



Photos: Redwood Creek (ReachA), prickly sculpin (*Cottus asper*)
Field crew

EVALUATION OF FISH AND HABITAT CHARACTERISTICS NEAR THE MUIR BEACH COMMUNITY SERVICE DISTRICT'S WATER SUPPLY WELL IN REDWOOD CREEK, MARIN CO, CALIFORNIA.

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COVER PHOTOS

Courtesy of Peter Van der Naillen (NPS VIP)

EXECUTIVE SUMMARY

The National Park Service conducted a multiyear study to determine the influence of well operations on instream flow conditions for fish within the Redwood Creek watershed, Marin County, California. The ultimate goal of the study was to identify mitigation measures that would ameliorate the effects of pumping operations on aquatic life and to identify scientifically based thresholds for monitoring and action. The results indicated a short lag time between pump activity and response in the creek during dry years and dry season conditions. Comparison of pumping activity and stream water surface levels showed connectivity between groundwater conditions at the well and adjacent creek water surface elevations. Under dry conditions, normal pumping rates can temporarily lower water surface elevations and sometimes below streambed surface. Dry creek conditions and disconnection of pool habitats have occurred for nearly 50% of the years since 1991. These conditions have occurred when rainfall amounts during the rain season (November through April) are less than 33 inches. The disconnected pools and dry creek areas are downstream of the Muir Beach Community Services District (MBCSD) facility and can extend 2.4 km to the creek's confluence with the Pacific Ocean. Isolated pools have resulted in significantly lower dissolved oxygen concentrations than pools with upstream riffles providing surface water inflow. Based on past data, extended weather conditions during the summer-fall low flow period can result in major changes in water surface elevations, pool connectivity and dissolved oxygen conditions.

No major differences in fish metrics can be detected sites upstream and downstream of the MBCSD facility during years with average or greater rainfall amounts during the rain season. However, densities, overall fish production, and diversity below the MBCSD facility are reduced during dry years. The few fish that manage to survive are generally plumper when compared to similar fish upstream of the MBCSD facility and to all sites during wetter years. Under dry year conditions, there is a potential for a 10 percent reduction in watershed fish production. The contribution of water withdrawal activities to this reduction is unknown.

We provide several recommendations that would help reduce impacts on instream fishery resources or fill key data gaps. These recommendations include: initiation of actions to obtain "take" authorization for listed fish, re-evaluation of current pumping schedule to protect natural streamflow patterns, changing the definition of "dry year" to 33 inches of rainfall during the rain season, and continued evaluation of means to reduce water consumption and/or increase water supply and storage.

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INTRODUCTION

The Redwood Creek watershed drains a 8.9 sq. mile area within southern Marin Co., California (Figure 1). The lands are within ownership of a handful of organizations: the Golden Gate National Recreation Area (GOGA), Mt. Tamalpais State Park, Marin Municipal Water District (MMWD), Green Gulch Farms, and the community of Muir Beach (Figure 2).

A well near Redwood Creek is the sole source of water for the community of Muir Beach. Consultants for the Muir Beach Community Services District estimated that fall monthly maximum well production (Water Years 1991-1997) ranged between 0.085 to 0.11 cubic feet per second (cfs) (Trihey and Assoc., unpub. data, 1997). According to modeling rather than field data, they concluded that short-term losses in streamflow from pumping activities could range up to 0.03 cfs (Trihey & Assoc., 1997).

In August of 1988, Muir Beach Community Services District (MBCSD) filed Application 29331 with the State Water Resources Control Board (SWRCB) to legitimize the diversion of up to 0.07 cfs (50.6 acre-feet per year). This application was protested based upon Environmental Considerations, Public Interest, Public Trust, and Other Issues by the California Department of Fish and Game (CDFG), California Department of Parks and Recreation, and the United States, National Park Service. A protest was also filed based on injury to Vested Rights on behalf of the United States, National Park Service.

In the National Park Service's protest based on Environmental Considerations, Public Interest, Public Trust, and Other Issues, it recognized MBCSD's need for water, but stated that,

“an assessment of the environmental impacts to Redwood Creek should be prepared to particularly evaluate the effects of the MBCSD's diversions upon coho salmon and steelhead trout and their habitats.”

In the protest based on injury to Vested Rights, it stated that,

“an assessment of depletions to Redwood Creek should be prepared to evaluate the effects of MBCSD's diversions upon the availability of water for downstream use.”

The National Park Service had taken a position that the protest would best be resolved and stream flows protected by extending municipal water service to Muir Beach and ceasing diversions from Redwood Creek. In 1997, the park modified this position proposing that if MBCSD could show that water could be taken from the wells without harming the creek ecosystem, then the park would withdraw its protest. This has resulted in the need to examine the physical relationship between the water diversion and the creek ecosystem. Numerous reports indicate that there is an area, near the MBCSD wells, where surface flow becomes intermittent. Protection of in-stream flow is perhaps the most important

aquatic resource protection project that can be undertaken in this watershed. To date, the MBCSD has conducted limited field investigations to assess impacts of their well operations on instream flows and aquatic life. In 1997, the MBCSD did conduct a review of existing data and developed a threshold instream flow level (0.53 cfs) for initiating mitigation measures (Trihey and Assoc. 1997).

Since 1988, several extreme low flow periods have occurred in lower Redwood Creek, the most recent event occurring in 2004. In these cases, surface flows were intermittent leaving dry stretches and pools isolated from surface flows of the creek (Hofstra and Anderson 1989, Smith 1994, and Smith 1997). These reduced flows impact not only the area extent of habitat, but also water quality, when reduced flows may limit aeration and directly reduce levels of dissolved oxygen (Smith 2003, Hofstra and Anderson 1989). These events reduce and sometimes eliminate the capacity of the habitat to support juvenile coho salmon (*Oncorhynchus kisutch*) and the steelhead trout (*Oncorhynchus mykiss*).

Both of these species are protected under the Endangered Species Act of 1973 (as amended). The coho salmon in Redwood Creek are part of the Central California Coast Evolutionarily Significant Unit and are listed as endangered by the National Marine Fisheries Service (NMFS) (70 FR 37160). Steelhead are part of the Central California Coast Distinct Population Segment listed as threatened by NMFS. Furthermore, critical habitat for coho salmon and steelhead in this area have been designated (62 FR 43937 and 70 FR 52488).

All parties are working towards implementing an agreeable plan to allow withdrawal of water from the Redwood Creek basin while protecting instream resources. In a letter dated October 31, 2000, the NPS withdrew its protest to MBCSD's water rights application. In January 2001, the State Board issued Permit 21085 which required the development of an adaptive management plan with help from a Technical Advisory Committee composed of representatives from MBCSD, SWRCB, NMFS, California Department of Fish and Game, California Department of Parks and Recreation, and NPS. This Adaptive Management Plan (AMP) included a water conservation plan, monitoring program, evaluation of alternative water sources and storage options, pumping schedule, and reporting schedule. Most importantly, the document was written and intended to be a "living" document that could be updated in the future.

Objectives

This project was part of a much larger investigation (GOGA-N-005.5 Redwood Creek Water Rights Study) which was intended to resolve the water rights protests, protect resources in Redwood Creek, and provide Muir Beach a dependable water supply for existing uses. To accomplish these goals, the investigation contained three components: Muir Beach community partnerships, a hydrologic study, and a fisheries study. Specific to the fisheries study, our goals were to:

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1. Establish relationships between water quality, groundwater, instream flow, physical habitat parameters and the native fish community, particularly the threatened coho and steelhead.
 2. Determine biologically based threshold levels for management actions.

BACKGROUND

General Well Operations

The Muir Beach Community Services District (MBCSD) was formed in 1958 and provides potable water to a small community at Muir Beach, Marin Co., California at the mouth of Redwood Creek (Figure 2). The MBCSD has 147 service connections, supplying approximately 350 persons (Martin 2000). Known potable water withdrawals for this community (then known as the Bello Subdivision) first occurred from a well established between 1898 and 1899 near the present-day Pelican Inn Restaurant (Martin 2000, MBCSD 2004).

The community well sites have been located at progressively further distances from the creek. Prior to 1996, water was pumped from a well about 6 m from the streambank. From June 1996 to 2004, the community of Muir Beach obtained its water from a shallow well located about 18 meters away from the edge of the stream (Trihey & Assoc. 1997, Leighton Hills, general manager MBCSD, pers. comm. 2007). This well extended 11 m below ground and in unconsolidated alluvial deposits in the Frank Valley portion of Redwood Creek (Martin 2000). In 2002, a new well was drilled to a depth of 18 m about 26 m away from the creek. This well went into service by 2004 (L. Hills, pers. comm. 2007). The pumps for the current and prior well (1996-2004 period) are 10 hp submersible Grundfos pumps that pump at a fixed rate (approx. 55 gallons per minute) (L. Hills, pers. comm. 2007).

Gross annual well production from 1990 to 1995 ranged from 37.7 acre-feet (46,500 cubic meters) to 52.43 acre-feet (64,700 cubic meters). For Water Year 1991 through 1997, the average well pumping rates varied from 0.05 cfs (0.001 cubic meters per second, cms) during the winter to 0.07 cfs (0.002 cms) from June through August (Trihey and Assoc., 1997). The maximum daily well production ranged from 0.08 cfs (0.002 cms) in the winter to 0.11 cfs (0.003 cms) in summer (Trihey and Assoc., 1997).

Starting in 2001, well operations were governed by the conditions of a water right permit issued by the State Water Resources Control Board (Permit 21085, issued January 19, 2001). The permit authorizes the MBCSD to take no more than 50.6 acre-ft of water per year. The permit also led to the development of an adaptive management plan to minimize impacts on the adjacent creek. The MBCSD established a multi-faceted conservation plan including a tiered rate structure designed to prevent excessive use of water, public information program, and leak

detection program. It established a gross water production rate of 45,000 gpd based on a 30-day average. Gross water production is limited to no more than 35,000 gpd during designated water conservation periods. Pumping duration was also restricted to no more than 14 hours per day and the maximum pumping rate is 53 gpm (0.12 cfs).

Following adoption of the adaptive management plan in 2001, water use during the dry season has declined. Average daily per capita water use for 1997-1999 for the month of October was 104 gallons (Table 1). Average daily per capita water use for 2001-2004 for the month of October was 85 gallons, a reduction of 18 percent (Table 1). In addition, mandatory conservation measures have resulted in temporary declines in overall water use. On October 9, 2002, a notice for conservation was sent to all customers resulting in decreasing daily water production from 37800 gallons (Oct 1-9) to 34100 (Oct 10-31). This drop represented an 11 percent reduction.

How does water use at Muir Beach compare with other nearby communities in Marin County? Good comparisons are difficult. Communities such as Point Reyes Station have intermixed residential, commercial, and agricultural users—making it difficult to tease out residential per capita use (David Bentley, pers. comm., North Marin Water District, 2005). Per capita comparisons are also complicated because accurate estimates of the number of residential users are not available. Philip Buchanan, the manager of the Bolinas Public Utilities District, estimated that they serve a residential population of 1500 - 1700 people (Town of Bolinas, Marin Co., CA). If one assumes that the true population lies halfway between, estimated daily per capita water consumption for Bolinas residents for October averages 102 gallons, a 17 percent higher usage than the Muir Beach community for the same period. Even when the smallest estimated population size of Bolinas is used, the Muir Beach community still has a lower per capita water use (85 vs. 95 gallons per person per day).

Past Work

GOGA had contracted the services of a hydrologic consulting firm to determine the effects of water diversions on instream flows in Redwood Creek. Using a flow-duration curve derived for Redwood Creek by USGS at nearby Arroyo Corte Madera del Presidio (which lacks diversions), Schanz et al. (1995) estimated that 0.0 cfs would occur roughly every four years and that periods of 0 flow (isolated pools) lasting 30 days or more would occur naturally once every 17 years.

The California Department of Fish and Game conducted the earliest work to assess the impacts of water diversions on fisheries in Redwood Creek (Snider 1984). Snider (1984) investigated the potential impacts of a diversion by a proposed hostel within the Redwood Creek watershed using the Toe-Width Method. The results indicated that preferred rearing flows for juvenile salmonids are generally absent for most of the year. The report determined flows of 9 cfs to be the mean preferred

rearing habitat flow. From May through October, it recommended that no diversion occur when natural flows fall below this mean preferred rearing habitat flow.

Under contract with the MBCSD, Trihey & Assoc. (1997) looked at the current well production regime and estimated streamflow losses to determine a flow threshold at which habitat for steelhead and coho would be impaired. Using data from Schanz et. al. (1995), they concluded that the existing well (18 m from the stream) could reduce streamflow by as much as 0.03 cfs after 12 hours of continuous pumping. They felt that this reduction would not affect fish habitat or fish numbers when streamflows are above 0.53 cfs. However, when streamflows are less than 0.53 cfs, fish loss would be proportional to the reduction in stream flow (Trihey & Assoc. 1997). At extremely low flows, reduction of habitat would be more detrimental to steelhead using shallow water habitats, while coho would be affected more by adverse water quality conditions (low dissolved oxygen). They recommended MBCSD develop a list of additional mitigation measures that MBCSD would be willing to implement when streamflows are less than 0.53 cfs.

Existing data indicate potential issues associated with water diversions and fisheries (Hofstra and Anderson 1989, Smith 1994). Long-term monitoring of juvenile salmonids in Redwood Creek using index stations was initiated by Dr. Jerry Smith (San Jose State Univ.) in 1992. One of the index stations was located downstream of the MBCSD facilities. His data showed 5 of 11 fall sampling events with dry streambed conditions that resulted in either the total absence of fish or reduced numbers relative to other stations (Table 2). He suggested that this loss was the result of either total loss of habitat (dry streambed) or from poor dissolved oxygen concentrations in the isolated pools. In 1997, he estimated that dry creek conditions between the MBCSD facilities and below the Pacific Way Bridge have resulted in the loss of 1300-1400 juvenile coho salmon.

Watershed Characteristics:

The Redwood Creek watershed is a 8.9 square mile watershed in Marin Co., California that is largely within public ownership. Much of the watershed is maintained as open space with watershed vegetation comprised mainly of mixed conifer forests, mixed hardwoods, chaparral, grasslands, and deciduous riparian communities.

Mean annual rainfall is 37.5 inches per year (Muir Woods National Monument weather station, National Climatic Data Center Cooperative Station # 46027, 1948 to present) with most of the annual rainfall occurring between October and April. Streamflows are characteristic of coastal California watersheds lacking snowmelt runoff. Peak winter flows measured by the USGS ranged between 330 to 1,800 cfs with summer flows ranging from 1 cfs to 0 cfs (isolated pools) (PWA 1994). The GOGA currently manages a stream gauging station (1997 to present) on Redwood Creek at the Highway One bridge. A typical hydrograph showing mean daily discharge data for our Highway One gaging station is provided in Figure 3.

Project Area Characteristics

The project area includes 1.5 km of creek extending upstream from the Highway 1 Bridge (0 km) to just above the Muir Woods Road bridge (Figure 4). The study area is bordered by Muir Woods/Frank Valley Road to the east and the fallow Banducci flower fields to the west.

The channel within the project area has undergone several changes within recent history. Around 1948 or 1949, the alluvial plain west of Redwood Creek was leveled to improve crop production. The historic intermittent tributaries that entered Redwood Creek within this reach were consolidated and realigned. Berms were constructed along portions of the creek to prevent flooding in prime agricultural areas. Historic photos from 1947 also show an incised channel and little if any riparian tree and shrubs. Since then riparian vegetation has regrown, but it is restricted to a narrow band along the steep channel banks and is primarily an even-aged stand of red alder (*Alnus rubra*) and some willows (*Salix lasiolepis*).

The project reach is heavily shaded and contains similar percentages of pool and shallower habitats (e.g., riffle and flatwater). Canopy density measurements in summer 1995 using a spherical densiometer within the project reach indicate heavy shading by overstory vegetation with very little variability (mean density= 95%, S.D.= 8%, n=17) (Fong 2002). Summer stream habitat inventories conducted throughout the project reach in 1995, 1998, and 1999 show a slightly higher percentage of pools (by length) than riffle and flatwater habitats for all three years.

As with many north coast streams, the stream fish assemblage is species poor. Four species of sculpins—Pacific staghorn sculpin (*Leptocottus armatus*), prickly sculpin (*Cottus asper*), coast-range sculpin (*C. aleuticus*), and riffle sculpin (*C. gulosus*) have been documented within the Redwood Creek watershed. In the lower freshwater reaches of Redwood Creek, threespine stickleback (*Gasterosteus aculeatus*) are common. Coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*) can be found from the mouth of Redwood Creek into the headwater reaches of the watershed.

Other aquatic vertebrates within the project area may include western pond turtle (*Clemmys marmorata*), river otter (*Lutra canadensis*), western toad (*Bufo borealis*), the federally threatened California red-legged frog (*Rana aurora draytonii*), Pacific chorus frog (*Pseudacris regilla*), California giant salamander (*Dicamptodon ensatus*), California newt (*Taricha torosa*), and rough-skinned newt (*Taricha granulosa*)— species that have been found in the watershed. None of the aforementioned vertebrates are likely to breed within the project area; however, they all may use the creek channel and adjoining riparian area as non-breeding habitat.

No sensitive aquatic invertebrates are likely from the project area. No endangered California freshwater shrimp within the Redwood Creek watershed were found during surveys conducted in 1986 and 1997 (Serpa 1986, Fong 1999). Surveys conducted by Hafernik (1992) in the Muir Beach area did not encounter the San Francisco fork-tailed damselfly (*Ischnura gemina*), Leech's Skyline diving beetle (*Hydroporus leechi*) or the Ricksecker's water scavenger beetle (*Hydrochara rickseckeri*).

METHODS

General Approach

Specific assessment tasks have been developed as part of the effort to identify appropriate management measures to protect fishery resources within the project area. These specific tasks included:

1. Identify linkages between pumping operations and stream habitat conditions, including water quality, under dry and wet year conditions
2. To assess the relative contribution of fish production within the study area to the entire Redwood Creek basin
3. Identify differences in juvenile salmonid characteristics between reaches upstream and downstream of MBCSD well.
4. Identify easily measured parameters that can be used as "triggers" for management actions.
5. Identify data gaps and provide suggestions to resolve them.

Period of Study

This assessment occurred over five, non-continuous years: 1998, 1999, 2001, 2002, and 2004. This wide time span allowed the assessment to occur over a range of rainfall and streamflow conditions. The study focused on the late spring through fall period because water withdrawals are the greatest and streamflow the lowest. We would be unlikely to discern any impacts of normal pumping operations to streamflows outside of this period. Maximum withdrawal rates are often less than the potential errors associated with estimating streamflow at our gaging station. To illustrate, mean daily streamflows in winter and spring are generally in excess of 1 cfs. If you used the general rule of thumb that streamflow measurement errors hover around 10%, this would amount to a measurement error of roughly 0.1 cfs. This potential measurement error is larger than the average well production for Water Years 1991 through 1997, where production ranged from 0.05 cfs (winter) to 0.07 cfs (June through August) (Trihey and Assoc., 1997).

Project Area

The study area included a 2-km stretch of Redwood Creek starting from the Highway One bridge. The study area was divided into three reaches. The

downstream end of our first study reach (Reach A) started at the Highway One bridge (1.3 km upstream from the Pacific Ocean). The middle study reach, Reach B, was located immediately below the MBCSD facilities and the control site, Reach C, just upstream. The reach distances and locations varied slightly between 1998 and 1999 (Figures 4-5). After 1998 we shortened the control reach and moved it closer to the well to minimize concerns regarding differences in physical habitat conditions that are not associated with well operation (Figures 6-7). Above the Frank Valley/Muir Woods Road Bridge, the channel is less confined and is situated further from the road. In general, reach locations and distances were as follows:

- Reach A) Downstream-most “treatment” (0 to 0.6 km)
- Reach B) Directly below “treatment” (0.6 to 1.2 km)
- Reach C) Above MBCSD facilities “control” (1.4 to 2.0 km {1998}; 1.2 to 1.6 km {all other years})

Fish and water quality data were collected at stations (pool units) selected systematically from a random start. The systematic selection was intended to ensure that sample sites were spread evenly. Generally, sample sites within these reaches were selected systematically (every fifth pool) using a random start. Most locations of the sampled stations were obtained using a GPS unit (Trimble GeoExplorer III) with a few sites determined by measuring the distance from a known coordinate in our GIS program (ArcView 3.3). The locations of the sampled stations are provided in Appendix I for each year.

Fish Assessment

General approaches in other instream flow assessment studies have quantified the relationship between fish habitat and streamflow and have predicted habitat value for target species and life stages under varying flow conditions. Generally, models are based on physical habitat conditions (e.g., water depth and velocity). Model results can come up with optimal conditions that are less than realistic.

As an example, we looked at estimated optimal and minimum flow conditions for juvenile salmonids in Redwood Creek based on techniques used on other local, northern California streams (Table 4). The results indicate that optimal rearing flows for juvenile salmonids in Redwood Creek would only occur under winter and spring baseflow conditions. Even minimum instream flows based on the Lagunitas Creek criteria would only be achieved during the early to late spring months in Redwood Creek. Based on these results, natural summer and fall streamflow conditions in Redwood Creek would always be suboptimal.

Therefore, rather than trying to use typical instream flow methodologies to predict physical habitat availability for fish, we looked at whether changing summer low flow conditions resulted in departures from a “good condition.” Through recent California court decisions (e.g., Mono Lake and Putah Creek), biologists have argued successfully for the protection of instream flows below

dams (Moyle et al., 1998). Their approaches went beyond single-species or single life-stage management and towards a desire to protect aquatic ecological health. Moyle et. al. (1998) defined "good condition" as whether a stream contained healthy individual fish in a healthy population that were part of healthy biotic communities. This approach requires the determination of "health" at three scales: individual, community, and population. The general question that we were trying to answer was as follows:

Is well pumping affecting "good condition" as discerned from differences between areas downstream and upstream of the well site?

Any study to assess "good condition" should ideally focus on all components of the ecosystem. It is possible that impacts from water diversion could impact other biotic components of the ecosystem-including the benthic invertebrate community, adjacent riparian vegetation, just to name two.

However, we focused on fish to assess whether water withdrawals affected the biological health of the stream. Standardized field sampling and data analyses for fish, particularly juvenile salmonids, were available. Also, fish data have often been the primary tool in arguing for instream flow protection for natural resources. Initial studies in Redwood Creek have provided information about what the authors had believed to be the extent and type of fishery impacts associated with water withdrawal that this study could draw upon (Smith 1994, Hofstra and Anderson 1989). The emphasis on a fisheries assessment is also consistent with the Park's requirements under the Endangered Species Act of 1973 (as amended). Results from this study would help establish thresholds for actions to protect two federally-listed species. Section 7(a)(1) of the Endangered Species Act directs Federal agencies to further the purposes the Act by carrying out conservation programs for listed species. In addition, if studies indicate adverse impacts of well diversions on listed species, an Endangered Species consultation with NMFS to cover the scope and impact of pumping operations on listed fish and designated critical habitat.

Given the study period (summer-fall), we looked at the scientific literature and our past work in local streams to determine the fish species and life stages likely present and possible impacts (Table 5). The predominant life stages and taxa affected would include juvenile coho and steelhead and sculpin (adult/juvenile). Any effects of streamflow reductions and habitat changes would be primarily associated with rearing habitat, although some sculpin and steelhead egg incubation and steelhead outmigration could be affected to a lesser extent (Table 5).

Fish Population Assessment

One of the study objectives was to assess the relative contribution of fish production within the study reaches (A-C) to the entire Redwood Creek basin. If the study reaches contributed substantially to basin production of fish, we would conclude that any impacts to fish production within these reaches would also be significant at the basin scale. To answer this question, we conducted a reach and basin-wide fish and habitat survey in 1998. In 1999, only a reach-wide fish and habitat survey was completed. Fish and habitat conditions in 1998 and 1999 represented “wet” conditions based on accumulated rainfall.

Habitat survey procedures followed those described in Dollof et al. (1993). Habitat units were identified to Level III (Flosi and Reynolds 1994) and the lengths measured to nearest 0.1 m with a hip chain. Average width was visually estimated for each habitat unit. On every fifth pool unit several widths were measured and used to calculate average width and measured surface area. A calibration ratio was calculated from paired estimated and measured widths and used to correct estimated surface areas (Dollof et al. 1993). For 1998 and 2004, we summarized habitat data for mainstem Redwood Creek from approximately km 0 (Pacific Way bridge in Muir Beach) to km 7.1 (Bridge 4 in Muir Woods).

To estimate fish abundance throughout the basin, we adapted the two-stage fish estimation procedures which involves extensive fish counts by snorkelers and infrequent calibration counts using standard multiple pass electrofishing removal efforts (Dollof et al. 1993). Electrofishing abundance estimates for fish were calculated using the computer program, MICROFISH 3.0 (Van deventer and Platts 1988).

Sampling activities focused on pool habitats. No shallow water habitats were sampled during the basinwide surveys. Although flatwater and riffle would be the habitats most affected by reduced flows, it was determined that riffle and flatwater habitats generally supported low numbers of YOY steelhead during the summer and few if any coho. Also, the shallowness of these habitats would preclude snorkel surveys. Riffle and flatwater habitats were sampled separately as part of index stations established initially by Dr. Jerry Smith and continued in his and GOGA’s long-term monitoring program. Data from index stations within the project area were used to extrapolate total fish losses at dewatered habitats.

Also, during data analyses we found relatively low correlation of snorkel counts (steelhead young of the year, 1+ and older) with electrofishing estimates in 1998. Therefore, we estimated basin and reach abundance of steelhead by expanding electrofishing estimates for sampled fish units to unsampled habitat units using a ratio of means estimator (Bohlin 1989). Because snorkel surveys are not able to accurately quantify sculpin, we also estimated sculpin abundance by expanding electrofishing estimates for sampled fish units to unsampled habitat units using a ratio of means estimator.

Electrofishing Procedures. In 1998-1999, selected pools were sampled in the beginning of the summer (flows approx. 1 cfs) and again in the fall (prior to rains) using multiple-pass electrofishing. In 2001 and 2004, fish sampling occurred once in September-October. Typically, two to four passes per pool were conducted with a programmable waveform backpack electrofisher (Smith-Root Model 12 B-POW). Fish were captured using straight direct current with the minimum voltage and frequency necessary for immobilization. Pursuant to our Section 10 permit, a log was kept of all settings, pertinent environmental conditions, and fish response. Potential sources of mortality or injury included general stress during capture and handling, respiratory failure, and hemorrhaging or spinal injuries associated with shocking. If a pattern of mortality or injury was recognized, techniques were altered to reduce impacts. Captured fish were sedated using carbon dioxide, identified to species, measured for fork length (nearest mm), and weighed (nearest 0.5 g in 1998 using Pesola spring scales and nearest 0.1 g with Ohaus Scout Model SC4010 {with weighing hook} in 1999). Scales from just below the dorsal fin were obtained from a subset of coho and steelhead of various lengths. Fish were kept in aerated holding buckets before and after handling, and allowed to recover fully before being released. During electrofishing surveys, young-of-the-year salmonids were kept in separate buckets from sculpin and older fish to avoid predation.

Aging of Steelhead. Juvenile steelhead were differentiated into age classes for analyses. We used the scale readings and abrupt changes in the shape of the length-frequency distributions of steelhead to identify age classes. Of the 2618 measured steelhead for 1998 and 1999, 165 scales were mounted and read (Rauber 2000). The data from scale readings corroborated information from the length-frequency distributions. There were four age classes of steelhead: YOY (0+), 1+, 2+, and 3+ (Rauber, unpubl. data, 2000). Young-of-the-year steelhead during the early summer through fall ranged in lengths from 70 to 113 mm. 1+ steelhead spanned a broader range of fork lengths (100 to 160 mm) and overlapped greatly with 2+ steelhead (130-180 mm) (Rauber 2000). The 3+ steelhead were all between 200 to 250 mm FL. Because of the difficulties in separating out 1+ and 2+ steelhead without reading the scales of every fish, we lumped both age classes together for analyses. Also, we used 100 mm as the criteria for distinguishing YOY and 1+ steelhead for our analyses.

Fish Community Assessment

We wanted to assess whether there were significant differences amongst the study reaches in terms of the proportional abundance of various fish species and age classes. It is possible that pumping impacts could affect certain species or age classes more than others. In West Union Creek, a headwater stream in the San Francisquito Creek watershed (San Mateo Co., CA), frequent stream drying events have resulted in loss of resident sculpins and have maintained a single species fish community of steelhead (Fong 2004).

We used two common indices (modified Simpson and Brillouin) to describe the proportional abundance of the fish community assemblage for each pool (Magurran 1988, Krebs 1989). Relatively high Brillouin index values indicate roughly equal proportions of fish from all possible age classes and taxa groupings. The formula is represented as:

$$H = \frac{1}{N} \log_e \left(\frac{N!}{n_i! n_{i+1}! \dots} \right)$$

where H = Brillouin's index, N= total number of individuals, n_i = number of individuals belonging to i^{th} grouping (Magurran 1988, Krebs 1989). We used the complement of the Simpson's index of diversity (Krebs 1989). It describes the probability that two individuals picked at random from the sampled community belong to different species, or in our case, different age classes or taxa groupings. This index is represented as:

$$1 - \hat{D} = 1 - \sum_{i=1 \text{ to } i} \left[\frac{n_i(n_i - 1)}{N(N - 1)} \right]$$

where $1 - \hat{D}$ = Simpson's index of diversity, N= total number of individuals, and n_i = number of individuals belonging to i^{th} grouping (Krebs 1989).

We also looked at differences in standing biomass for all fish taxa and age classes within the three reaches. We represented the standing biomass estimates for individual pools as the product of mean individual weight and estimated number of fish (by taxa and age class). Individual sculpin weights were predicted for 1998-1999 using lumped data from 1999 (n=5), 2001 (n=197), and 2002 (n=11) from the same area. The predicted weights were best described with a power function where

$$Y (\text{weight, g}) = 1.6861 \times 10^{-5} \times X^{2.95797} (\text{length, mm}), R^2=0.99.$$

The taxa groupings that we used included steelhead young-of-the-year, steelhead 1+/2+, juvenile coho, threespine stickleback, and sculpin. We separated steelhead into two groups because of differences in known habitat utilization. Steelhead young-of-the-year are often found in shallow-water habitats in association with juvenile coho while steelhead 1+/2+ fish are dependent upon pools with cover. Although there are four species of sculpins present within the watershed, species identification of the *Cottus* genera in the field proved difficult. Because of our difficulties in distinguishing juvenile sculpins to species and the potential for hybridization amongst co-occurring species (P. Moyle, pers. comm., 1997), we lumped all sculpin species for data analyses.

Individual Fish Assessment

We assessed whether there were differences in the health of individual fish between reaches by looking at the growth and condition of individually marked coho and steelhead juveniles in 1998-1999. We marked individuals using fluorescent elastomer tags (Northwest Marine Technology, Inc) injected into the caudal fin, head, and area above the eyes. We did not mark fish smaller than 50 mm because of the high risk of injury. We assessed growth of fish marked at the start of summer and recaptured in the fall by looking at their instantaneous growth rate (G , change in fork length and weight per unit time) where

$$G = \frac{(\ln Y_2 - \ln Y_1)}{t_2 - t_1}$$
 and t_1 is the time at the beginning of the sampling interval, t_2 the time at the end, Y_2 and Y_1 are the respective individual fish fork lengths at those times (Busacker et al. 1990).

Juvenile condition was also assessed using the Fulton's condition factor. Fulton's condition factor (K) is represented by

$$K = \frac{\text{Weight}(g)}{\text{Length}(mm)^3} \times 100,000$$
. High Fulton condition factor indicate "plumper" and presumably healthier fish.

Identify Linkages Between Pumping Operations And Stream Habitat Conditions

Water Surface Response To Pumping

In 1999, NPS researchers tried to identify the relationship between normal pumping operations (33 gpm or 0.07 cfs), subsurface water conditions, and stream water surface elevations (Martin 2000). The results showed a strong relationship between the pumping regime and subsurface water elevations in shallow piezometers near the streambanks. However, the study was not able to detect changes in surface water elevations resulting from the low pumping rates. Pumping effects on stream water surface elevations were hard to detect because of the magnitude of diel fluctuations that were attributed to evapotranspiration.

To determine the influence of pumping operations on streamflow and local groundwater, continuously recording dataloggers (Global Water WL-14, 15 ft cable) were installed in the creek and in the bank just downstream from the well. One pressure transducer was installed in the first riffle below the MBCSD footbridge and immediately downstream of the well (Figure 8). The slotted portion of the piezometer extended both below and above the streambed to record water surface fluctuations. A second datalogger and transducer were placed in a bank piezometer (ID# P6) installed by NPS researchers in 1999 (Martin 2000). The slotted portion of this bank piezometer was between 1.5 and 3.5 feet below ground

surface (Martin 2000). The dataloggers recorded water levels to the nearest 0.01 ft every 15 minutes.

The datalogger and transducers were calibrated in the office and checked after deployment. In 2001, the piezometers were -1.1% and -0.06% different from actual water height, respectively. In 2002, the piezometers were -0.21% and 0.95% different from actual water height, respectively. Data were analyzed by overlaying the time series plots of water surface elevations of streambank and riffle piezometers along with daily pumping rates.

Information on daily production was provided by the MBCSD. Monthly well logs from 1997 to 2004 were provided by the MBCSD's general manager (Donovan McFarland). Data in the well logs included date and time of site visits, weather conditions, meter readings, gallons pumped, and fields related to chlorine treatment. We used these logs to derive pumping durations which we used along with daily weather observations to interpret stream water surface conditions. The duration of pumping was determined by dividing the daily production by the fixed pump rate (55 gpm).

Length/Location of Isolated Pools and Dry Riffles

Field visits were conducted to determine whether there were differences in stream habitats above or below the MBCSD well. A GPS unit (Trimble GeoExplorer III) was used to map the stream thalweg within the project reach. Habitat surveys were conducted in the project reach to identify pools, riffles, flatwater, and dry areas (1998, 1999, 2001, 2002, 2004). Standard length, width, and depth measurements were obtained for these habitat units. Isolated pools were identified as critical features to map because of potential poor water quality conditions. Dry reaches were also mapped because they represented sites of lost fish productivity. This map information was used to determine the location of isolated pools and dry reaches relative to the well site.

Changes in Pool Characteristics

In 1998-1999, 15 pools were selected to obtain fish community data as described previously. We also gathered intensive data at these same sites including pool depth, area, and volume over the summer-fall. The intent was to determine if there were any significant differences in maximum pool depth, average pool depth, area, or volume at pools above or below the MBCSD well. Staff gages were installed at the deepest portion of each pool. Permanent transects were established perpendicular to flow for repeated measurements of water depths and widths. 3 to 5 transects were spaced equidistant along the length of the pool. Water depths (nearest 1 cm) were taken at fixed intervals along the transects, such that 8 to 10 measurements were obtained per transect. Thalweg distance, pool crest height, and maximum pool depth were obtained along the length of the pool units. Measurements were obtained once every two weeks.

Reaches were compared to determine if there are any significant differences in the net percent change in maximum pool depth and pool volume (Olson-Rutz and Marlow 1992). This data would have been useful to collect during dry years such as 2001-2002. However, personnel were not available to conduct this work. Data are only available to describe whether pool dimensions changed during wet years (1998-1999).

Water Quality Conditions

We approached the water quality assessment of pumping activities in four phases. First, a literature review was conducted to identify critical water quality parameters that would affect fish well-being and to identify any established water quality criteria. These water quality thresholds were summarized from the literature and used as “red flags” in our data analyses (Table 6).

We assumed that reduced flows could potentially increase un-ionized ammonia and stream temperatures while decreasing dissolved oxygen levels. Critical water quality values for temperature and dissolved oxygen seemed well-established in the literature and therefore, selected as important variables to monitor. Although important, we did not measure un-ionized ammonia at any location.

Both regulatory objectives and critical values from the literature were used as “red flags.” The Regional Water Quality Control Board-S.F. Bay Region identified cold-water fisheries as a beneficial use for the Redwood Creek watershed. For cold-water fisheries, they established a dissolved oxygen objective of 7.0 mg/l (RWQCB 199x). Based on controlled laboratory experiments on juvenile coho and steelhead, we used sublethal dissolved oxygen threshold of 5 mg/l and water temperature of 20° Celsius as additional “red flags” (Table 6). While studies have identified adverse effects at 4.5 mg/l and lower, we selected a threshold of 5 mg/l because of it would serve as a “red flag” identifying conditions before biological affects to juvenile salmonids occur.

The second phase involved the establishment of three, fixed monitoring stations in each reach to track temperature and dissolved oxygen over the duration of the sampling period. We referred to this dataset in the “Results” section as the “Intensive” sampling stations. The stations were intended to identify when conditions approached the “red flags.” We placed a water quality datalogger (Hydrolab Minisonde or Datasonde) in one of the sampled fish pools per reach. The sensors were situated near the pool bottoms. The dataloggers were programmed to record dissolved oxygen (percent saturation and concentration), water temperature, and specific conductance at 15-minute intervals. The dataloggers were serviced (dissolved oxygen membranes replaced, fresh batteries installed), calibrated, and data downloaded at two to three week intervals. Prior to field deployment, we checked the precision and accuracy of dissolved oxygen and temperature measurements.

The third phase involved the characterization of water quality throughout the three reaches. We referred to this dataset later as the “Extensive” sampling stations. It is possible that the three dataloggers were placed in pools that were not representative of the entire reach. Therefore, we decided to sample all index pools periodically for dissolved oxygen and temperature. Dissolved oxygen measurements were taken with a variety of meters (Hach Model 16046 and YSI Model 85 and 55) and with modified Winkler’s test (LaMotte DO test kit). Measurements were obtained in the morning. Because water quality is tied to physical and hydrologic conditions, we also recorded whether pools were connected by surface flows and the water depth at riffles entering into the pools. Individual water quality measurements for each year are provided in Appendices II-V.

Because of we had only one person collect the data, measurements of temperature and dissolved oxygen were conducted over a period of four hours. Because dissolved oxygen concentrations change throughout the day, we resampled the first pool of the day at the end of the sampling event. Dissolved oxygen levels would typically change by 0.2 mg/l during this period. We felt that this minor bias would not affect interpretation of our results.

The fourth and final phase involved the synthesis of water quality data and physical habitat measurements to determine a management “trigger” as well as a threshold value for initiating water conservation measures by the water district. The triggers must be robust and simple to measure. We determined that it was important to identify threshold streamflows or water surface elevations that would maintain "good conditions" for fish.

Precipitation and Streamflow

Precipitation data was used as a predictor of dry or wet year conditions. Daily rainfall totals were obtained from the Muir Woods National Monument station (National Climatic Data Center Cooperative Station # 46027). The period of record stretches from 1948 to present.

Water surface elevations have been continuously recorded at the Highway One Bridge across Redwood Creek since Fall 1997. The gaging station consists of an automatic rain gage, a pressure transducer (Instrumentation Northwest, 0-5 PSG), and datalogger (Campbell Scientific). Discharge values were established from a low flow rating curve relating water surface elevation and individual discharge measurements. Field discharge measurements were done in the field using Gurley pygmy meter, modified Parshall flume, or an electromagnetic flow meter (Marsh-McBirney Flo-Mate) depending upon flow conditions. Discharge estimates were computed using U.S.G.S.’s midsection method. During the summer of 1998, a v-notch weir was temporarily installed to improve accuracy of low-flow discharge estimates. Equipment problems, mainly associated with the battery charging apparatus and moisture, have resulted in data gaps.

DATA ANALYSES

Analysis of variance tests were used to determine if significant differences were present between the control and treatment reaches in terms of measured biological and physical parameters. Our first task was to determine whether habitat differences (mean pool volume, residual pool depth, surface area, and wood/undercut bank cover) occurred between reaches that were not associated with potential diversion impacts. This analysis was conducted on the late spring dataset (1998-1999 under flow conditions believed to swamp any diversion effects). Because cover data was obtained as percentages, we transformed the data using an arcsine transformation (Zar 1984). Any significant difference observed in the fall and not during the spring dataset would represent significant changes of interest rather than some pre-existing condition. Post-hoc tests (Scheffe's Multiple Comparison Test) were used to determine which of the three reaches were associated with significant differences.

Because the selection probability for each sample pool in the reach was not equal (systematic sampling from a random start), we determined sample variance for reach statistics using the following equation (sampling without replacement):

$$S_x^2 = \frac{S_x^2}{n} \frac{N-n}{N}$$

where $S_{\bar{x}}^2$ is the variance of the sample mean, N is the population size, and n is the sample size (Wensel 1991).

We also used a repeated measures analysis of variance design when analyzing the significance of fish and habitat changes over time from the same index pools. We followed procedures for this analysis as described in Maceina et al. (1994) and SAS (1998). Results were deemed significant at $P < 0.05$.

We used a regression tree (Systat 8.0) to explore the interactions of annual rainfall (wet versus dry years), stream connectivity and upstream versus downstream (from the well) location on dissolved oxygen at index pools for all sample dates (See Table 10). This analysis required us to treat pool measurements at the same index pool at different times in the same year as independent. This assumption seemed reasonable for dry years when dissolved oxygen in pools fluctuated depending upon connected streamflows. Also, up to three sampling events per year were analyzed in order to balance sampling effort amongst years. Regression trees are similar to ANOVA and other GLM models, however, they explicitly model and test all interactions (Dea'th and Fabricius 2000, Becker and Beissinger 2003). Model fit is measured with a proportional reduction in error, which is analogous to r^2 in general linear models. New variables are only retained if they are significant at $p < 0.05$. We did not validate the model with a training and cross-validation data set

because we are not attempting to build a predictive model, but rather test for differences among treatments.

RESULTS

Streamflow Conditions

A complete and accurate discharge record was only available for Water Years 1998-2000. The mean daily discharge record is provided in Tables 7-9. After this period, there were large gaps in the record which resulted from equipment problems and personnel turnover. The datalogger casing was inadequately sealed from the elements and damp air entering the case had caused data losses when dessicant was not changed frequently. We also had problems accurately estimating flows during the late-summer and fall because of extremely low flows in the creek. At extreme low flow conditions, flow measurements cannot be adequately obtained using standard wading measurements and equipment (e.g., pygmy Gurley meter). A modified Parshall flume (3 inch) was used during extreme low flow conditions, but it exhibited underflow problems.

The discharge record shows that minimum flows of 0.3 and 0.4 cfs were recorded in 1999 and 1998, respectively. The duration of these low flows was short, lasting about 4-5 days. Summer base flows during the survey period averaged 0.6 and 0.7 cfs in 1999 and 1998, respectively.

The instantaneous streamflow data were useful in determining the streamflows necessary for survival of fishes. When instantaneous streamflow dropped below 0.05 cfs at the Highway One bridge, portions of the creek were dry and pools became disconnected (Table 10). The length of dry habitat at streamflows below 0.05 cfs varied. The non-linear relationship between the amount of dry habitat and flows reflect the difficulties in accurately estimating low flows as well as other factors. No drying of the creek occurred when the minimum daily discharge for October exceeded 0.3 cfs (Table 1).

Observed Changes in Pool Habitats in Wet Conditions

Measurements of the index pool dimensions throughout the summer and fall of wetter-than-average years (1998-1999) showed only slight changes in maximum pool depth and pool volume. None of these changes indicated any significant differences between reaches upstream or downstream of the MBCSD facilities. These results suggest that during years similar in hydrologic characteristics to 1998-1999, no detectable effects of pumping activities can be seen on physical pool characteristics.

For 1998-1999 data, we found no significant differences between the three reaches in terms of changing water surface elevations, surface area or volume over time. Changes in pool surface elevation during the summer and fall study

periods were barely detectable, with the net change in elevation between the first and last measurements being 2 cm (Table 11-12). There were also negligible changes in the surface area of the index pools (Figure 9). In this photo of a typical index pool, the red flags marked the edge of water in June 1999 when the study started and the blue flags marked the final extent in October 1999 when the study concluded. The red and blue flags are very close together. There was a 17 percent loss in pool volumes between summer and fall (Table 13). Although Reach A experienced a higher loss in volume (-29%) than Reaches B (-9%) and C (-6%), the differences were not statistically significant (single-factor ANOVA, $p=0.07$).

Observed Changes in Water Surface Elevation in Dry Conditions

In 2001-2002, water level data from three continuously recording stations along Redwood Creek provided an interesting picture of water level fluctuations and their association with weather and pumping schedules. This data showed the influence of pumping activities on surface water elevations in the stream and water table elevations adjacent to the stream. Most importantly, it highlighted the connectivity between the stream and water withdrawal operations.

In general, the daily cycle of high and low water surface elevations at the piezometers near the MBCSD facilities were in phase with each other. If there was a lag time, it was shorter than our recording interval (15 min) (Figures 10-23). This daily water surface fluctuation was not evident further downstream at the Highway One Bridge, 1200 m downstream from the MBCSD bridge and well site (Figure 19).

The MBCSD bank piezometer had greater fluctuation in water levels than the instream piezometers. Daily surface water elevations fluctuated nearly 0.1 ft at the riffle site while the water table elevation in the adjacent bank piezometer had a daily fluctuation of about 0.2 ft.

The daily water surface fluctuations at MBCSD were nearly identical in both 2001 and 2002. From September 20-November 9, 2001, average daily fluctuation (measured from noon-noon) was 0.088 ft ($N=51$, standard deviation 0.044 feet). After eliminating dates with rainfall from consideration, average daily fluctuation from October 6-December 5, 2002 was 0.088 ft ($N=59$, standard deviation=0.030 ft). The magnitude of these fluctuations is nearly identical to the those reported by Martin (2000) in July 1999 for a v-notch weir 300 ft upstream of the MBCSD well site.

Daily water surface fluctuations at the MBCSD piezometers clearly show the effect of groundwater pumping on both the water table adjacent to the creek and the water surface elevation in the creek. This is evident in the timing, magnitude and duration of water level fluctuations. Water level fluctuations corresponded to the 14-hour well pumping schedule (1800 to 0800 hr). Stream and bank water

surface elevations would reach their lowest levels near 0800 hr, around the time when the pumping would cease. After 0800 hr, water surface elevation would rise sharply and would peak at 1200 to 1400 hour (PST) (Figures 10-23). Fluctuation of water table and surface water elevations were dominated by the effects of adjacent groundwater pumping, masking the effects of evapotranspiration. Data from Martin (2000) show a more expected pattern of peak water surface elevations at dawn declining during daylight hours which likely reflect evapotranspiration activities.

The strongest evidence of the effect of pumping activities on water elevations in the bank and stream piezometers occurred when the well pumps were inoperable for 24 hrs on two occasions in September and October 2001. When the well was not pumped, there was no fluctuation in water elevations in either the bank and stream piezometers for that day (Figures 11-13). The surface water elevation in the riffle remained about 4.5 cm above the creek bed during these periods (Sept. 30-Oct. 1 and Oct. 13-14) when the pump was not operated. A similar response occurred during a non-pumping period (Oct. 30-31) in 2002 near the end of the dry season (Figure 19). Water level fluctuations during non-pumping periods following a rain event around November 8, 2002 did not show as clear a response (Figures 20-22).

Differences in the duration of pumping are also reflected in both the water surface elevations and water table. For three days in October 2001, daily water production declined from 36,800 gallons (Oct. 11) to 22,152 (Oct. 12) to 0 (Oct. 13). The decline in pumping during these dates resulted in a water surface in the creek and water table that was maintained at a high level throughout that day (Figure 13).

Data from the riffle piezometer show periods where surface flow ceased. During 2001, the water surface at the riffle piezometer matched the streambed elevation or went subsurface on seven occasions in the fall (Figures 11-13). At each of these events, the dry condition was temporary lasting from less than an hour to up to 8 hours. These dry conditions occurred between midnight and the early morning in response to streamflow depletion by pumping from the MBCSD well.

Water surface elevations were also influenced by extended weather conditions. From Sept 28-Oct 1, 2001, this extended period of sun was mirrored by declines in the daily minimum water surface elevation and water went below the streambed (Figure 11). From October 2-8, 2001, an extended period of fog raised the lowest daily minimum water surface elevation by 3 cm while also dampening the amplitude of the daily water surface fluctuations by about 3 cm as well (Figure 12). Water surface elevations again declined during the next period of sunny weather from October 9-15, 2001.

Observed Dry Reach Conditions

Our study period incorporated two rainfall extremes. Precipitation data indicated that one of the wettest years for the period of record occurred during the study period (Rainfall Year 1997-1998) (Table 14). A total of 170 cm (67.01 inches) were recorded, making it the second wettest year for the period of record. Conversely, Rainfall Year 2000-2001 was the 7th driest year for the period of record.

Precipitation data was useful in identifying whether the creek would go dry in the fall. A strong relationship exists between rain season precipitation and observed connected or disconnected stream habitats downstream of the MBCSD facilities. Data regarding stream connectivity from 1992 to present are available from reports (Smith 2003, 1997, and 1994) and from NPS field surveys. Over the 14-year period, discontinuous flows were present in six years (1992, 1994, 1997, 2001, 2002, and 2004) (Table 14).

The criteria used by the AMP to identify a dry year (38.1 cm {15 inches} during the rain season-November through April) would not be adequate to identify years when the creek would go dry in the fall. None of the years from 1992 to 2004 were identified as “dry” under this criterion; yet six of those years had dry creek conditions in the fall.

From 1997 to present, the amount of the stream habitat that went dry was proportional to the total rainfall in the preceding year until a minimum rainfall level was reached. This minimum amount of annual rainfall needed to sustain streamflow through the dry season is between 78.7 cm (31 inches) and 83.8 cm (33 inches) (Table 15, Figures 24-25). Above this threshold, the stream remained connected through the dry season.

Within the project area, the disconnected pools and dry areas were concentrated in Reaches A-B between the Highway One Bridge and the MBCSD facility with minor amounts in the upstream Reach C (Figures 26-29). In October 2001, 39%, 50%, and 5% of Reaches A, B, and C respectively were dry. In October 2002, 29%, 12%, and 0% of Reaches A, B, and C respectively were dry. In 2004, 46%, 18%, and 1% of Reaches A, B, and C respectively were dry (Table 16).

However, the dry areas were not just restricted to the project reaches. On September 20, 2004, 510 m of dry streambed were also present from the Highway One Bridge to the mouth of Redwood Creek and the Pacific Ocean. This distance represented half of the 1047 m of dry habitat that was observed during a basin-wide habitat survey which stretched from the Pacific Ocean to 0.7 km above the MUWO upstream boundary on Redwood Creek. Figure 30 shows a photograph of typical dry creek conditions along Redwood Creek below the Pacific Way Bridge at Muir Beach in 2004.

These dry conditions resulted in losses of certain stream habitat types. Few shallow water riffle or flatwater units had water in Reaches A-B. Under summer-fall conditions in normal to wet years (e.g., 1998 and 1999), roughly 30 percent of the stream length in Reaches A and B were shallow-water habitats. During the three years with discontinuous flows, the amount of shallow-water habitats were 3 (2001), 13 (2002), and 15 (2004) percent (Table 16). For sites that had discontinuous flow, isolated pool units were present. Such conditions are less than desirable because of potential water quality, predation and passage issues.

A contributing factor to drying conditions within Reaches A and B may be the streambed topography. A stream profile survey was conducted in 1999 through the project area. Data from this survey identified some topographic "high spots" in Reaches A & B. Figure 32 shows that the streambed elevations for the pool heads were at or above the overall streambed grade from 0 to 700 m from the Highway One bridge. Because the streambed gravels in this reach were relatively porous, the profile data suggested that the water would be more inclined to move subsurface between pools in this area.

Water Temperature

Extensive Sampling. Red flag" water temperatures ($>20^{\circ}\text{C}$) during the summer-late fall did not occur at the index pools sampled in 1998, 1999, 2001 and 2002. The highest recorded temperature was 18°C from a pool with no riparian canopy cover. Water temperatures for the reaches were significantly different between sampling dates for each of the years (repeated measures ANOVA, $p<0.0001$). The regression tree analysis was used to identify factors associated with observed water temperatures. It showed significantly higher water temperatures during dry years (2001 and 2002 data) versus wet years (1998 and 1999 data) (Figure 41).

Intensive Sampling. "Red flag" water temperatures ($>20^{\circ}\text{C}$) during the summer-late fall did not occur during our sampling period at the continuously recording dataloggers in 1998, 1999, and 2001 (Table 17). Most of the sample sites were in well-shaded areas characteristic of the project area.

Water temperature data from the intensive sampling stations in 1998-1999 show distinct differences based on locations. The 1998-1999 temperature data showed a wider range in daily temperatures in the downstream direction (Figures 33-37). The upstream most station had the narrowest range of water temperatures. These observed differences may be explained by increased streamflow losses due to increased streambed infiltration and evapotranspiration in the downstream direction. Losing stream reaches tend to have a larger daily temperature fluctuation than gaining reaches, due to the absence of moderating influences from groundwater inflow (Constanz 1998). Finally, temperature data collected during this period showed a diel fluctuation in temperature with peak

temperatures shortly after noon and minimum temperatures occurring in the early morning (Figures 33-37).

The diel fluctuations in 2001 showed some patterns that may be reflect of creek disconnection. Unlike 1998-1999 when all stations had minimum and peak temperatures occurring at the same time, in 2001, the pool 455 meters downstream from the MBCSD foot bridge had peak daily temperatures occurring between 8-10 pm at night rather than early in the afternoon (Figure 40). This particular station was downstream of portions of dry creek such that flows had to travel subsurface before reaching the pool. The lagged response in peak daily temperatures may be the result of this condition. In any case, water temperatures never reached levels that would be harmful to aquatic life.

Dissolved Oxygen

Extensive Sampling. During wet years of 1998-1999, dissolved oxygen concentrations were consistently above the “red flag” concentration of 5.0 mg/l for all sample sites. No significant differences in mean concentrations occurred between the three sampling reaches. However, during years with lower streamflows (2001 and 2002), significant differences in mean concentrations between the three sampling reaches were observed. It appears that during these dry years, reaches A-B downstream of the well had mean dissolved oxygen concentrations much lower than upstream sites (Figure 42). Three of the sampled pools downstream of the MBCSD facilities had dissolved oxygen concentrations below 3 mg/l (lethal threshold for juvenile salmonids) for all sampling events in 2001. In contrast, sampled pools in Reach C, above the MBCSD facility, mean dissolved oxygen concentrations were above 5 mg/l for all sampled years, both wet and dry (Figure 42).

The regression tree analysis further identified factors associated with observed dissolved oxygen concentrations. The regression tree explained 74% of the variation in dissolved oxygen (Figure 43). Wet versus dry years explained 45% of the variation, while upstream/downstream location of sites explained an additional 18% of the data. Additional information regarding pool connectivity explained an additional 5 – 7% of the data. It is useful to read a tree backwards to see that the highest risk for low dissolved oxygen was in a dry year, downstream of the well, and where connectivity often failed (Figure 43). Substantial differences in dissolved oxygen are seen during dry years between upstream and downstream of the MBCSD facilities. Similarly, dissolved oxygen concentrations were significantly higher in connected pools versus disconnected pools both upstream and downstream of the MBCSD facilities. However, the upstream sites always had higher dissolved oxygen concentrations with upstream disconnected pools having similar dissolved oxygen to downstream connected pools.

Intensive Sampling. The association of water surface elevations and extended weather conditions were mirrored by dissolved oxygen concentrations. Increases in dissolved oxygen concentrations were associated with extended fog or overcast conditions. During September 15-22, 2001 and October 2-8, 2001, rising dissolved oxygen levels corresponded with an extended period of overcast and fog (Figures 10-12).

Dissolved oxygen concentrations below 5 mg/l were observed at several of our stations. In 1998-1999, these conditions had only occurred at our upstream “control” station. In 1999, dissolved oxygen concentrations reached lethal levels at the upstream control (0.7 mg/l). The low dissolved oxygen levels were likely the result of the initial placement of the datalogger at the deepest portion of the pool situated away from the pool head where oxygen concentrations would likely be higher. A precipitous decline in dissolved oxygen conditions was observed in 2001 at the Hydrolab water quality monitoring station just downstream of the MBCSD bridge (-13 m below MBCSD footbridge, Figure 11). Dissolved oxygen levels declined from around 6 mg/l on September 22, 2001 to about 3.5 mg/l on September 30, 2001. This rapid decline appeared to correspond to several factors: prolonged length of sunny weather, an increase in amplitude of daily water elevation fluctuations at the bank, and a decrease in water height above the riffle. Furthermore, this change also corresponded with the highest daily diversion for the months on September 27 and 29 (38,484 and 38,254 galls).

The data from our Hydrolab intensive monitoring station (-455 m below MBCSD footbridge) indicated that extremely poor dissolved oxygen concentrations were present—at least at the pool bottom. Dissolved oxygen concentrations were near zero for much of October 2001 except for a brief period of elevated levels following a brief rain (Figure 49). As with data from the upstream control station in 1999, the extremely low dissolved oxygen levels may be the artifact of the placement of the datalogger at the deepest portion of the pool away from the pool head. In deep pools with little mixing, stratified conditions can also develop. Surface dissolved oxygen measurement obtained on October 10, 2001 during the extensive sampling procedures was 2 mg/l higher than the datalogger measurement at the pool bottom (4.3 vs. 2.3 mg/l).

Data from 1998, 1999, and 2001 showed diel fluctuations in dissolved oxygen concentrations. All of the three reaches exhibited similar diel fluctuations in dissolved oxygen concentrations in 1998 (Figure 44). Lowest levels were reached shortly after midnight, presumably associated with respiration demands exceeding photosynthesis and peak concentrations occurring in early afternoon.

Fish Data

The first question that we wanted to answer was whether there were significant differences in fish metrics between the three reaches that were unrelated to instream flow conditions. Any pre-existing differences (e.g., naturally lower

numbers of fish below MBCSD facility because of poor physical habitat conditions) could result in an erroneous conclusions. Therefore, similar to conclusions from Trihey and Assoc. (1995), we assumed that at instream flows above 0.5 cfs, we would be unlikely to detect any affect to fish community characteristics from water withdrawal activities at the current, low withdrawal rates. This meant that at conditions above 0.5 cfs, any observed and significant differences in fish between the reaches represented differences in habitat unrelated to water withdrawal activities.

We tested for any significant differences amongst reaches in 1998 and 1999 when streamflows exceeded 0.5 cfs. Conveniently, we were able to sample in the summer when streamflows were relatively high. In 1998, fish were sampled in August when mean daily streamflows were 0.9 cfs. In 1999, fish sampling started in June when mean daily streamflows were 1.1 cfs. In 1998, there were no significant differences in total fish, juvenile coho, juvenile steelhead (young of the year and 1+), and sculpin amongst the three reaches (single-factor ANOVA). In 1999, some differences were present in sculpin and coho abundances. Reach B had significantly higher abundance of coho than other reaches while Reach C had higher abundance of sculpin. There did not seem to be a consistent pattern of significant differences in fish abundance between the reaches.

Individual

Information to assess the fitness of coho and various steelhead life stages was available in 1998-1999 during wet conditions and in 2001 under dry conditions. There was no significant differences in instantaneous growth (fork length*day⁻¹) between any of the reaches for juvenile coho, steelhead YOY, and steelhead 1+ (One-factor ANOVA, Table 18). Generally, YOY coho and steelhead grew from 0.002 to 0.009 g per day irregardless of the project reach. Steelhead 1+ generally had a reduced rate of growth when compared to YOY coho or steelhead. Many of the steelhead 1+ experienced loss of weight during the study period.

It was difficult to compare the individual fitness of fish during the dry conditions of 2001 because so many pools had few if any fish below the MBCSD facility. Of the 11 index pools sampled downstream of the MBCSD facility, five did not have any fish. Of the pools that had fish, mean Fulton's condition factor for steelhead and coho was consistently higher in pools downstream of the MBCSD facility than upstream (Table 19). Furthermore, mean Fulton's condition factor was higher for coho and steelhead YOY in Reaches A and B in a dry year (2001) than in wetter sample years. Under wet conditions, significantly higher densities of fish are present and the lower Fulton's condition factors for these taxa during these years suggests density-dependent food limitations.

Signs of stress in live juvenile salmonids as well as observations of dead juvenile and adult salmonids have been documented at isolated pools. In 2001, juvenile

salmonids in isolated pools showed signs of oxygen stress. Field notes indicate the presence of lethargic juvenile salmonids. In 2004, local Muir Beach residents had reported three run-back adult steelhead at the Pacific Way bridge near Muir Beach. In September 2004, at least two of these individuals had perished, presumably due to poor water quality conditions at the site (Figure 31). During sampling activities for dissolved oxygen, dead juvenile steelhead was found on September 10, 2001 at Pool #28 where measured dissolved oxygen concentration was 2.43 mg/l. Additional details regarding our observed associations between fish abundance and dissolved oxygen levels are provided later.

Community

Brillouin and Simpson indices were calculated for two wet years (1998-1999) and a dry year (2001). A two-factor ANOVA (year and reach effect) indicated that fish diversity between dry and wet years and reaches were significantly different (P -value < 0.05). A post-hoc Scheffe's test further indicated that dry years had lower Brillouin index than wet years and that reach C had significantly higher index value than reach A (Figure 53). These differences reflect the absence of fish in five of the eleven index pools in Reaches A and B that resulted in index values of zero. During the dry year of 2001, pools in Reach A and B that had fish generally lacked steelhead or coho.

Population

Two basin-wide fish surveys were conducted during the course of the study (1998 and 2004). However, data from 2004 are not presented for comparison. Sample sites selected in 2004 in Reach B of the study area were biased. They were concentrated at a long-term monitoring index stations established by Jerry Smith and created pools from a restoration project and did not reflect habitat conditions throughout the area. Furthermore, snorkel and electrofishing activities avoided sampling disconnected pools that appeared to have low dissolved oxygen conditions to prevent stress to individual fish. Selection of "good" sites to monitor provides a biased estimate of fish abundance in Reach B of the study area (e.g., suggests that more fish are present than actually present).

The two reaches (Reaches A and B) downstream of the well contribute significantly to the overall production of fish within the Redwood Creek watershed during wet years. In 1998, steelhead young-of-the-year, steelhead 1+ and older, and juvenile coho represented 25, 24 and 13%, respectively, of the watershed production (Table 20). The reaches are insignificant contributors, however, to the threespine stickleback population which occurs in much greater abundance downstream in emergent marsh habitats at Big Lagoon. The two reaches represented 19.4% of the pool habitat (by length) in mainstem Redwood Creek.

There were differences in fish abundances and biomass between sample years and study reaches that highlight the differences between Reach C sites and sites in Reaches A and B, particularly in dry years (Figures 51-52). There were significant differences in coho abundance (coho per m) by sample year and study reach (two-factor ANOVA, $P < 0.01$), with higher mean abundances in Reach C (upstream) versus Reach A (Scheffe's test, $P = 0.02$) (Figure 51). Significant differences in steelhead young-of-the-year abundance were present amongst the sample years, with higher mean abundances in wet years (1998-1999) than in the dry year (2001) (Scheffe's test, $P < 0.01$). Significant differences in biomass for sculpin and steelhead were present amongst the sample years, with higher mean biomass in a wet year (1998) than in a dry year (2001) (Scheffe's test, $P < 0.01$).

While the study reaches downstream of the well contribute significantly to the Redwood Creek fish population during wet years, fish production during dry years is much reduced. For this creek, steelhead young-of-the-year are frequently found in shallow-water habitats when juvenile coho salmon are present in the system. In 2001, when shallow-water habitats were rare due to dry conditions, we estimated only 62 steelhead young-of-the-year. This contrasts to 950 and 2282 steelhead young-of-the-year estimated in wetter years of 1998 and 1999, respectively. The surface area of shallow-water habitat was 10 times greater in 1998-1999 than it was in 2001 (Table 16).

A rough estimate regarding the potential loss of fish production in Reaches A and B can be calculated. In 1997, Jerry Smith estimated that dry creek conditions between the MBCSD facilities and below the Pacific Way Bridge have resulted in the loss of 1300-1400 juvenile coho salmon (Smith 1997). The estimate was based on mean coho abundance of 33.5 coho per 30.5 m at two index stations during years when sufficient streamflows were present. This estimated loss assumed that the entire creek between MBCSD facilities and the Pacific Way Bridge were dry. This assumption likely overestimated the amount of dry habitat. During 2001, which was a drier year than 1997, about 45% of the stream between the Highway One Bridge and MBCSD facilities was dry and it is likely that a similar percentage was dry between the Highway One and Pacific Way Bridges. If you assume that in 1997, 45% of the stream was dry downstream of the MBCSD facilities, the overall potential loss of juvenile coho salmon ranges between 585-630 individuals.

We wanted to provide an estimate of the potential loss of fish production for other dry years. We estimated the amount of fish lost in 2001-2002 by calculating the amount of pool and shallow-water habitats lost. We did this by assuming that the percentages of pool and shallow water habitats, if sufficient water had been present in 2001-2002, would be similar to the averages for 1998-1999. We then calculated the amount of pools and shallow-water habitats lost as the difference in habitat proportions between 1998/1999 and the target dry years (Table 21). We assumed that habitat conversion from shallow-water to dry habitat resulted in the total loss of fish production from these areas (Table 21).

2002 electrofishing data was used to determine the potential fish losses from the conversion of pools to shallow-water habitats. Mean densities of coho, steelhead young-of-the-year and sculpin in shallow-water habitats were 3, 33, and 21.5% less than pools, respectively. We assumed that under dry conditions, this proportional relationship should be consistent between years. We then used pool fish abundance (#/m) and total length of dry habitats for that year to determine losses when shallow-water units and pools dried.

Based on these estimates, there is reduced fish production for all taxa in Reaches A and B during dry years. Most of the losses occur in Reach A. For both years, sculpin were the taxa most affected by drying creek conditions. An estimated 594 and 504 sculpin may have been lost in 2001 and 2002, respectively (Table 22). Coho appear to be the second most affected taxa. An estimated 441 and 374 juvenile coho may have been lost in 2001 and 2002, respectively (Table 22).

The potential loss of habitat and fish is even greater when dry habitats downstream of the study area are taken into consideration. In 2004, the lengths of dry habitats between the Pacific Ocean and the project area were somewhat similar; therefore, doubling of the numbers would provide an approximation of lost fish production. So, for our 2001 data, we would estimate around 900 individual coho lost between the MBCSD facilities and the Pacific Ocean.

What is the significance of this loss to the Redwood Creek watershed? If you use our basinwide fish estimates for 1998 and 2004 as a benchmark, you would have around 4000-9000 coho, 2000-9000 steelhead young-of-the-year, 1000 steelhead 1+/2+, and 10,000 sculpin between MUWO and Muir Beach. The total losses below the MBCSD facilities to Muir Beach would range from 10-15% for coho, 2-10% for steelhead young-of-the-year, <1% of steelhead 1+, and 7-12% of sculpin for the watershed. The magnitude of overall loss in watershed fish production is probably around 10%.

Relationship Between Water Quality and Fish

A simple linear regression model was useful in describing the relationship between water quality and overall fish abundance. Minimum dissolved oxygen concentration was the best variable that described overall fish abundance for all fish taxa. Furthermore, this linear model provided the strongest explanation of the variability in actual abundance from predicted values when previously collected data from Redwood Creek during the dry year, 2001, was used (Figure 54, $p < 0.01$, $n=13$, $r^2=0.81$). The results also make intuitive sense. The model predicts near zero fish when dissolved oxygen concentrations approach zero ($Y=-0.134+0.73x$). Under wet years, a significant relationship exists between overall fish abundance and dissolved oxygen, but the model had reduced ability to explain the variability ($p=0.03$, $n=30$, $r^2=0.16$). The data suggested that in wet

years, dissolved oxygen conditions may play a role in explaining overall fish abundance, but other factors, perhaps related to food or space limitations may become new limiting factors for fish in wetter years.

Dissolved oxygen data from the intensive stations indicate a major difference in available suitable habitat for fish between wet and dry years. During wet years, pools downstream of the MBCSD facility have dissolved oxygen conditions throughout the entire pool that are above the “red flag” threshold for growth of juvenile salmonids. During dry years, pools downstream of the MBCSD facility have dissolved oxygen conditions at the bottom that are not only below the “red flag” threshold for growth but are below lethal thresholds. These conditions force fish to use a smaller portion of the pool—generally near the pool head where water is physically aerated by the riffle and surface. This condition likely exposes fish to greater predation risk from fish-eating birds such as herons.

DISCUSSION/RECOMMENDATIONS

No major differences in fish metrics can be detected sites upstream and downstream of the MBCSD facility during years with average or greater rainfall amounts during the rain season. Project data indicated that directly observable adverse effects on fish and stream condition occur when stream habitats are disconnected. This appears to occur during years when the rainfall season is less than 33 inches and under the existing water production schedule. Under these conditions, there are strong differences in water surface connectivity, amount of stream habitats, and dissolved oxygen concentrations between sites upstream and downstream of the MBCSD facility. This translates to greater overall fish abundance upstream of the MBCSD facility and reduced numbers downstream. Under these conditions, we have potential losses of probably 10% of the watershed fish production.

This study has not been designed to evaluate the percentage of these fish losses that may be attributable to water withdrawals. In extremely dry years, the stream would go dry naturally and fish losses would be a natural occurrence. Schanz et al. (1995) estimated that streamflows approaching 0.0 cfs and isolated pools would occur roughly 1 every 4 years even in the absence of water withdrawal activities. The greatest impact of current water withdrawals patterns would most likely be observed during “bubble years” when antecedent rainfall (around 33 inches) would be just barely enough to provide water surface connectivity.

The Technical Advisory Committee associated with the MBCSD’s water rights permit developed a document describing management tools to identify and measure critical conditions in the creek and leading to additional water conservation measures. This document was termed an “adaptive management plan” with agreed upon updates annually, with the recognition that projects like this will help refine operations to minimize impacts on instream fishery resources.

Based on the data from this study, several recommendations are provided that would help reduce impacts on instream fishery resources or to identify key data gaps that need to be filled.

1. *Initiate actions to obtain “take” authorization for listed fish and adverse modification of critical habitat.* Based on the results from this study, it appears that water withdrawal activities during dry years contribute to impacts to fish. The existing AMP does not authorize “take” of listed fish (D. Butler, NOAA-Fisheries, pers. comm., 2005). We would recommend that actions be taken to obtain “take” authorization from NOAA-Fisheries. Options that have been suggested to the MBCSD include development of a Habitat Conservation Plan or entering into a multi-agency agreement with federal agencies to allow for a Section 7 consultation. This process may result in the suggestion and adoption of conservation measures that could reduce potential impacts to fish resources.
2. *Protect natural streamflow patterns.* Currently, the MBCSD pumps from the evening through morning period to take advantage of lower electrical rates, but also because of previous recommendations from NPS that water withdrawals be timed to avoid the additive impacts of natural evapotranspiration losses and municipal water withdrawal on streamflow. Data from this study indicate that during the dry season of dry years, surface water elevations in the stream track water withdrawal activities. Analysis of diel fluctuations in stream water surface elevations near the MBCSD well indicates daily maximum levels occur in the late morning to afternoon while minimum levels occur during midnight and pre-dawn periods. These observations run contrary to natural water surface fluctuations that reflect evapotranspiration activities. In her review of 100 unimpaired, evaporation/infiltration-dominated western river and streams gaged by the USGS, the hour of peak flow occurred consistently in the morning during the summers (Lundquist 2004, Lundquist and Cayan 2002).

What are the biological implications of an altered streamflow pattern? There have been some studies that have looked at the effects of altered streamflow patterns on aquatic organisms. Sharp reductions in streamflow can cause catastrophic drift of stream insects as well as stranding of insects (Corrarino and Brusven 1983), thereby limiting the invertebrate production potential of the dewatered area. In their assessment of flow regimes in a regulated stream, Marchetti and Moyle (2001) found that a non-native fish assemblage in a Central Valley, California creek was favored by an unnatural flow regime.

NPS Management Policies (NPS 2006) provide basic guiding principles for Park staff and NPS units for natural resource management that are applicable here—“ *The National Park Service will strive to understand,*

maintain, restore, and protect the inherent integrity of the natural resources, processes, systems, and values of the parks while providing meaningful and appropriate opportunities to enjoy them.” Power *et al.* (1996) conclude that a sufficiently natural regime of flow variation is particularly crucial for river biota and food webs. It would be worthwhile to explore management options that would permit a more natural streamflow pattern. One potential option would be to evaluate a lower rate of continuous pumping over the late-summer and fall periods of dry years. Other options may include variable pumping rates that are tied to stream condition.

3. Continue to Implement Adaptive Management Plan

The development of the AMP has led to improved water conservation. Current conservation efforts during the dry season and following noticed water conservation periods have reduced water consumption below past levels and below levels of other nearby coastal communities. Any effort to further reduce overall summer-fall water withdrawal during dry years would be beneficial. It would be advantageous to continue pursuit of opportunities for reduction of water use, additional storage or water supply sources. Recommendations such as those provided by the Sierra Club (letter to Ed Dito, State Water Resources Control Board dated February 18, 2000) regarding an ultra low flush toilet rebate program may be feasible if grant monies are available. Although the AMP concluded that residential greywater reuse systems were impractical for residential use, it might be appropriate to consider this option for users with large irrigated landscapes. Alternative water sources such as desalinization may become feasible in the future.

4. Evaluate Possible Modifications to the Adaptive Management Plan.

The current water management plan uses water surface elevations as a trigger for creek walks to determine whether the stream is nearing disconnection. Information from this study indicates that there is a daily fluctuation of about 0.1 ft at the sentinel riffle below the MBCSD facility. This daily fluctuation of 0.1 ft can be considered the critical water depth, below which the creek has a high likelihood of becoming disconnected. To provide a buffer, daily creek walks should be initiated when the water depths reach 0.2 ft. Initiation of daily creek walks based on a fixed water depth had been discussed and agreed upon at the latest TAC meeting (March 30, 2005).

The location for these daily creek walks should be located between 0 and 700 m upstream from the Highway One Bridge because this site was most likely to go dry. The current practice of entering the creek at the Muir

Woods Road pullout at the Eucalyptus grove removal site (approx 450 m upstream of Highway One) is satisfactory.

The AMP defines a dry year as having rainfall during the rain season that totals 15 inches. We recommend that the definition of a dry year be tied to the occurrence of disconnected stream conditions. This occurs when rainfall of 33 inches or less occurs during the rain season.

We recommend continued collection of the qualitative weather data by MBCSD because of its usefulness in interpretation of water surface trends. Data interpretation may be improved with additional, simple measurement parameters including daily max/min air temperature and relative humidity. Because we are unable to quantify foggy conditions, modifications could be made to existing rain gage collectors to gather data on fog drip.

5. *Continue habitat restoration actions.*

Some of the fishery impacts below the MBCSD facilities may be blamed on past channel and floodplain management activities that occurred when the adjacent fields were managed as a flower farm. The 1999 stream profile identified long stretches of flatwater and riffle habitats at topographic high points below the MBCSD facility that dry frequently, resulting in fish loss. A recent restoration project in Fall 2003 completed by the GOGA helped transform some of these topographic high spots into a more natural sequence of alternating pools and shallow-water habitats. While most of these pools became disconnected in 2004, several at least retained enough water to support juvenile salmonids until the rains came. In prior dry years, this stretch would be entirely dry, resulting in total loss of fish. Additional physical habitat restoration activities may still be possible downstream of the MBCSD facilities.

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TABLES

Table 1: Comparison of minimum daily discharge and mean daily production at the Muir Beach Community Service District facility, Redwood Creek, Marin Co., CA

Year	Min. Daily Oct. Q ¹	Oct Mean Daily Production (gallons/day)	Muir Beach Daily Per Capita Consumption for Oct (gallons) ²	Bolinas Daily Per Capita Consumption for Oct (gallons) ²	Stream Condition in Sep/Oct of Calendar Yr ³
1992	N.D.	N.D.	N.D.		Dry
1993	N.D.	N.D.	N.D.		Wet
1994	N.D.	N.D.	N.D.		Dry
1995	N.D.	N.D.	N.D.		Wet
1996	N.D.	N.D.	N.D.		Wet
1997	N.D.	35241	101		Dry
1998	0.4	41426	118		Wet
1999	0.3	41335	118		Wet
2000	0.8	27450	78		Wet
2001	0.01	31494	90	83 - 95	Dry
2002	0.01	35203	101	99 - 113	Dry
2003	N.D.	29297	84	103 - 117	Wet ⁴
2004	0.002 ⁵	22861	65	95 - 107	Dry

¹Measured at the Highway One Bridge

²Based on estimate of 350 water service users for Muir Beach (Martin 2000) and 1500-1700 for Bolinas (P. Buchanan, pers. comm., 2005)

³Data from Smith (2003) and this study

⁴Creek connected downstream of MBCSD except at sites of recent channel restoration activities

⁵Instantaneous discharge measurement

N.D.: No data

Table 2: Fish data from index stations in Redwood Creek, Marin Co., CA

Table 3. Fall densities (number per 100 feet) for coho (bold) and YOY steelhead at sites on Redwood Creek from 1992 to 2003.

Site	1992	1993	1994	1995	1996	1997	1998	2000	2001	2002	2003
1. Upper Muir Wds (Miles 3.3, 3.6)			4 40								
2. Lower Muir Wds (Mile 2.8)	84 19	91 52	1 14	45 57	37 29	41 32	32 54	6 58	38 24	108 17	32 22
3. 0.35 mi > Kent Canyon (mile 2.1)			10 19			50 15	48 40	1 42	50* 3	83 28	40 32
4. 0.5 mi > 3 rd Bridge (mile 1.65)			0 61					0 47			
5. > 3 rd Bridge (mile 1.25)	30 16	30 26	0 20	43 51	54 27	26 7	20 23	0 21	47 4	65 1	24 30
6. Downstream of Diversion (mile 0.85)	4* 6	16 72	0* 0	56 132	28 45	0* 2	11 35	0 28	0* 0	23* 3	12 36
7. 1 st Bridge (mile 0.35)	33 29	14 34	0* 6	54 142		0* 12	46 84	0 36	0* 0		
Totals	45 23	46 56	2 34	42 97	39 33	23 15	32 47	1 39	27 6	70 12	27 30

*streambed drying

Data excerpted from Smith (2003). Note that "Totals" row at bottom represents grand mean densities of coho and YOY steelhead for all sampled stations for that sample year

Table 3: Total monthly precipitation at Muir Woods National Monument, Marin Co., CA (NCDC COOPSID 46027)

MONTH	1991- 1992	1992- 1993	1993- 1994	1994- 1995	1995- 1996	1996- 1997	1997- 1998	1998- 1999	1999- 2000	2000- 2001	2001- 2002	2002- 2003	2003- 2004
JUL	0.1	0.02	0.1	1.15	0.06	0.07	0.02	0.06	0.04	0.01	0.07	0.04	0.05
AUG	0.69	0.1	0.09	0.03	0.03	0.18	0.96	0.11	0.24	0.01	0.02	0.02	0.03
SEP	0.07	0.09	0.02	0.07	0.03	0.68	0.37	0.18	0.22	0.39	0.89	0.02	0.03
OCT	3.02	2.64	1.01	0.39	0.01	1.94	1.46	1.47	1.33	3.2	9.32	0.07	0.02
NOV	0.87	1.29	4.77	14.05	0.55	4.44	10.53	6.22	4.09	1.36	15.95	27.43	2.39
DEC	5.72	7.97	4.01	4.96	15.39	12.89	4.32	2.59	1.13	2.32	3.24	9.19	12.19
JAN	3.11	13.68	3.9	17.63	11.11	9.43	17.77	5.58	7.76	6.46	5.11	3.19	4.83
FEB	8.58	7.5	6.46	0.93	9.86	0.66	20.46	12.99	12.94	7.86	4.07	1.97	8.22
MAR	5.74	3.08	0.66	12.22	2.51	0.92	3.67	3.41	4.09	2.33	0.8	2.84	0.71
APR	1.67	2.05	2.58	2.51	4.75	0.83	2.97	2.39	3.03	1.06	0.94	1.31	1.14
MAY	0.02	1.79	1.83	2.34	4.07	0.33	4.38	0.38	2.98	0	0.05	0.01	0.24
JUN	1.41	1.65	0.18	0.79	0.03	0.48	0.1	0.14	0.23	0.35	<i>0.01</i>	<i>0.01</i>	0
TOTALS	31.00	41.86	25.61	57.07	48.40	32.85	67.01	35.52	38.08	25.35	40.47	46.10	29.85
NOV-APR TOTALS	25.69	35.57	22.38	52.30	44.17	29.17	59.72	33.18	33.04	21.39	30.11	45.93	29.48

*Italicized data from raingage at HWY 1 bridge

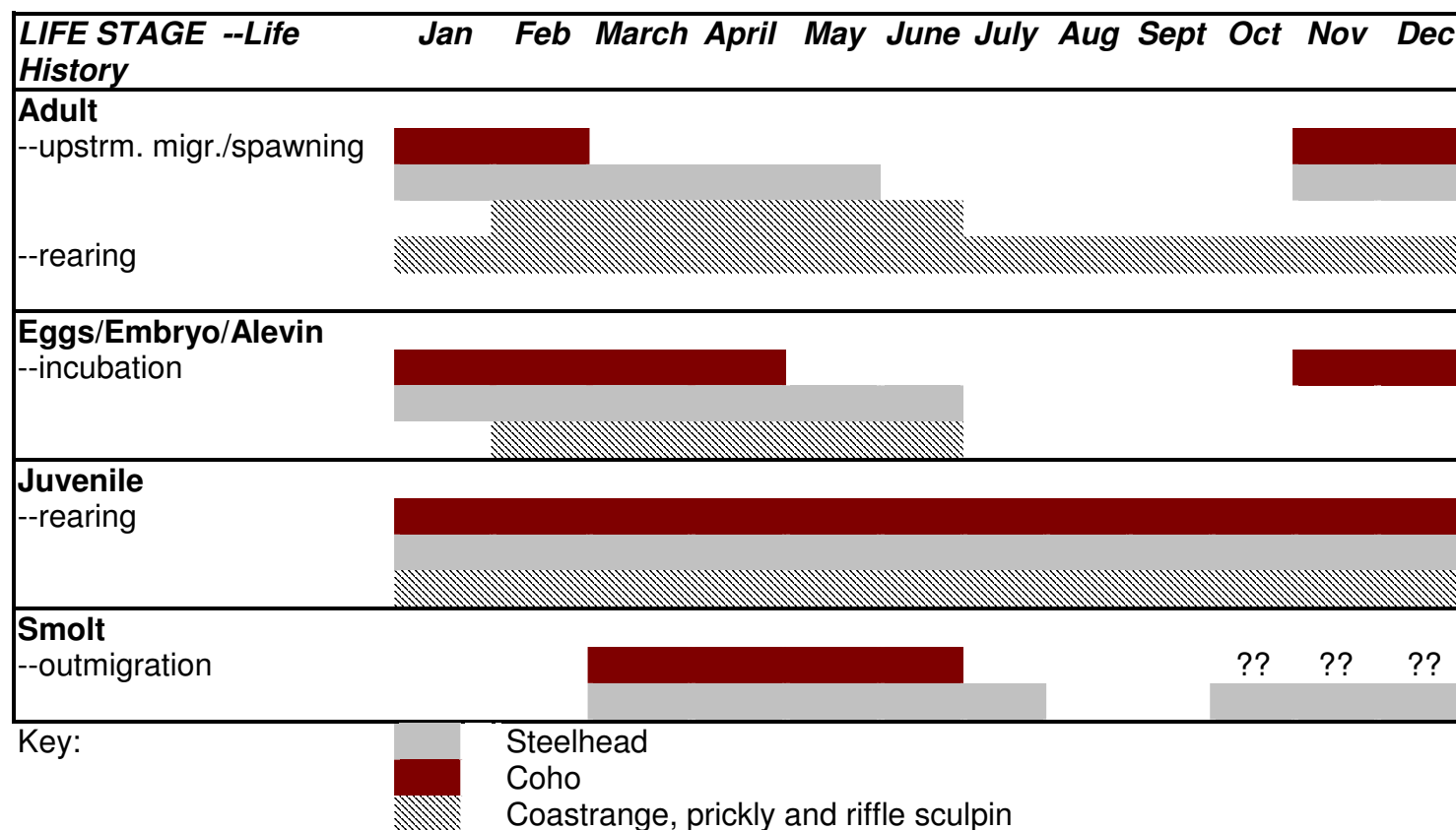
**November-April defined as rain season and dry season May-October

Table 4: Estimated optimal rearing flow conditions for Redwood Creek, Marin Co., CA.

Redwood Creek Optimal Rearing Flows (cfs)	Criteria Based Upon	Stream Criteria Was Developed For	Citation
2.5 – 6.25	20 – 50% average annual flow*	Russian River	SWRCB 1998- Attachment D
7.5 - 12	60-100% of average annual flow (Tennant Method)	General	
9	Toe-width method	Redwood Creek, Marin Co., CA	Snider 1984
4.4 – 6.25	Optimal rearing flows: 35-50% of average annual unimpaired flow (based upon maximum useable area from IFIM)	Lagunitas Creek, Marin Co., CA	SWRCB 1995
<u>Minimum required flows</u> 1.25	10% of average annual unimpaired flow between June and November	Lagunitas Creek, Marin Co., CA	SWRCB 1995

*Mean annual daily flow for Redwood Creek in WY 93, 99, 00: 12.1, 12.9, 13 cfs, respectively (slightly higher than ave. rainfall years).

Table 5: Coho, steelhead, and sculpin life history pattern for Redwood Creek, Marin Co., CA



??- Possible smolt outmigration assuming stream connected to ocean based on Shapovolav and Taft (1954).
 Life history information from Fong (1997), Kopec (1998a, 1998b), Manning et al. (1999), and Shapovolav and Taft (1954).

Table 6: Summary of flow-related stressors on juvenile steelhead and coho salmon

SPECIES (life stage)	STRESSOR	RESPONSE PARAMETER	EFFECT	CITATION
COHO egg-fry	Dissolved Oxygen during incubation	Fry size, mortality, migration, territoriality	Reduced size, increased mort. and migration, reduced territoriality	Mason (1969)
juvenile	Dissolved Oxygen	Acute, 96-hr LD ₅₀	2 ppm @12-20°C	Davidson et al. (1959)
juvenile	Dissolved Oxygen	Chronic, max swimming speed	Reduced at low dissolved oxygen	Davis et al (1963) McMahon (1983), Herrman et al. (1962), Brett and Blackburn (1981)
juvenile	Dissolved Oxygen	Growth	Negative or ceases <4.5 mg/l	Bell (1973), McMahon (1983)
juvenile	Temperature	Growth	Ceases above 20.3°C	Brett et al. (1958)
juvenile	Temperature	Acute lethality	25°C	
STEELHEAD egg-fry juvenile	Temperature during incubation Dissolved Oxygen	Embryonic development Acute lethality	$T \leq 12$ and $\geq 7^{\circ}\text{C}$ <3 mg/l	Raleigh et al. (1984) Raleigh et al. (1984)
juvenile	Temperature	Preference	13-19°C	Raleigh et al. (1984)
smolts	Temperature	Normal smoltification	$T > 4$ and $<13^{\circ}\text{C}$	Raleigh et al. (1984)

Table 7: Mean daily discharge for Redwood Creek at Highway One Bridge, Marin Co., CA. Water Year 1998

DAY	Oct 97	Nov 97	Dec 97	Jan 98	Feb 98	Mar 98	Apr 98	May 98	Jun 98	Jul 98	Aug 98	Sep 98
1	N.D.	N.D.	19.9	2.9	128.3	16.6	9.7	5.4	10.0	2.3	0.8	0.5
2			14.3	17.1	338.3	15.6	8.9	5.4	9.0	2.3	0.7	0.5
3			11.7	16.9	498.6	14.5	13.4	5.0	8.2	2.3	0.6	0.5
4			10.9	28.7	186.6	13.2	69.8	5.1	7.5	2.1	0.6	0.5
5			17.0	23.1	177.2	13.3	21.0	5.3	7.0	2.1	0.6	0.4
6			15.7	19.3	290.7	13.2	19.1	5.4	6.7	2.1	0.6	0.4
7			40.0	22.9	355.3	12.3	18.5	5.1	6.4	1.9	0.6	0.4
8			45.6	21.3	226.5	11.8	16.5	4.9	6.1	1.9	0.6	0.4
9			30.1	21.3	130.0	11.1	15.6	4.4	5.7	1.9	0.6	0.4
10			22.1	50.1	105.5	10.5	14.5	4.3	5.4	1.8	0.5	0.4
11			18.2	199.5	88.6	9.9	13.4	4.3	5.2	1.7	0.6	0.5
12			14.8	428.4	84.6	10.1	12.4	9.4	5.0	1.6	0.6	0.5
13			12.6	176.1	91.6	10.3	12.7	8.3	4.7	1.5	0.6	0.5
14			21.5	345.6	145.3	9.8	11.5	6.9	4.5	1.5	0.7	0.5
15			21.9	514.5	125.4	9.2	10.7	6.2	4.2	1.3	0.7	0.5
16			18.9	302.9	107.2	8.8	9.8	5.8	4.0	1.2	0.7	0.5
17			17.0	238.1	98.3	8.5	9.1	5.3	3.7	1.2	0.6	0.5
18			15.1	264.9	74.5	8.0	8.6	5.0	3.6	1.1	0.6	0.5
19		↓	12.9	211.7	207.0	8.0	8.1	4.7	3.5	1.0	0.7	0.5
20		4.1	11.3	130.5	166.0	7.0	7.7	4.5	3.4	1.0	0.9	0.5
21		2.5	10.0	63.0	209.6	7.0	7.2	4.2	3.3	1.4	0.8	0.5
22		1.9	8.8	44.5	174.5	6.0	6.9	4.1	3.2	1.3	0.8	0.5
23		16.8	7.9	41.4	167.2	10.0	7.3	3.9	3.2	1.2	0.7	0.5
24		7.8	7.2	41.2	135.1	14.0	7.0	3.8	3.1	1.2	0.7	0.5
25		6.3	6.5	38.1	95.7	12.3	6.3	3.8	3.0	1.1	0.7	0.5
26		75.3	5.9	42.8	67.1	11.1	6.0	3.6	2.8	1.1	0.8	0.4
27		37.8	5.5	64.1	45.8	10.3	5.7	5.3	2.7	1.0	0.7	0.4
28		20.3	5.3	45.4	41.2	9.9	5.5	15.7	2.6	0.9	0.6	0.4
29		15.1	5.0	103.9		9.1	5.3	15.7	2.6	0.9	0.6	0.5
30	↓	28.5	3.4	76.3		8.4	5.0	13.8	2.5	0.9	0.5	0.5
31			3.1	65.7		10.0		11.6		0.9	0.5	

Table 8: Mean daily discharge for Redwood Creek at Highway One Bridge, Marin Co., CA. Water Year 1999

DAY	Oct-98	Nov-98	Dec-98	Jan-99	Feb-99	Mar-99	Apr-99	May-99	Jun-99	Jul-99	Aug-99	Sep-99
1	0.5	3.7	29.8	1.8	52.8	74.6	12.1	4.1	1.6	0.8	0.5	0.5
2	0.5	3.5	35.1	1.6	38.0	63.0	10.6	4.0	1.8	0.8	0.5	0.5
3	0.5	3.7	91.1	1.5	28.7	63.8	9.6	4.4	1.7	0.9	0.4	0.6
4	0.5	3.9	30.3	1.4	20.7	51.9	8.7	3.8	1.7	0.9	0.4	0.7
5	0.4	3.6	17.4	1.3	18.0	43.2	10.8	3.6	1.6	0.9	0.4	0.6
6	0.4	9.3	21.9	1.2	66.1	35.7	9.5	3.4	1.6	0.9	0.6	0.6
7	0.4	9.8	15.6	1.2	502.2	28.3	8.4	3.2	1.4	0.8	0.6	0.6
8	0.5	6.4	12.9	1.2	210.5	27.8	10.7	3.0	1.3	0.9	0.5	0.6
9	0.5	2.4	10.7	1.1	236.1	28.2	9.4	2.9	1.5	0.9	0.4	0.7
10	0.4	1.9	8.9	1.1	148.6	22.7	10.0	2.7	1.5	0.9	0.5	0.6
11	0.4	3.6	7.6	1.0	97.5	19.3	86.6	2.7	1.5	0.8	0.7	0.7
12	0.5	2.1	6.6	1.0	71.3	15.0	67.3	2.6	1.5	0.8	0.6	0.7
13	0.4	1.7	6.2	1.0	56.9	12.1	48.7	2.5	1.4	0.8	0.5	0.6
14	0.4	1.3	5.5	0.6	46.9	11.9	36.5	2.3	1.4	0.8	0.4	0.6
15	0.4	0.9	5.5	1.1	38.9	11.4	27.3	2.3	1.4	0.8	0.3	0.6
16	0.4	1.0	5.2	3.7	236.5	10.2	20.2	2.2	1.4	0.7	0.3	0.6
17	0.4	1.7	4.8	4.0	366.9	9.3	14.4	2.1	1.3	0.7	0.3	0.5
18	0.4	1.3	4.5	72.1	168.6	8.5	11.3	2.1	1.2	0.7	0.4	0.6
19	0.4	0.8	4.1	69.4	123.6	8.2	9.9	2.1	1.2	0.7	0.7	0.5
20	0.4	0.6	4.0	188.8	111.9	7.6	8.8	2.1	1.2	0.7	0.8	0.5
21	0.4	0.6	3.6	116.4	137.8	7.3	8.1	2.0	1.1	0.7	0.7	0.5
22	0.4	2.7	3.5	76.3	118.5	7.0	7.7	2.0	1.1	0.6	0.7	0.6
23	0.4	8.4	3.2	101.5	95.7	9.9	6.8	1.9	1.1	0.6	0.8	0.6
24	1.0	8.0	3.1	75.5	77.7	14.2	6.4	1.9	1.1	0.6	0.9	0.6
25	5.0	4.2	2.9	58.8	105.8	90.6	6.1	2.0	1.1	0.6	0.8	0.5
26	4.3	3.0	2.9	49.4	82.2	61.2	5.7	1.9	1.0	0.6	0.7	0.5
27	4.3	4.0	2.7	39.0	66.0	43.8	5.2	1.9	0.9	0.6	0.7	0.4
28	4.4	2.9	2.6	31.2	66.1	33.0	4.9	1.9	0.9	0.5	0.8	0.3
29	3.9	59.9	2.5	25.3		25.6	4.6	1.7	0.8	0.5	0.8	0.3
30	3.6	70.3	2.4	21.4		20.4	4.2	1.7	0.8	0.5	0.6	0.3
31	3.8		2.0	77.4		17.0		1.6		0.5	0.5	

Values in italics are estimated

Table 9: Mean daily discharge for Redwood Creek at Highway One Bridge, Marin Co., CA. Water Year 2000

DAY	Oct-99	Nov-99	Dec-99	Jan-00	Feb-00	Mar-00	Apr-00	May-00	Jun-00	Jul-00	Aug-00	Sep-00
1	0.3	<i>0.3</i>	3.0	1.7	19.3	114	<i>3.8</i>	2.7	2.3	1.2	<i>0.8</i>	1.0
2	0.4	<i>0.3</i>	2.4	1.6	18.8	78.2	<i>3.6</i>	2.7	2.2	1.2	<i>0.8</i>	1.1
3	0.5	<i>0.3</i>	2.2	1.6	17.1	53.9	<i>3.5</i>	2.6	2.1	1.2	<i>0.8</i>	0.9
4	0.5	<i>0.3</i>	1.4	1.5	17.1	48.4	<i>3.3</i>	2.5	2.1	1.2	<i>0.8</i>	0.8
5	0.5	0.4	1.1	1.3	16.0	83.4	<i>3.2</i>	2.4	2.0	1.2	<i>0.8</i>	0.8
6	0.7	0.4	1.0	1.7	22.9	61.4	<i>3.0</i>	2.4	2.0	1.2	<i>0.8</i>	0.8
7	0.8	0.7	1.0	1.6	20.5	47.7	<i>2.9</i>	7.8	2.0	1.2	<i>0.8</i>	0.7
8	0.6	2.6	0.8	1.5	18.2	58.3	2.8	28.6	2.2	1.2	<i>0.8</i>	0.7
9	0.5	0.8	1.1	1.5	16.0	65.9	2.7	13.2	2.0	1.2	<i>0.8</i>	0.8
10	0.4	0.5	1.7	1.7	20.5	51.8	2.6	9.0	1.9	1.2	<i>0.8</i>	0.8
11	0.4	0.5	1.1	17.8	60.8	42.8	2.5	<i>8.7</i>	1.8	1.2	<i>0.8</i>	0.8
12	0.5	0.5	0.9	7.0	262	31.6	2.5	<i>8.3</i>	<i>1.8</i>	1.2	<i>0.8</i>	0.9
13	0.5	0.5	1.1	2.7	306	25.2	3.1	<i>8.0</i>	<i>1.7</i>	1.1	<i>0.8</i>	0.8
14	0.6	0.6	1.2	1.9	501	20.5	3.3	7.7	<i>1.7</i>	1.1	<i>0.8</i>	0.8
15	0.5	0.7	1.0	1.6	193	17.4	2.7	23.0	<i>1.7</i>	1.1	<i>0.8</i>	0.9
16	0.4	1.2	0.9	7.5	88.7	14.4	4.8	15.8	<i>1.7</i>	1.1	<i>0.8</i>	1.1
17	0.3	1.7	0.9	3.9	60.4	12.0	44.1	11.8	<i>1.7</i>	<i>1.0</i>	<i>0.8</i>	1.1
18	0.4	1.0	0.8	6.2	38.6	10.4	15.3	9.4	<i>1.6</i>	<i>1.0</i>	<i>0.8</i>	0.9
19	0.4	2.3	0.9	9.1	29.0	9.2	9.8	7.7	1.6	<i>1.0</i>	<i>0.8</i>	0.9
20	0.4	2.3	1.3	12.3	28.2	8.9	7.5	6.7	1.6	<i>0.9</i>	<i>0.8</i>	1.0
21	0.3	1.2	1.4	7.6	38.5	7.3	6.3	5.7	1.6	<i>0.9</i>	<i>0.8</i>	1.1
22	0.4	0.8	1.4	9.5	47.3	6.7	5.6	4.9	1.5	<i>0.9</i>	0.7	1.4
23	0.4	0.6	1.5	56.4	108	6.2	4.8	4.4	1.5	<i>0.9</i>	0.8	1.3
24	0.4	0.6	1.4	266	74.0	5.8	4.2	4.2	1.4	<i>0.8</i>	0.8	1.2
25	0.5	0.5	1.4	87.9	58.1	5.4	3.9	3.8	1.4	<i>0.8</i>	0.7	1.2
26	0.6	0.5	1.5	36.0	72.4	5.0	3.6	3.4	1.4	<i>0.8</i>	0.7	1.1
27	0.7	0.6	1.6	23.9	142	4.8	3.4	3.2	1.4	<i>0.8</i>	0.7	1.1
28	3.7	0.6	1.7	18.0	98.4	4.6	3.2	3.0	1.3	<i>0.8</i>	0.7	1.1
29	0.6	0.7	1.7	14.6	148	4.3	3.0	2.7	1.3	<i>0.8</i>	0.8	1.4
30	0.4	3.4	1.7	14.7		4.1	2.8	2.6	1.3	<i>0.8</i>	0.9	1.4
31	0.3		1.8	15.0		4.0		2.4		<i>0.8</i>	1.0	

Values in italics are estimated

Table 10. Instream flow and dissolved oxygen conditions at index pools between Highway One and MBCSD facilities, Redwood Creek, Marin Co.

Date	Mean daily Q (rated cfs)/ Instantaneous Q (cfs measured)	Noonish Water Surface Height@ MBCSD Sentinel Riffle	N	Mean DO (mg/l)	% of sampled pools that are isolated*
10/21/1998	0.4/ N.D.	N.D.	7	8.47	0
10/28/1998	4.4/ N.D.	N.D.	12	8.25	0
11/02/1998	3.5/ N.D.	N.D.	10	8.34	0
11/09/1998	2.4/ N.D.	N.D.	10	8.68	0
7/28/1999	0.5/ N.D.	N.D.	10	8.07	0
8/11/1999	0.7/ N.D.	N.D.	10	7.92	0
8/24/1999	0.9/ N.D.	N.D.	10	7.66	0
9/08/1999	0.6/ N.D.	N.D.	10	7.07	0
9/30/1999	0.3/ N.D.	N.D.	10	6.33	0
10/04/1999	0.5/ N.D.	N.D.	4	7.75	0
10/05/1999	0.5/ N.D.	N.D.	4	8.02	0
10/06/1999	0.7/ N.D.	N.D.	2	8.40	0
9/10/2001	0.01/ N.D.	48 mm	15	2.63	80
9/20/2001	N.D. /0.04	100	12	4.67	8
10/10/2001	N.D. /N.D.	68	12	4.38	33
10/08/2002	N.D. /0.007	N.D.	4	2.09	25
10/09/2002	N.D. /0.002	N.D.	5	3.50	40
10/23/2002	0.05/0.05	N.D.	9	7.58	0

N.D. No data

Table 11: Maximum pool depth (m) in Redwood Creek, Marin Co., 1998

Reach	Pool#	Aug 18-31	Sep. 21	Oct. 21	Oct. 28	Nov. 2	Nov. 9	Change in Depth (based on Nov. 2)	%Change
A	24	N.D.	0.68	0.67	0.68	0.69	0.70	0.01	0.90
	27	N.D.	0.60	0.59	0.59	0.60	0.61	0.00	0.00
	35	N.D.	0.40	0.44	0.40	0.46	0.50	0.06	14.58
	46	N.D.	0.52	0.51	0.52	0.52	0.53	0.00	-0.59
	51	N.D.	0.75	0.66	0.74	0.66	0.69	-0.09	-12.25
B	58	N.D.	0.61	0.60	0.58	0.58	0.59	-0.03	-5.51
	64	N.D.	0.52	0.50	0.52	0.50	0.51	-0.02	-4.65
	70	N.D.	0.67	0.67	0.65	0.65	0.67	-0.02	-3.18
	76	N.D.	0.65	0.65	0.66	0.65	0.67	0.00	-0.47
	80	N.D.	0.70	0.70	0.69	0.70	0.71	0.00	-0.43
C	103	N.D.	0.55	0.54	0.52	0.52	0.54	-0.03	-6.06
	121	N.D.	0.58	0.56	0.54	0.54		-0.04	-6.84
	123	N.D.	0.70	0.69	0.68	0.69		-0.02	-2.18
	126	N.D.	0.41	0.40	0.41	0.41		0.00	-0.74
	131	N.D.	0.67	0.67	0.64	0.64		-0.04	-5.45
MEAN								-0.02	-2.19
N.D.--no data									

Table 12: Maximum pool depth (m) in Redwood Creek for index station sites, Marin Co., 1999

Reach	Pool#	June 21-30	July 23	July 28	Aug 11	Aug 24	Sept 8	Sept 30	Oct 4-7	Oct 27	Change in Depth	%Change
A	4	0.91	0.90	0.90	0.91	0.91	0.91	0.90	0.92	0.90	-0.01	-0.67
A	6	0.52	0.52	0.52	0.52	0.52	0.53	0.51		0.51	-0.01	-2.34
A	11	0.81	0.80	0.80	0.80	0.80	0.80	0.79		0.79	-0.02	-1.88
A	15	0.45	0.43	0.44	0.43	0.43	0.43	0.42		0.42	-0.03	-6.77
A	18	0.66	0.60	0.59	0.57	0.57	0.57	0.53		0.51	-0.15	-22.17
A	24	0.45	0.44	0.44	0.44	0.45	0.45	0.42	0.43	0.42	-0.03	-6.10
B	30	0.56	0.56	0.56	0.62	0.62	0.56	0.56	0.56			
B	32	0.99		0.98	0.99	0.99	0.98	0.97		0.99	0.00	0.00
B	42	0.82		0.82	0.81	0.83	0.81	0.83		0.82	0.00	0.37
B	48	1.10		1.09	1.07	1.08	1.08		1.10	1.07	-0.03	-2.49
C	53	1.23		1.22	1.22	1.22	1.22		1.22	1.20	-0.03	-2.23
C	58	0.80		0.82	0.79	0.78	0.78	0.77	0.79	0.81	0.01	0.76
C	60	0.73		0.73	0.74	0.74	0.73	0.71	0.74	0.72	-0.01	-0.84
C	65	0.80		0.80	0.80	0.82	0.82	0.81	0.83	0.80	0.00	0.38
C	69	0.80		0.79	0.79	0.79	0.79	0.78	0.79	0.79	-0.01	-1.52
MEAN											-0.02	-3.25

Table 13. Pool volume (m³) for index pools in Redwood Creek, Marin Co., CA. 1999

Reach	Pool#	June 21-30	July 23	July 28	Aug 11	Aug 24	Sept 8	Sept 30	Oct 27	Change in Vol.	%Change
A	4	19.69	19.45		19.86				15.70	-4.00	-20
	6	9.08	9.02	9.08	9.13	9.13	9.23		8.36	-0.72	-8
	11	39.23	38.84	39.11	39.38	39.19	39.23	38.84	27.98	-11.25	-29
	15	6.81	6.51	6.87	6.65	6.89	6.81		4.47	-2.34	-34
	18	28.81	27.30	28.58	28.44	28.81	28.74	27.89	10.96	-17.85	-62
	24	19.34	18.97	19.34	19.22	19.72	19.34	18.38	14.84	-4.50	-23
B	30	27.70	27.55	27.85	30.97	27.70	24.57	27.85	28.73	1.03	4
	32	20.02			20.26	20.02	19.76	19.85	18.02	-2.00	-10
	42	44.11			43.56	45.06	43.51	44.79	34.75	-9.36	-21
	48	27.62			27.20	27.88					
C	53	43.43			43.43						
	58	35.10			33.99	34.85	34.98	34.59	36.40	1.31	4
	60	17.44			17.67	17.44	17.26	17.06	15.79	-1.65	-9
	65	40.43			40.64	41.49	40.86	39.81	41.11	0.68	2
	69	12.56			12.61	12.56	12.50	12.42	10.10	-2.46	-20
MEAN										-4.09	-17.51

Table 14: Precipitation totals and dry stream habitat conditions in Redwood Creek, Marin Co., CA

Rainfall Year (July 1 - June 30)	Rainfall Year PPT (in)	Total PPT Rank	Rain Season PPT (in)	Rain Season <15" in	Stream Condition in Sep/Oct of Calendar Yr ***
1991-1992	31.00	38	25.69	No	Dry
1992-1993	41.86	20	35.57	No	Wet
1993-1994	25.61	47	22.38	No	Dry
1994-1995	57.07	6	52.30	No	Wet
1995-1996	48.40	15	44.17	No	Wet
1996-1997	32.85	34	29.17	No	Dry
1997-1998	67.01	2	59.72	No	Wet
1998-1999	35.52	30	33.18	No	Wet
1999-2000	38.08	26	33.04	No	Wet
2000-2001	25.35	49	21.39	No	Dry
2001-2002	40.47	23	30.11	No	Dry
2002-2003	46.10	17	45.93	No	Wet**
2003-2004	29.85	40	29.48	No	Dry
Rain season Average*			33.06		
Yearly Average*	37.45				

Rain season defined as November-April

*Averages are for period of record (1948-2004)

**Dry conditions may be related to construction of new instream habitat, but not noted by Smith (2003)

***Data Source: Smith (2003) and NPS fieldwork for this report

Table 15: Ranked rain season precipitation and dry stream habitat conditions in Redwood Creek, Marin Co., CA

Rain season PPT (in)	Stream Condition
21.39	Dry
22.38	Dry
25.69	Dry
29.17	Dry
29.48	Dry
30.11	Dry
33.04	Wet
33.18	Wet
35.57	Wet
44.17	Wet
45.93	Wet
52.30	Wet
59.72	Wet

Rain season defined as November-April

Table 16: Habitat type composition by length (m) for Study Reaches A, B, and C. Redwood Creek, Marin Co., CA. 1998, 1999, 2001, 2002, and 2004.

REACH	DATA	July 1998*				June 1999*				October 2001			
		DRY	POOL	FW/ R	TOTALS	DRY	POOL	FW/ R	TOTALS	DRY	POOL	FW/ R	TOTALS
A	N		22	12	34		19	9	28	25	31	1	57
	Sum of length		441	144	585		437	108	545	234	352	11	597
	% of reach		75	25	100		80	20	100	39	59	2	100
B	N		17	15	32		11	11	22	14	18	2	34
	Sum of length		420	183	603		304	269	573	317	290	25	632
	% of reach		70	30	100		53	47	100	50	46	4	100
C	N		25	14	39		13	12	25	2	13	4	19
	Sum of length		453	120	561		256	145	401	15	218	43	276
	% of reach		79	21	100		64	37	100	5	79	16	100
TOTAL N		0	64	41	105	0	43	32	75	41	62	8	111
TOTAL LEN		0	1313	447	1760	0	997	522	1519	566	860	79	1505

*Field notes from NPS and J. Smith sampling events in October 1998 and 1999 indicate connected flows and no dry reaches

Table 16 (cont.): Habitat type composition by length (m) for Study Reaches A,B, and C. Redwood Creek, Marin Co., CA 1998, 1999, 2001, 2002, and 2004.

REACH	DATA	Oct. 2002				Sept. 2004			
		DRY	POOL	FW/R	TOTALS	DRY	POOL	FW/R	TOTALS
A	N	13	31	20	64	27	17	14	58
	Sum of length	171	354	71	596	283	230	109	623
	% of reach	29	59	12	100	46	37	18	100
B	N	3	21	6	30	11	20	15	46
	Sum of length	67	424	78	569	105	339	130	574
	% of reach	12	74	14	100	18	59	23	100
C	N	0	13	1	14	2	9	9	20
	Sum of length	0	303	10	312	3	139	157	300
	% of reach	0	97	3	100	1	46	53	100
TOTAL N		16	65	27	108	40	46	38	124
TOTAL LEN		238	1081	159	1477	392	708	397	1496

Table 17: Summary of continuously recording water quality data at project stations, Redwood Creek, Marin Co., CA.

Year	Period of Record	Stream Distance from MBCSD Bridge	Pool Unit #	n	Mean DO (mg/l)	Std. Dev.	Max DO (mg/l)	Min DO (mg/l)
1998	Oct 22 - Nov 12	-973m	24	1010	8.0	0.4	8.9	7.1
		-265 m	46	1010	7.7	0.4	8.6	6.8
		+575 m	121	1008	7.0	0.3	7.8	6.2
1999	Jun 30 - Oct 15	-710 m	24	4267	7.4	0.8	9.0	5.5
		-53 m	48	4335	6.9	1.0	8.5	5.3
		+355 m	69	4664	5.7	1.6	8.0	0.7
2001	Sept 12 - Nov 01	-13m	93	2388	5.4	0.9	6.9	1.9
	Oct 10 - Oct 31	-455m	64	1017	0.6	0.7	4.0	0.2

Year	Period of Record	Stream Distance from MBCSD Bridge	Pool Unit #	n	Mean Temp (°C)	Std. Dev.	Max Temp (°C)	Min Temp (°C)
1998	Oct 22 - Nov 12	-973m	24	1010	11.6	1.2	14.5	9.0
		-265 m	46	1010	11.5	0.9	13.3	9.1
		+575 m	121	1010	11.3	1.0	13.3	8.7
1999	Jun 30 - Oct 15	-710 m	24	4267	13.8	0.7	15.8	11.4
		-53 m	48	4335	13.6	0.5	15.0	11.9
		+355 m	69	4664	13.6	0.4	16.7	12.0
2001	Sept 12 - Nov 01	-13m	93	2388	13.0	0.8	16.0	9.8
	Oct 10 - Oct 31	-455m	64	1017	12.6	0.6	13.6	10.8

Table 18. Comparison of mean instantaneous growth for juvenile salmonids for index pools during from summer to fall 1998-1999, Redwood Creek, Marin Co., CA

Year	Reach	N	Coho (g*day ⁻¹)	N	SH YOY (g*day ⁻¹)	N	SH 1+ (g*day ⁻¹)
1998	A	4	0.002	4	0.003	4	-0.0001
	B	4	0.004	4	0.005	4	0.001
	C	4	0.005	4	0.003	4	0.002
P-value			0.36		0.31		0.78
1998	A	4	0.005	4	0.008	4	-0.001
	B	4	0.004	4	0.007	4	-0.001
	C	4	0.005	4	0.009	4	-0.001
P-value			0.81		0.25		0.95

Table 19. Mean Fulton's condition factor (K'), estimated total number of fish and 95% confidence interval (in parentheses) for pools in Redwood Creek between the Highway One Bridge and Muir Beach Community Service District's facilities, Marin

YEAR	CO (0+)	CO K'	SH (0+)	SH (0+) K'	SH 1+	SH 1+ K'	SCULPIN	STICK
1998	465 (55)	1.11	2282 (534)	1.12	181 (35)	1.04	1563 (432)	1
1999	266 (62)	1.15	950 (406)	1.16	180 (36)	1.05	751 (443)	0
2001	260 (158)	1.22	62 (61)	1.23	89 (56)	1.01	860 (540)	0

KEY: CO- coho salmon (*Oncorhynchus kisutch*), SH- steelhead trout (*O. mykiss*), SCULPIN- unidentified sculpin (*Cottus* spp.), STICK- threespine stickleback (*Gasterosteus aculeatus*)

Table 20. Estimated total number of fish ($\hat{Y}$), density (fish/m), standard error, and 95% confidence interval, and percent contribution to total number of fish for pools in Redwood Creek, Marin Co., California. Electrofishing survey, August and September, 1998.

Redwood Creek						Reaches A and B				
						Downstream of Muir Beach Comm. Serv. Dist. Well				
	CO (0+)*	SH (0+)	SH (1+)	Sculpin	Stickleback	CO (0+)*	SH (0+)	SH (1+)	Sculpin	Stickleback
Density (fish/m)	0.79	2.08	0.17	2.16	N.C.	0.71	2.67	0.21	1.83	N.C.
$\hat{Y}$	3510	9202	765	9570	1	465	2282	181	1563	1
Standard Error	221	1617	105	1358	N.C.	55	534	35	432	N.C.
95% CI	453	3306	215	2815	N.C.	124	1207	79	976	N.C.
% of mainstem	100	100	100	100	N.C.	13	25	24	16	N.C.

Redwood Creek – Estimate based on samples from Pacific Way Bridge to MUWO

Study Reaches A and B - Highway 1 to Muir Beach Pump Station Foot Bridge

*Estimates based on double sampling electrofishing and snorkel count

N.C.—Not calculated, a single three-spine stickleback was collected. Common downstream of Pacific Way Bridge.

Table 21: Estimated amount of habitat lost or converted during dry conditions in 2001 based on proportion of available habitat in 1998-1999 in Redwood Creek, Marin Co., CA

Reach	1998-99			2001		
	FW/R (%)	Pool (%)	Dry (%)	FW/R (%)	Pool (%)	Dry (%)
A	23	77	0	2	59	39
B	38	82	0	4	46	50
C	29	71	0	16	79	5

Reach	2001 REACH LENGTH (m)	Est. FW/R loss (m)	Est. Pool loss (m)
A	597	125	109
B	632	215	19
C	276	36	198

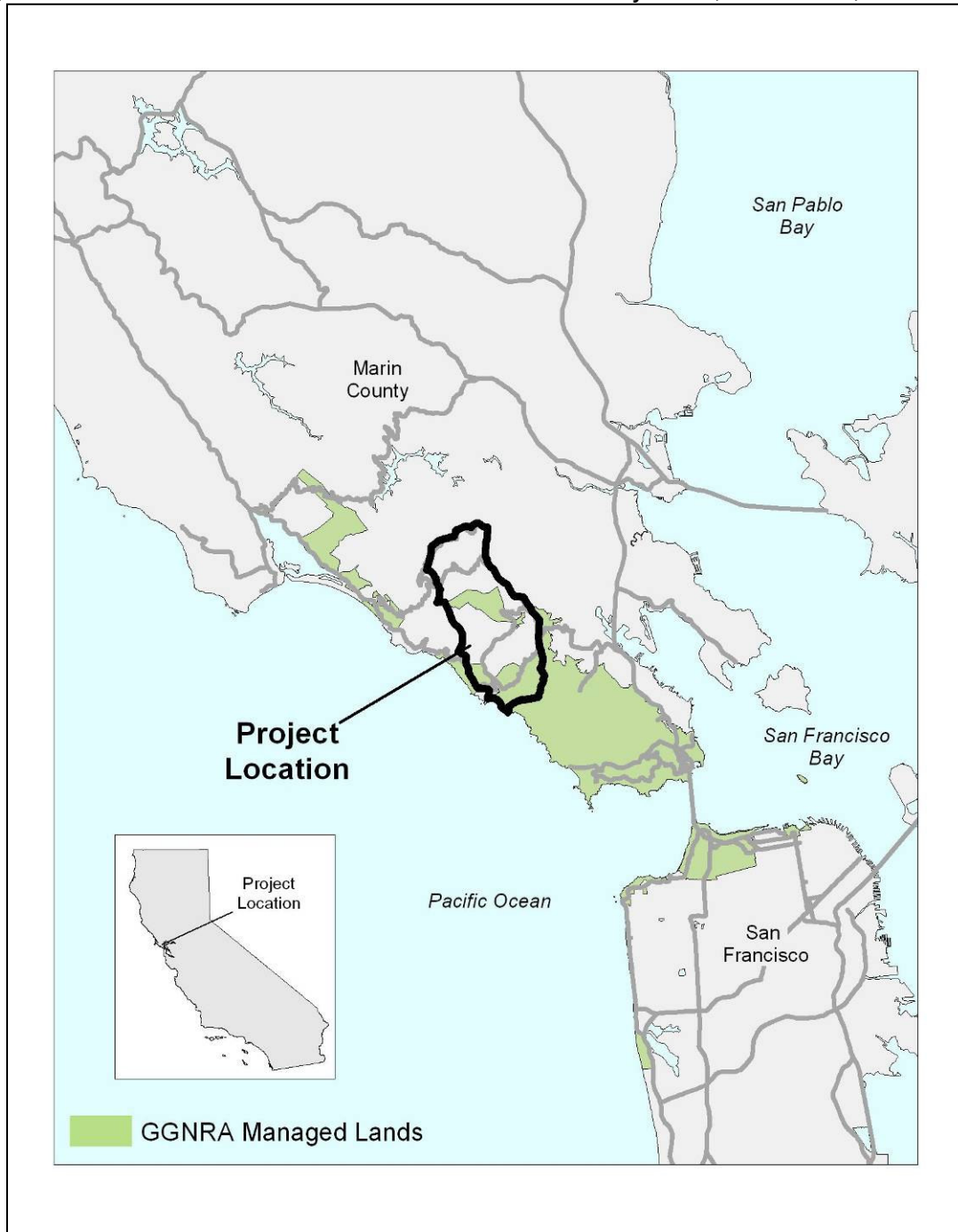
Table 22: Estimated reduction in fish production during dry conditions in 2001 and 2002 in Redwood Creek, Marin Co., CA¹

Taxa	Reach	2001			2002		
		# lost in fw/r	# lost in pool	TOTAL LOST	# lost in fw/r	# lost in pool	TOTAL LOST
COHO	A	8	306	314	4	364	368
	B	19	108	127	6	0	6
	C	1	0	1	0	0	0
SH YOY	A	16	58	74	33	263	296
	B	41	20	62	47	0	47
	C	2	0	2	0	0	0
SH1+	A	0	3	3	0	4	4
	B	0	1	1	0	0	0
	C	0	0	0	0	0	0
SCU	A	55	296	351	35	421	455
	B	139	104	243	49	0	49
	C	7	0	7	0	0	0

¹ Based on estimated pool abundances of fish in 2001 (from Reach C) and 2002 (from Jerry Smith Index Station Below Well sampled by NPS before creek fully disconnected)

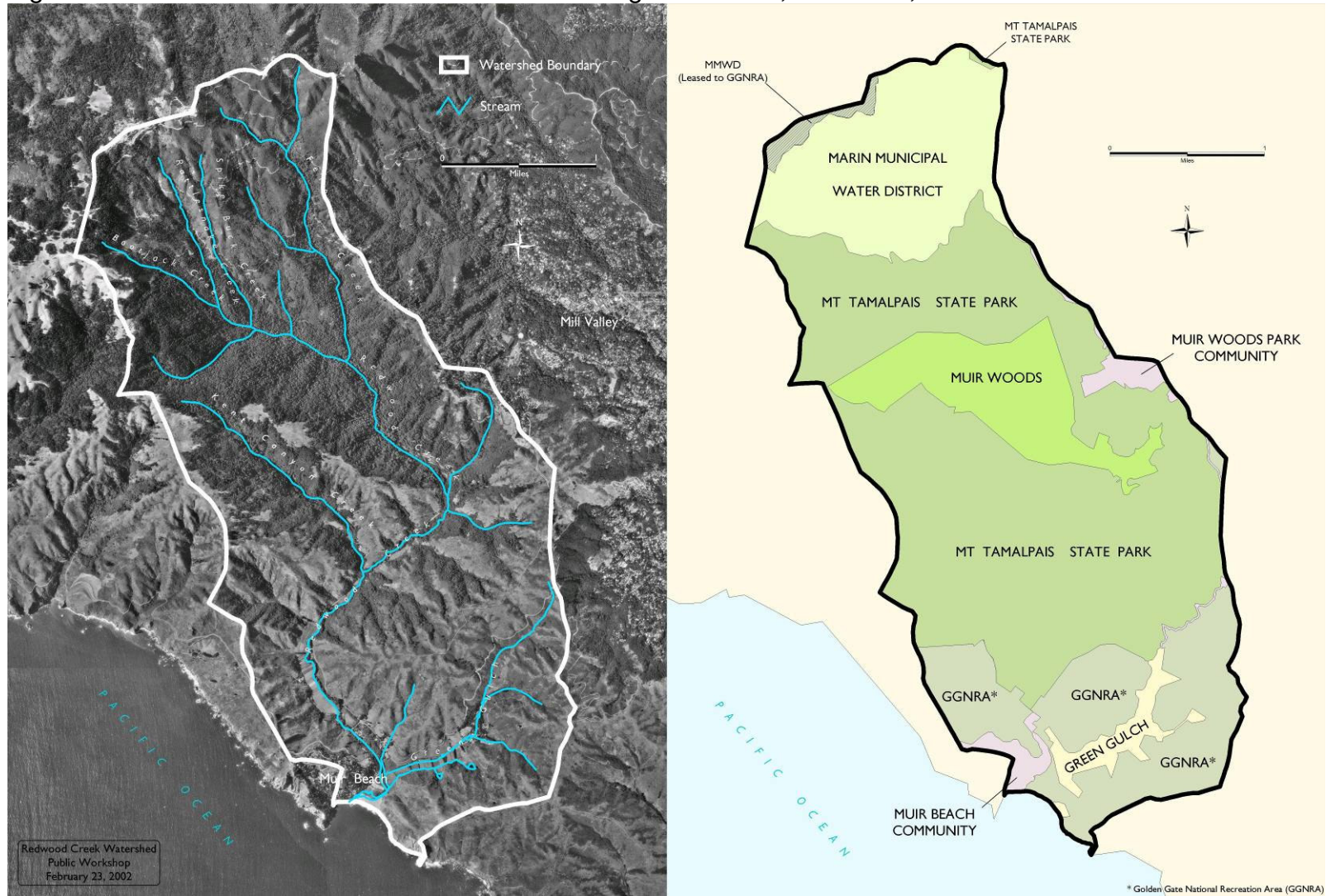
FIGURES

Figure 1: Redwood Creek and the San Francisco Bay Area, Marin Co., CA



(Prepared by Craig Scott, GOGA-Div. Natural Resource and Science)

Figure 2: Redwood Creek watershed and land management units, Marin Co., CA



(Prepared by Craig Scott, NPS-GOGA)

Figure 3: Mean daily discharge for Water Year 1999 at Redwood Creek at the Highway One Bridge, Marin Co., CA

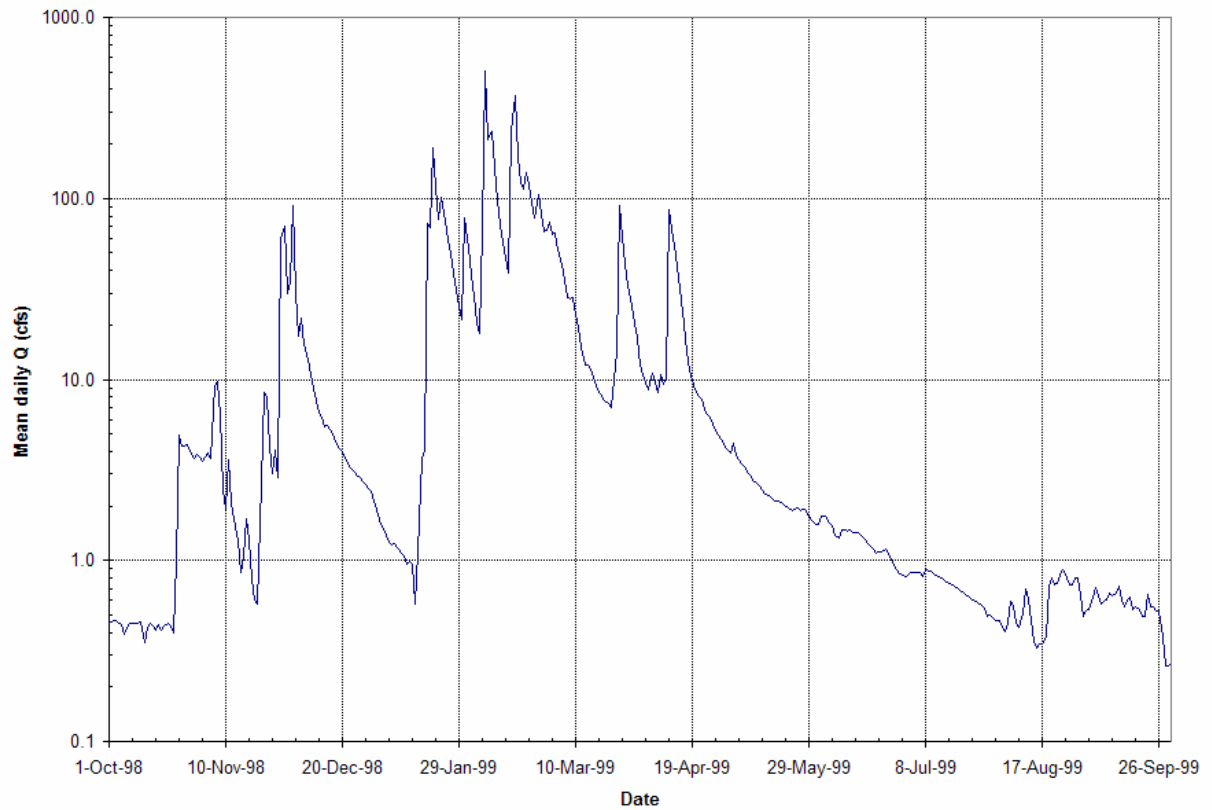


Figure 4: Map of index monitoring pools for 1998 sampling activities in Redwood Creek, Marin Co., CA

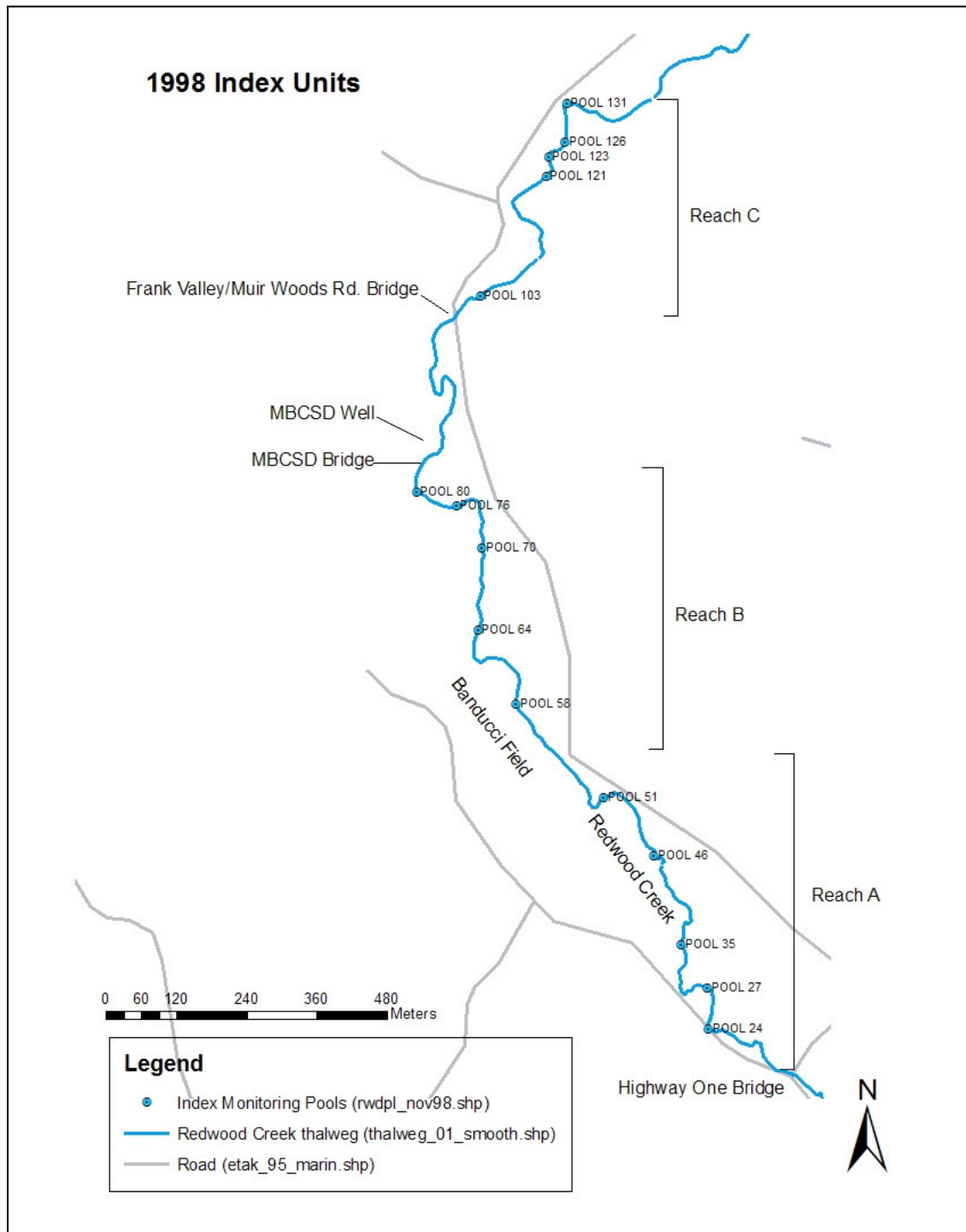


Figure 5: Map of index monitoring pools for 1999 sampling activities in Redwood Creek, Marin Co., CA

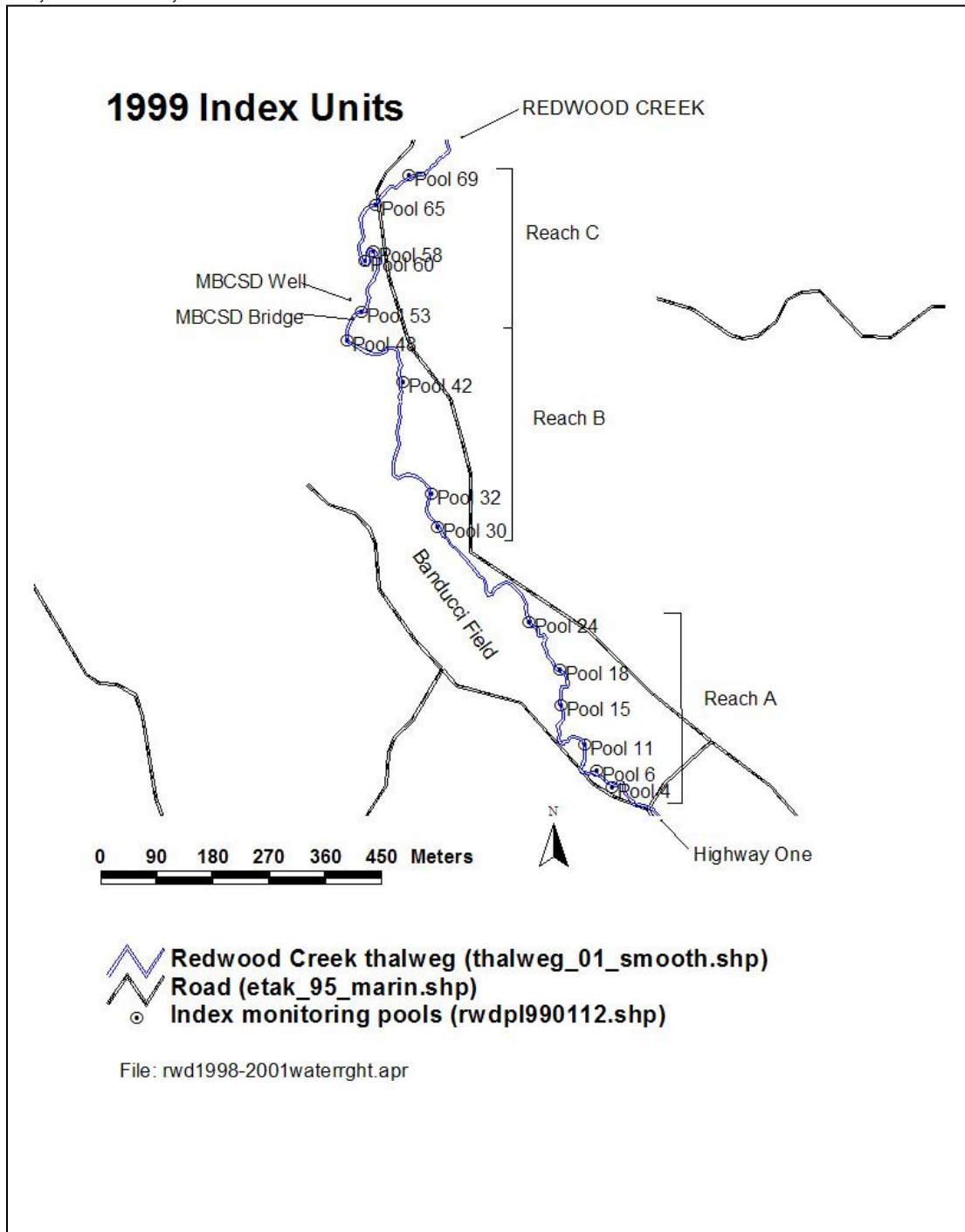


Figure 6: Map of index monitoring pools for 2001 sampling activities in Redwood Creek, Marin Co., CA.

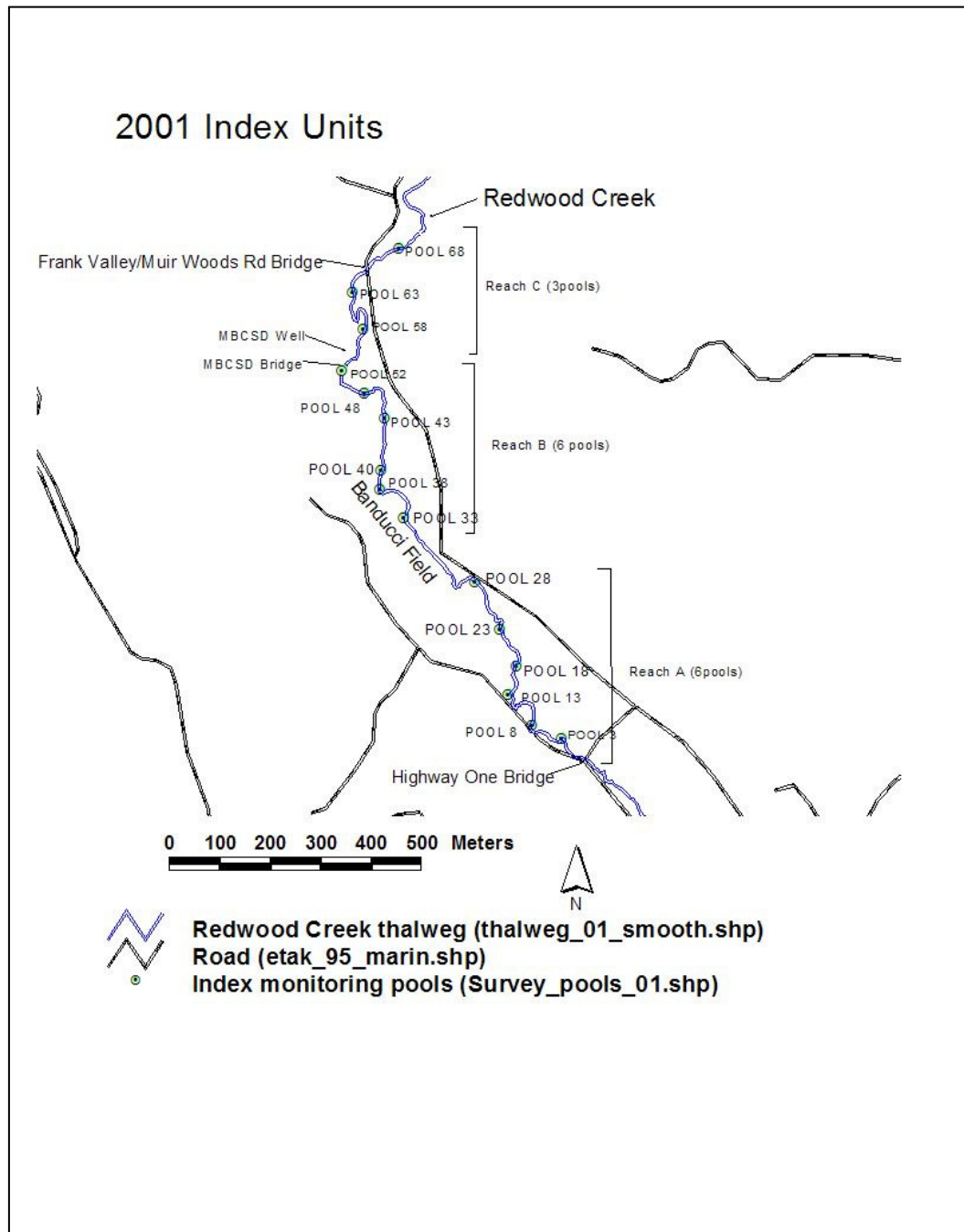


Figure 7: Map of index monitoring pools for 2002 sampling activities in Redwood Creek, Marin Co., CA

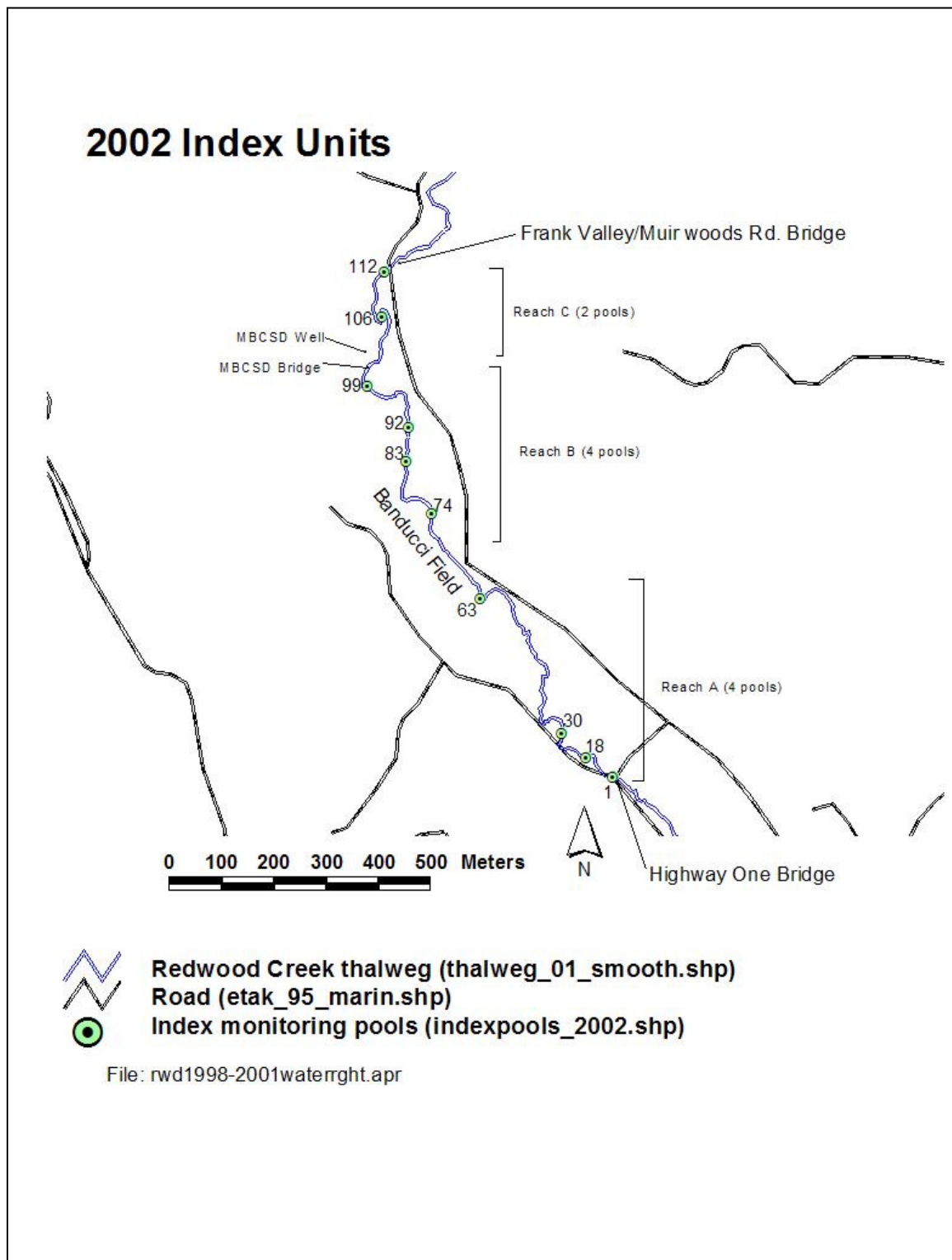


Figure 8: Planview map of riffle and bank piezometer (P6) below the Muir Beach Community Service District Bridge, Redwood Creek, Marin Co., CA, 2001-2002

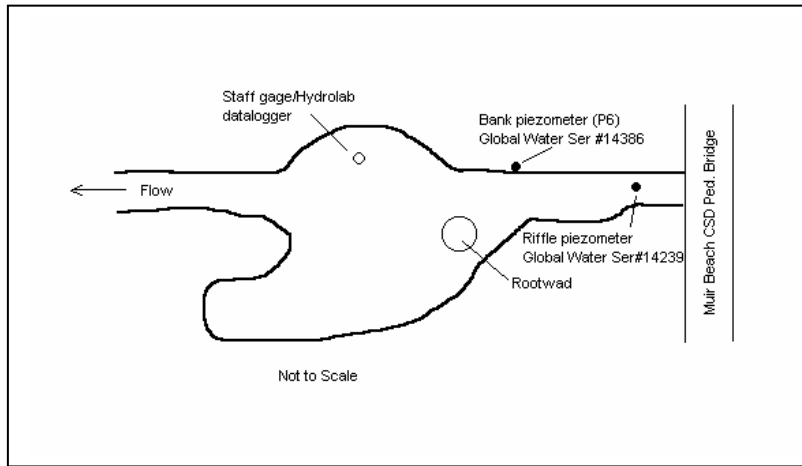


Figure 9: Photo of index pool on Redwood Creek, upstream of Highway One Bridge, Marin Co., CA



Note: Blue flags denote extent of wetted surface area on October 27, 1999 and red flags denote extent in June 1999.

Figure 10: Water surface elevations and water quality parameters, Redwood Creek, Marin Co., September 2001

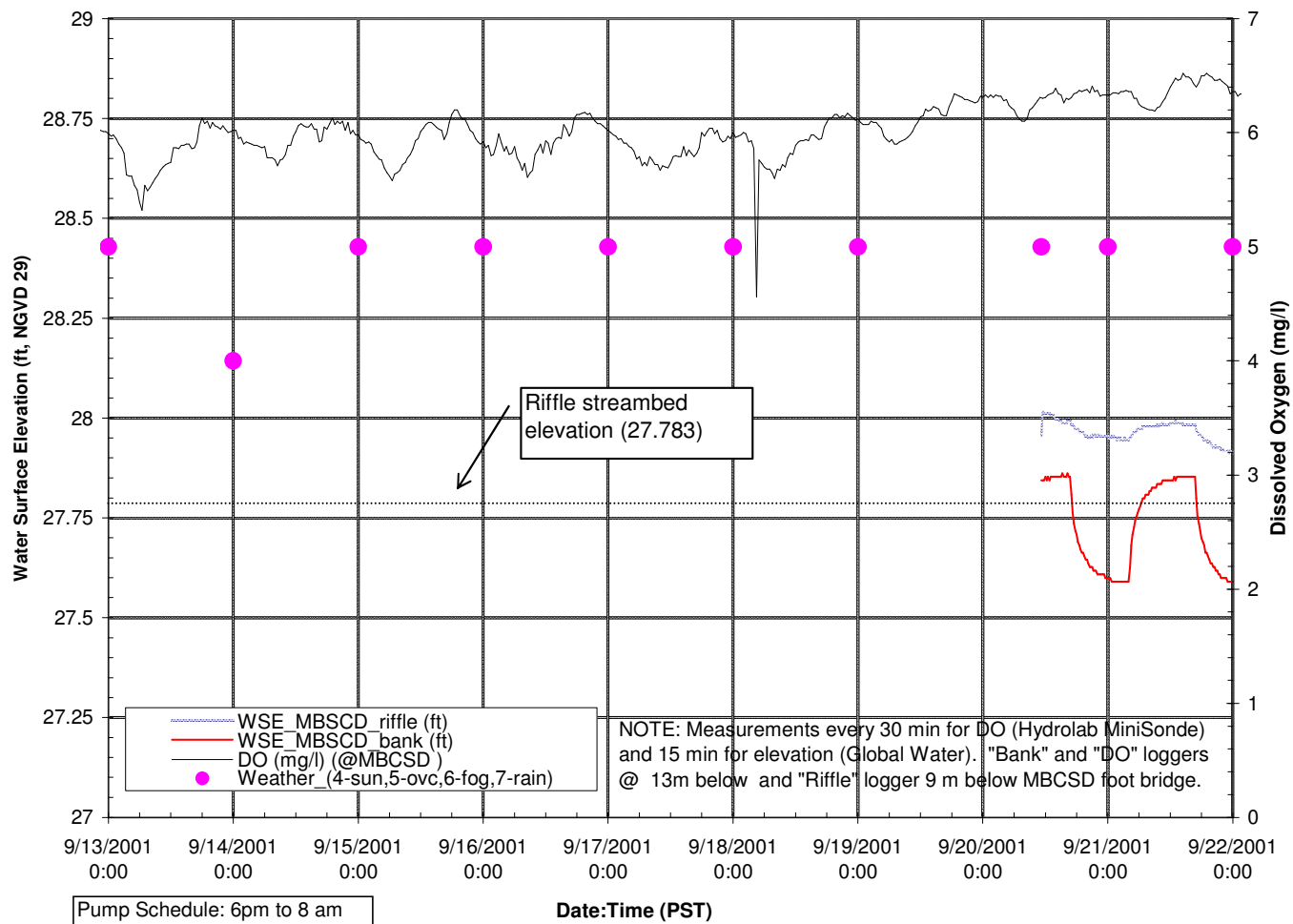


Figure 11: Water surface elevations and water quality parameters, Redwood Creek, Marin Co., September 2001

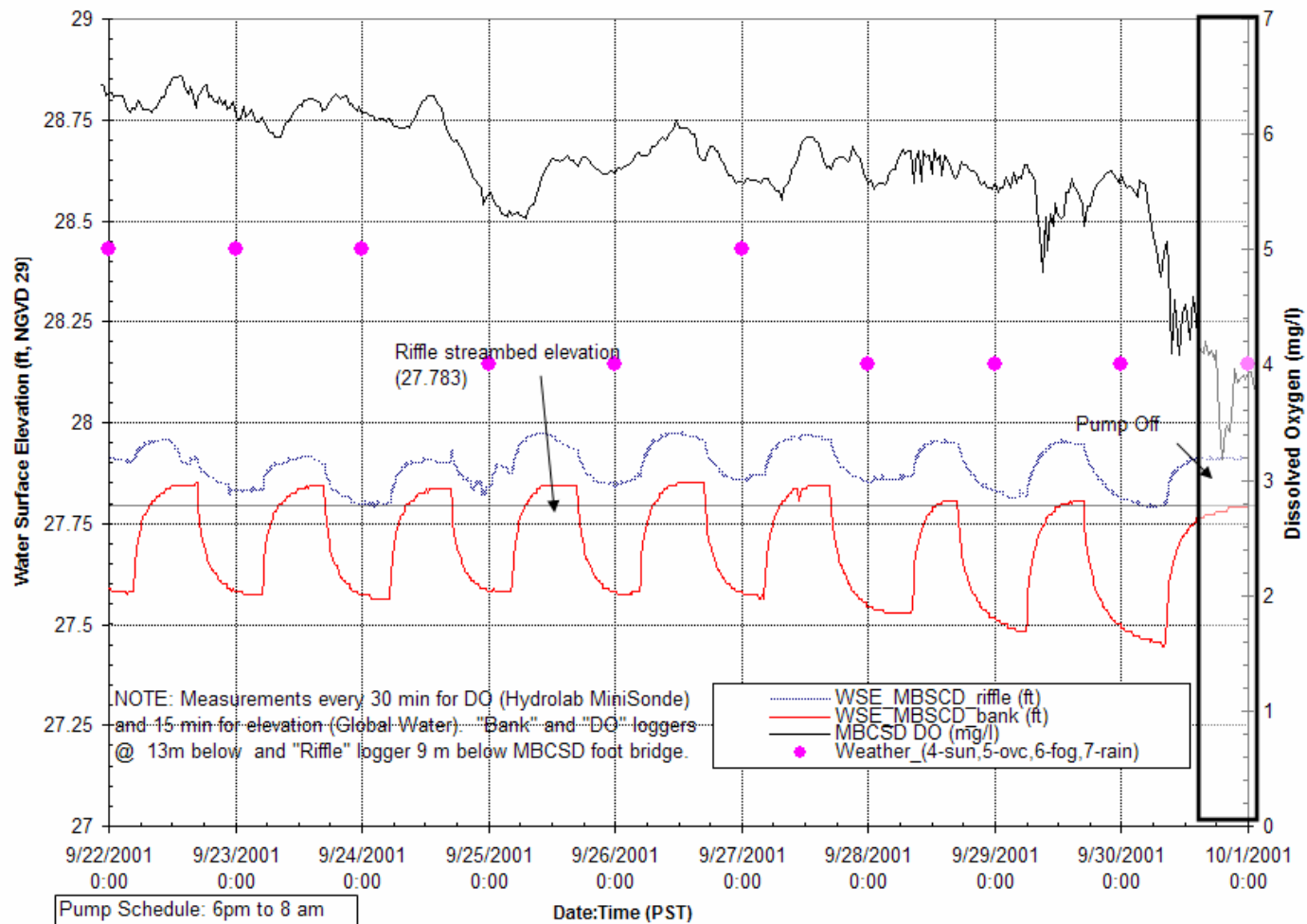


Figure 12: Water surface elevations and water quality parameters, Redwood Creek, Marin Co., October 2001

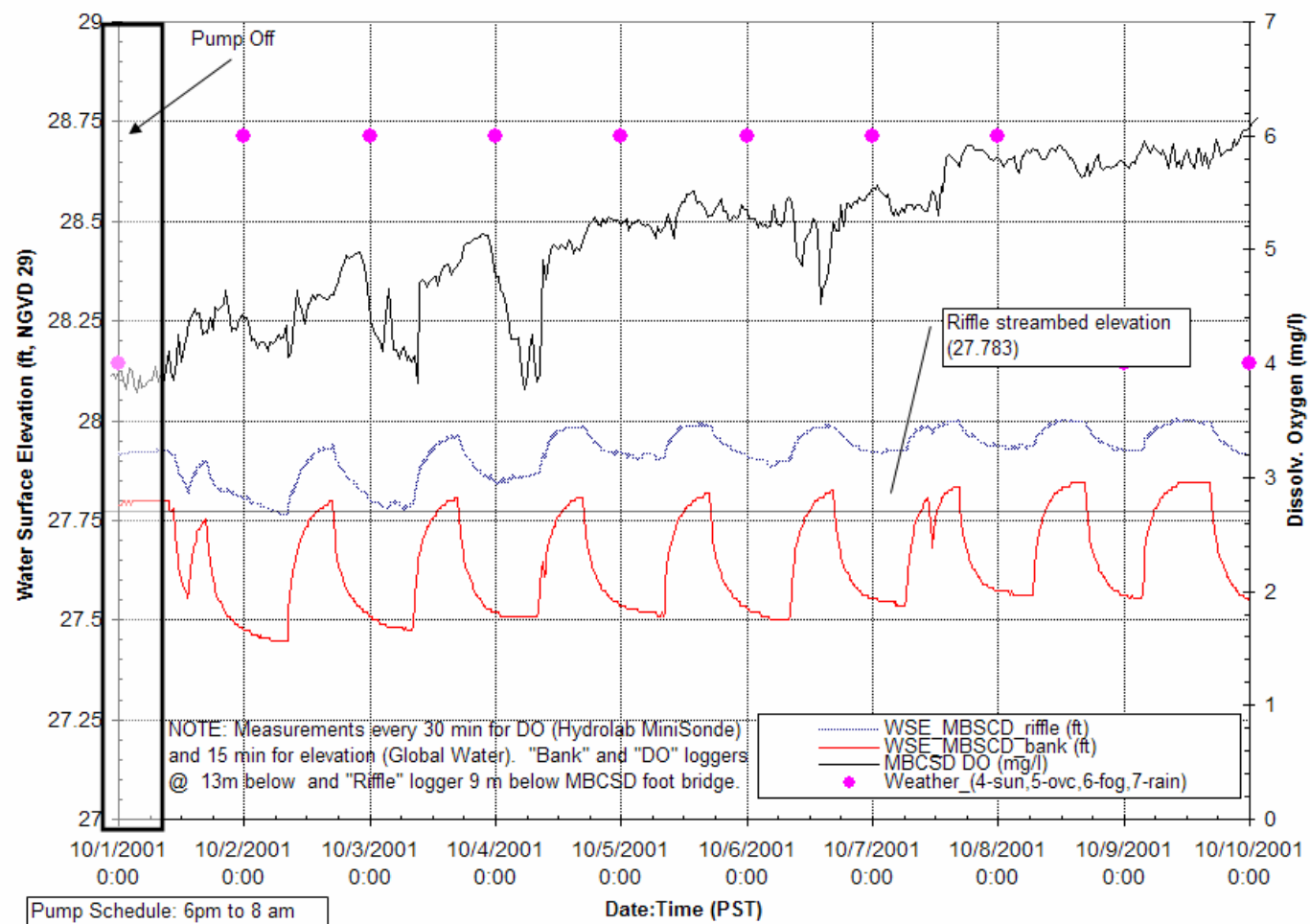


Figure 13: Water surface elevations and water quality parameters, Redwood Creek, Marin Co., October 2001 (cont.)

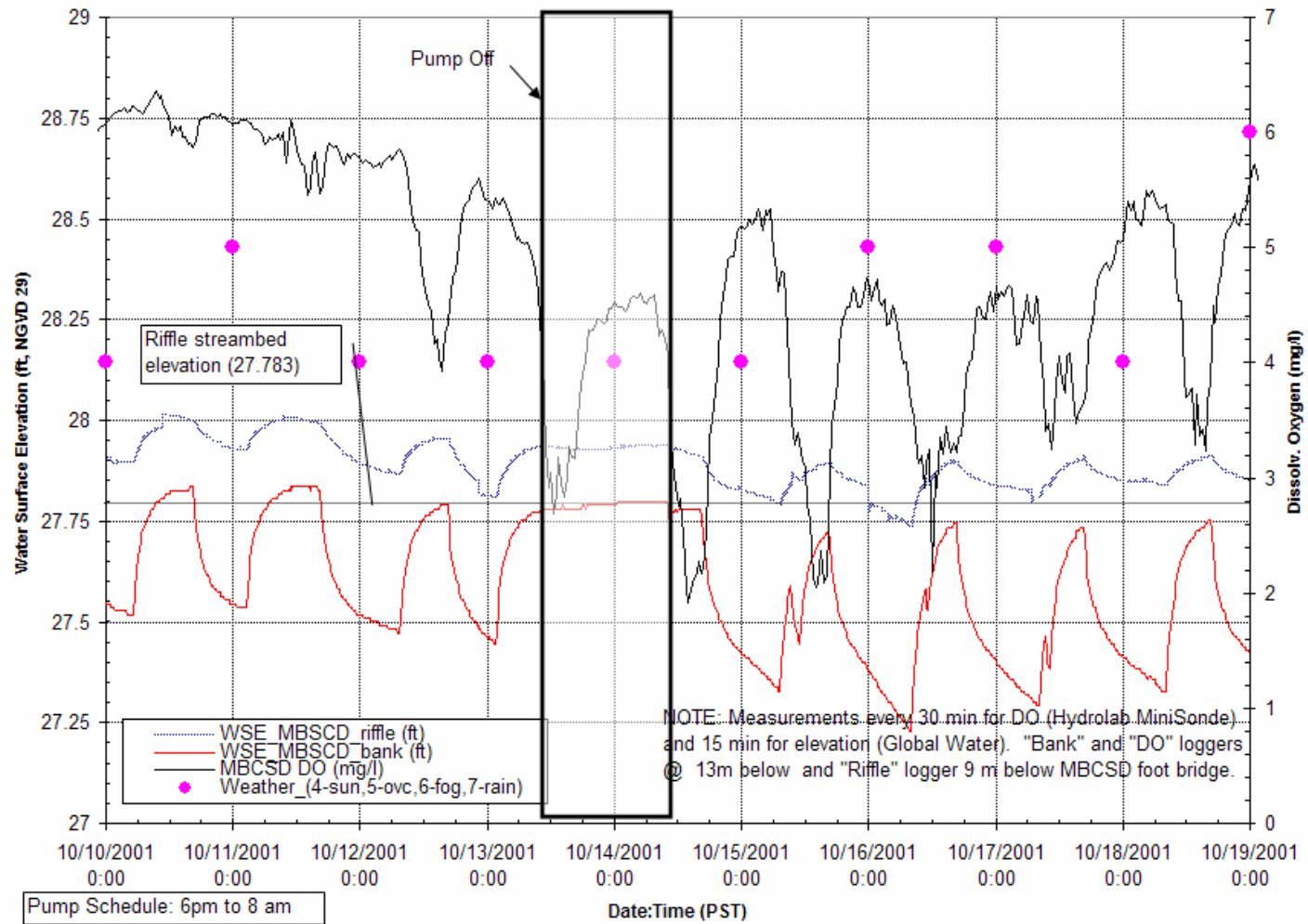


Figure 14: Water surface elevations and water quality parameters, Redwood Creek, Marin Co., October 2001 (cont.)

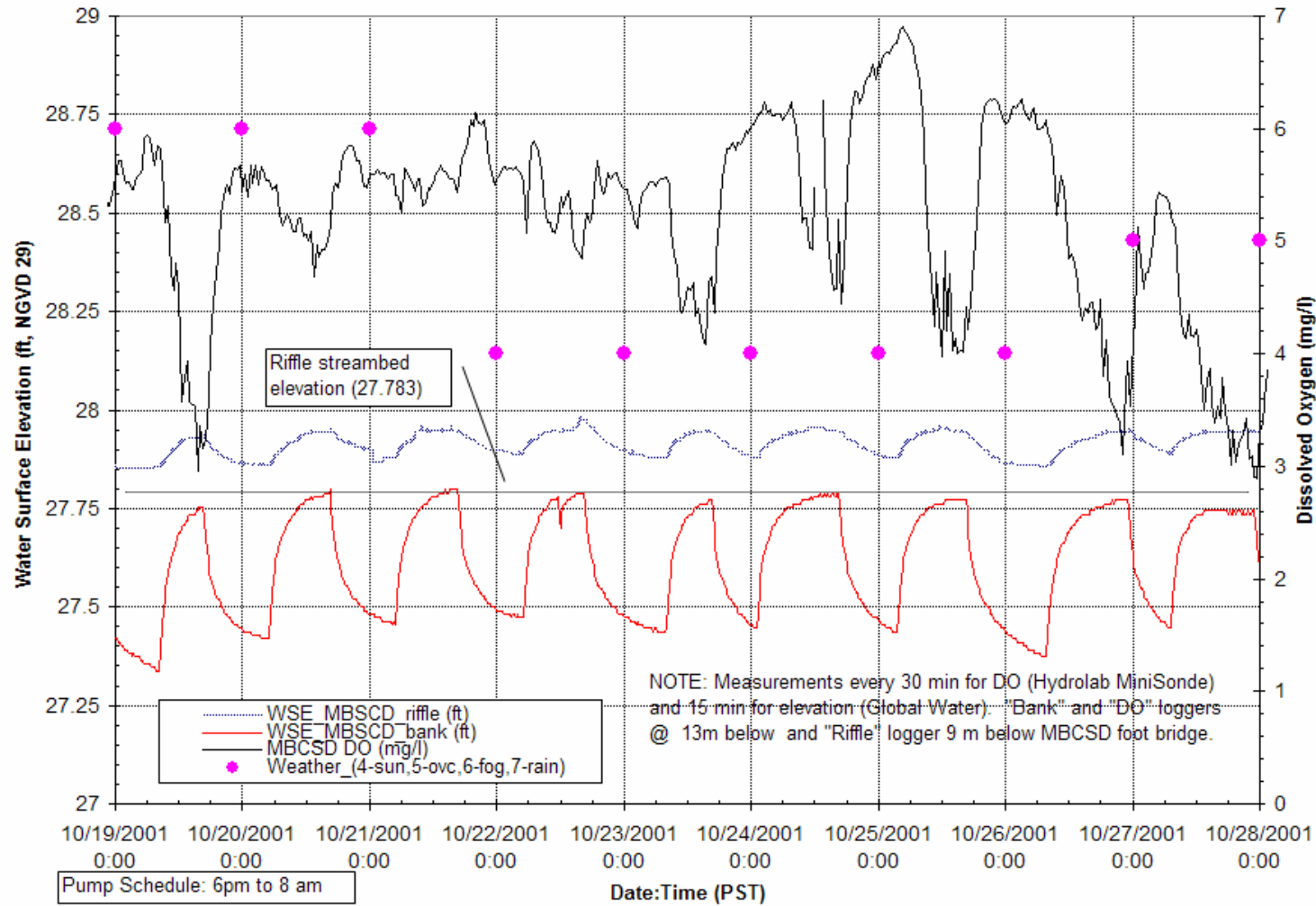


Figure 15: Water surface elevations and water quality parameters, Redwood Creek, Marin Co., October-Nov. 2001

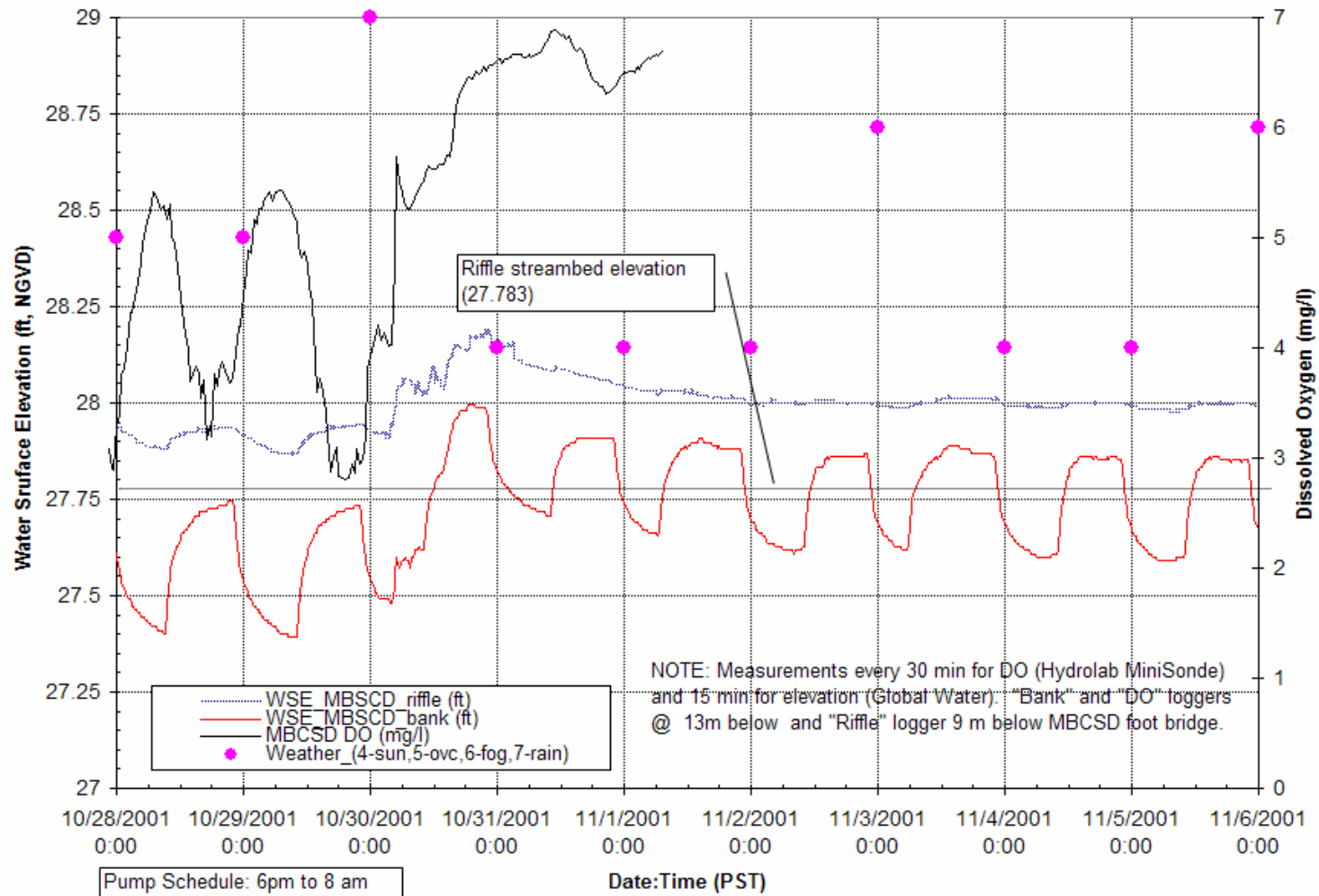


Figure 16: Water surface elevations and water quality parameters, Redwood Creek, Marin Co., November 2001

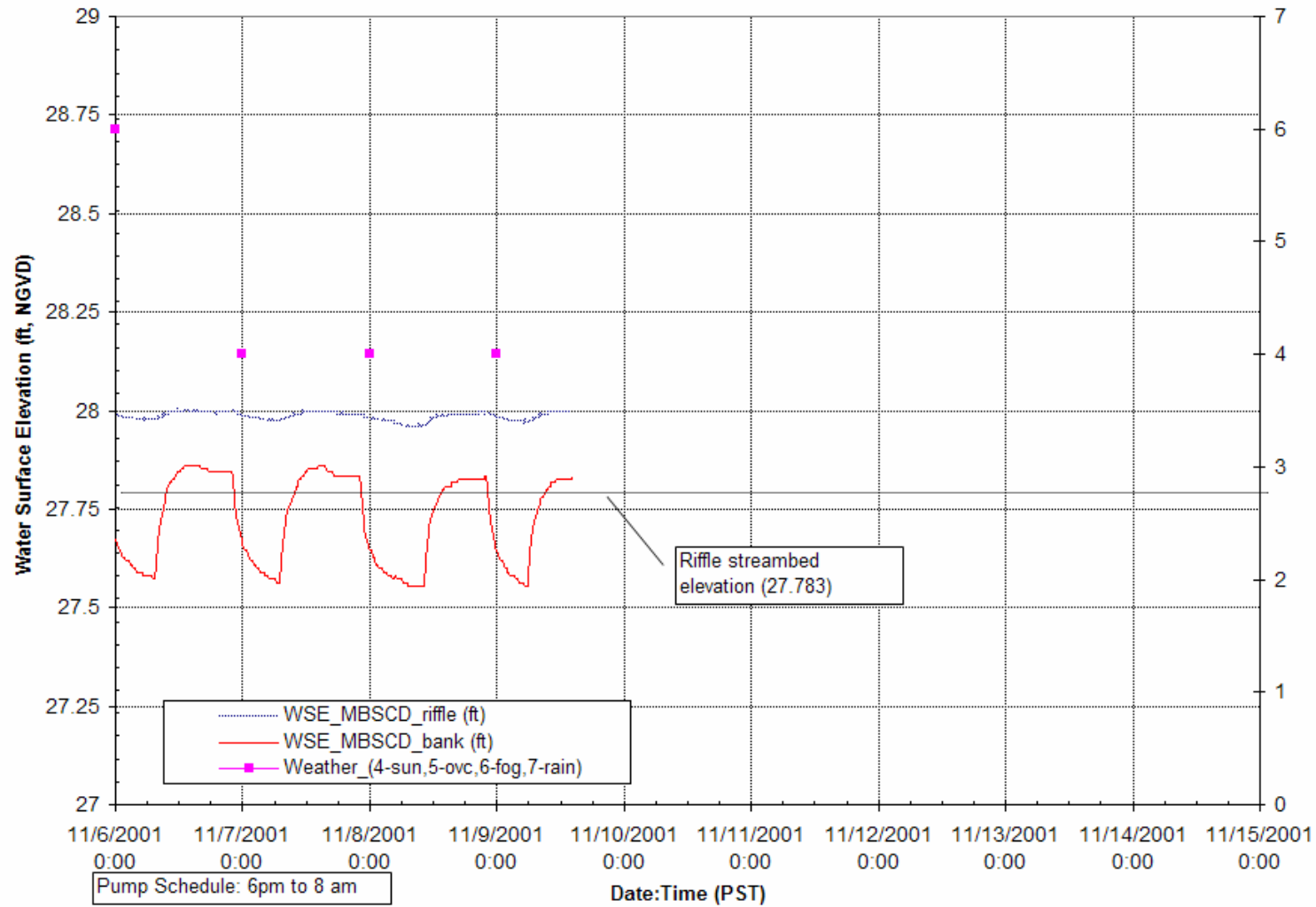


Figure 17: Water surface elevations, Redwood Creek, Marin Co., October 2002 (Riffle streambed elevation 27.64 ft)

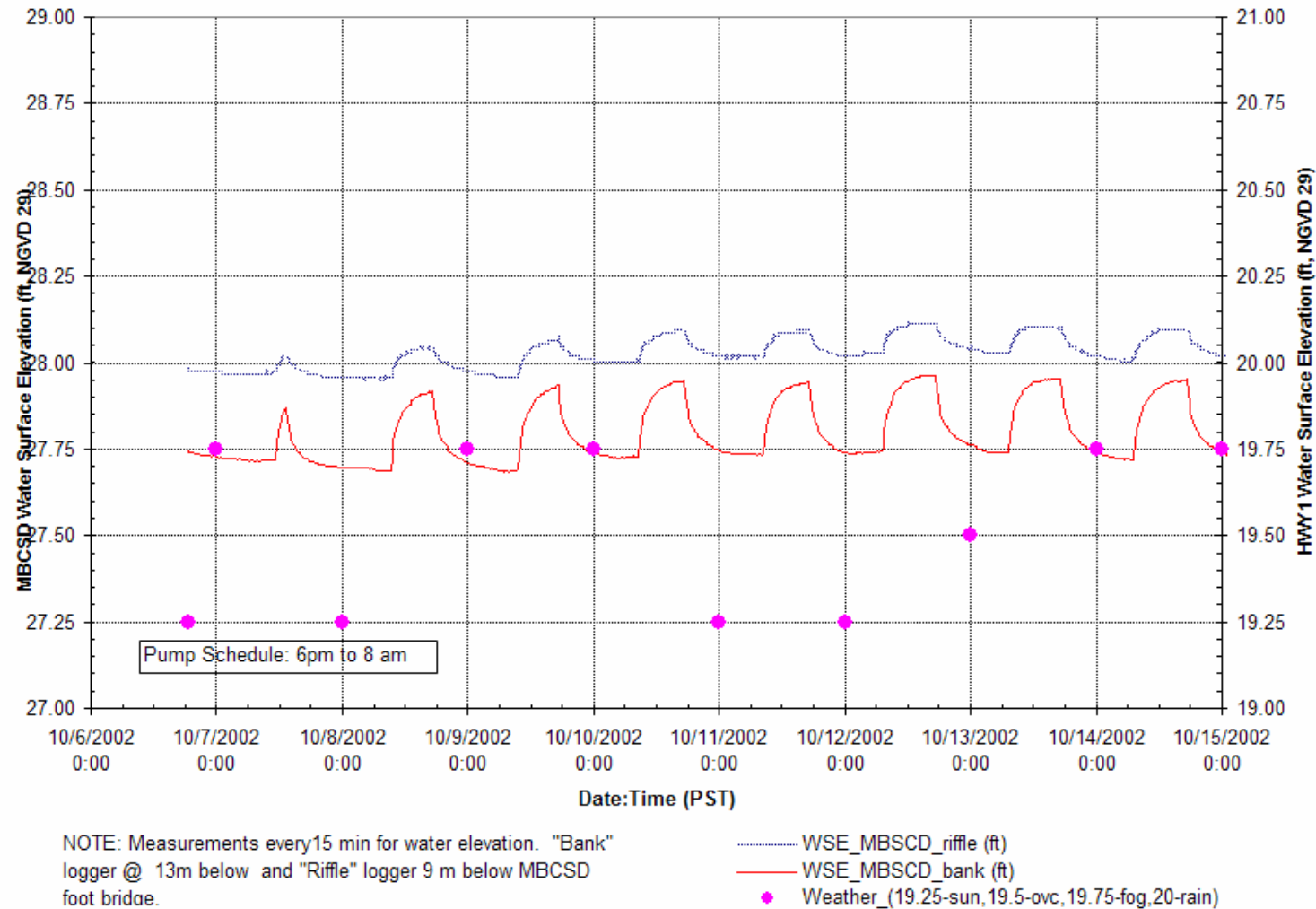


Figure 18: Water surface elevations, Redwood Creek, Marin Co., October 2002

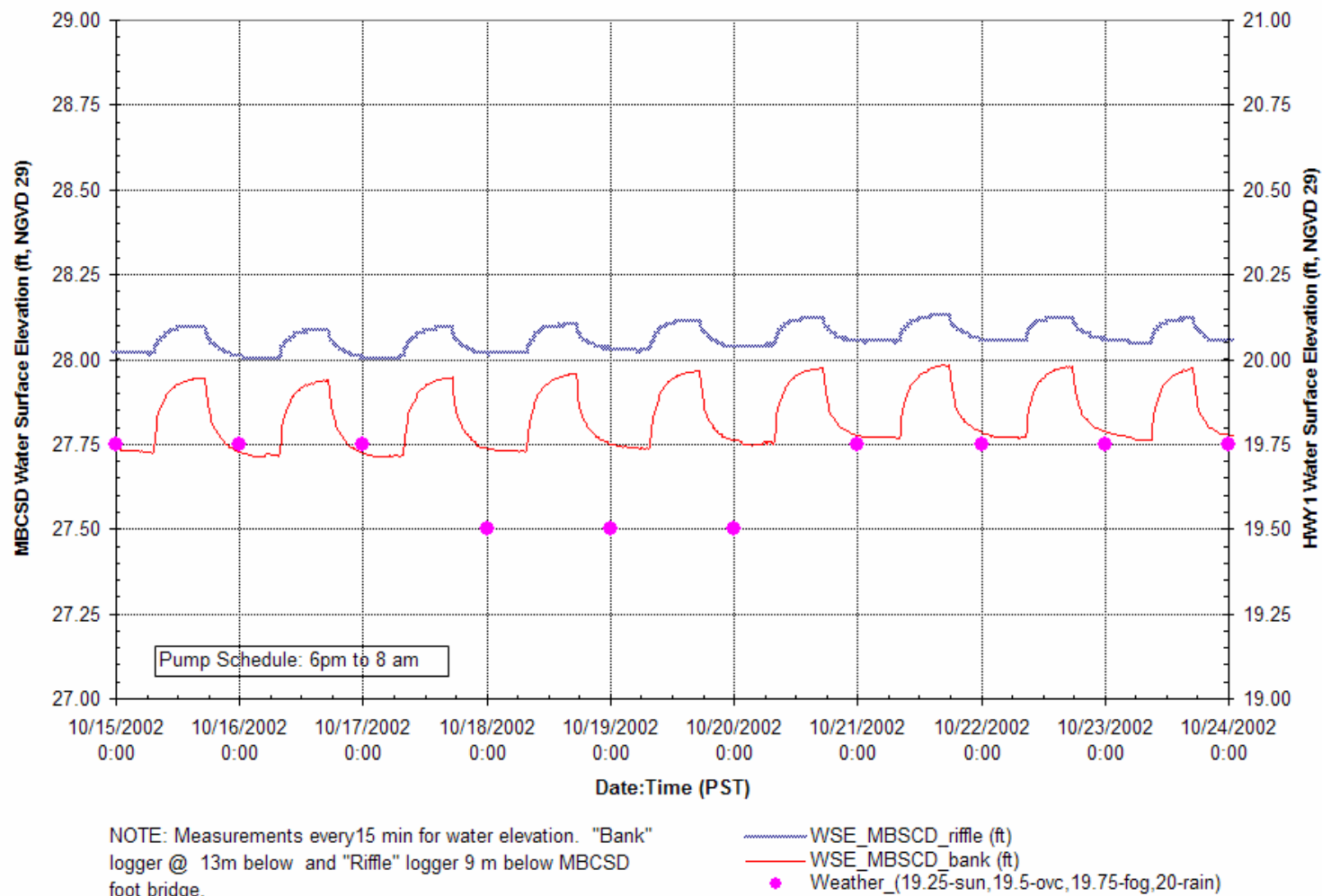


Figure 19: Water surface elevations, Redwood Creek, Marin Co., October-November 2002

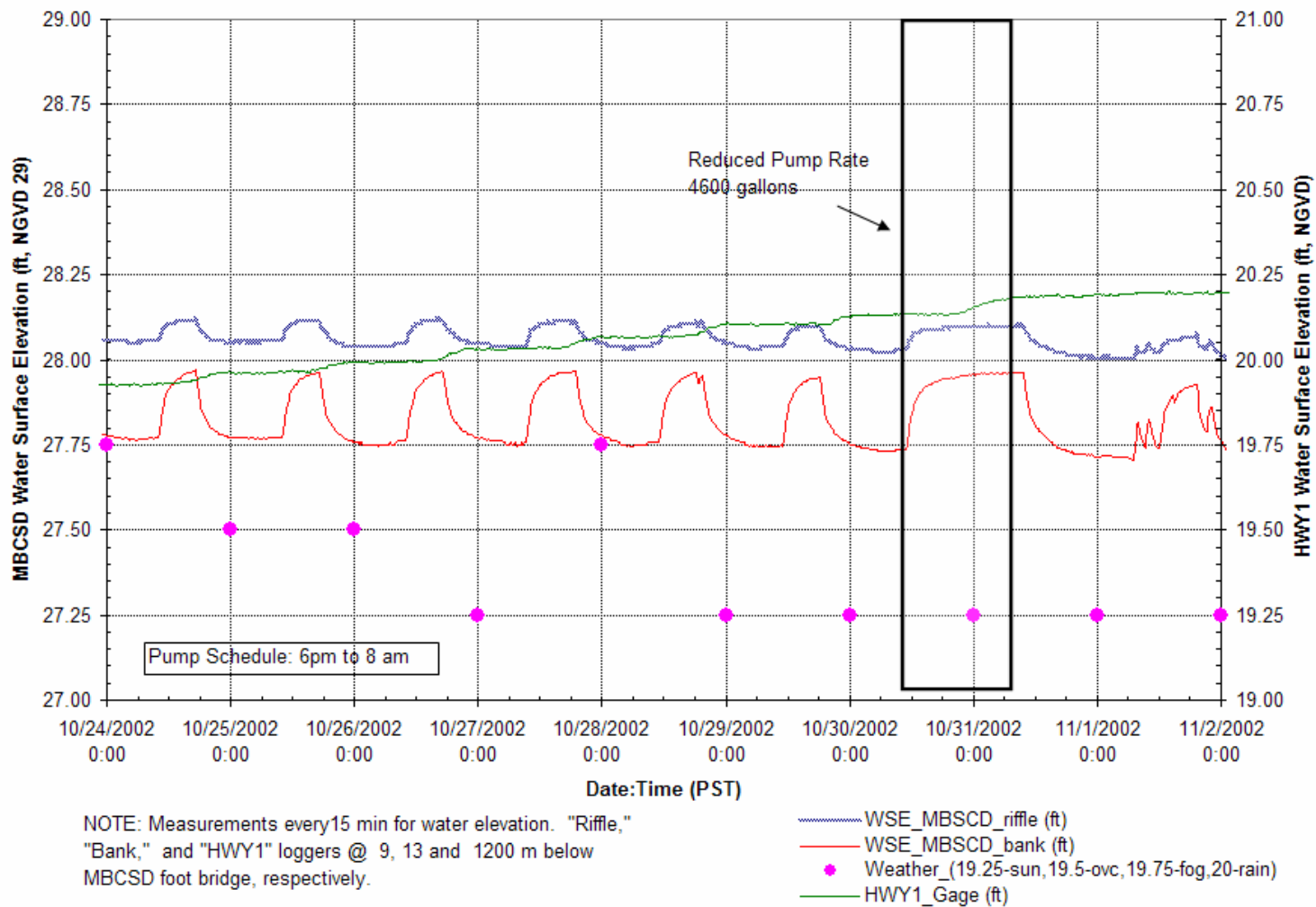


Figure 20: Water surface elevations, Redwood Creek, Marin Co., November 2002

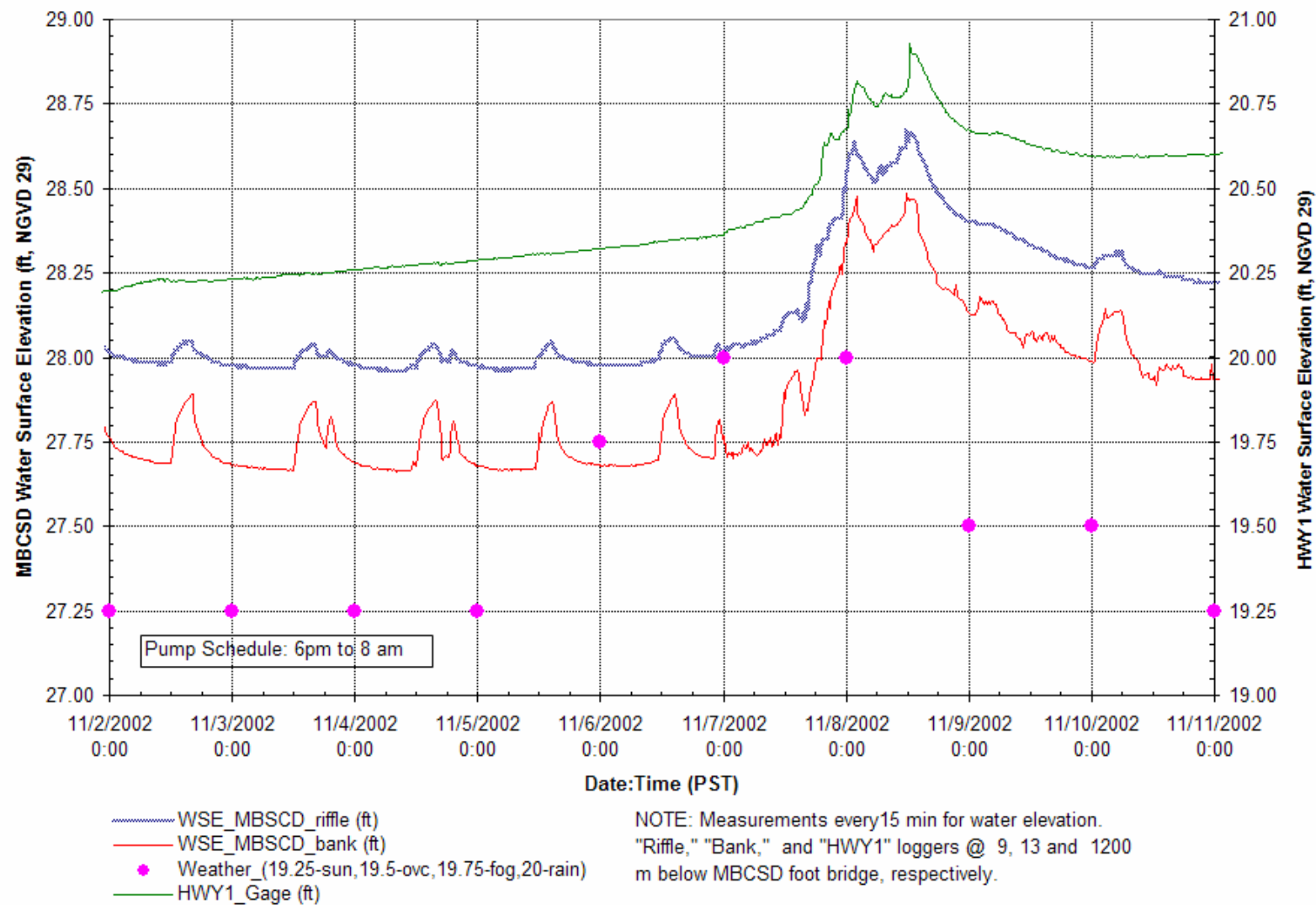


Figure 21: Water surface elevations, Redwood Creek, Marin Co., November 2002

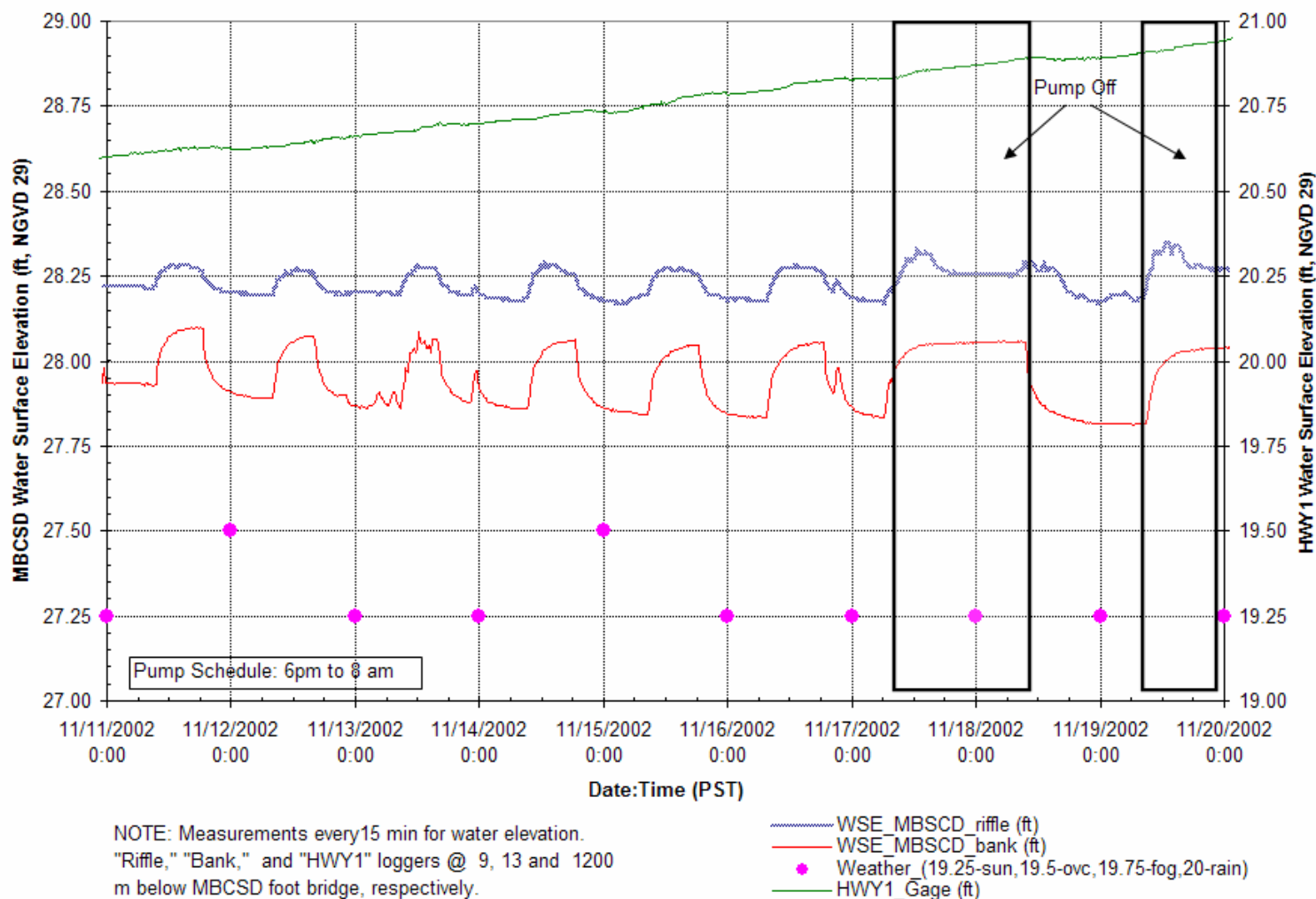


Figure 22: Water surface elevations, Redwood Creek, Marin Co., November 2002

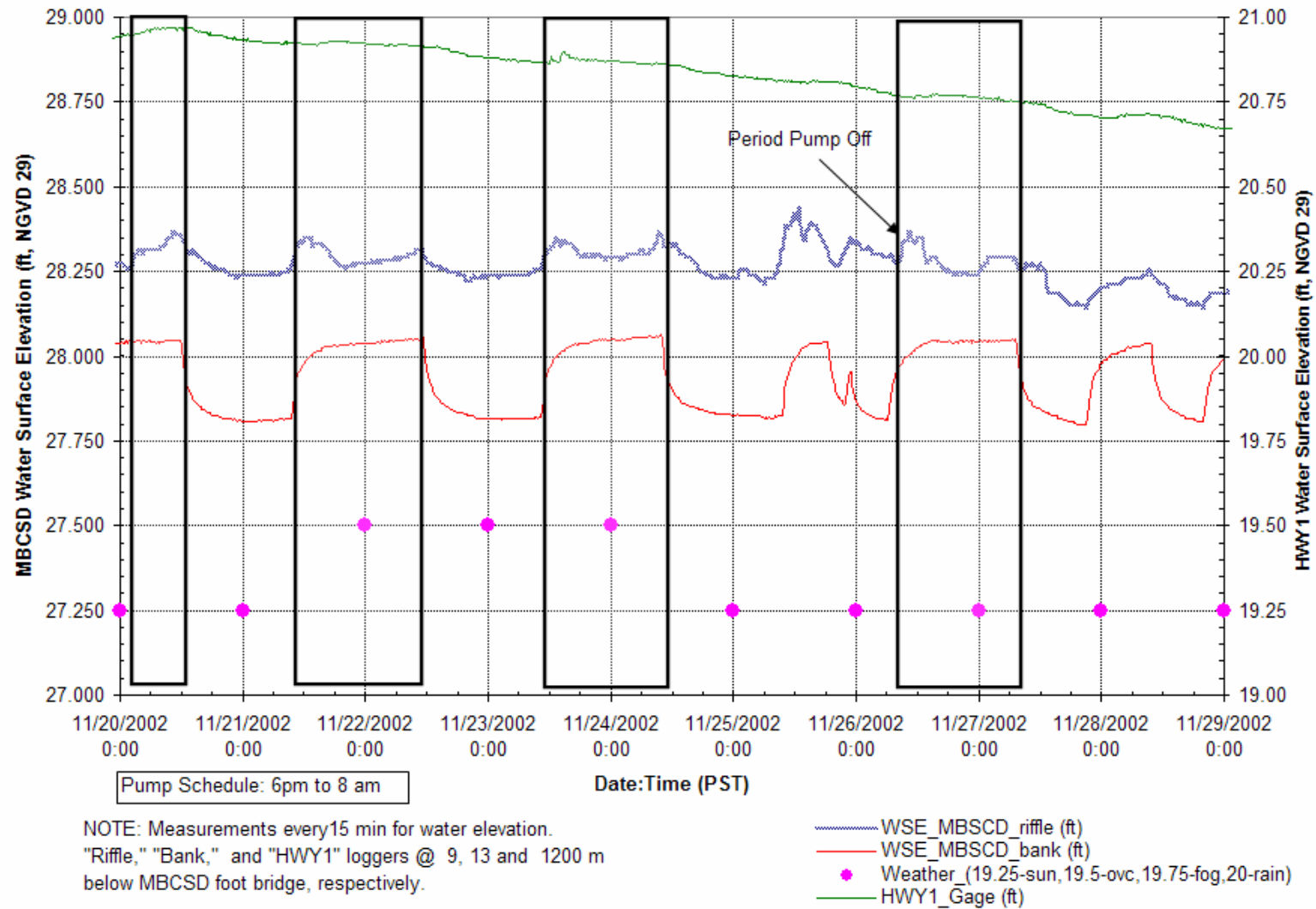


Figure 23: Water surface elevations, Redwood Creek, Marin Co., December 2002

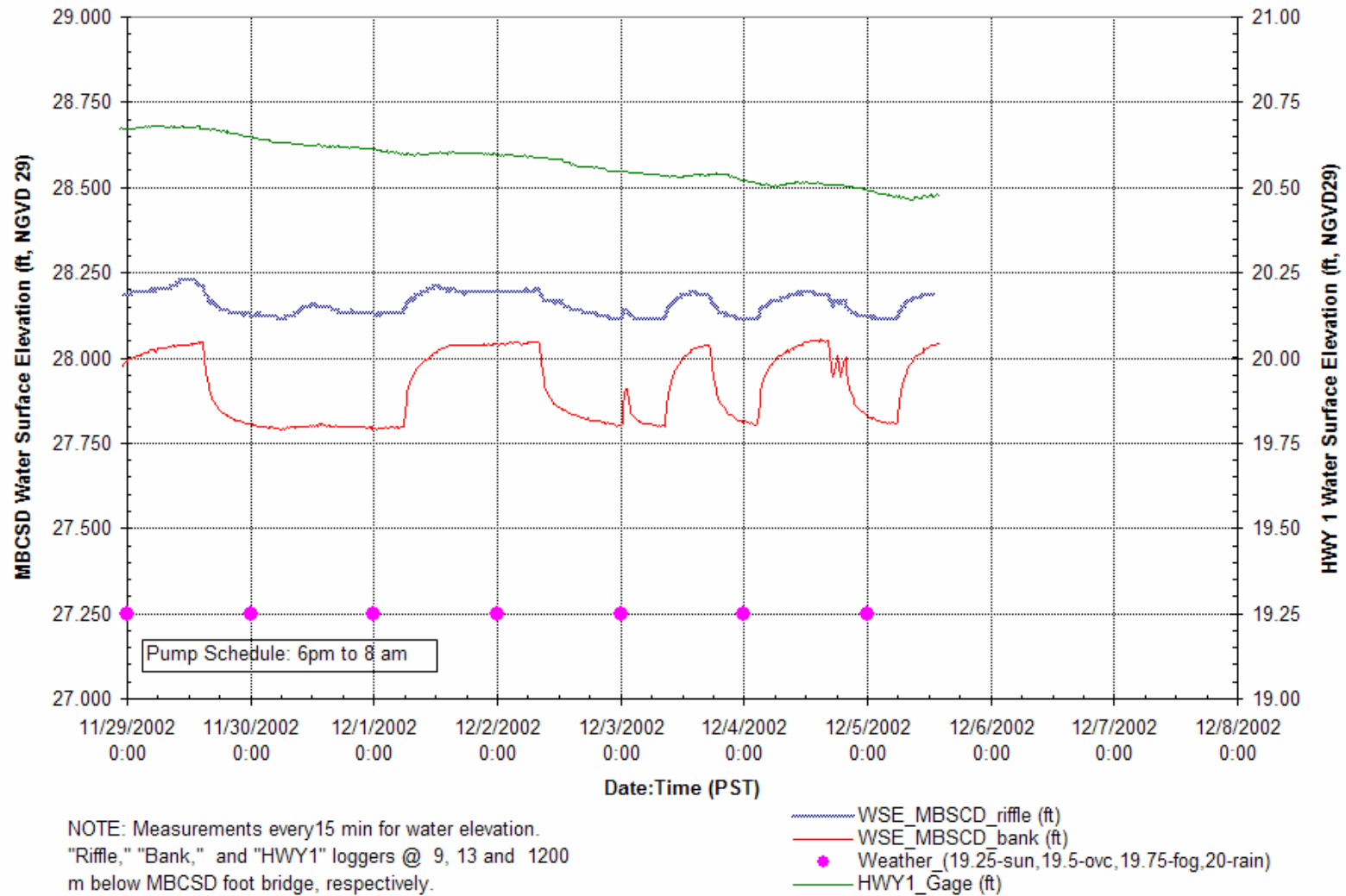


Figure 24: Rain season totals and the percentage of stream between Highway One bridge and MBCSD facilities that are dry (Reaches A-C) from 1997 to 2004, Redwood Creek, Marin Co., CA

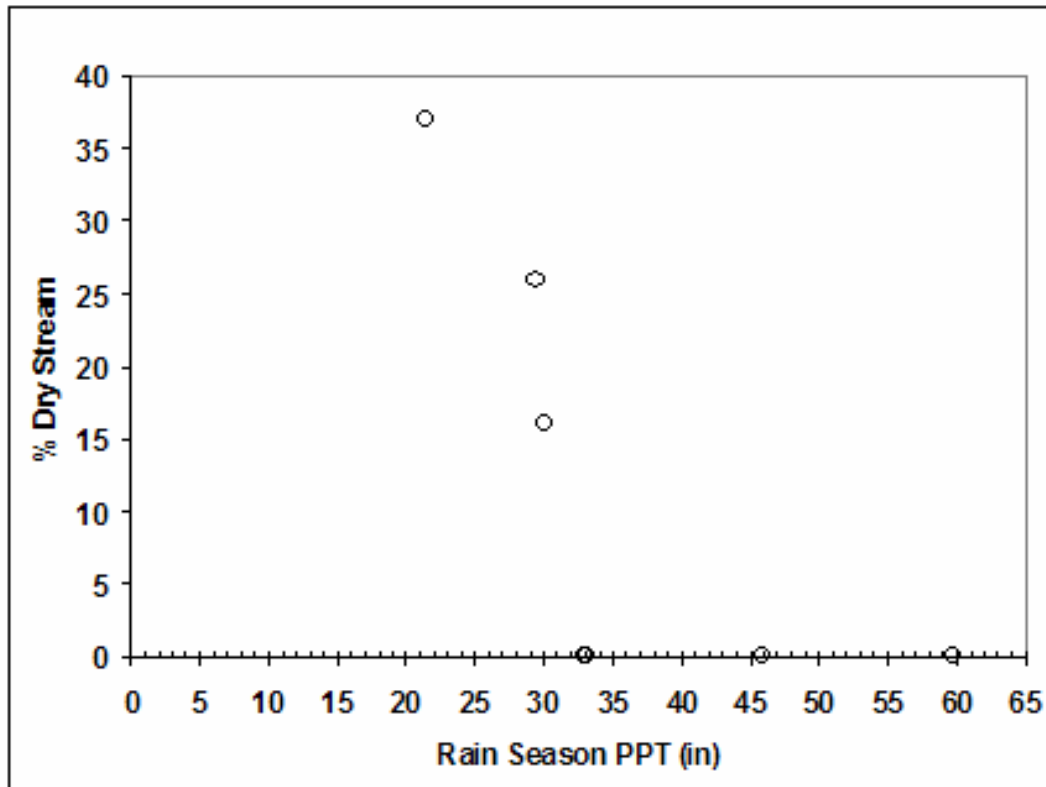


Figure 25: Comparison of Muir Woods National Monument precipitation data and dry conditions along Redwood Creek between Highway One and Frank Valley/MUWO Rd Bridges, Marin Co., CA

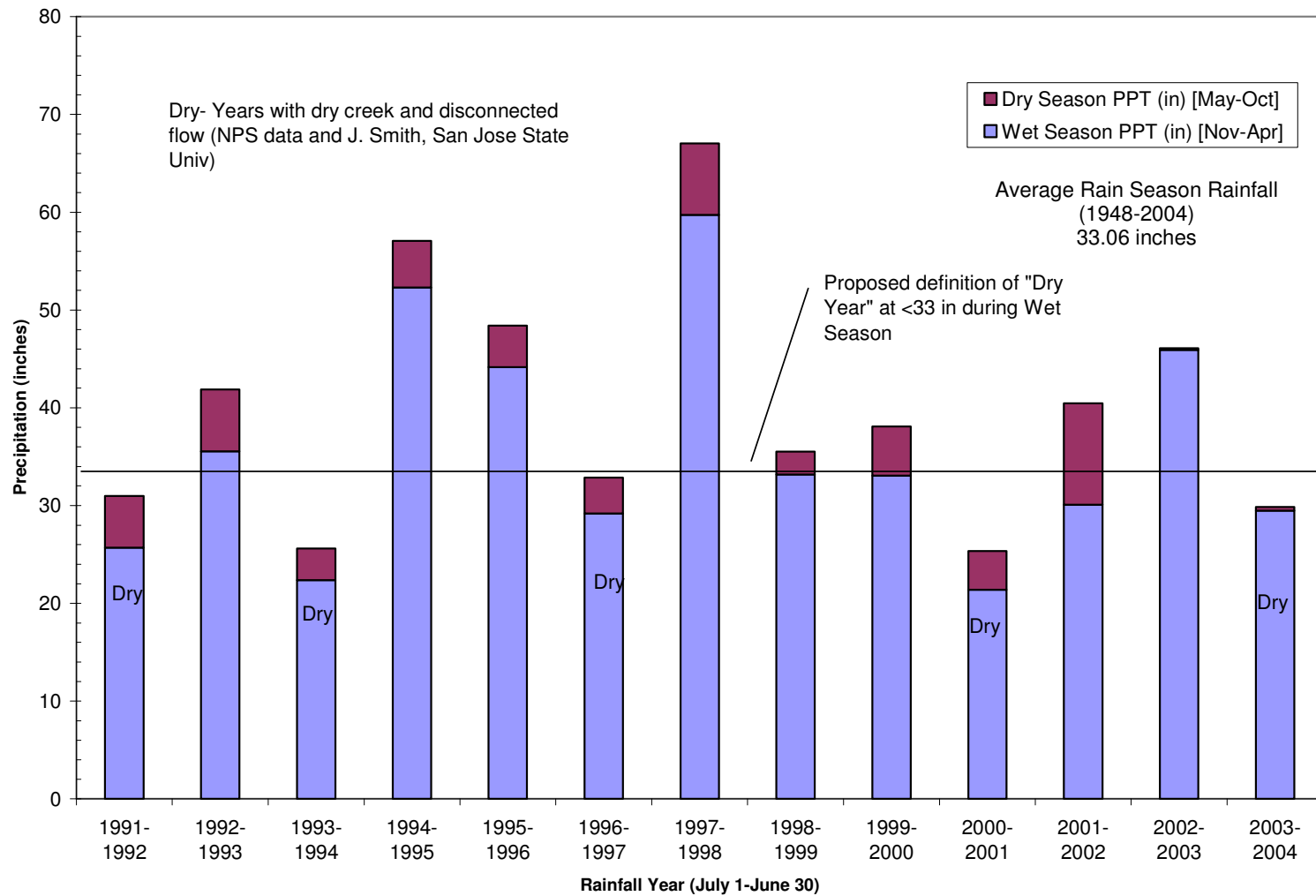
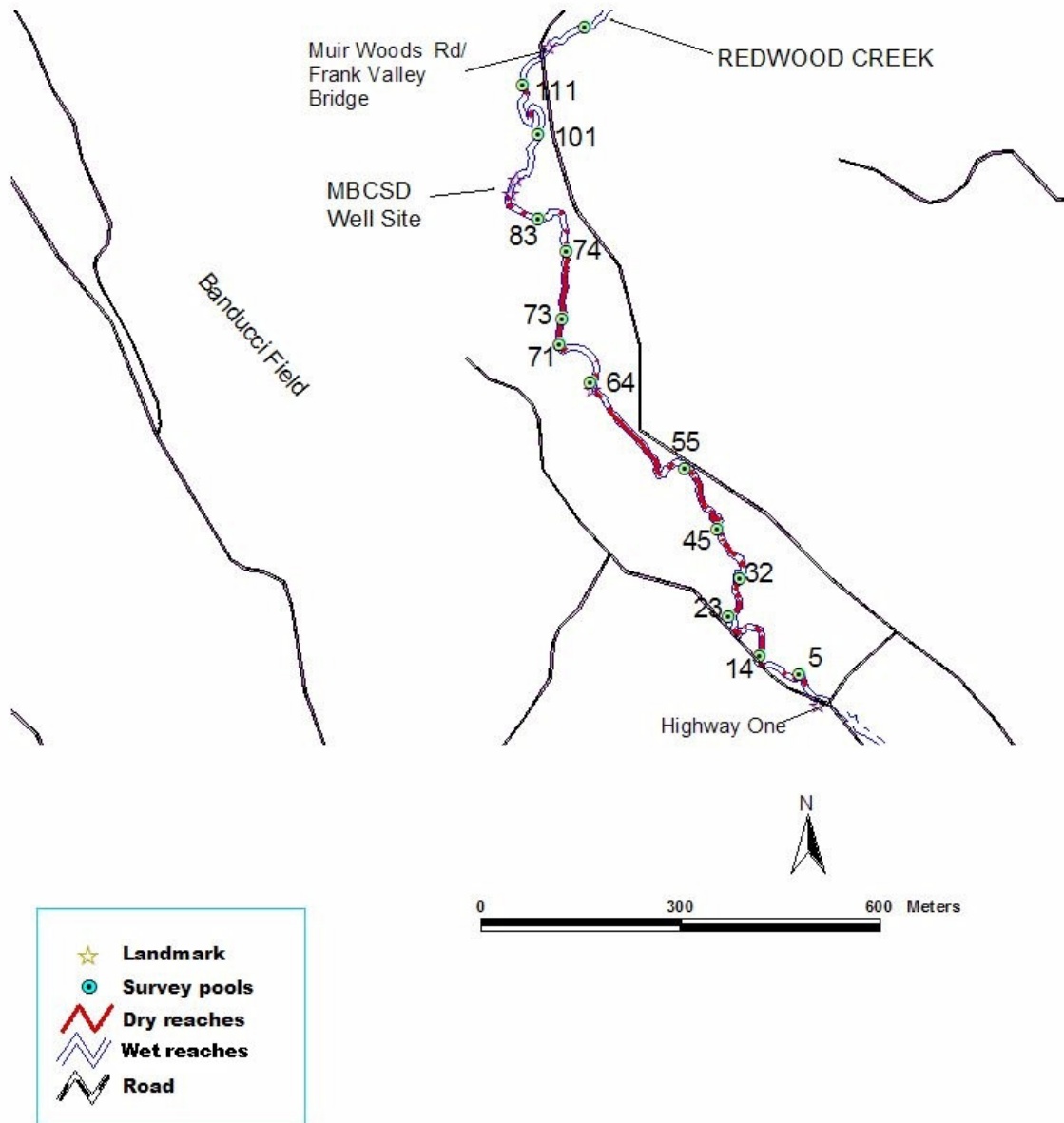


Figure 26. Planview map showing locations of isolated Redwood Creek habitat units between Highway One and Muir Woods Road bridges during October 17, 2001

October 17, 2001 Stream Habitat Inventory



J:\Common\ArcView\Home\IDARREN\RED-CRK\2001\rv_planv_01beta.apr
Rebecca Leonardson, 2001

Figure 27. Location of isolated Redwood Creek habitat units between Highway One and Muir Woods Road bridges during October 17, 2001 survey

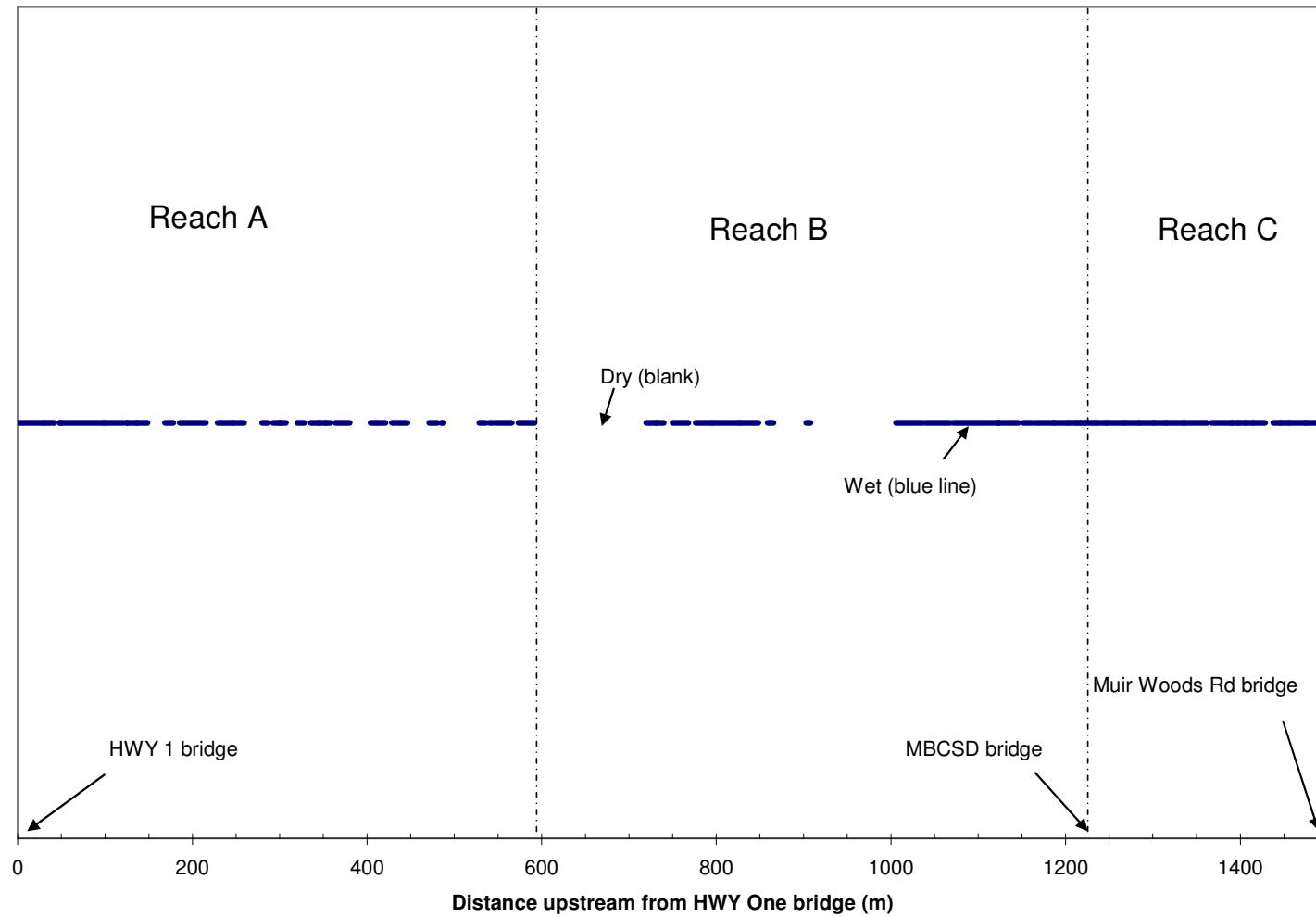


Figure 28. Location of isolated Redwood Creek habitat units between Highway One and Muir Woods Road bridges during October 8-9, 2002 survey

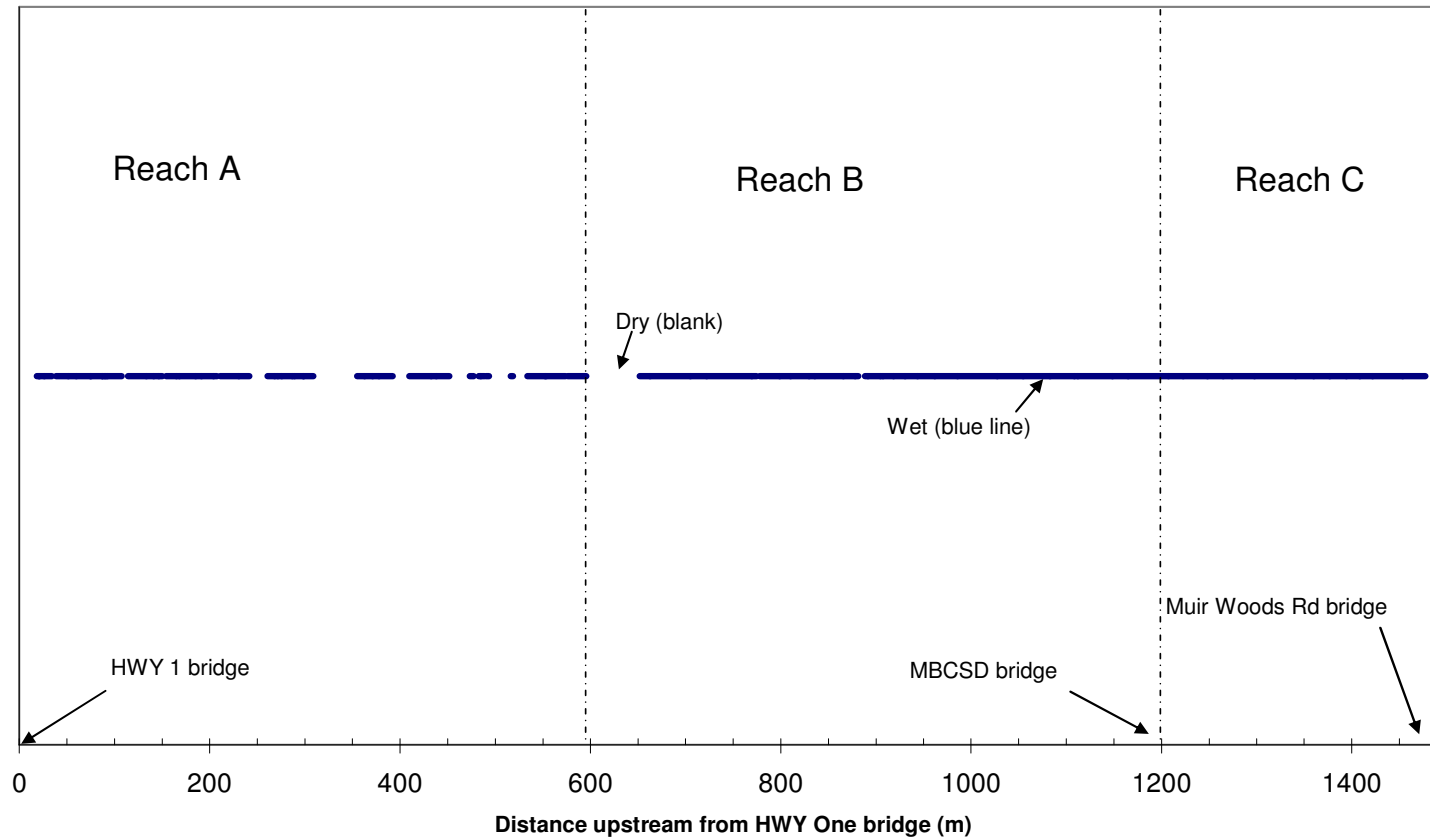


Figure 29. Location of isolated Redwood Creek habitat units between Highway One and Muir Woods Road bridges during Sept. 20-27, 2004 survey

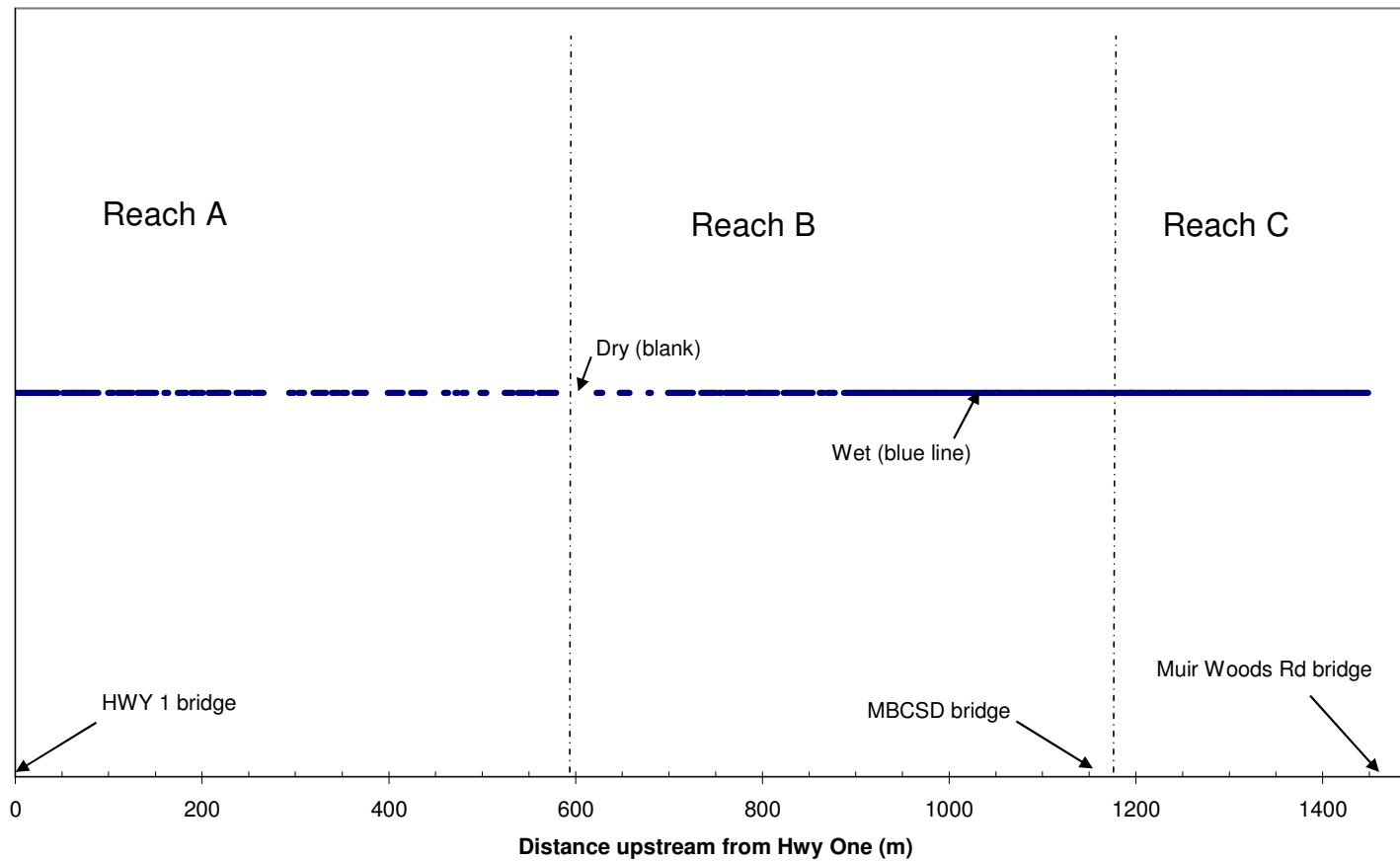


Figure 30: Photos of isolated stream habitat units along Redwood Creek in 2002



Photo Date: October 8, 2002

Photo of two isolated pools separated by dry/damp habitat

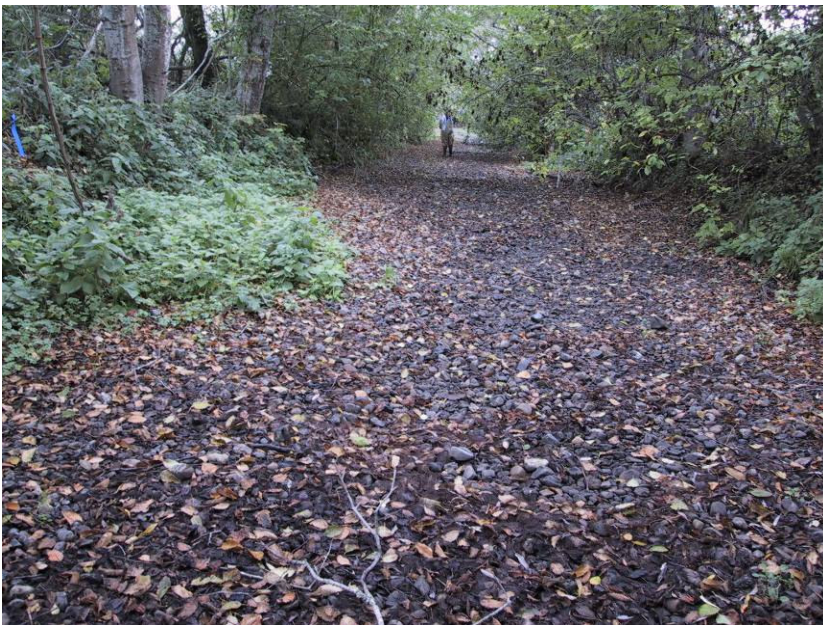


Photo Date: October 8, 2002

Photo of 56.3 m dry reach (flatwater or riffle habitat)

Figure 31. Photos of isolated stream habitat units along Redwood Creek, Marin Co. on September 29, 2004



A. Looking downstream of Pacific Way Bridge at isolated pools. Dead run-back adult steelhead trout in foreground.



B. Looking downstream at dry lateral scour pool across from house at 170 Pacific Way.

Figure 32: Longitudinal profile of Redwood Creek between Highway One and Frank Valley/Muir Woods Rd. Bridges, 1999, Marin Co., CA

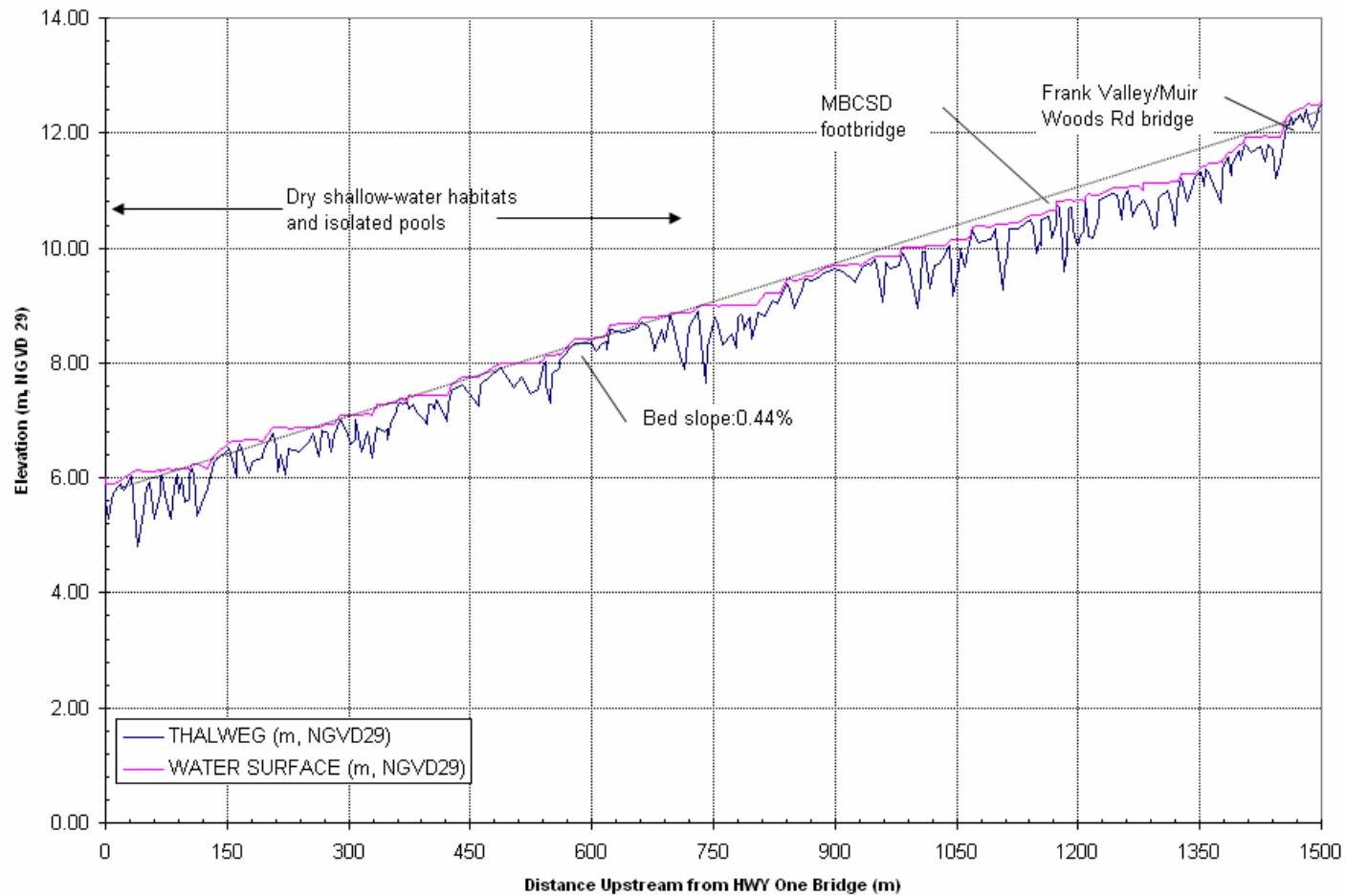


Figure 33: Pool Bottom Temperatures in Redwood Creek, Marin Co, Oct.-Nov 1998.

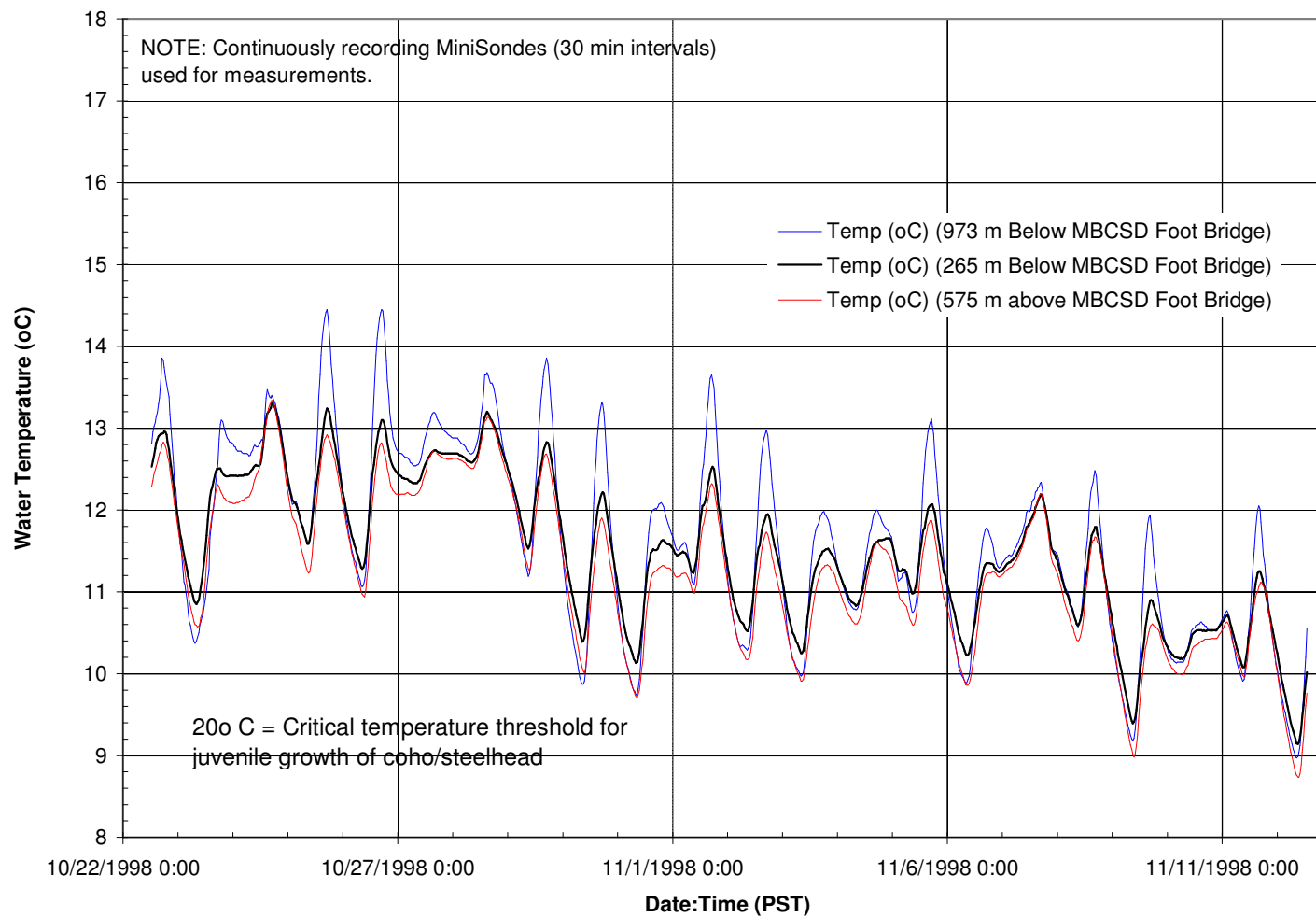


Figure 34: Pool Bottom Temperatures in Redwood Creek, Marin Co., July 1999

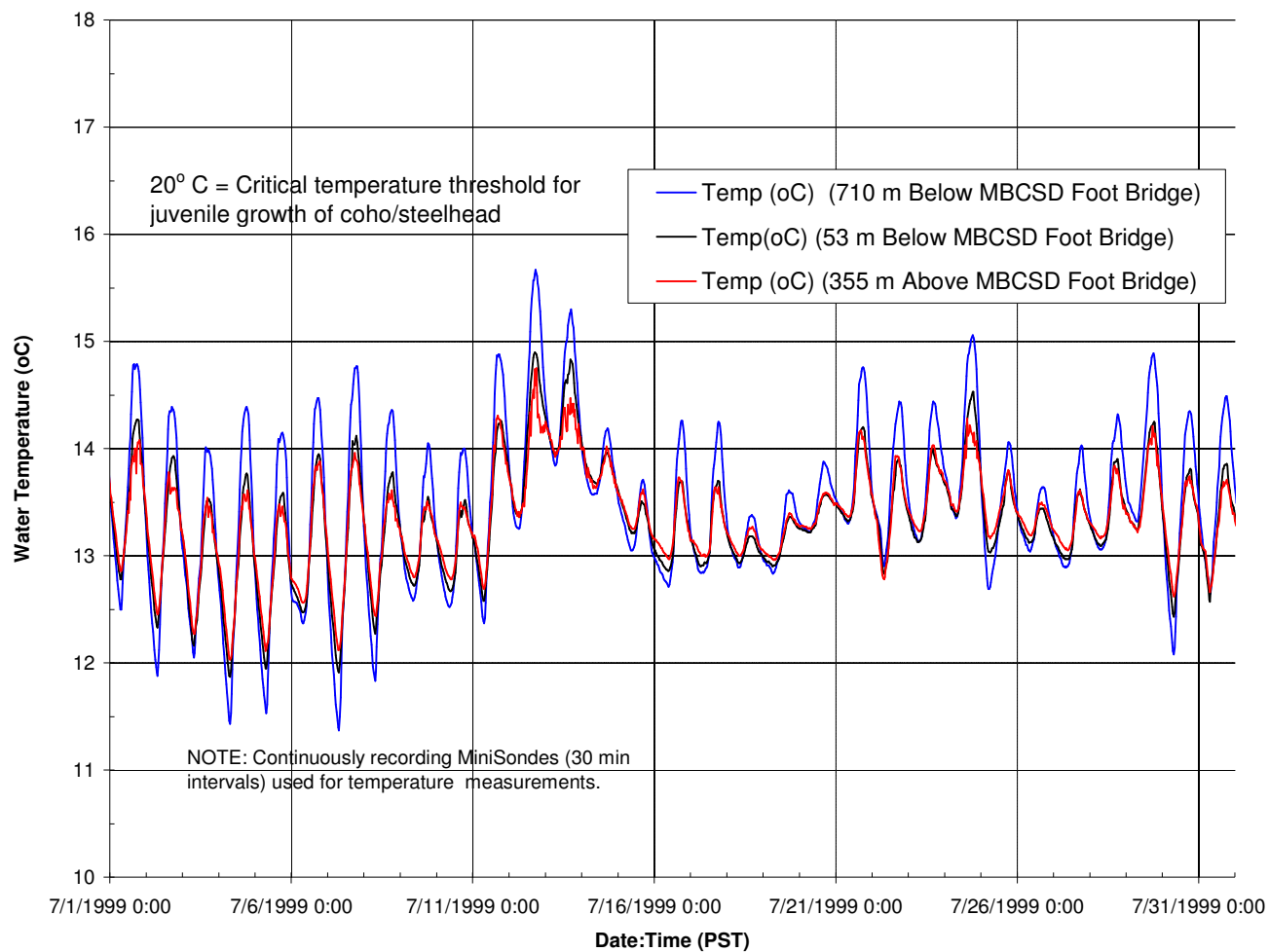


Figure 35: Pool Bottom Temperatures in Redwood Creek, Marin Co., August 1999

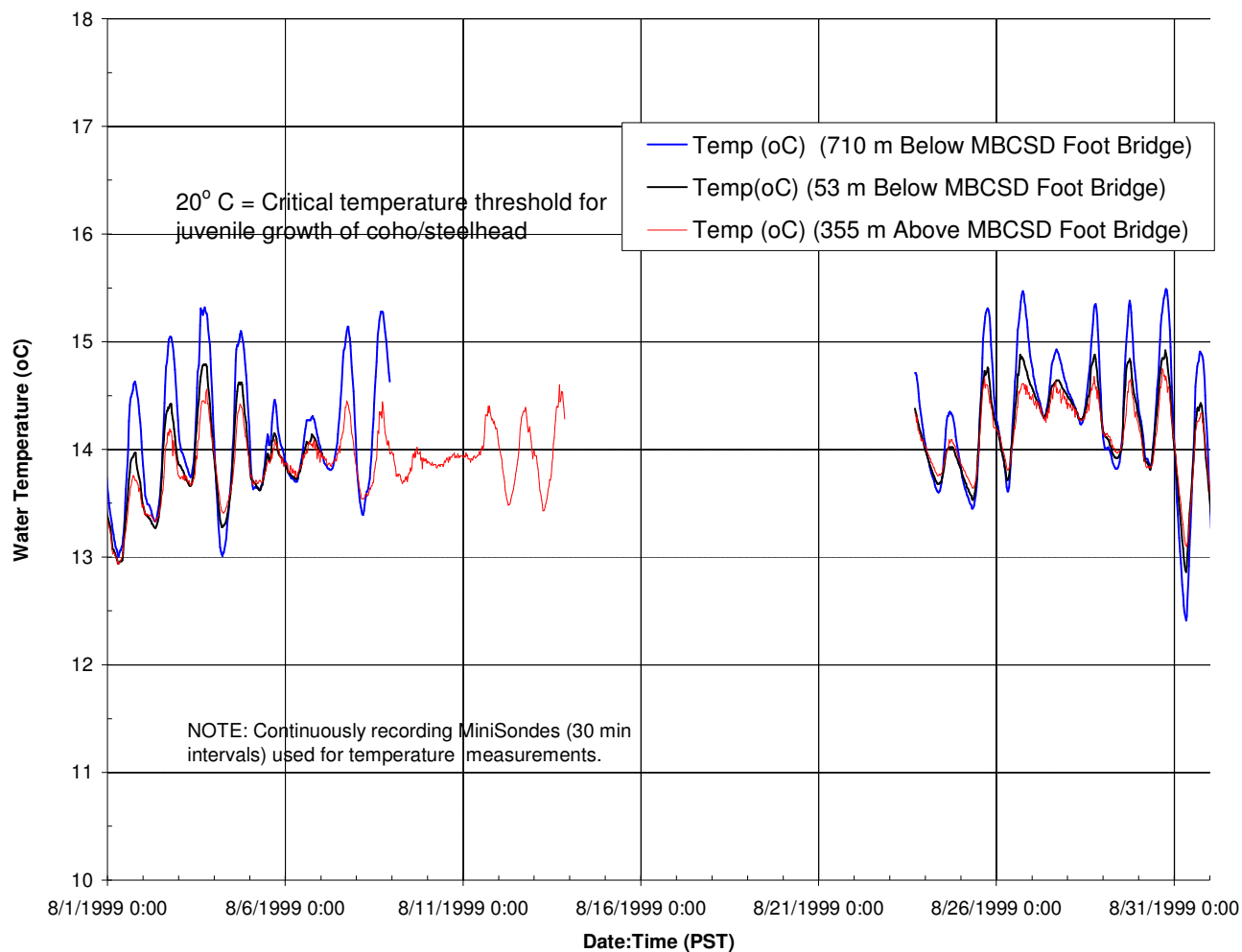


Figure 36: Pool Bottom Temperatures in Redwood Creek, Marin Co., September 1999

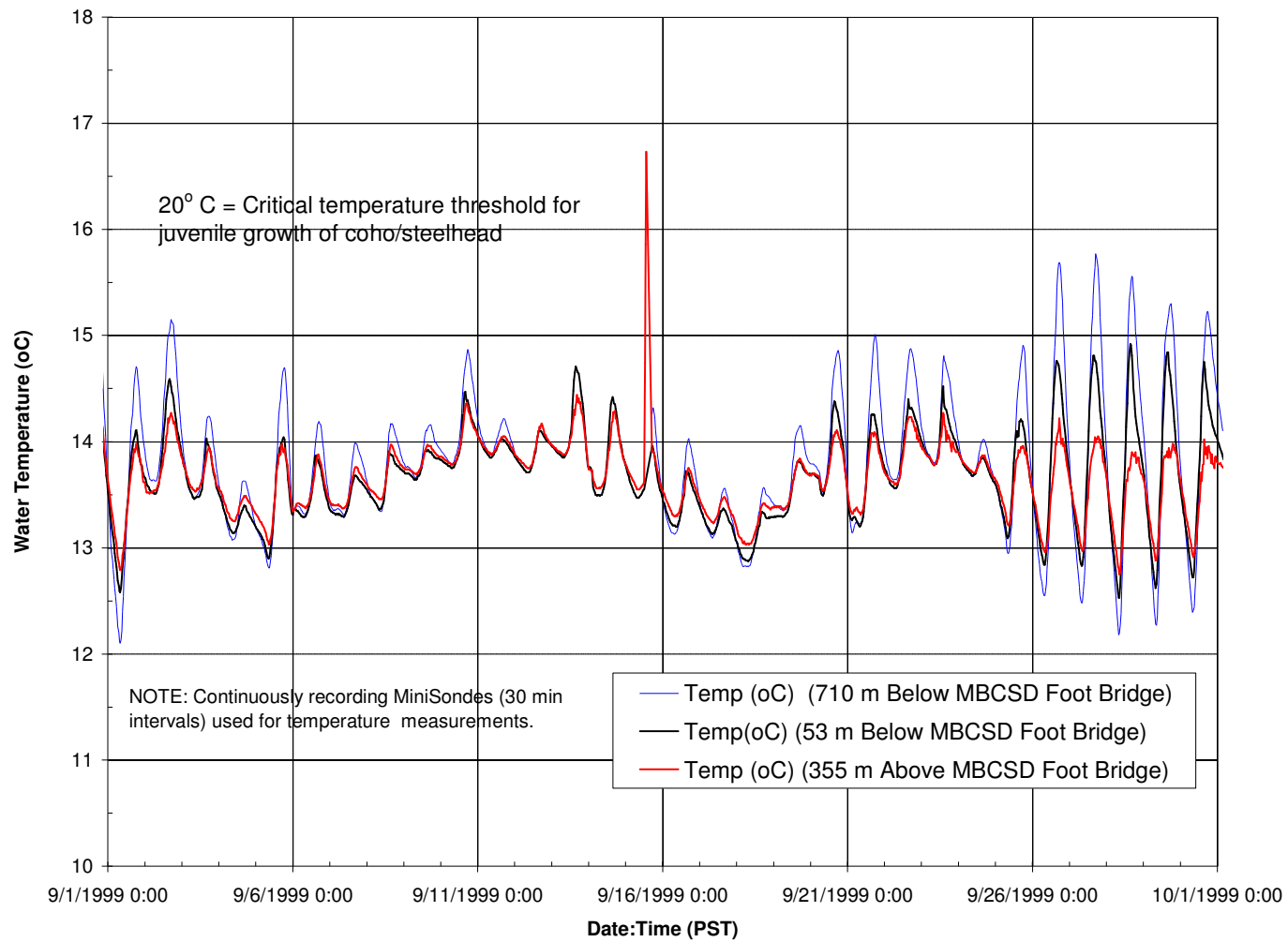


Figure 37: Pool Bottom Temperatures in Redwood Creek, Marin Co., October 1999

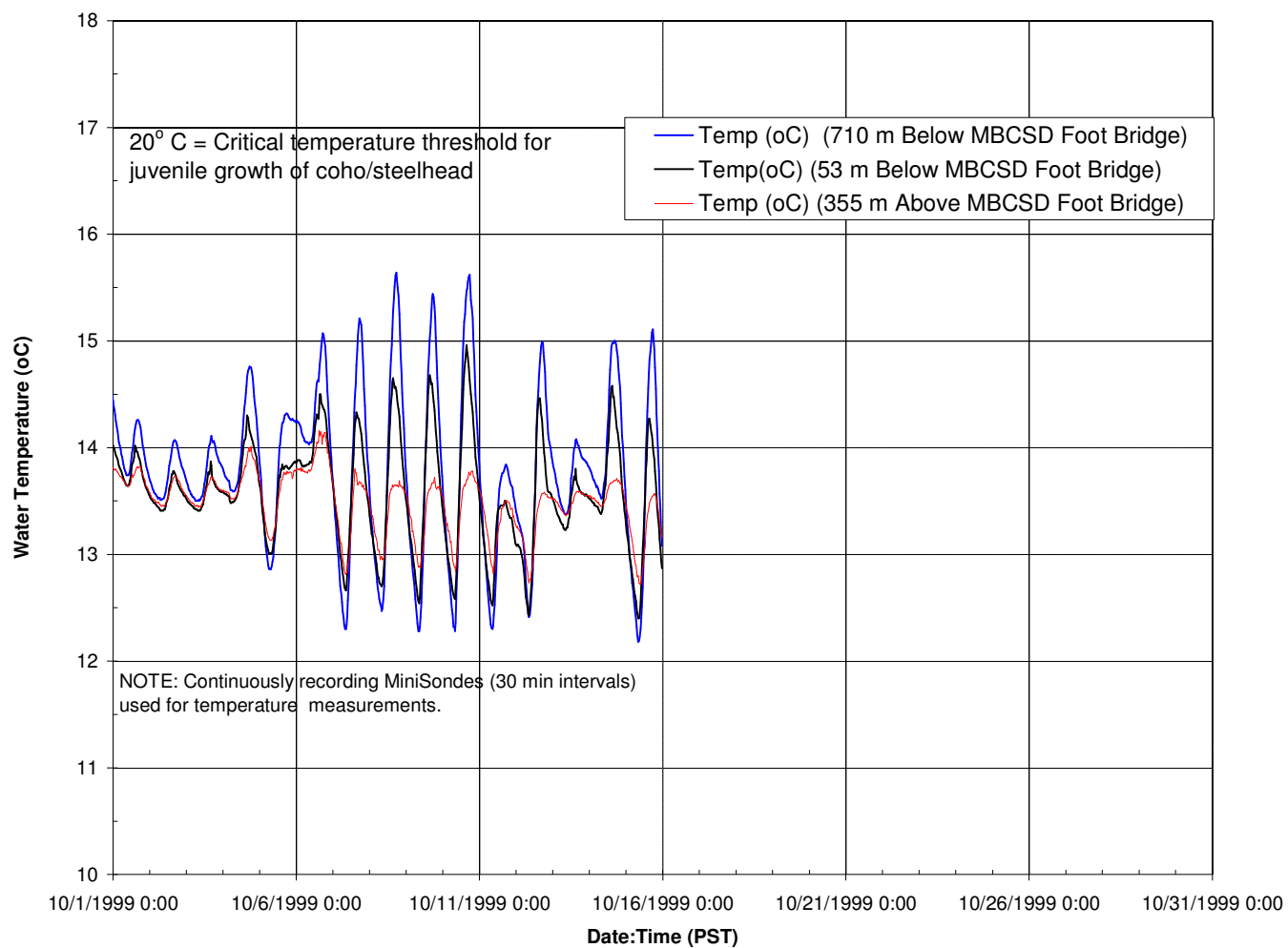


Figure 38: Pool Bottom Temperatures in Redwood Creek, Marin Co., August 2001

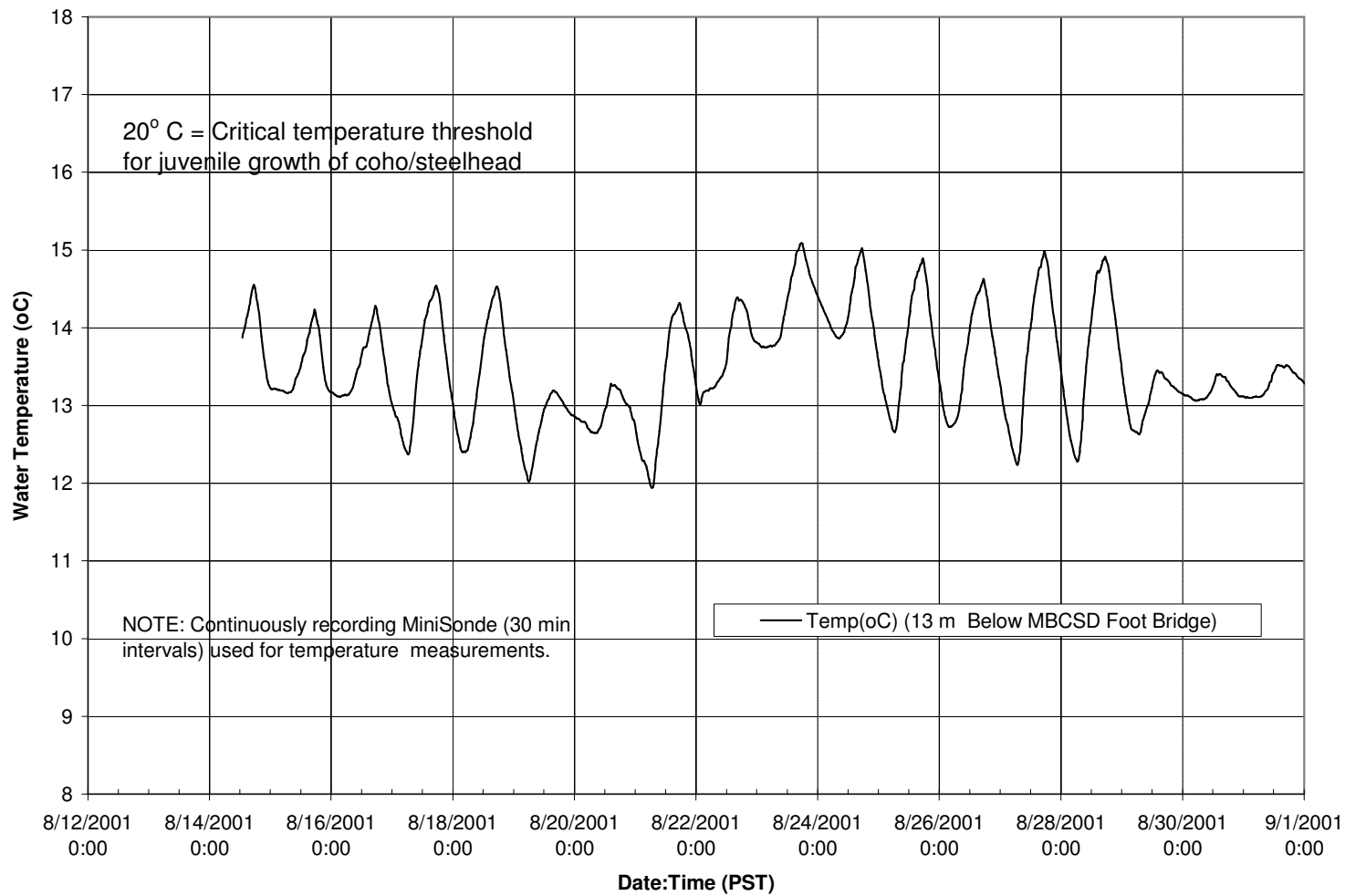


Figure 39: Pool Bottom Temperatures in Redwood Creek, Marin Co., September 2001

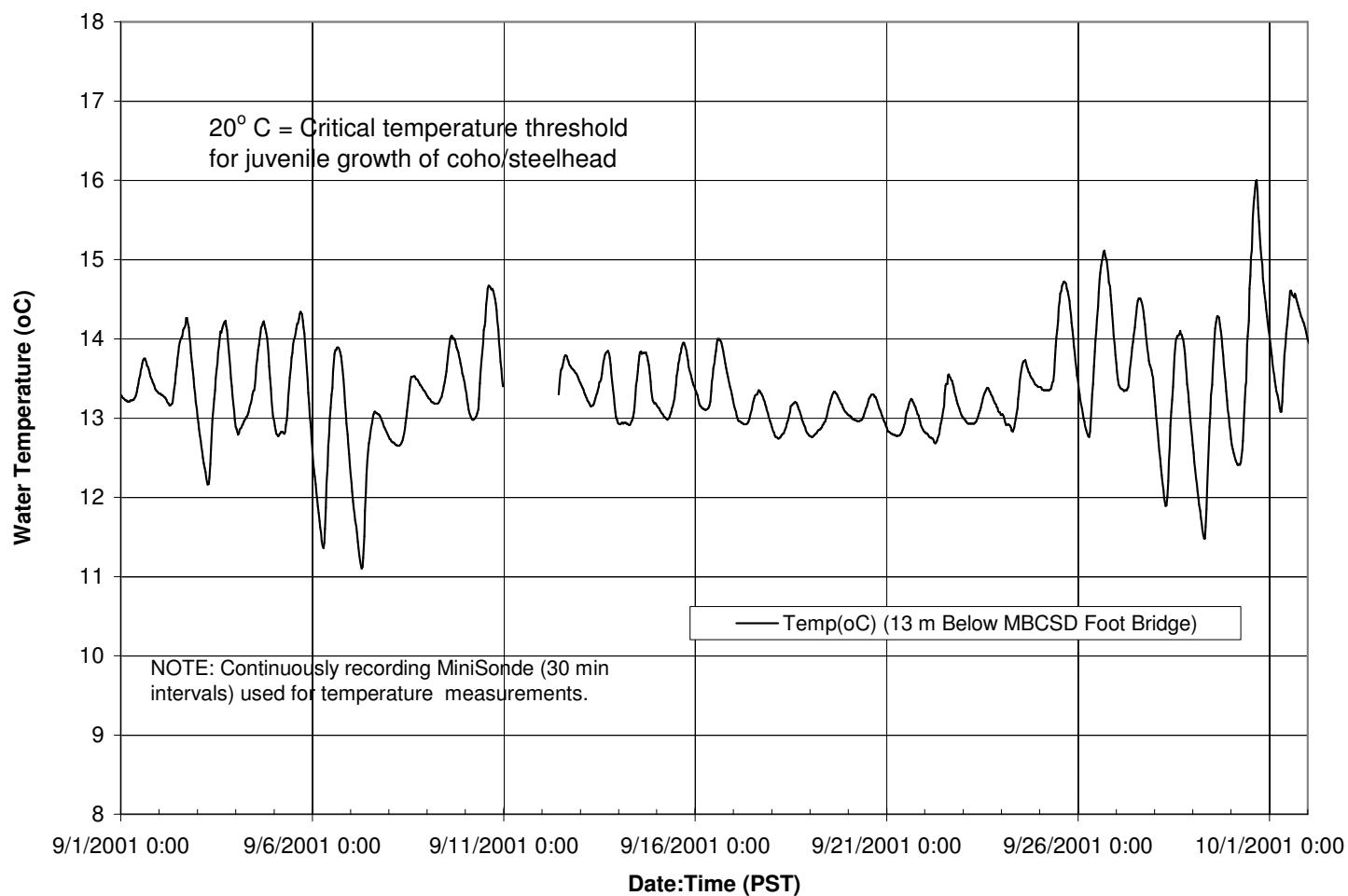


Figure 40: Pool Bottom Temperatures in Redwood Creek, Marin Co., October 2001

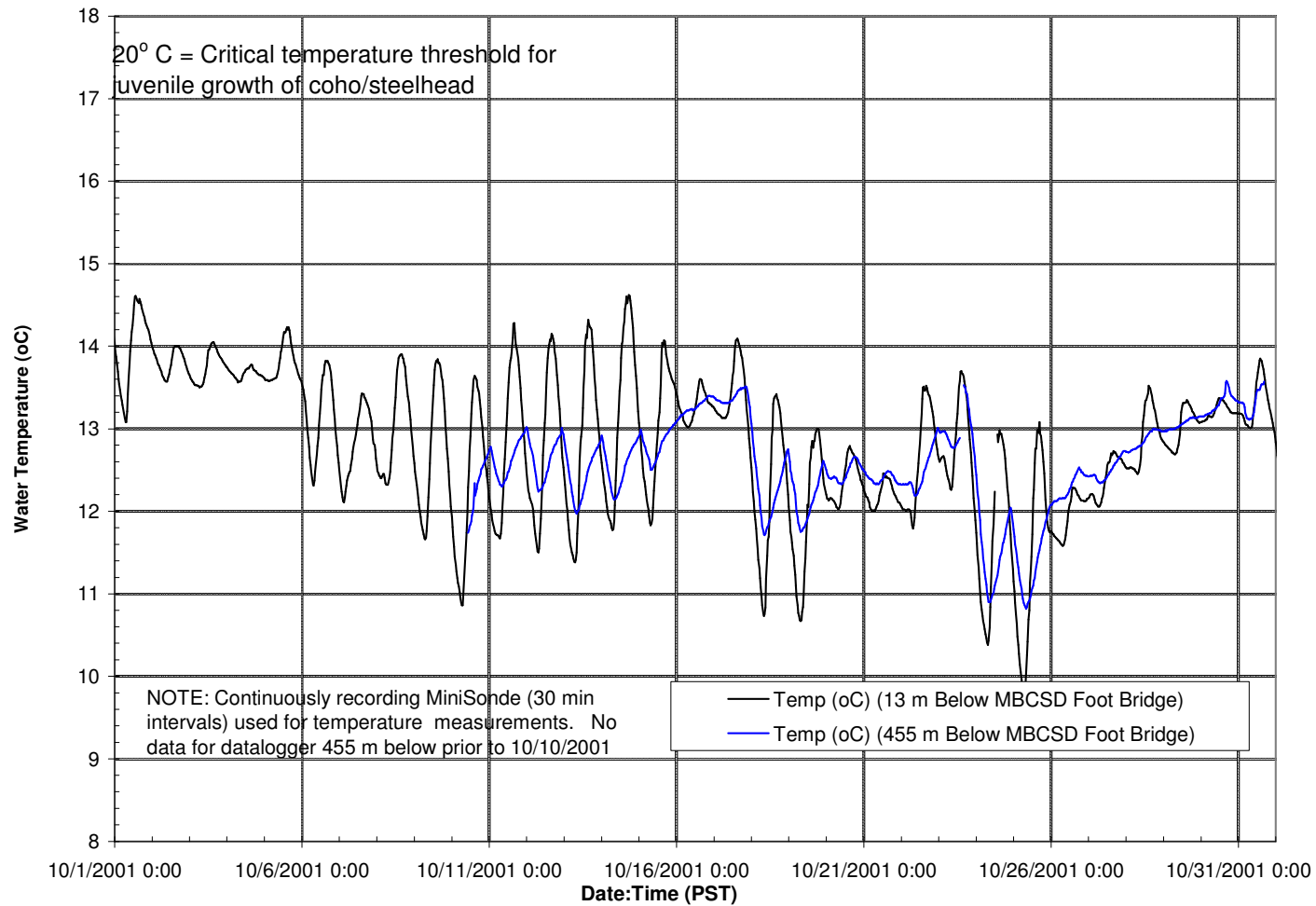


Figure 41: Interaction between Temperature, Year Type, Reach Location, and Pool Connectivity, Redwood Creek, Marin Co., CA
TEMP

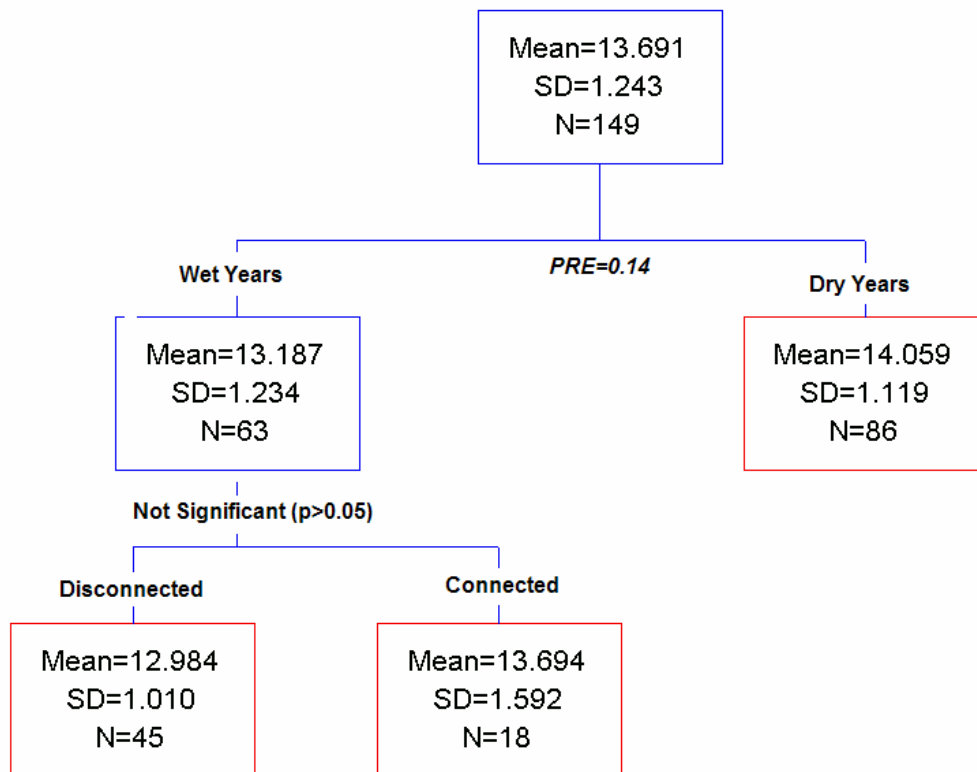


Figure 42: Mean dissolved oxygen concentration and standard deviation error bars for study reaches A-C, Redwood Creek, Marin Co., CA.

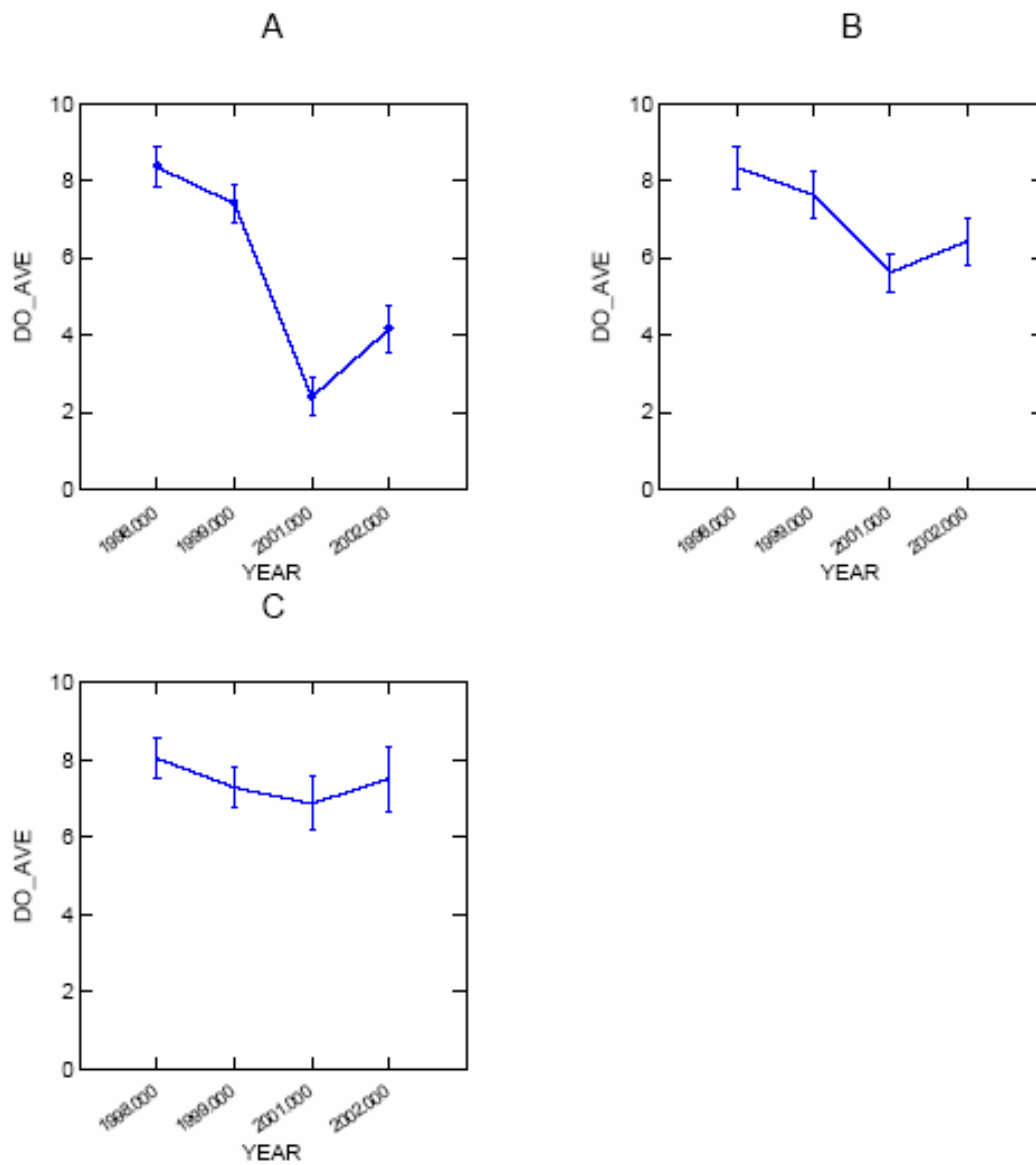


Figure 43: Interaction between Dissolved Oxygen, Year Type, Reach Location, and Pool Connectivity, Redwood Creek, Marin Co., CA for Data Collected From Index Pools in 1998-2002.

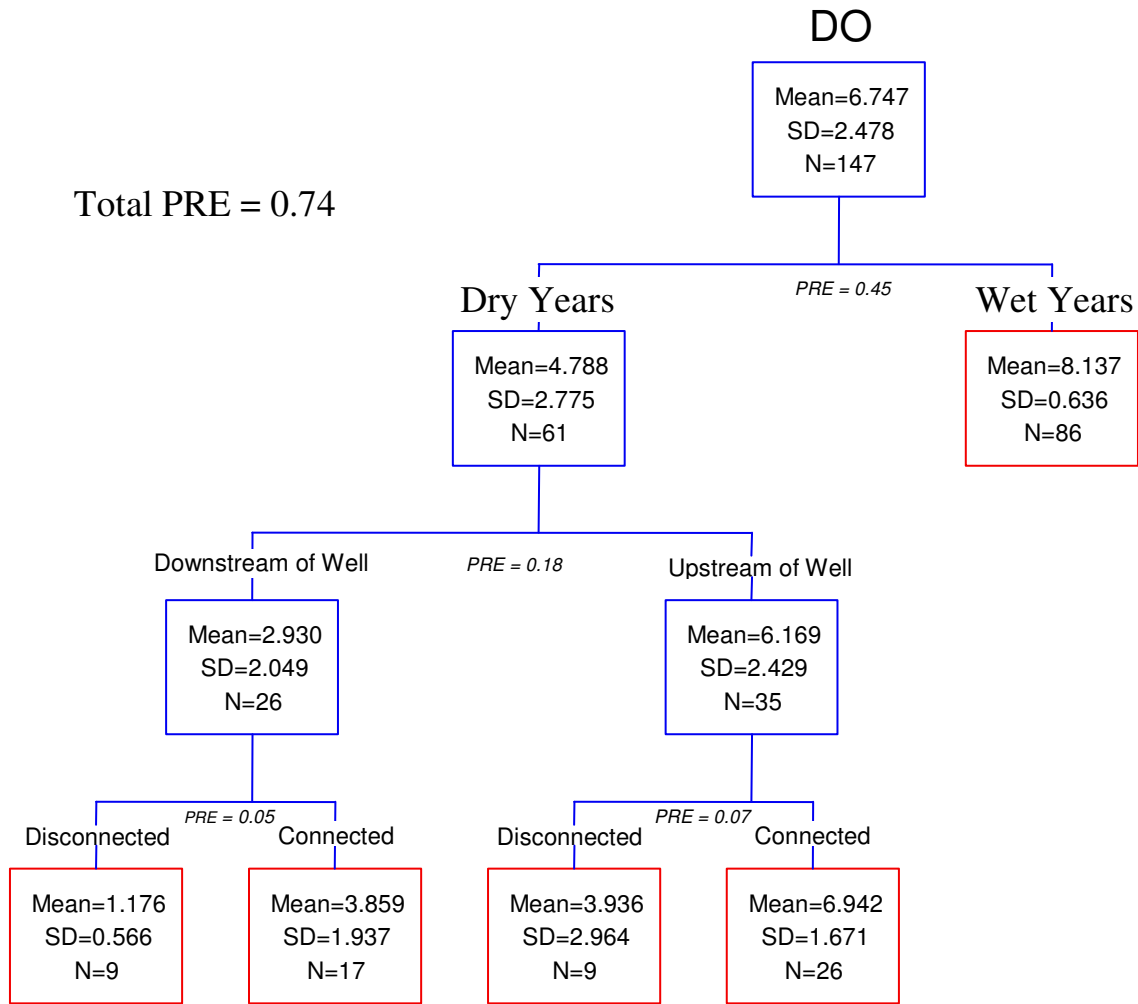


Figure 44: Pool Dissolved Oxygen Conditions in Redwood Creek, Marin Co., Oct.-Nov., 1998.

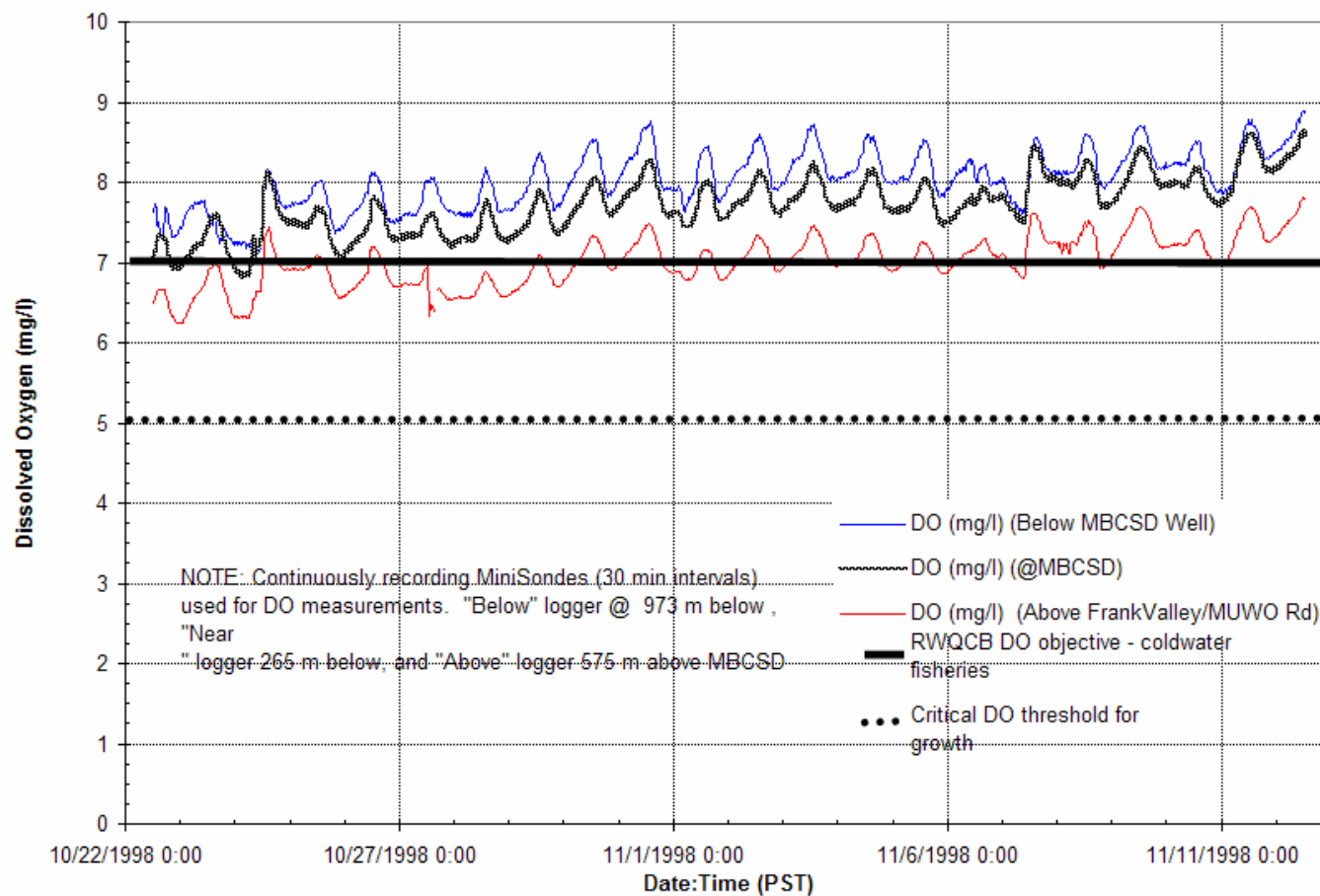


Figure 45: Pool Dissolved Oxygen Conditions in Redwood Creek, Marin Co., July 1999

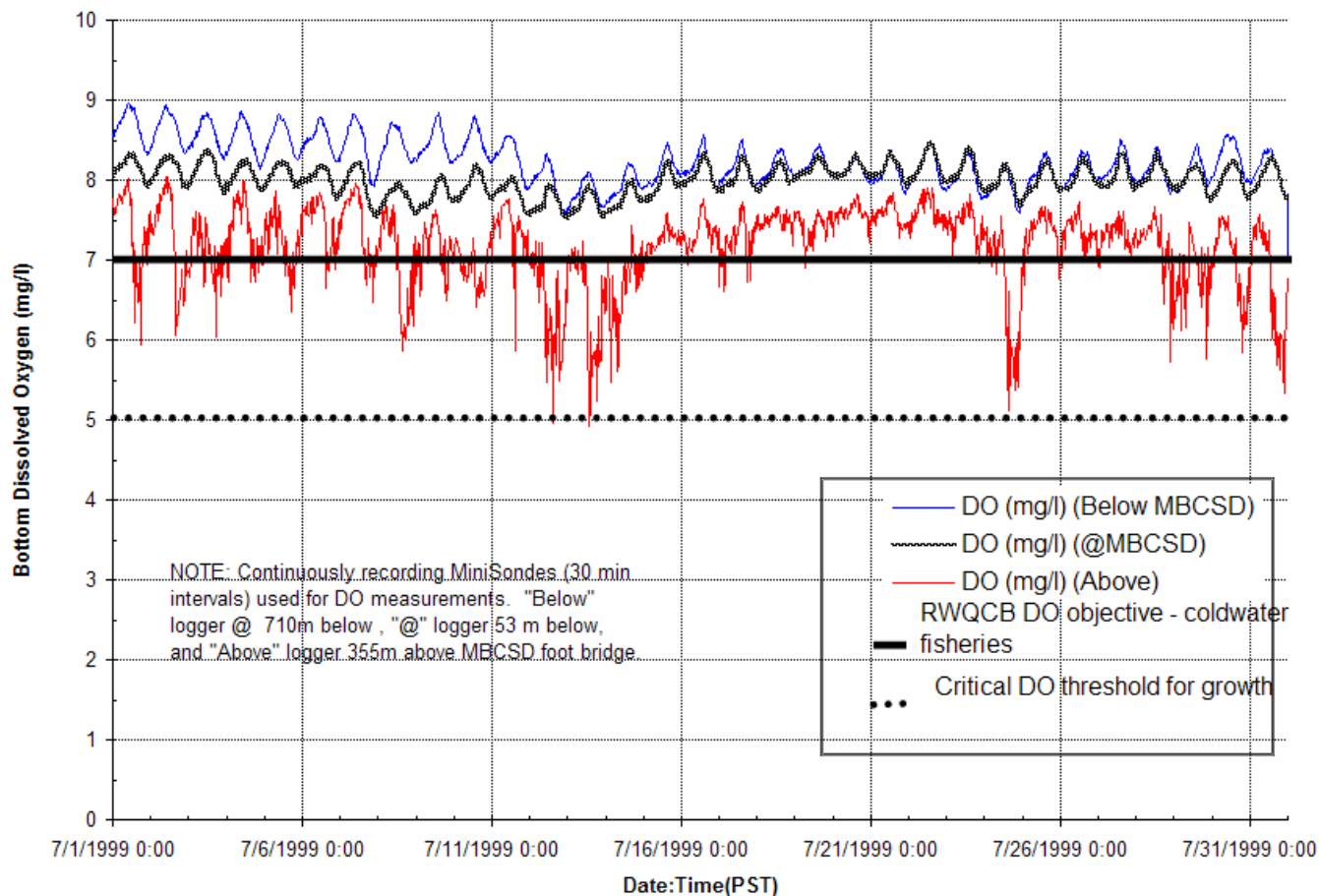


Figure 46: Pool Dissolved Oxygen Conditions in Redwood Creek, Marin Co., August 1999

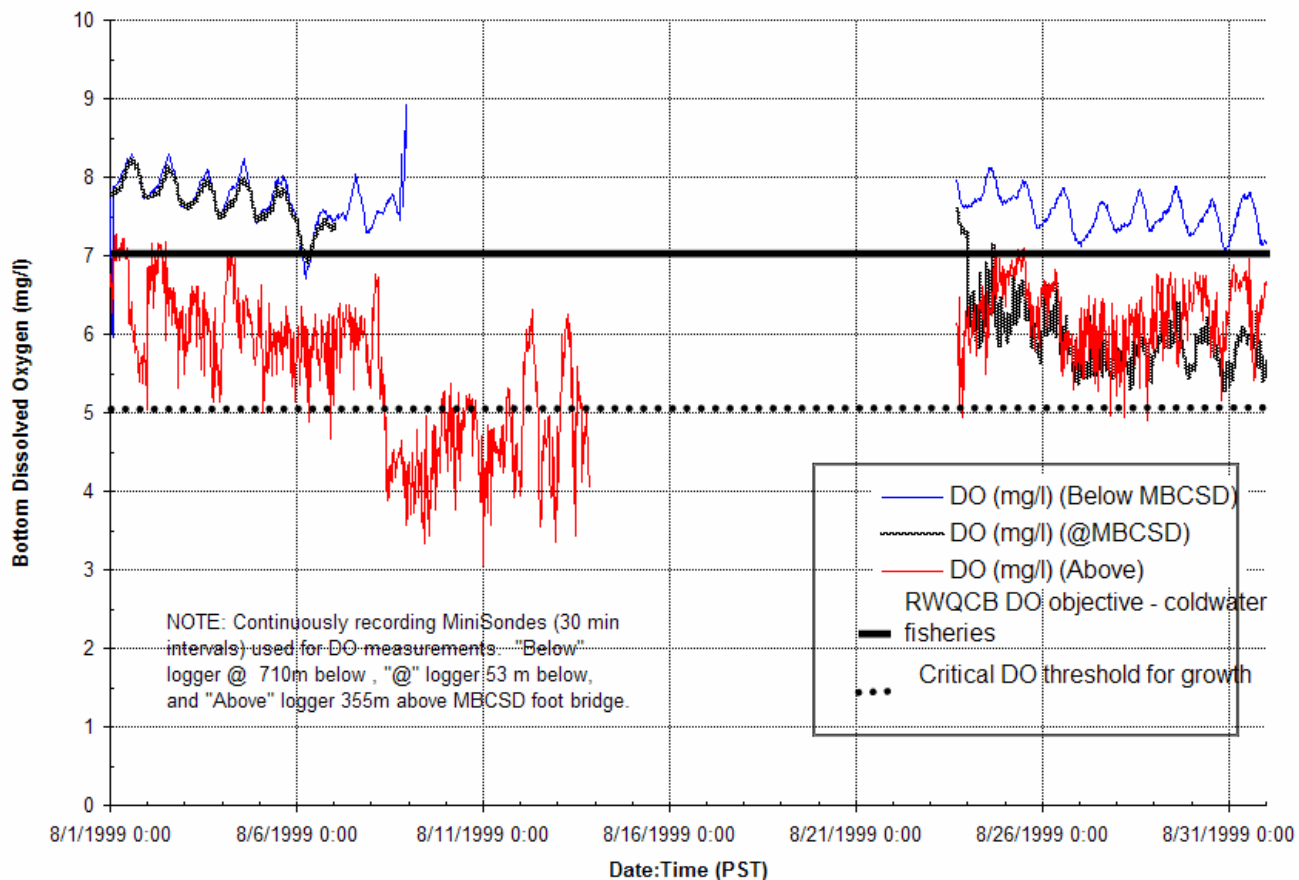


Figure 47: Pool Dissolved Oxygen Conditions in Redwood Creek, Marin Co., September 1999

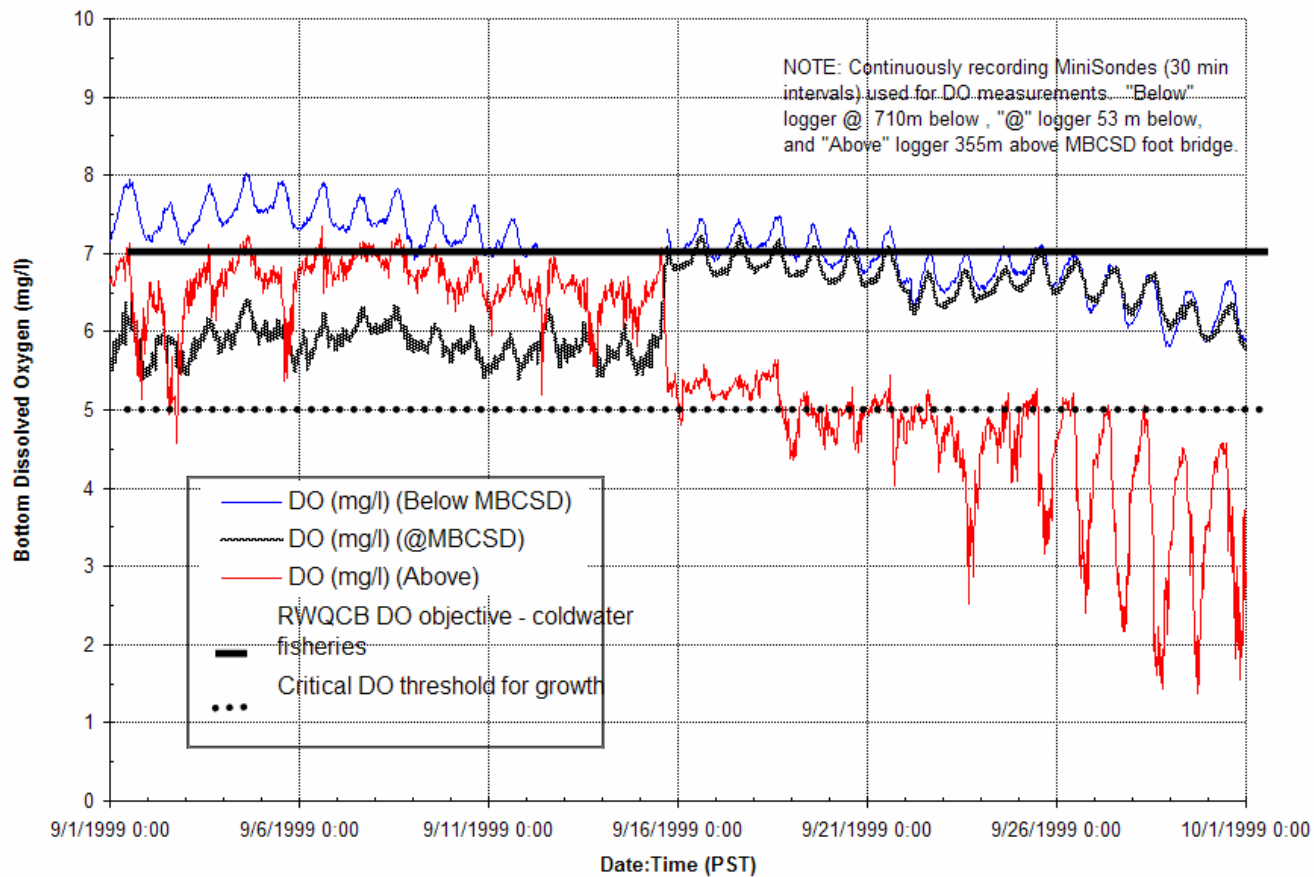


Figure 48: Pool Dissolved Oxygen Conditions in Redwood Creek, Marin Co., October 1999

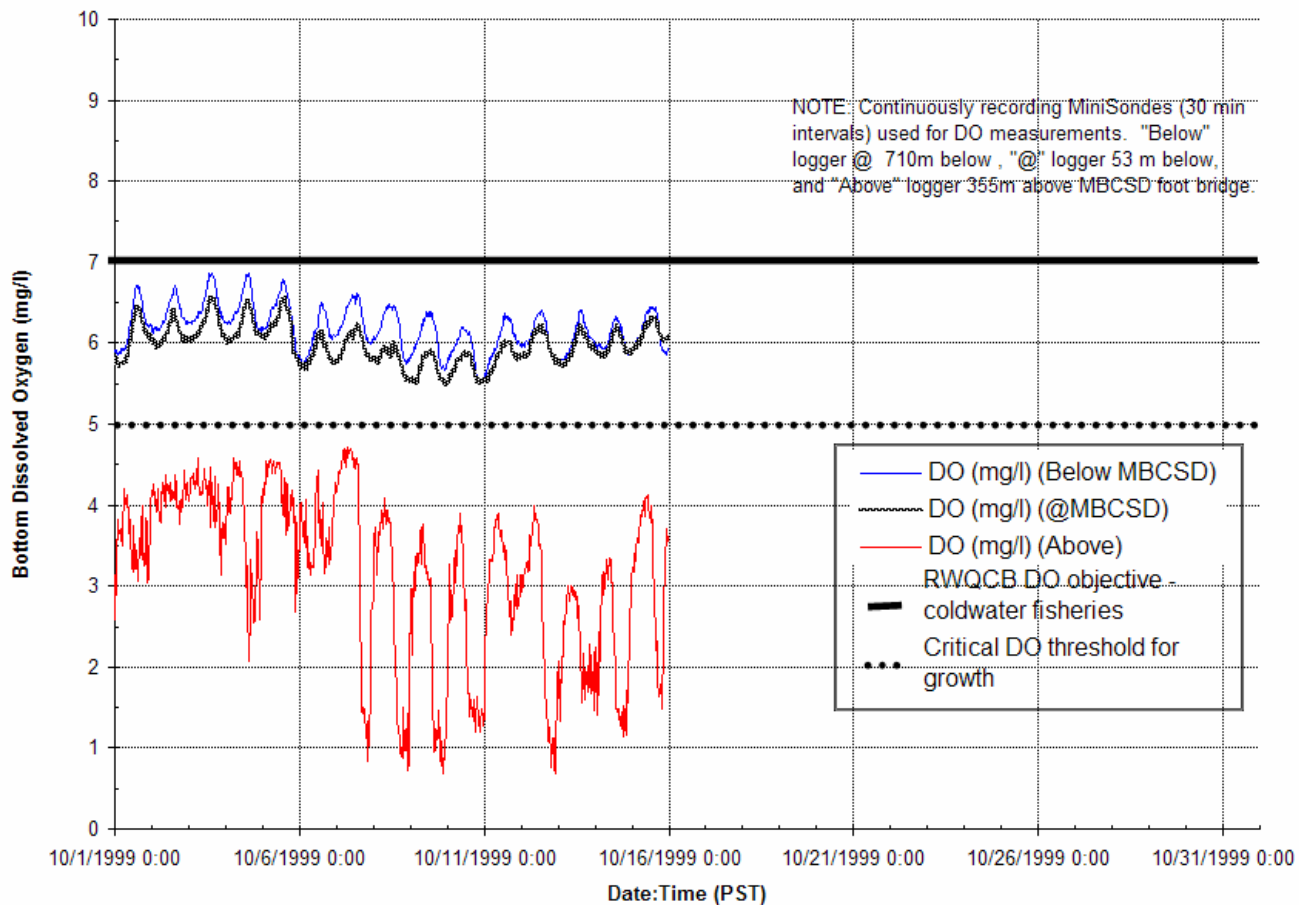


Figure 49: Pool Dissolved Oxygen Conditions in Redwood Creek, Marin Co., October 2001

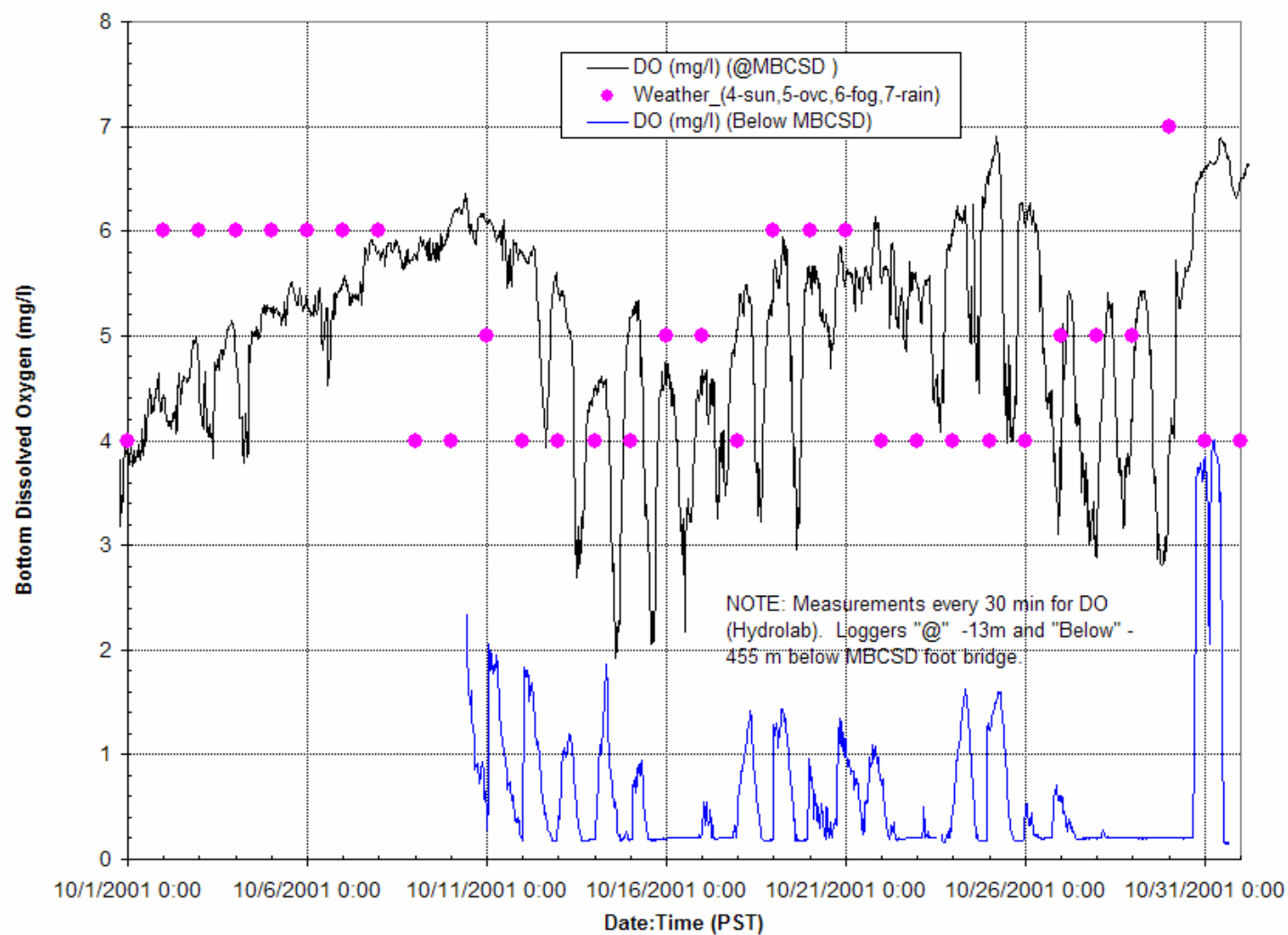


Figure 50: Mean Fish Abundance (Error Bars: ± 1 Standard Deviation) per Index Pool Units for Reaches Below (Reaches A-B) and Above MBCSD Well on Redwood Creek, Marin Co., September-October 1998, 1999 and 2001.

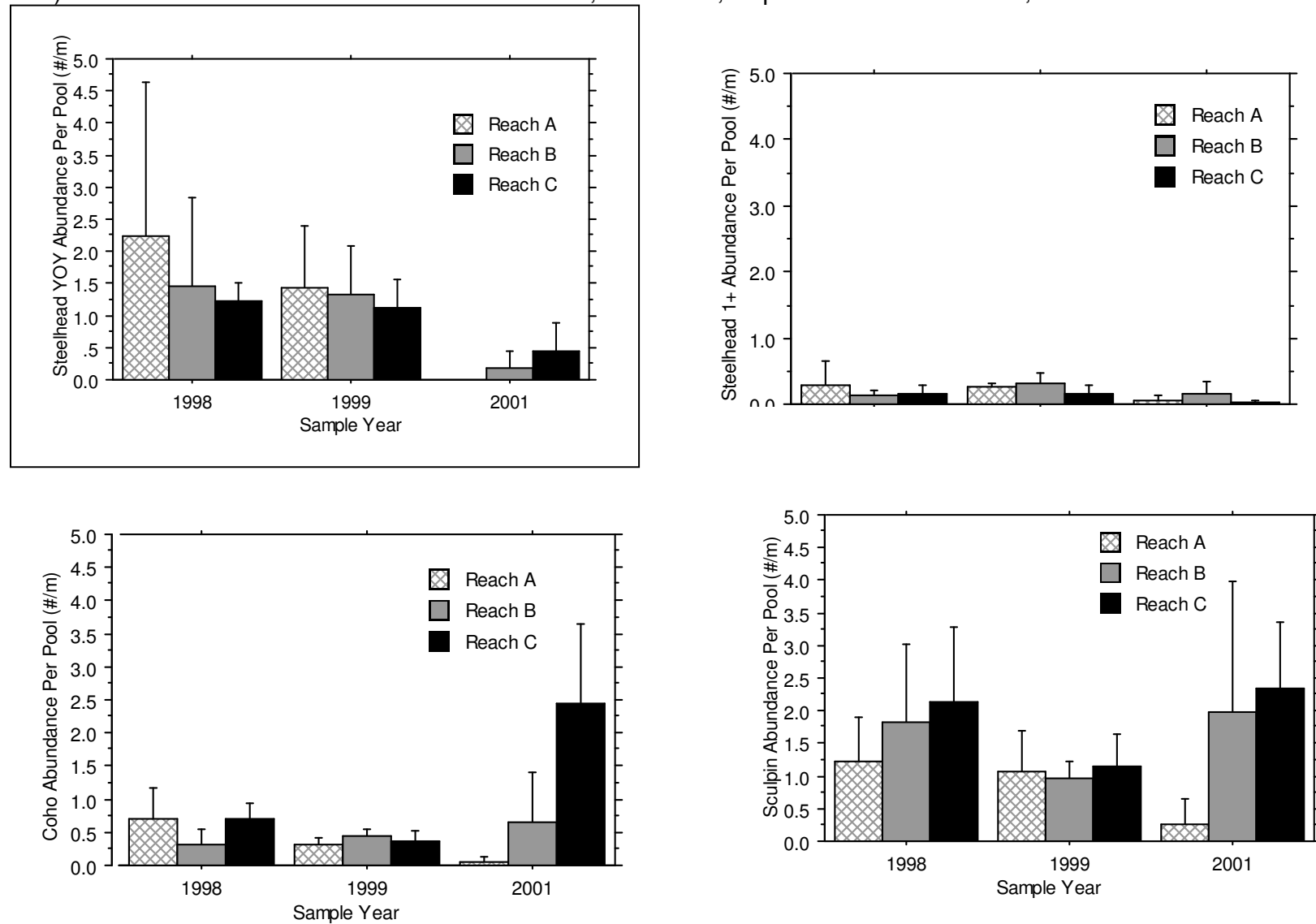


Figure 51: Total Fish Abundance (#/m) (Error Bars: ± 1 Standard Deviation) per Index Pool Units for Reaches Below (Reaches A-B) and Above MBCSD Well on Redwood Creek, Marin Co., September-October 1998, 1999 and 2001.

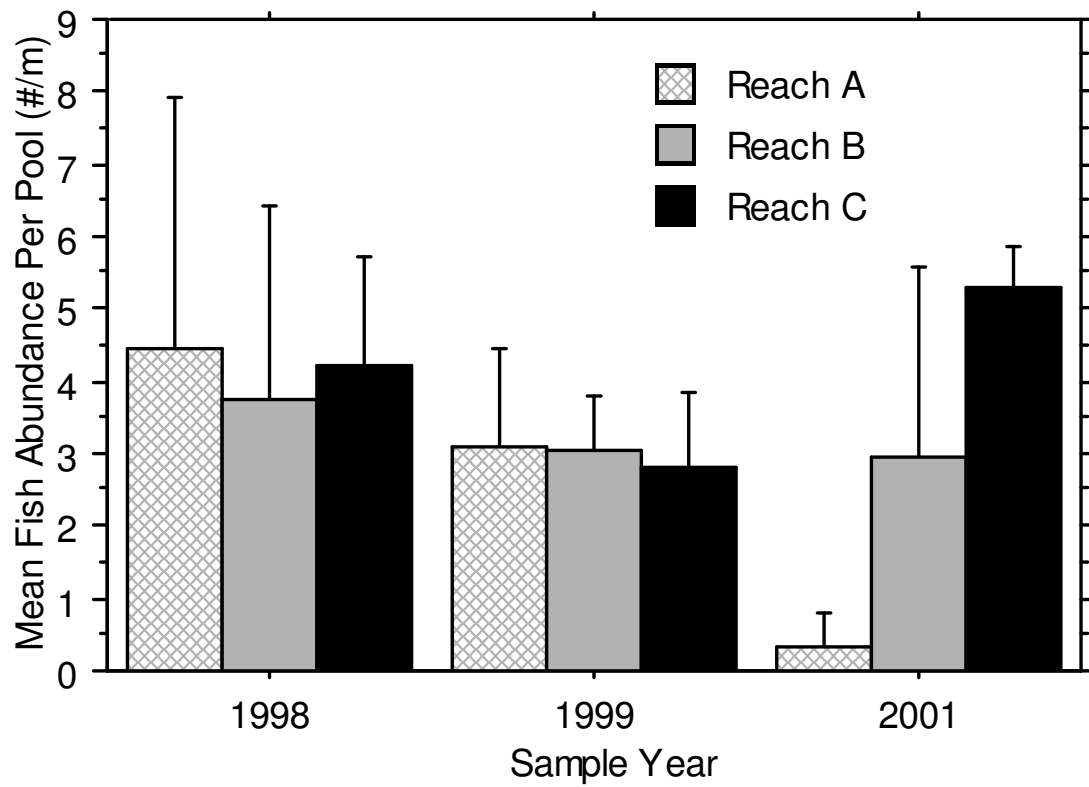


Figure 52: Mean Fish Standing Biomass (g/m) (Error Bars: ± 1 Standard Deviation) per Index Pool Units for Reaches Below (Reaches A-B) and Above MBCSD Well on Redwood Creek, Marin Co., September-October 1998, 1999 and 2001.

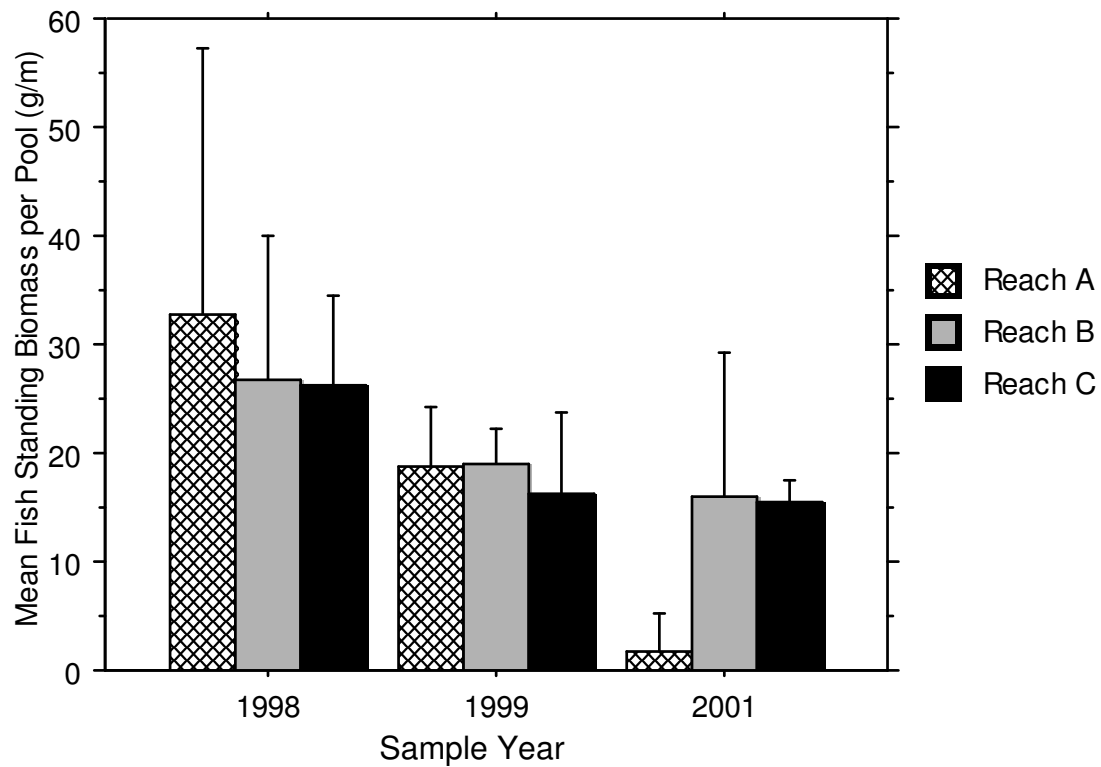


Figure 53: Mean Brillouin Index Values (Error Bars: ± 1 Standard Deviation) per Index Pool Units for Reaches Below and Above MBCSD Well (A-B) September-October 1998, 1999 and 2001.

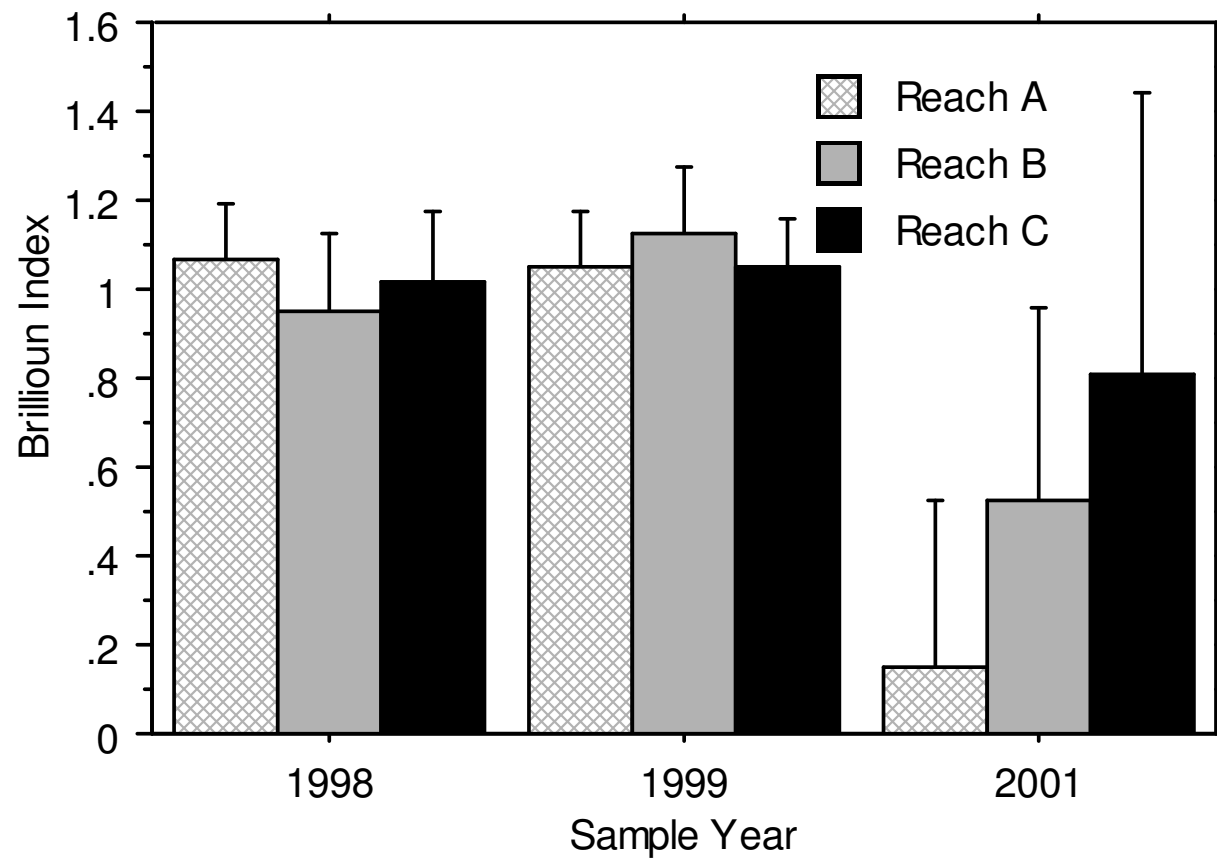
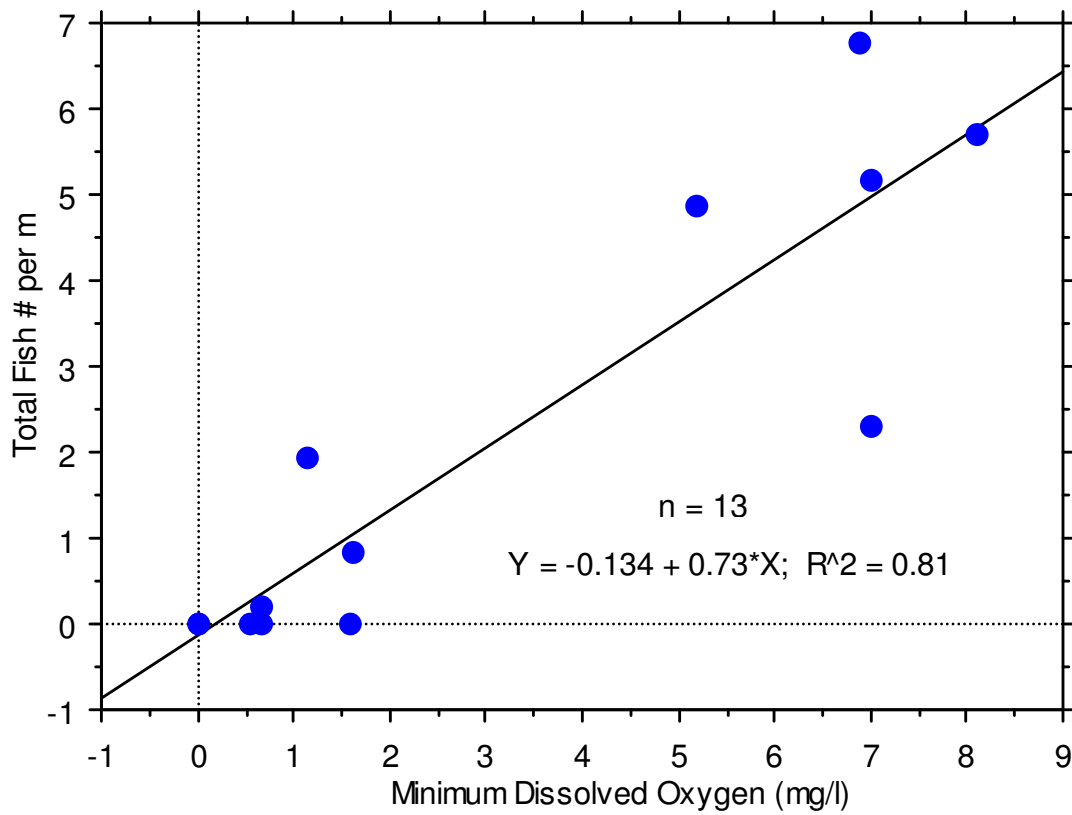


Figure 54: Simple linear regression model describing the association in a dry year between dissolved oxygen concentrations and total fish abundance per meter in Redwood Creek, Marin Co., CA, 2001



APPENDICES

Appendix I: Geographic coordinate data (NAD83) for water quality index pools,
Redwood Creek, Marin Co., CA

Year	Pool/ Unit#	UTM N	UTM E
1998	58	4191497	536750
	64	4191593	536685
	70	4191704	536693
	76	4191767	536674
	80	4191781	536628
	103	4192028	536682
	121	4192182	536771
	123	4192203	536780
	126	4192227	536802
	131	4192268	536799
1999	4	4191072	537035
	6	4191098	537012
	11	4191140	536992
	15	4191202	536954
	18	4191259	536952
	24	4191336	536902
	30	4191488	536756
	32	4191541	536746
	42	4191719	536701
	48	4191786	536613
	53	4191831	536636
	58	4191927	536654
	60	4191912	536640
	65	4192002	536658
	69	4192049	536711

Year	Pool/ Unit#	UTM N	UTM E
2001	3	4191081	537048
	8	4191108	536991
	13	4191168	536943
	18	4191225	536960
	23	4191298	536927
	28	4191391	536879
	33	4191519	536737
	38	4191575	536690
	40	4191614	536693
	43	4191715	536699
	48	4191765	536659
	52	4191821	536619
	58	4191892	536657
	63	4191966	536634
	68	4192052	536728
2002	1	4191042	537087
	18	4191077	537036
	30	4191122	536990
	63	4191379	536834
	74	4191543	536743
	83	4191640	536693
	92	4191708	536699
	99	4191783	536621
	106	4191920	536647
	112	4192007	536653

Appendix II: Water quality data for 1998 index pools

Date	Pool#	Time (PST)	Water Temp (°C)	DO (%Sat)	DO (mg/l)
10/21/98	46	10:53	12.4	99	10.6
10/21/98	51	11:25	12.5	72	7.7
10/21/98	58	12:32	12.1	76	8.2
10/21/98	64	12:35	13.1	83	8.7
10/21/98	70	13:08	12.5	81	8.6
10/21/98	76	13:33	13.3	74	7.7
10/21/98	80	13:44	13.4	74	7.8
10/21/98	103	14:00	12.8	60	6.3
10/21/98	121	14:39	12.7	65	6.9
10/21/98	123	14:55	12.8	66	7.0
10/21/98	126	15:00	12.8	83	8.8
10/21/98	131	15:55	12.2	73	7.9
10/28/98	24	1135	12.7	75	7.9
10/28/98	24	1334	13.3	75	7.8
10/28/98	27	1144	12.5	73	7.7
10/28/98	27	1341	13.4	72	7.5
10/28/98	35	1154	13	76	8.0
10/28/98	46	1200	13.2	83	8.8
10/28/98	51	1205	13.1	84	8.8
10/28/98	58	1212	13.2	74	7.8
10/28/98	64	1221	13.2	86	9.0
10/28/98	70	1231	13	85	8.8
10/28/98	76	1236	13.1	83	8.7
10/28/98	80	1243	12.8	78	8.2
10/28/98	103	1254	12.7	74	7.8
10/28/98	121	1301	12.6	80	8.6
10/28/98	123	1306	12.6	81	8.6
10/28/98	126	1311	12.7	82	8.6
10/28/98	131	1316	12.8	83	8.8
11/2/98	24	11:00	14.8	81	8.2
11/2/98	27	11:05	14.8	79	8.0
11/2/98	35	11:10	15.1	79	8.0
11/2/98	46	11:19	15.3	88	8.8
11/2/98	51	11:25	15.3	87	8.7
11/2/98	58	11:35	15.3	79	7.9
11/2/98	64	11:50	15.3	90	9.0
11/2/98	70	11:55	15.3	84	8.4
11/2/98	76	12:03	15.3	86	8.6
11/2/98	80	12:08	15.3	78	7.8
11/2/98	103	12:25	14.8	75	7.6
11/2/98	121	12:35	14.8	83	8.4
11/2/98	123	12:45	14.8	83	8.4
11/2/98	126	12:50	15.3	84	8.4
11/2/98	131	12:55	15.3	86	8.6
11/9/98	24	10:19	14.3	83	8.5
11/9/98	27	10:26	13.3	83	8.6

Date	Pool#	Time (PST)	Water Temp (°C)	DO (%Sat)	DO (mg/l)
11/9/98	35	10:30	13.8	75	8.4
11/9/98	46	10:40	15.3	90	9.0
11/9/98	51	10:43	13.8	75	8.8
11/9/98	58	10:50	13.8	75	8.3
11/9/98	64	10:55	15.3	90	9.0
11/9/98	70	11:03	13.8	75	8.7
11/9/98	76	11:08	13.8	75	8.9
11/9/98	80	11:12	13.2	82	8.6

Appendix III: Water quality data for 1999 index pools

Date	Pool#	Time (PST)	Water Temp (°C)	DO (%Sat)	DO (mg/l)
6/22/99	6	9:34	12.7	83	8.7
6/30/99	58		13.2	81	8.5
6/30/99	60		14.5		
7/23/99	4		13.0		
7/23/99	6		13.0	82	8.6
7/23/99	11		13.0	72	7.6
7/23/99	15		13.0	76	8.0
7/23/99	18		13.0	78	8.2
7/23/99	24		14.0	91	9.4
7/23/99	30		14.0	75	8.8
7/28/99	4		14.0	75	7.8
7/28/99	6		14.0	75	8.0
7/28/99	11		13.0	77	8.1
7/28/99	15		14.0	75	8.2
7/28/99	18		13.5	74	8.0
7/28/99	24		13.0	78	8.2
7/28/99	30		14.0	75	8.3
7/28/99	32		14.0	75	8.6
7/28/99	42		13.0	80	8.4
7/28/99	48		14.0	75	7.1
7/28/99	53		13.0	80	8.4
7/28/99	58		12.0	78	8.4
7/28/99	60		12.0	80	8.6
7/28/99	65		13.0	76	8.0
7/28/99	69		14.0	75	8.5
8/11/99	4	9:55	14.5	75	7.6
8/11/99	6	10:15	15.5	76	7.6
8/11/99	11	10:35	15.0	75	7.6
8/11/99	15	10:55	15.5	76	7.6
8/11/99	18	11:15	16.0	79	7.8
8/11/99	24	11:33	15.0	84	8.4
8/11/99	30	12:00	15.0	77	7.8
8/11/99	32	12:17	15.0	79	8.0
8/11/99	42	12:55	15.5	82	8.2
8/11/99	48	13:10	15.5	86	8.6
8/11/99	53	13:40	15.0	77	7.8

Date	Pool#	Time (PST)	Water Temp (°C)	DO (%Sat)	DO (mg/l)
8/11/99	58	14:00	15.5	82	8.2
8/11/99	60	14:15	16.0	87	8.6
8/11/99	65	14:30	15.0	85	8.6
8/11/99	69	14:50	15.0	79	8.0
8/24/99	4	10:33	14.0	75	6.4
8/24/99	6	11:06	14.0	75	7.6
8/24/99	11	11:15	14.0	75	7.6
8/24/99	15	11:40	15.0	71	7.2
8/24/99	18	11:59	14.0	75	6.0
8/24/99	24	12:19	15.0	83	8.3
8/24/99	30	12:39	15.0	80	8.1
8/24/99	32	12:46	14.5	82	8.4
8/24/99	42	13:17	15.0	83	8.4
8/24/99	48	13:40	15.0	85	8.6
8/24/99	53	14:11	15.0	81	8.2
8/24/99	60	14:30	15.0	85	8.6
8/24/99	65	14:48	15.0	80	8.1
8/24/99	69	15:03	15.0	81	8.2
9/8/99	4	10:00	13.5	74	6.5
9/8/99	6	10:15	13.5	74	7.2
9/8/99	11	10:30	13.5	74	6.5
9/8/99	15	10:45	13.5	74	7.3
9/8/99	18	11:00	13.5	74	7.9
9/8/99	24	11:15	13.5	77	8.0
9/8/99	30	11:30	13.5	74	6.3
9/8/99	32	11:45	13.6	63	6.5
9/8/99	42	12:00	13.5	74	6.6
9/8/99	48	12:15	13.6	76	7.9
9/8/99	53	12:45	13.6	56	5.8
9/8/99	58	13:00	13.6	61	6.3
9/8/99	60	13:15	13.7	65	6.8
9/8/99	65	13:30	13.8	70	7.2
9/8/99	69	13:45	13.8	70	7.2
9/30/99	4	9:45	13.1	55	5.8
9/30/99	6	10:00	13.1	54	5.7
9/30/99	11	10:20	13.1	58	6.1
9/30/99	15	10:40	13.4	58	6.0
9/30/99	18	10:53	13.4	67	6.9
9/30/99	24	11:08	13.4	67	7.0
9/30/99	30	11:22	13.4	54	5.6
9/30/99	32	11:37	13.4	56	5.8
9/30/99	42	12:02	13.4	66	6.9
9/30/99	48		13.5	74	7.5
9/30/99	53		13.5	74	6.0
9/30/99	58	13:00	13.8	55	5.7
9/30/99	60	13:10	14.1	71	7.3
9/30/99	65		13.9	75	6.5
9/30/99	69		13.9	75	5.6
10/4/99	4		17.3	78	8.0
10/4/99	4.5	10:10	13.8	72	7.5

Date	Pool#	Time (PST)	Water Temp (°C)	DO (%Sat)	DO (mg/l)
10/4/99	6		13.4	74	7.8
10/4/99	11		13.8	75	7.8
10/5/99	15		14.2	85	8.7
10/5/99	18		14.3	75	7.7
10/5/99	24		14.1	73	7.5
10/5/99	30		14.2	80	8.2
10/6/99	32		14.4	83	8.5
10/6/99	42		14.4	81	8.3
10/7/99	58		13.2		6.3
10/7/99	60		13.5		5.9
10/7/99	65		13.7		5.5
10/7/99	69		14.0		5.7

Appendix IV: Water quality data for 2001 index pools

Date	Pool#	Time (PST)	Upstrm Riffle Depth (mm)	Water Temp (°C)	DO (%Sat)	DO (mg/l)
9/10/01	3	9:49	0		15	1.6
9/10/01	4		0	13.7	19	2.0
9/10/01	8	10:45	0	13.7	6	0.7
9/10/01	13	10:57	0	13.7	5	0.5
9/10/01	18	11:05	0	13.9	15	1.6
9/10/01	19	11:11	0	14.0	11	1.1
9/10/01	23	11:17	0	14.2	8	0.9
9/10/01	28	11:28	25	14.3	24	2.4
9/10/01	29	11:40	0	13.8	5	0.5
9/10/01	33	11:46	2	13.9	11	1.2
9/10/01	38	12:05	0	18.0	87	8.2
9/10/01	40	12:22	0	15.1	30	3.0
9/10/01	43	12:32	0	14.6	16	1.6
9/10/01	48	12:40	20	15.8	74	7.3
9/10/01	52	12:48	48	14.0	68	6.9
9/10/01	58	13:03	45	14.4	51	5.2
9/10/01	63	13:16	40	14.8	96	9.7
9/10/01	68	13:28	25	14.1	49	5.0
9/11/01	3	12:18	0	13.3	15	1.6
9/11/01	8	12:22	0	14.0	23	2.3
9/20/01	3	7:39	20	13.0	43	4.6
9/20/01	8	7:42	5	13.2	9	0.9
9/20/01	13	7:48	20	13.2	46	4.8
9/20/01	18	7:54	115	13.1	40	4.2
9/20/01	23	7:59	35	13.2	22	2.3
9/20/01	28	8:06	65	13.3	33	3.4
9/20/01	33	8:14	40	13.3	34	3.6
9/20/01	38	8:22	25	12.9	71	7.5
9/20/01	40	8:27	30	13.0	82	8.6
9/20/01	43	8:35	0	13.1	17	1.7

Date	Pool#	Time (PST)	Upstrm Riffle Depth (mm)	Water Temp (°C)	DO (%Sat)	DO (mg/l)
9/20/01	48	8:39	27	12.9	71	7.5
9/20/01	52	8:52	100	13.0	66	7.0
9/20/01	58	8:55	55	13.0	57	6.0
9/20/01	63	9:03	42	12.9	77	8.1
9/20/01	68	9:07	49	13.0	68	7.2
9/20/01	3	9:23		13.1	44	4.7
10/10/01	3	12:15	0	12.1	17	1.8
10/10/01	8	11:00	0	13.7	9	0.9
10/10/01	13	10:59	10	12.4	27	2.9
10/10/01	18	10:52	101	11.9	41	4.4
10/10/01	23	10:45	25	13.3	19	1.9
10/10/01	28	10:40	58	13.0	32	3.3
10/10/01	33	9:43	32	12.0	43	4.6
10/10/01	38	9:38	0	12.0	65	7.0
10/10/01	40	9:35	0	10.0	72	8.2
10/10/01	43	9:31		12.6	15	1.6
10/10/01	48	0:25	20	12.2	81	8.8
10/10/01	68	8:15	46	11.0	59	6.4
10/10/01	63	8:08	33	10.5	76	8.4
10/10/01	58	8:04	53	11.3	54	5.8
10/10/01	52	7:45	68	10.7	64	7.2

Appendix V: Water quality data for 2002 index pools

Date	Unit #	Time (PST)	Upstream Riffle Depth (mm)	Water Temp (°C)	DO (%Sat)	DO (mg/l)
10/8/02	1	9:55	5	13.2	22.6	2.38
10/8/02	18	11:21	0	12.9	18.7	1.98
10/8/02	30	12:55	30	13.7	18.2	1.76
10/8/02	42	13:48	100	14.8	21.9	2.22
10/9/02	63	9:24	0	13.2	5.7	0.6
10/9/02	74	10:37	2	14.0	19.7	2.02
10/9/02	83	11:06	0	14.7	24.5	2.5
10/9/02	92	11:26	13	14.6	60.6	6.16
10/9/02	99	12:25	54	13.9	61.2	6.33
10/9/02	106	12:55	19	13.7	42.5	4.39
10/9/02	112	13:19		13.6	75.8	7.89
10/23/02	1	10:50	45	12.5	64.5	6.86
10/23/02	18	10:58	53	12.5	52.9	5.63
10/23/02	30	11:04	48	12.6	56.9	5.98
10/23/02	63	11:18	44	12.5	74.2	7.9
10/23/02	74	11:31	46	13.0	52.6	5.54
10/23/02	83	11:41	59	12.6	95.3	10.13
10/23/02	92	12:35	27	12.8	89.0	9.42
10/23/02	99	12:29	42	12.8	87.0	9.2
10/23/02	106	12:21	49	12.6	74.5	7.93
10/23/02	112	12:11	54	12.6	90.9	9.65

