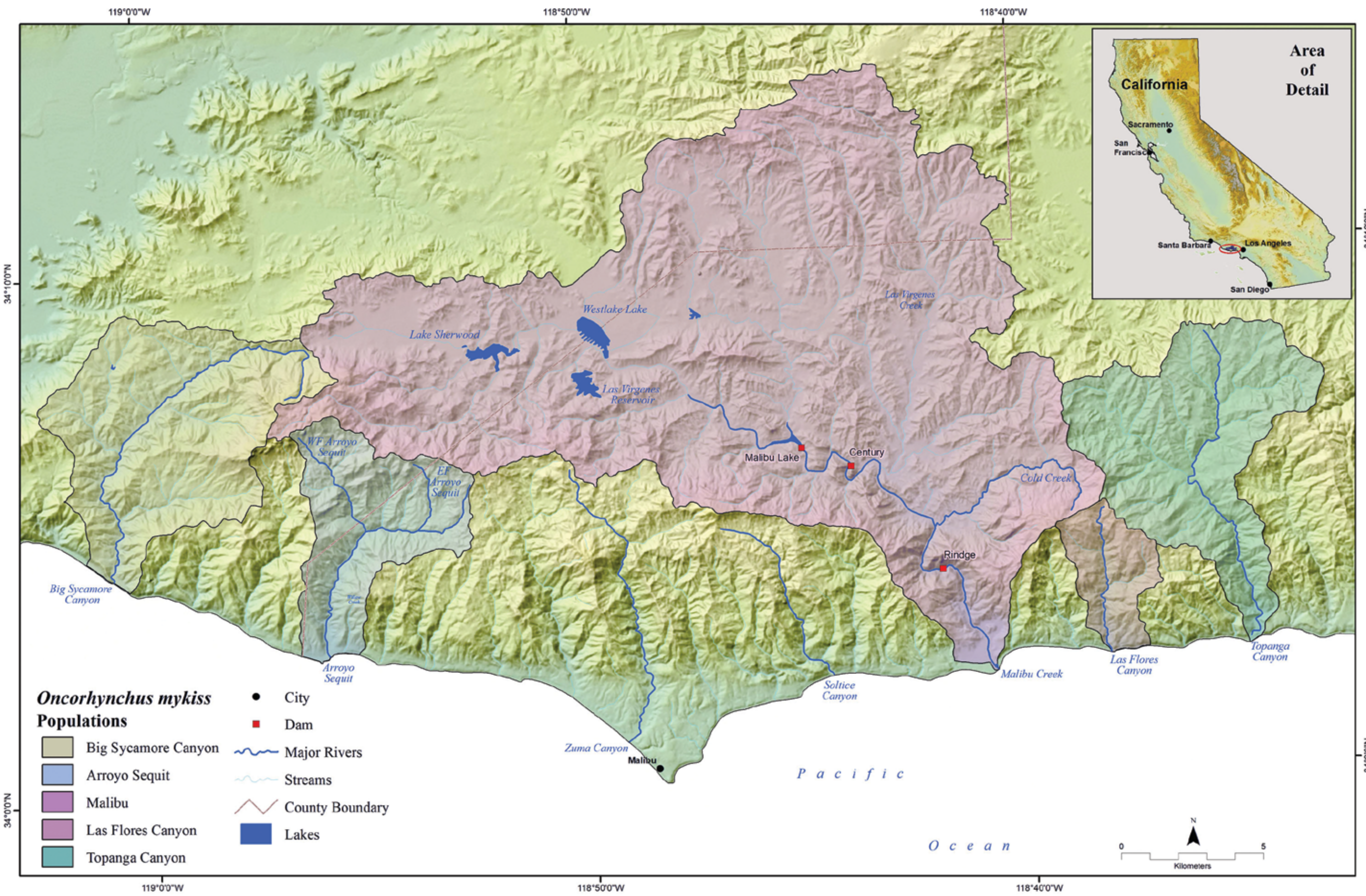

Figure 15. Santa Monica Mountains BPG. The following core 1 recovery populations must meet the four population-level viability criteria as either single populations or a group of interacting trans-watershed populations: Malibu Creek and Topanga Creek. The core 2 Arroyo Sequit recovery population must meet the four population-level viability criteria as either a single population or as part of a group of interacting trans-watershed populations. BPG viability would be further bolstered if the following core 3 recovery populations promote connectivity between populations and genetic diversity across the BPG: Big Sycamore Canyon and Solstice Creek. WF—West Fork; EF—East Fork.

in the Malibu Creek watershed, which contains the majority of steelhead spawning, rearing, and oversummering drought refugia habitat within this BPG, have blocked access to this habitat, increasing the risks of steelhead extirpations within the Santa Monica Mountains BPG.

The Mojave Rim BPG (Fig. 16) includes three large coastal watersheds with a total area of 8658 km^2, ~50% of which is in public ownership, including state and local parks and portions of the Angeles National Forest and San Bernardino National Forest. Approximately 46% of this BPG is designated as various forms of undeveloped open space. Urban development is concentrated along the coast and has encroached on coastal estuaries, reducing their size and habitat complexity; additionally, there is extensive residential development within some of the interior valleys that encroaches into chaparral-dominated mountainous areas (Capelli, 2007; Hunt & Associates Biological Consulting Services, 2008; Kier Associates and National Marine Fisheries Service, 2008b). These watersheds only exhibit short-duration, winter flows to the ocean, which are essential to promote the upstream migration and downstream emigration of steelhead. Nevertheless, these watersheds have a relatively high intrinsic potential ranking because of their large size and the amount of steelhead spawning, rearing, and oversummering drought refugia habitat within their headwaters. However, much of this steelhead habitat is currently above impassable barriers (Fig. 1; NMFS, 2012). These watersheds are dominated by chaparral vegetation in the interior (Clarke et al., 2007; Keeley and Davis, 2007; Parker et al., 2018) and an oak woodland and grassland complex in the lower elevations (Allen-Diaz et al., 2007; Bartolome et al., 2007; Davis et al., 2018; Eviner, 2018). The Mojave Rim BPG has an extensive wildland-urban interface and is therefore highly vulnerable to wildfire and postfire disturbances (Fig. 10; Syphard et al., 2012; Radeloff et al., 2018; Li et al., 2022).

The Santa Catalina Gulf Coast BPG (Fig. 17) includes coastal watersheds with a total watershed area of 8575 km^2, ~50% of which is in public ownership, including state and local parks and portions of the Cleveland National Forest. Approximately 79% of this BPG is designated as various forms of undeveloped

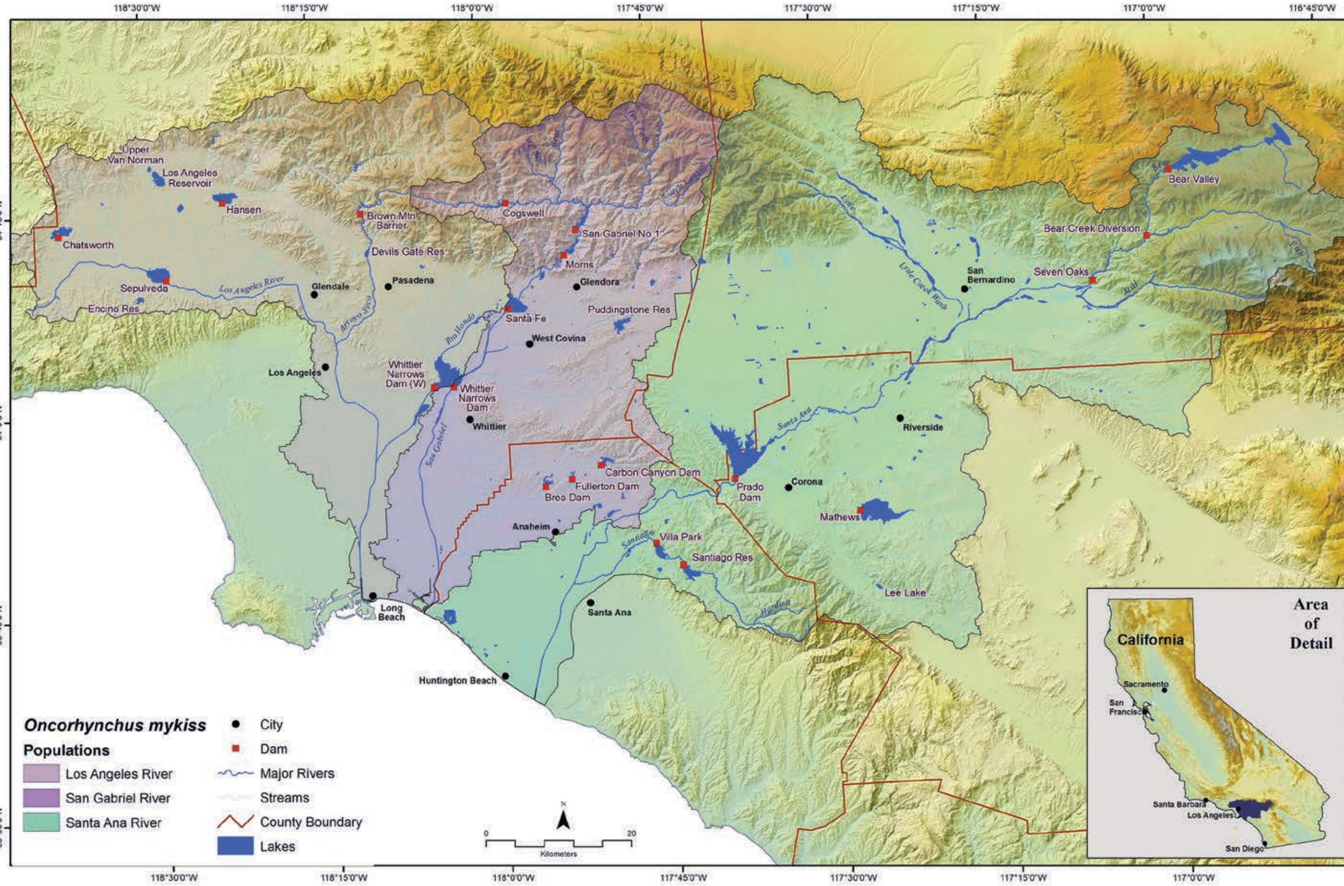

Figure 16. Mojave Rim BPG. The following core 1 recovery population must meet the four population-level viability criteria as either a single population or a group of interacting trans-watershed populations: San Gabriel River. The core 2 Santa Ana River recovery population must meet the four population-level viability criteria as either a single population or as part of a group of interacting trans-watershed populations. In addition, BPG viability would be further bolstered if the following core 3 recovery population promotes connectivity between populations and genetic diversity across the BPG: Los Angeles River (including its two major tributaries, the Arroyo Seco and Big Tujunga Creek).

open space. Urban development is concentrated along the coast and has encroached on coastal estuaries, reducing their size and habitat complexity; additionally, there is extensive urban development within the interior valleys of the major watersheds within this BPG (Capelli, 2007; Hunt & Associates Biological Consulting Services, 2008; Kier Associates and National Marine Fisheries Service, 2008b). Even in an unimpaired state, these watersheds experienced irregular winter flow to the ocean, which is essential to promote the upstream migration of steelhead, but they have a relatively high intrinsic potential ranking because of the large size of the watersheds and the amount of steelhead spawning, rearing, and oversummering drought refugia habitat within their headwaters. However, much of this steelhead habitat is currently above impassable barriers (Fig. 1; NMFS, 2012). These watersheds are dominated by chaparral vegetation in the interior (Keeley and Davis, 2007; Parker et al., 2018) and an oak woodland and grassland complex in the middle and lower elevations (Allen-Diaz et al., 2007; Bartolome et al., 2007; Davis et al., 2018; Eviner, 2018; see also Roberts et al., 2004; Roberts, 2008; Lightner, 2011). The Santa Catalina Gulf Coast BPG has an extensive wildland-urban interface and is therefore highly vulnerable to wildfire (Fig. 11; Syphard et al., 2012; Radeloff et al., 2018; Li et al., 2022).

DISCUSSION AND CONCLUSIONS

Southern California steelhead represent the southernmost populations of the species in North America, and they are threatened by numerous anthropogenic threats associated with a region occupied by over 23 million people. In theory, many of these threats can be ameliorated by proactive conservation measures involving both land- and water-use practices. However, in addition to anthropogenic disturbances that affect steelhead and their habitats, wildfire is a fundamental and inescapable recurring feature of the Mediterranean climate and the chaparral/coastal sage scrub–dominated landscape of southern California.

The effects of wildfires are diverse and complex, and they can be both beneficial and deleterious to steelhead and steelhead

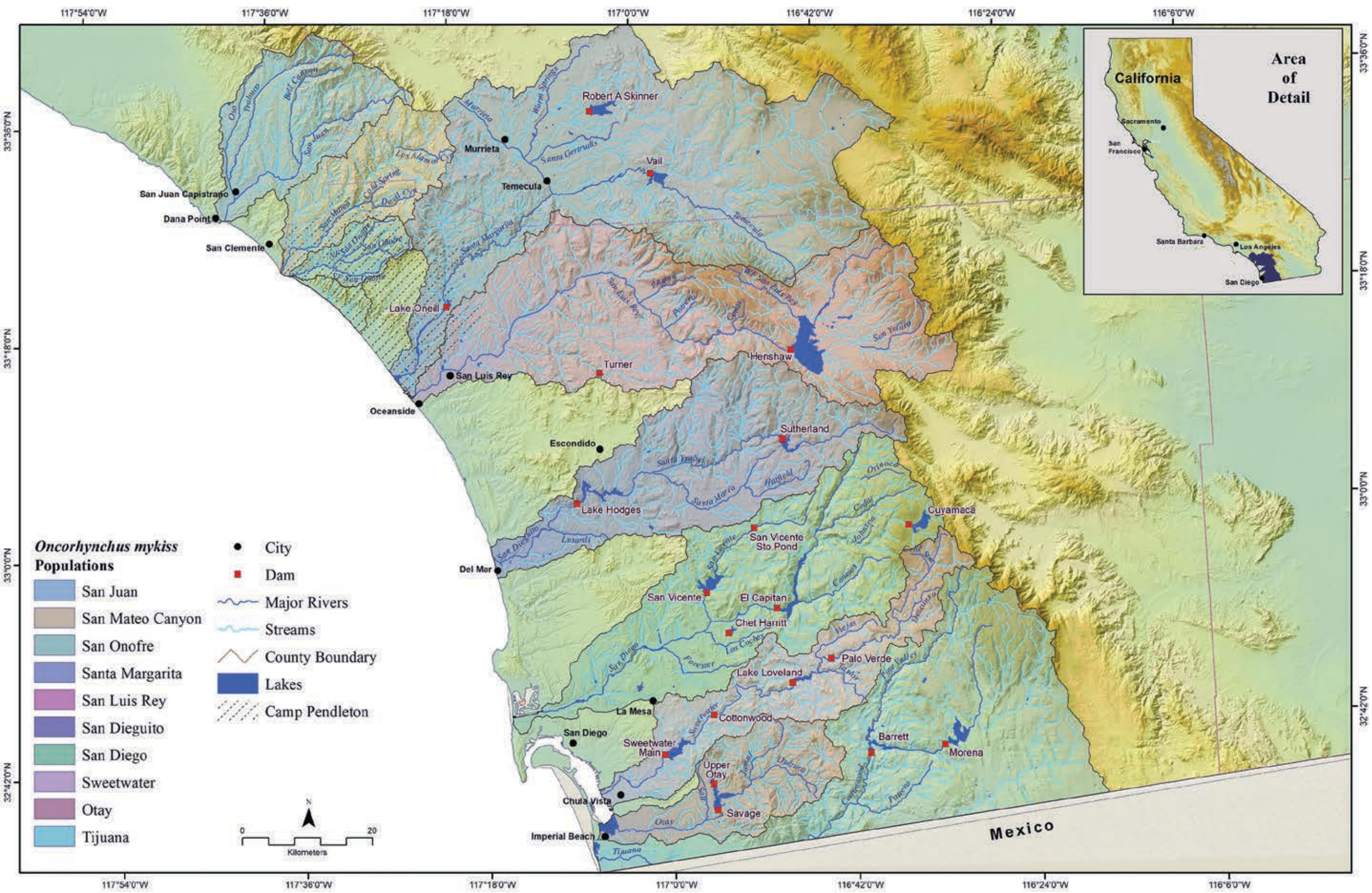

Figure 17. Santa Catalina Gulf Coast BPG. The following core 1 recovery populations must meet the four population-level viability criteria as either single populations or a group of interacting trans-watershed populations: San Juan Creek, San Mateo Creek, Santa Margarita River, and San Luis Rey River. The following core 2 recovery populations must meet the four population-level biological criteria as either single populations or a group of interacting trans-watershed populations: San Onofre Creek and San Dieguito River. In addition, two of the following core 3 recovery populations must meet the four population-level viability criteria: San Diego River, Sweetwater River, Otay River, and Tijuana River. The BPG viability would be further bolstered if the following core 3 populations promote connectivity between populations and genetic diversity across the BPG: San Diego River, Sweetwater River, Otay River, and Tijuana River. WF—West Fork; NF—North Fork; SF—South Fork.

habitats (e.g., promoting a short-term increase in base flows, but also temporarily accelerating sedimentation of pool habitat). Adverse effects of wildfires and postfire disturbances on aquatic habitats can be pronounced in tectonically active and semiarid environments. Even small wildfires can have a widespread effect on stream habitats due to sediment-transport processes that convey fine sediment downstream, burying larger bed-load material that provides spawning gravels for steelhead reproduction as well as substrate suitable to support benthic invertebrates (Shakesby and Doerr, 2006; Dunham et al., 2007; Cooper et al., 2015, 2021; Bixby et al., 2015; see also Beakes et al., 2014). However, only the most extensive wildfires with severely burned areas, coupled with an available supply of sediment, and followed by high-intensity rainfall triggering a catastrophic debris flow, have the potential to extirpate steelhead from an entire watershed (Brown et al., 2001; Boughton et al., 2007a; Keeley et al., 2012; Florsheim et al., 2017; Kibler et al., 2019; McLauchlan et al., 2020).

Some of the most significant adverse post-wildfire geomorphic processes affecting steelhead habitats include: (1) increases in hillslope erosion and sedimentation of channel morphology, including boulder-forced pools, step pools, and riffles, leading to loss of spawning, rearing, and drought refugia habitat; (2) modification of runoff patterns, including higher but shorter-duration peak flows, or in some cases sustained base flows as a result of reduced evapotranspiration; (3) changes in the water-temperature regime as a result of drought and/or reduction or loss of riparian vegetation, including higher water temperatures resulting in reduced dissolved oxygen levels (but in some circumstances temporarily reducing temperatures resulting from increased base flows); (4) alteration of nutrient transport and loading within watercourses affecting both instream vegetative growth and invertebrate production; (5) spread of nonnative, invasive vegetation, which may affect both evapotranspiration rates and invertebrate production important to rearing juvenile steelhead;

and (6) firefighting techniques, such as the use of fire retardants and physical modifications of the landscape to create temporary or permanent fire breaks (Poulton et al., 1997; Wicks and Randall, 2002; Wicks et al., 2002; Keeley et al., 2005; Capelli, 2009; Cooper, 2009; Coffman et al., 2010; Verkaik et al., 2013; Beakes et al., 2014; Dietrich et al., 2014; Coombs and Melack, 2013; Cooper et al., 2015; Klose et al., 2015; Florsheim et al., 2017; David et al., 2018; NMFS, 2018, 2022; Ball et al., 2021; Lieske, 2022). To address these wildfire-related issues, the Southern California Steelhead Recovery Plan produced by NMFS identified the development and implementation of an integrated wildland fire and hazardous fuel management plan as a recovery action for core recovery watersheds/populations. These plans should include monitoring, remediation, and adaptive management to reduce the potentially catastrophic effects of wildfire to steelhead and their habitats while preserving natural ecosystem processes, including sediment recruitment, transport, and deposition (NMFS, 2012; HDR Engineering, Inc., 2013).

While a recent analysis of the fire season in southern California found that the annual wildfire area in coastal southern California had not significantly changed in recent decades, under some climate change projections, driven by moderate to high greenhouse gas emission scenarios, the fire season is projected to be more intense and have an earlier onset and a delayed end (Scholze et al., 2006; Dennison et al., 2014; Garfin et al., 2018; Dong et al., 2022). An extended fire season, coupled with prolonged or reoccurring droughts, would result in additional cumulative stresses on the remnant steelhead populations in southern California by degrading hillslope and riparian habitats, and altering the streamflow patterns and sediment transport and deposition processes that create and maintain suitable steelhead habitats, particularly those essential for adult spawning and juvenile steelhead rearing (Battin et al., 2007; Moyle et al., 2013; Williams et al., 2015; Keeley and Syphard, 2016; Feng et al., 2019; Gudmundsson et al., 2021; Intergovernmental Panel on Climate Change, 2021, 2023).

Even absent large debris flows, wildfires followed by prolonged droughts, coupled with small-magnitude storms, can compound the adverse effects to steelhead and steelhead habitats. Postfire dry ravel processes continually deliver fine gravel-sized sediments to stream channels that degrade steelhead habitats. Small storms with limited capacity to move this sediment through the stream channel network, and to flush accumulated sediments from pools and riffle habitats, can prolong the period required to reestablish habitat conditions suitable for steelhead spawning, rearing, and oversummering refugia (Lamb et al., 2011; Florsheim et al., 2017; DiBiase and Lamb, 2013, 2019; Florsheim and Chin, 2022).

A refined wildfire fire-frequency and burn-area analysis reflecting future conditions could initiate a reevaluation of the DPS-wide criteria for redundancy and spatial distribution; however, there are limits to the number and spacing of core recovery watersheds/population that are possible within the Southern California Steelhead Recovery Planning Area. Additionally, the basic recovery strategy of population redundancy and spatial separation is currently compromised by water-supply developments such as dams and diversions, which have restricted access to much of the historic steelhead spawning and rearing habitat necessary to meet population-level and DPS-wide viability criteria (Boughton et al., 2007a). Furthermore, prolonged droughts, which increase the likelihood and extent of wildfires, tend to occur over spatial scales broader than the recovery planning area, and over multiple years or decades, and therefore they require an additional strategy for identifying and protecting drought-resilient oversummering steelhead rearing habitats rather than relying solely on redundancy and spatial separation of watersheds/populations (Boughton et al., 2007a; Boughton, 2010a, 2010b; Dagit et al., 2017; Deitch et al., 2018; Mount et al., 2018). Many of these drought refugia are located in the upper reaches of watersheds, which are characterized by pools and perennial reaches fed by springs and groundwater, but they are currently not accessible to upstream migration of steelhead because of dams or other fish-passage impediments (NMFS, 2012; CDFW, 2023). Restricted access to major portions of the core recovery watersheds compounds the threats posed by wildfire and large postfire disturbances to the recovery of southern California steelhead. Additional resiliency to the threats identified in the TRT's wildfire analysis could be achieved by removing or modifying the numerous fish-passage barriers (e.g., dams, diversions, road crossings, pipelines, flood-control structures, etc.) that impede or block access to upstream spawning and rearing habitats, particularly those that affect access to the protected habitats within the four U.S. national forests in southern California.

Steelhead in southern California exploit aquatic habitats extending from estuaries at the mouths of coastal rivers to the furthest reaches of headwater tributaries. Utilizing this diverse range of habitats to complete the reproductive phase of their life-history, steelhead have evolved a complex suite of adaptations that reflect the defining features of southern California: a dynamic landscape, characterized by a Mediterranean climate, tectonically active landforms, highly erosive soils, and a fire-dependent chaparral/coastal sage scrub plant community. Anthropogenic changes—including the pervasive effects of climate change—have added to the natural challenges facing this iconic species (Gumprecht, 1999; Alagona et al., 2012; Power et al., 2018; Dressler et al., 2023). Wildfire, along with its potential postfire geomorphic disturbances, now plays an outsized role in the life-history of this species. The recovery strategy developed by NMFS is aimed to maximize the potential for the recovery and persistence of southern California steelhead by expressly taking into account the ecological and evolutionary roles of wildfires.

LIST OF ACRONYMS

BPG—Biogeographic Population Group
CDFW—California Department of Fish and Wildlife
DPS—Distinct Population Segment
ESA—U.S. Endangered Species Act

ESU—Evolutionary Significant Unit
NMFS—National Marine Fisheries Service
NOAA—National Oceanic and Atmospheric Administration
TRT—Technical Recovery Team
USGS—U.S. Geological Survey
VSP—Viable Salmonid Population

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