Redwood Creek Watershed Assessment

Final Draft

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1. WATERSHED CHARACTERIZATION

This chapter of the Redwood Creek watershed Assessment presents a natural resource characterization of the Redwood Creek watershed in Marin County, California. It incorporates information and analysis from the Redwood Creek Watershed Existing Conditions report (Golden Gate National Recreation Area [GGNRA] 2003), synthesis and analysis of water quality and flow data available as of October 2005, and updated information from recent existing studies, including:

- Redwood Creek Sediment Budget Analysis (Stillwater Sciences 2004);
- draft Muir Woods Natural Resources Assessment (Hall 2008);
- updated fire management plans (National Park Service [NPS] 2005, Marin County Fire Department 2005, Leonard Charles & Associates and Wildland Resources Management 2008);
- documents on the Redwood Creek Restoration at Muir Beach and Banducci sites (e.g., Jones and Stokes 2007, Moffatt & Nichol and Jefferson Anderson & Associates 2009);
- rare plant and wetland surveys (e.g., Faden 2002, 2003b; Taylor 2003; Castellini et al. 2006; Baxter et al. 2009; Garcia and Associates 2009; NPS 2009);
- multiple recent wildlife and fish studies and monitoring efforts (e.g., Heady and Frick 2004; Fellers and Guscio 2004; Jensen et al. 2004; Reichmuth et al. 2005; Fong and Manning 2007; Carlisle et al. 2008); and
- analysis of recent stream flow and water quality data (Stillwater Sciences 2005a, San Francisco Bay Regional Water Quality Control Board [SFBRWQCB] 2008a, 2008b).

Preparation of this report did not include original data collection and analysis or synthesis of raw data collected after October 2005.

In 2002, public agencies in the Redwood Creek watershed joined with stakeholders and the public to define the Desired Future Conditions (DFCs) of the watershed (Vick 2003). The purpose of this process was to create a document based on consensus that outlines common goals for managing the watershed. This chapter provides a synthesis of existing natural resource conditions within this DFC framework. Since this document provides technical support for natural resource planning and decision making, we focus on those issues that interface with the natural resources. Information on cultural resources and visitor experience can be found in Auwaerter and Sears (2006) and Manning (2007) respectively. Traffic studies completed for the Comprehensive Transportation Management Plan will be incorporated into on-going General Management Plan updates for the GGNRA. The information provided in this chapter can be used to: (1) identify key issues for watershed management within the framework outlined by the DFCs, (2) identify where natural resources and processes are most affected by agency management, and (3) identify actions that are likely to improve watershed health. Together with Chapter 2. Human Uses and Values, the watershed characterization provides an information base for addressing critical management issues highlighted in Chapters 3 and 4 of the Redwood Creek Watershed Assessment. As a common technical reference point for jurisdictions and stakeholders, this document is intended to facilitate joint and/or coordinated efforts to improve the health and management of Redwood Creek watershed.

1.1 Regional Setting

Redwood Creek originates in steep headwaters on the southwestern slopes of Mt. Tamalpais, a 2,571 ft (784 m) peak in the Marin Headlands, north of San Francisco, California (Figure 1-1). The creek flows through Mt. Tamalpais State Park, forming Redwood Creek Canyon before passing through the heart of Muir Woods National Monument. At the downstream end of the monument, Redwood Creek Canyon gives way to Frank Valley, where the creek and its tributaries have incised into a relatively broad alluvial floodplain. After winding through Frank Valley and flowing through the Big Lagoon area further downstream, Redwood Creek empties into the Pacific Ocean at Muir Beach.

The total drainage area of Redwood Creek at its mouth is 8.8 mi^2 (22.7 km^2). Named tributaries in the headwaters include Bootjack, Rattlesnake, Spike Buck, and Fern creeks. Kent Canyon Creek, another major tributary (drainage area = 1.0 mi^2 or 2.5 km^2), joins Redwood Creek in Frank Valley (Figure 1-1). Green Gulch Creek drains the southeastern 1.1 mi^2 (2.9 km^2) of the watershed, contributing to the mainstem in the Big Lagoon area.

1.2 Ownership and Land Use

1.2.1 Public land ownership

Most of the Redwood Creek watershed is owned publicly, by the Marin Municipal Water District (MMWD), the Mt. Tamalpais State Park, and Muir Woods National Monument/GGNRA, which own and manage 17 percent, 52 percent, and 26 percent of the watershed, respectively (Figure 1-2). The remaining 5 percent of the watershed includes roads (managed by the California Department of Transportation, Marin County, and local service districts) and private properties in the communities of Muir Beach, Muir Woods Park, and Green Gulch Farm.

1.2.1.1 Marin Municipal Water District

The MMWD owns 969 ac (392 ha) in the upper watershed (17 percent of the total watershed land area). MMWD land includes an extensive network of trails and fire roads and numerous fire breaks. From 1942 to 2005, a 106-ac (43-ha) parcel of MMWD land straddling the upper watershed divide was leased by the federal government, first for an Air Force station, beginning in 1950, and later as part of the GGNRA, beginning in 1982 (Figure 1-2). The federal lease expired on June 30, 2005, and the land has since reverted to management by MMWD. MMWD manages the land according to the Mt. Tamalpais Vegetation Management Plan (VMP; MMWD 1995) and the VMP 2009 Update No. 4 (Leonard Charles & Associates 2009a), and the MMWD Protection Policy for the Mt. Tamalpais Watershed (MMWD 2002; Leonard Charles & Associates 2009b). The Protection Policy is designed "to retain MMWD's watershed lands in perpetuity for water supply, natural wildland, scenic open space and limited passive recreational purposes…" (MMWD 2002).

To this policy, the VMP adds the goals of managing MMWD lands in order to:

- maintain existing important biological resources;
- restore degraded habitats;
- use adaptive management to respond to changing conditions (e.g., associated with climate change and Sudden Oak Death [SOD]); and
- to minimize risk due to wildfire (Leonard Charles & Associates 2009a).

1.2.1.2 Mt. Tamalpais State Park

The California Department of Parks and Recreation (State Parks) owns and manages Mt. Tamalpais State Park, which was established in 1928. In the 1960s, the Park expanded into the Redwood Creek watershed. It has since grown to encompass 2,915 ac (1,180 ha) within Redwood Creek watershed (52 percent of the total watershed land area) and 6,314 ac (2,555 ha) overall. The Mount Tamalpais State Park General Management Plan (California Department of Parks and Recreation [CDPR] 1980) describes land use and facilities development plans, which have been subject to ongoing revision. Park facilities include an extensive network of hiking trails and fire roads, East Peak Visitor Center/Gardner Outlook, the Pantoll State Park Headquarters and camping area, the Alice Eastwood group camping area, the Frank Valley horsecamp, the Bootjack picnic area, and Mountain Theater. In addition to these public facilities, the State Parks operates a park ranger shooting range and staff housing in Frank Valley, at the mouth of Kent Canyon.

1.2.1.3 Muir Woods National Monument/GGNRA

NPS lands in the watershed include Muir Woods National Monument (established in 1908), and portions of the GGNRA, established in 1972; today the combined extent of these NPS lands approximates 1,470 ac (595 ha), or 26 percent of the watershed land area. The GGNRA was established in 1972 to preserve land for public enjoyment and open space (U.S. Congress 1972). In addition to Muir Woods National Monument, GGNRA manages areas in the watershed along Frank Valley, at Muir Beach, and along Coyote and Dias Ridges (Figure 1-1). GGNRA facilities in the watershed include an extensive network of trails, a parking lot and picnic area at Muir Beach, and Golden Gate Dairy, which is currently occupied by the Muir Beach Volunteer Fire Department and the Ocean Riders, a local equestrian group (Figure 1-1). Land use and zoning are described in greater detail in the Golden Gate/Point Reyes General Management Plan (NPS 1980).

Muir Woods National Monument's 554 ac (224 ha) are located entirely within the watershed. Facilities at Muir Woods include hiking trails, a visitor center, parking lots, administrative offices, a native plant nursery, and maintenance shops. Acquisition of the Conlon Canyon and Camino Del Canyon areas at the southern end of the monument was completed by the NPS by 1983. Under special agreements with the NPS, several former owners continue to live in Camino Del Canyon, and local groups, including the Hillwood School, the Society for Comparative Philosophy, and Cameron House, continue to use structures in Conlon Canyon for summer camps and other youth-oriented programs.

1.2.2 Private land ownership

1.2.2.1 Community of Muir Beach

The community of Muir Beach lies at the mouth of Redwood Creek (Figure 1-1). Land use in Muir Beach is described in the Muir Beach Community Plan (Muir Beach Improvement Association 1978).

When the community plan was written, approximately 300 people resided in the community in 129 single-family homes (not all of which are in the watershed). The most recent census data note 144 homes with 295 residents at Muir Beach (U.S. Census 2000). Lot sizes range from 3,000 ft^2 to 10 ac (279 m^2 to 4 ha), with some on coastal hillslopes, and others on the floodplain adjacent to Redwood Creek. The community water supply is provided from a well that is owned

and operated by the Muir Beach Community Services District (MBCSD) in Frank Valley (State Water Resources Control Board [SWRCB] 2001).

1.2.2.2 Green Gulch Farm

Green Gulch Farm is located along Green Gulch Creek, a tributary to lower Redwood Creek (Figure 1-1). Green Gulch Farm is a Soto Zen Buddhist community and one of three branches of the San Francisco Zen Center. The farm was established in 1972 on land that had been owned and operated as a ranch by George Wheelwright. Green Gulch Farm is an organic farm and a Zen learning center, offering public lectures and classes on gardening, meditation, and Buddhist philosophy and practices. The farm relies on Green Gulch Creek, its tributaries, and several springs for drinking water and irrigation. Many current land use practices at the farm are described in a 1984 maintenance manual (Larsen 1984).

1.2.2.3 Muir Woods Park

The Muir Woods Park neighborhood lies along the northeastern ridge of the watershed, in unincorporated Marin County (Figure 1-1). Land use and zoning in the neighborhood are described in the Tamalpais Area Community Plan (Marin County 1992). The neighborhood is zoned single-family-rural and open space. The Muir Woods Park neighborhood includes 590 parcels; 318 are commercial or residential developments and the remainder includes churches, schools, or public buildings (Berto 2002; as cited in GGNRA 2003). Of the remaining 272 parcels, Marin County estimates that 77 could potentially be developed with one or more housing units under the parameters of the Marin County General Plan and the Tamalpais Area Community Plan (Berto 2002; as cited in GGNRA 2003). The Tamalpais Area Community Plan states that "the County will consider programs to acquire the many forested undeveloped parcels in close proximity to Mt. Tamalpais State Park, Muir Woods National Monument and the lands of MMWD… In the event that acquisition is not feasible, the County will implement design guidelines to ensure that new development does not harm the park or water district lands" (Marin County 1992). Water to the area is provided by MMWD.

1.2.3 Watershed history

A comprehensive history of Redwood Creek watershed and the Marin County region was recently presented as part of a detailed NPS report on historical land-use in Muir Woods National Monument and incorporated in the *Final Report on the Landuse History of Muir Woods with Recommendations* (Auwaerter 2005; Auwaerter and Sears 2006). These reports are the basis for much of the watershed history summarized here, with exceptions cited in the text below.

1.2.3.1 Native Americans

Native people lived throughout present-day Marin and southern Sonoma counties for an estimated 7,000 years prior to European colonization (Duncan 1989). The Redwood Creek watershed was apparently controlled by the Huimen, the southernmost of about fifteen Coast Miwok tribes (see for example Bennett 1998). Archeological sites, including at least three shell middens on the perimeter of the former Big Lagoon at Muir Beach, attest to its Coast Miwok heritage (Meyer 2003), and prominent nearby places bear names derived from the Coast Miwok language. For example, the name "Tamalpais" is a Spanish adaptation of a Coast Miwok word meaning "west hill" or "coast hill."

Coast Miwok managed the land with fire, burning large areas to drive—and sometimes kill—game animals, and to manage vegetation for grazing, travel, growth of desirable species, and the collection of acorns and seeds (Duncan 1989; MMWD 1995). Over thousands of years, these management practices shaped the distribution and species composition of native plant communities. Anecdotal accounts and a study by Bicknell et al. (1993) suggest that hillsides were dominated by native perennial bunch grasses, with trees and woody vegetation occurring mainly in ravines and canyons. For example, after ascending slopes near Big Lagoon in 1849, Lieutenant Henry Wise of the US Navy reported that "there was no timber to be seen, and except the stunted undergrowth netted together in valleys and ravines, all was one rolling scene of grass, wild oats, and flowers" (e.g., Toogood 1980). At the time of Wise's account the onset of cattle grazing in the region was probably already affecting vegetation distributions locally (see next section). It nevertheless seems safe to assume that, at the coarse scale of the observation, landscape conditions were still largely reflecting the prolonged influence of Coast Miwok culture, rather than exhibiting the effects of the recent shift in management practice. It is likely that under pre-Euro-American contact conditions, redwood forests covered a greater part of the watershed than exists today, particularly along the north and east facing slopes and drainages (Bicknell et al. 1993).

1.2.3.2 Cattle grazing and timber harvesting

The Spanish founded the Presidio at San Francisco in 1776 and began establishing the mission communities that ultimately supplanted the tribal cultures of the Coast Miwok and other indigenous Bay Area peoples. Parts of the Redwood Creek watershed may have been grazed by cattle and harvested for timber starting in about 1817, with the formation of Mission San Rafael Arcangel (Munro-Fraser 1880).

Cattle grazing and timber harvesting intensified after 1838, when the Redwood Creek watershed was officially deeded to William Richardson (Auwaerter 2005; Auwaerter and Sears 2006) as part of a grant that included much of the Marin peninsula (19,571 ac [7,920 ha] in all). Richardson named the area "Rancho Saucelito" (saucelito is Spanish for 'little willow grove') and began grazing longhorn cattle. According to an 1847 census, as many as 2,800 head of cattle—the largest herd in Marin County—roamed the open range of Richardson's rancho. Richardson and his neighbor, David Reed, of the Rancho de Corte Madera del Presidio, harvested redwoods and other trees from the east side of Mt. Tamalpais, and, as partners, opened the first timber mill in Marin County in the 1840s (GGNRA 2003). By the 1850s, all of the easily accessible large timber on the bay-side of the mountain had been harvested. Timber harvesters turned their focus to old growth redwoods on the hills around Bolinas Lagoon and Lagunitas Creek watershed, both north of Redwood Creek, while continuing to harvest smaller trees along Richardson Bay for cordwood to heat homes and brick kilns. Logging had spread to the ridges above Muir Woods by the late 1800s. By the early 20th century, most of the old growth redwoods in the region had been harvested. Exceptions were the stand in present-day Muir Woods and 1,300 ac (526 ha) in Kent Canyon, which was selectively logged under its agricultural owner in the 1960s prior to being sold to State Parks (Philip Williams & Associates, Ltd [PWA] 2000).

1.2.3.3 Dairy farming

In 1856, the Richardson family sold Rancho Saucelito to San Francisco financier Samuel Throckmorton, who subdivided parts of it into 500- to 1,500-ac (202- to 607-ha) parcels for dairy farming (Auwaerter 2005; Auwaerter and Sears 2006). Demand for dairy products was growing with San Francisco's expanding population, and by 1880, Rancho Saucelito had been carved into 24 dairies, most of which were leased by Portuguese and Swiss immigrants. The beach was the

center of the community, with farmhouses scattered throughout the valleys under an agrarian culture that reflected the European immigrant heritage (PWA 2003).

In 1889, six years after Throckmorton's death, the rancho was acquired by the Tamalpais Land and Water Company (Auwaerter 2005; Auwaerter and Sears 2006). Much of the land was sold for tenant dairy farming. The biggest were: the Dias (or Hill) Ranch, which extended from Homestead Valley across Dias Ridge to the Pacific Ocean; the Brazil brothers' ranch, which extended from Frank Valley up Mt. Tamalpais past the Dipsea Trail; the Silva Ranch, located in lower Frank Valley; and the Bello Ranch (a.k.a. Golden Gate Dairy), which included Green Gulch, Muir Beach, and a portion of Frank Valley (Livingston 1994, Spitz 1997, Baron 2001, Jebens 2001, NPS 2006). Many of the tenant dairy farms continued operating into the mid-twentieth century.

1.2.3.4 Other agricultural uses

The dairies of Green Gulch and Frank Valley were eventually converted to other agricultural uses. In Frank Valley, Amadeo Banducci, Sr. began leasing portions of the Silva dairy in the 1930s for flower and vegetable farming (Livingston 1994; Figure 1-1). In 1948, Banducci purchased the property and operated the entire parcel as a flower farm (Culp 1998). Three years earlier, Green Gulch and Muir Beach had been purchased by George Wheelwright, who raised beef cattle. Wheelwright planted New Zealand grasses on new pastures, claimed from the Big Lagoon area using levees along Redwood Creek. In an effort to increase the area available for grazing, he burned and chained the pervasive shrub vegetation, and, for 3–4 years in the late 1950s, sprayed herbicides by helicopter over his property. By 1969 Wheelwright had donated Muir Beach to the State Park system, and by 1972 had sold Green Gulch to the San Francisco Zen Center under terms that would keep the area in agriculture with only minimal construction of buildings and facilities (Jebens 2001).

1.2.3.5 Railroads and roads and other infrastructure

The natural beauty and resources of Mt. Tamalpais and the Marin Coast have attracted recreationists from San Francisco and other nearby areas since the late 1800s (Auwaerter 2005; Auwaerter and Sears 2006). The first ferry service to Marin began in 1855, providing transportation from San Francisco to Point San Quentin. Ferry service to Sausalito was added in 1868. The area's first wagon road, completed in 1870, extended from Sausalito to Bolinas, along the present grade of Highway 1. The Eldridge Grade road, from San Rafael to the summit of Mt. Tamalpais, was completed in 1879.

Recreation at the summit expanded in 1896, with the opening of the Mill Valley and Mt. Tamalpais Scenic Railway by the Tamalpais Land and Water Company, which had backing from local financiers Sidney Cushing and Albert Kent. Dubbed "The Crookedest Railroad in the World," it carried tourists up 8.2 miles (13.2 km) of track, through 281 curves, from Mill Valley to the East Peak of Mt. Tamalpais. Once at the top, tourists could climb to the Marine Exchange lookout on East Peak, visit the Weather Bureau station (opened in 1898) and follow hiking trails to outlying areas.

In 1907, Albert Kent's son William built a spur to connect Muir Woods to the Mill Valley and Mt. Tamalpais Scenic Railway line. In 1913, the railroad was incorporated and named the Mt. Tamalpais and Muir Woods Railway.

Introduction of automobiles and extension of local roadways provided recreationists with alternative transport up Mt. Tamalpais. The Muir Woods Road was built in 1893, and from roughly 1905 to 1910, was extended to Frank Valley (Jebens 2001). Pacific Way was connected to Muir Beach in 1908. In 1925 and 1926, the Frank Valley and Muir Woods roads were upgraded (Jebens 2001). Panoramic Highway was opened in 1928.

The "Great Tamalpais Fire" of 1929 put an end to the railroad, which had been in decline due to the rising popularity of automobiles (Auwaerter 2005; Auwaerter and Sears 2006). The railroad was abandoned in the summer of 1930 and its rails, ties, engines, cars, and other equipment were removed from the watershed.

In October 1933, roughly 200 men of the Civilian Conservation Corps (CCC) arrived in the watershed and began work on infrastructure in Muir Woods and Mt. Tamalpais State Park. One CCC construction project featured excavation of a wide, flat channel and placement of rock revetment along Redwood Creek in Muir Woods National Monument. Today, the rock revetment armors 57 percent of the total bank length (i.e., 3,541 ft or 1,079 m) within the monument. Current park policy is to not restore areas of revetment that fall into disrepair and removal of the revetment has been recommended through the Coastal Zone Plan (Hall 2008; California Coastal Commission 1980). The NPS is currently evaluating the potential impacts and benefits of removing portions of the rock revetment as part of updating the GGNRA General Management Plan (GGNRA 2008). Other CCC projects included a stone-faced concrete bridge over Fern Creek, utility buildings and benches, and the Sidney B. Cushing Memorial Amphitheater (a.k.a. the “Mountain Theater”), which was built from native, serpentine stone near Rock Springs, on Mt. Tamalpais. The CCC completed its last project in Muir Woods in May 1941.

In 1937, when the Golden Gate Bridge was completed, annual visitation to Muir Woods tripled to more than 180,000 visitors per year. By 1947, an estimated total of 58 miles (93 km) of roads and trails had been constructed in the watershed (Pacific Watershed Associates [PacWA] 2002). Many were used primarily for ranching purposes. An additional 5 miles (8 km) of roads and trails were built between 1953 and 1965, and four more miles were added between 1971 and 1982 (PacWA 2002).

1.2.3.6 Hunting and hiking

In the mid 1800s, Redwood Creek land owner William Richardson and his family and friends hunted extensively in the area. Accounts from his hunting expeditions tell of abundant elk, deer, bears, and mountain lions on the slopes of Mt. Tamalpais (GGNRA 2003). After acquiring the land and leasing parcels for dairy farming, Samuel Throckmorton lined much of his remaining property with fences, guarding it for personal use as a game refuge and allowing access to only a select group of friends (Auwaerter 2005; Auwaerter and Sears 2006).

Hunting became increasingly popular as public access expanded after Throckmorton's death in 1883. However, efforts to reserve the land for private recreational use and limited public access continued as members-only hunting and outdoor clubs began leasing large sections of the mountain slopes from local ranchers. By the end of the 1880s most of the large game animals had been wiped out (GGNRA 2003). With large predators gone, the deer population grew and became a chief target of hunters.

As access improved with increasing infrastructure, hikers transformed the mountain into an outdoor recreation center (Auwaerter 2005; Auwaerter and Sears 2006). The Tamalpais Club (founded before 1880) maintained a summit register on East Peak. The first volume, spanning

1880–1887, records more than 850 names of men, women, and children from throughout the United States and Europe (GGNRA 2003). In the 1890s and early 1900s, several hiking clubs were formed (Auwaerter 2005; Auwaerter and Sears 2006). Among them were the Sight-seers in 1887, the Cross-County Club in 1890, the California Camera Club in 1890, the Columbia Park Boy's Club in 1894, the Sempervirens Club in 1900, the Sierra Club Local Walks Committee in 1906, the Tourist Club in 1912, and the California Alpine Club in 1914. These clubs organized hikes, built and maintained trails, established camps, and built a "Trailman's Cabin" at Bootjack Camp. In 1904, hikers from San Francisco's Olympic Club held a foot race from Mill Valley to the Dipsea Inn in Bolinas, along the Lone Tree Trail. This was the first Dipsea Race, a still-popular annual event.

The first trail map of the mountain, published in 1898, shows several trails—the Lone Tree (a portion of today's Dipsea), Cataract, Kent, Throckmorton, Bootjack, and West Point (now Rock Spring) trails—which still exist today. By the 1920s, hiking and overnight camping on the mountain were so popular that the San Francisco Examiner newspaper published daily weather predictions for Mt. Tamalpais. Hiking continues to be an important activity in the watershed today.

1.2.3.7 Commercial recreation

In 1896, the Tavern of Tamalpais was constructed near the summit, at the end of the Mt. Tamalpais Scenic Railway. In 1909, William Kent opened Muir Inn, which provided luxury accommodations at the end of his Muir Woods railroad spur, at the site now occupied by Camp Alice Eastwood. In 1912, the Mountain Home Inn was opened just outside the watershed, midway down the railroad spur between "Double Bow Knot" and Muir Woods. After many changes, the inn continues as a restaurant and bed and breakfast today. Kent's Muir Inn burned down in the 1913, was later reconstructed, and was finally torn down after the demise of the railroad. Joe's Place, a small food stand and weekend dance hall, was opened near the entrance to Muir Woods during World War I by Joe Bickeroff. In c.1930, Coffee Joe's was built nearby and Joe's Place closed in c.1942. Coffee Joe's became Muir Woods Inn, and, after being moved into the monument in the 1970s, it was converted to house the NPS gift shop.

Muir Beach has long been a popular tourist stopover. In 1919, Antonio Bello, a Portuguese dairyman, established a hotel at Muir Beach (GGNRA 2003). The hotel later burned down and was replaced in 1928 by a tavern and small cabins. The tavern closed in the 1960s after it was acquired by State Parks, which tore it down despite protests by local residents. All of the cabins were also torn down. Accommodations at Muir Beach are now provided by the Pelican Inn bed and breakfast, which was built on a fill pad in the 1970s.

1.2.3.8 The Mountain Play Association

In a long-standing tradition that dates back to 1913, the Mountain Play Association regularly hosts plays on the upper slopes of Mt. Tamalpais (Auwaerter 2005; Auwaerter and Sears 2006). The first Mountain Play was held at a natural depression in the hillside, with about 600 hikers in attendance. Plays continued on land donated by William Kent in 1916. Land ownership was transferred to Mt. Tamalpais State Park in 1936, and the Mountain Theatre, the present-day site of the plays, was completed by the CCC in 1939.

1.2.3.9 Conservation efforts

By the end of the 1800s, recreationists had begun supporting efforts to preserve the area's natural and scenic resources from impending urban encroachment. A local water company had identified Redwood Canyon as a potential reservoir site, and housing and road developers were becoming increasingly interested in the as yet untouched hillslopes of Mt. Tamalpais. The watershed was defended by a succession of local and regional conservation-minded groups including the Mount Tamalpais Forestry Association, the local hikers of the "Hill Tribe," the Mount Tamalpais National Park Association, the Tamalpais Conservation Club, the Sempervirens Club, the Sierra Club, and the California Club. William Kent, builder of Muir Inn and namesake of Kentfield, became a key participant in the conservation efforts. Outmaneuvering businessmen who wanted to dam the creek as a source of water for Mill Valley, Kent purchased Redwood Canyon and in December 1907, donated much of it to the federal government under the proviso that it be made a national monument. Just days after Kent's grant, President Theodore Roosevelt invoked the Antiquities Act, designating Redwood Canyon a national monument, with the name "Muir Woods", in honor of the famous conservationist and writer, John Muir. Kent eventually went on to serve in Congress and introduce the legislation that established the NPS in 1916 (Aurwaerter and Sears 2006).

The establishment of Muir Woods National Monument was the first in a series of notable conservation actions in Redwood Creek watershed. In 1912, MMWD was formed to protect the natural land resources in the upper part of the watershed and use it to provide water to the citizens of Marin. In July, 1917, after years of conflict between hunters and hikers, the Mt. Tamalpais Game Refuge was established, ending hunting on most of the mountain—as well as in the Lagunitas Creek watershed, from Alpine Lake downstream to the outlet. In 1928, Mt. Tamalpais State Park was established after three decades of pressure from conservation groups. Only 200 ac (81 ha) at its inception, Mt. Tamalpais State Park has since acquired, among other holdings, the Dias and Brazil dairy farms (in the 1960s), and has grown to include more than 6,300 ac (2,550 ha) of land on the mountain. The GGNRA was founded in 1972. The NPS began purchasing existing and defunct farms and incorporating them into GGNRA. By 1995, cattle grazing and farming within the watershed had been completely phased out, and the GGNRA had grown to include Muir Beach, Coyote Ridge, a portion of Dias Ridge, and the lower part of Frank Valley.

1.3 Climate

1.3.1 Current and Historical Records

Redwood Creek watershed experiences a typical Mediterranean climate with warm, dry summers and mild, wet winters. Average daily temperatures range from 40 to 70°F (4 to 21°C) throughout the year; freezing temperatures are extremely rare. Mean annual precipitation is 39.4 in (100 cm) near sea level and 47.2 in (120 cm) at the higher elevations along Mt. Tamalpais (Weeks 2006). Fog drip can add 10–20 in (25–50 cm) of water to vegetation per year in the San Francisco Bay Region; exact contributions of fog drip in the Redwood Creek watershed have not been measured (Weeks 2006).

The NPS began measuring precipitation at Muir Woods National Monument in 1941 and continues to record daily rainfall there. Annual rainfall for 1941 thru 2004 is shown in Figure 1-3. The average annual rainfall at the Muir Woods gauge is 37.5 inches (95.2 cm). Mean monthly precipitation is listed in Table 1-1 and plotted in Figure 1-4. Roughly 95 percent of the average annual total occurs between October 1 and April 30 (Figure 1-4). Table 1-1 includes "Available Water" estimates, calculated from mean precipitation values and mean potential

evapotranspiration (PET) values, which are based on evaporation from the nearby Lagunitas Reservoir evaporation pan and an estimated pan coefficient of 0.7 (PWA 2003).

Table 1-1. Monthly precipitation, potential evapotranspiration (PET), and available water.

Month	Mean monthly precipitation		Mean PET		Available water	
	(in)	(mm)	(in)	(mm)	(in)	(mm)
January	7.7	196	0.3	8	7.5	191
February	6.2	157	0.6	15	5.6	142
March	4.9	124	1.9	48	3.0	76
April	2.4	61	2.6	66	0	0
May	1.1	28	3.9	99	0	0
June	0.4	10	4.5	114	0	0
July	0.1	3	5.1	130	0	0
August	0.1	3	4.0	102	0	0
September	0.4	10	2.7	69	0	0
October	2.0	51	1.7	43	0.3	8
November	5.3	135	0.7	18	4.6	117
December	7.3	185	0.4	10	7.0	178
Total	**37.9**	**963**	**28.3**	**719**	**9.7**	**246**

PET values from PWA 2003. Available water is what remains after evapotranspiration losses (total precipitation minus total PET). Source: Stillwater Sciences (2005a).

1.3.2 Climate Projections

Weather along the California coast is subject to climatic cycles, including the Pacific-North American Oscillation, the El Nino Southern Oscillation, and the Pacific Decadal Oscillation (Andrews et al. 2004). These cycles, which occur on three year or more scales, effect changes in temperature and precipitation, as well as frequency of extreme weather events. A uni-directional change in the climate of Redwood Creek watershed has also occurred over the past 50 years, with average annual temperatures likely increasing similar to the State of California average of approximately 1.5^{o}F. On average, the eight major global climate change models (global circulation models or GCMs) project continued increases in annual temperatures for Redwood Creek watershed, ranging from 3°F to 6°F increases by 2080 (The Nature Conservancy [TNC] 2009). The greatest increases in temperature are projected to occur from July through September, with smaller changes occurring during mid-winter. Model projections are in agreement that increased temperatures will be accompanied by increased frequency and severity of extreme events such as heat waves, flooding, and wildfires (Cayan et al. 2008). The projected increase in mean annual temperature and frequency in extreme events could also result in an increase in the frequency of scouring floods and prolonged droughts (Karl 2009).

The 'ensemble' of major model projections regarding the effects of climate change on precipitation and fog along north coastal California, average an approximately 5 percent decrease in precipitation for the low, moderate and high atmospheric CO_2 scenarios (TNC 2009). However, differences among models for the precipitation changes are great, and nearly evenly split between projections of substantial increases versus substantial decreases in precipitation by 2080.

Coastal fog is a critical part of the annual water budget for north coastal vegetation, providing from 10 to 40 percent of the annual water supply for coastal redwoods, particularly during the summer months when precipitation is low and coastal fog is frequent (Dawson 2007). The net effects of climate change on coastal fog formation are not clear. A comparison of historical

coastal fog frequency (number of fog days) with sea level air pressure over the northeast Pacific suggests that high pressure off the Oregon coast enhances summer fog by pushing moist air southeast along the coast where it meets cool air from Alaska and from deep water upwelling to create coastal fog (Dawson and Johnstone 2008). The effects of climate change on inland low pressure created when interior air cells rise as they are warmed during the day and draw moist air towards the coast, are also unclear. However, since climate change scenarios indicate that inland summer temperatures could increase over the 21st century, it seems plausible that these onshore flows induced by inland low pressure could increase, thereby increasing movement of moist air towards the coast where it can form fog (Lehre 1974, Cayan et al. 2006a). Changes in the occurrence of coastal cool air that can meet these moist air masses to create fog, including the Alaskan currents and deep water upwelling, are also not well understood and add additional uncertainty to any projections regarding coastal fog over the next 50 to 100 years.

Mean sea level (MSL) along the California coast is projected to rise from 4 to 28 in (11 to 72 cm) in the next 80 years (Cayan et al. 2006b). Combined with the increase in extreme events, MSL rise is likely to cause an increase in the frequency of coastal storm surges, or coastal flooding events. Increases in MSL will also result in 'marine transgression' (landward migration of the shoreline), landward migration of coastal wetland salinity gradients, and changes in size and extent of estuaries and coastal lagoons (see Section 1.8.3. Wetland and Seeps found in lower Redwood Creek).

1.4 Hydrology

1.4.1 Available stream flow records

Stream flow records for the watershed are discontinuous, with the largest data gap between the early 1970s and late 1980s. From 1962 to 1973, the United States Geological Survey (USGS) measured annual peak flows in Redwood Creek at the Frank Valley Bridge (contributing area = 6.4 mi^2 or 16.6 km^2). From 1986 to 1988, the USGS quantified "summer" and "winter" flows at the Pacific Way Bridge, at the Muir Woods Bridge and in Green Gulch. The timing, location, and magnitude of measured flows from 1962 to 1988 are listed in Table 1-2.

Table 1-2. Point measurements of stream flow for the Redwood Creek watershed (1962—1988).

Date	Location	Type of measurement	Source	Flow	
				(cfs)	(m^3s^{-1})
Redwood Creek					
2/13/1962	Frank Valley Road	Annual storm peak	USGS	880	24.9
10/13/1962	Frank Valley Road	Annual storm peak	USGS	800	22.7
1/20/1964	Frank Valley Road	Annual storm peak	USGS	100	2.83
1/6/1965	Frank Valley Road	Annual storm peak	USGS	410	11.6
1/4/1966	Frank Valley Road	Annual storm peak	USGS	1,300	36.8
1/21/1967	Frank Valley Road	Annual storm peak	USGS	295	8.35
1/30/1968	Frank Valley Road	Annual storm peak	USGS	630	17.8
12/15/1968	Frank Valley Road	Annual storm peak	USGS	1,040	29.4
1/21/1970	Frank Valley Road	Annual storm peak	USGS	1,780	50.4
1971	Frank Valley Road	Storm peak	USGS	*	*
1972	Frank Valley Road	Storm peak	USGS	*	*
1973	Frank Valley Road	Storm peak	USGS	*	*
Aug. 1974	Lower Redwood Creek	Summer	NPS	0.56	0.016
Sept. 1974	Lower Redwood Creek	Summer	NPS	0.31	0.0088
1/31/1986	Muir Woods	Winter	USGS	51	1.4

Date	Location	Type of measurement	Source	Flow	
				(cfs)	(m^3s^{-1})
1/31/1986	Pacific Way	Winter	USGS	86	2.4
6/26/1986	Muir Woods	Summer	USGS	0.77	0.022
6/26/1986	Pacific Way	Summer	USGS	0.66	0.019
2/13/1987	Muir Woods	Winter	USGS	114	3.22
3/13/1987	Pacific Way	Winter	USGS	30	0.85
6/10/1987	Muir Woods	Summer	USGS	0.62	0.018
6/12/1987	Pacific Way	Summer	USGS	0.68	0.019
1/5/1988	Muir Woods	Winter	USGS	42	1.2
1/5/1988	Pacific Way	Winter	USGS	73	2.1
6/7/1988	Muir Woods	Summer	USGS	0.70	0.020
6/7/1988	Pacific Way	Summer	USGS	0.78	0.022
9/4/1988	Frank Valley Road	Summer	NPS	0.06	0.002
Green Gulch Creek					
1/30/1986	Green Gulch Farm	Winter	USGS	909	0.28
6/25/1986	Green Gulch Farm	Summer	USGS	0.01	0.0003
3/13/1987	Green Gulch Farm	Winter	USGS	1.2	0.034
6/12/1987	Green Gulch Farm	Summer	USGS	0.01	0.0003
3/23/1988	Green Gulch Farm	Winter	USGS	0.04	0.001
6/2/1988	Green Gulch Farm	Summer	USGS	0.01	0.0003

Adapted from PWA et al. 1994 and PWA 2003 by Stillwater Sciences (2005a).
* Records from 1971, 1972, and 1972 are referenced but not reported in any of the data sources.

From March 1992 to September 1993, daily flow was monitored continuously in Redwood Creek at the Pacific Way Bridge using an automatic water level recorder (PWA et al. 1994). The NPS has been monitoring flow, with some data gaps, at the Highway 1 Bridge since Water Year (WY) 1998. The NPS also monitored flow in both main branches of Green Gulch Creek from 2003 to 2005. In an effort to better quantify the relationship between water surface level and discharge at the Highway 1 Bridge (and also to quantify sediment transport rates), the NPS hired an independent contractor to measure flow (and sediment transport) during high flow events in WY 2003 and WY 2004 (Stillwater Sciences 2004, Environmental Data Solutions [EDS] 2004). Water surface levels were monitored continuously at the Muir Woods Road Bridge during portions of the high flow periods of 2003 and 2004. The timing and location of continuous flow monitoring efforts on Redwood Creek are summarized in Table 1-3. Figure 1-5 shows the location of the gages on a watershed map.

Table 1-3. Continuous records of stream flow for the Redwood Creek watershed.

Dates		Location	Notes	Source
From	To			
Redwood Creek				
March 1992	Sept. 1993	Pacific Way	Discontinued effort	PWA
1998	Present	Highway 1 Bridge	Ongoing, semi-continuous measurements	NPS
Jan. 2003	March 2004	Muir Woods Road	Discontinued effort	EDS
Green Gulch Creek				
2003	2005	Green Gulch Farm	Two gauges, semi-continuous*	NPS

Sources: PWA (2000); EDS (2004)
* Data from Green Gulch Creek are semi-quantitative.

Even with the recent addition of nearly seven years of semi-continuous flow measurements, the stream gauging history of Redwood Creek is too short and sporadic for development of a reliable long-term flow-duration curve for peak floods. In an attempt to overcome this limitation in previous studies, the Redwood Creek flow data have been combined with extrapolative analyses of hydrologic data from neighboring watersheds. For example, in one early study (Lehre 1974), flood frequency estimates were developed from a coupled analysis of the USGS peak flows (listed in Table 1-2) and regional rainfall data. More recently, a flood-routing analysis of the Frank Valley Bridge data (Table 1-2) was coupled with records from a nearby USGS gauge (on the Arroyo Corte Madera in Mill Valley) and the first two years (1998 and 1999) of data from the Highway 1 Bridge to develop a composite, 24-year record of annual peak flow estimates (PWA 2000). A log-Pearson type-III statistical analysis of that data yielded the peak flow recurrence relationship summarized in Table 1-4.

Uncertainties in the Table 1-4 flood magnitudes, while difficult to quantify precisely, are undoubtedly very high, due to the extrapolative methods that were used to generate the relationship. One goal of a recent stream flow data analysis effort was to add to the growing database of peak flows and thus contribute to more precise quantification of the flow-duration relationship for Redwood Creek.

Table 1-4. Estimated peak flood recurrence relationship for Redwood Creek at the Highway 1 Bridge

Annual peak flood recurrence interval (years)	Flood magnitude	
	(cfs)	(m^3s^{-1})
1.5*	570	16.1
2	805	22.8
5	1,600	45.3
10	2,270	64.3
25	3,270	92.6
50	4,140	117
100	5,100	144

Sources: PWA 2000, 2003; * Moffat & Nichol and Jeff Anderson & Associates 2009

1.4.2 Water surface level as a function of time

The time series of daily average water surface level data from WY 1999–2005 at the Highway 1 Bridge and Muir Woods Road Bridge gauges are plotted in Figures 1-6 and 1-7, respectively. Many of the stage measurements for the Muir Woods Road Bridge gauge are zero, representing days of sensor operation in which stage never rose above the pressure transducer. These are plotted as red "X" symbols in Figure 1-7. The pressure transducer was located at 104.91 ft (31.98 m) NAVD, or approximately 0.78 in (20 mm) above the bed at the edge of the creek. Hence stage measurements for "zero-pressure" days are only semi-quantitative. Data gaps in Figures 1-6 and 1-7 represent periods in which the water level sensor was either not installed or installed and not operating.

1.4.3 Stage-discharge relationships

In order to convert the time-series of Figures 1-6 and 1-7 into time series of mean daily flow, it is necessary to first develop site-specific relationships between discharge and stage. Point

measurements of stream discharge and stage for some of the Redwood Creek watershed gauges have been repeatedly recorded by NPS personnel and others (EDS 2004) and can be used to develop site-specific stage-discharge relationships as described below.

1.4.3.1 Highway 1 Bridge

The stage-discharge data for Highway 1 Bridge are plotted in Figure 1-8. For a given stage there is substantial variability in discharge, particularly at low flows. For example, discharge varies by up to 3 orders of magnitude at stage readings below about 2.5 ft (0.8 m) (EDS 2004).

Estimation of discharge from stage using a simple regression analysis of Figure 1-8 data would lead to large uncertainties for the low-, to mid-range flows that dominate the time-series of stage data for Redwood Creek. Instead, a stratified analysis of the data is warranted, because there have been substantial shifts in the relationship between stage and discharge over time. Under the date-based groupings shown in Figure 1-9 for low flows, the data define three distinctly different non-linear, power law relationships of the form

$$\text{stage} = a \times \text{discharge}^b$$

where a and b, the power-law intercept and the power-law slope, are fitted regression parameters. Regression statistics are summarized in Table 1-5.

Date-based grouping of data also helps resolve stage-discharge relationships for mid-range flows, as shown in Figure 1-10 (with regression statistics reported in Table 1-5). Two clearly different relationships are apparent for the mid-range flows. Possible reasons for the shift in flow rating curves for low and mid-range flows are discussed in Section 1.4.4.

Paired measurements of flow and stage for high flows are only available for WY 2003–2005. As a result, a rating curve for high flow conditions can only be constructed for WY 2003–2005. This makes unambiguous identification of shifts in the high flow rating curve over time impossible. Nevertheless, given that both the mid-flow and low-flow curves show substantial offset from one interval to the next, it seems likely that the high flow curve would exhibit an offset as well (if data from the earlier interval were available for comparison). Application of the 2003–2005 high-flow rating curve to the preceding period is not easy to justify.

The power-law slope of the mid-flow regression for 2003–2005 is significantly steeper than the power-law slope of the 2003–2005 high-flow curve (Figure 1-11), with a clear break in slope at stage roughly equal to 2.5 ft (0.8 m).

In developing an estimate of the high flow rating curve for 1998–2002, it seems reasonable as part of a first approximation to assume (1) that channel geometry is such that the threshold between high and mid-flows has remained at the 2.5 ft (0.8 m) stage indicated in Figure 1-11 and (2) that the regression slope from the WY 2003–2005 high flow curve is applicable to the preceding period. These assumptions permit assessment of a hypothetical stage-discharge relationship that can be used to estimate discharge for high flows of the 1998–2002 interval. The hypothetical line is plotted in Figure 1-12 (dashed black line). The slope and intercept estimates are listed in Table 1-5.

Table 1-5. Stage-discharge relationships: power law regression statistics.

Range of dates with measurements[1]		Power law		Curve applies to data from period[2]		Type of flow with range of applicable stages (H)
From	To	Intercept	Slope	Start	End	
Highway 1 Bridge						
12/5/1998[3]	1/5/2000	$12.3\times10^{-3} \pm 0.6\times10^{-3}$	13.1 ±1.5	10/25/1998	1/5/2000	Low (H ≤1.67 ft)
3/30/2000	7/16/2001	$1.9\times10^{-4} \pm 0.5\times10^{-4}$	20.3 ±4.1	1/6/2000	9/30/2002	Low (H ≤1.72 ft)
10/10/2002	12/2/2004	$4.6\times10^{-9} \pm 3.6\times10^{-9}$	38.2 ±5.1	10/1/2002	2/15/2005[6]	Low (H ≤1.67 ft)
12/5/1998[3]	3/8/2001	1.290 ±0.002	4.1 ±0.6	10/25/1998	9/30/2002	Mid (H ≤2.5 ft)[4]
1/8/2003	2/15/2005	0.0442 ±0.0004	7.1 ±0.23	10/1/2002	2/15/2005[6]	Mid (1.67<H ≤2.5 ft)
--[5]	--[5]	5.9 ±1.4	2.4 ±0.2	10/25/1998	9/30/2002	High (H>2.5 ft)
12/18/2002	2/21/2005	3.33 ±0.03	2.4 ±0.2	10/1/2002	2/15/2005[6]	High (H>2.5 ft)
Muir Woods Road Bridge						
1/24/2003	2/25/2004	125 ±10	0.72 ±0.18	11/28/2003	2/25/2004	All

1 Indicates range of dates for which stage and discharge measurements are available
2 Indicates period over which the regression statistics apply in the analysis
3 Stage and discharge measurements from early October 1998 were ignored in this analysis due to complications from hydraulic changes related to removal of a weir at the gauge
4 Mid-level regression statistics apply to flows with stage H>1.67 ft (0.51 m) and H≤2.5 ft (0.76 m) for 10/25/98 to 1/5/00, and to flows with stage H>1.72 ft (0.52) and H≤2.5 ft (0.76 m) for 1/6/00 to 9/30/02.
5 No stage-discharge data are available for high flows in WY 1998–2002 (see text).
6 Data from after 2/21/2005 are not considered in this analysis due to channel changes (and complications) related to effects of a piece of large woody debris (LWD) that settled in the channel near the gauge. A new rating curve will likely be necessary for data that post-date 2/21/05.

1.4.3.2 Muir Woods Road Bridge

The stage-discharge data for the Muir Woods Bridge are plotted in Figure 1-13. Unlike the data from the Highway 1 Bridge, the data from Muir Woods Road are more or less consistent with a single power-law relationship between stage and discharge. Even if they were not, the small sample size (n=6) would have precluded any breakdown of the data into subgroups. The estimated slope and intercept of the power-law relationship are reported in Table 1-5. The significance of the stage-discharge relationship for Muir Woods Road Bridge may be artifactually high due to the grouping of data at low and high stages (with no observations in between).

1.4.3.3 Green Gulch Creek gauges

Data from the two gauges in the Green Gulch Creek subwatershed are discontinuous and regarded as semi-quantitative due to technical problems with the pressure transducers (M. DeBlasi, Hydrologic technician, NPS/GGNRA, Sausalito, California, pers. comm., 9 May 2005). One of the Green Gulch Creek gauges is located within the backwater influence of Redwood Creek, making it only minimally diagnostic of flow from the Green Gulch Creek subwatershed.

1.4.4 Potential causes of flow rating curve shifts

Changes in cross-sectional area and flow dynamics at a gauge lead to fundamental changes in its stage-discharge relationship. The shift in the flow rating curves shown in Figure 1-12 suggests that the gauge at the Highway 1 Bridge has been prone to substantial changes in channel conditions and flow dynamics over the period of record. This is consistent with anecdotal observations of conditions at the gauge. For example, when NPS installed the Highway 1 Bridge gauge in 1998, the concrete bottom of the box culvert at the bridge was visible. By the fall of 2005, it was covered with sediment about 1 ft (0.3 m) deep (C. Shoulders, Ecologist, NPS/GGNRA, San Francisco, California, pers. comm., 2006). There are at least two plausible explanations for the shift in rating curve over time: 1) effects of natural variability in channel geometry and flow dynamics, and 2) effects of modifications in the channel downstream of the gauge.

1.4.4.1 Effects of natural variability in channel slope and shape on the rating curve

Channel slope drops from 0.9 percent at the upstream end of Frank Valley to 0.4 percent near the Highway 1 Bridge and drops even more to 0.1 percent further downstream where channel bed material shifts from gravel to sand (Stillwater Sciences 2004). Hence, channel slope and morphology change substantially near the gauge, such that the area may be naturally prone to episodic scour and deposition of sediment during rising and falling flood stages. The apparent shift in the rating curves over time (Figure 1-12) is consistent with progressive aggradation (with decreasing discharge for a given stage as a function of time), which may be a natural response to ongoing delivery of sediment from the upper watershed.

A case in point of natural channel changes at the Highway 1 Bridge gauge occurred recently, after WY 2005 storms, when a large piece of wood began migrating downstream toward the bridge and caused noticeable changes in flow dynamics at the gauge (M. DeBlasi, pers. comm., 9 May 2005). These observations at first seem to cast doubt on the reliably of data from WY 2005. However, stage-discharge data from the early part of the water year fit within patterns observed for WY 2003–2004, suggesting that changes in WY 2005 were minor, at least until sometime before the March 22, 2005 flow and discharge measurements, when NPS field technicians first included a comment about the wood lodging in sediment near the bridge and affecting flow at the

gauge. Precisely when the wood began to affect flow at the gauge is not known. As part of a conservative approach, data from after February 15, 2005 were not considered in this analysis, due to the potential effects of the wood on flow dynamics at the gauge. A new set of rating curves will need to be developed for the gauge for post-March 2005 stage data.

1.4.4.2 Effects of channel modifications by humans on the rating curve

As discussed in greater detail in Section 1.4.3, the channel and floodplain in the reach below the Highway 1 Bridge have been extensively modified over the last several decades, resulting in altered channel hydraulics and sediment transport capacity. Human modifications also reduced floodplain area downstream of the Pacific Way Bridge. These effects, together with delivery of sediment from large storms in the late 1990s and several large log jams downstream of the Pacific Way Bridge, promoted sediment build-up in the channel near Pacific Way. The zone of aggradation eventually extended roughly 800 ft (243 m) downstream of the bridge and grew in depth by 5 ft (1.5 m) at the bridge between 1993 and 2002 (Klein et al. 2002). It is possible that the downstream aggradation may have affected flow and sediment transport dynamics further upstream, at the gauge. This may have contributed to the aggradation at the Highway 1 bridge and thus might help explain the shift in the flow rating curves from 1998 to 2002 (Figures 1-9 and 1-12).

In 2002, in response to increased flooding at Pacific Way and the increased potential for avulsion to adjacent pastureland, the NPS and Marin County Department of Public Works implemented flood reduction measures including removal of woody debris jams from the creek and excavation of sediment from 460 lineal ft of creek near Pacific Way. These changes would generally be expected to lead to net degradation of the channel—which would be inconsistent with the observed aggradational shifts in the rating curves from 2002 to 2005 (Figures 1-9, 1-10, and 1-12). However, the remedial measures of 2002 were unable to remove a log jam which was preventing the creek from occupying the larger of its two channels downstream of Pacific Way. This may have contributed to the continued aggradation which was shown in a post-2002 time-series of creek profiles (EDS 2005) to have reached pre-dredging levels at the bridge by the summer of 2004. NPS responded to the observed aggradation by removing the wood jams that were blocking the right fork of the channel, and by excavating 2–3 ft (0.6–0.9 m) of fine sediment from another 150 linear ft of channel. During the first storm after the 2004 dredging and wood removal, the mainstem of the creek reoccupied its right fork. This appeared to allow moderate flows to recede more quickly; however, a February 2005 profile for the bridge area shows even more aggradation occurred there (B. Merkle, NPS, pers. comm., 2006) A 40-ft (12-m)long log jam adjacent to the low-flow channel near the Muir Beach parking lot was removed in October 2005. In October 2005, NPS also removed most of the fill pad that served as the visitor picnic area. This added substantially to the creek's floodplain width at that point.

Given that most of the post-2002 modifications were focused downstream of the Highway 1 Bridge (where flooding and economic impacts were greatest), it is not clear whether they could have affected the stage-discharge relationship at the gauge. It is possible that the post-2002 modifications had no effect on the trend of aggradation at the Highway 1 Bridge.

1.4.5 Discharge as a function of time

Using the stage-discharge relationships developed in Section 1.4.3, time series of discharge were developed from the time series of stage measurements from each gauge.

1.4.5.1 Highway 1 Bridge

The time-series of mean daily flows for the Highway 1 Bridge gauge for Oct, 25 1998–Feb. 15, 2005 are plotted in Figure 1-14. Annual peak mean daily flow ranges from 80 to roughly 390 cfs (2 to roughly 11 m^3s^{-1}), and were highest in WY 1999 and 2000.

Figures 1-15 and 1-16 show subsets of data from Figure 1-14 and include uncertainties estimated from the power-law regression parameters of Table 1-5. Figure 1-15 shows mean daily flow for the wet season of WY 2004, a year with a relatively low peak mean daily flow, and Figure 1-16 shows mean daily flow for WY 1999, a year with a relatively high peak mean daily flow.

1.4.5.2 Muir Woods Road Bridge

The time series for mean daily flow at the Muir Woods Road Bridge is plotted in Figure 1-17. The record for the Muir Woods Road Bridge gauge is much shorter than the record for Highway 1 Bridge. Data from the two gauges can nevertheless be compared with one another, to determine whether there is a correlation between the two data sets for the overlapping period of record. Figure 1-18 shows mean daily flow at the Muir Woods Road Bridge plotted against mean daily flow for the Highway 1 Bridge. There is no correlation between the data for the overlapping period of record. If there were a strong correlation, it might have been possible to use the relationship to scale daily flow from the Highway 1 Bridge gauge to the Muir Woods Road Bridge gauge, thus greatly expanding the interval of flow estimates for the Muir Woods Road Bridge.

The lack of correlation of Figure 1-18 could be due to spatial variations in precipitation rates across the watershed (which would lead to variations in relative contributions of flow from tributaries—such as Kent Canyon Creek—from storm to storm). It might instead be due to differences in hydrologic response related to intrinsic differences in contributing areas. For example, it is possible that steep areas upstream of Muir Woods Road Bridge, with their thin soils, have quicker saturation and delivery of flow, in comparison to the thick alluvial fills of Frank Valley, immediately upstream of the Highway 1 Bridge. The relative importance of these factors is difficult to determine in the absence of quantitative data on spatial variability in precipitation and flood response characteristics of contributing watershed areas.

1.4.6 Peak flows and seasonality

Flow in Redwood Creek varies seasonally with precipitation (Figure 1-19). Low flow in the summer and fall are typically in the range of 0 to 1 cfs (0 to 0.03 m^3s^{-1}) at the Highway 1 Bridge. Winter baseflow, between storm events, is typically between 1 and 10 cfs (0.03 and 0.3 m^3s^{-1}), with short-duration, peak flows of 100 to 1,000 cfs (28 to 280 m^3s^{-1}) during winter storms. Annual peak flows for the analyzed period of record are listed in Table 1-6. The stage record for the WY 2002 wet season is incomplete, raising the possibility that the annual peak flood was not recorded (and is higher than the value listed in Table 1-6). There is some indication that this may be the case, based on inspection of in the precipitation record shown in Figure 1-19; daily rainfall totals were often higher than 1 inch/day (25.4 mm/day) from late November through December 2001, and undoubtedly contributed to increased flows in the creek. However, whether flows rose above the 399 cfs (11.3 m^3s^{-1}) reported in Table 1-6 is difficult to determine in the absence of stage measurements for late 2001. The uncertainties in the peak floods for 1998–2002 are high, but difficult to quantify, due to a lack of corroboratory data for the hypothetical high-flow rating curve for WY 1999–2002. Along with flood magnitude, Table 1-6 also lists each peak flood's estimated return period—based on the peak flood-recurrence interval relationship generated in previous work (PWA 2000). Peak flow from WY 1999–2005 imply return intervals of 1 to 2

years, which is more or less the range one might expect, given the short sampling interval and the fact that annual rainfall has been within about 20 percent of the 65-year average from 1999 to 2005 (Figure 1-3).

Table 1-6. Annual peak instantaneous floods at the Highway 1 Bridge, WY 1999–2005.

Date	Water year	Instantaneous magnitude (cfs)	Implied return period* (years)
2/16/1999	1999	794	1.95
2/14/2000	2000	804	2
2/21/2001	2001	112	1
2/19/2002	2002	399†	1.15
12/12/2002	2003	268	1.05
1/11/2004	2004	540§	1.5
12/27/2004	2005	639	1.6

* Based on peak flood-recurrence interval relationship as plotted in PWA 2000 (their Figure 1-7) and summarized here in Table 1-4.

† The record for the WY 2002 wet season is incomplete, raising the possibility that the annual peak flood was higher (but not recorded)

§ According to anecdotal accounts of the extent of flooding on the Banducci floodplain, it appears that December 30, 2003 and January 1, 2004 flood levels were higher than they were on January 11, 2004. Although data from the Muir Woods Road Bridge gauge (EDS 2004) confirm that this is the case, data are not available for the Highway 1 Bridge for either December 30, 2003 or January 1, 2004. This makes our estimate of the magnitude of the peak instantaneous flood for WY 2004 a minimum estimate.

1.4.7 Uncertainties in flow estimates

As noted in the discussion of Figures 1-8 through 1-12, the combined set of stage-discharge data for the Highway 1 Bridge gauge show wide scatter on a log-log plot, with clear relationships emerging only when the data are grouped by date. However, even when the data are grouped by date, there is residual scatter in the relationships between stage and discharge, particularly at low flows (Figure 1-9). One reason for this may be unreported (and difficult to quantify) uncertainties in the flow measurements themselves. When flows are low, velocities are also low and are difficult to measure precisely, even with well-calibrated current meters. Uncertainties in flow measurements are generally expected to be highest (on a percent-of-the-total basis) for low flow measurements, due to relatively high percent errors in velocity measurements. One way to assess this kind of measurement uncertainty is to measure flow repeatedly at times when flow is not changing much. The extent to which such repeated flow estimates differ from one another is a reflection of the uncertainty in the measurements.

The magnitude of low flows may be an important limiting factor for the sustainability of the creek's aquatic ecosystem. Hence, assessment of a better defined relationship between stage and discharge for low flows should be a priority of future work at the gauge.

Quantifying discharge at high flows is also important, because the vast majority of the creek's total flow occurs during the high flow season between October 1 and April 30. Hence, an additional priority for ongoing maintenance of the gauge is higher frequency collection of discharge measurements at high flows, to better define the relationship between stage and discharge at high flows.

1.4.7.1 On the use of instantaneous stage measurements for estimating discharge

Daily peak instantaneous water surface elevations were available for all years (making development of Table 1-6 possible). However, there were some important inconsistencies in the other types of data that were available for the period of record. In particular, the stage data supplied by NPS for the Highway 1 Bridge gauge for some water years consisted of daily average estimates of stage, while data for other water years included instantaneous measurements of stage recorded every 15 minutes. For consistency in their analysis of the flow data, Stillwater Sciences (2005a) converted the 15 minute data into daily average water surface levels (Figure 1-6), and then calculated mean daily flows for each day using the instantaneous flow rating curves (Figure 1-12).

It is important to note that errors are introduced into mean daily flows calculated in this way. In general, if some quantity of interest (in this case flow) is calculated from a nonlinear function of another quantity (in this case stage), the average value of the quantity of interest will not be equal to the function evaluated at the average of the other quantity (Ang and Tang 1975). Hence, due to nonlinearities in the stage-discharge relationships, mean daily flows calculated directly from instantaneous measurements of stage will differ somewhat from mean daily flows calculated from average measurements of stage. This is shown in Figure 1-20 for data from WY 2005 at the Highway 1 Bridge. Data that plot above or below the 1:1 line shown in Figure 1-20 are estimates with errors that were introduced by the methods used in the analysis.

If 15 minute data were available for the entire dataset, the correct approach would have been to convert the 15 minute stage data into a time series of 15 minute flow data (rather than average the stage measurements by day), and then estimate mean daily flows by averaging flows by day. The approach that Stillwater Sciences (2005a) used is nevertheless appropriate for two reasons. First, it is the only approach that can be applied consistently for the entire dataset (because some 15 minute data were not made available). Second, most of the errors in the mean daily flow measurements are small and occur at low flows (Figure 1-20)—and thus have minimal implications for the analysis. Even so, as a general rule for future analyses of Redwood Creek stream flow, time-averaging of flow data (to generate mean daily flow estimates, for example) should be carried out only after instantaneous discharge is inferred directly from instantaneous measurements of stage.

1.4.8 Flow diversions

Water is diverted directly from Redwood Creek and its tributaries by MMWD and Green Gulch Farm (Johns 1993, PWA 1995, Martin 2000). MMWD has rights to divert water at seven locations in the upper watershed, on Fern, Laguna, Spike Buck, and West Fork Rattlesnake creeks, the total water quantity associated with these rights are not precisely known (Johns 1993) (Figure 1-21). Diversions on Fern and Laguna creeks supply the West Point Inn. The West Fork Rattlesnake Creek diversion feeds Mt. Tamalpais State Park. Other diversions, marked on Figure 1-21 with black-centered circles, have not been used in recent years. MMWD supplies water to Muir Woods National Monument from sources outside of the watershed.

Green Gulch Farm has developed an elaborate system of reservoirs to store and divert flow from Green Gulch Creek and its tributaries for irrigation, stock watering, fire protection, recreation, and domestic use. This system includes five small reservoirs, diversions on the mainstem Green Gulch Creek, and two reservoirs on tributaries to the creek. The farm has a state water right for diversion of 17 ac-ft (21,000 m^3) per year from the mainstem of Redwood Creek. The farm also has an unused diversion on Redwood Creek in Big Lagoon, with an annual right to 47 ac-ft

(58,000 m^3), contingent on withdrawal between April 15 and September 30 (Johns 1993). The farm's domestic water supply is derived primarily from a spring on an unnamed tributary northeast of their visitor parking lot. Water is stored in a 20,000 gallon tank. Two other springs that previously supplied drinking water dried up in about 1997. A new back-up groundwater well was installed at the edge of the Green Gulch fields in about 2000.

The Muir Beach Community Services District (MBCSD) supplies water to the Muir Beach community, serving approximately 350 people through 147 connections (Martin 2000). The MBCSD operates a well on the Redwood Creek floodplain near the Banducci property. In 2001, the MBCSD received a permit from the SWRCB to withdraw up to 50.6 ac-ft (62,400 m^3) per year from the well (SWRCB 2001). Acquisition of the MBCSD water rights permit required development and implementation of an Adaptive Management Plan (AMP) with assistance from the Technical Advisory Committee (MBCSD 2005). The AMP includes a water conservation plan, a streamflow monitoring plan, and a pumping schedule, to protect instream flows for salmonids during critical low flow periods. According to the AMP, when reduced flow begins to affect the continuity of pools (creating adverse conditions for salmonids), the MBCSD must reduce its pumping rate from an average of about 45,000 gallons per day (gpd) to no more than 35,000 gpd and enforced water conservation measures must go into effect. The AMP also required that the MBCSD increase its storage capacity (from 250,000 gallons to 300,000 gallons) and explore funding possibilities for additional increases storage capacity, to permit reduced pumping during low flow periods. Two of the more likely funding options identified thorugh this process include construction of storage tanks in Frank Valley and/or a desalination facility. The District is planning a small increase in storage capacity (from 250,000 to 300,000 gallons); however the District would require additional outside funding in order to create a greater storage area (e.g. 1.8 million gallons was identified as necessary to eliminate well pumping during the 45 day driest period of the year) or a desalination facility. Voluntary water conservation is encouraged via annual reminders.

The Banducci residence receives its domestic water supply from a spring in the drainage west of the main house. Mt. Tamalpais State Park taps groundwater wells for use at the Mt. Tamalpais Lookout, the Mountain Theater, Camp Alice Eastwood, and residences at Kent Canyon. Camp Hillwood, in Camino del Canyon, maintains a water tank for fire protection, with water drawn from a tributary.

1.5 Geology and Geomorphic Processes

1.5.1 Geology and soils

The Marin Headlands are part of the California Coast Ranges, which formed over the last several million years in response to crustal shortening associated with compression between the Pacific and North America tectonic plates (Wahrhaftig 1994). Most of the Redwood Creek watershed is underlain by rocks of the Franciscan accretionary assemblage (Figure 1-22), a highly deformed mixture of sedimentary, metamorphic and igneous rocks of late Jurassic and Cretaceous marine origin (Wahrhaftig 1994; Blake et al. 2000). Incoherent shale and sandstone dominate (Figure 1-23), with slopes that tend to be highly susceptible to landsliding and debris flows. Occasional blocks of bedded limestone and chert occur in the watershed, as do coherent blocks of greywacke, a type of sandstone and serpentine (Blake et al. 2000).

In the headwaters, bedrock weathers to a thin (1 ft [0.3 m]) gravelly loam (Natural Resources Conservation Service Soil Survey Geographic—SSURGO—classification) directly overlying

bedrock. Lower in the watershed, surface soils are clay loams that give way to clay at depth, and ultimately to bedrock. The Frank Valley floor is covered in Quaternary alluvial fill, which presumably accumulated in response to rising baselevel associated with sea level rise over the last 10,000–15,000 years (Figure 1-23). Extensive alluvial deposits also occur in the lower part of Green Gulch Creek, upstream of the Big Lagoon area. Exposures reveal that the floodplain deposits are dominated by fine loam, which is interspersed with layers of fine gravel that increase in frequency and grain size with depth. The mainstem alluvial valley fill in lower Frank Valley is at least 37 ft (11.3 m) deep, and may be locally as deep as 90 ft (27.4 m) (Laudon 1988, as cited in PWA 2000; Martin 2000). Muir Beach is a Holocene beach and sand deposit at the mouth of Redwood Creek (Figure 1-23).

Just offshore, the San Andreas Fault forms the strike-slip boundary between the Pacific and North America tectonic plates, running along a roughly North-by-Northwest trend. Since the early 1900s, ruptures on the San Andreas Fault system have locally produced 3 large (magnitude > 6.5) earthquakes, including "The Great San Francisco Quake" of 1906 and the Loma Prieta earthquake of 1989.

1.5.2 Geomorphic processes

Geomorphic processes in Coast Range watersheds can be grouped into two main categories, according to whether they are induced by natural processes or human disturbances (Table 1-7). A suite of processes can be identified under each category, with different processes occurring preferentially in certain areas of the watershed (Table 1-7). For example, production of sediment occurs in upper watershed areas by conversion of bedrock to soil, whereas sediment transport on slopes is generally accomplished by a combination of mass wasting processes including soil creep, biogenic transport (e.g., tree-throw, rooting, and animal burrowing) and shallow landsliding (Stillwater Sciences 2004).

Sediment delivery from hillslopes in the Redwood Creek watershed occurs primarily by mass movements in the forms of landsliding and debris flows. Roughly 46 percent of the watershed's hillslope surfaces have been mapped as landslide deposits (Wentworth et al. 1997). El Niño storms in January 1982 triggered 20 debris flows in the Redwood Creek watershed, with a majority occurring in the Green Gulch sub-watershed, a tributary canyon upstream of the Banducci property, and Conlon Canyon in the Camino del Canyon subwatershed. In January 1997, heavy rainfall triggered a large landslide which blocked the Camino del Canyon Road. Rains of 1997 also destabilized the slope behind the Muir Woods concession building, causing failure of an old dirt road, which made notable contributions of sediment to Redwood Creek. Landslides on watershed slopes sometimes do not affect sediment delivery to the Redwood Creek mainstem due to a lack of connectivity between the landslide and the channel network (Stillwater Sciences 2004). Hillslope processes are described in greater detail in Section 1.4.4. A shaded relief topographic map of the watershed is shown in Figure 1-24.

Table 1-7. Sediment production and transport processes of watersheds of the California coast range.

Category	Process
Natural processes	
Production of sediment	1. Conversion of underlying bedrock to soil mantle
	2. Landsliding of bedrock
	3. Scree generation
Hillslope mass wasting processes (mostly sediment delivery)	4. Creep and biogenic transport
	5. Shallow landsliding
	6. Deep-seated landsliding
Hillslope overland flow erosion	7. Sheetwash, rainsplash, and rill erosion
Channel incision processes	8. Channel head advance
	9. Gully incision
	10. Bank erosion
	11. Mainstem incision
Channel sediment routing and storage	12. Sediment transport
Human disturbances	
Road-related	13. Cut and sidecast failures
	14. Surface wash
	15. Bed surface erosion
	16. Crossing failures
	17. Drainage gullying and slope destabilization
	18. Accelerated runoff and channel destabilization
Agricultural	19. Surface wash rilling and gullying
	20. Accelerated runoff and channel destabilization
	21. Hillslope vegetation removal and landsliding
	22. Riparian vegetation removal and channel destabilization
Urban	23. Construction phase sediment pulse
	24. Connection of drainage network
	25. Post-construction low sediment and accelerated runoff
Channel management	26. Channel destabilization via straightening and relocation
	27. Channel destabilization via LWD removal
	28. Sediment reduction through bank revetment, dams

Source: Stillwater Sciences (2004).

1.5.3 Channel morphology

A digital elevation model (DEM) with an assumed channel initiation threshold of 2.5 ac (1 ha), indicates that the watershed contains 76 mi (122 km) of channel and has a drainage density of 5.4 mi/mi^2 (km/km^2). Low order headwater streams coalesce into several major tributaries including Bootjack, Rattlesnake, Spike Buck, and Fern creeks (Figure 1-1). Contributing drainage areas of sub-watersheds are summarized in Table 1-8.

The narrow upper watershed tributaries are incised into the underlying Franciscan mélange. Above the confluence of Fern and Upper Redwood creeks, where Redwood Creek becomes a fifth-order channel (Strahler 1952), streams are steep, with slopes typically greater than about 12 percent and often exceeding 20 percent (Figure 1-25). No detailed, quantitative field surveys of channel conditions have been conducted in the upper tributaries, but reconnaissance indicates that a dominantly step-pool channel morphology with bouldery creek beds and gravel and cobbles occurring locally in small pools.

Channel slope in the mainstem Redwood Creek and the Fern Creek tributary drops to between 4 and 8 percent, about a quarter of a mile upstream of the Fern Creek confluence, near the upstream border of Muir Woods National Monument (Figure 1-25). The channel has a mixed gravel-cobble bed below the confluence of Fern Creek (Kimball and Kondolf 2002), and channel slope decreases to less than 2 percent within Muir Woods where a distinct alluvial floodplain of limited extent begins. Channel straightening, a large weir, and revetments along the banks constructed by the CCC in the 1930s have resulted in a highly static channel morphology throughout the Muir Woods National Monument. LWD jams in channels play an important role in forming bars and pools (e.g., Montgomery et al. 1995), and are probably reduced in Muir Woods relative to pre-disturbance conditions, due both to channel straightening and to the legacy of routine wood removal which was practiced by NPS until 1986. A plane-bed morphology dominates in the Monument, and a total of 45 pools span the 7,500-ft (2,286-m) reach, with an average spacing of three bankfull channel widths (Kimball and Kondolf 2002): bankfull widths are suspected of being greater now than before the channelization works. While the estimated pool spacing is lower than the 5–7 bankfull-width average for free-formed reaches of unregulated rivers (e.g., Leopold and Wolman 1957, Leopold et al. 1964, Keller and Melhorn 1978), it is in rough agreement with the 1–4 bankfull-width average for steeper, step pool reaches (Whittaker 1987, Chin 1989, Grant et al. 1990). Even so, indications that pool spacing is often a sensitive function of LWD loading (Montgomery et al. 1995) imply that the now-abandoned wood removal practices of the NPS may have substantially reduced pool spacing relative to historical conditions in the monument. In 2001, the NPS placed LWD at one location in the monument and is currently monitoring pool development at the site.

Table 1-8. Drainage areas of Redwood Creek sub-watersheds*.

Sub-watershed	Drainage area	
	(km^2)	(mi^2)
Upper Redwood Creek	5.1	2.0
Fern Creek	2.8	1.1
Kent Canyon	2.5	1.0
Camino del Canyon	0.8	0.3
Green Gulch	2.9	1.1
Redwood Canyon	2.0	0.8
Upper Frank Valley	3.9	1.5
Lower Frank Valley	2.2	0.8
Total watershed	**22.7**	**8.8**

* See Figure 1-1 for subwatershed boundaries.
Source: Stillwater Sciences (2004).

After flowing southeasterly through Redwood Canyon and out of Muir Woods, the creek turns sharply and flows southwesterly into Frank Valley where it gains a significant alluvial floodplain. A series of short, steep tributaries join the mainstem after crossing alluvial fans that have been deposited along the margins of Frank Valley. A relatively large right-bank tributary, Kent Canyon Creek (1 mi^2 / 2.5 km^2), joins the mainstem in Frank Valley (Figure 1-1) and its alluvial fan appears to influence the planform of Redwood Creek which, in the vicinity, is situated towards the left side of the valley. In lower Frank Valley, the channel turns back to the southeast before draining to the Pacific Ocean. Channel slope in Frank Valley drops from 0.9 percent at its upstream end to 0.4 percent at the Highway 1 Bridge. Bed texture is gravel and cobble in the valley (Kimball and Kondolf 2002, Stillwater Sciences 2004; Figure 1-26). Throughout much of Frank Valley, the creek channel is incised and isolated from its floodplain (Stillwater Sciences 2004). Historical maps of GGNRA lands within Frank Valley indicate that the sections of the

channel were altered by farming practices between the late 19th century and mid-20th Century (PWA 2000), including the realignment of the creek away from a valley-central position in several places. Also in Frank Valley, the creek intermittently abuts Muir Woods Road with implications for road stability in locations where the creek is eroding into the alluvial terrace.

As in Muir Woods, the frequency of LWD deposits is thought to be low, compared to historical conditions. However, LWD frequency is on the rise due to contributions from recent tree fall—which are no longer removed from the creek—and a series of new, engineered wood jams, introduced by NPS in a 3,800-ft (1158-m) reach of creek upstream of the Highway 1 Bridge as part of a series of enacted and proposed restoration actions designed to re-connect the incised Banducci Reach with its floodplain (PWA 2000, 2002; Kamman Hydrology & Engineering 2006; NPS 2007a, 2007b). In addition to installation of the engineered log jams, restoration of this reach included regrading channel banks and lowering the floodplain in proximity to Redwood Creek to encourage greater seasonal floodplain inundation, better riparian habitat and greater topographic complexity of the channel bed. Two years of monitoring since installation show that the installed wood has produced desirable results such as increasing channel complexity, development of pools deep enough to support Coho salmon (*Oncorhynchus kisutch*) rearing in summer, and increasing the likelihood of floodplain inundation (C. Shoulders, pers. comm. with B. Orr and C. Riebe, 6 June 2005).

Redwood Creek's gravel-bed persists downstream of the Highway 1 Bridge and into the Big Lagoon area where channel slope decreases to 0.1 percent and a higher proportion of sand is evident. The channel and floodplain in the reach below the Highway 1 Bridge have been modified substantially over the last several decades. Major modifications in the reach have included:

- construction of floodwalls, placement of bank revetment and realignment of the creek to the valley right between the Highway 1 and Pacific Way bridges resulting in a perched, static channel planform;
- construction of a levee across Big Lagoon, conversion of a portion of lagoon habitat to pasture, and isolation of most of the floodplain from the creek causing in-channel and near-channel sedimentation to be intensified (Stillwater Sciences 2004);
- realignment Green Gulch Creek (a 1.1 mi^2 or [2.8 km^2] tributary that drains directly into Big Lagoon) into two straightened ditches to maximize available horse pasture;
- construction and then extension after 1982 of a dirt/gravel fill parking lot that projects tangentially into the lagoon and reduces the available river corridor for Redwood Creek;
- construction of the Pacific Way bridge and concrete box culvert across Redwood Creek at the upstream end of Big Lagoon, promoting upstream sediment deposition and frequent avulsion of the creek into a lower elevation central valley location during large flood events causing flood hazard; and
- consequentially, a requirement for periodic dredging (now largely discontinued except in emergency –see below) of the creek channel to maintain conveyance capacity.

These channel modifications have reduced functional floodplain area and altered channel hydraulics and sediment transport capacity which, combined with delivery of sediment derived from large storms in 1998, have resulted in substantial aggradation in Redwood Creek below Highway One bridge and into the Big Lagoon area. Channel surveys indicate approximately 5 ft (1.5m) of channel aggradation occurred between 1993 and 2002 (Klein et al. 2002), resulting in increased flooding, an unstable channel alignment and a heightened risk of avulsion to adjacent pasture (which is several feet lower than the creek bed). Measures to reduce flooding and the risk

of avulsion were implemented in 2002 by Marin County and NPS and included (1) removing sediment from 460 ft (140 m) of the lower creek, (2) removing approximately four woody debris jams from the creek, (3) excavating a 300-ft-long (91-m-long) pilot channel through a sediment deposit that had closed off the mouth of the creek, (4) constructing two armored dips in a levee road to provide hydraulic connectivity while reducing erosion of the levee, (5) removing a flap gate in a levee culvert to facilitate flood routing from the wetland area to the Pacific Ocean, (6) removing dead trees at risk of falling into the channel to reduce the likelihood of future obstruction, (7) installing biotechnical bank protection (willow mattresses) upstream of the Pacific Way Bridge to prevent enlargement of floodplain channels, and (8) excavating a small trench at the low point on Pacific Way east of the Pacific Way Bridge. Strategically, the NPS has worked with consultants to understand the nature of sediment dynamics in the watershed (Stillwater Sciences 2004, see section 1.5.4) and to develop a long-term restoration plan for the lower reach of Redwood Creek at Muir Beach (PWA et al. 2004). Detailed descriptions and evaluations of restoration alternatives for this 38-acre project are aimed at restoring a functional, self-sustaining ecosystem, and are presented in the Environmental Impact Statement/ Environmental Impact Report (EIS/EIR) prepared by the NPS and Marin County (NPS and Marin County 2007). Restoration implementation began in summer 2009.

1.5.3.1 Channel morphology-aquatic habitat relationships

A large set of channel morphology data is available from salmonid habitat quality surveys conducted by the NPS in 1995 (Fong 2002). Mapped habitat types included pools (subdivided into main channel, scour, step, and backwater categories), riffle and flatwater, and miscellaneous (e.g., cascade and dry). Recorded channel characteristics included entrenchment, average bankfull channel depth, frequency and volume of large woody debris ("woody material" in Fong 2002), residual pool depth, length and width of undercut bank, overhanging and instream cover, and substrate size composition (by visual estimate only). The habitat typing methodologies referenced in Fong 2002 include those of Overton et al. 1993 and Dolloff et al. 1997. Of the methodologies referenced, Overton et al. 1993 gives the most complete definition of habitat types, which in turn are based on Bisson et al. 1982, though "flatwater" is not defined. It is assumed that flatwater is more or less synonymous with a "run" or a "glide" as described in Overton et al. 1993, but this is not certain. The minimum size threshold for what constitutes a measurable piece of large woody debris is not defined in Fong 2002, but it is assumed that it matches the criteria described in Overton et al. 1993 that "large woody debris is defined as pieces of wood at least 10 ft (3 m) in length or two-thirds the channel width and 4 in (0.1 m) in diameter at one-third the distance from the large end." Habitat data were analyzed for the seven stream reaches listed in Table 1-9 and shown in Figure 1-25 on the Redwood Creek channel profile.

Table 1-9. Redwood Creek habitat survey reaches.

Reach No.	Description	Length (ft)	Length (m)
1	Big Lagoon to Pacific Way	2,434	748
2	Pacific Way to Highway 1	1,391	424
3	Banducci (Highway 1 to State Park Boundary)	4,534	1,382
4	State Park Boundary to Kent Canyon	3,484	1,062
5	Kent Canyon to Dipsea Trail	7,539	2298
6	Dipsea Trail to Bridge 4	6,076	1852
7	Fern Creek	1,299	396

Source: Fong 2002

The frequency distribution of major habitat types (i.e., pool, riffle, and flatwater) by reach is shown in Figure 1-27. The frequency of large wood is quantified as the number of pieces per 328 ft (100 m) and is shown for each reach in Figure 1-28. Most reaches had less than 15 pieces per 328 ft. Wood frequency is probably lower and the pieces smaller in diameter than under pre-disturbance conditions, due to a legacy of channel wood removal practices (discontinued in the monument in 1986) and replacement of old growth with second growth in areas outside of Muir Woods. A lower wood frequency will generally tend to reduce the frequency of complex debris jams and thus reduce frequency of deep pools. There are currently few pools of sufficient depth (i.e., 1.6 ft [0.5 m]) for summer coho salmon habitat in the Redwood Creek watershed (Figure 1-29). Pool habitat is particularly scarce in reaches 6 and 7 (Table 1-9), within Muir Woods National Monument, probably due—at least in part, in Reach 6—to the legacy of the 1930s channelization projects (noted above). Pools in Reach 7 are probably scarce due to a transition to a step-pool morphological regime associated with natural variations in channel slope and sediment supply. Pools are more common in reaches downstream of Muir Woods and were most extensive in Reach 1. Pools deeper than 1.6 ft (0.5 m), however, were scarce in all reaches except Reach 1, accounting for just 3–32 percent of the surveyed channel length. More than 50 percent of Reach 1 was observed to have pools with depth 1.6 ft (0.5 m) or greater, but much of that habitat was located in a single excavated borrow ditch that has probably been reduced in size due to increased sedimentation since 1996. Additional information about aquatic habitats is discussed in Section 1.7.

1.5.4 Sediment budget

The morphology and natural maintenance of the Big Lagoon wetland ecosystem has been adversely affected by recent sedimentation from the Redwood Creek watershed (Stillwater Sciences 2004). To help in their evaluation of strategies for restoring the lagoon, the GGNRA retained Stillwater Sciences to develop a sediment budget for the watershed, and to use it to estimate the rate of sediment supply to the lagoon. Results from the sediment budget analysis have been presented in a detailed report (Stillwater Sciences 2004) and are summarized here.

A sediment budget should provide a snapshot of the geomorphic evolution of watershed slopes and channels, including an assessment of available sediment transport rates, for evaluation of the relative importance of different processes and contributing areas (Reid and Dunne 1996). Key elements of a sediment budget include:

- an inventory of material that is (or may become) available for delivery from sediment sources (which include hillslope soils, colluvial hollows, and floodplain deposits);
- an inventory of material that is stored in sediment sinks (such as floodplains and hollows);
- estimates of transport rates among interconnected sediment sources and sinks;
- an estimate of the net rate of sediment transport out of the watershed (at the mouth).

The Redwood Creek sediment budget was developed from (1) a watershed elevation model based on existing digital data, (2) field reconnaissance of sediment source areas, (3) mainstem channel surveys and dendrochronology—which helped quantify rates of change of sediment storage in the lower reaches of the creek, (4) estimates of sediment production and transport rates derived from previous studies in neighboring watersheds, and (5) modeling of sediment transport in Redwood Creek (Stillwater Sciences 2004).

1.5.4.1 Delineation of changes in the Redwood Creek sediment budget over time

Changes in land use can cause significant changes in rates of sediment production and transport by accelerating erosion from sediment sources and by destabilizing material stored in sediment sinks. Human-induced changes in rates of sediment production and transport may continue to occur as a legacy, long after the cessation of changes in land use, with landscape elements adjusting slowly to new conditions. After consideration of the history of the Redwood Creek watershed (Section 1.2.3), along with observations from initial field reconnaissance, it became clear that historical changes in land use may have caused substantial changes in the watershed's sediment budget over time (Stillwater Sciences 2004). Hence it was necessary to develop separate sediment budgets for different time periods, with intervals defined by changes in human land use in the watershed.

To document factors that might have influenced sediment processes within the watershed, and thus help delineate distinct intervals of human land use for the sediment budgets, a watershed disturbance chronology was developed from available historical data and previous studies (Stillwater Sciences 2004, based on Hildreth 1966, McBride and Jacobs 1978, Bicknell et al. 1993, PWA et al. 1994, PWA 1995, PWA 2000, Martin 2000, Jebens 2001, Kimball and Kondolf 2002, Klein et al. 2002 and PacWA 2002). Based on this synthesis of events (tabulated in Appendix A), four periods of development in the watershed were defined (Stillwater Sciences 2004):

- Pre -European (pre-1840). A period dominated by a combination of natural processes and the influence of Coast Miwok culture. Sediment production from upslope areas was retained for the most part in Frank Valley, resulting in a low sediment yield to Big Lagoon.
- European Arrival and Resource Development (1841–1920). The period of greatest land use change as Redwood Creek was settled by Europeans. Runoff and sediment production rates in upslope areas was altered, causing incision in the alluvial reaches of Redwood Creek and thus increasing sediment yield to Big Lagoon.
- Engineering as Management (1921–1980). The period of greatest creek disturbance as land use intensified. Intensification of processes initiated in the previous period continued to promote incision of the creek and increase sediment yield to Big Lagoon.
- Recovery and Restoration (1981–2002). A period of increased conservation. Upslope processes began to recover towards pre-disturbance conditions. The legacy of human disturbance in the channel network kept sediment yields to Big Lagoon high, relative to pre-disturbance conditions.

Characteristics, activities, and the hypothesized sediment responses for each of the sediment budget periods are summarized in Table 1-10.

Table 1-10. Major watershed disturbances and hypothesized sediment transport responses.

Period	Time period	Characteristics and activities	Hypothesized sediment response
Pre-European	pre-1840	• Oak woodland and meadow floodplain with grassland on hillslopes, maintained by burning • Redwoods in canyons and valley • Upland prairies maintained by natural fires • Riparian fringe along Redwood Creek. • Big Lagoon is lagoon-like, at least seasonally	• Low sediment production, primarily of fine sediment by creep and biogenic processes • Shallow landslides during storm events. • Sediment supply to mainstem channel may be low due to lack of connection to Frank Valley tributaries • Tributary fan deposition and overbank flooding in non-incised channel allows sediment storage and valley alleviation
European Arrival and Resource Development	1841 to 1920	• Lower valley: removal of floodplain woodland, introduction of extensive then intensive grazing and dairy farming, replacement of native perennial grasses with annual exotics • Logging of Redwoods, late in Redwood Creek due to its relative inaccessibility, soil stripped for clay following logging • Construction of first roads, trails, trains, tourism, triggering of accidental fires • Riparian fringe along Redwood Creek removed, possible local realignment of lower Redwood Creek near Pacific Way • Levees, conversion of Big Lagoon to pasture • Beginnings of the land protection movement at Muir Woods to save "last remaining redwoods"	• Reduced tree cover and grazing causes greater volume sand and greater peakedness of storm flows • Replacement of native grasses with non-natives provides less effective resistance to erosion • Both factors combine to increase tributary sediment yields, increase tributary connectedness during high flow events and initiate incision of the channel mainstem. • Incision confines flows, reverses former sediment storage and increases sediment yields further; incised channel capable of transporting coarser sediment

Period	Time period	Characteristics and activities	Hypothesized sediment response
Engineering as Management	1921 to 1980	• Riparian flower and hay farming • Progressive transfer of farms to State and National Parks. • More exotics (eucalyptus, heather). Tree removal firebreaks, fires suppressed. • Logging of 1,300 ac (Kent Canyon, 1960s) • Muir Woods infrastructure created; parking lots through cut and fill, further trails constructed. • Roads upgraded, Highway 1 embankment effectively dams lower watershed. • Local water extraction in Frank Valley for irrigation and Muir Beach community. • Redwood Creek in Muir Woods extensively 'protected' by riprap and grade control, realigned (assumed), LWD removed. • Redwood Creek in Frank Valley locally realigned for roads/bridges (assumed), leveed, subject to small-scale gravel extraction, floodplain regraded at Banducci farm. • Redwood Creek in Big Lagoon dredged, dammed (then dam removed), leveed, Green Gulch channelized, reservoirs constructed, parking lot constructed.	• Continuation of previous trends; potential decrease in tributary sediment production as former farmland is converted to parkland, but increases due to riparian farming, from Kent Canyon, due to logging, from Muir Woods due to addition of roads and trails • Engineering measures halt incision in Redwood Canyon but may cause greater flashiness of flows • Sediment production may increase in lower watershed as channels are straightened and leveed • Most sediment production from Green Gulch intercepted by reservoirs • Effective depositional area in Big Lagoon reduced by levees and fill
Recovery and Restoration	1981 to 2002	• Land use conversion from grazing to park land. Most of watershed publicly owned; exotic grasslands, forested tributaries, pines in upper watershed. • Prescribed burn experiments. • Some water pumping but no irrigation. • Parking lot extended at Muir Beach. • Riparian and LWD recovery. • Terrestrial wetland species invade Big Lagoon.	• Tributary sediment sources other than from roads and trails may begin to wane as agriculture ceases. • Increasing roughness of mainstem channel as LWD volume increases may act to trap greater sediment volumes. • Continuation of reduced area for sediment deposition in Big Lagoon and interception of Green Gulch sediments

Source: Stillwater Sciences (2004).

1.5.4.2 Sediment yields of major geomorphic processes

Long-term average sediment production rates

Taken together, field reconnaissance and cosmogenic dating from the neighboring Tennessee Valley, suggest that significant portions of the upper watershed were probably not delivering much of their sediment to the Redwood Creek mainstem in the pre-1840 period (Stillwater Sciences 2004). Instead, the sediment derived from hillslopes appears to have been impounded in alluvial fans and floodplain deposits in Frank Valley. An estimated 30 percent of the watershed was isolated from the mainstem Redwood Creek in this way. In the absence of site-specific data on sediment production, the remaining 70 percent of the watershed was assumed to have a pre-1840 sediment delivery rate of approximately 169 t km^{-2} yr^{-1}—the long-term (i.e., 1,000- to 10,000-year) average soil production rate from neighboring Tennessee Valley (Heimsath et al. 1997). Averaged over the entire Redwood Creek watershed area, the 169 t km^{-2} yr^{-1} from actively contributing areas is 117 t km^{-2} yr^{-1} (accounts for the observed isolation of 30 percent of the watershed).

Hillslope and streamside landslides

Hillslope and streamside landslides were mapped using sequential aerial photography and field reconnaissance. Landslide mapping was used to estimate the area affected by landslides in the interval between each set of photos. These areas were converted to volumes using area-to-volume relationships determined in previous work for neighboring Lone Tree Creek (Lehre 1982). The net rate of sediment delivery to the Redwood Creek mainstem from hillslope and stream-side landslides was estimated to be 45 t km^{-2} yr^{-1}. This is lower than might be expected, based analysis of rates from neighboring basins. There are several possible reasons for the discrepancy including the relatively coarse scale of the aerial photography and difficulty in remote identification of landslide scars in heavily forested areas (which are common in the Redwood Creek watershed). The lower-than-expected estimated delivery from landslides may also be due to a difference in land management practices with the conservation-oriented history of the Redwood Creek watershed contributing to a relatively lower rate of sediment delivery from landslides.

Erosion along tributaries

Sediment delivery by erosion along the edges of tributaries is the sum of delivery from (1) soil creep and landsliding close to the channel, (2) channel enlargement due to changes in upstream runoff, and (3) incision driven by base level changes in Redwood Creek downstream. The estimated rate of sediment delivery from erosion along tributaries was based on measured lengths and widths of actively eroding stream banks in the Redwood Creek watershed coupled with an analysis of published data on bank erosion depths from neighboring Lone Tree Creek. Data compiled from field reconnaissance indicated that the combined sediment delivery from erosion along second-, third-, and fourth-order streams is 59 t km^{-2} yr^{-1}.

Road-related erosion and sediment transport

Estimates of sediment transport rates from roads, trails and road-crossing failures were based on data from a previous study (PacWA 2002). Sediment delivery from road and trail surfaces was estimated to be very low, at about 2 t km^{-2} yr^{-1}. The somewhat higher 6 t km^{-2} yr^{-1} estimated rate of episodic, road-related sediment delivery is a minimum estimate, due to a lack of survey data for the entire set of post-construction road-related erosion sites. Cutbank erosion was estimated to be much higher, with a watershed-wide total of about 40 t km^{-2} yr^{-1}. Rates of road-related sediment transport were applied to each of the sediment budget periods according to the corresponding estimated extent of roads and trails completed during the period. For example, nearly 100 percent of watershed roads and trails were constructed (and contributing to erosion) by

the start of the fourth, most recent sediment budget period, whereas an estimated 75 percent contributed to erosion in the third period and roughly 15 percent contributed in the second period.

Sediment delivery from Green Gulch Creek

Sediment trapping in Green Gulch reservoirs since the 1950s has made sediment yields to Big Lagoon from Green Gulch sub-basins negligible during the most recent sediment budget period. For the preceding three periods, Green Gulch was assumed to contribute sediment according to the estimated rates as outlined above.

Rate of alluvial fill on the Redwood Creek mainstem

Lower Redwood Creek is developed in deep alluvial fill, which presumably accumulated in response to sea level rise during the late Holocene. Rates of alluvial valley fill in Redwood Creek (from Redwood Canyon to Big Lagoon) during the pre-1840 period were estimated by dividing the total volume of fill by radiocarbon dates of organic material found in basal sediments of Big Lagoon, lower Frank Valley, and Walker Creek (a neighboring watershed). Based on these calculations, Frank Valley appears to have aggraded at an average of 1 mm yr^{-1} from 3,500 B.P. to 1840. This translates to 83 t km^{-2} yr^{-1}—or roughly 70 percent of the estimated long-term average production rate (117 t km^{-2} yr^{-1}) of watershed slopes—making the alluvial valley fill a relatively substantial sink for sediment during pre-European times.

Post-1840 incision of the Redwood Creek mainstem

Roughly coincident with European arrival in the watershed, Redwood Creek appears to have begun incising into its Holocene alluvial fill—thus enhancing sediment delivery to Big Lagoon. Rates of incision along the mainstem for each period since 1840 were derived from estimated incision volumes (from cross-sectional survey) and a chronology of incision (constrained by alders that were dated using dendrochronology). Results indicate that the rate of incision has been highest in Upper Frank Valley. The average sediment yield from incision for the mainstem creek as a whole was roughly constant, at about 180 t km^{-2} yr^{-1}, from approximately 1841 to 1980, but dropped to just 48 t km^{-2} yr^{-1} during the final period, from 1981 to 2002. Field surveys in mainstem Redwood Creek, coupled with field estimates of vegetation age, indicate that an additional 4 t km^{-2} yr^{-1} of sediment has been produced by recent bank erosion.

Incision of tributaries

Incision of the Redwood Creek mainstem has caused base level lowering for the watershed as a whole, and thus has led to incision (or gullying) of tributaries into their Holocene fills. Sediment delivery from incision of tributaries was estimated from the product of the cross-sectional area of incision (from field measurements of width and depth) and the affected stream length (from field reconnaissance). Incision rates of tributaries presumably progressed in step with mainstem incision rates, which changed over time (see above). Hence, in developing a time series of sediment budgets for Redwood Creek, it was important to scale the total sediment delivery from the incision of tributaries by the fractional amount of mainstem incision that occurred in each time period. It was also important to account for spatial variability in mainstem incision rates (i.e., the observation that incision rates were greatest in upper Frank Valley), due to the implied spatial variability in base level lowering rates. The sediment delivery rate from incision along tributaries was estimated to be 9, 7, and 2 t km^{-2} yr^{-1} for the three most recent sediment budget periods.

1.5.4.3 Net sediment yield of the Redwood Creek Watershed

The net sediment yield from Redwood Creek watershed for each sediment budget period can be calculated as the sum of the components identified above. The results are summarized in

Table 1-11 and plotted in Figure 1-30. Sediment yields in the periods that post-date European land use are up to an order of magnitude higher than the background, natural rate of sediment delivery of the pre-1840 period. Much of the inferred increase in sediment yields is due to the inferred release of abundant sediment from the storage in the floodplain ("Channel yield" in Figure 1-31), which had previously been an effective trap for sediment from the upper watershed (i.e., such that it was acting as a sediment sink rather than a source in the pre-1840 period). In the most recent sediment budget period (1981–2002), total sediment yield dropped by about a factor of two, but is still more than five times faster than it was in the pre-European period. The recent decline in sediment yield, relative to 1841–1980 rates, mainly reflects the inferred reduction in sediment eroded from the floodplain—a change that may be due, at least in part, to the well-documented recent shift from agricultural to parkland uses in the lower watershed (see Table 1-10 and Appendix A).

Table 1-11. Watershed sediment yields estimated from the sediment budget for each period.

Measure	Unit rate	Time period			
		Pre-1840	**1841–1920**	**1921–1980**	**1981–2002[1]**
Delivery from hillslope and channel erosion processes	t km^{-2} yr^{-1}	117	111	140	147
Sediment eroded from floodplain	t km^{-2} yr^{-1}	-83[2]	193	184	50
Total sediment yield	**t km^{-2} yr^{-1}**	**34**	**304**	**324**	**198**

[1] Rate includes contributions from Green Gulch, which did not contribute to Big Lagoon during the 1981–2002 period.
[2] Minus sign indicates sediment went into storage on the floodplain
Source: Stillwater Sciences (2004).

1.5.4.4 Uncertainties in sediment yields and other complications

Estimates of sediment yield summarized here have several sources of uncertainty that can be roughly grouped into two categories: measurement uncertainties and uncertainties in assumptions.

Each method for estimating sediment yields has its own specific set measurement uncertainties. For example, the land-cover-dependent uncertainties inherent in air-photo mapping of streamside and hillslope landslides are very different from uncertainties inherent in field estimates of bank erosion.

Each method also has its own set of assumptions, which can have a wide range in inherent levels of speculation. For example, the extrapolative assumption that erosion from tributary banks has been constant over time is less plausible for earlier periods, because the tributary bank erosion estimates are based on contemporary measurements (which are unlikely to strongly reflect rates from the past).

Rates for the most recent sediment budget period probably have the lowest uncertainties, due to the availability of a large set of quantitative observations and data. Rates for the other periods are not as well constrained and in many cases are simply extrapolations of present rates. Errors in sediment yields are high for the two middle time periods (1841–1920 and 1921–1980) due to lack of information on erosion from construction of railroads, roads, trails, and buildings; erosion rates

from these sources were neglected because they could not be reliably calculated, even though it is clear they were probably significant given that much of the construction occurred before implementation of Best Management Practices. Errors in sediment yields are high for the earliest time period because lack of data necessitated the greatest generalizations.

An additional complication in the interpretation of the sediment budgets stems from a lack of specific data on erosion and sediment delivery from agricultural sources. Effects of changes in agricultural land use are subsumed more generally within the estimates of sediment delivery discussed above.

Sediment budget estimates could be refined substantially with additional information on landslides (i.e., their distribution, frequency, and size), erosion from surfaces adjacent to tributary streams, sediment production from roads and trails, and better constraints on mainstem incision rates. Additional information regarding direct effects of past construction and agricultural activities would also improve the estimates of the sediment budget.

1.5.4.5 Rates of sediment deposition in Big Lagoon

The sediment yields of Table 1-11 can be used to estimate sedimentation rates for Big Lagoon, but an essential additional step is estimation of the lagoon's sediment trapping efficiency. Sensitivity analysis shows that the proportion of total sediment yield deposited in the lagoon could range from 14 to 100 percent, depending on the assumed relationship between sediment size and trapping efficiency. Estimates of sediment deposition in Big Lagoon are summarized in Table 1-12.

Table 1-12. Rates of sedimentation in Big Lagoon for each sediment budget period.

Measure	Unit rate	Time period			
		Pre-1840	1841–1920	1921–1980	1981–2002
Estimated volumetric sediment yield to Big Lagoon	$m^3\ yr^{-1}$	454	4057	4324	2376[1]
Estimated sedimentation rate from sediment yield[2]	$mm\ yr^{-1}$	0.6–4.5[3]	5.7–40.6[3]	6.1–43.2[4]	3.3–56.6[5]
Sedimentation rate assuming all bedload (14%) and 50% of remaining load is deposited[6]	$mm\ yr^{-1}$	2.6	23.3	24.7	32.3
Estimated sedimentation rate from various sources	$mm\ yr^{-1}$	1.12–1.18[7] 0.8–1.2[8]	11.2[9]	11.2[9]	5.8–86.8[10]
Rate of sea-level rise	$mm\ yr^{-1}$	1.05-1.5[11]	1.12[12]	2.13[12]	2.13[12]

1 Rate excludes sediment yield from Green Gulch Creek which no longer contributes sediment to Big Lagoon.
2 The low-end estimate assumes that only bedload (14 percent of the yield) is trapped; the upper estimate assumes 100 percent trapping rate (such that the total yield settles in Big Lagoon).
3 Deposition area is 10 ha = 100,000 m^2.
4 Deposition area is 10 ha prior to 1960, and 4.2 ha for 1960–1980.
5 Deposition area is 4.2 ha = 42,000 m^2.
6 A hypothetical scenario that could be refined by sediment surveys above and below Big Lagoon.
7 Inferred from long core BL008 of Meyer (2003).
8 Long-term floodplain aggradation rate
9 Inferred from cores by Wells (1994, as cited in PWA et al. 1994).
10 Based on in-channel field re-survey data 1992–2002 (PWA 2003) from Pacific Way to Willow/Alder Grove.
11 Atwater and Hedel (1976).
12 Zervas (2001).
Source: Stillwater Sciences (2004).

Under the assumption that all bedload and 50 percent of the suspended load is deposited in the lagoon, the estimated sedimentation rates increased from 2.6 to 24 mm yr^{-1} from the first to second period, then held steady on average through the third period, and finally increased further to 35 mm yr^{-1} in the most recent period, despite a reduced overall sediment yield, due to a factor of roughly two decrease in the area available for sediment deposition (which resulted from engineering modifications of the lagoon).

The pre-1840 rate is nearly two times higher than the rate of eustatic sea level rise. The estimates of sedimentation rates for the pre 1840, 1841–1920, and 1921–1980 periods are also nearly two times higher than rates of sedimentation implied by analysis of lagoon sediment cores. This suggests that the assumed sediment trap efficiency may be too high. Even so, in all periods since 1840, the sediment budget and sediment core data independently predict rates of sedimentation in Big Lagoon that are at least an order of magnitude higher than rates of sea-level rise. This suggests that Big Lagoon has been filling since the onset of European settlement, with sedimentation that far exceeds than the rate of sea level rise.

1.5.4.6 Effects of large floods

The majority of sediment deposition in Big Lagoon presumably occurs during and shortly after large floods, rather than on a steady, average-annual basis. Hydrological records and narrative

data indicate that notable floods in the watershed occurred approximately once per decade from 1920 to 1970 (i.e., in 1925, 1935, 1946, 1956, 1967), and twice per decade thereafter (i.e., in 1970, 1973, 1982, 1986, 1995, 1998). The two largest storm events since 1920 occurred on January 4, 1982 and, from narrative accounts, on February 11, 1925. Bedload transport modeling of the lower Frank Valley reach was conducted for three scenarios: (1) low flows, from 1998–2001, yielding a rate of 225 t km^{-2} yr^{-1}, (2) "average" long-term data, from 1965–1986 (including the 1982 storm of record), yielding a rate of 480 t km^{-2} yr^{-1}, and (3) high flows, from the 1982 high flow year, yielding a rate of 2,230 t km^{-2} yr^{-1}.

Modeled sediment transport rates compare favorably with rates estimated from the sediment yield to Big Lagoon. Importantly, the transport modeling results suggest sediment delivery in wet years with high flows may be ten times higher than sediment delivery in dry years with low-flows (corresponding to 210 mm versus 21 mm of deposition per year into the existing 10.4 ac or 4.2 ha lagoon). Modeling results, taken together with the observation that notable storms are occurring more frequently, seem to corroborate anecdotal accounts of rapid, recent lagoon infilling. Further, the results suggest that increases in El Nino-driven storm events will significantly increase the overall sediment yield from the watershed.

1.5.4.7 Projected future sediment yields

Any use of Tables 1-11 and 1-12 for estimates of future sedimentation in Big Lagoon would be inherently speculative, in the absence of additional quantitative data on hillslope erosion and channel incision and migration. Moreover, the uncertainties in the available rates (from Tables 1-11 and 1-12) are undoubtedly high, and thus limit the confidence of any conclusions that might be drawn about differences among the rates. Some inter-comparisons are nevertheless instructive and worth considering as a basis for speculation about future sediment yields. For example, contemporary rates of erosion from the watershed are roughly similar to pre-disturbance rates (at 147 t km^{-2} yr^{-1} now versus 117 t km^{-2} yr^{-1} then—Table 1-11) and will probably stay that way. Even so, effects of European settlement appear to have resulted in a fundamental shift in the way sediment is routed through the watershed, with incision and degradation of floodplain deposits replacing the aggradation that seems to have dominated before about 1840. It is not clear how much certainty can be attached to the observation (Table 1-11) that the rate of sediment delivery from incision appears to have diminished in recent times (in the period 1981–2002 as compared to the period 1840–1981). Moreover, the pulse of incision that appears to have started in the mid-1800s has not yet finished working its way through the channel network and is therefore likely to continue influencing sediment delivery to the lagoon for some time to come. It is difficult to identify circumstances under which near-term, future sediment yield to Big Lagoon could plausibly drop very far below about 150 t km^{-2} yr^{-1} (Stillwater Sciences 2004).

1.5.4.8 Effects of human land use on sediment yields

Isolation of the effects of human disturbance on sediment budgets is problematic. Approximately 50 percent of the watershed's contemporary sediment yield is accounted for by erosion from roads and trails and by channel incision that has presumably resulting from human disturbance. In comparison, the overall effect of human disturbance on sedimentation in Big Lagoon has apparently been a five-fold increase in sediment deposition rates (due to the combined effects of increased sediment deposition and reduced depositional area). If differences in total sediment yield are used as a basis for comparison, the peak of human disturbance occurred in 1921–1980 and resulted in an additional yield of 303 t km^{-2} yr^{-1} of sediment.

1.6 Water Quality

1.6.1 Regulatory setting

In California, water quality is controlled under an interdependent system of federal and state laws which arose following the enactment of the Federal Clean Water Act (CWA) of 1970. The California SWRCB and the State's nine Regional Water Quality Control Boards (RWQCBs) work in a coordinated effort to implement and enforce the CWA, as provided for in the State's Porter-Cologne Water Quality Act of 1969. The SWRCB carries out its water quality protection authority through the application of specific Regional Water Quality Control Plans, formulated and adopted by the RWQCBs, which submit these plans to the SWRCB for review. The RWQCB basin plans provide standards through: 1) a designation of existing and potential beneficial uses; 2) water quality objectives to protect those beneficial uses; and 3) programs of implementation needed to achieve those objectives.

The 1995 San Francisco Bay Region Water Quality Control Plan (SFRWQCB 1995) is the master policy document for the San Francisco Bay Region. This plan identifies beneficial use designations for most water bodies, water quality objectives to protect those beneficial uses, and a strategy to achieve designated water quality objectives. Designated beneficial water uses of Redwood Creek depend on water quality from the surrounding watershed. Beneficial uses (abbreviations in parentheses) range from shellfish harvesting (SHELL), agricultural production (AGR), irrigation and potable water supply (MUN), recreation (REC-1, REC-2), and support of the fish (FRSH, WARM, COLD, SPWN) and wildlife (WILD) resources that inhabit the project study area (SFRWQCB 1995). The beneficial uses by ecological resources include cold and warm water aquatic habitat, spawning, shellfish and wildlife. Table 1-13 presents water quality objectives developed under Section 303 of the CWA as they apply to beneficial uses within the Redwood Creek watershed.

Table 1-13. Surface water quality criteria to support designated beneficial uses.

Basin plan water quality objective (potentially affected beneficial uses)	Symbol or abbreviation	Numeric water quality criteria to support beneficial use	Reference	Notes
Bacteria (MUN, REC-1)				
Total coliform	-	Marine and Fresh Water < 10,000 per 100 ml	USEPA 2003	Water contact recreation, Single Day Sample
		Marine and Fresh Water log mean <240 per 100 ml		Water contact recreation, 30 Day Average
		log mean <100 per 100 ml	SFBRWQCB 1995	Municipal Supply, 30 Day Average
Fecal coliform	-	Fresh: 90th percentile <400 per 100 ml	USEPA[1] 2003	Water contact recreation, 30 Day Average
		Marine and Fresh: log mean <200 per 100 ml		Water contact recreation, 30 Day Average
		Fresh: 90th percentile <4000 per 100 ml		Non-contact recreation, Single Day Sample
		Marine and Fresh: log mean <2000 per 100 ml		Non-contact recreation, 30 Day Average
		log mean <20 per 100 ml		Municipal Supply, 30 Day Average
Escherichia coli	-	Fresh: 235 per 100 ml	USEPA 2003	Water contact recreation, Single Day Sample
		Fresh: 126 per 100 ml	USEPA 2003	Water contact recreation, 30 Day Average
Enterococcus	-	Marine: 104 per 100 ml Fresh: 61 per 100 ml	USEPA 2003	Water contact recreation, Single Day Sample
		Marine: 35 per 100 ml; Fresh: 33 per 100 ml	USEPA 2003	Water contact recreation, 30 Day Average
Biostimulatory substances (COLD, WARM, SPAWN)				
Nitrate-nitrite	NO_3-N+NO_2-N	0.16 mg/L as N	USEPA 2000a	Regional Reference Value for EPA Ecoregion III
Total nitrogen	TKN	0.36 mg/L as N	USEPA 2000a	Regional Reference Value for EPA Ecoregion III
Total phosphorous	TP	0.030 mg/L as P	USEPA 2000a	Regional Reference Value for EPA Ecoregion III

Basin plan water quality objective (potentially affected beneficial uses)	Symbol or abbreviation	Numeric water quality criteria to support beneficial use	Reference	Notes
Chemical constituents (AGR, COLD, MUN)				
Alkalinity	-	100 mg/L	Ayres and Wescott 1976	Irrigation Drainage
Aluminum	Al	0.2 mg/L	CDHS[2] 2005	Title 22 Secondary Maximum Contaminant Level (MCL)
Arsenic	As	0.34 mg/L (CMC); 0.15 mg/L (CCC)	CDHS 2005	Title 22 Primary MCL
Cadmium	Cd	0.005 mg/L	CDHS 2005	Title 22 Primary MCL
Calcium	Ca	None		
Chloride	Cl	250 mg/L	CDHS 2005	Title 22 Secondary MCL
Copper	Cu	1 mg/L	CDHS 2005	Title 22 Secondary MCL
Iron	Fe	0.3 mg/L	CDHS 2005	Title 22 Secondary MCL
Lead	Pb	0.015 mg/L	CDHS 2005	Title 22 Primary MCL
Magnesium	Mg	None		
Mercury	Hg	0.002 mg/L	CDHS 2005	Title 22 Primary MCL
Nickel	Ni	0.1 mg/L	CDHS 2005	Title 22 Primary MCL
Nitrate-nitrite	NO_3-N+NO_2-N	10 mg/L	CDHS 2005	Title 22 Primary MCL ("Blue baby Syndrome")
Potassium	K	None		
Silver	Ag	0.1 mg/L	CDHS 2005	Title 22 Secondary MCL
Sodium	Na	None		
Zinc	Zn	5 mg/L	CDHS 2005	Title 22 Secondary MCL
Dissolved oxygen (COLD, WARM, SPAWN)				
Dissolved oxygen	DO	> 7 mg/L (minimum)	SFBRWQCB 1995	Aquatic life protection in cold water habitat; for nontidal waters
		> 5 mg/L (minimum)	SFBRWQCB 1995	Aquatic life protection in cold water habitat; for nontidal waters
		> 80% sat in 50% of samples	SFBRWQCB 1995	Aquatic life protection
pH (COLD, SPAWN, WILD)				
pH	-	6.5–8.5	SFBRWQCB 1995	Aquatic life protection

Basin plan water quality objective (potentially affected beneficial uses)	Symbol or abbreviation	Numeric water quality criteria to support beneficial use	Reference	Notes
Temperature (COLD, SPAWN, WILD)				
Temperature	-	< 5ºF (2.8ºC) above natural receiving water temperature.	SFBRWQCB 1995	Site-specific criteria may be developed for representative species of each beneficial use
TOXICITY (COLD, SPAWN)				
Aluminum	Al	0.75 mg/L (CMC*); 0.087 mg/L (CCC*)	CDHS 2005	Title 22 Secondary MCL
Ammonia as N	NH_3-N	24.1 mg/L (CMC); 4.1–5.9 mg/L (CCC)	USEPA 2000b	CTR criteria over 0–20°C assuming pH 7.0
		5.6 mg/L (CMC); 1.7–2.4 mg/L (CCC)	USEPA 2000b	CTR criteria over 0–20°C assuming pH 8.0
		0.9 mg/L (CMC); 0.3–0.5 mg/L (CCC)	USEPA 2000b	CTR criteria over 0–20°C assuming pH 9.0
Cadmium	Cd	0.4 mg/L (CMC); 0.34 mg/L (CCC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 10 mg/L as $CaCO_3$
		0.83 mg/L (CMC); 0.95 mg/L (CCC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 25 mg/L as $CaCO_3$
Copper	Cu	1.6 mg/L (CMC); 1.3 mg/L (CCC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 10 mg/L as $CaCO_3$
		3.79 mg/L (CMC); 2.85 mg/L (CCC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 25 mg/L as $CaCO_3$
Lead	Pb	4.35 mg/L (CMC); 0.17 mg/L (CCC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 10 mg/L as $CaCO_3$
		13.98 mg/L (CMC); 0.54 mg/L (CCC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 25 mg/L as $CaCO_3$
Nickel	Ni	68.44 mg/L (CMC); 7.44 mg/L (CCC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 10 mg/L as $CaCO_3$
		149.96 mg/L (CMC); 16.14 mg/L (CCC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 25 mg/L as $CaCO_3$
Silver	Ag	0.08 mg/L (CMC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 10 mg/L as $CaCO_3$
		0.37 mg/L (CMC)	USEPA 2000b	CTR for unfiltered sample assuming hardness of 25 mg/L as $CaCO_3$

Basin plan water quality objective (potentially affected beneficial uses)	Symbol or abbreviation	Numeric water quality criteria to support beneficial use	Reference	Notes
Zinc	Zn	17.03 mg/L	USEPA 2000b	CTR for unfiltered sample assuming hardness of 10 mg/L as $CaCO_3$
		37.02 mg/L	USEPA 2000b	CTR for unfiltered sample assuming hardness of 25 mg/L as $CaCO_3$

1 U.S. Environmental Protection Agency
2 California Department of Health Services

For water quality objectives under biostimulatory substances, ambient water quality criteria recommendations from the USEPA (2000a) were used to represent typical reference levels to determine whether nutrient levels were higher than those found at other locations of similar geologic, hydrologic and plant communities. Although these were not originally proposed as hard criteria, the USEPA developed these guidelines to provide for the protection and propagation of aquatic life and recreation. Table 1-13 includes criteria based upon the lower 25th percentile of several thousand samples collected within the Sierra Nevada and California's Central Valley. USEPA adopted these levels to represent background levels in undisturbed watersheds.

For water quality objectives related to toxicity, Title 22 (California Department of Health Services [CDHS] 2005) and the California Toxics Rule [CTR] (USEPA 2000b) were used to determine acceptable levels of ammonia, nitrate and trace metals. 40 CFR § 131.38 establishes Criterion Maximum Concentrations (CMC) as the highest concentration to which aquatic life can be exposed for a short period of time without deleterious effects. Criterion Continuous Concentrations (CCC) are defined as the highest concentration to which aquatic life can be exposed for an extended period of time (4 days) without deleterious effects. Because of differences in acute and chronic toxicity of many elements and compounds in Table 1-13 to aquatic organisms as well as variations in acute and chronic toxicity in relation to ambient water conditions such as pH or hardness, several entries have multiple criteria. The criteria for six of the metals (cadmium, copper, lead, nickel, silver and zinc) are reported for unfiltered (i.e., total metals) samples from the CTR (USEPA 2000b) and calculated in 5 mg/L increments of hardness since the level at which each of these metals is reportedly toxic to aquatic life is lower at lower hardness levels. In addition, the CMC and CCC levels for ammonia are a function of both pH and temperature and are presented over a range of 0–20°C in pH increments of 1 s.u. (standard unit).

1.6.2 Available water quality data

Madej (1989) summarized the results of six USGS water quality sampling events conducted twice per year from 1986 through 1988 at several locations in the lower Redwood Creek watershed. Two locations in Redwood Creek (Muir Woods Bridge and Pacific Way Bridge) were sampled along with samples from the lower portion of the Green Gulch tributary (lower Green Gulch). The report provides perhaps the earliest metals data for the watershed, mostly below detection limits and well below regulatory standards with the exception of anomalously high copper results (80 ug/L) at Muir Woods and Pacific Way bridges in 1987. Although no follow-up sampling has been performed since that time to confirm these results within the mainstem of Redwood Creek, copper data collected for the stables at the Golden Gate Dairy tributary to Redwood Creek indicated dissolved copper levels from 1–10 ug/L in 2001, falling to below 1 ug/L in 2002 (NPS 2002). With background hardness levels on the order of 40 mg/L as $CaCO_3$, the historical samples for total copper within lower Redwood Creek are in excess of freshwater toxicity criteria for aquatic life (4–6 ug/L) established under the CTR (USEPA 2000b).

In the 1986–1988 monitoring, higher levels of coliform bacteria and phosphorus were identified within the lower Redwood Creek watershed than at other locations within the GGNRA (Madej 1989). For example, the highest concentration of phosphorus (PO_4) recorded in the Redwood Creek watershed was 0.08 mg/L at Muir Woods Road bridge in February 1987, whereas the concentrations at downstream stations during the same period was one quarter of this value. Although no intensive sampling was conducted to determine compliance with the 30-day-log-mean criteria for bacteria (Table 1-13), high fecal coliform levels were documented, with the highest reading of 8,000 MPN fecal coliform/100 mL occurring at Muir Beach in March 1987. Because these findings raised concerns over septic contamination of the lower watershed, Muir

Woods National Monument has since been taken off septic disposal of domestic wastewater. Sewage from Muir Woods is currently pumped over Mt. Tamalpais to Mill Valley, where it is treated and discharged by the Sewerage Agency of Southern Marin.

Based upon concerns over nutrients raised by USGS (Madej 1989), PWA (1993) collected and summarized water quality data at a number of sites in the lower Redwood Creek watershed from 1986 to 1993, particularly as it related to habitat conditions in the brackish backwater lagoon area (Big Lagoon) adjacent to Muir Beach. Harding-Lawson and Associates (1991) sampled upstream of the Highway 1 bridge for a Muir Beach Community Services District water quality study. Upstream of the Golden Gate Dairy horse stables and Banducci flower farms in Franks Valley, fecal coliform measurements on Redwood Creek were generally within the range of 30 MPN/ml with higher levels downstream of the stables. Samples from lower Green Gulch indicated that runoff from horse and agricultural activities in this area were also significant sources of coliform and nitrogen (PWA 2003).

Between February and May 1994, thirteen locations were sampled in the Redwood Creek watershed by researchers at the University of San Francisco (Podlech at al. 1994), including many headwater tributary locations. Samples were analyzed for physical water quality (i.e., temperature, DO, conductivity, pH), nutrients, minerals, metals, bacteria and benthic macro-invertebrates (BMI). Elevated metals concentrations in headwater samples were attributed to Serpentine soil formations. Nutrients and bacteria were lowest in headwater areas and increased below Muir Woods.

Beginning in the mid 1990s, the NPS implemented an intensive water quality monitoring program in the lower Redwood Creek watershed related to equestrian trail use and management practices at the Golden Gate Dairy, where 29 horses were in stables or pasture (Vore 1997). In 1997–1998 water quality monitoring, waters were tested for fecal coliform at Muir Woods, Pacific Way, Muir Beach, Golden Gate Dairy, and Green Gulch Creek (Vore 1997). In these tests, median fecal coliform at Muir Woods and Green Gulch was within CDHS single sample criteria (Table 1-13). Samples at Pacific Way, Golden Gate Dairy, and Big Lagoon exceeded laboratory detection limits and exceeded health standards, indicating fecal coliform contamination. The 1997–1998 monitoring also indicated elevated levels of total suspended solids (TSS) in runoff from the Golden Gate Dairy (Beutel 1998). In storm water samples taken at Muir Woods, Pacific Way, and the Golden Gate Dairy, mean TSS concentrations were 14 mg/L, 48 mg/L, and 263 mg/L, respectively. Since this study, the NPS and Ocean Riders, the occupant at Golden Gate Dairy, have implemented measures to reduce sediment erosion and runoff contamination from the dairy by reducing the number of horses, removing horses from the hillside pastures, and removing stables next to the tributary and creating a vegetated buffer zone, among other measures.

From 1999–2004, the NPS continued to monitor water quality in the vicinity of Golden Gate Dairy as well as Green Gulch to determine the need for additional management measures. Water quality monitoring studies completed during this period suggested that the stables in the Redwood Creek watersheds may be pollution sources to downstream waters within the Park (Vore 1997, Beutel 1998, and Fong and Canevaro 1998). In particular, samples collected at sites downstream of the stables are higher in bacteria, nutrients (NH_3, NO_3, PO_4), sediments (Conductivity, TSS) and oxygen demand (Low DO or high BOD) than those at upstream sites. More recent monitoring conducted since improved management of stables at the Golden Gate Dairy shows general reductions in bacteria concentrations (PWA 2003). However, downstream locations continue to exhibit elevated nutrient concentrations and the beach was posted in the summers of 2003 for exceeding state standards for recreational contact, and more recently in 2005, due to 20-day exceedance violations for *Enterococcus* in ocean water samples collected by the Marin

County Environmental Health Services Department (DHS). A recent follow-up analysis of data collected by NPS in 2004–2005 was conducted by Stillwater Sciences, suggesting current land use practices at the stables and other locations continue to result in excess nutrients and bacteria to the lower watershed (Stillwater Sciences 2005a). Four additional sampling events completed by DHS in August 2005 focused on low-flow conditions. Results from these efforts show higher concentrations of bacteria at all sampled locations downstream of the Highway 1 bridge than locations upstream of the Highway 1 bridge (DHS, Aug. 2005, unpublished data), with individual samples regularly exceeding the single day criteria for *E. coli. and Enterococcus* (Table 1-13). However, no beach samples collected in August 2006 were found in excess of the applicable bacteria criteria for contact recreation.

1.6.3 Comparisons of water quality data with applicable criteria

On the basis of the data compiled since the late 1980s in the Redwood Creek watershed (summarized above and detailed in Appendix B), a brief review of whether water quality supports designated beneficial uses is provided below. Overall, there are no known water quality impairments for agricultural and municipal uses.

1.6.3.1 Bacteria

In addition to State DHS requirements for bacteria in municipal water supplies, Table 1-13 shows the Basin Plan (SFRWQCB 1995) water quality objective for bacteria in waters designated for contact recreation (REC-1). For comparison to water quality objectives for bacteria, Appendix B provides a long-term data summary, and Stillwater Sciences (2005a) provides a summary of the log-mean (i.e., average) of the long-term bacterial results for the seven sampling events conducted in 2004–2005. Although no consecutive daily samples were collected on which to calculate the log-mean or exceedance probabilities, municipal water supply uses may not be supported below Muir Woods on the basis of high fecal coliform results, and downstream of Heather Horse Camp on the basis of total coliform. Water contact recreation (REC-1) uses would also not be supported at most downstream locations in lower Redwood Creek on the basis of total coliform and enterococcus exceedances.

The results presented to date suggest the need for regular sampling events (> 5 events in 30 days) to confirm the nature of the apparent exceedances as well as targeted follow-up sampling at particular locations. Other potential sources of bacteria that have not been validated through sampling include: 1) fugitive leachate from septic systems within the town of Muir Beach and properties adjacent to Redwood Creek, and 2) equestrian related loadings at the Redwood Creek trail crossing upstream of the Banducci property. Although no comprehensive data on septic system management was reviewed for this report, the Pelican Inn reported undertaking septic maintenance in about 2003, and Green Gulch Farm replaced an old septic tank in the upper farm fields in summer 2005.

1.6.3.2 Biostimulatory substances

The Basin Plan requires that water shall not contain biostimulatory substances which promote aquatic growths in concentrations that cause nuisance or adversely affect beneficial uses. Nutrient levels found in 2004–2005 as well as in separate surveys conducted by SFRWQCB (2008a)(Section 1.6.4) are consistent with historical data reported in PWA (2003) and suggest the continuing contribution of nutrients above regional reference levels. Given the low dissolved oxygen levels encountered at several downstream locations during summer and autumn (Appendix B), it is apparent that nutrient enrichment (i.e., eutrophication) is occurring within the

lower Redwood Creek watershed. On the basis of the estimated nitrogen to phosphorus ratios shown in Appendix B, the upper watershed appears to be largely nitrogen limited (TIN:PO_4 < 10), with ratios greater than this indicating a switch to phosphorus limitation during some sample events and at locations within the lower watershed (Cooperider 2004). These measurements indicate that phosphorous should have a greater biostimulatory effect than nitrogen in the lower portions of the watershed. Phosphorous can be introduced to waters through residential or agricultural fertilizer applications, septic tank seepage, and associated with fine sediment. Because of the higher relative levels of downstream phosphorus at Heather Horse Camp, Golden Gate Dairy and Green Gulch, additional sediment control measures and limitations on fertilizer use may reduce observed eutrophication effects and measured nutrient levels in the lower Redwood Creek watershed.

1.6.3.3 Chemical constituents

The Basin Plan requires that water designated for use as domestic or municipal supply shall not contain concentrations of chemical constituents in excess of the MCLs specified in the provisions of Title 22 of the California Code of Regulations. Observed levels of nitrate and ammonia (Appendix B) were well below regulatory levels for drinking water uses. Other than historical cadmium levels that exceeded the Table 1-13 criteria, no exceedances in Title 22 contaminants were found.

1.6.3.4 Dissolved oxygen

Dissolved oxygen concentrations in water depend on several factors, including temperature (i.e., colder water absorbs more oxygen), the volume and velocity of water flowing in the water body (re-aeration), salinity, and the amount of organisms using oxygen for respiration. This last factor (respiratory consumption) is, in turn, strongly influenced by the availability of eutrophic nutrients (N and P), naturally derived from allochthonous sources (e.g., leaf litter), but more commonly arriving in runoff from fertilized agriculture, human and animal wastes. The Basin Plan requires that the monthly median of the mean daily dissolved oxygen concentrations shall not fall below 85 percent of saturation in the main water mass. Minimum dissolved oxygen levels are required to remain above 7 mg/L at all times for cold water beneficial uses and above 5 mg/L for warm water uses (Table 1-13).

Appendix B shows that samples collected within the lower watershed from 1993 through 2005 are routinely at or below the cold water dissolved oxygen objective of 7 mg/L during August, September, and October (Table 1-13). Continuous water quality data within lower Redwood Creek (dissolved oxygen summarized in Table 1-13) was collected over 4 years (1998, 1999, 2001, and 2002) (Fong and Manning 2007) as well as recent SFRWQCB (2008a) surveys (Section 1.6.4) also support the observations of low dissolved oxygen in prior surveys. On the basis of the low dissolved oxygen levels observed in one or more sampling events, it is apparent that sites within lower Redwood Creek do not support designated beneficial uses of cold and warm water aquatic habitat during the late summer/early fall period. Although conditions appear to improve with higher flows and pool connectivity (Fong and Manning 2007), continued episodes of lower dissolved oxygen at downstream locations suggest that existing land use practices result in DO levels that do not meet standards for cold and warm water aquatic habitat.

1.6.3.5 pH

The Basin Plan requires that the pH shall not be depressed below 6.5 nor raised above 8.5. Although a single sample exceedance for the Camino del Canyon tributary occurred after NPS

limed the road for erosion control (Fong and Canevaro 1998), no other exceedances of Basin Plan criteria were identified (Appendix B).

1.6.3.6 Temperature

Water temperatures within the Redwood Creek watershed generally range from 51–59°F (11–15°C (Appendix B), with occasionally higher temperatures up to 64–66° F (18–19°C) in late summer and early fall (September–October). Although these temperatures are within the tolerance of many aquatic organisms, peak summertime temperatures within un-shaded areas downstream of Pacific Way have been reported to exceed 68°F (20°C) (PWA 2003, their Appendix B). Although later summer water temperatures in recent (SFRWQCB 2008a) and historical data (Appendix B) approach recommended criteria for Coho salmon and steelhead trout (Sullivan et al. 2000), long-term monitoring using calibration-checked thermographs would be required to validate temperature exceedances at particular locations.

1.6.3.7 Toxicity

The Basin Plan requires that waters shall be maintained free of toxic substances in concentrations that produce detrimental physiological responses in human, plant, animal, or aquatic life. Of the parameters examined in Appendix B, ammonia levels were the only ones with the potential for aquatic toxicity. Observed ammonia concentrations (Table 1-13) were well below toxicity levels established under the California Toxics Rule (Table 1-13). At the pH values found in this study (pH=7–8 standard units) unionized ammonia (NH_3 vs NH_4^+) represents 1–5 percent of the total ammonia levels, with corresponding concentrations well below the 0.025 mg/L water quality objective as an annual median concentration of unionized ammonia shown in Table 1-13. In terms of direct toxicity due to metals, the moderate levels of alkalinity and hardness found throughout the study area decrease the proportion of free ions of many trace metals, making them less toxic. No exceedances of Basin Plan criteria (Table 1-13) were identified in the historical data (Appendix B).

1.6.4 Current water quality monitoring efforts

Between 2001 and 2005, the San Francisco Bay Region Surface Water Ambient Monitoring Program (SWAMP) used a rotating basin sampling design to perform year-long surveys of water quality conditions in a select number of watersheds around the Region, including four sites within Redwood Creek: Muir Woods (d/s of Spike Buck Creek), Miwok Bridge (d/s of Muir Woods Bridge), lower Redwood Creek (at Pacific Way), Green Gulch tributary (lower), and at Muir Beach (at Pedestrian Bridge) (SFRWQCB 2008a).

Water quality monitoring included BMI and physical habitat sampling at the three Redwood Creek sites (# of taxa, % environmentally sensitive orders [EPT], fine sediment, etc.); continuous monitoring of in situ water quality at all sites (temperature, DO, pH, conductivity); analytical water chemistry (nutrients at the lower Redwood Creek and Green Gulch tributary sites); and dry season sampling of total coliform bacteria at Muir Beach. Findings from these monitoring surveys are summarized below.

- Although the BMI community metrics for mainstem Redwood Creek sites were indicative of minimal disturbance, BMI samples from Green Gulch tributary exhibited reduced taxonomic richness, EPT richness, and % Sensitive EPT with large accumulations of fine sediment (>70 percent).

- Although the Basin Plan does not contain specific water temperature objectives for Redwood Creek (Table 1-13), water temperatures were generally within thresholds for Coho salmon and steelhead trout (Sullivan et al 2000) with the exception of short term excursions above 17ºC in lower Redwood Creek.
- Dissolved oxygen was also found to be generally above the 7 mg/L criterion for coldwater habitat (Table 1-13).
- No exceedances of water quality objectives for pH (6.5–8.5) or specific conductivity (<1,000 us/cm) were observed in Redwood Creek or the Green Gulch tributary.
- Data for nutrients indicated exceedances of regional reference guidelines (USEPA 2000a) in lower Redwood Creek and within the Green Gulch tributary, although these reference conditions may be inappropriate for watershed with some degree of urban development (SFBRWQCB 2008a).

Follow-up sampling, for the parameters above as well as additional parameters, was planned for the Miwok Bridge site in the 2007–2008 SWAMP work plan (SFBRWQCB 2008b) with reporting expected in 2010.

1.7 Aquatic Species and Habitats

1.7.1 Fish, amphibians, and aquatic reptiles

The Redwood Creek watershed is known to harbor at least 20 native aquatic vertebrate species, including nine native fishes (Table 1-14), nine native amphibians, and two native aquatic reptiles (one turtle and at least one species of garter snake). Two non-native fish species and one non-native turtle have also been identified in the watershed (Tables 1-14 and Appendix C).

1.7.1.1 Fish

Numerous investigations have been conducted since 1992 to document fish distribution and abundance in Redwood Creek and its estuary. Fish surveys were conducted in 1992 and 1993 for an Environmental Assessment (EA) (PWA et al. 1994). Subsequent investigations have included a report on the use of lower Redwood Creek and Big Lagoon by juvenile coho salmon and steelhead (*Oncorhynchus mykiss*) (Fong 1996), annual distribution and abundance surveys for juvenile coho salmon and steelhead (Smith 1994b, 1995, 1996, 1997, 1998, 2000, 2001), salmonid outmigrant trapping in 1996 (Fong 1997a), an anadromous salmonid spawner and carcass survey, conducted in the winter of 1996–1997 (Fong 1997b), and a study of the use of the Big Lagoon estuary (and other central California estuaries) by rearing coho salmon and steelhead (Laidig 2003). Table 1-14 shows the fish species documented in the watershed from 1992–2002.

In addition to the species documented during the above surveys, NPS has observed Sacramento blackfish (*Orthodon microlepidotus*) and yellowfin gobies (*Acanthogobius flavimanus*) in the tidal lagoon, and Fellers and Guscio (2004) observed Sacramento pikeminnow (*Ptchocheilus grandis*) in Green Gulch Creek (Table 1-14).

Table 1-14. Fish species documented in Redwood Creek and the Big Lagoon estuary, 1992–2002.

Fish species	Native (N) or Introduced (I)	Year observed	Source	Tidal Lagoon	Redwood Creek
Sacramento blackfish (*Orthodon microlepidotus*)	I[a]	1992	PWA et al. (1994)	X	
Topsmelt (*Atherinops affinis*)	N	1995	Fong (1996)	X	
Coho salmon (*Oncorhynchus kisutch*)	N	1992 1993 1994 1995 1996 1997 1998 2000 2001 2002	PWA et al. (1994); Fong (1996, 1997a, 1997b); Smith (1994b, 1995, 1996, 1997, 1998, 2000, 2001); Laidig (2003)	X	X
Steelhead (*Oncorhynchus mykiss*)	N	1992 1993 1994 1995 1996 1997 1998 2000 2001 2002	PWA et al. (1994); Fong (1996, 1997a, 1997b); Smith (1994b, 1995, 1996, 1997, 1998, 2000, 2001); Laidig (2003)	X	X
Threespine stickleback (*Gasterosteus aculeatus)*	N	1992 1993 1994 1995 1996 2001 2002	PWA et al. (1994); Smith (1994b); Fong (1996, 1997a); Laidig (2003)	X	X
Prickly sculpin (*Cottus asper*)	N	1992 1993 1994 1995 1996	PWA et al. (1994); Smith (1994b); Fong (1996, 1997a)	X	X
Coast range sculpin (*Cottus aleuticus*)	N	1995	Fong (1996)	X	
Riffle sculpin (*Cottus gulosus*)	N	1992 1993 2001	PWA et al. (1994); Smith (2001)		X
Pacific staghorn sculpin *Leptocottus armatus*)	N	1992 1993 1995	PWA et al. (1994); Fong (1996)	X	

Fish species	Native (N) or Introduced (I)	Year observed	Source	Tidal Lagoon	Redwood Creek
Striped bass (*Morone saxatilis*)	I	1992 1995 2002	PWA et al. (1994); Fong (1996); Laidig (2003)	X	
Sacramento perch (*Archoplites interruptus*)	I[a]	1993	PWA et al. (1994)	X	
Yellowfin goby (*Acanthogobius flavimanus*)	I	1992 1993	PWA et al. (1994)	X	
Starry flounder (*Platichthys stellatus*)	N	1992 1993	PWA et al. (1994)	X	

[a] Native to other California river systems; introduced into the Redwood Creek drainage.

In addition to the 1996–97 anadromous salmonid spawner and carcass survey, the NPS has conducted annual surveys to document live adult coho salmon, carcasses, and redds in the Redwood Creek watershed from 1994–95 through 2004–05 (Reichmuth et al. 2005). One-time spawner surveys were also conducted by the California Department of Fish and Game in 1969, 1977–78, and 1985–86 (Reichmuth et al. 2005). The results of all adult coho salmon surveys to date are summarized in Section 1.7.3.1 (see Table 1-16).

1.7.1.2 Amphibians and aquatic reptiles

The following herpetological surveys have been conducted by NPS staff, USGS researchers, and contractors since 1992 in the Redwood Creek Watershed:

- **1992–1993**: surveys for amphibians and reptiles in wetland and riparian habitats in Big Lagoon and ponds in Green Gulch (PWA et al. 1994)
- **1993**: frog and frog habitat surveys in upper Redwood Creek in vicinity of Muir Woods National Monument and Frank's Valley (primarily focused on foothill yellow-legged frog habitat), as well as in the area of Big Lagoon (Ely 1993, PWA et al. 1994)
- **1997**: California giant salamander surveys in the upper Redwood Creek watershed (Fong and Howell 2006)
- **1998**: California red-legged frog breeding surveys at ponds and wetlands within Green Gulch Valley by Cook.
- **2002–2003**: intensive California red-legged frog surveys—including radio-tracking—in and around Big Lagoon (Fellers and Guscio 2004) (further addressed in Section 1.7.3)
- **2004**: California red-legged frog breeding season surveys in the area of Big Lagoon (Wood 2004)
- **2003–2006**: California red-legged frog surveys within the boundary of the GGNRA, including continued investigation of amphibians in Big Lagoon and lower Redwood Creek (Fong and Campo 2006).

All amphibians and reptiles recorded in Redwood Creek watershed (or predicted to occur based on habitat conditions), including terrestrial species, are listed in Appendix C. Scientific names are included in the Appendix C tables, but are hereafter excluded from the text for efficiency in the discussion that follows. In Big Lagoon, California newts, rough-skinned newts, Pacific chorus frogs, ensatinas, and slender salamanders were all seen with some frequency (PWA et al.

1994, Wood 2004). California red-legged frogs were seen regularly, but in low numbers, as discussed in more detail in Section 1.6.3. California giant salamanders have been observed in the upper Redwood Creek watershed, particularly in headwater tributaries to Redwood Creek, both perennial and intermittent (Fong and Howell 2006, Garcia and Associates 2007). Fong and Howell (2006) suggest that giant salamanders could be used as an indicator species for the watershed, because (1) they are typically associated with habitat features characteristic of healthy stream conditions (e.g., abundance of larger substrates and undercut banks), (2) they are less mobile than anadromous fish, which means that population trends may be more closely tied to local habitat conditions, and (3) they can be sampled with relative ease. There have been several reports of western pond turtles in Redwood Creek (PWA et al. 1994, Fong 2002); however, there has been a lack of sightings in the last several years (Jones and Stokes 2007). It is important to note that the non-native bullfrog, an invasive species that could potentially prey on and/or outcompete several of the native amphibian species, has not been observed in the Redwood Creek watershed, although it is known to occur in the adjacent Tennessee Valley watershed (PWA et al. 1994).

Foothill yellow-legged frogs (a California Species of Special Concern) have historically been found along Redwood Creek (Ely 1993, Fong 1997). Although suitable habitat still exists for the species, no foothill yellow-legged frogs have been found during surveys conducted over the past fifteen years (Ely 1993, PWA et al. 1994). It is presumed that this species may have been extirpated from the Redwood Creek watershed.

1.7.2 Aquatic invertebrates

Aquatic macroinvertebrates are important as food for fish and as indicators of stream conditions. A limited number of aquatic invertebrate studies have been conducted within the Redwood Creek watershed. Much of the research has been to inventory the invertebrate taxa and apply basic metrics to the data in order to provide biotic indicators of water quality conditions related to fine sediments, organics, and water temperature. Other studies were focused on a single species or specific habitat. Comparison among these studies are difficult due to differences in sampling methods and study goals.

The SFRWQB (2008a) conducted benthic macroinvertebrate studies as part of the SWAMP between 2001 and 2005 as described in Section 1.6.4 Current water quality monitoring efforts.

The NPS conducted invertebrate surveys in mainstem Redwood Creek in 1995 and 1997 at six locations and found that invertebrate communities differed between the downstream-most site and those upstream (Fong 2002). Specifically, the downstream site, located below the Pacific Way Bridge, exhibited lower species diversity and higher proportions of dominant taxa. This study also found that higher invertebrate abundance was associated with smaller substrate particle sizes, and concluded that reaches that experience higher shear stress (as indicated by larger substrate particle sizes), may result in lower densities of benthic macroinvertebrates.

Additional invertebrate surveys in seasonal and perennial wetlands near the mouth of Redwood Creek have been conducted by the NPS (Fong et al. 2003) and Philip Williams and Associates (PWA et al. 1994). Fong et al. (2003) found that the pasture wetlands in the vicinity of the mouth of Redwood Creek supported higher invertebrate densities and species diversity than Redwood Creek and the other seasonal wetlands adjacent to the creek. Within wetland sites, vegetated margins had higher invertebrate densities and species diversity than open water areas. Mainstem Redwood Creek sites had moderate to low invertebrate abundance and diversity compared to backwater and off-channel habitats. These results are similar to those reported by PWA (1994) as

part of the Big Lagoon environmental assessment, which found invertebrate abundance and diversity to be greater in habitats outside of the mainstem channel of Redwood Creek, such as perennial ponds, especially in late winter. This study pointed out that during late-winter and spring surveys conducted in 1993, there was reduced density at sites in the mainstem of Redwood Creek relative to the off-channel habitats, suggestsing that high-flow events in winter and spring may displace macroinvertebrates downstream but leave those in off-channel habitats relatively undisturbed. The PWA et al (1994) study concluded that insect abundance (density) and diversity was positively correlated with the amount of aquatic and emergent vegetation.

Species-focused studies have also been conducted within the Redwood Creek watershed. In 1997 and 1998, the USGS performed a study to determine the abundance and distribution of California giant salamander and the non-native signal crayfish (*Pacifastacus leniusculus*) in the upper Redwood Creek watershed (Fong and Howell 2006). The study found signal crayfish throughout the mainstem of Redwood Creek, but not in first-order streams or upstream of fish barriers. Instances of predation on larval giant salamanders by signal crayfish were recorded, but larval salamanders appeared to prefer different habitat than signal crayfish. This may indicate that competitive exclusion is taking place, but further studies are needed to confirm whether this is the case.

A habitat-focused invertebrate survey was conducted by Kimball et al. (2002) as part of a project to explore the feasibility of riprap removal in Redwood Creek. The goal of the survey was to determine differences in the invertebrate community between two types of banks, natural and rip-rapped. Higher invertebrate diversity and abundance were found along natural banks compared to rip-rapped banks. The study concluded that natural banks within Redwood Creek provide higher quality habitat for invertebrates than rip-rapped banks.

The SFBRWQCB (2008a) stated that because of the limited sampling history and geographic extent of existing BMI data, establishing trends that allow assessment of long-term changes in ecological conditons is not possible. However, additional studies may occur within the watershed since Redwood Creek has been selected as a reference site for SWAMP studies because of the relatively high quality of the BMI community (SFRWQCB 2008a). Such additional surveys of macroinvertebrates in Redwood Creek are needed to identify any long-term trends.

1.7.3 Special-status aquatic species

Three aquatic species protected by the state and/or federal Endangered Species Acts occur in the watershed. These are coho salmon, steelhead, and California red-legged frog. Steelhead and California red-legged frog are listed as threatened under the Federal Endangered Species Act. The federal listing status of the coho salmon found in the Redwood Creek watershed was upgraded from threatened to endangered in June, 2005 (70 FR 37160). Coho salmon is also listed as endangered under the California Endangered Species Act, and California red-legged frog is considered a Species of Special Concern by California Department of Fish and Game (CDFG). Because these species require a range of habitat types and are especially sensitive to habitat disturbance and degradation, they may serve as indicators of ecosystem health in the watershed.

No sensitive aquatic invertebrates are considered likely to be present in the Redwood Creek watershed. The NPS conducted surveys in the watershed in 1986 and 1997 to document the occurrence of California freshwater shrimp (*Syncaris pacifica*), but recorded no individuals of this species (Serpa 1986, Fong 1997c and 1999). In addition, surveys conducted in the Muir Beach area in 1992 did not encounter the San Francisco fork-tailed damselfly (*Ischnura gemina*), Leech's Skyline diving beetle (*Hydroporous leechi*), or the Ricksecker's water scavenger beetle

(*Hydrochara rickseckeri*), all of which were considered sensitive species by the U.S. Fish and Wildlife Service (USFWS) (Category 2) at the time of the surveys (Hafernik and Mead 1992).

1.7.3.1 Coho salmon (*Oncorhynchus kisutch*)

Coho salmon found in the Redwood Creek watershed belong to the Central California Coast evolutionarily significant unit (or ESU; National Marine Fisheries Service [NMFS] 1997), which includes (1) coastal drainages from Punta Gorda in northern California south to and including the San Lorenzo River in central California (although coho salmon are occasionally observed further south), and (2) the drainages of San Francisco and San Pablo bays, excluding the Sacramento-San Joaquin River basin. This ESU is listed as endangered under both the federal (NMFS 1996, 2005) and state (CDFG 2002) Endangered Species Acts. Designated critical habitat includes all river reaches and estuarine areas accessible to coho salmon within the ESU's geographic area (NMFS 1999). Redwood Creek is included in the critical habitat designated for this ESU, which was announced on September 2, 2005 and became effective January 2, 2006 (70 FR 52488). NMFS is expected to release a draft recovery plan in winter 2009/2010.

Coho salmon populations in California have generally declined, and this species no longer occupies many of the streams in California where these fish have historically occurred (Hassler et al. 1991, Brown et al. 1994). Brown et al. (1994) estimated that coho salmon populations in California have decreased to less than 6 percent of the size reported for the 1940s. In the Central California Coast ESU, where historical populations of naturally spawning fish are estimated to have numbered between 50,000 and 125,000, current abundance is estimated to be less than 5,000 fish, with many of these considered to be of hatchery origin (Brown and Moyle 1991, Bryant 1994, CDFG 1994).

Similar to the rest of the ESU, the Redwood Creek population appears to be in low abundance since the 1970s, although data describing adult coho salmon abundance and distribution in Redwood Creek prior to 1995 are sparse. Surveys for adult coho salmon were conducted by CDFG in 1969, 1977–78, and 1985–86 (Table 1-15). Since the winter of 1994–95, the NPS has conducted more comprehensive monitoring of coho throughout the watershed, including documenting adult abundance, spawning distribution (redd surveys), and juvenile abundance and distribution. Early surveys in the watershed (prior to 1997) used the peak live plus cumulative dead (PLD) index to estimate adult escapement (Table 1-15). However, this approach does not take into account observer detection error or a protracted spawning period, and is a minimum estimate based on the peak observations of fish. More recent monitoring has used an Area Under the Curve (AUC) approach, taking into account residency time of spawners, and an observation efficiency for surveyors (assumed to be 50 percent). Since monitoring began, estimated adult abundance has ranged from a low of zero adults in 1999–2000 and 2007-2008 to 171 adults in 2004–2005 (Table 1-15).

Table 1-15. Summary of results of coho salmon spawner surveys conducted in the Redwood Creek watershed.

Year	Number of surveys	Survey length (km)	PLD Index[a]	AUC range 50% OE RT 8–17 days[b]	Total carcasses	Total redds	Source
1969	1	3.2	24	--	4	--	CDFG as cited in Del Real et al. 2007
1977–1978	1	3.2	36	--	3	--	CDFG as cited in Del Real

Year	Number of surveys	Survey length (km)	PLD Index[a]	AUC range 50% OE RT 8–17 days[b]	Total carcasses	Total redds	Source
							et al. 2007
1985–1986	1	7.2	50	--	--	--	CDFG as cited in Del Real et al. 2007
1994–1995	5	8.4[c]	58	--	22	--	NPS Fong 1995 as cited in Del Real et al. 2007
1995–1996	5	8.4[c]	27	--	18	--	NPS Fong 1996 as cited in Del Real et al. 2007
1996–1997	6	8.4[c]	57	--	15	--	NPS Fong 1997 as cited in Del Real et al. 2007
1997–1998	7	9.4[d]	65	177–376	30	80	NPS Manning 1999 as cited in Del Real et al. 2007
1998–1999	11	9.4[d]	39[e]	78–167	10	58	NPS CSRP as cited in Del Real et al. 2007
1999–2000	6	8.4[c]	10	16–35	1	7*	NPS CSRP as cited in Del Real et al. 2007
2000–2001	5	9.4[d]	49	148–314	13	35	NPS CSRP as cited in Del Real et al. 2007
2001–2002	5	9.4[d]	105[f]	233–494	63	47	NPS CSRP as cited in Del Real et al. 2007
2002–2003	5	9.4[d]	24[g]	43–92	3	7*	NPS as cited in Del Real et al. 2007
2003–2004	6	9.4[d]	67	86–182	25	43	NPS as cited in Del Real et al. 2007
2004–2005	7	9.4[d]	171[h]	338–718	76	93	NPS as cited in Del Real et al. 2007
2005–2006	5	9.4[d]	27[e]	55–117	5	12	NPS as cited in Del Real et al. 2007
2006–2007	9	9.4[d]	28[i]	46–98	6	21	NPS as cited in Del Real et al. 2007
2007–2008	7	9.4[d]	0	--	0	0	NPS 2008

[a] PLD is the adult population estimate, derived from the combined peak count of live and cumulative dead adult salmon.
[b] The Area Under the Curve (AUC) method is dependent on two variables, observer efficiency (OE) and fish residence time (RT) in the freshwater following entry.
[c] Includes the main stem of Redwood Creek and Fern Creek.
[d] Includes the main stem of Redwood Creek, Fern Creek, and Kent Creek.
[e] Includes 2 peaks, 7 weeks apart.
[f] Includes 2 peaks, 22 days apart.
[g] Includes 2 peaks, 33 days apart.
[h] Includes 2 peaks, 25 days apart.
[i] Includes 3 peaks, 26 and 24 days apart.
* Poor survey conditions resulted in low observer efficiency.

Coho salmon in the southern extent of their range have a fixed three-year maternal brood year cycle that makes them particularly vulnerable to natural and anthropogenic catastrophic events (Anderson 1995). In most Central Coast watersheds, all brood year lineages are severely reduced and only few streams sustain naturally spawning populations (CDFG 2002). In Redwood Creek, there are currently two brood years (2005/2006 and 2006/2007 escapements) that are in low

abundance but consistently viable. The 2007/2008 brood class was steadily increasing in population size until 2007, when a complete crash was observed. The reasons for the crash are not known, but may be related to extremely poor ocean conditions and subsequent low marine survival of the smolts produced in 2005 (MacFarlene et al. 2008).

Recent genetic analyses have been conducted using coho salmon tissue and scale samples collected from fresh carcasses during the annual NPS spawner surveys. A phylogeographic tree derived from these analyses indicates that coho salmon found in Redwood Creek and Pine Gulch Creek are a distinct subgroup that does not show close genetic relationship with any other coho salmon subgroup in the Central California Coast ESU (Garza and Gilbert-Horvath 2003). Although these results were based on sampling only one fish, they suggest that the Redwood Creek population is not heavily influenced by hatchery introductions. In addition, the results also suggested the population was not suffering the reduced genetic diversity that is a signature of recent bottlenecks. Overall, this limited information suggests that the current population has the genetic integrity to increase in abundance, in comparison to those populations that are apparently composed mostly of strays from other basins or from hatcheries.

Adult coho salmon return to Redwood Creek as two- or three-year-olds and have been observed in the creek from November through February. Life history timing for coho salmon in Redwood Creek is shown in Table 1-16. Peak spawning in Redwood Creek typically occurs from mid-December to mid-January (Reichmuth et al. 2005). In the Redwood Creek watershed, spawning has been observed in the mainstem creek from the Pacific Way Bridge to the upstream boundary of Muir Woods National Monument at river mile (RM) 4.8 or river kilometer (RK) 7.7, and in Fern Creek, from its confluence with Redwood Creek upstream to the first impassable falls, at approximately 0.4 mi (0.6 km) upstream of the Redwood Creek confluence (Fong 1997b). Based on observations since 1997, redd densities are typically highest near the main visitor access areas of Muir Woods, approximately RM 3.1–3.7 (RK 5–6) upstream from the ocean, although the reasons for this are not known (Carlisle et al. 2008).

Table 1-16. Coho salmon life history timing in Redwood Creek.

Life Stage	Month																							
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sept		Oct		Nov		Dec	
Adult migration and spawning																								
Incubation																								
Rearing																								
Outmigration																								

Sources: Fong (1997a), Manning et al. (1999), and Shapovalov and Taft (1954)

Eggs incubate in the gravel for 5–7 weeks before hatching, depending on water temperatures (Shapovalov and Taft 1954). After hatching, the alevins remain in the gravel surviving on their yolk sacs for an additional 2–4 weeks and emerge from the gravel as fry from March until May (Shapovalov and Berrian 1940, Hassler 1987). Juvenile coho salmon migrate to sea as age 0+ young-of-the year (YOY) or remain in fresh water for up to 15 months and emigrate as age 1+ smolts. While rearing in fresh water, juvenile coho are typically associated with low velocity pools or off-channel habitats with complex cover, especially that provided by LWD (Shirvell 1990, Bustard and Narver 1975, Bugert 1985, Nickelson et al. 1992).

Rearing juveniles have been reported in Redwood Creek from the Rattlesnake Creek confluence to Big Lagoon, in Fern Creek to the falls, and in Kent Canyon to the falls (located approximately 0.4 mi or 0.6 km upstream of the confluence with Redwood Creek) (Fong 1997a; Arnold 1971, as cited in Snider 1984). Outmigrant trapping conducted in Redwood Creek in 1996 captured YOY coho salmon primarily in March, while smolt outmigrants were captured in late April and early May (Fong 1997a). Analysis of adult coho scales (n=57) found that about 5 percent of returning adults had spent up to 2 years in freshwater (all individuals were female) (Rauber 2000), as has been observed in other California coastal streams (Bell and Duffy 2007).

Dr. Jerry Smith of San Jose State University has monitored juvenile coho salmon at five reference sites in the watershed since 1995 (Smith 1995, 1996, 1997, 1998, 2000, and 2001) (Table 1-17). Linear abundance (fish per 100 ft) of juvenile coho salmon documented in these surveys ranged from a low of 1.1 in October 2000 to a high of 42 in August 1995 (Table 1-18). Smith has identified two factors that potentially limit coho salmon production in the watershed: 1) lack of sufficient pool habitat to support oversummering (especially during dry years) and 2) poor overwinter survival during wet years (e.g., Smith 2001). Smith (e.g., 2001) concludes that lack of summer habitat provided by deep pools (i.e., > 0.5 m) with complex cover combined with low late-summer and fall flows in the lower creek is the primary factor limiting coho salmon production in the watershed during dry years.

Findings from Smith (2000) as well as others (e.g., Fong and Manning 2007) support Smith's hypotheses. In the lower watershed, and particularly downstream of the MBCSD well, low flows cause pools to become disconnected during late summer and early fall (Fong and Manning 2007). The disconnected pools and dry creek areas are downstream of the well and can extend 1.5 mi (2.4 km) to the creek's mouth at the Pacific Ocean (Fong and Manning 2007). During dry year conditions (< 33 inches of precipitation) juvenile coho salmon densities are significantly lower downstream of the facility than upstream (Fong and Manning 2007). Under dry year conditions Fong and Manning (2007) estimated an overall potential for a 10 percent reduction in watershed fish production.

During years with higher than average rainfall, see Section 1.3 Climate, floods may be a more critical limiting factor. Smith (2000) hypothesizes that high mortality caused by high flows during wet years may have severely reduced the abundance of the 1997 year class, suggesting that redd scour and/or a lack of floodplain connectivity and access to refugia from high flows may limit production during wet years. Substantial numbers of fry are displaced in the spring from upstream and find their way to the Big Lagoon area (Reichmuth et al. 2006) in both wet and dry water years. This displacement may be a density-dependent response coupled with the absence of velocity refugia (such as floodplains, side channels, and alcoves) upstream (Koski 2009). These findings suggest that the Big Lagoon area may provide important winter habitat since it has extensive secondary channels and floodplains (Fong 2002). In 2009, the NPS initiated a restoration of the channel downstream of the Highway 1 bridge to increase winter habitat for juvenile coho salmon by restoring the channel, allowing natural flooding to occur, and by increasing LWD frequency (Jones and Stokes 2007).

In a study on the likely effects of climate change on salmon habitat, Battin and others (2007) identified three critical hydrologic factors that could affect salmonid species, including changes in: (1) peak flow during egg incubation; (2) stream temperatures during pre-spawning; and (3) minimum flow during spawning. In Redwood Creek watershed, changes in winter flows are not consistently projected (Section 1.3), however peak flows, associated with extreme events, are expected to increase in frequency and intensity (Cayan et al. 2006a). Stream temperatures during

late summer are expected to increase with increased late summer and early fall air temperatures (TNC 2009). One strategy for addressing the stresses expected with climate change is to build robustness in the populations and redundancy and resilience in their habitats as early as possible, so that the populations (e.g. increase the number and maintain the genetic viability) and their habitat are able to survive the projected changes (Battin et al. 2007).

Table 1-17. Redwood Creek sites sampled for coho salmon and steelhead by J.J. Smith, 1995–2001.

Year	Citation	Site and dates sampled							
		1	2	3	4	5	6	7	8
1992	PWA et al. (1994) Smith (1994b)		20 Aug			19 Sep	19 Sep 14 Nov	23 Jul 14 Aug 14 Nov	23 Jul 14 Aug 14 Nov
1993	PWA et al. (1994) Smith (1994b)		24 Jun			19 Aug	24 Jun 10 Sep	8 Jun 10 Sep	4 Jun 8 Jun 19 Aug 10 Sep
1994	Smith (1994b) Smith (1994a)	26 Jul	7 Jul 30 Oct	26 Jul 30 Oct	8 Jul	7 Jul 30 Oct	7 Jul 30 Oct[a]	8 Jul 30 Oct[a]	8 Jul
1995	Smith (1995)		22 Aug			22 Aug	23 Aug	23 Aug	
1996	Smith (1996)		2 Nov			2 Nov	2 Nov		
1997	Smith (1997)		27 Sept	5 Oct		27 Sept	27 Sep[a]	27 Sep[a]	
1998	Smith (1998)		9 Oct	30 Oct		30 Oct	9 Oct 30 Oct	9 Oct	
2000	Smith (2000)		18 Oct	14 Oct	14 Oct	14 Oct	14 Oct	14 Oct	
2001	Smith (2001)		23-24 Oct	20 Oct		20 Oct	20 Oct	20 Oct	

Notes:
[a] Isolated pools only
Site Locations:
Site 1: Upper Muir Woods – 2 sites (mi 3.3 and 3.6)
Site 2: Lower Muir Woods – 2 sites (mi 2.5 and 2.8)
Site 3: 0.35 mi upstream of Kent Canyon (mi 2.1)
Site 4: ½ mi upstream of 3rd bridge (a.k.a. "trail downstream of Kent") (mi 1.65)
Site 5: Upstream of 3rd bridge (mi 1.25)
Site 6: Downstream of diversions (mi 0.85)
Site 7: 1st bridge (mi 0.35)
Site 8: Pools above delta (mi 0.15)

Table 1-18. Habitats sampled and estimated mean number of coho and steelhead per 100 ft (30 m) in Redwood Creek in 1994–1998, 2000, and 2001 (from Smith 2001).

Sample date	Number of sites	Habitat types sampled				Total length sampled (ft)	Fish/100 ft (30 m)		
							Coho salmon[a]	Steelhead	
		Pool	Glide	Run	Riffle			0+	1+, 2+
July 1994	7	58	25	12	6	1,287	2	69	14
Oct. 1994	5	83	10	4	3	1,018	2	34	6
Aug. 1995	4	41	30	19	10	796	42	97	4
Nov. 1996	3	51	31	11	7	604	39	33	11
Sept.–Oct. 1997	5	72	18	9	1	984	23	15	5
Oct. 1998	5	58	25	15	1	1,174	32	47	4
Oct. 2000	6	71	27	3	0	1,077	1.1	39	15
Oct. 2001	5	78	15	0	7	956	27	6	6

[a] All coho salmon were assumed to be age 0+

1.7.3.2 Steelhead (*Oncorhynchus mykiss*)

Steelhead found in the Redwood Creek watershed belong to the Central California Coast distinct population segment (or DPS; NMFS 2006), which includes coastal drainages from the Russian River to Aptos Creek and the drainages of San Francisco and San Pablo Bays, excluding the Sacramento-San Joaquin River watershed. This DPS is listed as threatened under the federal Endangered Species Act (NMFS 2000). This steelhead DPS is not currently listed under the California Endangered Species Act.

Detailed adult abundance estimates are not available for steelhead in Redwood Creek; however, based on opportunistic observations during regular sampling for coho salmon, there is a consistent run of around 20 adults (assuming two adults per redd) in Redwood Creek (Carlisle et al. 2008), with a higher than average abundance observed in 2006/2007. It is acknowledged that this is likely an underestimate, because steelhead adults are elusive, their redds are more cryptic than coho salmon, and their spawning season is longer in duration than the surveys conducted for coho salmon. In general, steelhead stocks throughout California have declined substantially. The most current estimate of the population of steelhead in California is approximately 250,000 adults, which is roughly half of the population that existed in the mid-1960s (McEwan and Jackson 1996).

Throughout their range, steelhead exhibit highly variable life history strategies with large differences in run timing and the amount of time spent rearing in fresh water. Populations are broadly categorized into two reproductive groups, winter-run (or "ocean maturing") and summer-run (or "stream maturing"). Steelhead in the Central California Coast DPS, including in Redwood Creek, are winter-run. Life history timing for Redwood Creek steelhead is shown in Table 1-19. In Redwood Creek, adult steelhead have been observed from December through May. Unlike most other anadromous Pacific salmon species, steelhead are capable of returning to the ocean and migrating back upstream to spawn more than once, although some die after their first spawning. Because of the late spring spawning of steelhead, flow conditions may preclude access back to the ocean by runback steelhead. Each year, visitors and staff have observed adult steelhead in the deep backwater and mainstem pools by the Big Lagoon pedestrian bridge. It is unclear whether any of these steelhead make it back out to the ocean.

Table 1-19. Steelhead life history timing in the Redwood Creek watershed.

Life stage	Month																							
	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sept		Oct		Nov		Dec	
Adult migration and spawning																								
Adult (kelts) return to sea																								
Incubation																								
Rearing																								
Outmigration																								

Sources: Fong (1997a), Manning et al. (1999), and Shapovalov and Taft (1954)

After entering the creek, adults migrate upstream to suitable spawning locations. Hofstra and Anderson (1989) reported steelhead spawning in Redwood Creek up to the confluence with Rattlesnake Creek. Earlier surveys, however, report juveniles rearing upstream in Spike Buck,

Rattlesnake, and Bootjack creeks and in Fern Creek within the Mt. Tamalpais State Park, suggesting that steelhead once spawned further up in the watershed (Arnold 1971, as reported in Snider 1984). Based on surveys conducted for coho salmon since 1997, steelhead redd densities are typically highest near the main visitor access areas of Muir Woods, approximately RM 3.1–3.7 (RK 5–6) upstream from the ocean, in the same reach where coho salmon spawning is most often observed (Carlisle et al. 2008).

After spawning, fertilized eggs incubate in the gravel for 3–14 weeks before hatching, depending on water temperatures (Shapovalov and Taft 1954). Alevins remain in the gravel substrate for an additional 2–5 weeks before emerging in spring or early summer. Once emerged, steelhead fry move to shallow-water, low-velocity habitats, such as stream margins and low gradient riffles (Hartman 1965, Everest et al. 1986, Fontaine 1988). As they increase in size and their swimming abilities improve in late summer and fall, juveniles move to areas with cover and show a preference for higher velocity, deeper mid-channel areas near the thalweg (Hartman 1965, Everest and Chapman 1972, Fontaine 1988).

Juvenile steelhead can rear in fresh water for 1 to 4 years before migrating to the ocean as smolts and spend an additional 1 to 3 years in the ocean before returning to their natal streams to spawn (Shapovalov and Taft 1954, Behnke 1992). Analysis of scales collected from juvenile steelhead in Redwood Creek (n=165) documented juveniles ranging in age from 0+ to 3+ years (Rauber 2000). Although the period of fresh water rearing is variable, steelhead typically rear in freshwater for two years before smolting. Through the same study, NPS analyzed scale samples from two adult steelhead from Redwood Creek and determined that one of the adults had spent one year rearing in fresh water and two years at sea; the other had spent two years rearing in fresh water and one year at sea (Rauber 2000), suggesting the potential for successful marine survival of smolts less than two years old.

Juvenile steelhead typically emigrate to the ocean from April through June. In Lagunitas Creek (just north of the Redwood Creek watershed), steelhead emigration has been reported to begin in early March and end in June (Bratovich and Kelley 1988). The typical peak steelhead smolt emigration period occurs in mid-April in other central and southern coastal California streams (*e.g.,* Waddell Creek, Santa Cruz Co. [Shapovalov and Taft 1954]; Lagunitas Creek, Marin Co. [Bratovich and Kelley 1988]; Arroyo de la Cruz, San Luis Obispo Co. [Nelson 1994a]; Gazos Creek, San Mateo Co. [Nelson 1994b]). In Redwood Creek, the NPS has documented YOY year steelhead moving downstream during large storms as early as March (Fong 1997a).

During three years of outmigrant trapping (2005–2007), fewer than 20 steelhead smolts were observed in each year (Carlisle et al. 2008). Low estimates of smolt production would indicate low population abundance, unless production from habitats downstream of the trap is significant, or if steelhead in Redwood Creek can smolt successfully as age 0+ and were therefore underestimated at the trap. Based on the relatively large (>500 in 2007) number of observations of steelhead fry moving downstream during spring, it is possible that rearing could occur in the Big Lagoon habitat downstream of the trap, with smolt production from that habitat undetected by outmigrant trapping.

Steelhead, due to their ability to return to the ocean after spawning and their tendency to spawn at a variety of ages, have not shown pronounced annual variability in abundance in Redwood Creek. Abundance of YOY steelhead, however, was particularly low in 1997 and 2001, and particularly high in 1995 (Table 1-17). Smith (1997, 2001) attributes low YOY steelhead abundance to loss of suitable rearing habitat and reduced food availability resulting from low summer and fall stream flows, especially at the most downstream sites. The impacts of low summer and fall flows

on steelhead may also be exacerbated by groundwater pumping from the wells that supply the town of Muir Beach and impoundments at Green Gulch Farms. This portion of the watershed has been shown to be used extensively by rearing coho salmon and steelhead when suitable conditions exist, at which time it appears to be important rearing habitat. The effects of low stream flows in this area include reduced availability of rearing habitat and macroinvertebrates for juvenile coho and steelhead, as well as poor water quality (elevated temperature, low dissolved oxygen). This is especially important in dry years, when flows are naturally low. Smith (1994a, 1994c) and Fong and Manning (2007) analyzed the effects on coho salmon and steelhead of streamflow reductions in Redwood Creek due to drought and groundwater pumping. Smith (1995, 2001) repeatedly noted that groundwater pumping from the wells near the town of Muir Beach can exacerbate the effects of low stream flows in lower Redwood Creek and the upper portion of the tidal lagoon, as was confirmed by the analysis of Fong and Manning (2007).

1.7.3.3 California red-legged frog (*Rana draytonii*)

The California red-legged frog is the largest native frog in the western United States. Its range extends along the coast from Mendocino south to northwestern Baja California, Mexico, and inland through the northern Sacramento Valley into the foothills of the Sierra Nevada mountains (Stebbins 2003, Shaffer et al. 2004). A narrow range overlap with northern red-legged frog (*Rana aurora*) occurs in Mendocino County (Shaffer et al. 2004). Habitat loss, habitat fragmentation, construction of reservoirs and water diversions, overexploitation, and introduction of exotic predators and competitors (such as bullfrogs) have contributed to reducing the species' range by approximately 70 percent compared to historical conditions (USFWS 2002). Critical habitat for this species was established on April 13, 2006 (USFWS 2006), though the USFWS has recently proposed expanding it (USFWS 2008). No critical habitat has been designated in the Redwood Creek watershed.

California red-legged frog habitat is generally characterized by still or slow-moving water with deep pools (usually at least 2.3 ft (0.7 m), though frogs have been known to breed in pools less than 2.3 ft deep) and emergent and overhanging vegetation (Jennings and Hayes 1994). Its habitats include wetlands, wet meadows, ponds, lakes, and low-gradient, slow-moving stream reaches with permanent pools. Although some adults may remain resident year-round at favorable breeding sites, others may disperse up to a mile or more (Fellers and Kleeman 2007). Movements may be along riparian corridors, but some individuals move directly from one site to another without apparent regard for topography or watershed corridors (Bulger et al. 2003, Scott and Rathbun 2007).

California red-legged frogs sometimes enter a dormant state during summer or in dry weather (aestivation), finding cover in small mammal burrows, moist leaf litter, root wads, or cracks in the soil. California red-legged frogs are typically active year-round in coastal areas because temperatures are generally moderate (USFWS 2002, Bulger et al. 2003).

Breeding occurs between late November and late April (Jennings and Hayes 1994). Females lay egg masses containing approximately 2,000–6,000 eggs (USFWS 2002, Scott and Rathbun 2007). Eggs hatch within 6–14 days and tadpoles require approximately 11–20 weeks to metamorphose (USFWS 2002). Metamorphosis occurs from May to September, and individuals become reproductively mature in two to three years (Bulger et al. 2003).

Introduced species that have been known to prey on California red-legged frogs include bullfrogs, fish (including mosquitofish, bass, and sunfish), and crayfish (Hayes and Jennings 1986). Bullfrogs may both prey upon and compete with California red-legged frogs (Hayes and Jennings

1986, Cook and Jennings 2001, Cook 2002). Bullfrogs appear more readily adaptable to anthropogenic disturbance, including habitat fragmentation, habitat degradation, and altered hydrology (Hayes and Jennings 1986, D'Amore et al. 2009). During a controlled study, Lawler (1999) found that only 5 percent of California red-legged frog tadpoles survived in ponds with bullfrogs present.

The NPS, USGS, and contractors have conducted several surveys for California red-legged frogs in lower Redwood Creek; adult frogs have been found in lower Redwood Creek, in the wetlands adjacent to lower Redwood Creek (i.e., the Restoration of lower Redwood Creek at Muir Beach), and in an auxiliary pond within the Green Gulch Creek watershed (Ely 1993, Cook 1998, Fong 2000, Wood 2004, Fellers and Guscio 2004, Garcia and Associates 2007). Intensive surveys were conducted by the USGS in 2003 and 2004 as part of the the Restoration of lower Redwood Creek at Muir Beach (Fellers and Guscio 2004). These surveys included day and night surveys, egg and tadpole searches, and radio-tracking of adult frogs. The results indicated that the California red-legged frog population in the Big Lagoon area is small, with only an estimated 14 adults and three egg masses in 2003 and 2004 (Fellers and Guscio 2004). No successful breeding activity was documented in Big Lagoon during follow-up surveys from 2004 to 2006 documented (Fong and Campo 2006). One frog was tracked to the lower reaches of Green Gulch Creek and adults have been tracked moving up lower Redwood Creek (Fellers and Guscio 2004, Fellers and Kleeman 2005). One frog had apparently moved between Big Lagoon and an auxiliary pond in the Green Gulch Creek watershed—in 2007 biologists at Garcia and Associates (GANDA) found the frog at the Green Gulch pond with a pit tag inserted during 2003 surveys by USGS at Big Lagoon (C. Shoulders, Natural Resource Specialist, Golden Gate National Recreation Area, pers. comm. with D. Fong, 2007). To date, however, no adults or egg masses have been found in upper Redwood Creek (Fellers and Guscio 2004, Fellers and Kleeman 2005).

In the early 1990s, aggradation of the Redwood Creek channel caused groundwater elevations in the Green Gulch pasture (adjacent to Redwood Creek) to increase by about a foot. A malfunctioning culvert under a levee kept surface water ponded in the pasture, which was subsequently the area where California red-legged frogs were most typically found breeding. Removal of some of the sediment in 2002 from one of the most obstructed portions of the channel caused a slight lowering of the water table, which then caused the ponded area to dry sooner than in previous years, thereby unintentionally preventing tadpoles from metamorphosing. The NPS has since replaced the metal floodgate that backs water up into the Green Gulch pasture with a flashboard structure that prevents water from draining into Redwood Creek in the spring, resulting in extended ponding that allows California red-legged frog tadpoles to complete their metamorphosis (Jones and Stokes 2007). As part of the Restoration of Lower Redwood Creek at Muir Beach—a 38-ac project aimed at restoring a functional, self-sustaining ecosystem at Muir Beach—riparian and aquatic habitat restoration measures are designed to improve conditions for the small population of California red-legged frogs that appears to have declined precipitously in the last fifteen years. Measures proposed for lower Redwood Creek will attempt to restore the hydrological conditions that create and maintain habitat for California red-legged frogs in the watershed, as opposed to maintaining habitat that relies on the continuing existence of a constructed levee that itself inhibits ecosystem functions, as well as ongoing human intervention (Jones and Stokes 2007).

1.7.4 Aquatic habitat

In addition to the limited aquatic habitat data collected as part of several of the above fish investigations, a comprehensive stream habitat inventory was conducted in 1995 by GGNRA staff (Fong 2002). This inventory includes data on channel morphology, substrate, water

temperature, habitat types, LWD, residual pool volume, streamside cover, riparian canopy density, and benthic macroinvertebrates for approximately five miles of Redwood Creek to Bridge 4 in Muir Woods. Geomorphology (channel form) aspects of this study are summarized in sections 1.5.3 Channel morphology-aquatic habitat relationships. In a separate study, woody debris abundance and distribution in Redwood Creek from 1994–1996 were reported by Vore (1996) for reaches in and immediately downstream of Muir Woods, and PWA (2000) includes data on LWD frequency in portions of the watershed.

The results of the numerous fish surveys performed between 1992 and 2002 are summarized in Appendix D. Survey data have indicated that coho salmon and steelhead year class success in Redwood Creek may be highly dependent on habitat and flow conditions (e.g., Smith 1997, 2001). By dewatering shallow habitats and reducing pool volume, low flows can reduce food availability by lowering benthic macroinvertebrate production and delivery, and can limit the area of suitable rearing habitat. Conversely, high winter flows can damage redds, reconfigure the stream channel, and displace rearing salmonids from preferred rearing habitat. The availability (i.e., distribution and abundance) of valuable instream cover, especially LWD in upper stream reaches, is largely responsive to high flows. Vore (1996) found that woody debris in Redwood Creek appeared to be recruited to upstream reaches during the winter of 1994–95 and redistributed downstream in 1996 in response to storm events (see also Section 1.5.3. Channel morphology-aquatic habitat relationships).

Portions of Redwood Creek in Muir Woods were channelized in the 1930s to prevent flooding (see Section 1.2.3.5. Railroads and roads and other infrastructure). Effects of channelization have included channel widening and a relatively homogeneous, plane-bed channel morphology with little connection between the channel and its floodplain. The lack of floodplain connectivity may limit the availability of velocity refuge habitat that can be important for coho salmon during high winter flows. Several grade control structures in the creek within Muir Woods have limited channel incision, and rock revetment lines much of both banks in this reach. Until 1986 the NPS removed woody debris from the creek. Woody debris is now left in the creek, aiding the formation of pools which provide important rearing habitat for juvenile coho salmon and steelhead. Stillwater Sciences (2009) found that winter habitat for juvenile coho salmon under current conditions is limited in availability, but that proposed restoration of lower Redwood Creek at Muir Beach (Jones and Stokes 2007) has the potential to dramatically increase winter rearing habitat by restoring the connection to floodplain and off-channel rearing habitat, and by increasing LWD frequency.

Although only limited data are apparently available on LWD frequency in Redwood Creek, this habitat feature is known to be of key importance for rearing salmonids. In 2003 the NPS implemented a restoration project at the Banducci site in lower Redwood Creek, which includes LWD additions, levee removal, and floodplain regrading. Project monitoring has to date documented inundation of the lowered floodplain at the expected flows, and formation of pools and bars at several of the engineered log jams. As discussed above, proposed restoration of lower Redwood Creek at Muir Beach(Jones and Stokes 2007) also has the potential to increase LWD frequency.

Although features such as LWD jams may provide some value as winter refuge for salmonids, cover consisting of interstitial spaces in cobble or boulder substrate is the key attribute defining winter habitat suitability for juvenile steelhead (Hartman 1965, Chapman and Bjornn 1969, Meyer and Griffith 1997). Filling of coarse substrate interstices by fine sediment can severely reduce the amount of cover available for overwintering juvenile salmonids. Measures to reduce fine sediment delivery, especially in upstream reaches (e.g., Muir Woods) where YOY steelhead

densities are typically high (Smith 2000), may improve winter habitat quality for juvenile salmonids.

1.8 Terrestrial and Wetland Vegetation and Habitats

Existing vegetation and terrestrial habitats in the Redwood Creek watershed are a product of pre-settlement era vegetation and Native American management, overlaid with 150 years of Euro-American management and associated impacts. Thus, while the ancient redwoods in Muir Woods have been protected as a National Monument since 1908, important changes in natural processes that maintain the ancient forest and other natural areas in the rest of the watershed have caused, and in some cases, are continuing to cause, shifts in plant community structure and composition. For example, historical changes in land use, including intensive 18th and early 19th century grazing, timber harvesting, road and rail road construction, and subplanting of the Native American burning regime with 20th century fire suppression, have resulted in large conversions of native grasslands to annual grass and shrub lands, increased accumulation of wildfire fuels and associated increases in wildfire hazard, and changed riparian and wetland extent and distribution. Proliferation of invasive non-native species, particularly in highly trafficked roadsides and trails, require ongoing eradication and prevention efforts. Relatively new threats, including the spread of SOD and local effects of climate change on existing vegetation, make managing the evolving landscape even more complex.

1.8.1 Vegetation Classification and Mapping

During the 1995 Vision Fire in Point Reyes, NPS realized that not having a map of vegetation types severely limited their ability to predict and more effectively combat fire. As a result of this experience, constructing a vegetation type classification and map became a priority for the NPS. A vegetation map and classification can also provide an important foundation piece for other management concerns, such as monitoring wildlife habitat use, and monitoring rare plant species populations and community types. The NPS contracted ESRI and AIS to map vegetation cover types in the watershed using interpretation of aerial photography combined with ground truthing of sample plots (Moritsch et al. 1998). The NPS mapping effort, which covers the central and southern portion of the Redwood Creek watershed, is based primarily on interpretation of 1:24,000 scale true color aerial photographs taken in 1994. Aerial photo-interpretation, based on ground truthing to check signature photo-textures by type, was performed to the alliance level for all polygons, and to the vegetation association level where possible (Moritsch et al. 1998). Three to seven sample plots representative of each vegetation type, for a total of 360 plots, were then field surveyed using a modified releve method (plot size: 400 m^2 for shrub and herbaceous types; 1,000 m^2 for forested types; Moritsch et al. 1998). Based on this field data, vegetation was classified to the association level, as defined by Sawyer and Keeler-Wolf (1995), using multivariate techniques (Moritsch et al. 1998). A field accuracy assessment of the draft vegetation map was performed by NPS personnel in 1999 and a low level of accuracy to at the alliance level was measured (accuracy of 42.5 percent).

A coarser level of classification, termed the superalliance, was found to provide a more accurate representation of field conditions (accuracy of 71.4 percent), and is presented in Figure 1-32, with several minor modifications. These modifications include altering two superalliance names to better fit the Redwood Creek watershed community composition. Because the original vegetation map and the superalliances were created for a much greater area than the Redwood Creek watershed (including Pt. Reyes), the names of two superalliances include species that are not found in this watershed, and their titles therefore falsely imply that these two species are fairly

dominant. These include the Open Grassy Coyotebrush–Yellow Bush Lupine and Introduced Perennial Grassland-Deschampsia superalliances. Since yellow bush lupine (*Lupinus arboreus*) does not occur in the watershed and *Deschampsia*, as discussed below, has not been observed or reported in the watershed, these species names were dropped from the superalliance titles. Also, the Pacific Reedgrass-Carex Juncus superalliance is only represented in the Redwood Creek watershed by disturbed plant communities that include species of that superalliance (8.9 ac). Similarly, the Dune Lupine-Dune Sagewart-Dunegrass superalliance refers to the more diverse dune communities in Pt. Reyes, but in the Redwood Creek watershed is represented by depauperate dune communities that include a few common dune species intermixed with non-native invasive plants. Another important modification to the superalliance classification is that the upper Redwood Creek watershed includes areas supporting serpentine chaparral; these areas are included in the Redwood Creek vegetation map based on polygons delineated in a MMWD vegetation map and overlaid on the NPS classification layer (MMWD 2004). The MMWD vegetation map is not shown in its entirety because, other than the serpentine types, the MMWD polygons and vegetation types were largely in agreement with the NPS vegetation map.

The final vegetation map for Redwood Creek watershed identifies 26 distinct superalliances under the NPS vegetation mapping scheme, including areas classified as 'Built-up Urban Disturbance', 'Disturbed', 'Water' and 'Active Pasture or Agriculture', and the MMWD vegetation category on serpentine chaparral. These various community types can be lumped into seven general cover types for the watershed – Douglas-fir-redwood forest, mixed hardwood forest, chaparral/evergreen scrub, grassland, riparian woodland, herbaceous wetland and coastal communities, and a seventh category of dominantly human-altered cover types referred to as 'other'. A cross-walk of these seven general cover types, the 26 NPS superalliances, and the extent of the superalliances in the watershed are summarized below (Table 1-20).

Table 1-20. Crosswalk of general vegetation cover types presented in the text to NPS mapped vegetation types.

General cover types	NPS superalliances	Hectares	Acres	Percent Acres
Redwood- Douglas-fir forest	Redwood- tanoak	380.3	939.7	
	Douglas-fir	323.3	799	
Mixed hardwood forest	Bishop pine-giant chinquapin	0.9	2.3	
	California bay-coast live oak	313.0	773.5	
	Eucalyptus	9.8	24.3	
Chaparral	Mature coyotebrush-coffeeberry-poison oak	256.2	633.2	
	Chamise-manzanita	247.2	610.9	
	Coyotebrush- California sagebrush	150.7	372.3	
	Serpentine-chaparral	19.8	48.9	
	Coyotebrush-blueblossom	10.4	25.8	
	Open grassland with coyotebrush	249.4	322.4	
Grassland	Native weedy grassland	130.5	616.4	
	Introduced perennial grassland	13.0	32.1	
Riparian woodland	Red alder	26.5	65.4	
	Arroyo, red, black, and yellow willow	17.8	44	
Coastal communities	Pacific reedgrass-carex-juncus	3.6	8.9	
	Beaches or mudflats	2.9	7.2	
	Dune lupine-dune sagewort-dunegrass	2.0	5	
	Pickleweed- saltgrass	1.4	3.4	
Other	Built-up urban disturbance	47.7	117.8	
	Active pasture or agriculture	41.0	101.3	
	Heather fields	11.5	28.4	
	Disturbed	4.7	11.5	
	Monterey pine- Monterey cypress	2.1	5.3	
	Dunes	0.3	0.8	
	Water	0.9	2.2	
Total	Grand total	2,267.0	5,601.90	

1.8.2 Upland and Ripariam Vegetation Types

Brief descriptions of the general upland and riparian vegetation types are provided below.

1.8.2.1 Redwood-Douglas-fir Forest

The Redwood-Douglas-fir forest cover type includes the Redwood-Tanoak and Douglas-fir superalliances mapped by NPS. This forest type covers approximately 1,700 ac (~700 ha) on steep slopes and deep canyons of the watershed (Figure 1-32). This forest type represents a central range of coast redwood forests extending from San Francisco to southern Humboldt County, where Douglas-fir (*Pseudotsuga menziesii*) is co-dominant with redwood (*Sequoia sempervirens*) and tanoak (*Lithocarpus densiflorus*) grows as a mid-canopy species. Further north, both redwood stands and Douglas-fir forests generally occur in wetter areas where other conifer species such as western hemlock (*Tsuga heterophylla*) are co-dominant; further south to Monterey, redwoods are genetically distinct and occur with less understory shrubs and more mid-canopy hardwoods (Howell 1970, Sawyer et al. 2000).

The redwoods occupying the canyon floor of Muir Woods National Monument are the only remaining old growth redwood forest in the Mt. Tamalpais area (Fairley and Heig 1987), and is somewhat isolated compared to other areas to the south and north where old growth redwood stands are more extensive. Some redwood trees in Muir Woods may be as much as 1,000 years old. Other tree species occurring in the forest subcanopy include big leaf maple (*Acer macrophylum*), California bay laurel (*Umbellularia californica*), and, along Redwood Creek, red alder (*Alnus rubra*). Species composition on slopes differs from the alluvial valley floor, with some redwood, Douglas-fir, bay laurel, tanoak, and madrone (*Arbutus menziesii*) being more common on slopes than on the valley floor.

The redwood trees in Muir Woods were the focus of most conservation efforts in the decades following establishment of the site as a national monument in 1908, and, based on analysis of age distribution in Muir Woods (McBride and Jacobs 1978), the number of redwood seedlings and sprouts in Muir Woods is sufficient to continue the dominance of redwoods well into the future. The understory and ground cover, however, were quickly eliminated due to extensive use of the forest floor for picnicking, camping, ballgames, vehicle access, and even collection of ferns and rhododendrons by visitors. Soil compaction associated with frequent human trampling is also associated with reduced vegetation cover (Krenzelok 1974). By the 1950s, Muir Woods prohibited collection of all vegetation and fungi by visitors, and rangers began revegetation efforts (Fairley and Heig 1987; Hall 2008). Revegetation efforts accelerated in the 1980s and 1990s and were supported by NPS management actions to restrict visitor access to trails. Understory cover today is probably the most extensive that it has been in a century, but one redwood ecologist has observed that the subcanopy is far less dense than would be expected in an undisturbed old growth forest (W. Russell, Scientist, USGS Western Ecological Research Center, Sausalito, California, pers. comm. with C. Shoulders, 2002). For instance, huckleberry (*Vaccinium ovatum*) is typically extensive in an old growth forest, but scarcely found at Muir Woods (W. Russell, pers. comm., 2002). Additional challenges remain for managing these forests in order to develop more old growth characteristics; these challenges include allowing for more natural disturbance regimes, allowing for increased frequency of tree –fall gaps created by fallen trees, and preventing or reducing compaction which can stress the redwood shallow root systems, possibly making the trees more prone to disease (Krenzelok 1974, W. Russell, pers. comm., 2002), and managing the forest to minimize negative effects associated with SOD (see Section 1.8.5.1 below).

1.8.2.2 Mixed hardwood forest

The mixed hardwood forest cover type is dominated by the California Bay-Coast Live Oak superalliance mapped by NPS (although it also includes the Eucalyptus and Bishop Pine-Chinquapin superalliances). This forested type covers approximately 800 ac (~325 ha) of the watershed, primarily on the slopes of drainages in the lower portion of the watershed (Figure 1-32). California bay laurel, tanoak, and coast live oak (*Quercus agrifolia*) dominate the mixed hardwood forest, and madrone, chinquapin (*Chrysolepis chrysophylla*), and canyon live oak (*Quercus chrysolepis*) contribute to the relatively dense canopy of the forest. A brushy understory includes species such as poison-oak (*Toxicodendron diversilobum*), toyon (*Heteromeles arbutifolia*), and sword fern (*Polystichum munitum*). The mixed hardwood forest typically grades into the coyote-brush dominated chaparral scrub community on the upper slopes.

1.8.2.3 Chaparral

The chaparral cover type is comprised of the Serpentine Chaparral type mapped by MMWD, and the following superalliances mapped by NPS: Chamise-Manzanita, Coyotebrush-Blueblossom, Coyotebrush-California Sagebrush, Mature Coyotebrush-Coffeeberry-Poison Oak, and Open Grassy Coyotebrush. Taken together, the chaparral superalliances cover approximately 2,150 ac (~870 ha) of the watershed, typically occupying the upper hill slopes (Figure 1-32). The chaparral habitat is characterized by a dense, closed canopy of evergreen shrubs and a paucity of herbaceous vegetation in the dark understory. Dominant species include coyotebrush (*Baccharis pilularis*), Eastwood manzanita (*Arctostaphylos glandulosa*), hoary manzanita (*A. canescens*), chamise (*Adenostoma fasciculatum*), buckbrush (*Ceanothus cuneatus*), wavyleaf ceanothus (*C. foliosus*), blue blossom (*C. thyrsiflours*), interior live oak (*Quercus wislizeni*), and yerba santa (*Eriodictyon californicum*). Other less common shrub species include bush poppy (*Dendromecon rigida*), and wavyleaf silktassel (*Garrya elliptica*). Species composition of the chaparral cover type is fairly consistent throughout the watershed, although there is considerable variation with regard to species relative dominance. Herbaceous species are largely restricted to gaps within the canopy and sunny openings created by service roads and trails. Among the more noticeable herbaceous to marginally woody species are wooly Indian paintbrush (*Castilleja foliosa*), milkwort (*Polygala californica*), tall star lily (*Zigadenus fremontii*), and bear grass *(Xerophyllum tenax*). Many rare, threatened, or endangered plant species (e.g., CNPS lists 1 and 2) occur within the chaparral habitats of the watershed, including Marin manzanita (*A. virgata*), Mt. Tamalpais thistle (*Cirsium hydrophilum* var. *vaseyi*), and Santa Rosa thin-lobed horkelia (*Horkelia tenuiloba*).

On serpentine substrates, which occur along the upper hillslopes of Mount Tamalpais (Figure 1-23), chaparral gives way to a mosaic of balds, barrens and vegetated islands dominated by prostrate shrubs and bunch grasses. This serpentine chaparral community is highly diverse in both structure and species composition. Dominant shrubs include Mt. Tamalpais manzanita (*A. hookeri* ssp. *montana*), Jepson's ceanothus (*Ceanothus jepsonii*), and leather oak (*Quercus durata*). Dominant bunch grasses include serpentine reed grass (*Calamagrostis ophitidis*), squirreltail grass (*Elymus elymoides*), and Sandberg blue grass (*Poa secunda*). Among the profusion of annual and perennial forbs that thrive on the margins of these shrubs and bunch grasses are serpentine onion (*Allium falcifolium*), Oakland star tulip (*Calochortus umbellatus*), serpentine spring beauty (*Claytonia exigua*), pink baby's breath (*C. gypsophiloides*), and serpentine morning glory (*Calystegia collina*). Many endemic, and numerous rare, threatened, or endangered plant species occur in these serpentine chaparral habitats, including the aforementioned Mt. Tamalpais Manzanita, as well as Tiburon buckwheat (*Eriogonum luteolum*

var. *caninum*), Marin County navarretia (*Navarretia rosulata*), Mt. Tamalpais jewelflower (*Streptanthus glandulosus* ssp. *pulchellus*) and Mt. Tamalpais thistle.

1.8.2.4 Grassland

The grassland cover type is comprised of the Native-Weedy Grassland and Introduced Perennial Grassland superalliances mapped by NPS. Perennial and annual grasslands cover approximately 650 ac (~260 ha) of the watershed and occur along ridgetops and slopes, primarily in the southern half of the watershed (Figure 1-32).

Today, less than 0.1 percent of California's native grasslands remain (Barry 1972). As in the rest of the state, many grasslands in Redwood Creek watershed have been almost completely converted to plant communities dominated by non-native annual grasses introduced from the Mediterranean region. However, approximately 130 ha (616 ac) of Native-Weedy Grassland persist in Redwood Creek watershed, and represent important remnants of these severely diminished native grasslands. In the Native-Weedy Grassland superalliance, native perennial bunchgrasses co-exist with a subtle, but rich diversity of native forbs (e.g., blue-eyed grass [*Sisyrinchium bellum*] and footsteps of spring [*Sanicula arctopoides*]). The successive blooms of native grassland flora in early spring create one of the spectacular natural events of the watershed.

The locations of these remnant native grasslands in the watershed have not been thoroughly inventoried or accurately mapped since their sizes are generally far below the minimum 5-ac mapping unit used for the NPS vegetation map (Moritsch et al. 1998), making it difficult for resource managers to prioritize protection measures, such as non-native invasive species removal and prescribed burns. MMWD is currently mapping grasslands within their purview, and will rank the quality of sites next year (2006) (Stillwater Sciences 2005b). Some locations of native grassland that have been informally noted in the watershed by resource managers include:

- a dense stand of the feathery red fescue (*Festuca rubra*), with a diverse mix of other native grassland species, stretching across the ridge near the intersection of the Coastal Trail and the Deer Park Fire Road;
- a forest opening along Panoramic Highway near the Bootjack Trail, which supports very large bunches of California fescue (*F. californica*);
- dense stands of California oatgrass (*Danthonia californica*) and purple needlegrass (*Nassella pulchra*) found on slopes near the Miwok trail and mixed stands of these species on Diaz Ridge;
- small pockets of native meadow barley (*Hordeum brachyantherum*) occurring at limited locations, such as on Diaz Ridge just west of Panoramic Highway;
- native junegrass (*Koeleria macrantha*) along with other native grasses occurring on slopes at the base of Coyote Ridge near the Green Gulch Farm trail to Muir Beach;
- a dense blend of red fescue, California brome (*Bromus carinatus*), and California oatgrass occurring east side of Panoramic Highway at Four Corners. French broom (*Genista monspessulana*) has been removed repeatedly at this site throughout the past decade to protect the native grassland;
- mixed stands of purple needlegrass common at the Three Sisters site, which extends to the Sun Trail above Muir Woods (Stillwater Sciences 2005b); and
- remnant patches of native grassland along the Coast View trail (Stillwater Sciences 2005b).

Some native species that would be expected to occur in the Redwood Creek watershed, such as tufted hairgrass (*Deschampsia caespitosa* spp. *holciformis*), have not been documented by any recent vegetation surveys.

Non-native annual grasses dominating most of the watershed's grasslands include wild oats (*Avena barbata*), soft chess (*Bromus hordeaceous*), ripgut brome (*Bromus diandrus*), ryegrass (*Lolium multiflorum*) and other common annual grasses. These grasses are so extensive as to be considered permanent members of the grassland community (Heady 1977). Several non-native invasive perennial grass species also occur, including Harding grass (*Phalaris aquatica*), tall fescue (*Festuca arundinacea*), and kikuyu grass (*Pennisetum clandestinum*). Panic veldt grass (*Erhata erecta*) has become more common in recent years and persists in the riparian corridor through Franks Valley. Invasive plant species are discussed in more detail in Section 1.8.6. Non-native invasive plants.

1.8.2.5 Riparian woodland

The riparian woodland cover type is comprised of the Arroyo/Red/Black/Yellow Willow and Red Alder superalliances mapped by NPS, but arroyo willow (*Salix lasiolepis*) by far the single most dominant willow species in this watershed. Riparian woodland covers approximately 110 ac (~45 ha) of the watershed and occurs along Redwood Creek and its tributary channels (Figure 1-32). Riparian vegetation along the mainstem creek and tributary drainages downstream of Muir Woods is dominated by native species, including red alder, which generally grows very close to bankfull elevations, and arroyo willow (*Salix lasiolepis*). Other tree species that occur more infrequently in the riparian corridor include buckeye (*Aesculus californica*), bay laurel, and coast live oak. The only cottonwoods (*Populus* sp.) known to occur in the watershed, were planted by residents along the Green Gulch tributary, and are not native to the watershed (W. Johnson, pers. comm., 1999, as cited in GGNRA 2003). Common shrubs occurring in the riparian corridor include red elderberry (*Sambucus racemosa*), dogwood (*Cornus sericea*), and twinberry (*Lonicera involucrata*). The native California blackberry (*Rubus ursinus*) is probably the single-most common native understory species. Other native understory species include thimbleberry (*Rubus parviflorus*), stinging nettle (*Urtica dioica*), wild cucumber (*Marah fabaceous*), gooseberry (*Ribes divaricatum* and *Ribes sanguineum*), sword fern, lady fern (*Athyrium filix-femina*), and false solomon's seal (*Smilacina racemosa*). Two locations of the relatively uncommon bleeding heart (*Dicentra formosa*), a summer deciduous plant, are known – one on the east bank of the Redwood Creek mainstem near Heather Horse Camp and one on the west bank of the Redwood Creek mainstem at the Banducci Site. Non-native species that occur in the watershed include cape ivy (*Delairea odorata*), English ivy (*Hedera helix*), and morning glory (*Calystegia silvatica* ssp. *disjuncta*). Non-native riparian species are discussed in more detail in Section 1.8.6. Non-native invasive plants.

The extent of riparian vegetation in Frank's Valley today is somewhat greater compared to the mid-1900s. Dairy ranchers and farmers living in the valley from the late 1800s through the mid-1900s typically cleared trees along the creeks and used adjacent floodplains for grazing and row crop agricultural (A. Banducci, pers. comm. with C. Shoulders, multiple conversations 15 May 1998–2000; and T. Brazil, pers. comm. with C. Shoulders, May 1999; both as cited in GGNRA 2003). Aerial photographs, taken in 1947, show significant portions of the creek without tree cover. Where trees did occur, the width of the riparian vegetation was often no more than that of a single tree. Fields and floodplains adjacent to the channel were either heavily grazed or farmed to the edge of the channel bank.

Although likely still limited in its lateral extent due to channel incision and consequent narrowing of the effective floodplain, the riparian corridor through Frank's Valley has widened significantly during the 30+ years since ranching ended there. Alders and willows form a generally contiguous canopy, and native understory species occur throughout the corridor. A large number of California bay laurel saplings, a very slow-growing species, are scattered throughout the alluvial valley, noticeably in locations where mature California bay laurels do not occur (C. Shoulders, pers. obs., 2002, as cited in GGNRA 2003). This suggests a successive wave of recovery following that of the fast-growing, pioneer alders and willows that quickly re-established when ranching ended. Since agriculture at the Banducci site ended much more recently in 1995, the riparian corridor there is generally characterized by a single line of alder trees at the creek's edge, with little shrubby understory. NPS implemented restoration actions in 2003 to expand the width of the riparian corridor by 80 ft (24 m) along 1,300 linear ft in this reach. After grading to reconnect a portion of the channel with its historic floodplain, this area is now extensively covered by alder seedlings and saplings, some planted and most naturally recruited.

Full recovery of native riparian vegetation appears to be limited in some areas where particularly aggressive non-native species have become established. A good example of this is at the confluence of the Kent Canyon tributary and Redwood Creek. Historic maps (U.S. Coast Survey 1853) show an extensive wooded area at this confluence. In photographs taken in 1947, this area appears to have been cleared and was probably grazed by cattle; tree cover is limited to the immediate channel banks. Today, the riparian corridor is somewhat wider at this site than it was in 1947, but the grazed area is dominated by the persistent perennial invasive grass, tall fescue and the noxious biennial poison hemlock (*Conium maculatum*), which produces large quantities of seed and establishes monocultures in wet areas. At this site, as with numerous other areas adjacent to the creek, the recovery of native species is probably not likely without active restoration efforts.

Riparian vegetation at Muir Beach has followed a transition opposite to that of Frank Valley. In this area the extent of woody riparian vegetation has expanded over the last 150 years. The riparian forest became established along the present course of lower Redwood Creek only during the last 30–40 years. The expansion of riparian vegetation extent at Muir Beach appears to be correlated with the man-made alterations to the creek channel and floodplain that began in the 1960s, which apparently changed the hydraulic and sediment deposition patterns, creating conditions appropriate for recruitment and establishment of riparian trees. Aerial photographs from 1946 and 1952 show the diverted creek course running through close-cropped agricultural lands, a setting consistent with observations of residents at the time. By 1965, photos show the double row of Monterey pines, reportedly planted along the road in the 1930s, adjoining riparian trees, and some riparian trees or shrubs extending upstream. By then, the dense willow forest adjacent to the present parking lot was established in the area previously occupied by roads and buildings. Restoration of lower Redwood Creek at Muir Beach will replace much of this riparian forest with emergent wetlands (X acres of riparian forest to emergent wetland) (Jones & Stokes 2007).

1.8.2.6 Coastal communities

The Coastal Community cover type includes the Pacific Reedgrass-Carex-Juncus, Pickleweed-Saltgrass, Beaches or Mudflats, and the Dune Lupine-Dune Sagewort-Dunegrass superalliances. The first two superalliances are emergent wetlands, and are described under Section 1.8.3 Emergent wetland below. Beaches and Mudflats are mostly unvegetated areas where sand is deposited by wind and/or water at Muir Beach. These areas can be colonized at very low cover

by several native annual plant species such as California salt bush (*Atriplex californica*), yellow sand verbena (*Abronia latifolia*), and coast strawberry (*Fragaria chiloensis*).

Areas along the steeper slopes of Muir Beach to the north and south of Redwood Creek mouth are mapped as the Dune Lupine-Dune Sagewort-Dunegrass superalliance. As mentioned above, these polygons support communities that include several of the superalliance native indicator species such as dune sagewort (*Artemsia pycnocephala*), beach morning glory (*Calystegia soldanella*), and beach evening primrose (*Camissonia cheiranthifolia*), beach burr (*Ambrosia chamissonis*), California bee plant (*Scrophularia califonica*), yellow sand verbena, and native dune grasses. However, these native dune grasses, such as American dunegrass (*Leymus mollis* ssp. *mollis*) and Pacific wildrye (*Leymus pacificus*), cover less area than European annual grasses such as ripgut brome (*Bromus diandrus*) and European beachgrass (*Ammophila arenaria*). Although large amounts of iceplant (*Carpobrotus edulis*) were removed from the south beach in the 1990s (C. Shoulders, memo, 5 March 2003), these dunes are still riddled with non-native forbs such as European sea rocket (*Cackile maritime*) and iceplant.

1.8.3 Wetlands and seeps found in lower Redwood Creek watershed

Wetlands have been mapped several times in lower Redwood Creek, including the reach from the Banducci restoration site downstream, as well as the lower Green Gulch tributary area (Figure 1-33). Caltrans initially delineated CWA Section 404 jurisdictional wetlands in lower Redwood Creek watershed in 1993 (PWA et al. 1994). In 2002 and again in 2003, the NPS updated this wetland mapping and classification following Cowardin et al. 1979 (Schirokauer 2003). Most recently in July 2006, Section 404 wetland delineations were checked for development of an EIR in support of the Lower Redwood Creek Restoration at Muir Beach (Jones and Stokes 2007). Sixty-two ac of wetlands were mapped in lower Redwood Creek based on a methodology adapted from Cowardin and the U.S. Army Corps of Engineers Delineation Manual that uses vegetation, soils, and hydrology as indicators of wetland conditions (Castellini et al. 2006; USACE 1987). Plant species were considered indicative of wetland conditions if they were classified as Obligate Wetland Species (OBL) or Facultative Wet Wetland (FACW) (Reed 1996), but not if they were classified as Facultative Wetland (FAC), unlike the USACE (1987) criteria. Team members from the GGNRA and Point Reyes National Seashore (PORE) made this decision based on the observation that in the coastal fog belt, the distribution of many FAC plant species includes uplands as well as wet areas and so these species are not indicative of wetland conditions (Castellini et al. 2006). The 2006 mapping confirmed the previous wetland mapping efforts and is presented in Figure 1-33. Although these mapped wetlands overlap with the NPS superalliance vegetation types described in Table 1-20, there is little specific agreement in the wetland types between the two efforts (Figures 1-32 and 1-33, respectively). Since the 2006 wetland mapping was a more focused and high resolution effort, and is based on multiple field efforts as well as aerial photo-interpretation, it most likely offers a more precise representation of wetland types and boundaries within the lower Redwood Creek area as of spring 2009 than does the NPS superalliance map.

It should be noted that resource management activities being implemented as part of the Lower Redwood Creek Restoration at Muir Beach will alter the spatial extent and classification of wetlands in project area. .

1.8.3.1 Emergent wetland

Prior to restoration at lower Redwood Creek, a brackish marsh west of the Muir Beach parking lot was dominated by salt rush (*Juncus leseurii*), salt grass (*Distichlis spicata*), and silverweed

(*Potentilla anserine*). Native salt marsh species formerly observed in these areas in 1992–3 also included jaumea (*Jaumea carnosa*), alkali heath (*Frankenia salina*), and grindelia (*Grindelia stricta*). These areas fall under the two coastal emergent wetland superalliances Pacific Reedgrass-Carex-Juncus and Pickleweed-Saltgrass

Pre-project freshwater emergent wetlands were dominated by cattails (*Typha latifolia*), with spikerush (*Eleocharis macrostachya*), water plantain (*Alisma plantago-aquatica*), silverweed (*Potentilla anserine*) and water parsley (*Oenanthe sarmentosa*), bulrush (*Scirpus* spp.), tall cyperus (*Cyperus eragrostis*), dotted smartweed (*Polygonum punctatum*), and baltic rush (*Juncus balticus*). Many non-native weeds were also common, especially along the levee roads and trails; the most common of these were ox-tongue (*Picris echioides*) and knotgrass (*Paspalum* spp.).

The Lower Redwood Creek Restoration project includes creation of a backbarrier lagoon and seasonally brackish to freshwater marsh near the creek mouth (Jones and Stokes 2007). Revegetation goals include establishing species tolerant of variable fresh to saline conditions and capable of rapid re-establishment after scouring and accretion events. Species selected for this include rushes (*Juncus lesuerii* and *J. phaeocephalus*), bulrush (*Scirpus pungens*), saltgrass, sedges (*Carex obmupta*, *C. praegracilis*) and forbs (*Aster chilensis, Cicuta douglasii* and *Rumex occidentalis*) (Friedel 2009).

Climate projections for northern coastal California indicate that mean sea level rise could inundate large portions of the planned wetland complex at Muir Beach. Landward migration of the shoreline and the brackish freshwater marsh along lower Redwood Creek could occur, along with increasingly frequent and intense winter storm flows from upstream (Baye 2008). Plant species that are adapted to frequent disturbance, such as willow, alder, and bulrush, have high resilience because they reproduce readily on newly deposited substrate and will likely survive such climatic stresses(Baye 2008). Rhizomaceous species and other species with dense rooting structures will also provide additional bank stability as resistance to effects of increased storm intensity and frequency. Redundancy in multiple willow and herbaceous species in the riparian zone provides strength against potential species vulnerabilities.

Freshwater wet meadows are being replanted along the alluvial fan of Green Gulch and the un-named tributary to its southwest as part of the Lower Redwood Creek Restoration at Muir Beach during the fall and spring of 2009 and 2010 (Jones and Stokes 2007, Friedel 2009). The intent of these replantings is to establish diversity of freshwater wetland communities for upper, mid and lower elevations that can withstand yearly variations in groundwater levels fed by Green Gulch creek and the un-named tributary. Species planned for planting include sedges (*Carex praegracilis*, *C. barbarae*), rushes (*Juncus balticus* and *Eleocharis macrostachya*), and native grasses and forbs (*Leymus triticoides, Hordeum brachyantherum, Equisetum arvense*, and *Artimisia douglasiana*). Several areas are designed to be permanently saturated or inundated, such as the 'frog pond'. With the intent of precluding establishment of cattail monocultures while allowing for establishment of a diverse native plant community, these areas will be planted with bulrushes and other hydrophytes (e.g., *Scirpus spp.*, *Sparganium eurycarpum* and *Juncus effusus*).

1.8.3.2 Scrub-shrub wetland

Scrub-shrub wetlands are dominated by arroyo and shining willow (*S. lucida*), with an understory of thimbleberry, blackberry (*Rubus ursinus* and *R. discolor*), and red elderberry with patches of herbaceous species such as stinging nettle, non-native water parsley (*Oenanthe sarmentosa*) and hedgenettle (*Stachys ajugoides*). Non-native species include cape ivy and English ivy. Prior to implementation of the Lower Redwood Creek Restoration, scrub-shrub wetlands were located

west of parking lot (permanently flooded and saturated); north east of parking lot (saturated); and between the Pacific Way and Highway 1 bridges (seasonally flooded). Revegetation plans combine shrub and forested riparian community types into a single 'riparian' plant palette (Friedel 2009). This is discussed under 'Forested Wetlands' below.

1.8.3.3 Forested wetland

This type is the same as described above in Section 1.8.2.5. Riparian Woodland and is dominated by red alder, several willow species, blackberry and elderberry shrubs. Riparian woodlands occur along the transport and depositional reaches of Redwood Creek and its tributaries. Prior to implementation of the Lower Redwood Creek Restoration, red alder and willow riparian communities occupied the banks and floodplains adjacent to lower Redwood Creek between the Pacific Way and Highway 1 bridges.

Implementation of the Lower Redwood Creek Restoration project involves moving sections of the lower Redwood Creek channel to the lowest point on the floodplain and replanting adjacent banks and several floodplain areas with native species (Jones and Stokes 2007, Friedel 2009). The proposed planting palette includes red alder, willow, California wax myrtle (*Myrica californica*), dogwood (*Cornus sericea*), twinberry honeysuckle, red elderberry, rhododendron (*Rhododendron occidentale*), grasses and forbs (e.g., *Leymus triticoides*, *Artemsia douglasiana*, *Carex obnupta*, *Scirpus macrocarpus*, *Equisetum arvense*, *E. hyemale*, and *Lilium pardalinum*) (Friedel 2009).

1.8.3.4 Streambed and unconsolidated bottom wetland

Subtidal unconsolidated stream bottom occurs at the mouth of Redwood Creek as it drains into the ocean at Muir Beach. Areas classified as streambed include lower Redwood Creek, Green Gulch and unnamed tributary channels, which are intermittently exposed during the dry season. Sparse cover of ruderal species occurs in these areas late in the season, but these plants are regularly scoured out during high flow events. No revegetation plans exist for these areas.

1.8.3.5 Seeps and springs

The NPS hired Mike Faden, a private contractor, to survey seeps and springs in 2003 along the northwestern portions of upper Redwood Creek as well as along Dias Ridge, Canyon del Camino, Kent Canyon, and parts of Muir Woods. During 2005, Faden extended this survey to include Stinson Beach and the bluffs above; Green Gulch and Muir Beach. Over both surveys, 48 springs and seeps were documented within Redwood Creek watershed (Faden 2003a and Faden 2005). Areas were designated as springs only when standing or flowing water was present, or when a film of surface water was observed (Faden 2005). Besides location, field data recorded as part of these surveys include water temperature, conductivity, dominant plant species, and surface substrate. Large springs (e.g., over 1 gpm) were documented near – and are used by - the Green Gulch Center. Characteristic seep vegetation within grasslands and chaparral include lady fern (*Athyrium felix-femina*), Pacific reedgrass (*Calamagrostis nutkaensis*), slough sedge (*Carex obnupta*), giant horsetail (*Equisetum telmateia* ssp. *braunii*) and California wax-myrtle; within forested areas, lady fern and giant chain fern (*Woodwardia fimbriata*) were consistent indicators and redwoods and arroyo willow were common to springs, but also often found in areas without springs (Faden 2003a, 2005).

1.8.4 Vegetation changes and the role of fire

1.8.4.1 Fire history

Fire played an important role in shaping vegetation communities in coastal California. Although lightening induced fires were historically unusual in northern coastal California due to infrequent lightening strikes during the dry season (approximately one strike every five years; Sunget and Martin 1984), the Coastal Miwok managed the land using (among other things) frequent, low intensity fires for over 8,000 years prior to Euro-American occupation (Levy 1978). Coastal Miwok used fire to drive game, facilitate the collection of acorns and seeds, kill insects and small mammals for food, promote growth of seed-bearing annuals, increase the extent of grazing areas, and maintain open areas for temporary shelter and travel. Early Euro-American settlers continued to use fire through the 1900s to increase grazing lands for livestock. As more people settled in southern Marin, fire suppression became the prevailing practice. Fires were often ignited, but they were generally suppressed and confined to small areas. As a result, fire frequency in the watershed has been greatly reduced. McBride and Jacobs (1978) evaluated fire history at Muir Woods and concluded that, prior to the earliest recorded fire in 1850, the Muir Woods area probably burned on the order of once every 22 to 27 years. Fire suppression can affect redwood regeneration, forest succession, and ultimately forest structure and composition. It can also lead to increased fuel loads that can cause more intense burns when fires occur. The recorded fire history of the Redwood Creek watershed is shown in Table 1-21. Changes in fire frequency and intensity have affected fuel loads, plant community structure and composition in the watershed, particularly in the grasslands, chaparral, and Redwood–Douglas-fir forests.

Table 1-21. Recorded fire history of Mt. Tamalpais.

Year	Location	Comment
1859	Mt. Tamalpais	Burned for three months
1881	Mill Valley through NE portion of Redwood Creek watershed	65,000-ac (26,000-ha) wildland fire. Accidentally spread from a brush pile fire in Mill Valley.
1891	From Ross over to the extreme northern portions of the watershed.	12,000 ac (4,800 ha) of Mt. Tamalpais burned. Fire started near Ross.
1913	Mt. Tamalpais Summit, Blithedale and Cascade canyons, most of Fern Canyon.	2,600 ac (1,100 ha) burned, started near West Point Inn, probably ignited by railroad sparks
1919	From Pipeline Reservoir to Muir Woods	Undocumented extent
1929	Mill Valley to Fern and Cascade canyons	"Great Tamalpais Fire" burned 2,500 ac (1,000 ha)
1931	Muir Woods	Illegal campfire charred redwoods in Cathedral Grove
1932	Panoramic Highway to Muir Woods	60 ac (24 ha) burned, including 2 (0.8 ha) ac within the Muir Woods boundaries
1959	Kent Canyon	50 ac (20 ha) burned near logging operations on Brazil Ranch.
1965	¼-mile (0.4 km) from Muir Woods southeast boundary	150 ac (61 ha) burned

Source: MMWD 1995

1.8.4.2 Grassland to Shrubland conversion and fire suppression

Increased urbanization, fire suppression, and decreased grazing in the watershed have all contributed to the gradual conversion of grasslands to shrublands. Leonard Charles and

Associates compiled historical photographs taken in the watershed and took current photographs from those same locations. Qualitative observations of these photographs, which are presented in MMWD (1995), reveal a sharp reduction in grassland area and an increase in shrubland area since the 1920s. Bicknell et al. (1993) provide the best information available to date on historical grass and shrubland composition in the watershed and changes from historical to current conditions. The Bicknell study area included State Park lands in the lower portion of the watershed (i.e., downstream of Muir Woods National Monument) and to the north. The study relied on a combination of (1) review of historical accounts, (2) interpretation of aerial photography, and (3) analysis of phytolyths to document pre-historic and current vegetation conditions at the study sites. For this study, prehistoric vegetation was defined as "that which existed prior to occupation of the Mt. Tamalpais State Park area by Euro-American settlers" (Bicknell et al. 1993). Current and pre-historic vegetation composition for Bicknell et al. "Site A", approximately half of which is within the Redwood Creek watershed, is shown in Figure 1-34. This analysis indicates that grassland area has been reduced by approximately 64 percent since European settlement due to conversion of grasslands to shrubland and shrubland/grassland mosaic. Although many ranchers practiced burning to maintain grasslands for forage (Bicknell et al. 1993) following displacement of native populations, subsequent cessation of deliberate burning has likely allowed for shrubland conversion (Bicknell et al. 1993, Evett 2000).

1.8.4.3 Fuel and fire hazard management

A fire hazard map for all of Marin County, developed by the county fire department and based on fuel, slope and aspect, shows that most of the upper portions of Redwood Creek watershed have high to very high fire hazard (Marin County Fire Department 2005). Fire management issues throughout the watershed include fuel loading (especially as a result of SOD in Muir Woods), control of invasive species, visitor safety, and access/egress routes for adjacent residential communities. Fuel and fire management in the Redwood Creek watershed is implemented separately by the three major public agencies (e.g., MMWD, GGNRA, and State Parks through the county); each agency has their own guiding fire/vegetation management plan. Marin County identified priority action areas based on the primary goal of reducing fire risk along the wildland-urban interface (Leonard Charles & Associates and Wildland Resources Management 2008). The GGNRA Fire Management Plan (FMP) identifies ten goals in its Fire Management Plan (GGNRA FEIS 2005) which include public safety as well as protection private property and structures, and protection of natural resources. Similarly, the MMWD Fire Hazard Management Plan includes 'maintaining existing significant biological resources' along side 'minimizing risk to life and property from wildfire' as primary goals (Leonard Charles & Associates and Wildland Resources Management 2008). For the Muir Woods Fire Management Unit, GGNRA also identifies preservation of the 'pristine character' of Muir Woods as a priority. Three objectives would be pursued by GGNRA in order to attain this goal: 1) restore the role of fire in the relevant vegetation communities; 2) reduce fuel loading and the threat of catastrophic wildfire; and 3) further study fire effects in old-growth coast redwood forest. These objectives are being pursued through a mix of prescribed fire and mechanical fuel reduction. Prescribed fire is planned to restore the fire regime in the redwood/Douglas-fir forest and for control of non-natives in the Conlin Avenue area near the maintenance yard (GGNRA 2005).

Institutional differences in emphasis result in slight variations on the types of activities implemented under the three jurisdictions in the watershed. Marin County resources are focused on fuel reduction, creation and maintenance of fuel breaks, and outreach to residents about creating and maintaining defensible space and evacuation plans. While MMWD and GGNRA emphasize human safety and evacuation routes, they also integrate prescribed burns with

mechanical fuel management as a means of reducing wildfire risk and restoring some of the natural disturbance processes to the forest, grasslands and shrublands. GGNRA goals also include using fire management to sustain and restore natural resources and improving understanding of fire through research and monitoring (NPS 2005). The range of activities include creation and maintenance of fire/fuel breaks and brush removal, prescribed burns in targeted areas, fire suppression, and ensuring safe access and evacuation in case of wildfire (Stillwater Sciences 2005b; Leonard Charles & Associates and Wildland Resource Management 2008).

Fuel Breaks

MMWD maintains a 30-ft (9-m) fire break on its property along Panoramic and East Ridgecrest Boulevard (Leonard Charles & Associates and Wildland Resources Management 2008). Marin County picks up responsibility for maintaining a fuel break along Panoramic Highway down to the intersection with Highway 1 (Leonard Charles & Associates and Wildland Resources Management 2008). Similarly, GGNRA maintains fire roads to allow for safe access by emergency vehicles in Muir Woods. MMWD has found that when French or Scotch broom (*Genista monspessulas* and *Cytisus scoparius*, respectively) invade areas opened as fuel breaks, maintenance requires annual rather than every 3 to 5 year weed control, which substantially increases the cost of maintaining the fuel breaks (Leonard Charles & Associates and Wildland Resources Management 2008).

Fuel Reduction Projects and Prescribed Burns

Marin County identified priority action areas for reducing fire risk along the wildland-urban interface, including clearing fire-prone trees at two locations along Panoramic Highway along the northwestern border of the watershed (Marin County Fire Department 2005). MMWD and GGNRA also have identified critical areas in need of fuel reduction to reduce wildfire hazard. Prescribed burns have been used in the watershed, both for fuel load reduction and management of non-native invasive plant species.

Since the 1993 GGNRA Fire Management Plan, several prescribed fires have been executed in Muir Woods, including three burns in redwood/Douglas-fir forests (9-ac upper Dear Park; 52.5-ac Dear Park 2 burn; and the 35-ac Johnson prescribed fire), and two burns to control non-native broom species at the lower end of Camino Del Canyon. All of these burns were conducted between 1993 and 2001. In the 1990s, Mount Tamalpais state park and Marin county executed a number of burns to control non-native plant species and coyote brush invasion in grasslands along Panoramic Highway, north of Three Sisters, and along Muir Woods road (above the Sun Trial) (D. Boyd, State Parks, pers. comm., 2005).

Although these prescribed burns were successful and provided vital information on controlling invasive species such as French and Scotch broom, few burns have been possible since 2000. During this time, the use of prescribed burning in Redwood Creek watershed has become increasingly constrained by high associated costs in relation to available funding, complexity of logistical issues such as appropriate weather conditions, constraints related to smoke management, and coordination among various agencies (Stillwater Sciences 2005b). In spite of these logistical challenges, the 2005 GGNRA FMP, as well as the Marin County and MMWD FMP's all call for continuation/renewal of strategies involving prescribed burns in the future.

Fire Suppression

Fire suppression is still an important component of fire management practices in the area (Stillwater Sciences 2005b). According to the GGNRA FMP FEIS (2005), the current policy for all considered alternatives is to suppress all unplanned ignitions aggressively and with human

safety as a top priority. GGNRA and the Marin County Fire Department have a cooperative agreement to work together to control wildfires (Marin County Fire Department 2005).

1.8.5 Special-status plant species

The NPS GGNRA natural resources staff provided Stillwater Sciences with a list of special-status plants that have been observed or could potentially occur in the Redwood Creek watershed (NPS 2005, unpublished data). Additionally, a list of potentially occurring special-status plant species was generated using the California Natural Diversity Database (CNDDB; CDFG 2009), and California Native Plant Society (CNPS) Inventory of Rare and Endangered Plants (CNPS 2009) based on records for the two U.S. Geological Survey 7.5-minute topographic map quadrangles covering the Redwood Creek watershed (Point Bonita [467D] and San Rafael [467A] quadrangles]. The list of potentially occurring special-status plant species include those species that have been documented to occur, either historically or recently, and have the following status designations: state or federally threatened, endangered, candidate, proposed threatened, or proposed endangered; species listed as rare by the state; and species listed as CNPS 1A, 1B, 2 and 4. The 2005 NPS special-status plant list and the 2009 database generated list were reviewed and combined into one table. The compiled list includes habitat associations, specific locations within the watershed, and potential threats and is provided in Table E-1, Appendix E.

Many of the special-status plant species that occur in the watershed are serpentine-endemic species or found in coastal habitats (i.e., coastal bluff, dunes, scrub, marshes and swamps) (Table E-1, Appendix E), although a few special-status species occur in valley and foothill grassland, broadleafed upland forest, and coniferous forest.

1.8.5.1 Special-status plant surveys

Special-status plant surveys and monitoring have been conducted within sections of the Redwood Creek watershed by the following groups:

- NPS, 1998–2004
- M. Faden (2002, 2003b) and J. Taylor (2003) for the NPS, *and*
- MMWD

The 2009 database queries contain all reported special-status plant occurrences within the watershed's boundaries (Table E-1, Appendix E).

Results from the 1998–2004 special-status plant surveys conducted by NPS within the GGNRA are compiled in the *GGNRA Special-Status Vascular Plant Inventory and Monitoring Efforts Report* (Speith and Taylor 2009). During these surveys six special-status plants (California bottlebrush grass [*Elymus californicus],* Oakland star tulip, hooker's Manzanita [*Arctostaphylos hookeri* ssp. *montana],* serpentine reed grass, Tiburon buckwheat, and Mt. Tamalpais jewelflower) were identified in the Redwood Creek watershed within the Muir Woods National Monument, Four Corners, and the Mill Valley Air Force Station, located along the west peak of Mt. Tamalpais and the very upper reaches of the Redwood Creek watershed.

California bottlebrush grass is widely distributed throughout Muir Woods (NPS 2009). Monitoring recommendations include a survey every three years to ensure threats of invasive species do not impair the population. Patches of Oakland star tulip were located at Four Corners on non-serpentine soils, atypical for this species since all other populations located within Golden Gate National Parks inhabit serpentine soils (Speith and Taylor 2009). Surveyors noted the

population may be under threat by French broom invasion and monitoring is recommended every three years. Six special-status plants are located within the Mill Valley Air Force Station, many with multiple populations (Hooker's manzanita, Tiburon buckwheat, Mt. Tamalpais jewelflower, Oakland star tulip). No special-status plant species located at this site are considered under immediate threat and monitoring intervals of 2 or 3 years is recommended. The results and survey recommendations for all special-status plant populations can be found in Table E-2, Appendix E.

Additional surveys were conducted within the Redwood Creek watershed for the NPS by Michael Faden (2002, 2003b) and Jeanne Taylor (2003). Faden's 2002 surveys targeted the following special-status plants: tower mustard (*Arabis glabra*), San Francisco wallflower (*Erysimum franciscanum*), California bottlebrush grass, and Lobb's aquatic buttercup (*Ranunculus lobii*) within Green Gulch, Diaz Ridge, Big Lagoon, and the Banducci Site with no findings. Taylor's 2003 special-status plant surveys were conducted at Big Lagoon (Muir Beach) only for the following special-status plants: pink sand verbena (*Abronia umbellata* ssp. *Breviflora*), swamp bellflower (*Campanula californica*), San Francisco spineflower (*Chorizanth cuspidata* var. *cuspidate*), Pt. Reyes bird's-beak (*Cordylanthus maritimus* ssp. *Palustris*), Marin knotweed (*Polygonum marinese*), and Lobb's aquatic buttercup. No special-status plants were located during these surveys. Three special-status plant occurrences of rose rock cress (*Arabis blepharophylla*), Oakland star tulip, and San Francisco wallflower were documented in Faden's 2003 surveys of Green Gulch, Four Corners, Mill Valley Air Force Station, Coyote Ridge, Big Lagoon and Muir Beach and are listed in Table E-3, Appendix E (Faden 2003b).

The MMWD surveyed for special-status plants along a number of trail and road sections within the Mt. Tamalpais watershed area for their finalized *Comprehensive Roads and Trails Management Plan* (Leonard Charles and Associates 2005). As part of baseline studies for the plan, MMWD conducted special-status plant surveys in May of 2004 along trails within the Redwood Creek watershed. Results from the surveys are provided in Table E-4, Appendix E and include the following species: Mt. Tamalpais manzanita, Mt. Tamalpais jewelflower, Carlotta Hall's lace fern (*Aspidotis carlotta-halliae*), Shreve oak (*Quercus parvula* var. *tamalpaiensis*), Mt. Tamalpais thistle, serpentine reed grass, Marin County navarretia, and Oakland star tulip. MMWD manages lands supporting every population of Mt. Tamalpais thistle in the watershed (this taxon is endemic to Mt. Tamalpais). John Herr, of the U.S. Department of Agriculture, has monitored this plant in the watershed for 10 years as part of a larger study on the effects of introduced biocontrol agents (introduced to control non-native thistles) on native thistles (Stillwater Sciences 2005b). The two populations occur in the Redwood Creek watershed and are in decline (Stillwater Sciences 2005b).

The *Biodiversity Management Plan for Marin Municipal Water District Lands* (Garcia and Associates 2009), a supplement to the *2009 Vegetation Management Plan Update*, includes special-status plant occurrence maps and data within the MMWD lands, including areas within the Redwood Creek watershed. The special-status plant occurrences located within MMWD lands are based on a 1990 inventory by Charles Patterson and personal observations by Doreen Smith, the Rare Plant Coordinator of the Marin Chapter of CNPS (Garcia and Associates 2009), and can be downloaded from the MMWD website. Goals and objectives to maintain, enhance, and restore special-status plants and habitats for future management for MMWD lands is presented in the *2009 Vegetation Management Plan Update* (Leonard Charles and Associates 2009a)

1.8.6 Non-native invasive plants

Non-native invasive plants pose a significant threat to the quality of the native plant communities in the Redwood Creek watershed. Invasive species displace native vegetation, alter the structure and function of plant communities, and dominate species composition, thereby reducing biodiversity.

1.8.6.1 Invasive plant survey and mapping efforts

The distribution and spread of non-native invasive plant species are being surveyed and mapped in various locations throughout the watershed. However, no consistent or coordinated on-going efforts occur on a watershed wide basis. The NPS identified and mapped locations of invasive plant species throughout the entire watershed in 1999 (GGNRA, unpublished data). This survey identified a total of 39 invasive species occupying 921 ac (373 ha) in the watershed, or 16 percent of its total area (Figures I-35 through I-37). A list of invasive plant species documented in these surveys is provided in Table E-5, Appendix E. Of the area dominated by invasive species, 16 percent is in riparian habitat, 24 percent is in grassland, and 27 percent is in scrub/grassland (Table E-6, Appendix E). Invasive species occurred primarily along roads and trails, which provide disturbed, exposed soil where these species can easily become established. Roads and trails also function as conduits for the spread of invasive species, particularly those with wind-dispersed propagules. Reconnaissance surveys have since occurred within portions of the watershed providing an updated status of the documented invasive plant species as well as of new populations. Two resources providing current material on non-native invasive plant populations in the Redwood Creek watershed include the *Long Term Invasive Species Management Plan for Muir Woods* (Baxter et al. 2009) and Weed Watchers, the NPS volunteer-based invasive plant early detection program, (*website:* *http://science.nature.nps.gov/im/units/sfan/vital_signs/Invasives/weed_watchers.cfm*).

Recent results for non-native invasive plant surveys conducted by NPS within Muir Woods (560 ac) and bordering area within the Redwood Creek watershed (124 ac) are documented within the *Long Term Invasive Species Management Plan for Muir Woods* (Baxter et al. 2009). Surveyed areas were divided into five management areas with priority ranking for each. Management area descriptions, priority ranking decisions, and the approximate area of invasive mapped plants for each are provided in Table 1-22. During these surveys mapped locations of the following six non-native invasive plants were updated: licorice plant (*Helichyrisum petiole*), Himalayan blackberry (*Rubus discolor*), Cotoneaster (*Cotoneaster* sp.), English ivy, forget-me-nots (*Myosotis latifolia*) and French broom (Baxter et al. 2009). English ivy and panic veldt grass were recently located within Muir Woods National Monument and extensively mapped within the management areas due to their rapid spread since the 1999 surveys (Baxter et al. 2009). The *Long Term Invasive Species Management Plan for Muir Woods* provides detailed invasive plant findings per management area and discusses methods for future control and eradication per site location based on GGNRA's Best Management Practices as shown in Table E-7 in Appendix E.

Table 1-22. Management areas surveyed in 2009 for non-native, invasive weed assessment for Muir Woods and bordering areas within the Redwood Creek watershed (Baxter et al. 2009).

Priority ranking	Management area	Management area location	Total area	Approximate area with invasive weeds
1	Redwood Forest and Riparian	Main Forest paved paths, Fern Creek, Hillside, Bootjack, and Ben Johnson trails. Ranked highest priority for maintaining the integrity of the core riparian and old growth redwood habitat, endangered species habitat and importance as a major National Park visitor viewshed.	382 ac	≤6.81 ac
2	Entrance Area	Main and Annex parking lots, Education Lab/ Old Inn, Dipsea trail, Old Service Road, Redwood Creek Nursery, and the Concrete bridge. Ranked second for its role as a central hub of species introduction (past and present) and significance for visitor viewshed among facilities.	49 ac	≤22.03 ac
3	Upper Deer Park Fire Road-	Upper Deer Park Fire Road, Dipsea, and Ben Johnson trails. Ranked second for protection of intact redwood plant community in the uppermost section of the watershed from invasion along exposed ridgeline	138 ac	1.25–12.25 ac
4	Camp Eastwood/Oceanview trail	Camp Alice Eastwood, Fern Creek, and Oceanview trails. Ranked fifth as a management priority due the ecological significance of the endemic Marin manzanita and historic management by NPS on State Park property up gradient of the main forest.	78 ac	6.5–13.58 ac
5	Camino del Canyon	Druid Height steps, Conlon Rd and Camino del Canyon Road. This section, with its historic residential land use impacts, is identified for habitat enhancement and control of spread of established invasives in the mixed coniferous forest.	68 ac	≤40 ac

NPS also provides updated mapped locations of non-native invasive weeds within the GGNRA priority subwatersheds (including Redwood Creek watershed [GGNRA 12-1–12-9]), as a part of the volunteer-based invasive plant early detection program, Weed Watchers. Updated mapped locations of non-native invasive plants within the Redwood Creek watershed can be viewed on the Weed Watchers website.

The collective efforts of volunteers and NPS staff involved in the Golden Gate Weed Watchers program continue to annually (2007–2009) detect, map, control and eradicate invasive weeds throughout San Francisco Bay Area Network, which includes many of the Redwood Creek

watershed trails and roads. Through the Golden Gate Weed Watchers program many invasive species in the watershed are now mapped and managed using the methods from *Early Detection of Invasive Plant Species in the San Francisco Bay Area Network a Volunteer-Based Approach* (Williams and Speith 2008). Annual reports and maps documenting the end of the year results are provided on the NPS Weed Watchers website.

The MMWD is also currently mapping non-native invasive plant species within its purview and actively managing invasive plants throughout their watershed lands (Stillwater Sciences 2005b). Invasive plants on MMWD lands are typically found along pipelines, power lines, tanks, roads, and trails. Invasive species of concern on MMWD lands include French broom, Scotch broom, Monterey pine, Monterey cypress (*Cupressus macrocarpa*), jubata grass, yellow star thistle (*Centaurea solstitialis*), and purple star thistle (*Centaurea calcitrapa*). Broom species infest approximately 1,000 ac (400 ha) of MMWD lands (Redwood Creek sites are "outliers" to the main infestations (Figures I-35 through I-37).

1.8.6.2 Invasive non-native plant control efforts

MMWD, NPS and the State Parks are all engaged in on-going efforts to control non-native invasive plants on their lands. Invasive species that have been the target of recent NPS GGNRA control efforts include: cape ivy (*Delaria odorata*), French broom, Scotch broom, pampass grass (*Cortaderia jubata*), eucalyptus (*Eucalyptus globulus*) (although the species is not considered to be a major issue in the watershed), Monterey pine (*Pinus radiata*), and forget-me-not. The distribution of these species in 1999 is shown in Figure 1-35. The NPS identified cape ivy as a control priority in 1998 after witnessing its extremely rapid proliferation in native riparian vegetation communities. Alvarez (1999) conducted a field study to determine the effects of cape ivy invasion on plant communities within the GGNRA. Within the Redwood Creek vicinity, plots where cape ivy was dominant (> 70 percent cover) had lower plant species diversity, altered species composition in favor of non-native species, and reduced abundance and diversity of seedlings (Alvarez 1999). In plots where cape-ivy was removed, there was a significant increase in plant species richness, predominantly due to increases in seedling recruitment of grasses and forbs (Alvarez 1999). Cape ivy invasion was also been found to alter the riparian terrestrial invertebrate community within Redwood Creek (Fisher et al. 1997). Plots invaded by cape-ivy had significantly decreased abundance of flies (*Diptera*) and beetles (*Coleoptera*) and increased abundance of springtails (*Collembola*) than plots that were devoid of the ivy (Fisher et al. 1997).

In 1999, cape ivy occupied up to 40 ac (16 ha) along Redwood Creek from Muir Beach almost to Muir Woods; whereas during the late 1980s it was recorded at infrequent locations with such a low rate of cover that it was not considered an imminent threat. Since 1998, approximately 5 ac (2 ha) of cape ivy have been removed from the Redwood Creek riparian corridor by NPS at the Banducci site, reducing its cover in that area from approximately 40 percent to less than 1 percent in the first year after removal, with a quantified increase in cover by native species four years after removal. The labor-intensive removal cost an average of about $15,000 per ac ($37,000 per ha). An estimated total of 9.7 ac of cape ivy is planned for removal in the Redwood Creek riparian corridor in 2009. NPS plans the removal of 4.6 ac of cape ivy upstream of Pacific Way and 1.3 ac downstream, with a subsequent removal of 1.3 ac of cape ivy downstream in later phases. In Muir Woods, the steady work of hundreds of volunteers over two decades has nearly eliminated forget-me-nots from the monument.

MMWD completed a broom eradication project at Throckmorton Fire Station in 2004 and considers the project to be a major success, though it notes that broom management is very labor intensive. The Throckmorton project involved brush removal in conjunction with the licensed

application of herbicide, which is applied to recently cut stems between June and October ("whack-and-spray" method). Brush removed during cutting is stacked for subsequent pile burning during winter. Maintenance is required at least 1–2 times annually, and MMWD crews have observed a 98-99 percent broom mortality rate. MMWD has tested various control methods for broom species in the last ten years with varied success. Treatments include handpulling, annual mowing, annual mowing with follow-up herbicide application, periodic prescribed burn with annual mowing, and periodic prescribed burn with annual mowing and follow-up herbicide application. A summary of broom control techniques is provided in *Chemical Weed Control Techniques for MMWD* (Leonard Charles and Associates et al. 2008). As part of the *2009 Vegetation Management Plan Update,* MMWD is reviewing all potential methods and techniques for future application.

State Parks began broom eradication on about 100 ac (40 ha) at the Three Sisters site below Panoramic Way, near the Muir Woods Park neighborhood, in 1994. The site extends to the Sun trail above Muir Woods. The use of controlled burning (completed annually for a three-year period) was successful at this location because it was a large site with good road access, allowing the fire to burn hot enough to kill the broom (Stillwater Sciences 2005b). Maintenance, however, will be required in perpetuity to prevent re-infestation, which was noted to be significant at the site in 2005 (Stillwater Sciences 2005b). Another successful invasive species control project in the watershed was conducted by Mt. Tamalpais State Park west of Panoramic Highway near Muir Woods Road. This project eliminated a 10-ac (4-ha) stand of French and Scotch broom through a series of prescribed burns conducted since 1994, with follow-up spot application of herbicides. These operations cost approximately $95,000. State Parks has also implemented an eradication plan for pampass grass on their lands (Stillwater Sciences 2005b), including infested areas along Highway 1 near Green Gulch.

Invasive species that occupy significant area in the watershed but have not generally been the target of extensive control efforts (except in the Muir Woods National Monument and bordering areas and those sections mapped by the Weed Watchers program) include cotoneaster, velvet grass (*Holcus lanatus*), tall fescue (*Festuca arundinaceae*), harding grass, kikuyu grass (*Pennisetum clandestitum*), bull thistle (*Cirsium vulgare*), Italian thistle (*Carduus pycnocephalus*), and mustards (*Brassica nigra* and *Brassica rapa*). Cotoneaster, spread by birds, has been observed to be fairly widespread in the understory of scrub on the hillside at the Banducci site. It can be difficult to control, since a cut stem will yield multiple new sprouts, and it threatens to become a significant control issue in the future. Panic veldt grass has become well-established in the riparian areas in recent years, extending recently into Muir Woods National Monument, where year round hand removal and chemical treatment as well as seasonal mechanical treatment are scheduled to occur by NPS staff, hired contractors, volunteer groups, and Muir Woods docents, interns, and interpretive staff (Baxter et al. 2009). This species is hard to control because it grows well in shade and also survives periodic inundation. The distribution of these species in the watershed is shown in Figure 1-36.

Highly invasive species that occur in the watershed, but still occupy very limited area, include yellow star thistle, giant reed grass (*Arundo donax*), starflower (*Helichrisum petidare*), ox-eye daisy (*Leucanthemum vulgare*), capeweed (*Arctotheca calendula*), purple star thistle, and Himalaya blackberry. The distribution of these species in the watershed is shown in Figure 1-37. Starflower has claimed extensive areas on nearby Bolinas Ridge and is likely to become more common in the watershed in upcoming years.

1.8.6.3 Sudden oak death

Since 1995, an epidemic referred to as Sudden Oak Death (SOD) has claimed tan oak, coast live oak, and black oak (*Quercus kellogii*) in coastal areas from Monterey to Humboldt County in California, and Curry County in Oregon (California Oak Mortality Task Force 2005). Large numbers of trees have died quickly from this pathogen, which drew the attention of scientists, task forces, and the state of California in a race to identify the pathogen and curb its rapid spread. The fungus-like organism has now been identified as *Phytopthera ramorum*, a relative of the organism that caused the Irish potato famine.

Tanoak die-off was first observed in Muir Woods in 1995, at the earliest stages of the epidemic, when tanoaks on canyon slopes showed the late-stage symptoms of yellowed and dead, brown leaves dominating the canopy foliage. Maps of affected tanoaks in Muir Woods prepared in 2000 showed greater die-back in areas adjacent to trails, particularly those east of Oceanview Trail, between Oceanview Trail and Redwood Creek Trail, along Hillside Trail on the west side of Redwood Creek, and along the Ben Johnson Trail. Fewer trees with SOD symptoms occurred in more remote areas with less exposure to visitors (Hooten 2000). The disease is creating openings in the forest canopy that may increase the risk of Douglas-fir encroachment and non-native plant invasion into Muir Woods. The resulting levels of dead foliage, branches and mid-canopy trees are substantially increasing fuel loads and associated wildfire risk in the affected forests.

In research conducted by the California Oak Mortality Task Force, numerous other species have been identified as *Phytopthera* host plants. Many of these species, such as huckleberry, California bay laurel, madrone, California buckeye, bigleaf maple (*Acer macrophyllum*), California coffeberry (*Rhamnus californica*), and toyon occur in or near Muir Woods, but SOD symptoms have not been observed on species other than tanoak there. However, most species can be sources of infection and spread by releasing SOD spores from infected foliage (Rizzo and Barbelotto 2003). Redwood has also been identified as a host plant (Davidson et al. 2003). SOD can also be spread during the rainy season on the soles of shoes or tires.

1.9 Terrestrial Wildlife

1.9.1 Species occurrence and distribution

The Redwood Creek watershed provides habitat for a diverse assemblage of terrestrial invertebrates, amphibians, reptiles, birds, and mammals. Numerous wildlife surveys have been conducted in portions of the watershed in the last 15 years that provide both qualitative and quantitative information about species composition, distribution, and abundance in the watershed. In addition to species documented during these surveys, known habitat associations and species distribution information can be used to infer potential occurrence of a number of additional species in the watershed (CDFG 2008).

Vertebrate species documented in the watershed include at least eight reptile species (Appendix C), approximately 200 bird species (including waders, waterfowl, gulls, and seabirds) (Appendix F, Table F-1), and about 34 mammal species (Appendix F; Table F-2). Bird species include year-round residents, seasonal visitors, and migrants. Species that have been documented or are predicted to occur in the watershed are shown in Appendices C and F, which also include typical habitat associations for each species. Terrestrial animals that may be found in the Redwood Creek watershed are discussed below, organized by habitat types found in the watershed. Amphibians and aquatic reptiles are treated in Section 1.7 Aquatic Species and Habitats.

Scientific names for vertebrate species are included in the Appendix tables C and F, but are hereafter excluded from the text for efficiency in the discussion that follows.

While the majority of terrestrial wildlife studies in the Redwood Creek watershed have focused on vertebrates, there have also been a few surveys for rare or unique terrestrial invertebrates. Muir Beach used to support large numbers of overwintering monarch butterflies (*Danaus plexippus*); habitat restoration and management has been recommended for this species (Monroe 2003). Few monarchs appear to use the area for overwintering at present, and it is likely that the region is now used primarily as foraging habitat (Jones and Stokes 2007). A preliminary survey for the federally endangered Myrtle's silverspot butterfly (*Speyeria zerene myrtleae*), which has been recorded in Marin county, was conducted in 1992 at Muir Beach (Hafernik and Mead 1992); however, neither the species nor its larval host plant, western dog violet (*Viola adunca*), were observed. The mission blue butterfly (*Icaria icarioides missionensis*) is the only other special-status invertebrate that has been documented to occur in close proximity to Redwood Creek watershed, as indicated by a CNDDB search of the San Rafael and Point Bonita 7.5-minute quadrangles. This species was recorded at Fort Baker, between the Golden Gate Bridge and Redwood Creek watershed, in 1981. However, no individuals were observed during subsequent surveys conducted in 1984 and 1985 (CNDDB; CDFG 2005). A robust population of mission blue butterflies was recently found in nearby Oakwood Valley, which makes it the northernmost population documented to date (Arnold and Lindzey 2003).

1.9.2 Wildlife habitat relationships

1.9.2.1 Redwood-Douglas-fir forest

Redwood-Douglas-fir forest covers over one-third of the Redwood Creek watershed and provides habitat for approximately 11 reptiles, 49 bird species, and 20 mammal species (Appendix C, Appendix F). Special-status animal species that have been detected in redwood-Douglas-fir habitat include northern spotted owl (*Strix occidentalis caurina*) (federally threatened), olive-sided flycatcher (state Species of Special Concern), and two bat species (western red bat and Townsend's big-eared bat, both state Species of Special Concern).

Redwood-Douglas-fir habitat supports an average-to-high bird diversity and low bird abundance compared to other habitats in the watershed. Bird species most commonly encountered include chestnut-backed chickadee, Pacific-slope flycatcher, spotted towhee, Wilson's warbler, and winter wren. Hermit warbler, red-breasted nuthatch, and pileated woodpecker also use these habitats. Most notable is the presence of the northern spotted owl and the apparent absence of the federally endangered marbled murrelet.

Marin County, including the Redwood Creek watershed, may support the highest known densities of northern spotted owls in the western United States (Stralberg et al. 2008). Throughout most of their range, northern spotted owls are found in mature or old-growth forests characterized by dense, multi-layered canopies. However, northern spotted owls use a variety of habitats and may use forests with different characteristics for nesting, roosting, and foraging, providing the habitat has a multi-layered structure and dense canopy cover (Adams et al. 2004). In Marin County, they have been observed in second-growth Douglas-fir, coast redwood, bishop pine, mixed conifer-hardwood, and evergreen hardwood forests, as well as old-growth stands of coast redwood and Douglas-fir (Hatch et al. 1999, Adams et al. 2004). Between 1998 and 2005, 195 northern spotted owl nests were found during surveys in Marin County at Muir Woods, Point Reyes National Seashore, and Golden Gate National Recreation Area (Jensen et al. 2006). Both logging and fire have resulted in younger forests in Marin County (Adams et al. 2004). Nest type,

whether an open platform or cavity, appears to depend on the age of the forest (LaHaye and Gutierrez 1999). A very high percentage of nests in Marin County are open platforms (91 percent), while a small percentage are in cavities (9 percent). Most nests in older forests tend to be in cavities; the ratio of nest types in Marin is similar to the ratio observed in other younger-aged forests (Buchanan and Irwin 1993).

Marin County populations, including those at Muir Woods, represent the southern limit of northern spotted owl distribution. The local population in Marin is relatively isolated, resulting in minimal gene flow with northern spotted owl populations to the north along the coast (Barrowclough et al. 2005, Jensen et al. 2006). If northern spotted owls in Marin are or become genetically isolated, the local population could be at increased risk of extinction from catastrophic events (e.g., fire) or by long-term reductions in productivity or survivorship. For this reason, protection and management for northern spotted owl populations in Marin County is of particular importance (Jensen et al. 2006). Researchers recommend that all coniferous forest habitats in Marin County be considered potential northern spotted owl habitat, and that management activities do not reduce habitat quality or nesting success of northern spotted owls (Jensen et al. 2004).

Additional threats to northern spotted owls include urban development along open space boundaries, disturbance due to recreational activities, potential for catastrophic wildfires along the urban/wildland interface, wildland fuel management, continued range expansion of barred owl (*Strix varia*), and West Nile Virus, which was recently confirmed in Marin County (Jensen et al. 2006). Also of concern is the die-off of tree and shrub species due to Sudden Oak Death occurring throughout spotted owl habitat in Marin County, which may have long-term impacts on nesting habitat and prey populations (Adams et al. 2004, Jensen et al. 2006).

In the updated Northern Spotted Owl Final Recovery Plan, the USFWS considers competition from barred owls as the most significant threat to the northern spotted owl (USFWS 2008). Barred owls have been recorded in Marin County, including Muir Woods, for six consecutive years. In 2007, NPS biologists documented the first confirmed breeding of barred owls in Marin County; a barred owl pair and two fledglings were observed in historical northern spotted owl territory within Muir Woods (Jensen et al. 2008).

Marbled murrelet surveys, including intensive censuses, eggshell surveys, and shore-based surveys, were conducted from 1995 through 1998, but no confirmed sightings were reported (Chow 1996, Gardali and Geupel 2000). At least two studies assessing offshore distribution and abundance reported no marbled murrelets in waters adjacent to Muir Woods during the breeding season (Briggs et al. 1987, Ralph and Miller 1995), nor have surveys detected murrelets in the nearshore waters off of Muir Beach (Gardali and Geupel 2000). The absence of marbled murrelets in the watershed may be explained by the fact that relatively few trees in the area appear suitable for marbled murrelet nesting (Hamer and Nelson 1995, Gardali and Geupel 2000, Gardali, pers. obs.).

Mammals, including opossums, shrews, moles, coyotes, gray fox, raccoons, skunks, mountain lions, and bobcats, have all been detected in redwood-Douglas-fir forest in the watershed. Deer mice were found to prefer this habitat over others in the watershed (Howell et al. 1999). Vagrant shrews were detected exclusively in redwood stands (Howell et al. 1998, Howell et al. 1999). Several bat species utilize redwood hollows in Muir Woods as day roosts, night feeding roosts, or maternity roosts (Heady and Frick 2004).

1.9.2.2 Grasslands

Grasslands in the Redwood Creek watershed provide habitat for at least three reptile species, 12 mammal species, and 36 bird species (Appendix C, Appendix F). Special-status species that have been detected in grasslands on or near the watershed include northern harrier, olive-sided flycatcher, and loggerhead shrike, all of which are state Species of Special Concern.

Common reptiles that have been documented in grassland habitats in the watershed include northern alligator lizard, western terrestrial garter snake, and western fence lizards. Reptiles such as these provide an important prey species for birds and mammals.

In a landbird inventory study of all San Francisco Bay Area National Parks, habitats dominated by non-native annual grasses supported nearly the lowest species diversity and abundance of birds (Flannery et al. 2001). Species commonly found in annual grassland habitats include turkey vulture, western bluebird, American kestrel, killdeer, house sparrow, savannah sparrow, white-crowned sparrow, and song sparrow. House sparrows (a non-native species) and savannah sparrows are more abundant in this habitat compared to others in the watershed (Flannery et al. 2001). Grassland bird species are in decline in most parts of the country due to the continuing loss of native grasslands (Sauer et al. 1995). Unfortunately, little information is available regarding bird abundance and distribution California grasslands (California Partners in Flight 2000).

Mammal species found in annual grasslands of the watershed include coyote, gray fox, striped and spotted skunks, bobcat, black-tailed deer, deer mouse, western harvest mouse, and California meadow vole. Three introduced mammals that may pose a threat to native wildlife have been documented in the watershed are domestic dogs, feral cats, and black rats (Takegawa 2003). Non-native introduced game birds, such as turkeys and chukar partridges (*Alectoris chukar*) have become more prevalent in recent decades and could pose a threat to native bird and animal species (pers. com. Bill Merkle Sept. 2009).

1.9.2.3 Mixed hardwood forest

Mixed hardwood forest provides habitat to at least six reptile species, 61 bird species, and 17 mammal species (Appendix C, Appendix F). Mixed hardwood forest provides an important food source, acorns, to birds and mammals. Special-status species that have been detected in mixed hardwood forest on or near the watershed include northern spotted owl (discussed above), loggerhead shrike (a state Species of Special Concern), and western red bat (also a state Species of Special Concern).

Mixed hardwood forests support average to above-average bird species diversity and average to high species abundance in the San Francisco Bay area (Flannery et al. 2001). Species of greatest abundance in mixed hardwood forests include chestnut-backed chickadee, song sparrow, dark-eyed junco, Wilson's warbler, Pacific-slope flycatcher, and acorn woodpecker. Less frequently encountered are belted kingfisher, black-throated gray warbler, pileated woodpecker, and hermit thrush.

Reptiles using mixed hardwood types that have been documented in the watershed include western fence lizard, rubber boa, and sharp-tailed snake.

Mammals associated with mixed hardwood forests in the watershed include shrew, coyote, gray fox, skunk, bobcat, black-tailed deer, deer mouse, mountain lion, western gray squirrel, and

dusky-footed woodrat. Though not often seen, bobcats and mountain lions play an important role in the food web as top carnivores. Dusky-footed woodrats are found in greater abundance in coast live oak-California bay habitat, compared to redwood-Douglas-fir and grassland habitat types, and may rely on oaks for food and cover (Howell et al. 1998). The dusky-footed woodrat is important as a primary prey species, in both frequency and biomass, of the northern spotted owl (Barrows 1980).

1.9.2.4 Coastal scrub and chaparral

Coastal scrub and chaparral covers approximately one-third of the Redwood Creek watershed and provides habitat for at least three species of reptiles (Appendix C), 31 species of birds, and 14 species of mammals (Appendix C, Appendix F). Special-status species that have been detected in coastal scrub or chaparral on or near the watershed include yellow warbler, a state Species of Special Concern.

This habitat supports low bird diversity and abundance compared to other habitat types in the watershed (Flannery et al. 2001). In fact, the southern ridge of the watershed, Coyote Ridge, had the lowest bird diversity index in this habitat type compared to all other surveyed sites in the GGNRA (Gardali and Geupel 1997). The most abundant bird species documented in coastal scrub habitats include white-crowned sparrow, wrentit, and spotted towhee.

Though several mammal species may be found using scrub and chaparral habitats, brush rabbit is one species found in the Redwood Creek watershed that is mainly associated with this habitat type (Jameson and Peeters 1988, Howell et al. 1999).

1.9.2.5 Riparian woodland

Riparian woodlands are extremely valuable for wildlife since they provide water, favorable microclimates, and important movement corridors. Although these areas comprise less than five percent of the Redwood Creek watershed, they provide breeding, foraging, and cover resources for at least six reptile, 72 bird, and 22 mammal species (Appendix C, Appendix F). Special-status species that have been documented in riparian woodland within the watershed include willow flycatcher (state-listed as endangered), and yellow warbler (a state Species of Special Concern).

Riparian woodland supports above-average to high bird species diversity and abundance compared to other habitat types in the watershed (Flannery et al. 2001). Species commonly encountered in this habitat include song sparrow, Swainson's thrush, and Wilson's warbler. Black-headed grosbeaks, black phoebes, orange-crowned warblers, song sparrows, warbling vireos, western wood-pewees, Wilson's warblers, ash-throated flycatchers, yellow warblers, northern orioles, and common yellowthroats are more abundant in this habitat compared to others in the watershed.

From 2000 to 2002, White et al. (2005) examined the habitat use of Swainson's thrush (*Catharus ustulatus*), particularly post-fledging juveniles, within the Redwood Creek and Lagunitas Creek watersheds. Swainson's thrush nests were found only in riparian areas, but adults with broods and independent juveniles were more often found in habitats adjacent to the riparian forests. Adults with broods and independent juveniles were located in upland vegetation 38 percent and 56 percent of the time, respectively. Key habitats for independent juveniles were determined to be mixed-hardwood forests, north-slope coastal scrub, and riparian vegetation, all of which overlapped areas of fruiting shrub thickets. Swainson's thrushes were never found in annual grassland, grazed annual grassland, or Eucalyptus (*Eucalyptus* spp.) habitats. The study

concluded that land management should be focused not only on improving nest success, but should also consider habitat selection and use by juvenile birds.

Nest predation and brood parasitism have been well-documented within the Redwood Creek watershed. Michaud et al. (2004) studied its effects on nesting success of Wilson's warbler (*Wilsonia pusilla*). Nest predation appeared to be the biggest cause of nest failure for Wilson's warbler, but there was also a high incidence of brood parasitism by brown-headed cowbirds (*Molothrus ater*). The effects of nest predation and brood parasitism combined resulted in low rates of nesting success. Other research has indicated that brood parasitism by brown-headed cowbirds on Swainson's thrushes (4 percent) is much lower than on Wilson's warblers (33 percent), despite their nesting in similar habitats (White and Gardali 2004). The nests of Swainson's thrushes appeared better concealed, which may make them less susceptible to parasitism. Additionally, Swainson's thrushes are partially frugivorous, which may not be optimal for cowbird nestlings, possibly reducing the rate of nest parasitism because cowbirds may prefer to parasitize the nests of other species, or by reducing cowbird nestling survival. Although differences in Wilson's warbler and Swainson's thrush nesting behavior were not addressed in this study, they may contribute to the disparity in brood parasitism rates.

In the mid-1990s, researchers determined that nearly one-third of the riparian shrub and herbaceous species in the Redwood Creek riparian corridor was non-native (PWA et al. 1994). Since understory plant density and diversity are important habitat characteristics for nesting riparian birds , recent efforts have been made to remove the invasive non-native plant species Cape ivy from almost 6.2 ac (3.5 ha) of streamside habitat. Following Cape ivy removal, nesting bird species diversity and abundance substantially increased (Scoggin et al. 2000).

North American river otters have recently returned to Redwood Creek, which may indicate that riparian habitat conditions are improving (B. Merkle, pers. comm., 2009). The shrew-mole and broad-footed mole were only detected in this habitat type (Howell et al. 1998, Howell et al. 1999).

1.9.2.6 Wetlands

Seasonal wetlands provide habitat for six reptile species, 83 bird species, and eight mammal species (Appendix C, Appendix F). Special-status species that have been documented in seasonal wetlands near Big Lagoon include northern harrier, tricolored blackbird, and yellow-headed blackbird, each of which is a state Species of Special Concern. Historical reductions in wetland habitat may have decreased wildlife abundance, diversity, productivity, and distribution in the Redwood Creek watershed.

Reptile species that utilize wetlands within the watershed include common garter snake and western pond turtle. Commonly encountered bird species include mallard, American wigeon, American coot, killdeer, black phoebe, marsh wren, and red-winged blackbird (Stallcup 1995). Mammal species include western harvest mouse (Takekawa et al. 2003), deer mouse, California meadow vole, and river otter. Dusky-footed woodrats have been observed in riparian areas as well as dense scrub on hillsides (B. Merkle, pers. comm., 2009).

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Figures

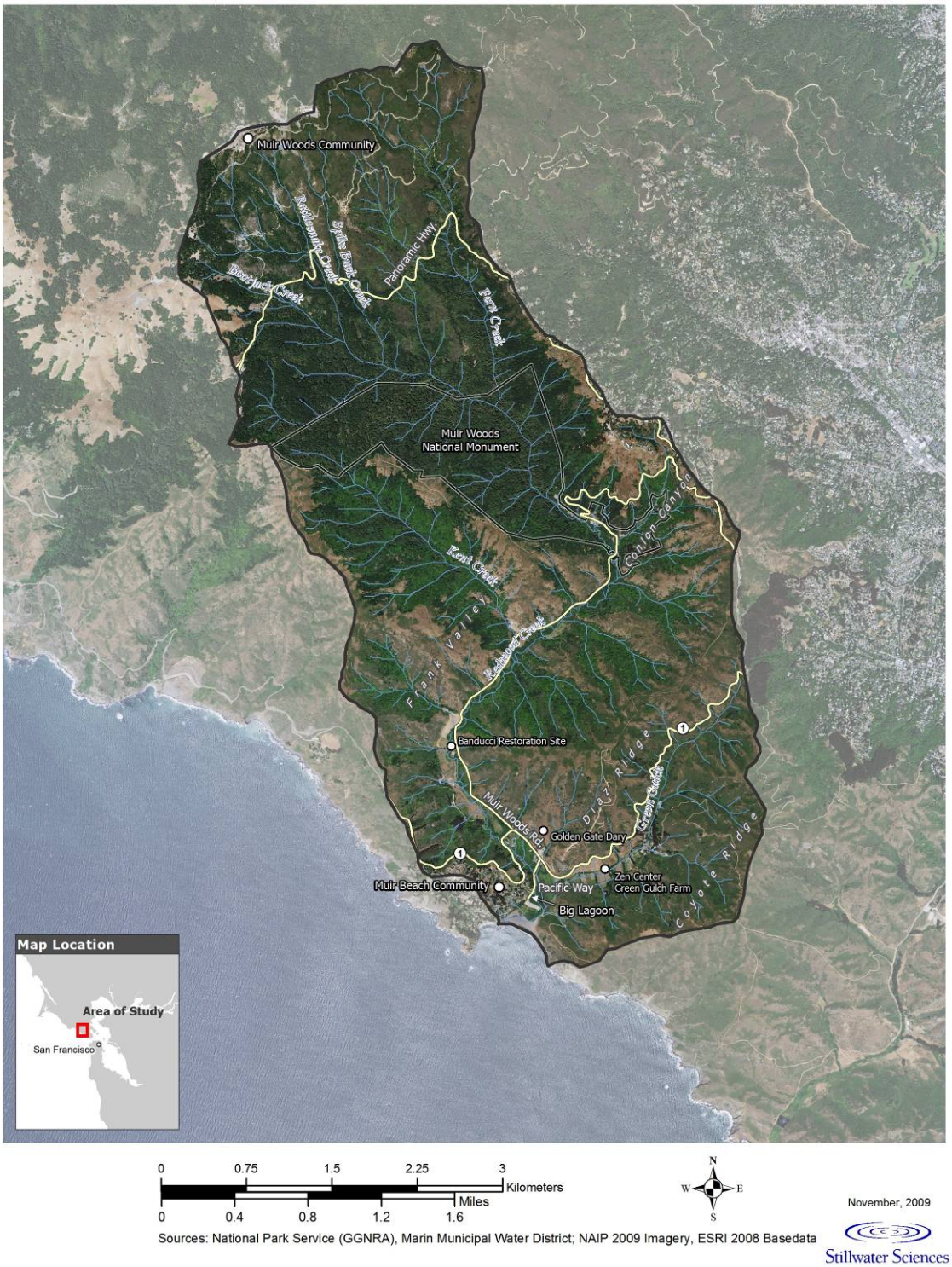


Figure 1-1. Redwood Creek watershed and regional setting, with major roads and reference areas. Source: Stillwater Sciences 2004.

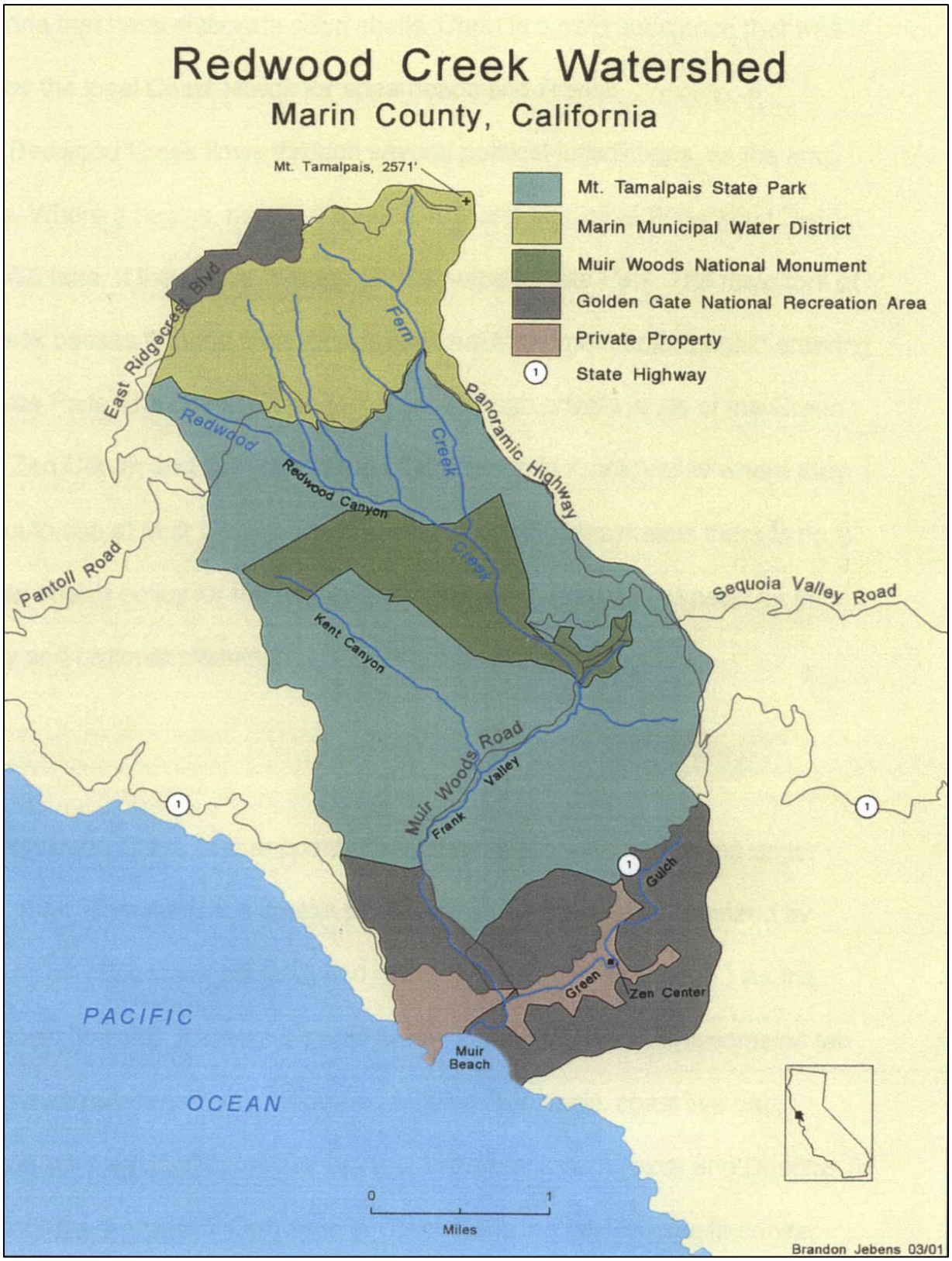


Figure 1-2. Land ownership in the Redwood Creek watershed. Source: Jebens 2001.

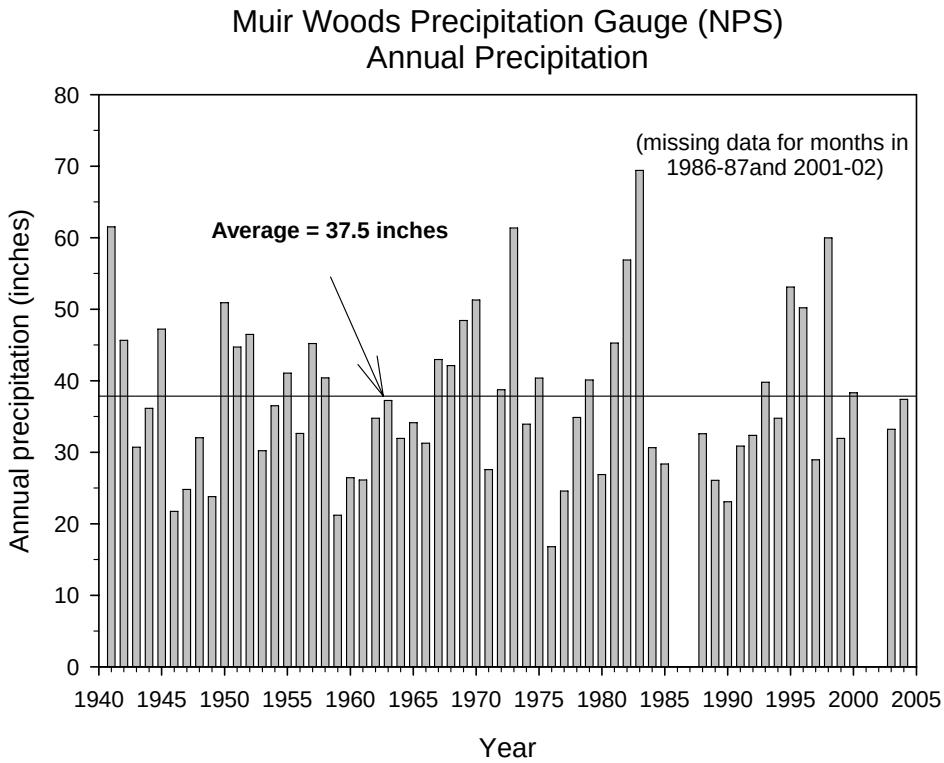


Figure 1-3. Annual precipitation at the Muir Woods precipitation gauge for calendar years 1941–2004.

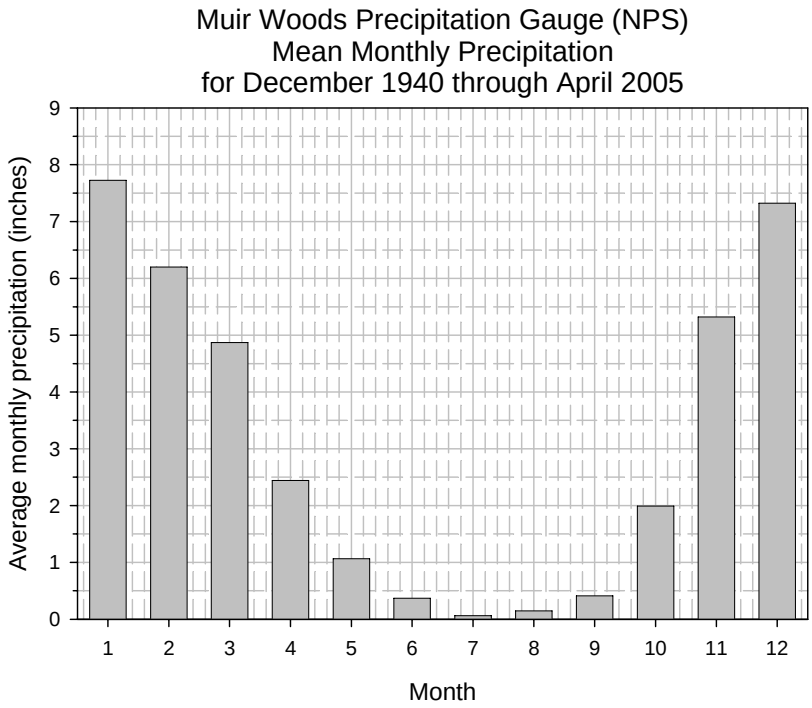


Figure 1-4. Mean monthly precipitation at the Muir Woods rain gauge. On average roughly 95% of the total annual precipitation occurs between October 1 and April 30.

Figure 1-5. Locations of continuous-monitoring stream gauges. Source: EDS 2004.

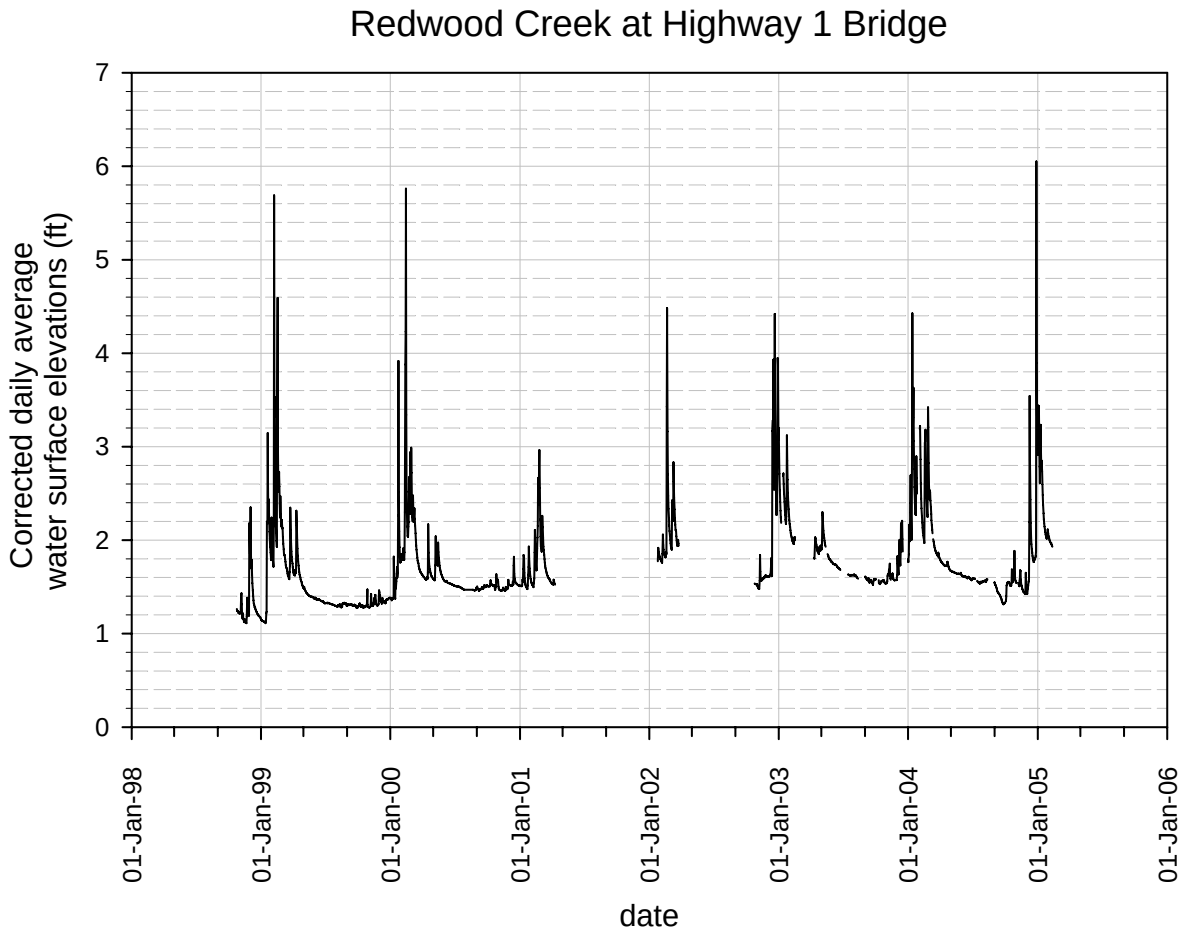


Figure 1-6. Time series of daily average water surface elevations (referenced to the top of the pressure transducer) from Redwood Creek at the Highway 1 Bridge gauge. Data are corrected for sensor drift by interpolation, using sensor calibration measurements that were periodically recorded during site visits by NPS personnel. Gaps are intervals for which no data are available.

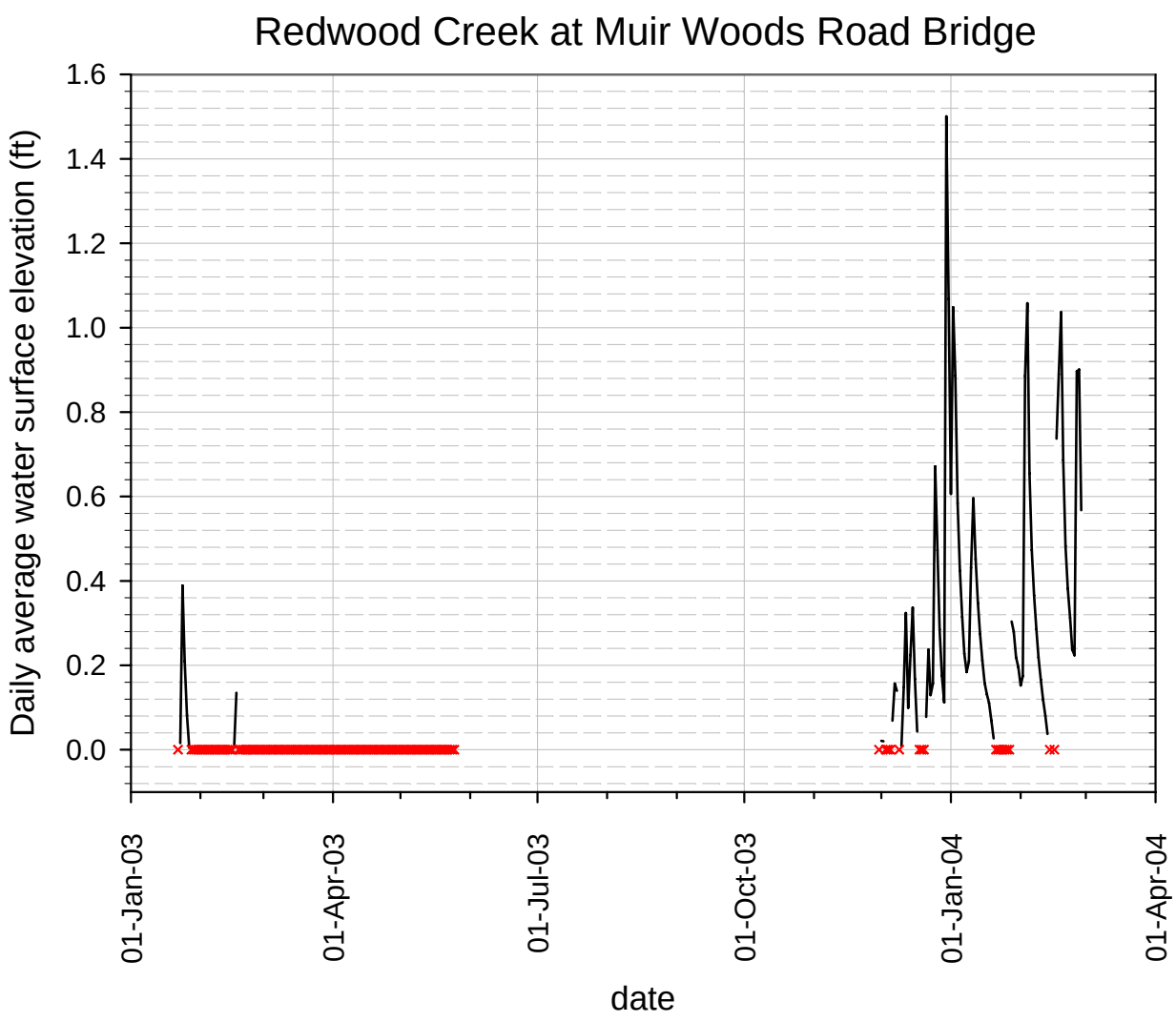


Figure 1-7. Time series of daily average water surface elevation (referenced to the top of the pressure transducer) for Redwood Creek at the Muir Woods Road Bridge gauge. Red "X" symbols mark days of sensor operation in which stage never rose above the sensor (see text). Gaps are intervals for which no data are available (i.e., in periods when the sensor was not operating). Data source: EDS 2004.

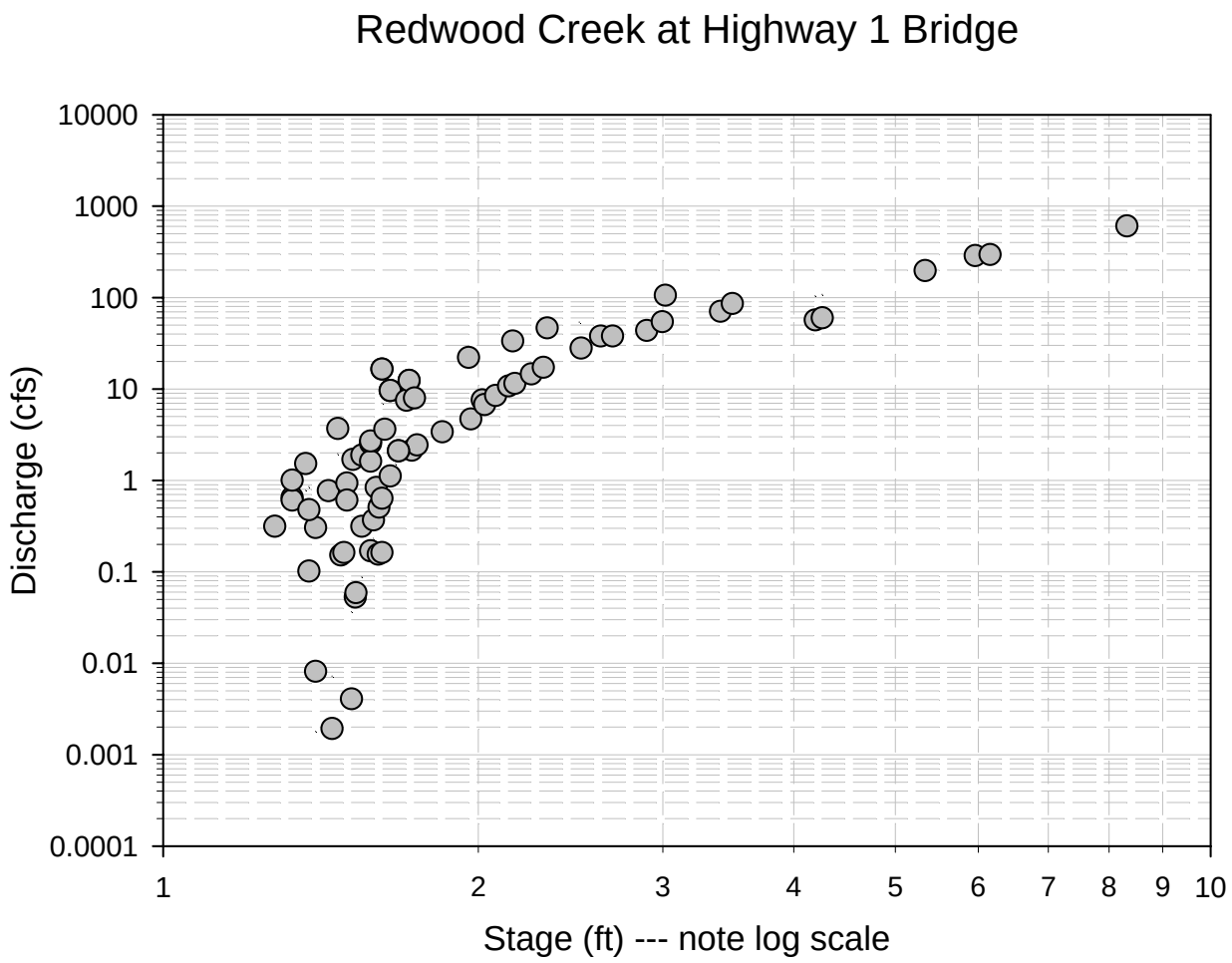


Figure 1-8. Stage-discharge data for Redwood Creek at the Highway 1 Bridge. The data show substantial scatter, particularly at low stages.

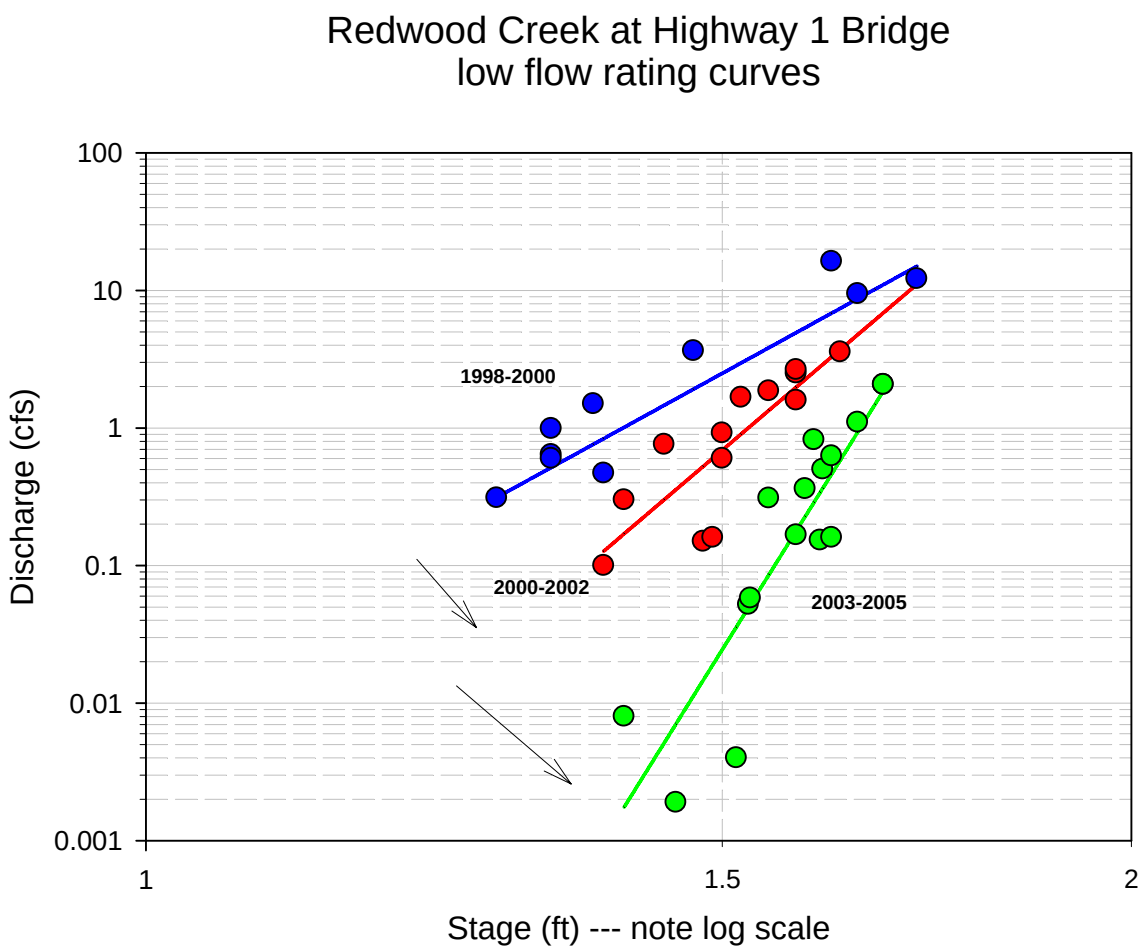


Figure 1-9. Stage-discharge relationships for low flows on Redwood Creek at the Highway 1 Bridge. Blue circles are data from Oct. 1998–Jan. 5, 2000, red circles are data from Jan. 6, 2000–Sept. 30, 2001, and green circles are data from WY 2003–2005. Lines show best fits to data, based on nonlinear regression (see text). The regression analysis produces statistically significant, power law relationships (see Table 5 for regression statistics).

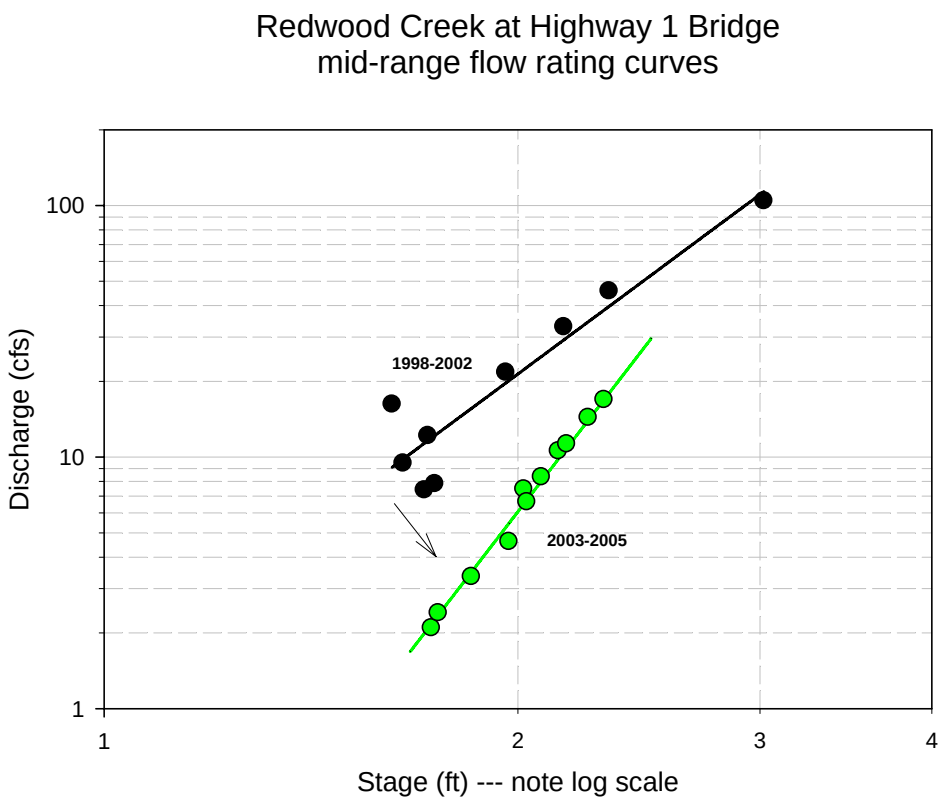


Figure 1-10. Stage-discharge relationships for mid-range flows on Redwood Creek at the Highway 1 Bridge. Black circles are data from Oct. 1, 1998–Sept. 30, 2001 and green circles are data from WY 2003–2005. Lines show best fits to data, based on nonlinear regression (see text). The regression analysis produces statistically significant, power law relationships (see Table 5 for regression statistics).

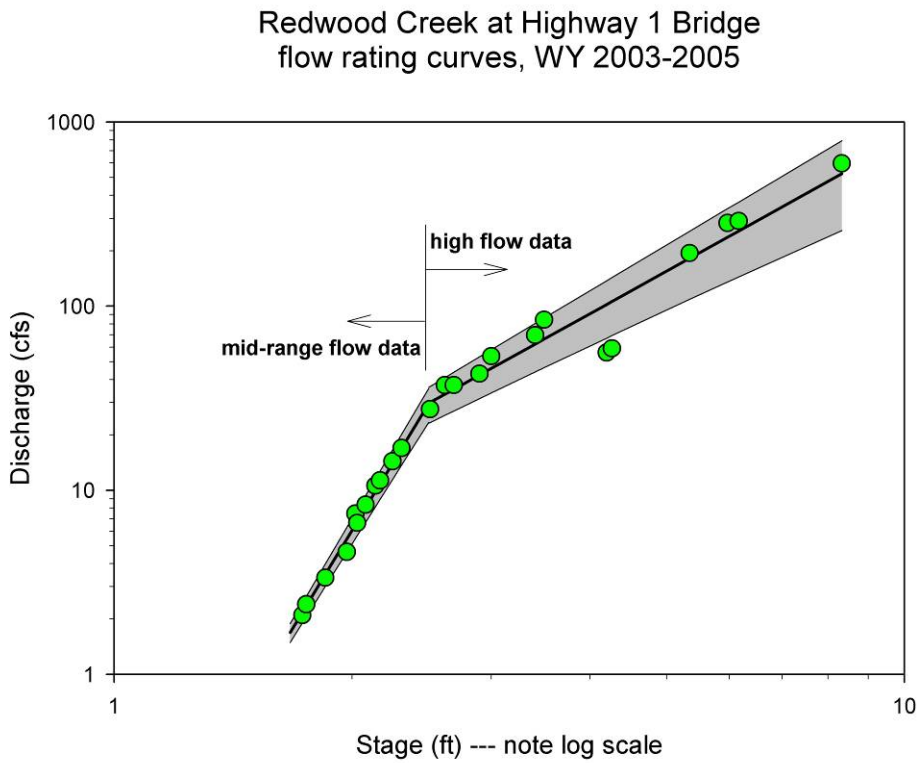


Figure 1-11. High- and mid-range stage-discharge data for Redwood Creek at the Highway 1 Bridge gauge for WY2003–2005. Thick lines through data show best-fit regressions, with uncertainties (shaded areas) propagated from one standard error of the mean of the regression parameters. The mid-range curve has a significantly steeper slope, implying that the hydraulic geometry and roughness of the channel are such that the stage-discharge relationship changes above a threshold stage of about 2.5 ft (0.8 m).

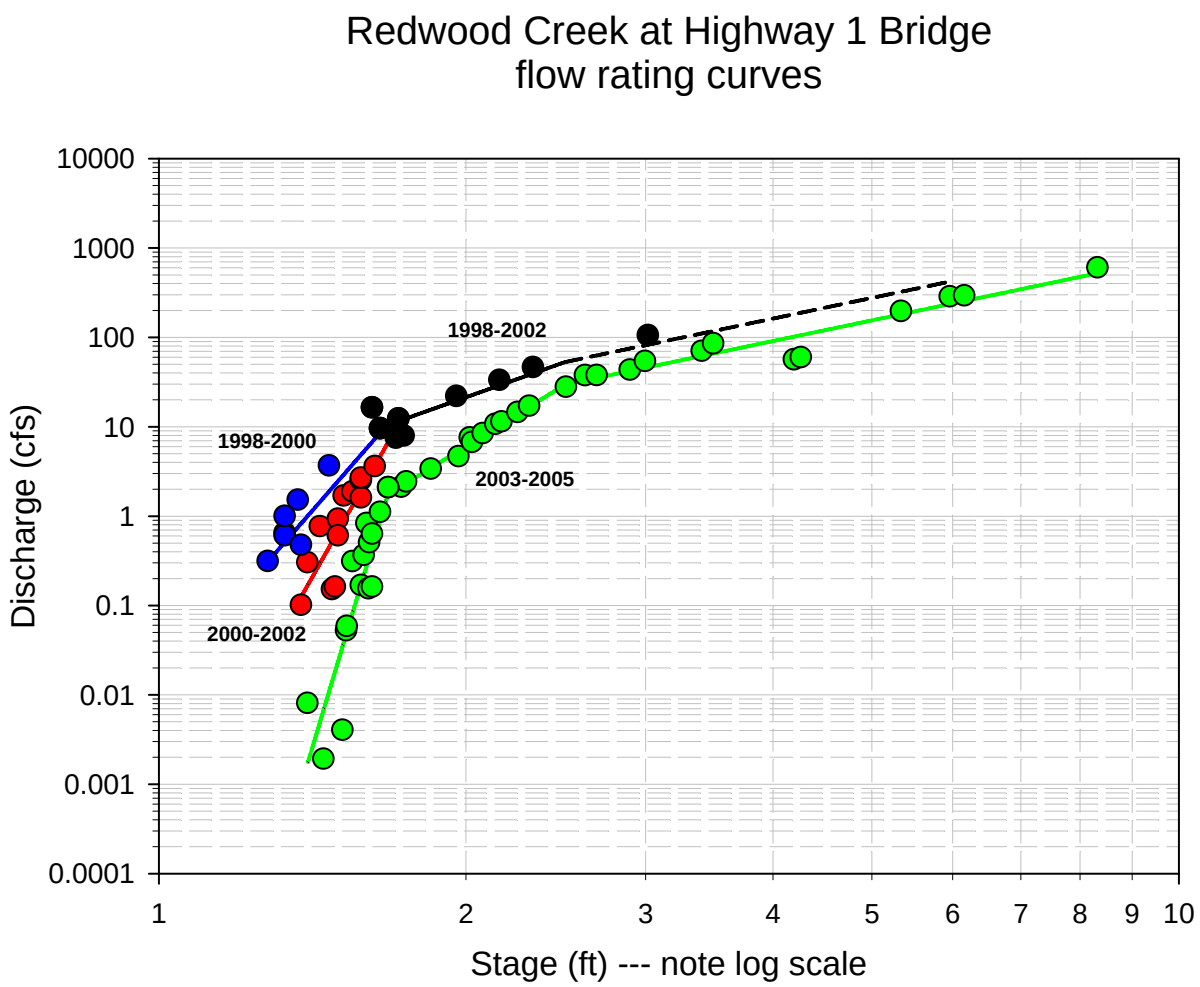


Figure 1-12. Stage-discharge data for Redwood Creek at the Highway 1 Bridge for all flows. Dashed black line shows estimated high-flow curve for 1998–2002. Source:

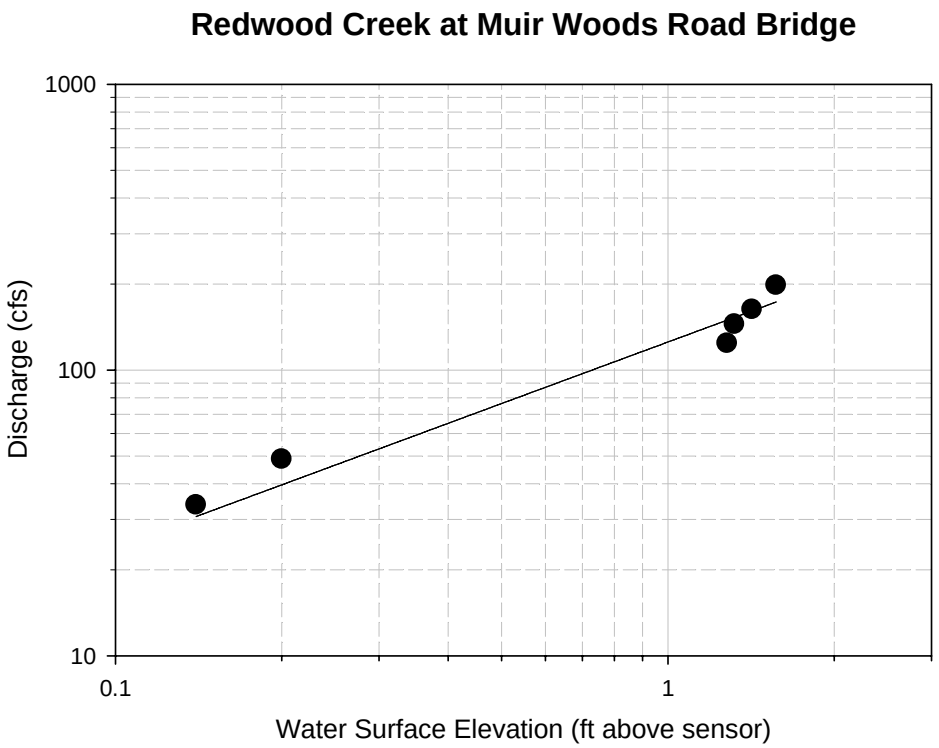


Figure 1-13. Stage discharge relationship for the Muir Woods Road Bridge gauge. Data source: EDS 2004.

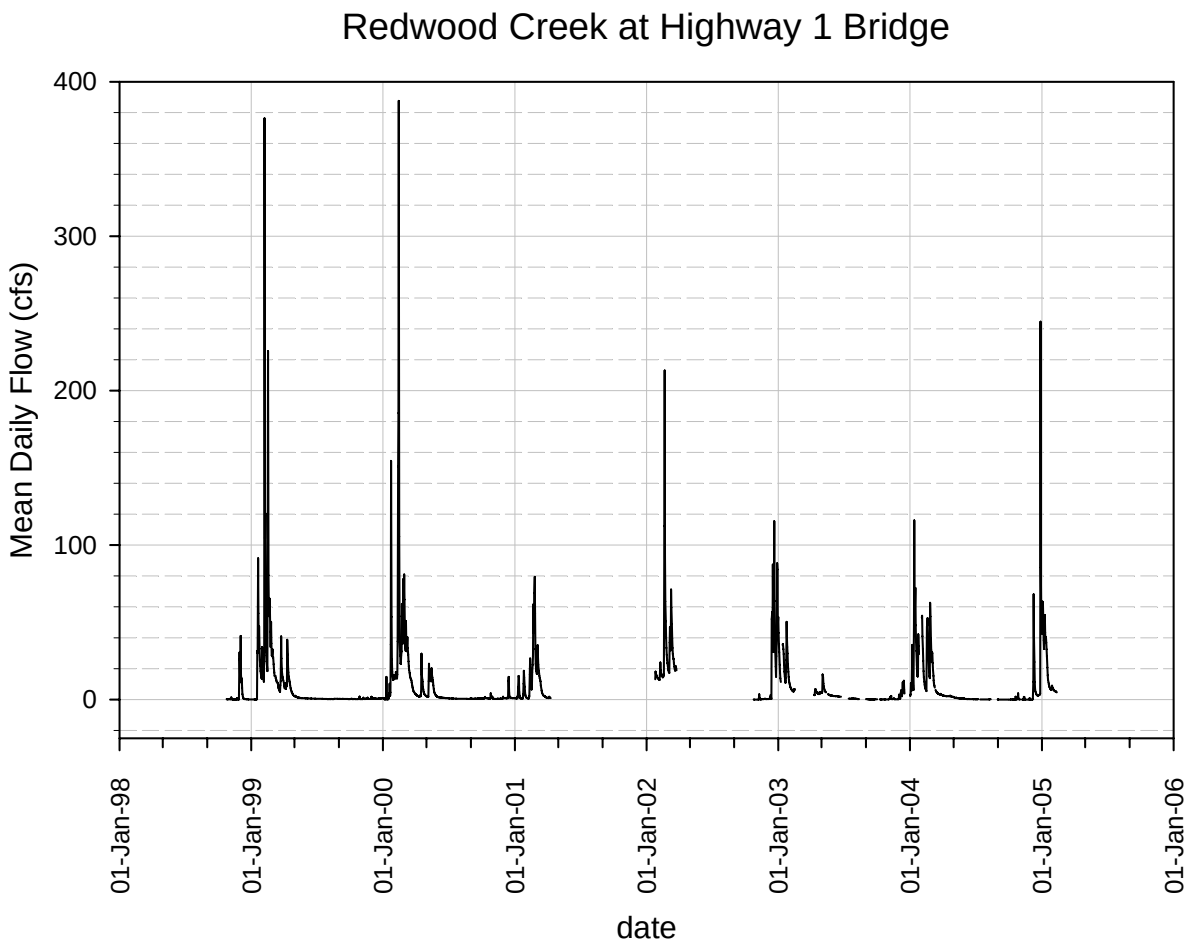


Figure 1-14. Time series of mean daily flows for Redwood Creek at the Highway 1 Bridge gauge. High flows (i.e., greater than about 100 cfs [2.8 m^3s^{-1}] from before January 2002 have high uncertainties, due to a lack of corroboratory data for the assumed high flow-rating curve (see text).

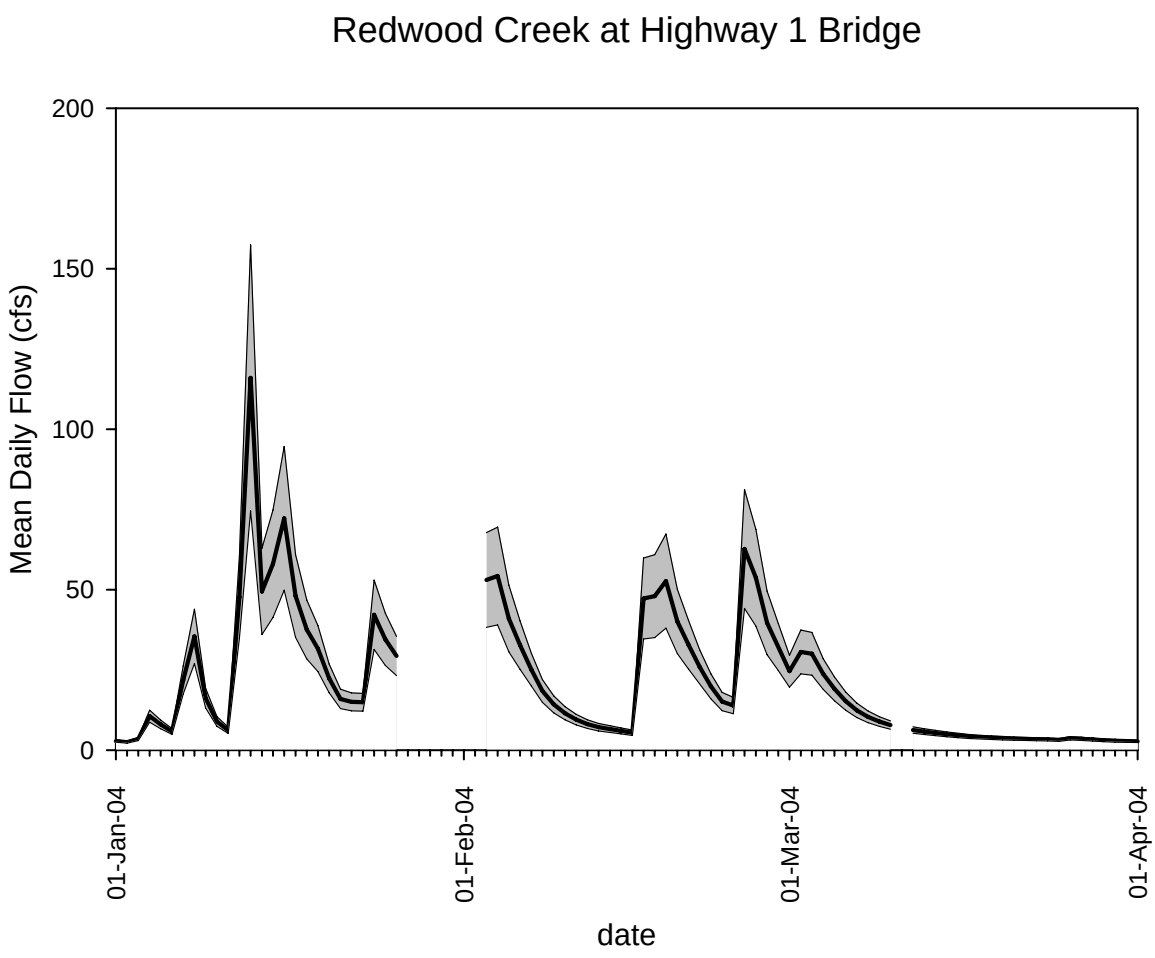


Figure 1-15. Mean daily flow for the wet season of WY 2004, a year with a relatively low peak mean daily flow. Shaded area shows uncertainty in mean daily flow, propagated from uncertainties in regression parameter estimates. Upper and lower confidence intervals are calculated from the mean (thick line) ± one standard error.

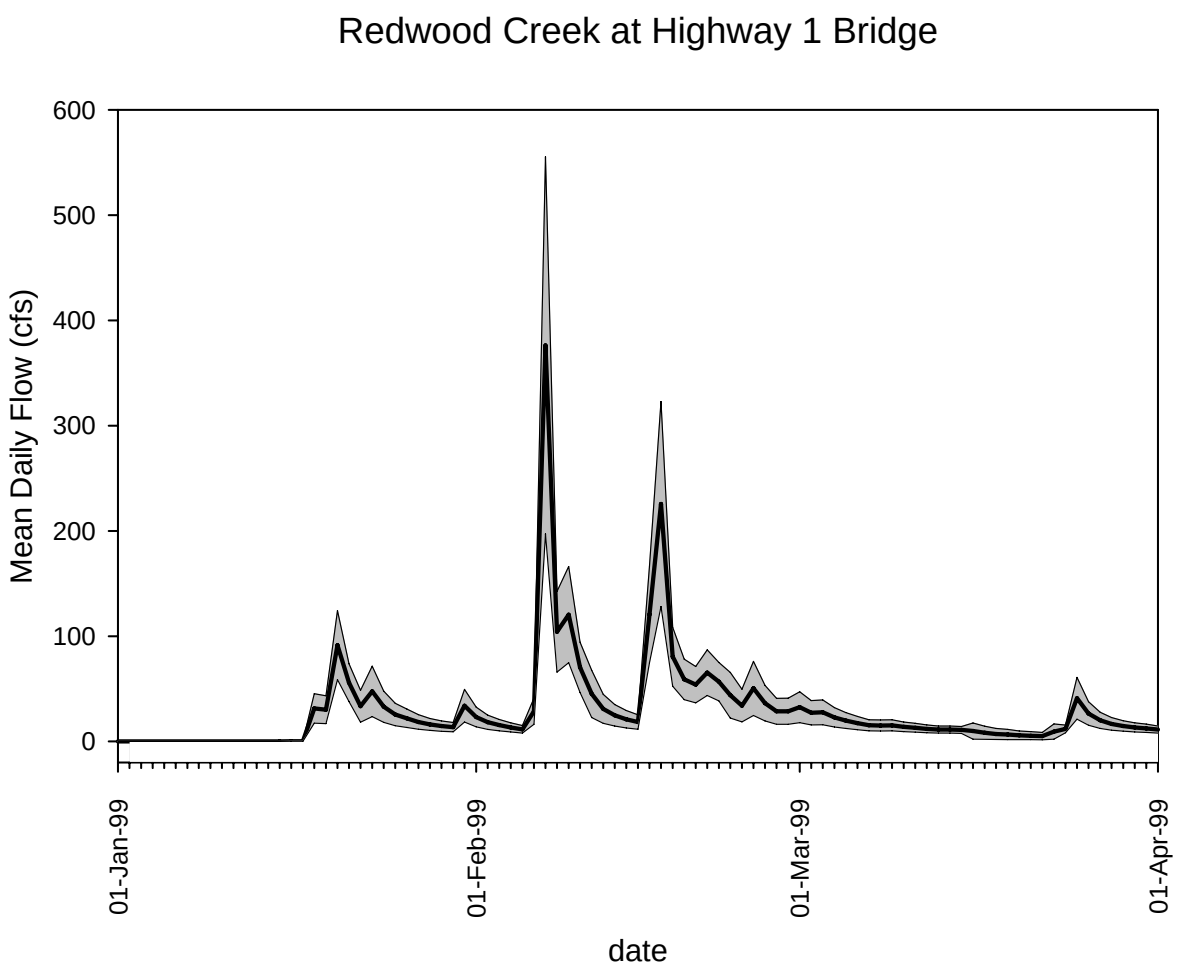


Figure 1-16. Mean daily flow for the wet season of WY 1999, a year with a relatively high peak mean daily flow. Shaded area shows uncertainty in mean daily flow, propagated from uncertainties in regression parameter estimates. Upper and lower confidence intervals are calculated from the mean (thick line) ± one standard error.

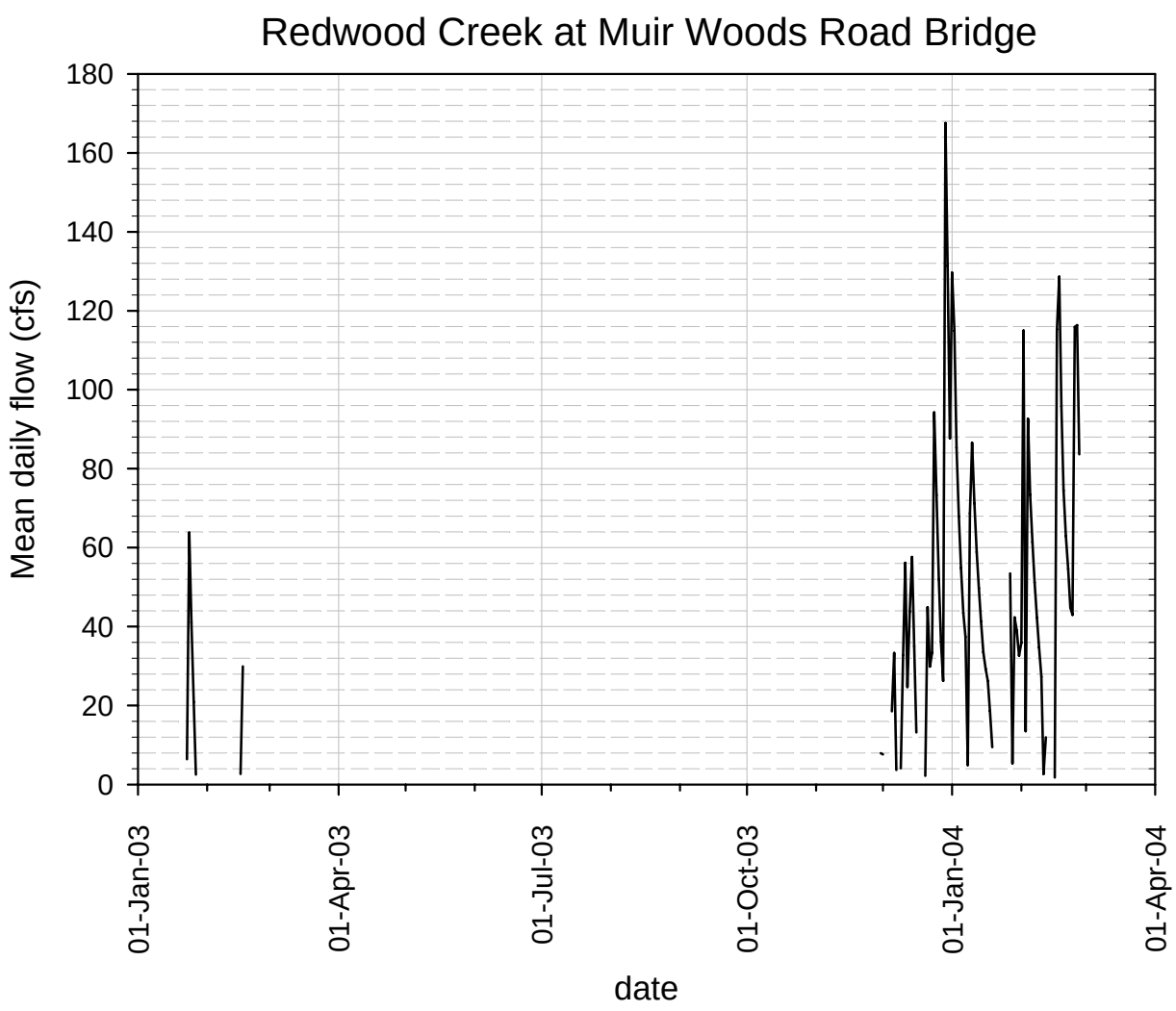


Figure 1-17. Time series of mean daily flows for Redwood Creek at the Muir Woods Road Bridge gauge based on the stage data of Figure 6 and the rating curves of Figure 1-12.

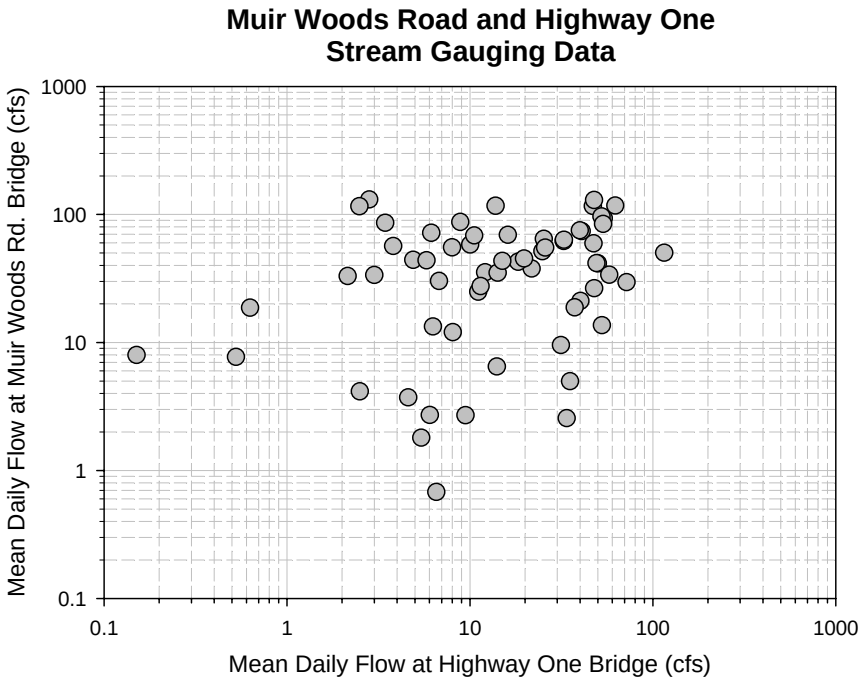


Figure 1-18. Mean daily flow at Muir Woods Road Bridge plotted against mean daily flow at the Highway 1 Bridge.

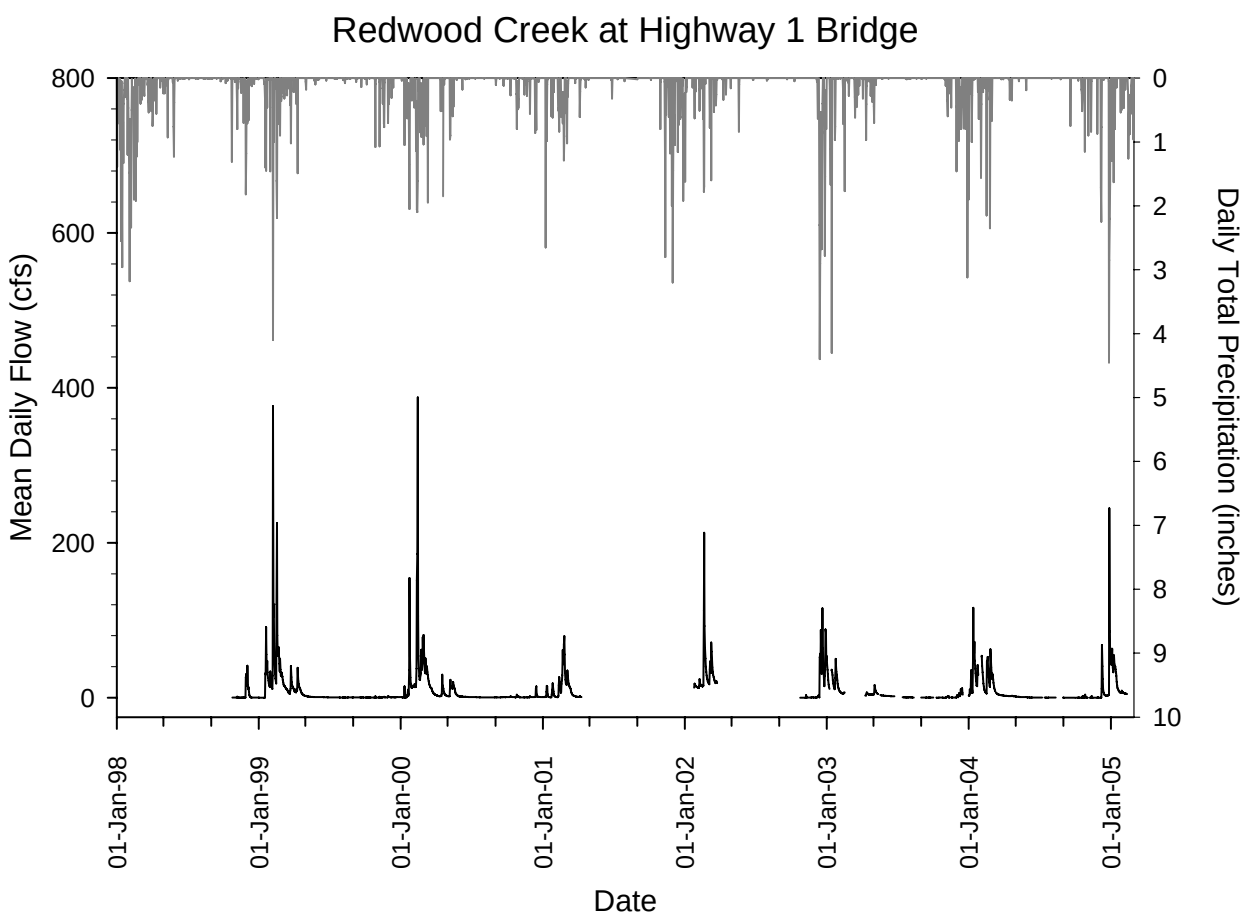


Figure 1-19. Mean daily flow at the Highway 1 Bridge (left axis, black line) and total daily precipitation at the Muir Woods rain gauge (right axis, gray line) plotted for the analyzed period of record.

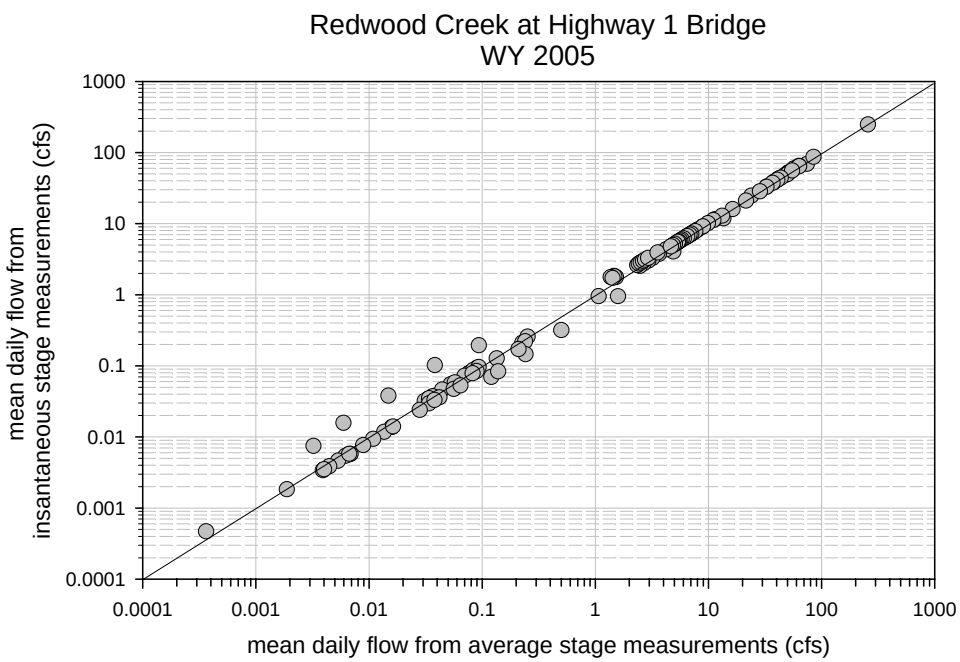


Figure 1-20. Mean daily flows, calculated from instantaneous measurements of discharge, plotted against mean daily flows, calculated from average measurements of discharge, for WY2005 at the Highway 1 Bridge. Data that plot above or below the 1:1 line are estimates with errors introduced by the methods used in this analysis.

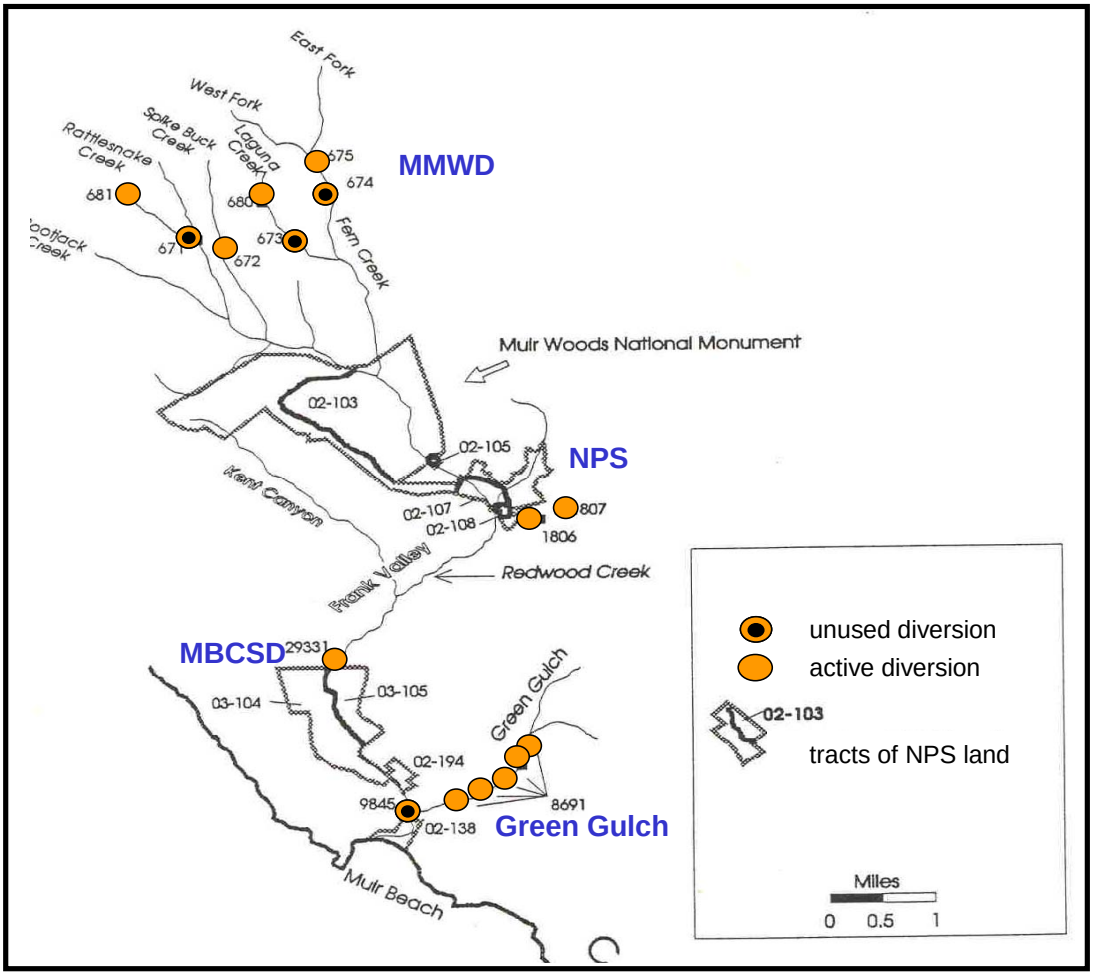


Figure 1-21. Active and unused water diversions in the Redwood Creek watershed. Source: Johns 1993.

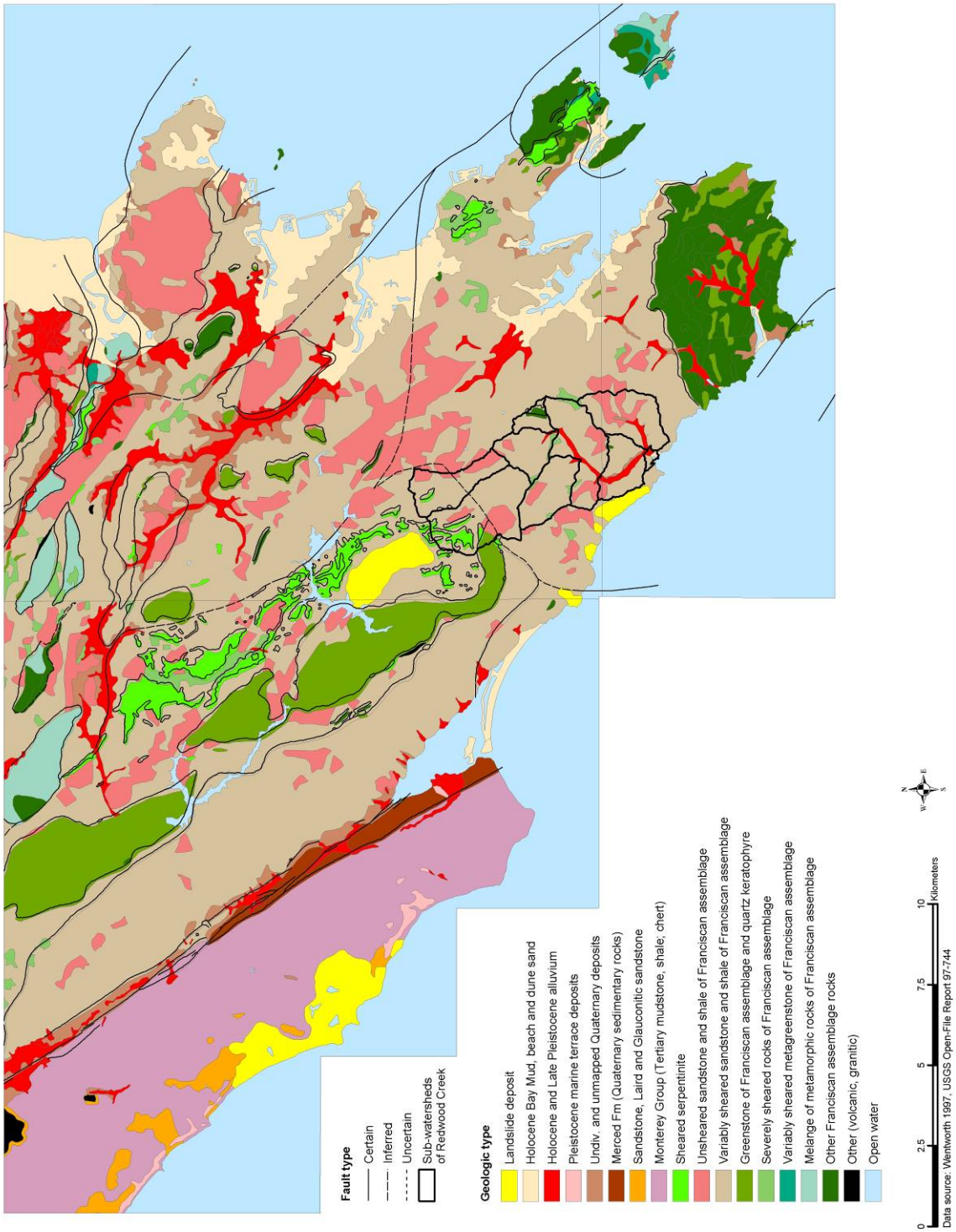


Figure 1-22. Generalized map of geology and faults: Marin Peninsula, California. Source: Wentworth 1997, as presented by Stillwater Sciences 2004.

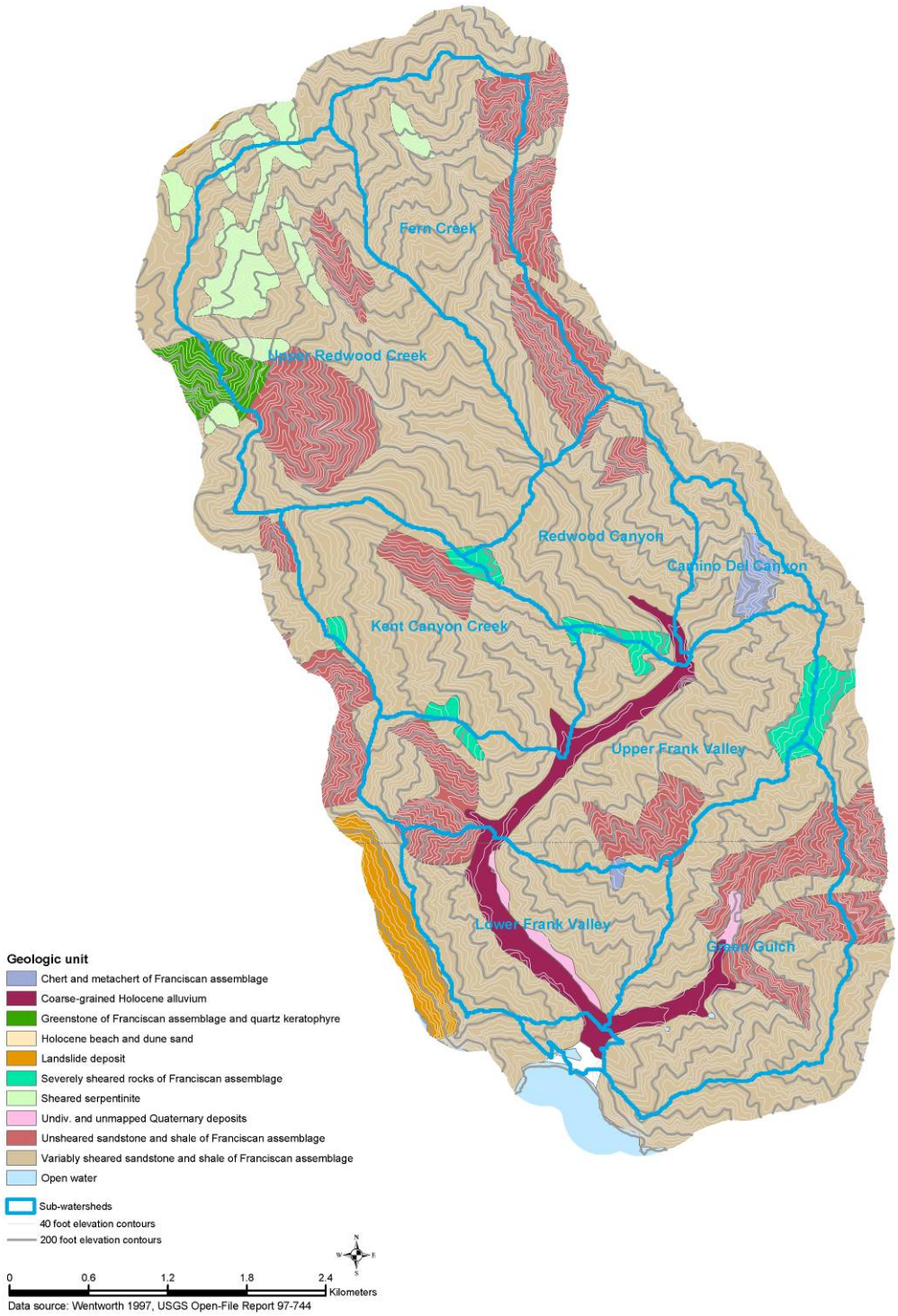


Figure 1-23. Watershed geology. Source: Wentworth 1997, as presented by Stillwater Sciences 2004.

Figure 1-24. Shaded-relief topographic map of the Redwood Creek watershed. Adapted from Stillwater Sciences 2004.

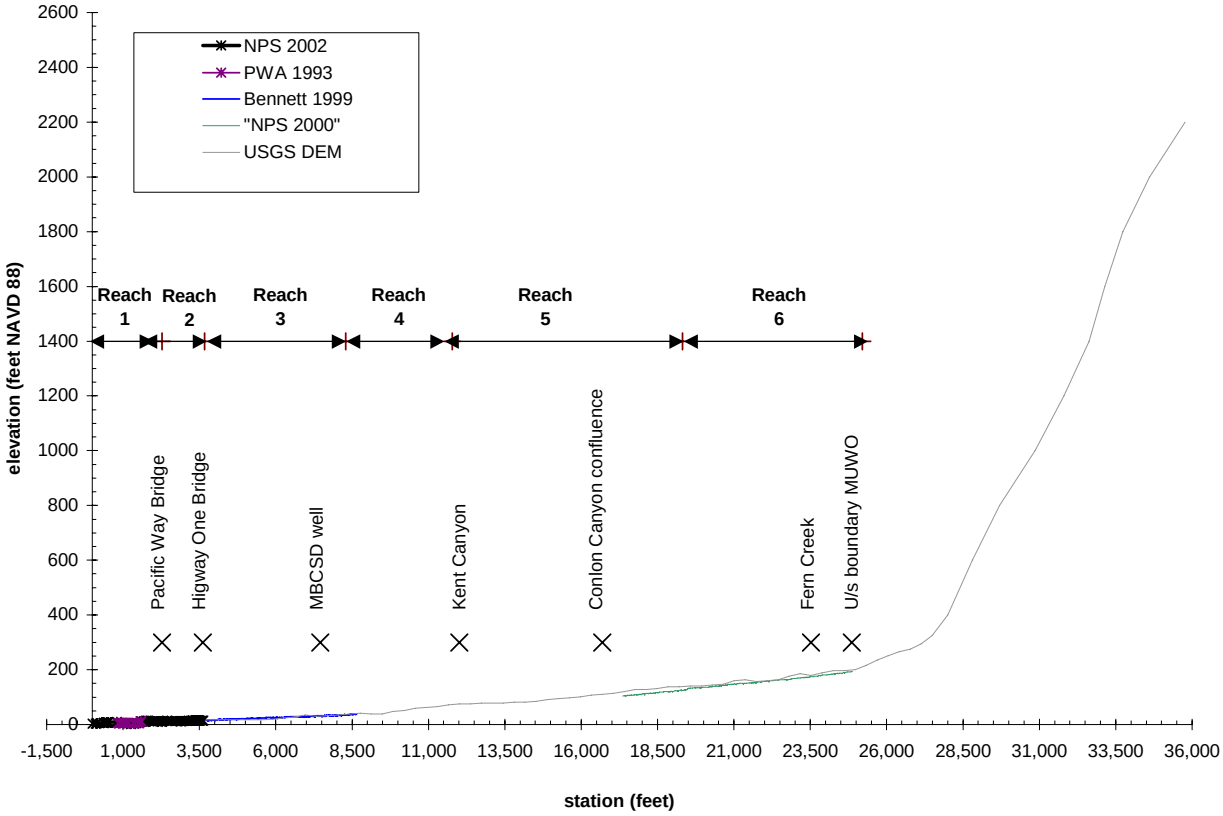
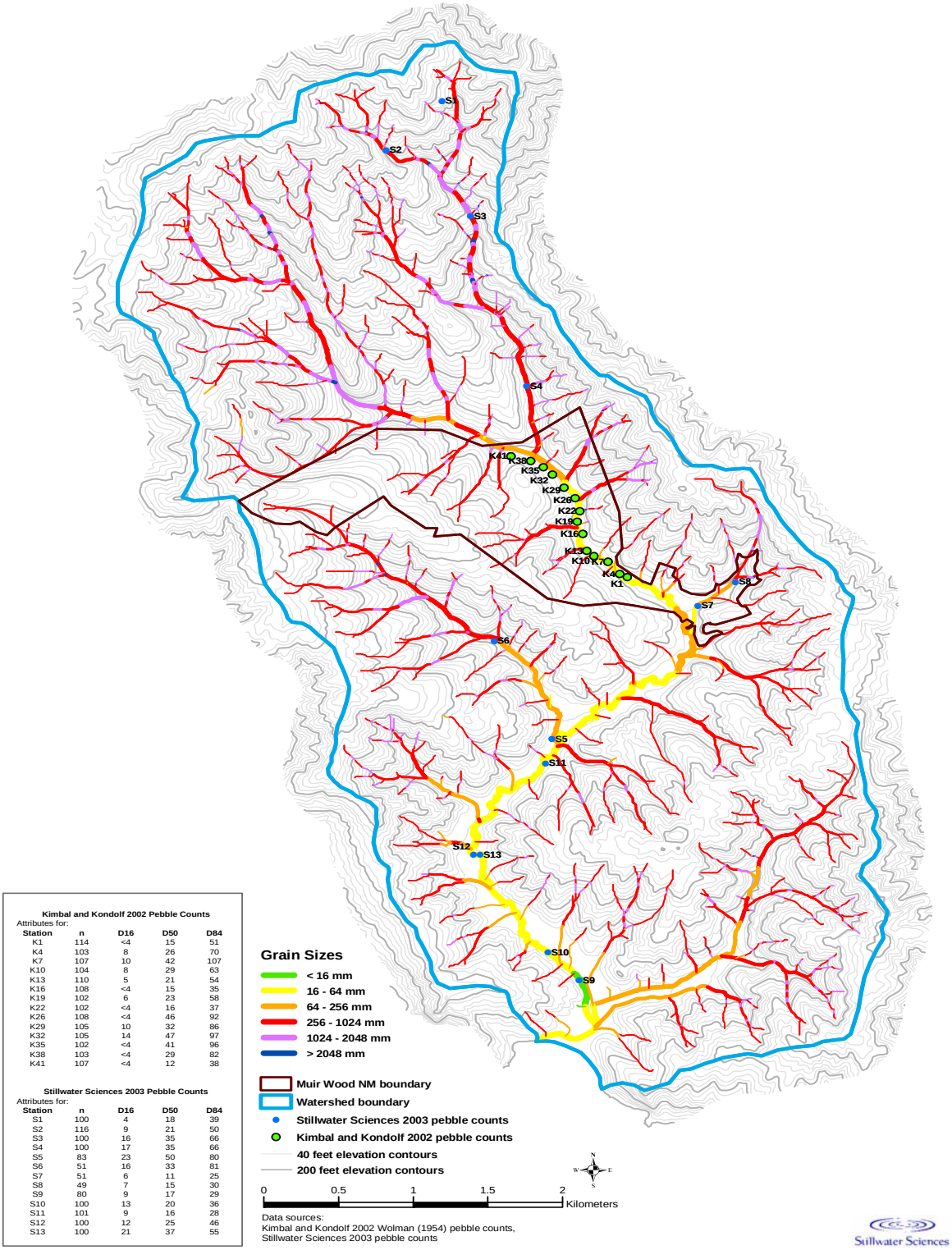


Figure 1-25. Redwood Creek channel profile with delineation of NPS habitat mapping reaches. Sources: NPS unpublished data, USGS DEM, Fong 2002.



Kimbal and Kondolf 2002 Pebble Counts

Attributes for:

Station	n	D16	D50	D84
K1	114	<4	15	51
K4	103	8	26	70
K7	107	10	42	107
K10	104	8	29	63
K13	110	5	21	54
K16	108	<4	15	35
K19	102	6	23	58
K22	102	<4	16	37
K26	108	<4	46	92
K29	105	10	32	86
K32	105	14	47	97
K35	102	<4	41	96
K38	103	<4	29	82
K41	107	<4	12	38

Stillwater Sciences 2003 Pebble Counts

Attributes for:

Station	n	D16	D50	D84
S1	100	4	18	39
S2	116	9	21	50
S3	100	16	35	66
S4	100	17	35	66
S5	83	23	50	80
S6	51	16	33	81
S7	51	6	11	25
S8	49	7	15	30
S9	80	9	17	29
S10	100	13	20	36
S11	101	9	16	28
S12	100	12	25	46
S13	100	21	37	55

Figure 1-26. Median grain size estimated from slope-area relation and field sampling. Source: Stillwater Sciences 2004.

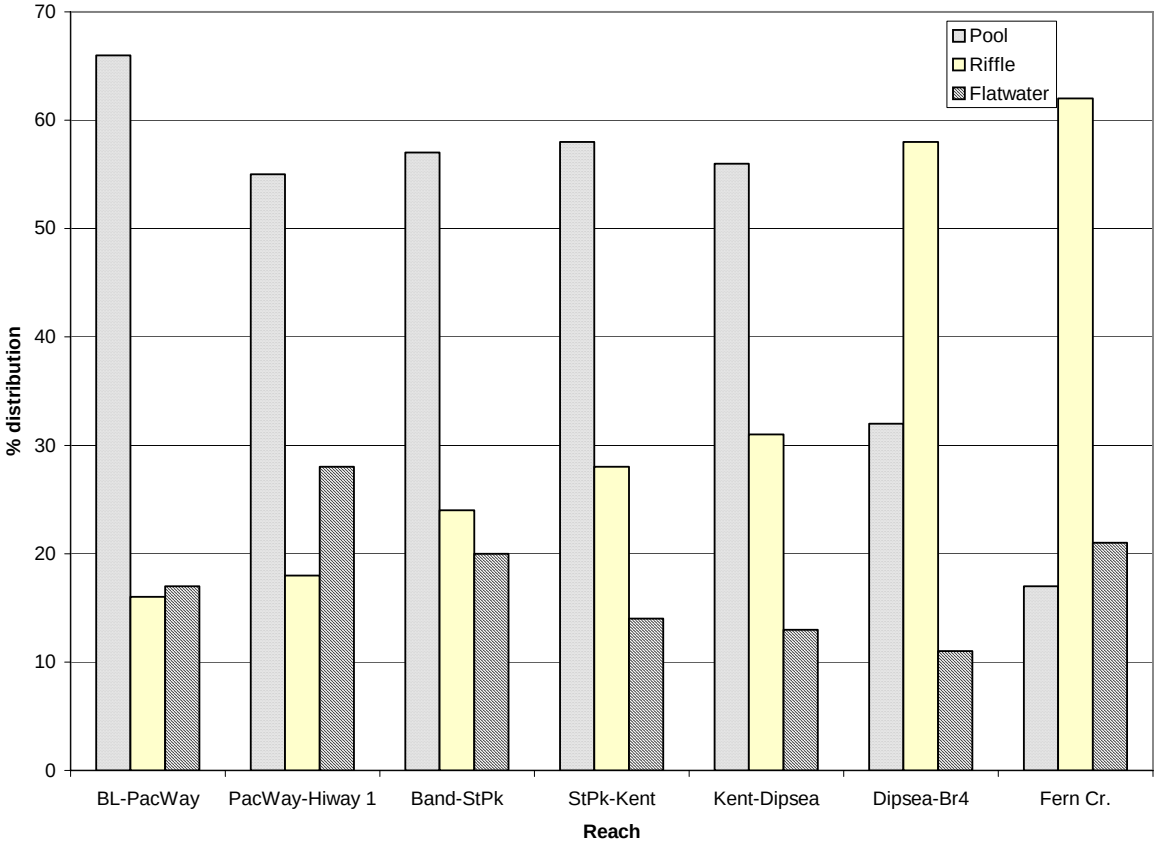


Figure 1-27. Habitat types and distribution in the mainstem Redwood Creek and Fern Creek showing a decline in riffle area and increase in pool area with increasing distance downstream from the Fern Creek reach. Source: Fong 2002.

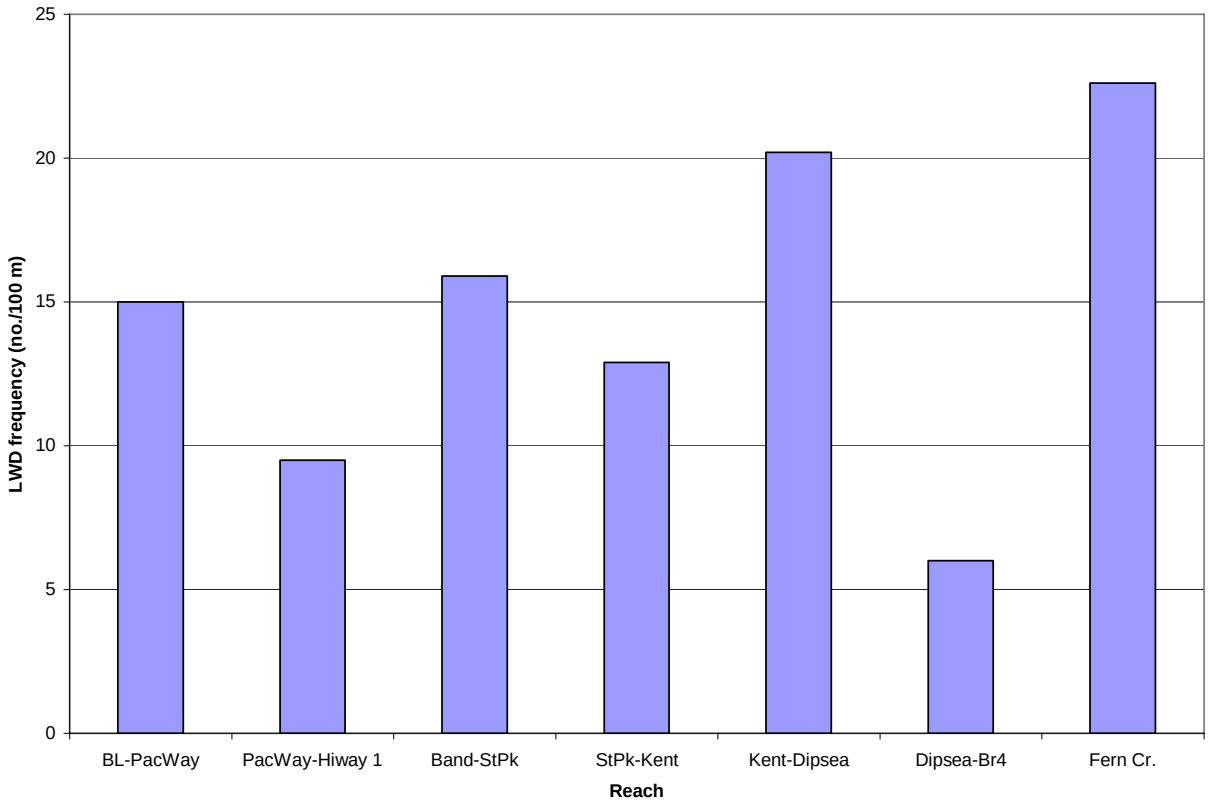


Figure 1-28. Large woody debris (LWD) distribution in Redwood and Fern creeks. Source: NPS unpublished data, MMWD unpublished data.

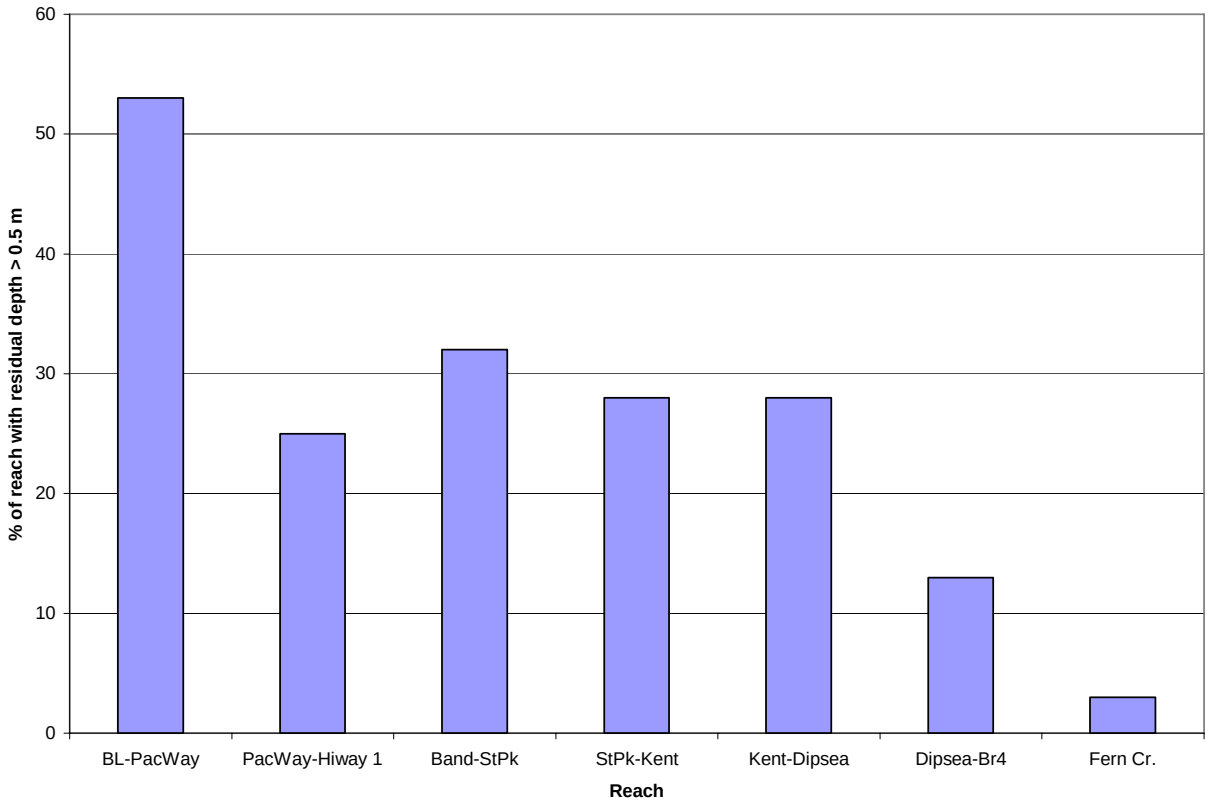


Figure 1-29. Distribution of pools deeper than 1.6 ft (0.5 m) in Redwood and Fern creeks, showing an increase in pool area with increasing distance downstream from Fern Creek. Source: NPS unpublished data, MMWD unpublished data.

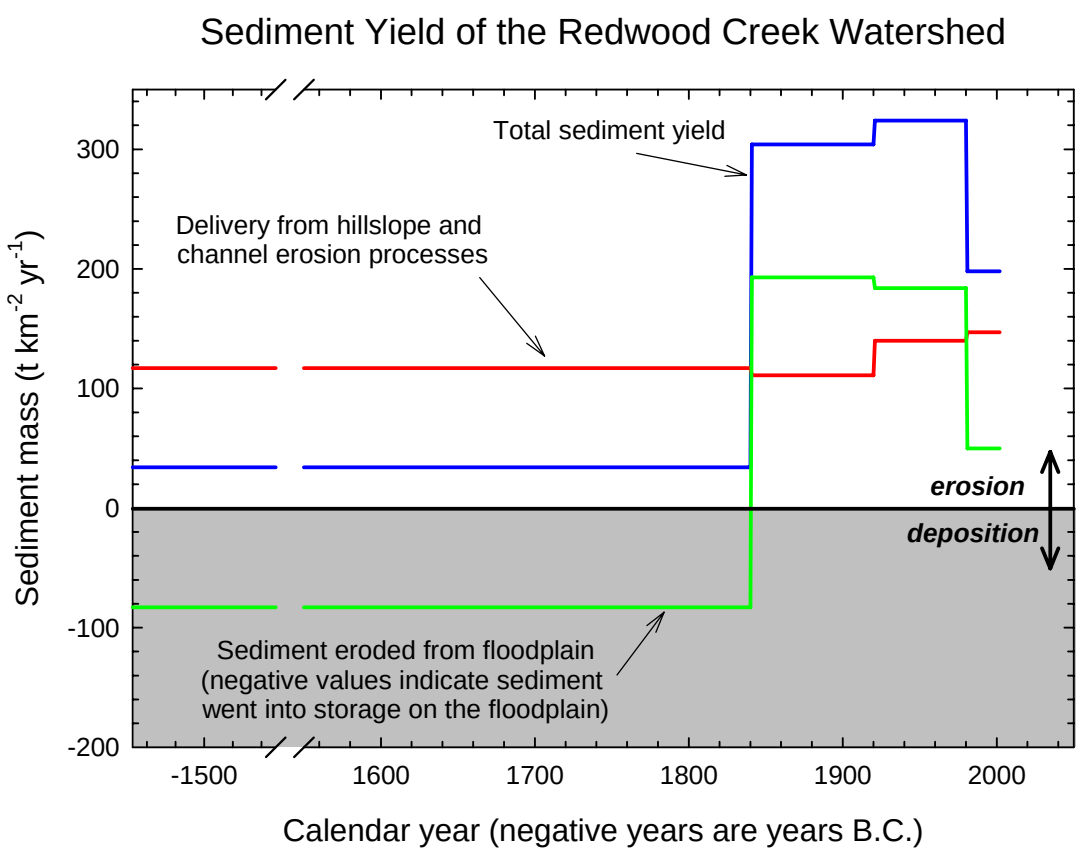


Figure 1-30. Estimated time series of total sediment yields from Redwood Creek. Adapted from Stillwater Sciences 2004.

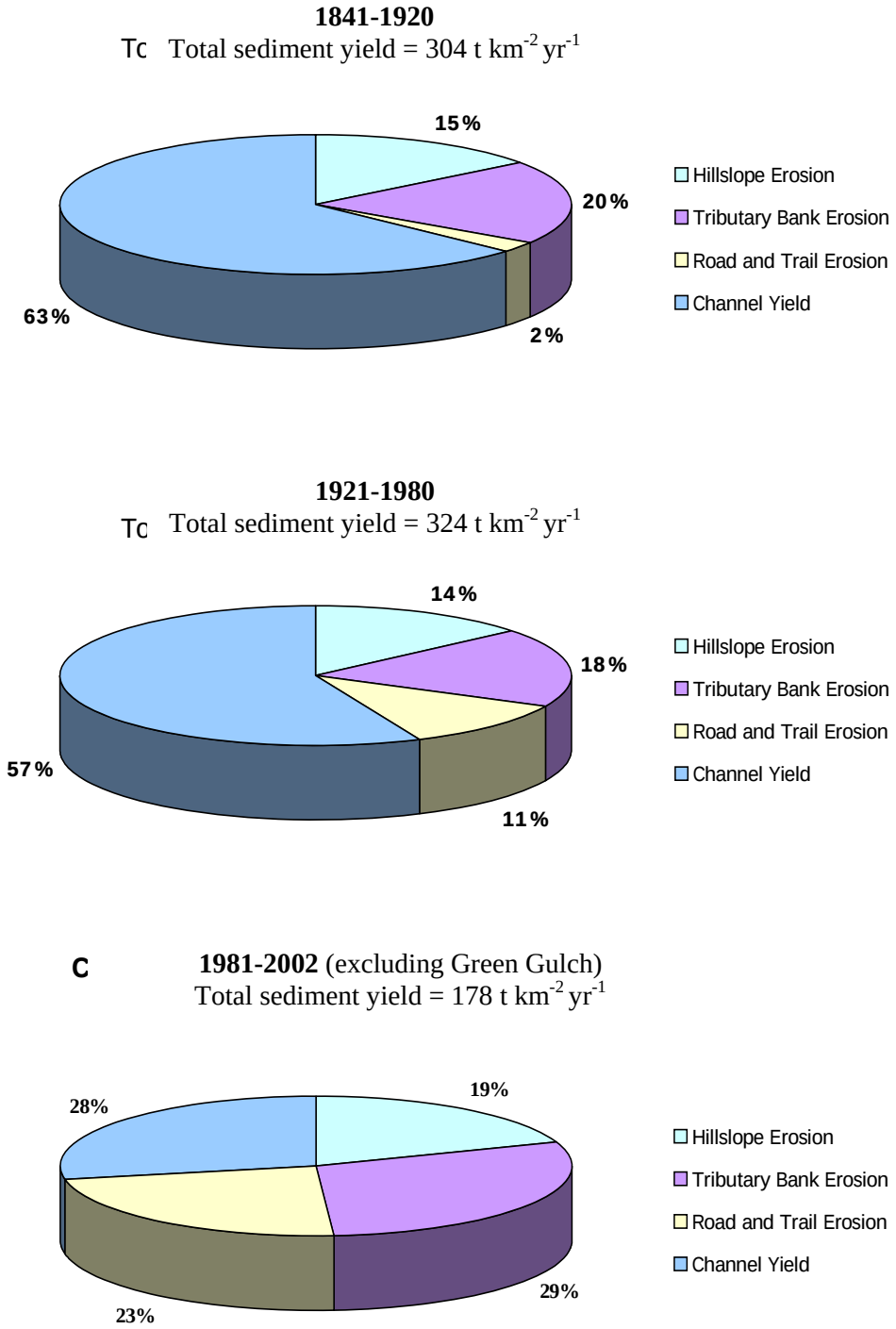


Figure 1-31. Relative contributions of sediment sources expressed in charts as percentages of the total sediment yield from the Redwood Creek watershed for the post-1840 sediment budget time periods. Adapted from Stillwater Sciences 2004.

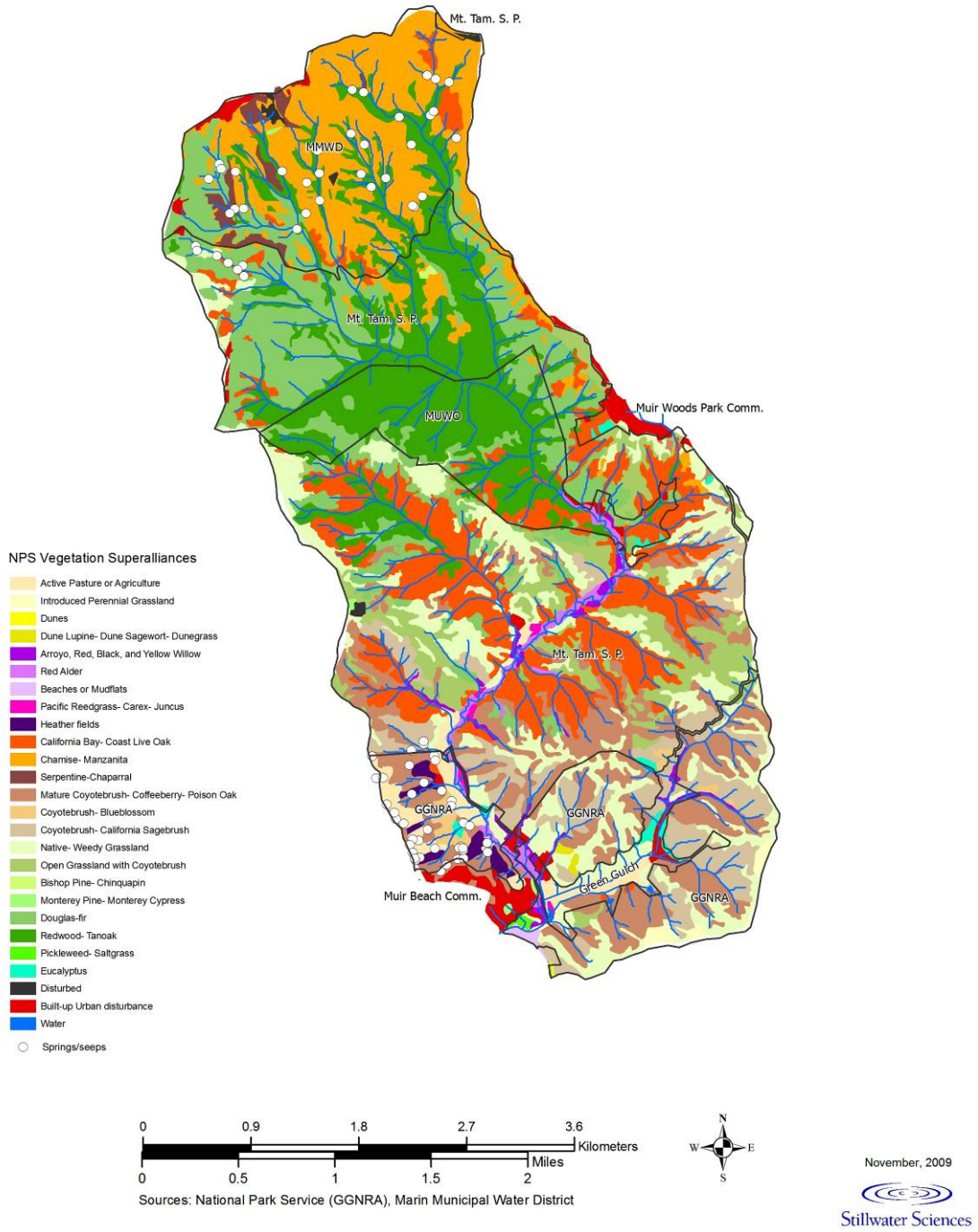


Figure 1-32. Vegetation cover types in the Redwood Creek watershed. Sources: NPS and MMWD, unpublished data; Faden 2005.

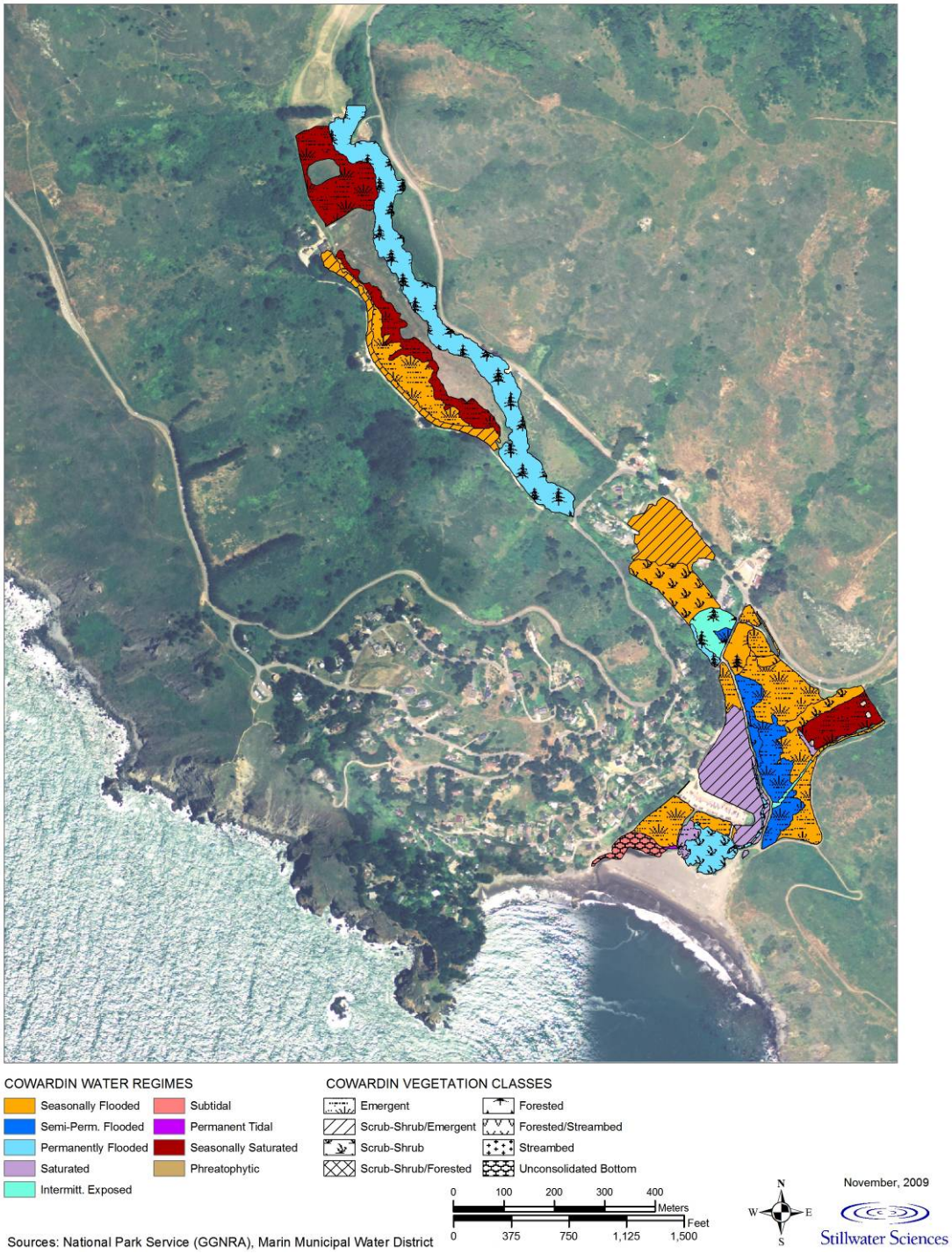


Figure 1-33. Wetlands delineated in Lower Redwood Creek Watershed based on methodology adapted from Cowardin et al. (1979).

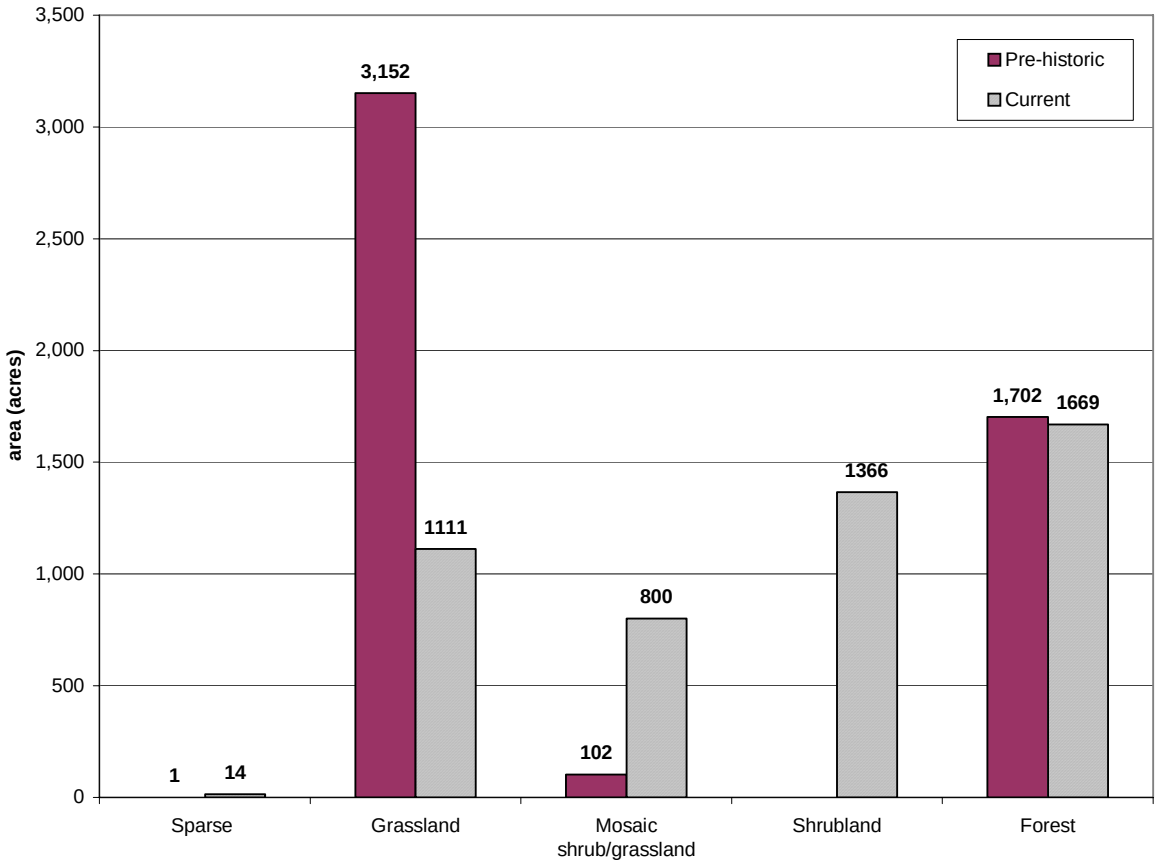


Figure 1-34. Current and pre-historic (i.e., pre-European) vegetation composition for Bicknell et al. "Site A", approximately half of which is within the Redwood Creek watershed. Adapted from Bicknell et al. (1993).

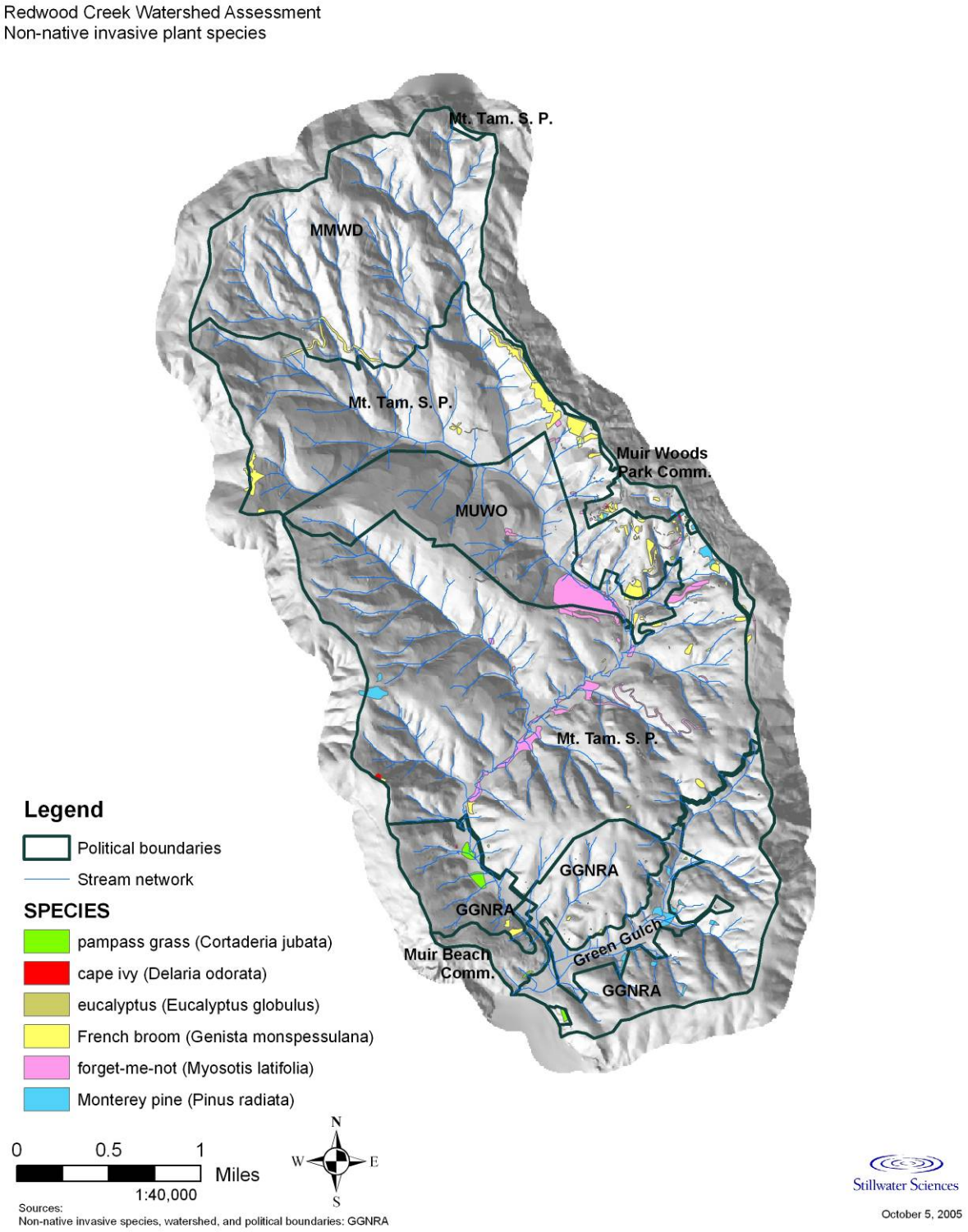


Figure 1-35. Distribution of non-native invasive plant species that have been the target of recent control efforts in the Redwood Creek watershed. These species include cape ivy (*Delaria odorata*) pampass grass (*Cortaderia jubata*), eucalyptus (*Eucalyptus globulus*), French broom (*Genista monspessulana*), forget-me-not (*Myosotis latifolia*), and Monterey pine (*Pinus radiata*). Source: NPS unpublished data.

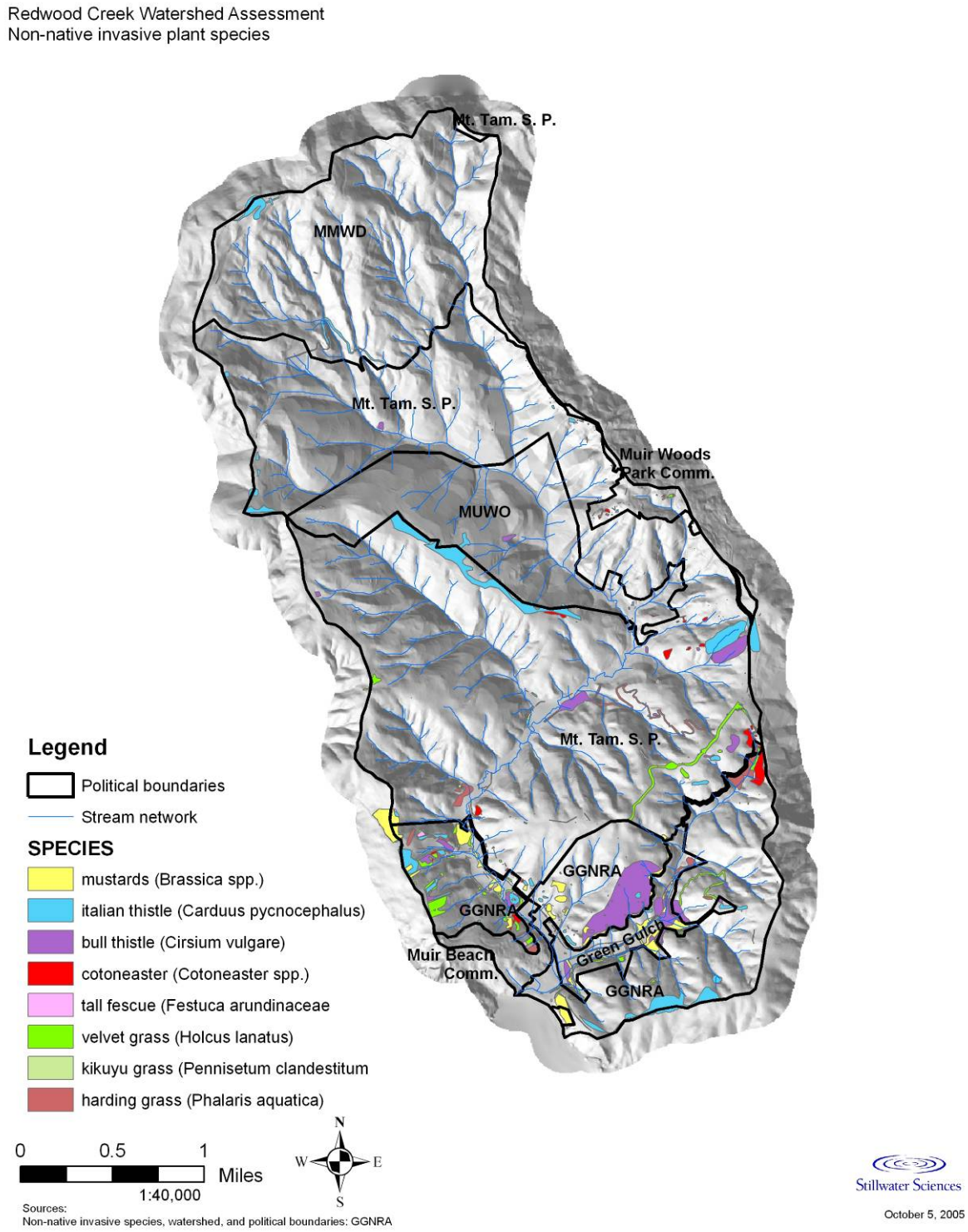


Figure 1-36. Distribution of non-native invasive plant species that occupy a significant area of the Redwood Creek watershed, but have not been the target of extensive control efforts. These species include cotoneaster (*Cotoneaster* sp.), velvet grass (*Holcus lanatus*), tall fescue (*Festuca arundinaceae*), harding grass (*Phalaris aquatica*), kikuyu grass (*Pennisetum clandestitum*), bull thistle (*Cirsium vulgare*), Italian thistle (*Carduus pycnocephalus*), and mustards (*Brassica* spp.). Source: NPS unpublished data.

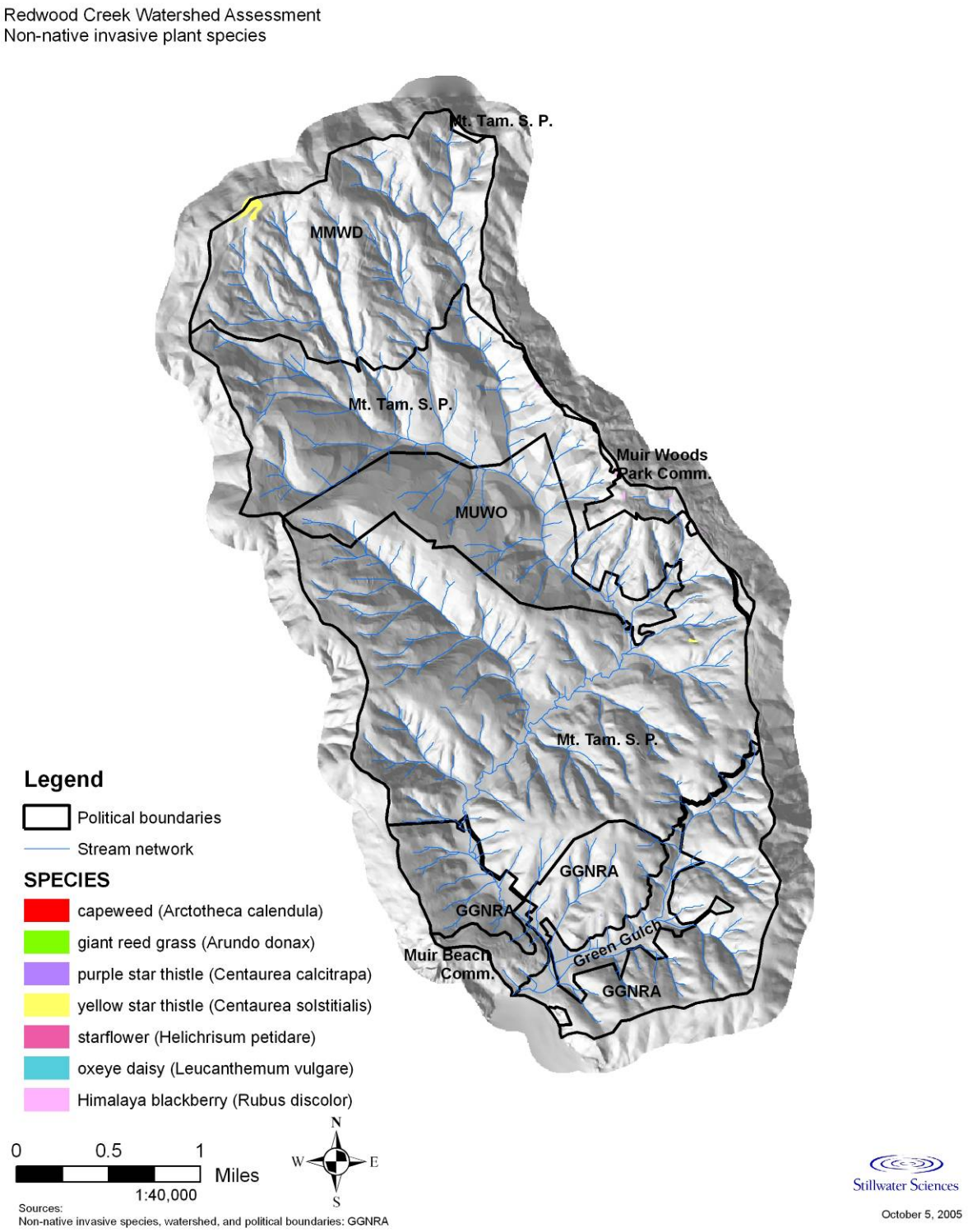


Figure 1-37. Distribution of non-native invasive plant species that are highly invasive, but currently occupy only limited areas within the Redwood Creek watershed. These species inlcude yellow star thistle (*Centaurea solstitialis*), giant reed grass (*Arundo donax*), starflower (*Helichrisum petidare*), ox-eye daisy (*Leucanthemum vulgare*), capeweed (*Arctotheca calendula*), purple star thistle (*Centaurea calcitrapa*), and Himalaya blackberry (*Rubus discolor*).