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ANALYSIS OF LAND USE IMPACTS ON WATER QUALITY AND QUANTITY IN REDWOOD CREEK

prepared for

The National Park Service

Golden Gate National Recreation Area

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I. INTRODUCTION

The Redwood Creek watershed is unique among California coastal watersheds of its size in that it remains largely undeveloped and is protected as State and Federal Park lands. The creek has largely recovered from historical grazing activities in the watershed, and now supports sustainable populations of coho salmon, steelhead, and special status species such as the western pond turtle and the red-legged frog. Both steelhead and coho salmon have recently been petitioned for listing under the Endangered Species Act. A preliminary enhancement plan has been developed that would restore and enhance over 16 acres of wetland and open water habitat at Big Lagoon at the mouth of Redwood Creek (Philip Williams & Associates, Ltd. *et al.,* 1994).

Restoration of the historical Big Lagoon wetlands would provide extensive ecological benefits, and the National Park Service has recognized that it is important to manage the restored wetlands, creek, and contributing watershed as a comprehensive and integrated ecosystem. As part of this approach, and to complement planning funded by Caltrans which focused on wetlands restoration at Big Lagoon, the National Park Service (NPS) retained Philip Williams & Associates, Ltd. (PWA) to study the impacts of various land use activities in the watershed on creek flows, water quality, and sedimentation. This study, described herein, addresses the following issues:

1. What are the impacts of well withdrawals by the Banducci Flower and Bulb Farm and the Muir Beach Community Services District on creek flows?

2. What are the relative impacts of agriculture, horse operations, domestic leach fields, and other land uses on creek water quality?

3. What is the total sediment yield from the Redwood Creek watershed, and how much have land use activities increased the sediment load to the creek?

To address these issues, a water quality and flow monitoring program was implemented beginning in August, 1993 and ending in July, 1994. This report summarizes the monitoring data, and provides recommendations to reduce the impacts of the various land uses on Redwood Creek.

II. SUMMARY AND RECOMMENDATIONS

A. IMPACTS OF PUMPING ON FLOWS IN REDWOOD CREEK

While pumping the Muir Beach SCO and Banducci wells have an immediate input on the flow in the creek (referred to here as the instantaneous creek flow rate, or the volumetric flow rate that is observed in the creek at a specific time and location). The primary impacts of reduced instantaneous flow rates are on the amount of habitat available to fish, insects and amphibians in the shallow riffles that occur between pools. Pumping also has a long-term impact on the volume of water flowing into pools and wetland areas. This impact is quantified here by the effect of pumping on creek flow rates averaged over a specified period (daily, weekly, or over the course of a season). Reductions in long-term average flow rates affect the water quality and amount of habitat in pools and wetland areas.

Groundwater modeling indicates the Banducci wells decrease the instantaneous creek flow rate below Franks Valley by about 0.14 cfs when pumping. The model predicts that the Muir Beach CSD well decreases instantaneous creek flows by as much as 0.09 cfs. If these wells all pump at the same time, instantaneous creek flows are decreased by up to 0.23 cfs.

The wells do not pump continuously, and consequently their impact on long-term average flows is lower than their impact on instantaneous flows. The model predicts the wells decrease the monthly average flow in Redwood Creek by 0.06 cfs during peak irrigation months (0.02 cfs from Banducci, 0.04 cfs from Muir Beach CSD). During average years, flows in the creek in the late dry season would naturally be on the order of 0.1 to 0.2 cfs without pumping. In periods of severe drought, the creek probably would have periods of no surface flow even without pumping.

Measured flow data in the creek verify that the Banducci wells cause instantaneous losses on the order of 0.08 to 0.15 cfs from the creek. The flow data are less consistent with regard to the Muir Beach CSD well. Flows were observed to decrease near the well on four occasions, but no decreases were observed on three other occasions when the pumps were operating. There are inherent difficulties in measuring the impacts of the wells, since measurement errors in current meter surveys can easily surpass 0.1 cfs.

The effect of these losses is to increase the frequency and duration of periods when the creek is dry below Franks Valley. Using a flow-duration curve derived from flow data on Arroyo Corte Madera, Redwood Creek would naturally have dry periods lasting seven or more days once every four years. The estimated losses due to well pumping would increase the frequency of this to about once every two years.

The relative impacts of water losses on creek fish habitat are seasonal, and are greatest in the late summer of drought years when flows naturally drop below 0.5 cfs. The short-term flow losses that occur during pumping can have serious impacts on both the fish populations using the shallow habitats and on the insect populations that provide essential food for fish in the deeper pools. Long-term flow reductions decrease the volumes and water quality of pools, reducing both juvenile fish survival and growth.

The impacts of pumping can be reduced by bringing in an outside water supply from the Marin Municipal Water District (MMWD), water conservation/demand reduction, moving the wells 50 to 100 feet from the creek, and/or ensuring that the Banducci and Muir Beach CSD wells pumping periods do not overlap. If the National Park Service or Muir Beach CSD choose to move the wells, additional hydrogeologic studies will be needed to determine if wells 50 to 100 feet from the creek will be productive and will not reduce creek flows.

B. WATER QUALITY IMPACTS

Nitrogen and phosphorous loadings affect the water quality in downstream pools and wetlands by increasing algae growth, thus reducing the amount of dissolved oxygen available to fish, amphibians, and aquatic insects. Coliform bacteria are indicative of fecal pollution that could transmit pathogenic viruses and bacteria to aquatic wildlife. Low dissolved oxygen levels have been observed in the lower reaches of Redwood Creek near Muir Beach. Sources of nutrients include fertilizers that runoff the fields during storms, horse operations on the hillsides and floodplain, and septic leach fields. Coliform bacteria could be derived from horse manure and septic leach fields.

In wet weather nutrient and coliform bacteria levels in Redwood Creek increase downstream of the Banducci Farm, but are generally highest near Muir Beach. Runoff from the Banducci floodplain fields (covering about 29 acres) causes part of this increase, but the largest source appears to be the horse operations on NPS and Green Gulch lands (with hillside pastures, lowland pastures, and stables covering over 200 acres). Stormwater samples from Green Gulch Creek and the ditch draining Tinker's Stables and hillside pastures showed extremely high levels of nitrogen (1.3 to 1.6 mg/l), phosphorus (0.15 to 4.8 mg/l), and coliform (>2400 #/100ml).

Dry-weather (summer) fecal coliform counts are below 50 #/100ml upstream of Banducci. These increase to about 300 #/100ml below Banducci and 1900 #/100ml at Pacific Way, which are well above standards for water contact recreation. There was no surface runoff from areas used by horses during this period, and this increase is probably due to leakage from domestic septic leach fields on the creek floodplain between Pacific Way and Highway 1.

C. SEDIMENT EROSION IMPACTS

Estimates of total sediment yield from Redwood Creek vary over a wide range (10 to 980 tons/square mile/year). The most representative data indicate the total annual yield is on the order of 150 tons/square mile/year, or about 1200 tons/year.

The majority of the sediment from the Redwood Creek watershed is derived from the steep hillsides. Of the identified land-use related sediment sources, the hillside pastures (covering about 196 acres) contribute the largest sediment load. This sediment is currently trapped in the low-gradient ditches and seasonal wetlands lying between Highway 1 and the Redwood Creek levee. If the Big Lagoon enhancement plan is implemented, this sediment would discharge directly into the restored freshwater wetlands and lagoon.

Sediment loads from the Banducci floodplain fields (29 acres), Green Gulch fields (22 acres), and lowland horse pastures (21 acres) are much smaller due to the low slopes hi these areas. Sediment loads from these land uses are significantly higher than they would be under natural conditions, but are still small relative to the total sediment load from the Redwood Creek watershed.

Adequate analytical methods are not available to quantify the sediment erosion impacts of the hillside Banducci fields. Areas planted with mature heather probably do not contribute sediment at rates much above natural erosion rates. Hillside areas planted with annuals and bulbs would have much higher erosion rates per acre, since these steep areas are highly susceptible to erosion when disturbed by plowing and vegetation removal.

D. RECOMMENDATIONS TO REDUCE WATER QUALITY AND SEDIMENT EROSION IMPACTS

1. Banducci Farm

Measures to reduce the water quality and sediment erosion impacts should focus on both source control and treatment of discharged water. Fertilizing practices for the Banducci Farm should be reviewed to ensure that the amount of fertilizer that washes off the soil surface is limited; White and Plate (1978) provide a summary of Best Management Practices for fertilizer use. These include avoiding excessive fertilizer applications, timing applications to maximize nutrient uptake by plants, incorporating fertilizers into the soil (rather than surface application through irrigation water), and applying nitrogen in forms that limit mobility. Surface applications of manure should be avoided.

The amount of sediment produced by the fields can be reduced by maintaining a continuous planting of cover crops when fields are fallow. This is currently done to a degree, but we did observe periods in the winter when sections of the Banducci fields were barren. Plantings on the steep hillsides should be limited to heather and other shrubs with root systems that protect soil from erosion; flower bulbs and annuals should only be planted on the floodplain fields.

High coliform levels near the Banducci Farm could be due to horse use of streamside trails and nearby riding rings, but may also be related to use of the riparian corridor as a restroom by field workers. On-site sanitation should be reviewed to ensure that there are adequate restroom facilities and education of field workers.

The Banducci fields currently drain away from the creek to an unlined ditch; this provides an opportunity to control and treat field runoff. The ditch should be reconfigured as a water quality swale to remove sediment, particulate pollutants, and some dissolved pollutants. Nutrient removal can be enhanced by routing field runoff through a 20 to 50 foot grassed buffer strip before discharge into the swale.

To provide both a habitat and water quality buffer, the Banducci fields should be set back by at least 50 feet from the top of the creek bank. This buffer zone can be planted with native riparian vegetation, and a low berm (about 0.5 feet high) should be constructed to ensure no direct drainage of runoff from the fields into the creek.

2. Horse Operations

Horse operations have been identified as a significant source of sediment, nutrients, and coliform bacteria in Redwood Creek and adjacent wetlands. The following are recommendations for reducing pollutant and sediment loads from these areas:

- Horses should be removed from the seasonal wetlands in the lower Green Gulch pastures. Pasturing of horses in these areas results in direct loading of coliform and nutrients into vulnerable shallow wetlands.

- Ideally, horses should not be pastured on the steep hillslopes. If horses do remain on these sites, they should be kept off bare hillslopes until vegetation is reestablished. Feeding areas and gates should be designed to minimize congregation of horses at the base of the slopes. Sediment erosion should be monitored after revegetation to determine if the number of horses per pasture areas should be reduced.

- A buffer zone consisting of a biofilter strip and native vegetation should be provided to separate the hillside pasture hi Green Gulch from Green Gulch Creek if horses remain hi these areas.

- Manure should be removed frequently from stables, paddocks, and riding facilities. This is especially important during and just prior to the rainy season.

- Runoff and sediment erosion from all stables, paddocks, and riding facilities should be controlled. Intensively-used areas should be bermed-off to control and direct runoff. Drainage should be collected into vegetated swales or passed through a grass buffer strip and conveyed to a sediment trap/retention basin before discharging to wetlands and riparian resources.

3. Green Gulch Farm

As with Banducci, fertilizing practices for the Green Gulch Farm should be reviewed to ensure that Best Management Practices are followed to limit the amount of fertilizer available for runoff at the soil surface (White and Plate, 1978). These include avoiding excessive fertilizer applications, timing applications to maximize nutrient uptake by plants, incorporating fertilizers into the soil (rather than surface application through irrigation water), and applying nitrogen in forms that limit mobility. Surface applications of manure should be avoided. Cover crops should be planted when fields are fallow in the rainy season.

Most of the Green Gulch fields drain away from the creek, and runoff is detained and treated to some degree by the vegetated windbreaks. Pollutant loads could be further reduced by draining the fields into swales and filter strips located at each windbreak before discharging to Green Gulch Creek and the lower pasture wetlands.

Green Gulch Creek has been extensively channelized, and is currently eroding and downcutting. Restoring this channel would reduce sediment loads to the pasture wetlands, and improve riparian habitat.

4. Septic Leach Fields

The water quality data show that domestic septic systems on the Redwood Creek floodplain may be the primary source of coliform in the creek during the summer. Further studies should be conducted to determine if these septic systems can be repaired or improved to reduce coliform loadings to acceptable levels. Compliance of these systems to Federal, state and local regulations should also be checked.

III. HYDROLOGY OF THE REDWOOD CREEK WATERSHED

A. WATERSHED CHARACTERISTICS

Redwood Creek drains a 7.46 square mile watershed that begins on the southern slopes of Mt. Tamalpais and includes Fern Creek, Kent Canyon, and Franks Valley (Figure 1). The creek originates from springs on the southeast flank of Mt. Tamalpais, and flows through Redwood Canyon before entering Franks Valley. The creek enters the ocean through an intermittently tidal lagoon at Muir Beach. Green Gulch, with a watershed area of 1.26 square miles, enters the creek immediately upstream of the lagoon.

Elevations in the watershed range from about +2 feet at Muir Beach to +2600 feet NGVD at the peak of Mt. Tamalpais. The upper watershed and hillslopes are steep, with slopes ranging from 15 to 75 percent. After leaving Muir Woods the creek flows through alluvial deposits in Franks Valley, where ground slopes are generally 2 to 5 percent. Vegetation is composed of mixed conifer forests in the upper valleys, mixed hardwoods, chaparral and grasslands on the slopes, and a corridor of riparian vegetation (willows and alders) along Redwood Creek (Myers, 1990).

Major land owners include the National Park Service (Muir Woods National Monument and the Golden Gate National Recreation Area), Mt. Tamalpais State Park, MMWD, and the Green Gulch Farm. Most of the watershed is currently reserved for passive recreational uses such as hiking and sight-seeing. The most developed recreational area is at Muir Woods National Monument, which is intensively used by tour groups and other visitors. Other significant land uses include the Banducci bulb and heather farm in Franks Valley, stable operations in Green Gulch and Franks Valley, agriculture in Green Gulch, and residential development at Muir Beach.

B. CLIMATE

Daily rainfall within the watershed has been recorded by the National Park Service at the Muir Woods Ranger Station since 1941. Table 1 summarizes the mean annual and monthly rainfall statistics. On average, 95 percent of the annual rainfall occurs from October through April, with the highest rainfall in January and the lowest in August.

Pan evaporation is one indicator of potential evapotranspiration (PET) losses within a watershed, and is measured by the Marin Municipal Water District at the Lagunitas Reservoir. Table 1 summarizes mean annual and monthly evaporation statistics. Using a pan coefficient of 0.7 to convert pan evaporation to potential evapotranspiration, PET estimates range from 0.27 inches in January to 5.11 inches in July.

C. HYDROGEOLOGY

Soils on the steep hillsides and ridges in the watershed are moderately deep loams and gravelly-loams (Soil Conservation Service, 1979). Permeabilities are low to moderate, and the potential for runoff and erosion is high. Alluvial deposits predominate on the valley floors and alluvial fans, and consist of very deep silt loams and clay loams with low to moderate permeabilities. Runoff and erosion potential on the alluvial soils is low, primarily because of the low slopes (2 to 5 percent).

Bedrock in the region is comprised of rocks of the Franciscan Group, a series of sedimentary, metamorphic, and igneous rocks of Late Jurassic and Cretaceous age (Laudon, 1988). Redwood Creek has downcut through a graywacke sandstone to form Redwood Canyon and Frank Valley. This sandstone is extremely hard and slightly to moderately fractured in most exposures. In the upper watershed the bedrock is covered by 4 to 10 feet of soil/colluvium.

The floor of Franks Valley is covered with alluvial fill deposited by Redwood Creek since the end of the last ice age. Rising sea levels during this period raised the base level of coastal streams, causing the streams to cease downcutting and begin to build up their floodplains by depositing alluvium (Laudon, 1988). The thickness of these deposits is variable, and is greatest near the center of the valley. Driller reports for the Muir Beach CSD wells indicate the alluvium is at least 37 feet thick, and consists of layers of gravel, sandy gravel, sandy clay, and clay (Figure 2). Seismic refraction studies by Harding Lawson and Associates (1991) show alluvium extending to 20 feet depth, underlain by 80 to 125 feet of weathered bedrock (Figure 3).

The uppermost groundwater in Franks Valley occurs as an unconfined aquifer in the surface alluvium and weathered sandstone. Static (unpumped) water levels are typically 6 to 10 feet below the ground surface near the creek. In the winter groundwater levels are higher than the Redwood Creek bed, and the aquifer contributes to creek storm- and baseflows. In the summer and early fall groundwater levels drop to near or below the creek bottom, and the creek may lose water as it flows through Franks Valley.

D. REDWOOD CREEK HYDROLOGY

The hydrologic regime of Redwood Creek is similar to that of many northern coastal streams. Early season storm flows are comprised primarily of direct storm runoff, and recede quickly after rainfall ends. By January groundwater storage is sufficient to maintain high baseflows, and post-storm recessions can last for over seven days. Flows in the late spring and summer dry season are derived from groundwater and springs in the upper portion of Redwood Canyon. Limited groundwater storage is available in the alluvial deposits in the lower valleys, and by the end of the summer dry season the creek can have virtually no surface flow.

1. Summary of Existing Hydrologic Data

With the exception of data collected for the Big Lagoon restoration study, there has been no continuous streamflow measurement on Redwood Creek. During the 1960's the U.S. Geological Survey measured annual peak flows in Redwood Creek upstream of Franks Valley (USGS, 1970). The USGS also measured flows in Redwood Creek and Green Gulch twice per year between 1985 and 1988. These historic flow data are summarized in Table 2, and show peak annual storm flows ranging from 300 to 1,800 cfs. Early summer flows measured by the USGS are generally on the order of 0.7 cfs.

Streamflows were monitored continuously for the Big Lagoon study at the Pacific Way bridge from March 1992 through January, 1994. This gage is located downstream of the Muir Beach CSD and Banducci wells, and the measured flows reflect the effects of pumping. Figure 4 shows the recorded daily average flows at the Pacific Way bridge for this period. The 1991-92 season was the last of six consecutive drought years. Groundwater storage was sufficient to maintain flows greater than 1.0 cfs through April, but flows dropped to below 0.5 cfs by June and below 0.01 cfs by September. In September and October aquatic habitat existed primarily in isolated pools fed by underflow through the creek gravel beds.

The winter of 1992-93 was a wet year, with 42 inches of rainfall recorded at Muir Woods from October, 1992 through September, 1993 (about 20 percent higher than average). The first large storms occurred in December, followed by nearly 14 inches of rain hi January. The largest storm event occurred on January 20th, with a peak instantaneous flow rate of 370 cubic feet per second (cfs). By the end of January, there was sufficient water in groundwater storage to maintain between-storm baseflows of 10 to 30 cfs. Flows remained above 1 cfs through June of 1993, and did not drop below 0.5 cfs until the end of July. By the end of the dry season in October, 1993 flows had decreased to 0.08 cfs.

Green Gulch Creek was not monitored as part of the Big Lagoon study. Previous USGS monitoring efforts recorded storm flows as high as 10 cfs in the winter and as low as 0.1 cfs in the early summer (Table 2). The watershed has limited groundwater storage, and flows are diverted and stored in two small reservoirs for irrigation. As a result, the creek contributes no observable flow to lower Redwood Creek during the late dry season.

As part of this study instantaneous flow measurements were taken in the late summer/fall of 1993 and spring/late summer of 1994. The purpose of these measurements was to identify changes-in summer streamflows that could be attributed to the Muir Beach Community Services District and Banducci wells. These data and their implications are discussed in detail in Section IV.

2. Frequency of Low Flows

During drought years flows in Redwood Creek drop well below 0.01 cfs by late summer. In 1992 the minimum 30 day average flow rate was 0.01 cfs, and the minimum five month average flow rate was about 0.13 cfs. To establish the frequency and recurrence intervals of these observed low flows, a flow-duration curve was derived for Redwood Creek at Pacific Way from historical data collected by the USGS at Arroyo Corte Madera del Presidio. This creek drains 4.7 square miles of primarily undeveloped land, and has 19 years of daily average flow data. Based on this flow-duration curve (Figure 5), the minimum 1992 observed 30 day Redwood Creek flow of 0.01 cfs would occur on average once every 13 years. A minimum average flow of 0.0 cfs would occur on average once every four years.

3. Flood Frequency

Lehre (1974) derived a flood-frequency relationship for Redwood Creek based on 12 years of peak flow measurements collected at the Franks Valley Bridge. Based on this, the 100-year flood in Redwood Creek would have a peak discharge of about 3300 cfs. The 10 year peak would be about 2000 cfs, and the two year peak would be about 800 cfs.

IV. IMPACTS OF WATER WITHDRAWALS

A. WATER USAGE IN FRANKS VALLEY

The Muir Beach Community Services District (CSD) and the Banducci flower bulb and heather farm are the two major water users in Franks Valley. The Muir Beach CSD currently pumps water from one well located about 20 feet from Redwood Creek (Figure 6). This well is 37 feet deep, and the casing is perforated from 15 to 37 feet depth. This well is the primary domestic water supply for the Community of Muir Beach, and is typically pumped from 6 pm to 6 am each night at a rate of 60 gpm (0.13 cfs). On a daily average basis the well draws about 0.07 cfs. Typical drawdowns of about 15 feet have been observed in the well during pumping (Hyde, 1991). Drawdown is defined here as the observed decrease in the elevation of the ground water table after pumping begins.

The Banducci Farm operates two irrigation wells, each located about 10 feet from Redwood Creek (Figure 6). Driller logs are not available for these wells, but they are presumed to tap the same mix of alluvium and weathered bedrock as the Muir Beach CSD well. Flow meters were installed on these wells in September, 1993 as part of this study; prior to this the wells were not metered.

The Banducci wells typically draw about 80 gpm (0.18 cfs) each when operating. The two wells are not usually pumped simultaneously, and operate for a total of about 25 hours per week (Banducci, personal communication). During dry periods each planted area requires about 11/2 hours of irrigation every few days, and an individual well may be pumped as long as 6 hours on peak irrigation days. In September, 1993 the two wells pumped a daily average flow of 0.034 cfs. In October daily average water usage dropped to 0.014 cfs as irrigation demand declined. In April and May, 1994 the daily average water usage was about 0.025 cfs.

B. ANALYSIS OF IMPACTS ON REDWOOD CREEK FLOWS

1. <u>Hydrologic Connection Between Wells and Redwood Creek</u>

The Muir Beach and Banducci wells all draw water from the alluvium that makes up the uppermost Franks Valley aquifer. This aquifer is unconfined, and is hydraulically connected to Redwood Creek. (Note that in an unconfined aquifer there are no significant geologic barriers to water infiltration from the surface, and the hydrostatic pressure of the water table is equal to atmospheric pressure.) Figure 7 is a cross-section of the creek at the upstream Banducci well, and shows that in the late summer/early fall of 1993 the creek and static groundwater table were at about the same level.

During pumping groundwater levels are drawn down near each well as the aquifer is dewatered. The radial extent of drawdown increases as the rate and period of pumping increase. As illustrated in Figure 8 the creek acts as a constant head boundary, where the water level is maintained at a relatively constant level during pumping by flows from upstream. The net result is that the hydraulic gradient is steepest between the creek and the well, and a higher proportion of pumped water is drawn from the creek than from the rest of the aquifer. This effect is especially evident when wells are located close to the creek, and after long periods of pumping.

Seismic refraction data collected by Harding-Lawson and Associates (1991) indicate that the Muir Beach CSD well was drilled into 20 feet of alluvium followed by about 17 feet of weathered bedrock. Of the screened section, five feet is in alluvium and 12 feet is in weathered bedrock. There is no indication of a confining layer separating the alluvium and bedrock, and these two formations are probably hydraulically connected as a single aquifer. Pumping from wells drilled into the upper weathered bedrock would therefore drawdown water levels in the alluvium and induce loss of streamflow. There is considerable uncertainty about the location of the boundary between the alluvium and bedrock; driller logs for the Muir Beach wells indicate that the alluvium extends below 37 feet depth. The differences between the seismic refraction data and driller logs could be due to both the inherent imprecision of these two measurements, as well as natural variations in the stratigraphy at different locations.

2. Groundwater Modeling

The impacts of pumping were evaluated using an analytical technique developed by Glover and Balmer (1954) and described by Todd (1959) to estimate the proportion of pumped water that is derived from a nearby stream. This model is based on the non-equilibrium Theis solution of the equations governing radial flow to a well. Applying the Theis solution to a well pumping near a stream, Glover and Balmer developed a nomograph relating the proportion of pumped water drawn from the stream to various aquifer and the distance of the well from the stream. This non-equilibrium solution assumes that the aquifer properties are homogenous and isotropic, and that drawdown is small compared to the saturated thickness of the aquifer. The stream is treated as a constant head boundary using the principle of superposition of the linear flow equation (i.e. image wells). The following aquifer properties were used:

Specific yield = 0.2
Transmissivity = 3000 gallons per day per foot (gpd/ft)

The specific yield was derived from estimated aquifer properties used by Harding-Lawson and Associates (1991). The original Harding-Lawson estimate of transmissivity (2000 gpd/ft) was adjusted to match the observed 15 foot drawdown in the Muir Beach well. This adjustment was made to correct for uncertainties in the estimated permeability and thickness of the aquifer material.

Figure 9 shows the rate at which streamflow is lost to pumping over the course of the 12 hour pumping period at the Muir Beach CSD well. By the end of the period the well draws about 0.09 cfs from the creek. On a daily average basis the well draws about draws about 0.04 cfs from the creek and 0.03 cfs from groundwater.

Figure 10 shows the results for one of the Banducci wells. After six hours an individual well draws about 0.14 cfs from the creek. Together the wells drew a daily average flow of 0.02 cfs from the creek and 0.01 cfs from groundwater during September 1993.

After the wells cease pumping there is a recovery period during which water levels are still low and the creek is losing water to replenish the groundwater table. Recovery of water levels was analyzed by applying the Theis model (Freeze and Cherry, 1979). The creek was treated as a constant head boundary, and drawdown was calculated as a function of time from the end of pumping. As shown in Figure 11, water levels in the *Muir* Beach CSD well are initially drawn down by about 15-16 feet at the well and by two feet near the creek. After about six hours water levels in the well recover within one foot of the static level, and drawdowns near the creek are negligible. Thus, there is sufficient time between pumping periods for the water table to fully recover.

3. Observed Effects of Pumping on Redwood Creek Flows

To verify the results of the groundwater analysis, flow measurements were taken at locations upstream and downstream of each pump during the late summer and early fall of 1993 and the spring of 1994 (Table 3). With the exception of the August 13,1993 value, all of the flow measurements shown in Table 3 were taken in the early morning, within one hour after the Muir Beach CSD wells had shut down, and therefore reflect the impacts of Muir Beach CSD pumping. Measurements were taken on six occasions when the Banducci pumps were operating and four occasions when they were not.

There are numerous difficulties in measuring flow differences on the order of 0.1 cfs, and for this reason the data shown in Table 3 are not always consistent with regard to the impacts of the pumps. During the dry season much of the creek flow is subsurface flow through the porous gravel beds, and flow measurements taken with current meters probably do not represent the entire creek flow. Current meters are also subject to other inaccuracies, especially in very shallow water, and measurement errors on the order of 0.1 cfs can easily occur even under the most controlled conditions.

With these caveats in mind, these data still provide insight into the impacts of the pumps. In the early spring when flows are greater than about 1 cfs the creek flow rate increases through Franks Valley. At these times groundwater levels are still elevated from the rainy season, and the surface aquifer is flowing into the creek. The effects of the pumps during these periods cannot easily be seen, although they may be reducing the amount of groundwater that would naturally flow into the creek.

When flows are less than about 1 cfs the creek begins to lose water as it moves through Franks Valley. During these periods the water table is lower than the creek bottom and the creek begins to drain into groundwater. To some extent this might occur naturally, especially in drought years. However, groundwater pumping causes water levels to drop sooner and more severely.

Flow measurements taken above and below the Banducci Farm generally show losses of 0.08 to 0.15 cfs, which compares well to the 0.13 cfs loss predicted by the analytical groundwater model. Flows decrease throughout the pumping/irrigation season (even between pumping events), indicating that pumping also has a significant impact on long-term groundwater storage.

While the analytical groundwater model predicts a loss of 0.09 cfs due to the Muir Beach CSD well, the flow measurements are less conclusive about the impacts of this well. On four occasions flow losses of 0.02 to 0.15 cfs were observed. On three other occasions when the pumps were operating no decrease in creek flows was measured below the Muir Beach CSD well. No losses were also observed on August 13, 1993, when flows were measured about four hours after the pumps had shut down.

C. IMPLICATIONS FOR AQUATIC HABITAT

The data indicate that the two wells reduce long-term average flows in the dry season by a combined 0.06 cfs. In an average or wet year the Muir Beach CSD well reduces monthly average flows hi the late dry season by about 30%. The Banducci wells reduce these flows by another 15%. In drought years these two wells can effectively remove all surface flow in the late summer/early fall.

The effect of pumping-related flow losses is to increase the frequency and duration of periods when the creek is dry below Franks Valley. Based on the flow-duration curve derived from flow data on Arroyo Corte Madera (Figure 5), Redwood Creek would naturally have dry periods lasting seven or more days once every four years. The estimated losses due to well pumping would increase the frequency of this to once every two years. In the monitored drought year of 1992 the creek would probably have gone dry even without pumping, but this would have occurred later in the dry season.

The relative impacts of water losses from the creek are seasonal. From December through May flows in the creek are generally well above 1.0 cfs, and the short-term loss of 0.14 to 0.23 cfs during pumping is not critical. In the early summer "natural" flows generally range from 0.5 to 0.75 cfs; in this case the loss of flow by pumping has little effect on the number of steelhead, but does inhibit fish growth by reducing the availability of food and habitat for juveniles (Smith, 1994). In the late summer/early fall upstream flows drop to between 0.1 (drought years) and 0.2 cfs (wet to average year), and the impacts of the wells becomes critical to fish survivability as well as growth. Short-term losses of 0.14 (Banducci alone) to 0.23 cfs (Banducci and Muir Beach combined) at these times are sufficient to dry up shallow run and riffle habitats; this can reduce fish populations in the stream by as much as 80 percent (Smith, 1994). Even drying up the creek for a short period has serious impacts on both the fish populations using the shallow habitats and on the insect populations that provide essential food for fish in the deeper pools. The primary impacts of reduced monthly average flow rates are (1) smaller pool size; and (2) less new water in pools for oxygenation. This results in less dissolved oxygen for aquatic organisms living in pools. Low dissolved oxygen is the key factor limiting juvenile fish survival in the pools near Muir Beach.

D. RECOMMENDATIONS

The following alternative water withdrawal strategies could reduce the impacts of pumping on Redwood Creek flows. These recommendations do not consider state laws or regulations concerning water rights, or Federal law, regulations, and policy concerning use of Federal lands and waters within units of the National Park System. These, as well as other laws, regulations, and policy, could affect the viability of the alternatives.

1. Alternative Water Sources

If Muir Beach were to purchase water from the Marin Municipal Water District and discontinue pumping, flows in Redwood Creek would increase by about 0.09 cfs during the night. Monthly average flows in the creek would increase by 0.04 cfs. If Banducci purchases water from the MMWD or another source, downstream flows would increase by as much as 0.14 cfs (as compared to current flows during peak pumping). Monthly average flows would increase by 0.02 cfs.

2. Water Conservation

The amount of water drawn from the creek is a direct linear function of the volume pumped from the well, meaning a 50 percent reduction in pumping would result in 50 percent less water drawn from the creek.

3. Increase Distance of Wells from Creek

The impact of a well on streamflows decreases with distance from the creek. One alternative would therefore be to redrill the Banducci and Muir Beach wells further from the creek. Figure 12 shows how the Glover-Balmer model predicts the peak amount of water drawn from the creek decreases with distance. If both wells were moved 100 feet from the creek the model predicts that pumping would have virtually no impact on streamflows.

The model is a simplified representation of the true groundwater flow field in the area, and the model predictions should be verified by pump tests before installing new wells. In particular, the true extent and characteristics of the Franks Valley aquifer are unknown. It is likely that the alluvium aquifer is thickest near the creek, and wells located further from the creek will be less productive. If this alternative is pursued further a field program with test wells should be undertaken to refine the conclusions presented here and confirm the predictions of the analytical model.

4. Shorten the Length of Pumping Periods

The amount of water drawn from the creek increases with duration of continuous pumping. Rather than operating the Banducci wells for six continuous hours, the wells could be pumped for no more than two hours at a time (allowing at least six hours between pumping periods for recovery of groundwater levels). Even if current total pumping volumes remain the same, this would increase creek flows during pumping by about 0.04 cfs, and increase daily average flows downstream by 0.01 cfs.

Because of the limited available storage facilities and constant demand, there is little potential for modifying the period of pumping for the Muir Beach Wells. Increasing reservoir storage could provide more flexibility for different management strategies.

5. <u>Time Pumping to Minimize Cumulative Impacts of Banducci and Muir Beach Wells</u>

The maximum impact on creek flows occurs when the Banducci wells operate in the early morning when the creek flows are affected by Muir Beach pumping. The Banducci wells should operate no earlier than six hours after the Muir Beach wells stop pumping to allow recovery of the creek pre-pumping levels. This would reduce the maximum short-term flow loss from 0.23 to 0.14 cfs, but would mean that Banducci could not begin pumping until 12 pm

V. WATER QUALITY

A. OBSERVED WATER QUALITY PROBLEMS IN LOWER REDWOOD CREEK

A key finding of the Big Lagoon Preliminary Environmental Assessment was that dissolved oxygen levels hi the deep pools near Muir Beach fell well below 5 mg/l hi the late summer. As a result, most of the juvenile fish in these pools died between August and October, 1992. Wind-induced circulation helped maintain adequate dissolved oxygen levels hi the tidal lagoon, but low dissolved oxygen levels occurred on still days.

The low dissolved oxygen levels in the pools and lagoon are believed to be related to poor circulation (due to low flows) and nutrient pollution from various upstream land uses. Excessive nutrients (nitrogen, phosphorus) can increase algal growth, which hi turn consumes oxygen in the water column.

Previous sampling (1986-1988) by the U.S. Geological Survey found fecal coliform levels that exceeded State and EPA standards for drinking water and contact recreation in Redwood Creek at Pacific Way. Coliform bacteria are commonly used to identify the presence of fecal pollution (human or animal) in water. High coliform counts indicate the potential presence of pathogenic organisms as well as increased biological oxygen demand (BOD).

B. POLLUTANT SOURCES

Pollutant sources in the watershed include agricultural operations, horse stables and pastures, and domestic Wastewater leach fields. Nutrients in water commonly originate from fertilizers used in agricultural operations. After fertilizers are applied to the soil, they can be washed off into streams during storms and discharged during dry weather in excess irrigation water. Agricultural sources in the Redwood Creek watershed include the Banducci Farm and the Green Gulch Farm.

The Banducci flower fields on the Franks Valley floodplain drain away from Redwood Creek into a vegetated and unlined drainage ditch that discharges to the creek just upstream of the Highway 1 bridge. Banducci uses primarily organic fertilizers in the form of pellets that are buried around the roots during planting. They are not using manure at this time, and do not apply fertilizer through irrigation water. The fields would probably only contribute nutrients to the creek during storms when sediment and any exposed fertilizer would be washed off of the fields into the field drainage ditch.

The Banducci heather fields consist of relatively mature and naturalized shrubs planted on the slopes rising from the Franks Valley floor. These fields drain downslope and cross the dirt road before entering the ditch that serves the lower flower fields. Once established the heather requires little maintenance, and is interspersed among the natural vegetation. The shrubs are irrigated but are generally not fertilized, and the heather fields probably do not contribute nutrient loadings above background levels. Other hillside areas are planted with bulbs and annuals, and are presumably fertilized in the same manner as are the floodplain fields.

The Green Gulch Farm also uses only organic fertilizers, including various seaweed products, compost produced on-site, and horse manure from the Tinker stables. Runoff, sediment, and pollutants from these fields flow overland to Green Gulch Creek, which discharges into seasonal wetlands in lower Green Gulch before entering Redwood Creek upstream of the Muir Beach parking lot. Flow from these fields passes through several vegetated windbreaks which probably provide some pollutant and sediment prior to discharge to Green Gulch Creek.

Manure from the Tinker stables and pasturing operations contribute both coliform and nitrogen to the creek. The stables and paddocks drain into a deep ditch that crosses Highway 1 through a culvert before entering a series of drainage ditches that eventually flow into Green Gulch Creek near the Redwood Creek levee. During the summer several horses are pastured in lower Green Gulch adjacent to the Redwood Creek levee. In the winter this area frequently ponds, and horses are moved to hillside pastures located between Green Gulch Creek and Highway 1.

There are several other sources of coliform and nitrogen pollution along Redwood Creek upstream of Pacific Way. A number of houses discharge domestic Wastewater to septic leach fields on the creek floodplain between Highway 1 and Pacific Way. There are trails along the creek that are used by horses, and a small riding ring is located hi Franks Valley above Banducci's farm. It is also possible that workers from Banducci's fields occasionally use the Redwood Creek corridor for elimination of human waste.

C. SUMMARY OF MEASURED WATER QUALITY DATA

As summarized in Table 4, water quality data from several previous studies are available for locations along Redwood Creek and Green Gulch Creek. Most of these studies focused on pollutants that would be anticipated from stables and agricultural activities, such as nitrates and nitrites, fecal coliform, and phosphorus. The USGS sampled water quality twice per year from 1986 through 1988 at several locations in the Redwood Creek watershed. Harding-Lawson and Associates collected samples from November through March, 1991 near the Muir Beach Community Services District Wells (Harding-Lawson and Associates, 1991).

To evaluate the relative impacts of the various pollutant sources, PWA sampled water quality in Redwood Creek and Green Gulch Creek once in dry weather on August 31,1993 and twice during a storm on December 13-14,1993. Grab samples were collected from Redwood Creek upstream and downstream of Banducci's farm, at Pacific Way, and hi the backwater channel above the Muir Beach parking lot. Samples were also taken from Green Gulch Creek above and below the lower pasture, and from the drainage ditch that flows past Tinker's Stables. Sample locations are shown on Figure 13, and measured concentrations are summarized in Table 4.

Prior to 1989, Muir Woods treated Wastewater in a septic leach field. This system was discontinued in 1989 because of observed water quality problems. Because the USGS data collected in Redwood Creek prior to 1989 could include the effects of the Muir Woods leach field, these data can not be used to identify water quality impacts under present conditions.

1. Water Quality Objectives

Water quality objectives for different types of beneficial uses have been developed for the San Francisco Bay basin by the San Francisco Bay Regional Water Quality Control Board (1990). Fecal coliform levels should be less than 200 #/100ml for water contact and 20 #/100ml for drinking water. Nitrate and nitrite concentrations should be less than 10 mg/l as N for drinking water. There are no specific water quality objectives for aquatic life that apply to nutrients, such as nitrogen and phosphorus, since these parameters generally do not have direct toxic effects. The relative impacts of high nutrient concentrations on aquatic life must generally be linked on a case-by-case basis to observed water quality and dissolved oxygen problems.

2. Wet-Weather Water Quality

Table 5 shows mean wet-weather concentrations of fecal coliform, nitrate and nitrite, and total phosphorus in Redwood Creek for post-1989 data. Both nitrogen and phosphorus increase between Muir Woods and Highway 1, indicating that runoff from the Banducci Farm is a significant source of these nutrients. Nitrogen levels are highest in lower Redwood Creek near Muir Beach, indicating input from either the Tinker stables or Green Gulch Farm. Phosphorus concentrations remain relatively constant between Banducci and lower Redwood Creek.

Wet-weather coliform counts are generally below 500 #/100ml upstream of Banducci, but increase to over 2400 #/100 ml below Banducci. Coliform counts remain high downstream to lower Redwood Creek. This indicates that there is a high source of coliform bacteria on or near the Banducci Farm.

Wet-weather nutrient levels are highest in Redwood Creek near Muir Beach. Runoff from the Banducci floodplain fields (covering about 29 acres) contributes to this, but the largest source appears to be the horse operations in Green Gulch (with hillside pastures, lowland pastures, and stables covering up to 200 acres). To identify the relative contributions from the horse operations, the USGS and PWA sampled from various drainage ditches in Green Gulch (Table 4). Samples from the drainage ditch from Tinker's Stables and Green Gulch Creek showed high levels of nitrogen (1.3 to 1.6 mg/l), phosphorus (0.15 to 4.8 mg/l), and coliform (>2400 #/100ml).

3. Drv-Weather Water Quality

Table 5 also summarizes mean dry-weather concentrations of fecal coliform, nitrate and nitrite, and total phosphorus at locations along Redwood Creek for post-1989 data. For the most part dry-weather concentrations of nitrogen and phosphorus are low at all sample locations, with the exception of one phosphorus concentration of 0.095 mg/l below Banducci Farm (from August 31, 1993). These results indicate that summer flows are derived primarily from groundwater that is low in nitrogen and phosphorus.

Dry-weather fecal coliform counts are below 50 #/100ml upstream of Banducci. These increase to about 300 #/100ml below Banducci and 1900 #/100ml at Pacific Way, which are well above standards for water contact recreation. There was no surface runoff from areas used by horses during this period, and this increase is probably due to leakage from domestic septic leach fields on the creek floodplain between Pacific Way and Highway 1.

D. RECOMMENDATIONS

1. Banducci Farm

Measures to reduce the water quality and sediment erosion impacts of the Banducci Farm should focus on both source control and treatment of discharged water. Banducci's fertilizing practices should be reviewed to ensure that the amount of fertilizer that washes off the soil surface is limited; White and Plate (date unknown) provide a summary of Best Management Practices for fertilizer use. These include avoiding excessive fertilizer applications, timing applications to maximize nutrient uptake by plants, incorporating fertilizers into the soil (rather than surface application through irrigation water), and applying nitrogen in forms that limit mobility. Surface applications of manure should be avoided. Our field observations indicate that Banducci currently uses most of these recommended practices.

The amount of sediment produced by the fields can be reduced by maintaining a continuous planting of cover crops when fields are fallow. This is currently done to a degree, but we did observe periods in the winter when sections of the field were barren.

High coliform levels near the farm could be due to horse use of streamside trails and nearby riding rings, but may also be related to use of the riparian corridor as a restroom by field workers. On-site sanitation should also be reviewed to ensure that there are adequate restroom facilities and education of field workers.

The fields currently drain away from the creek to an unlined ditch; this provides an opportunity to control and treat field runoff. The ditch should be reconfigured as a water quality swale to remove sediment, particulate pollutants, and some dissolved pollutants. This would require widening the ditch and planting it with irrigated perennial grass (Figure 14). Well-designed swales can provide 60 to 80 percent removal of suspended particles from agricultural runoff, but are less effective at removing nutrients (EPA, 1987). Nutrient removal can be enhanced by routing field runoff through a 20 to 50 foot grassed buffer strip before discharge into the swale; this could provide 60 to 80 percent removal of nitrates and phosphates (EPA, 1987, Thompson *et al.,* date unknown).

The fields currently are plowed right up to the edge of the Redwood Creek bank. To provide both a habitat and water quality buffer, fields should be set back by at least 50 feet from the top of the creek bank. This buffer zone can be planted with native riparian vegetation, and a low berm (about 0.5 feet high) could be constructed to ensure no direct drainage of runoff from the fields into the creek.

2. <u>Tinker's Horse Stables</u>

The water quality data show that horse operations are significant sources of coliform and nitrogen pollution hi lower Redwood Creek and adjacent wetlands. The following are recommendations for reducing pollutant loads from these areas:

- Horse should be removed from the seasonal wetlands in the lower Green Gulch pastures. Pasturing of horses in these areas results in direct loading of coliform and nutrients into vulnerable shallow wetlands. Pollutants from these areas eventually flow into ponded areas hi lower Redwood Creek, resulting hi summer algal blooms and low dissolved oxygen.

- Ideally, horses should not be pastured on steep hillslopes. If horses remain hi these areas, a buffer zone consisting of a biofilter strip and native vegetation should be provided to separate the hillside pasture in Green Gulch from Green Gulch Creek. As shown in Figure 15, this buffer zone should include about 20 to 50 feet of irrigated turf grass to provide filtration and pollutant removal, followed by about 50 feet of riparian vegetation.

- Manure should be removed frequently from stables, paddocks, and riding facilities. This is especially important during and just prior to the rainy season. The most effective strategy would be to remove manure prior to each forecasted storm event.

- Runoff and sediment erosion from all stables, paddocks, and riding facilities should be controlled. Intensively-used areas should be bermed-off to control and direct runoff. Drainage should be collected into vegetated swales (Figure 14) or passed through a grass buffer strip (Figure 15) and conveyed to a sediment trap/retention basin before discharging to wetlands and riparian resources. About 67 cubic yards of sediment storage should be provided per acre of disturbed area (CDM, 1993).

3. <u>Domestic Leach Fields</u>

The water quality data show that domestic septic systems on the Redwood Creek floodplain may be the primary source of coliform in the creek during the summer. Creek coliform levels at this time exceed standards for contact recreation, and could potentially cause health problems among waders and bathers in the lower creek pools. These septic systems should be inspected and repaired.

4. Green Gulch Farm

The fertilizing methods used by the Green Gulch Farm are generally acceptable for limiting nutrient pollution. Horse manure from Tinker's Stable should not be used unless it is thoroughly cured and incorporated into the soil. Other organic fertilizers (slow-release granules, etc.) are preferred.

Most of the Green Gulch fields drain away from the creek, and runoff is detained and treated to some degree by the vegetated windbreaks. Pollutant loads could be further reduced by draining the fields into swales and filter strips located at each windbreak before discharging to Green Gulch Creek and the lower pasture wetlands.

Green Gulch Creek has been extensively channelized, and is currently eroding and downcutting. Restoration of this channel would involve excavation of a stable and more natural channel, providing grade control structures to reduce downcutting, removal of exotic vegetation, and establishing a 50 foot riparian buffer adjacent to each bank. Such a restoration effort would reduce sediment loads to the pasture wetlands, and would improve riparian habitat.

VI. SEDIMENT EROSION

Various land uses within the Redwood Creek watershed have the potential to increase sediment loads to Redwood Creek. In this section the sediment loads from each land use are quantified and compared to the total sediment yield for the Redwood Creek watershed.

A. SEDIMENT EROSION PROCESSES

The dominant hillslope erosion processes in a basin are influenced by the climate, vegetation, geology, and land use history. Hillslope erosion processes in Redwood Creek and Green Gulch basins include land slides and soil slips, gullies originating at culvert outfalls below the highway, soil creep, and sheet erosion, particularly on hillslope pastures where vegetation is denuded. Channel bank erosion in Green Gulch Creek and Redwood Creek also contributes sediment downstream to the site of the proposed Big Lagoon restoration. During most years (with relatively low rainfall), not all of the sediment eroded from hillslopes is contributed to the stream channel, rather, sediment mobilized goes into storage on the lower parts of slopes, or in channel and gully beds and banks. Lehre (1982) studied Lone Tree basin adjacent to Redwood Creek for the period between 1971 and 1974. Lehre estimated that 53 percent of the sediment mobilized on hillslopes reached the channel and that most of the removal of sediment from storage takes place during storms with recurrence intervals greater than 10 to 15 years (Lehre, 1982).

A general description of the important erosional processes in GGNRA is provided in Wahrhaftig (1974). The controlling factors and relative importance for each of these processes are discussed below.

1. Landslides

A common type of landslide in the Marin Headlands involves shallow slides called soil slips (Ellen, *et al.,* 1988). Typical soil slips triggered by the 1982 storm in the San Francisco Bay Region originated on steep slopes (26 to 40 degrees) and left scars 1 to 3 meters deep and 5 to 15 meters wide. Soil from these scars was mobilized as debris flows and contributed sediment to the creeks at the base of the slopes (Ellen, *et al.,* 1988). These soil slips occurred following the intense rainfall in 1982 in locations where water was concentrated, commonly in swales or colluvial hollows. Lehre (1982) suggests that colluvial deposits in hollows were the primary source of landslides in Lone Tree basin. Remnant scars from soil slips originating in the 1982 storm are apparent in the Redwood Creek basin above the Banducci Farm. One fresh scarp, probably from the winter of 1993, is apparent in the Green Gulch basin.

In addition to soil slips, landslides may also occur as debris slides. These are particularly common in fill material downslope of fire roads.

2. Gullies

Gullies form on slopes due to a concentration of runoff. Gullies cut headword and transport sediment toward the creek at the bottom of the valleys. Gullies often form at culvert outfalls in the erodible fill material below Highways. Some gullies are present on hillslopes in swales and are unrelated to roads. These gullies may be associated with prior land use including grazing which causes soil compaction and concentration of runoff. Wahrhaftig (1974) notes that gullying has accelerated where tracks and trails go directly upslope, at culvert outfalls, and where roads and trails have inadequate water-breaks.

3. Soil Creep

Creep is a slow and continuous mass movement process where hillslope soil and colluvium move downslope under the force of gravity. Soil creep can also result from expansion and contraction due to freezing and thawing, wetting and drying, or as a result of biotic processes such as animal burrows and tree falls. Landscapes affected by creep have rounded ridge crests and broadly convex slopes. Since these landforms are common in GGNRA, creep is assumed to play a major role in transporting sediment downslope to the creeks (Wahrhaftig, 1974).

4. Sheet Erosion

Sheet erosion is effective in contributing sediment downslope on unvegetated slopes. Vegetative cover reduces sheet erosion by: 1) insulating soil from the direct effects of running water and rainfall impact; 2) increasing soil strength from root binding; 3) reducing overland flow by promoting porous soil structure; and by 4) reducing overland flow velocity and therefore the capacity of the flow to entrain and transport soil particles (Statham, 1977). Sheet erosion is also dependent on the magnitude and intensity of rainfall.

Different kinds of vegetation have been shown to affect rates of transport by sheet erosion. Ellison (1945) found that a cover of organic litter such as crop residue could be significantly reduce soil loss in run-off. Different crops were also shown to have varying effects on overland flow velocity and rate of erosion, with grass cover reducing erosion more significantly than wheat, which was in turn better than corn. Rates of sheet erosion are increased by several orders of magnitude in tilled and cropped areas (Statham, 1977). The presence of a cover crop during the rainy season significantly reduces the potential for erosion.

5. Bank Erosion

Channel bank erosion occurs in incised streams when flow undercuts the toe of the bank during storms, causing failure. Erosion is a natural processes which occurs as flow exerts a force on the bed and the banks of the channel. The process of erosion may be accelerated by land use activities which increase runoff and peak flow or which remove riparian vegetation. Episodic channel widening in response to incision is the way a creek adjusts toward a new stable condition. It is likely that the creeks will continue episodic bank failure until a new equilibrium is attained.

B. LAND-USE RELATED SEDIMENT SOURCES IN THE REDWOOD CREEK BASIN

Land use practices in the Redwood Creek and Green Gulch basins include floodplain and hillside agriculture, floodplain and hillslope pasture, residential development, and recreational use. A map of the dominant land use activities in Redwood Creek and Green Gulch basins is shown in Figure 16.

1. Banducci Flower Farm

The Banducci Farm in Redwood Creek Basin includes 29 acres of farmed floodplain and hillslopes. Currently, the farmed area is sloped very gently toward the west, away from Redwood Creek (Banducci, 1994; personal communication). Top soil eroded from the farmed area by sheet erosion would be carried toward the swale which drains the floodplain field as well as the hillslope. The swale trends toward the southeast and enters Redwood Creek upstream of the Highway 1 Bridge. Sediment contributed from the farmed areas would be deposited in the swale or carried to Redwood Creek. No bare areas were observed on the hillslopes planted with heather. Bare areas between rows of flowers on the hillslopes would probably be retained on the hillslope below.

Bank erosion is common along some portions of Redwood Creek adjacent to Banducci Farm. Bank erosion may in part be caused by channel incision due to prior land use practices such as grazing which compacted soil and increased overland flow and peak stream discharges over the past century. Historical levee construction and modification of the channel also contributes to channel instability and bank erosion.

2. Hillslope Pastures

Horses are pastured on up to 188 acres of hillslope land above Tinker's Stable and on land lying between Green Gulch Creek and Highway 1. Grazing has reduced vegetative cover over most of this area, but the most intense erosion occurs at the base of the hillslopes where horses congregate (especially near feeding areas and gates). At these locations the hillslopes are denuded, allowing sheet erosion and gullying to occur. Extensive gullying can be seen on the north-facing slope behind the stables, where gullies over two feet deep have formed. This sediment is washed off and deposited into the low-gradient drainage ditch running along Highway 1 into the lower Green Gulch pasture.

3. Lowland Pastures

A horse riding ring on the gently sloped area just upstream of the confluence of Green Gulch and Redwood Creeks is bare, however, a small berm appears to prevent sediment from being transported off the site. An open pasture between the horse riding ring and the proposed restoration site has some small bare areas which may be subject to sheet erosion. Another horse riding ring is present upstream of the Banducci Farm in Redwood Basin.

4. Green Gulch Farm

The Green Gulch Farm includes 22 acres of farmed floodplain. In some of the fields at Green Gulch Farm, drainage appears to be toward the creek while in others, runoff is directed toward a berm at the lower end of the field which appears to prevent drainage. Soil eroded from fields not planted with cover crops would be transported west toward the area of the proposed lagoon restoration or north to Green Gulch Creek in locations where levees are not continuous. The hillslope horse pasture on the northwest slope above Green Gulch Creek has some areas where vegetation is denuded, and sheet erosion can occur. Hillslopes on the southeast side of Green Gulch Creek are vegetated with chaparral, and small reservoirs trap sediment from several of the small tributary basins before it can enter Green Gulch Creek.

A debris slide in road fill material downslope of the fire road in Green Gulch basin originated during the winter of 1993. Several gullies are present in the hillslopes of Green Gulch Creek, the majority of which are related to culvert outfalls below the highway. Channel bank erosion is prevalent in Green Gulch Creek. Channel banks are vertical and flow undercuts the toe of the slope during storms, causing bank failure.

C. TOTAL SEDIMENT YIELD FROM REDWOOD CREEK BASIN

Methods to estimate watershed sediment yield range from detailed field investigations to regionalized methods. In this study, we compare the results of a widely used regional method to the results of sediment yield estimates from intensive field investigations of sediment erosion and deposition processes and rates conducted in the Lone Tree Basin adjacent to Redwood Creek (Lehre, 1982; Reneau, 1988; Reneau, *et al*, 1990; and Wilson, *etal.*, 1989).

1. Estimates of Sediment Yield in Nearby Basins

Sediment yield from the Lone Tree Creek basin and other nearby basins are probably similar to the sediment mobilization and the sediment reaching the channel for both Redwood Creek and Green Gulch Creek. These areas all have a Mediterranean climate, are underlain by the Franciscan Assemblage, and are vegetated by a mix of grass, brush, and forest.

Lehre (1982) estimates that the long term average sediment yield in Lone Tree basin is 135 tons/square mile/year. Reneau (1988) developed sediment yield estimates ranging between 50 and 72 tons/square mile/year for two locations in the Lone Tree basin. Reneau also estimated sediment yield from the San Pedro Ridge east of Redwood Creek basin as 10 to 80 tons/square mile/year.

2. Pacific Southwest Inter-Agency Committee (PSIAC) Method

The PSIAC method is a regional method that may be used to estimate sediment yields in the Pacific Southwest. The method gives a broad estimate of sediment yield and is intended for planning purposes, rather than detailed studies. The method is most accurate for basins greater than 10 square miles, however, it is used for the Redwood Creek and Green Gulch basins (drainage area approximately 9 square miles) to provide a general estimate of sediment yield to compare to field studies in nearby watersheds.

The PSIAC uses factors representing geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, channel erosion, and sediment transport to estimate sediment yield. Factors used for Redwood Creek are summarized below:

FACTORS	DESCRIPTION OF SEDIMENT YIELD LEVEL
surface geology (5)	rocks of medium hardness; moderately weathered and fractured
soils (5)	medium textured soil
climate (5)	storms of moderate duration and intensity
runoff (5)	moderate peak flows, moderate volume of flow per unit area
topography (20)	steep upland slopes (>30 percent), high relief; little floodplain development
ground cover (-10)	area completely protected by vegetation, rock fragments, litter. Little opportunity for rainfall to reach erodible material
land use (0)	less than 25 percent cultivated; less than 50 percent intensively grazed; ordinary road and other construction
upland erosion (0)	no apparent signs of erosion
channel erosion (10)	moderate flow depths, medium flow duration with occasionally eroding banks or bed

Using the PSIAC method, the total rating for Redwood Creek is 40 which corresponds to a sediment yield estimate of about 390 to 980 tons/square mile/year. This is a very generalized estimate which can be used for planning purposed only, and is not suitable for identifying the localized impacts of different land-use practices. The PSIAC method give estimates within the same order of magnitude as Lehre's (1982) estimate for Lone Tree basin but an order of magnitude higher than Reneau's (1988) estimates for Lone Tree basin and San Pedro Ridge. The site specific studies are probably more accurate than the regional PSIAC method.

3. Sedimentation of the Historical Big Lagoon Wetland

An estimate of basin sediment yield was developed as part of the restoration studies of Big Lagoon using sediment corings and historical maps to identify the quantity of sediment deposited in wetlands at the mouth of Redwood Creek between 1851 and the present (Philip Williams & Associates *et al*, 1994). Results of this study suggest that the historical sediment yield that led to the filling of the lagoon was about 270 tons/square mile/year. This historical value represents the period when grazing occurred in the watershed.

4. Summary of Sediment Yield Estimates for Redwood Creek Basin

Table 6 summarizes the results of the three methods discussed to estimate sediment yield from Redwood Creek Basin. The estimates range from as low as 10 to as high as 980 tons/square mile/year. The values derived from the Lone Tree basin studies are probably the most representative, and indicate a sediment yield on the order of 150 tons/square mile/year. This translates to a total annual yield of about 2700 tons per year.

D. ESTIMATED SEDIMENT LOAD FROM DISTURBED LAND

While there are no reliable methods for estimating land-use specific sediment yield from hillsides, Soil Conservation Service methods can be used to estimate the relative increase in sediment yield from areas with shallow slopes, such as the Banducci fields, the Green Gulch Farm, and the lowland pastures. The Universal Soil Loss Equation (USLE) is a predictive equation which estimates the soil loss by sheet and rill erosion in relatively flat lying areas where field data are not available (Wischmeier and Smith, 1979). The USLE is most appropriate for areas of less than a few square miles, and estimates yield as a product of the following factors:

$$A=RKLSCP$$

where A is the soil loss (in tons/acre/year)
R is the rainfall erositivity index K is the soil credibility index L is the hillslope-length factor S is the hillslope gradient factor C is the cropping management factor P is the erosion control practice factor

Many of these factors are subjectively estimated based on experience in the area; the values used in this study were derived from conversations with the local Soil Conservation Service office (Charlotte

Epifanio, 1994; personal communication). Table 7 summarizes the values used. The *R* factor is based on data from a contour map in Wischmeier and Smith (1979). The *K* factor, from the Marin County Soil Survey (SCS, 1985) is based on the assumption that soils in the floodplains are similar to the Blucher Cole Complex (105). The *LS* factor is particularly difficult to estimate because the topographic map available for this study is at a scale of 1:24,000. Of all these factors, the cropping management factor *C* is most sensitive to changes in land-use, and includes the effect of vegetative cover, the sequence of crops in rotation, the stage of the crop, tillage practices and residue management. In Frank Valley and hi Green Gulch while crops are growing, a representative *C* factor of 0.26 was used. The C factor may increase to 0.36 when the field is fallow. The C factor for a fully vegetated natural floodplain with riparian vegetation could be as low as 0.001.

The *P* factor varies with such techniques as contour cultivation, strip cropping, and terracing. *P* values recommended by the SCS (Charlotte Epifanio, 1994; personal communication) are 1.0 for rangeland and 0.8 for cropland.

Estimated erosion rates for the various land uses hi the basin using the USLE are shown in Table 8. The table provides estimates of sediment yield under both current and hypothetical undisturbed conditions. Although the total sediment yield from the floodplain agricultural activities is higher than the yield that would have occurred under natural conditions, it is still a relatively small fraction of the total basin yield (primarily because of the low slopes on the floodplains).

Suspended Sediment Samples

Suspended sediment concentrations were measured by Madej (1989) for streams in GGNRA. Madej found that suspended sediment concentrations in GGNRA streams is relatively low (4 to 162 mg/l), but suggested that measurements be taken during the highest flow discharges. One set of measurements sampled by PWA on December 14, 1993 indicates a yield of 120 mg/l above the Banducci Farm and 250 mg/l below the farm and 990 mg/l from the channel draining Tinker's Stable. Lower Green Gulch Creek had a sediment yield of only 20 mg/l. Although these samples represent only one storm, they suggest that agricultural activities at the Banducci Farm and the horse stable contribute sediment to Redwood Creek which raises the suspended sediment yield above that expected for streams in GGNRA.

E. RECOMMENDATIONS

The majority of the sediment from the Redwood Creek watershed is derived from the steep hillsides. Of the identified land-use related sediment sources, the hillside horse pastures (covering up to 188 acres) contribute the largest sediment load. This sediment is currently trapped in the low-gradient ditches and seasonal wetlands lying between Highway 1 and the Redwood Creek levee. If the Big Lagoon enhancement plan is implemented, this sediment would discharge directly into the restored freshwater wetlands and lagoon.

Sediment loads from the Banducci floodplain fields (29 acres), Green Gulch fields (22 acres), and lowland horse pastures (21 acres) are much smaller due to the low slopes in these areas. Sediment loads from these land uses are significantly higher than they would be under natural conditions, but are still small relative to the total sediment load from the Redwood Creek watershed.

The following recommendations for reducing sediment yield from disturbed land in the watershed include strategies that will minimize sediment erosion at the sources and monitor techniques to retain sediment before it enters stream channels to reduce sediment yield over time. These sediment control measures are similar to measures recommended in Section V, and also provide water quality improvement.

1. <u>Banducci Farm</u>

Continue to plant cover crops to prevent sheet erosion of bare soil during the rainy season.

Construct a continuous low berm maintained parallel to the creek at the top of bank to prevent any sheet erosion from directly entering Redwood Creek in locations where the field may be sloped toward the creek.

Provide a vegetated riparian buffer between agricultural activities and the creek.

Improve drainage flowing on the west side of Banducci Farm so that any fine grain sediment settles out before it reaches Redwood Creek. This can done by reconfiguring the ditch as a broad vegetated swale, as recommended in Section V. Vegetated buffer strips will further remove sediment from runoff by providing filtration.

2. <u>Horse Stable Operations</u>

Ideally, horses should not be pastured on the steep hillslopes and alternative sites should be identified. If horses do remain on these sites, they should be kept off bare hillslopes until vegetation is reestablished. Feeding areas and gates should be designed to minimize congregation of horses at the base of the slopes. Sediment erosion should be monitored after revegetation to determine if the number of horses per pasture areas should be reduced.

Provide a vegetated buffer between the hillslope pasture and Green Gulch Creek, as recommended in Section V.

Revegetate pastures on low gradient land, and construct a low berm to pond drainage to ensure that sediment eroded by sheet wash does not enter nearby wetlands and riparian areas.

3. Green Gulch Farm

Continue planting cover crops to prevent sheet erosion of bare soil during the rainy season.

Direct drainage away from Green Gulch Creek toward the lower portion of each field. The dividers between each field should be modified so that agricultural runoff is ponded and fine grained sediment has a chance to settle out. Maintenance should occur on an as needed basis to ensure that runoff from the fields does not enter Green Gulch Creek without some pre-treatment.

Provide riparian vegetation buffer between dirt roads and Green Gulch Creek to help filter out fine grain sediment before it reaches the creek.

Restore Green Gulch Creek to minimize bed and bank erosion and improve habitat.

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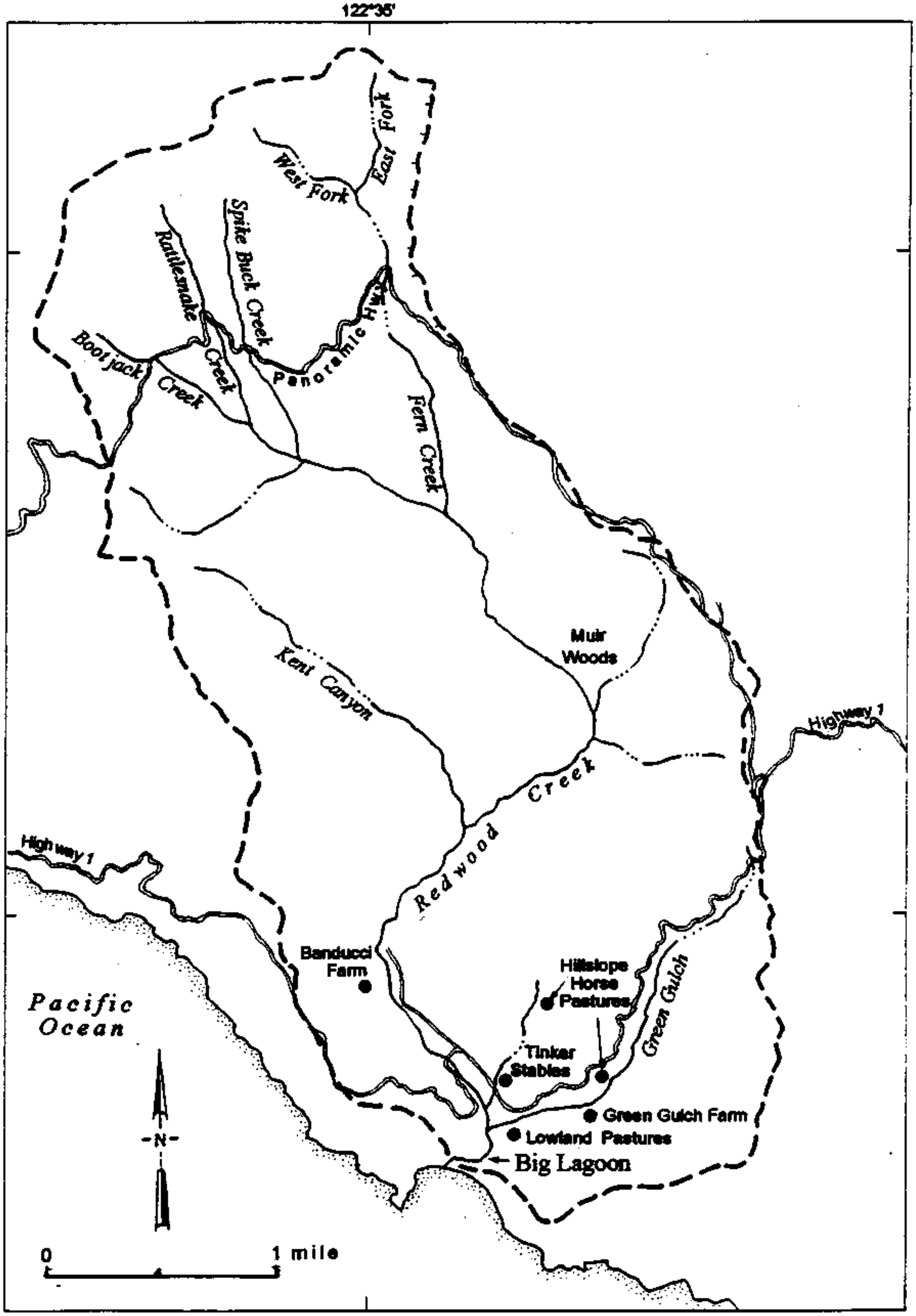
FIGURES



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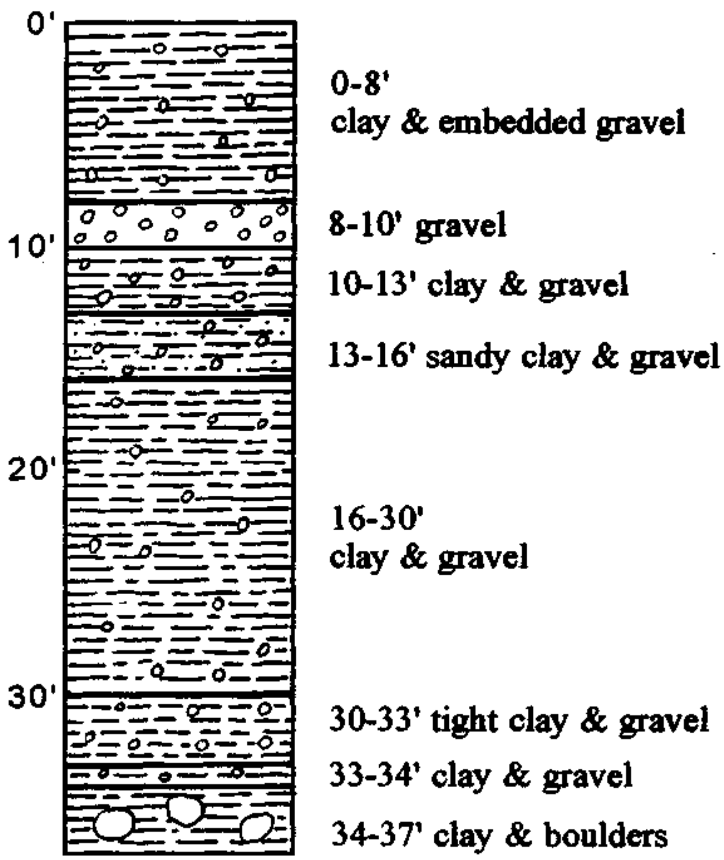
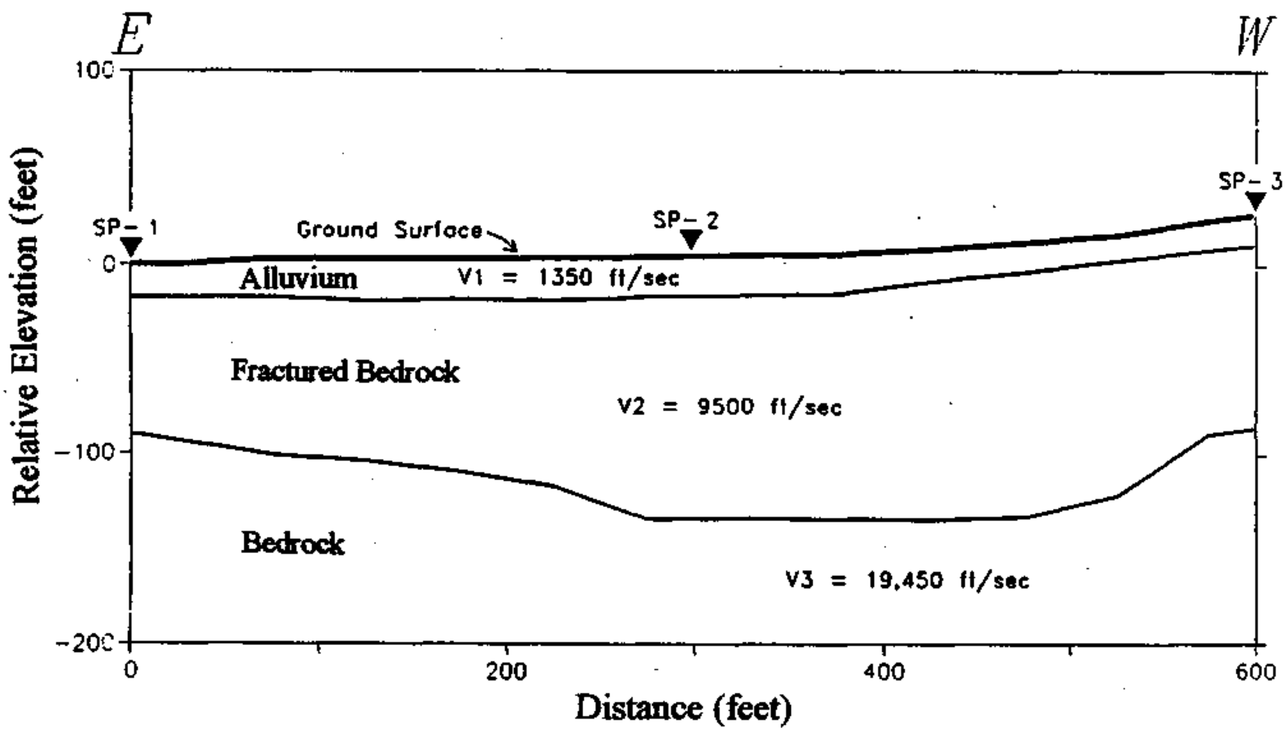
Redwood Creek
Watershed Map

Figure
1



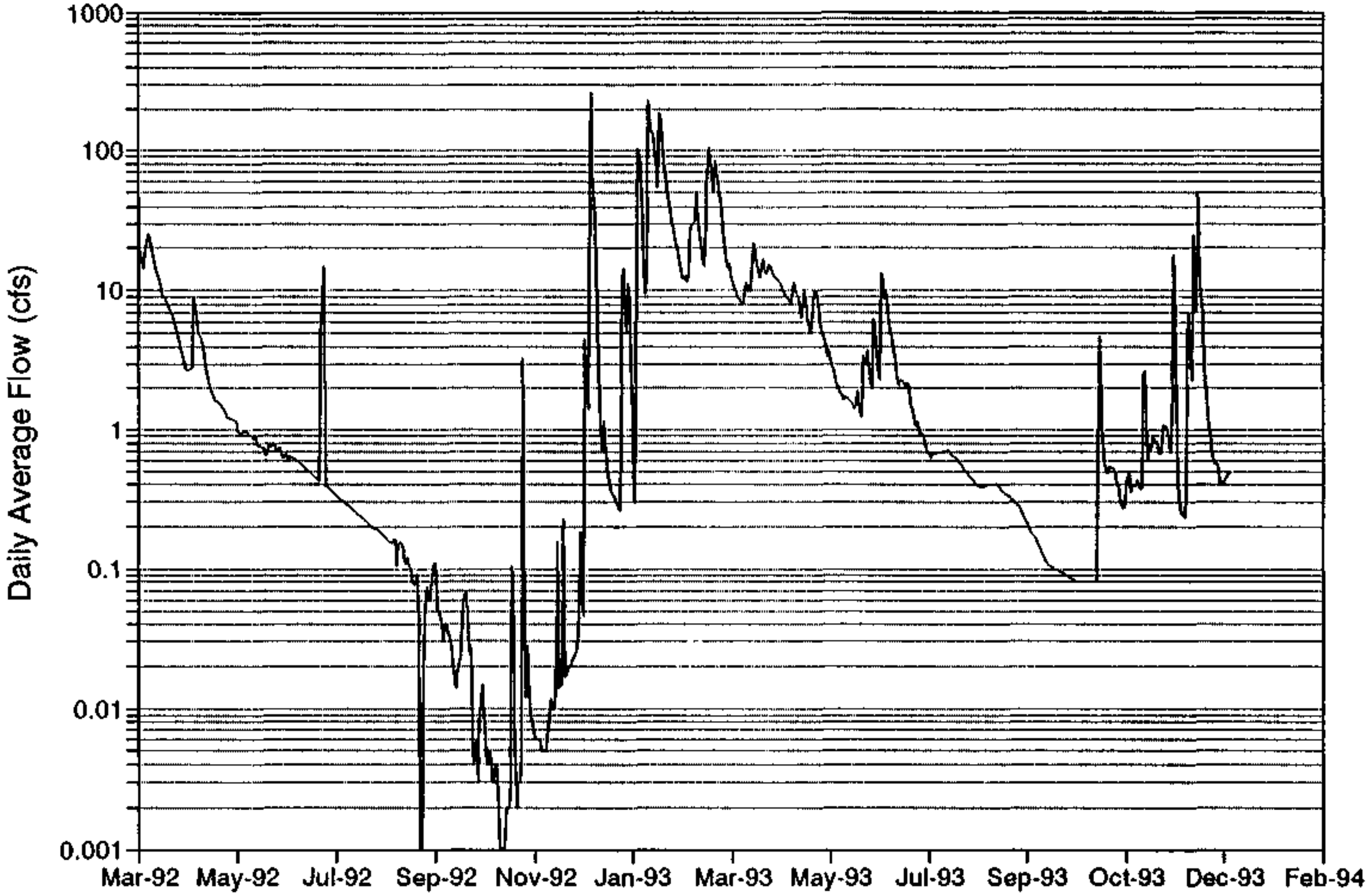
Well #2: 015 / 07W - 01R02
65 gpm, 15 ft drawdown after pumping 32 hours

Philip Williams & Associates, Ltd. Consultants in Hydrology	Driller's Logs for Muir Beach Wells	Figure 2



Source: Harding Lawson Associates

Philip Williams & Associates, Ltd. Consultants in Hydrology	Seismic Refraction Profile of Franks Valley near Muir Beach Wells	Figure 3



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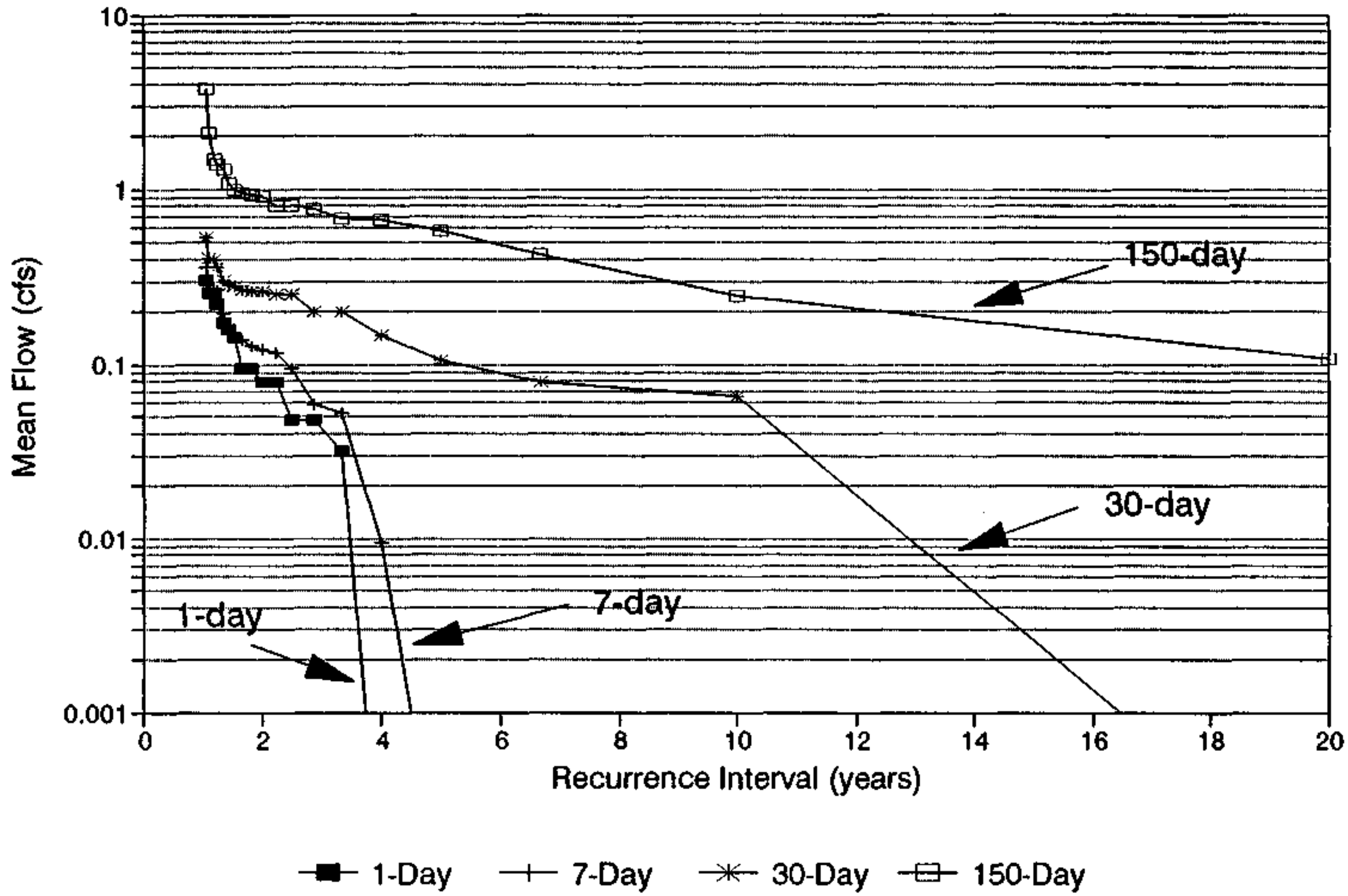
Daily Average Flows in Redwood Creek
1992-1993

Figure
4



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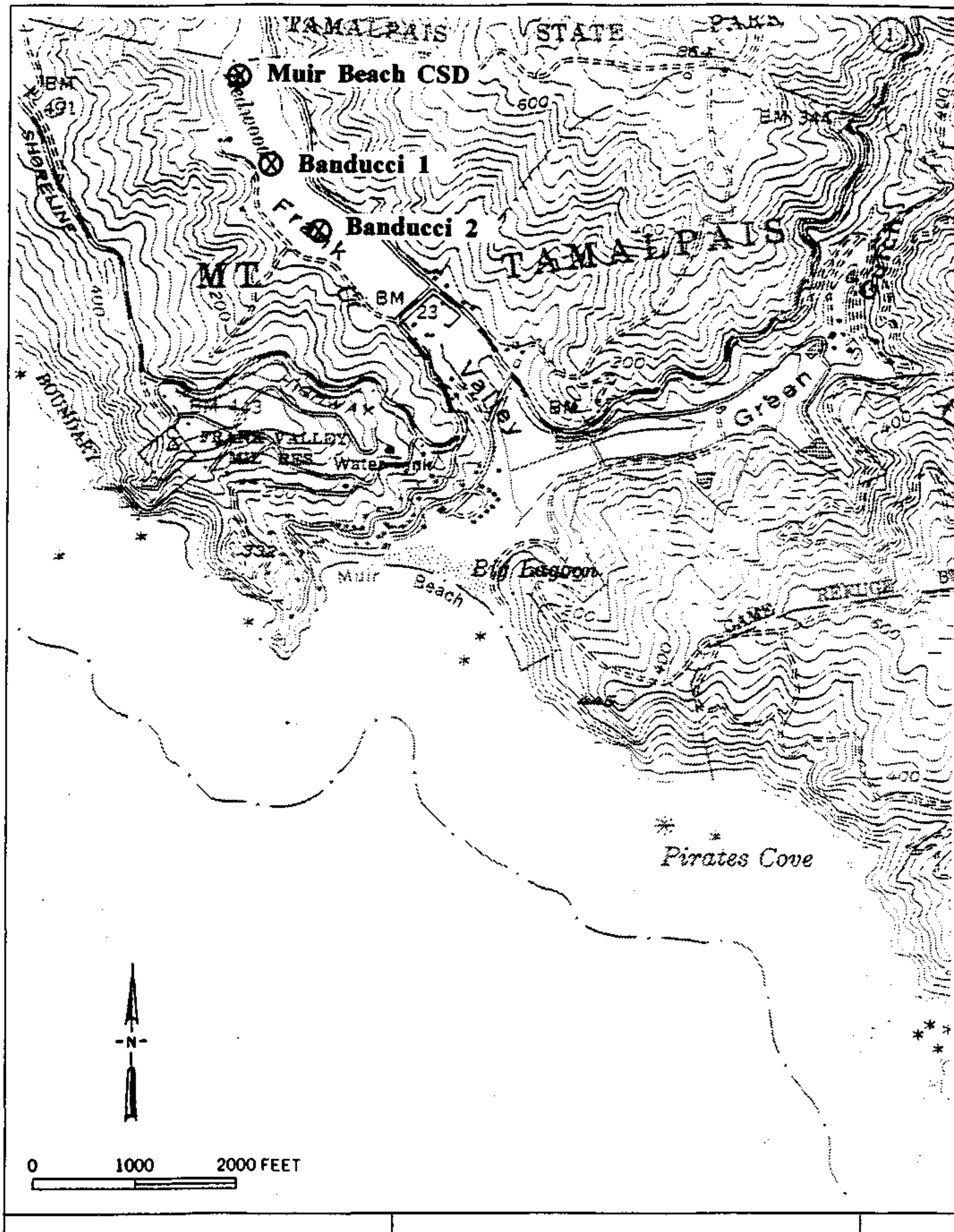
Flow Duration Curve for Redwood Creek
Derived from Arroyo Corte Madera Data

Figure
5



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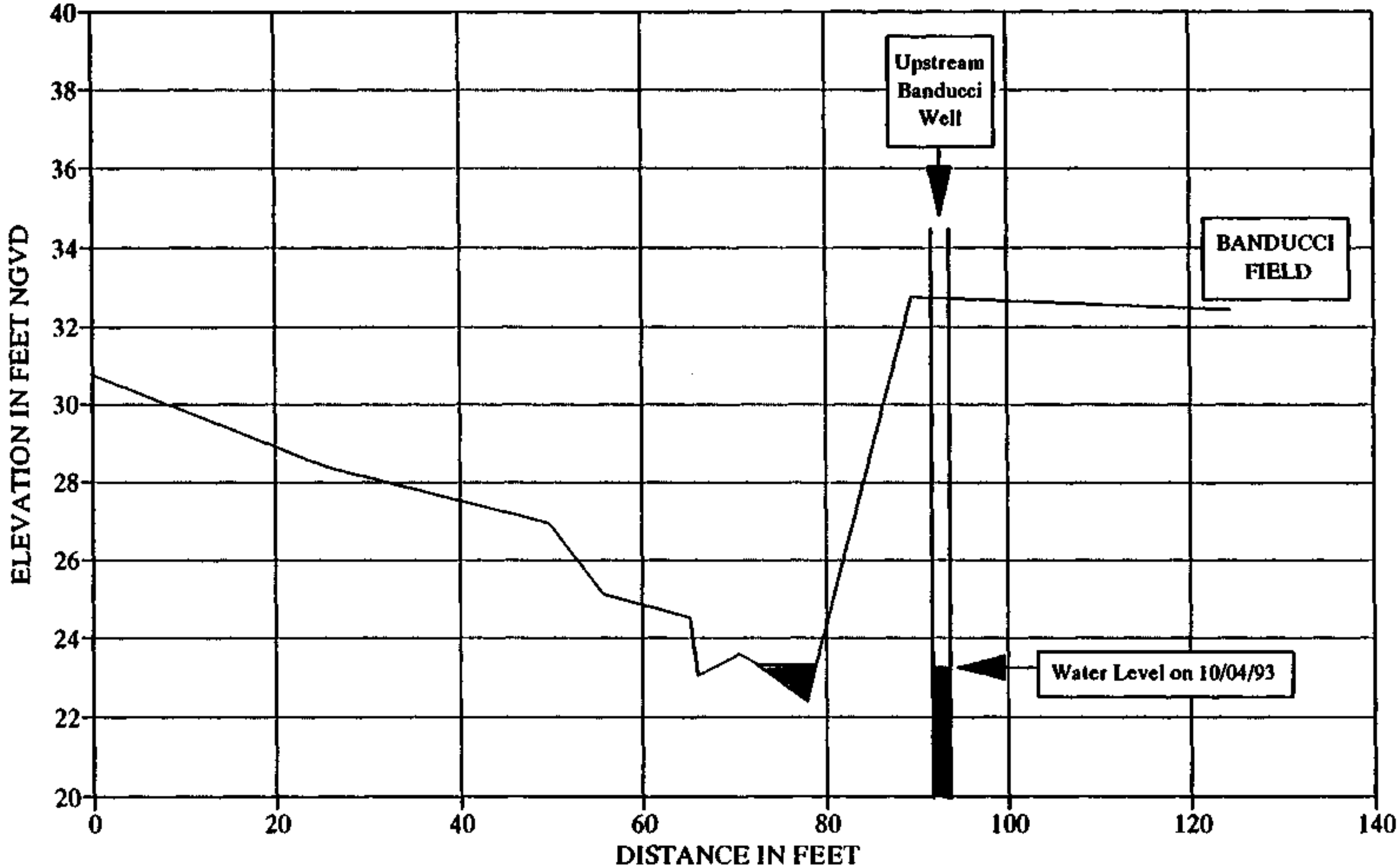
Well Locations

Figure 6



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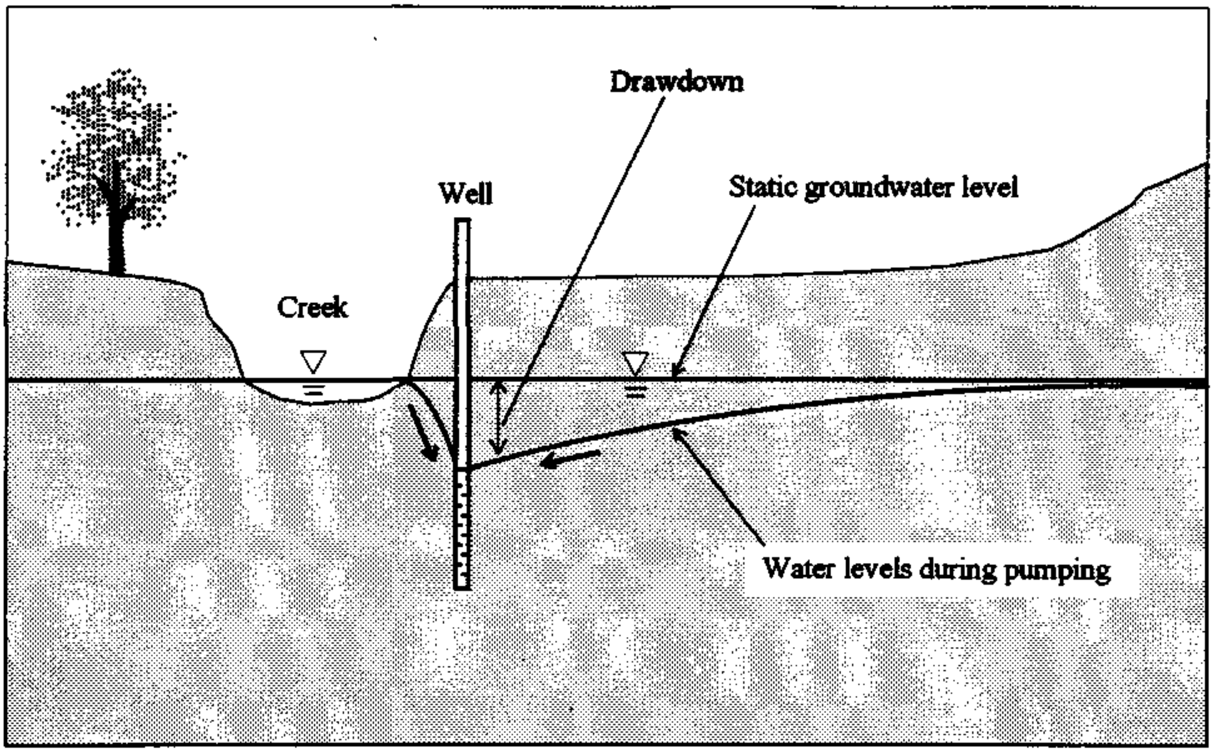
Cross Section of Redwood Creek at the Upstream Banducci Well

Figure 7



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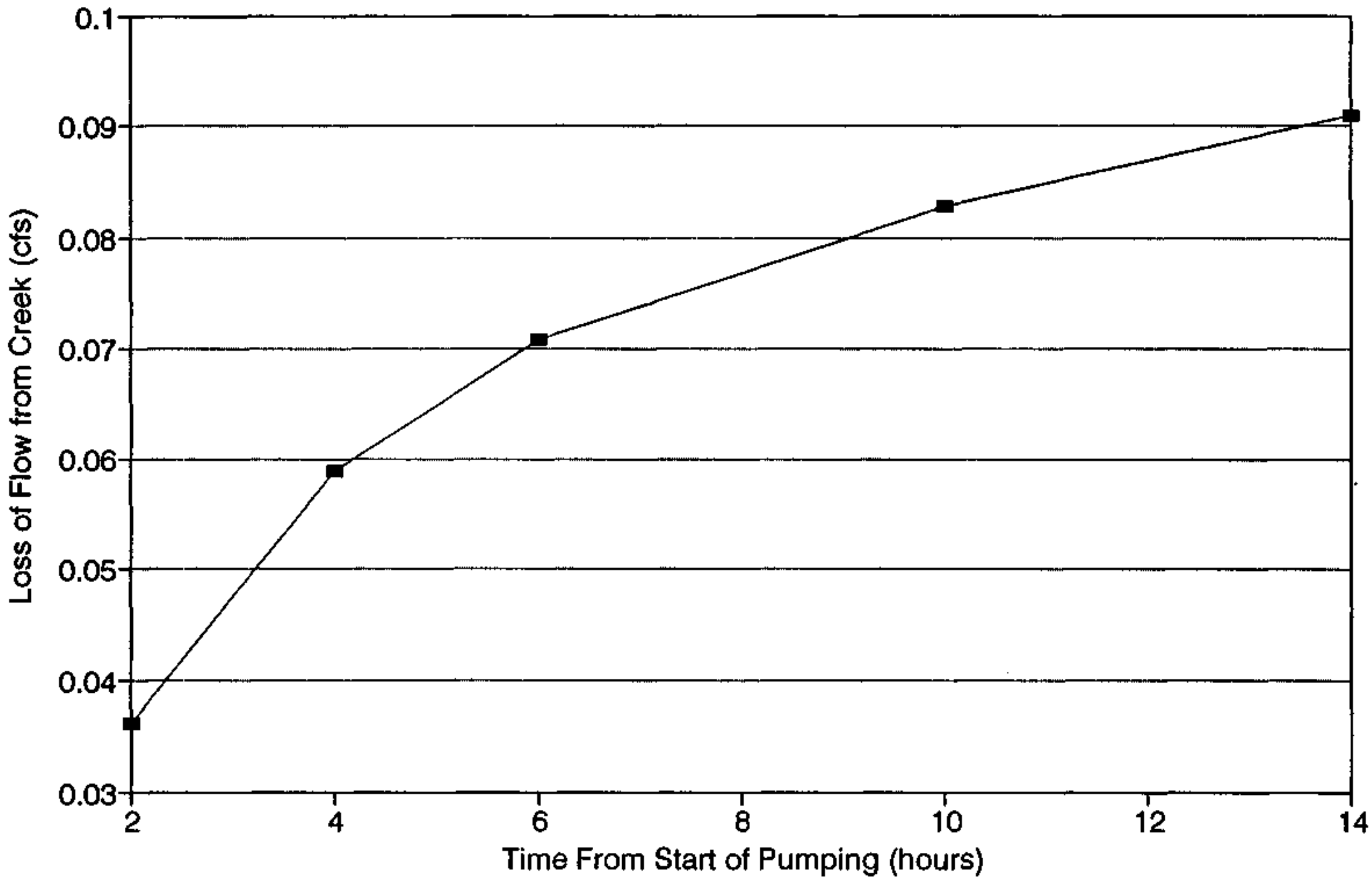
Groundwater Drawdown for a Well Pumping Near a Creek

Figure 8



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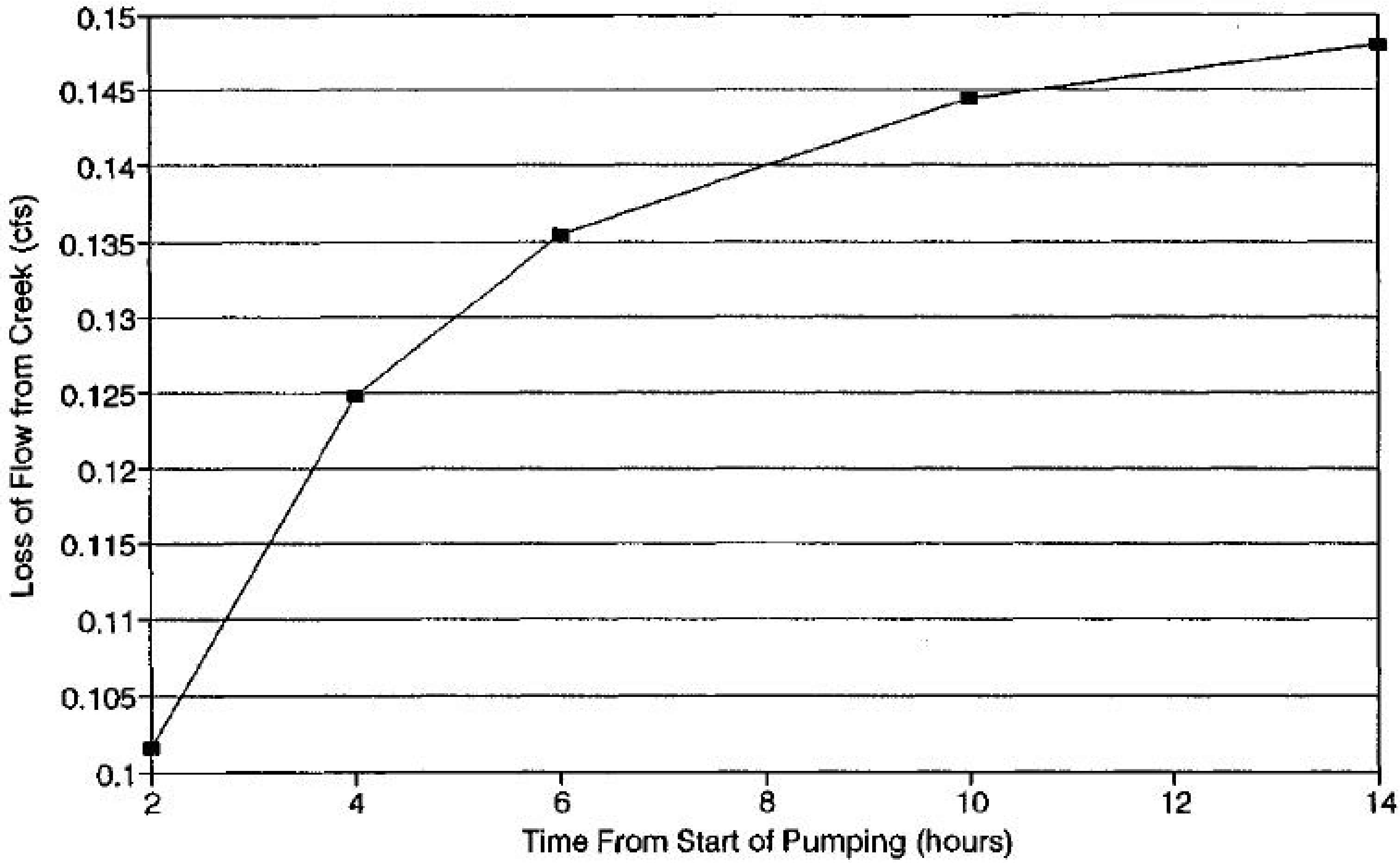
Estimated Impact of the Muir Beach CSD Well on Redwood Creek Flows

Figure 9



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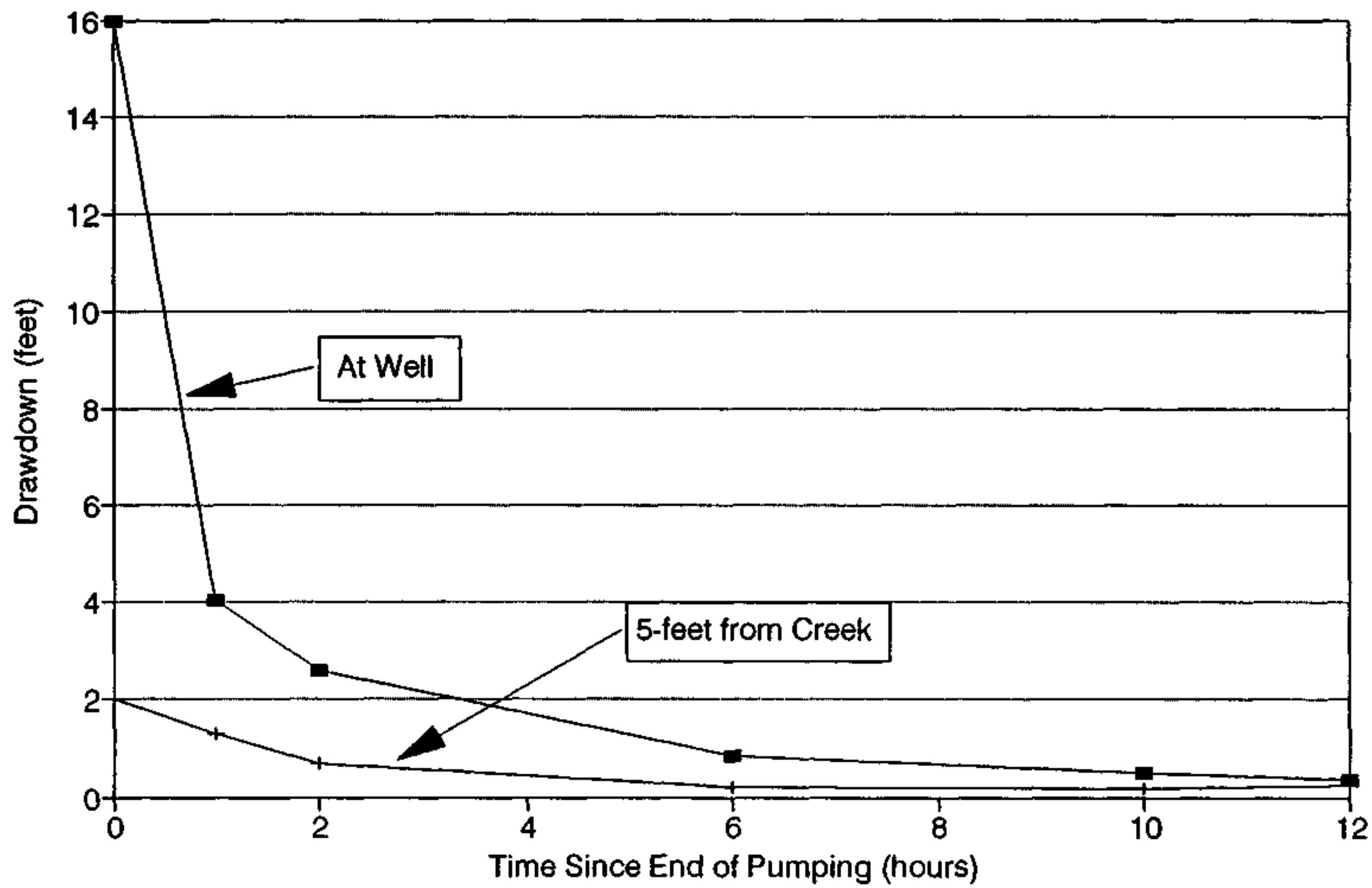
Estimated Impact of One Pumping Banducci Well on Redwood Creek Flows

Figure 10



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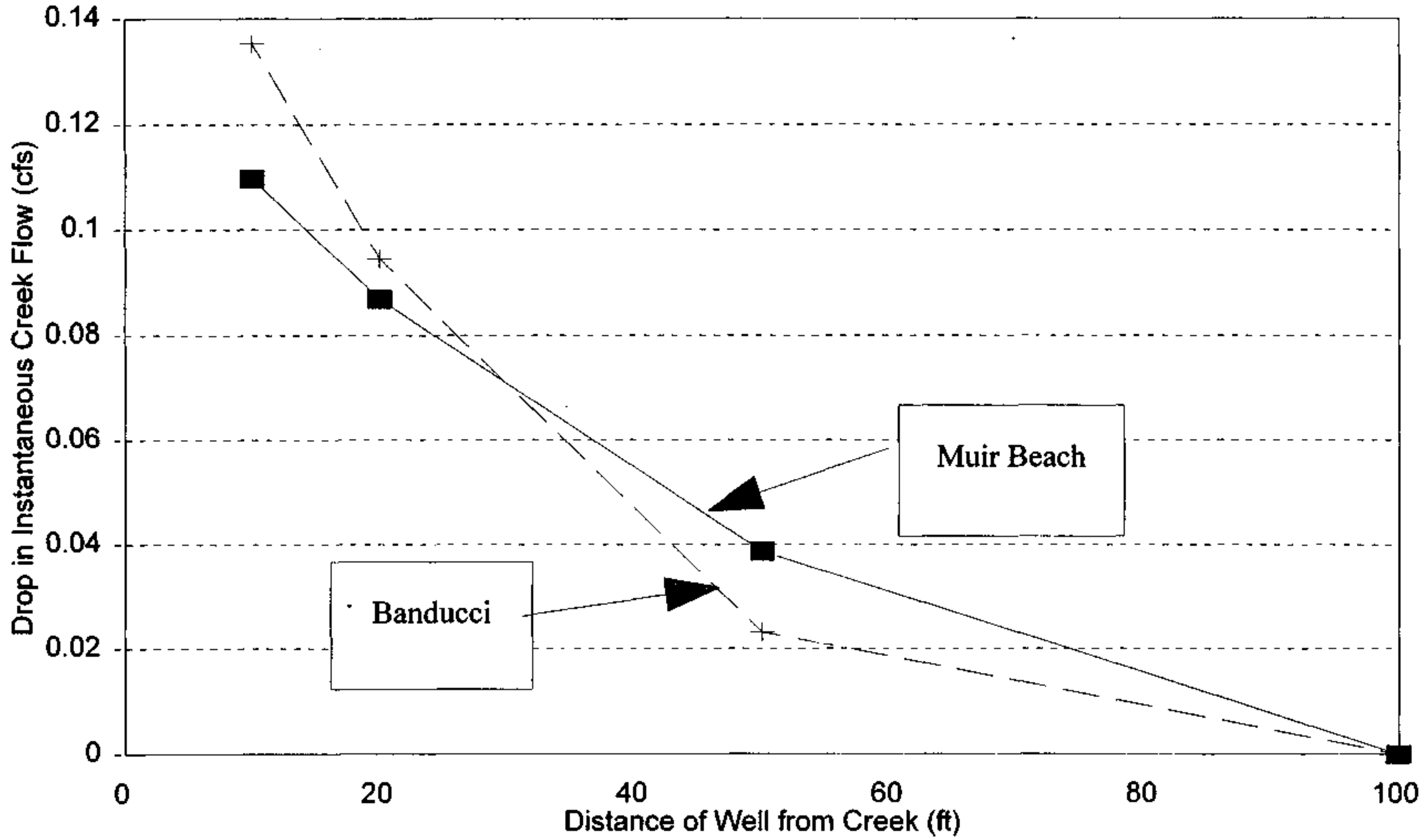
Recovery of Groundwater Levels Near the Muir Beach CSD Well after End of Pumping

Figure 11



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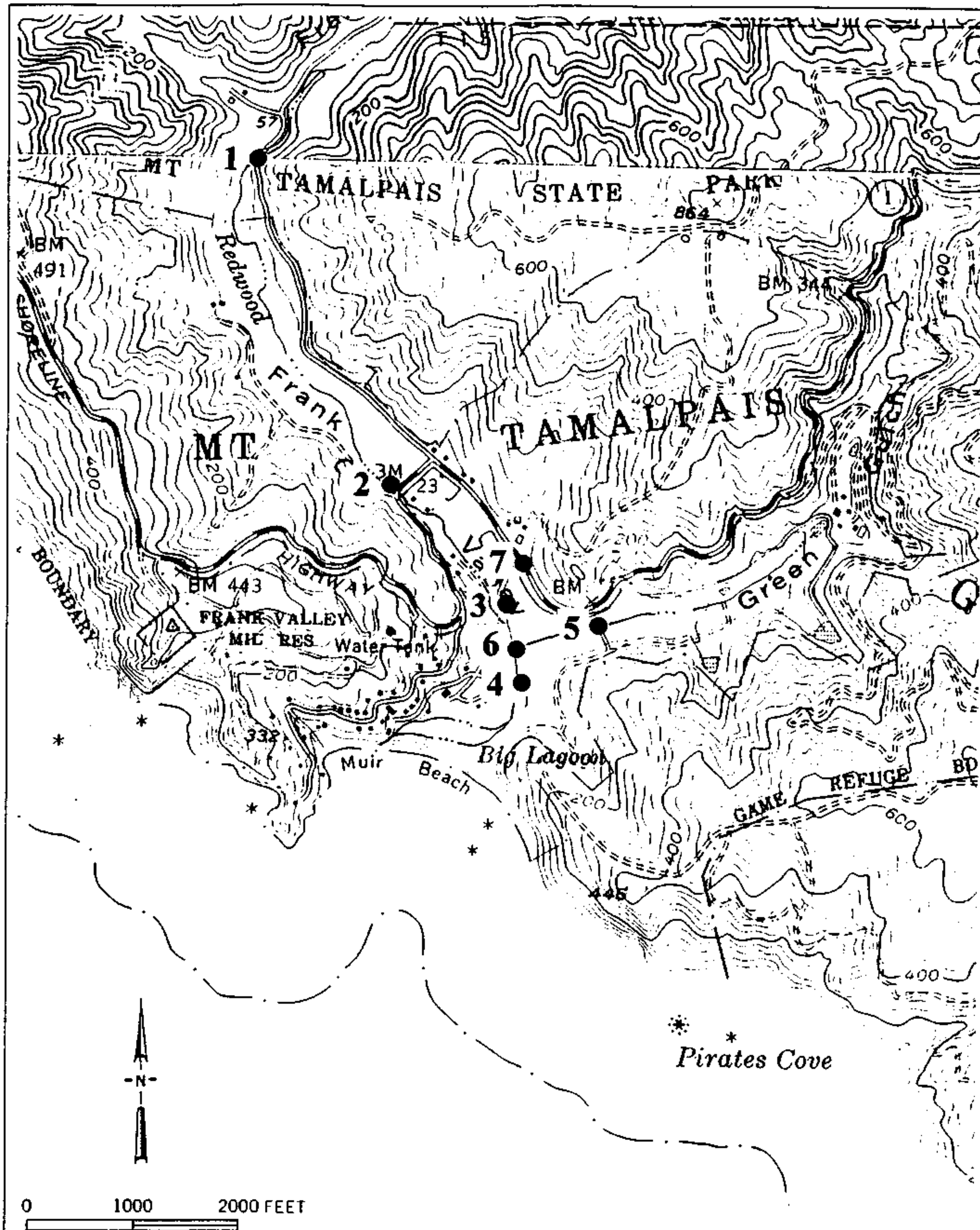
Estimated Loss of Creek Flow as a Function of Well Distance from the Creek

Figure 12



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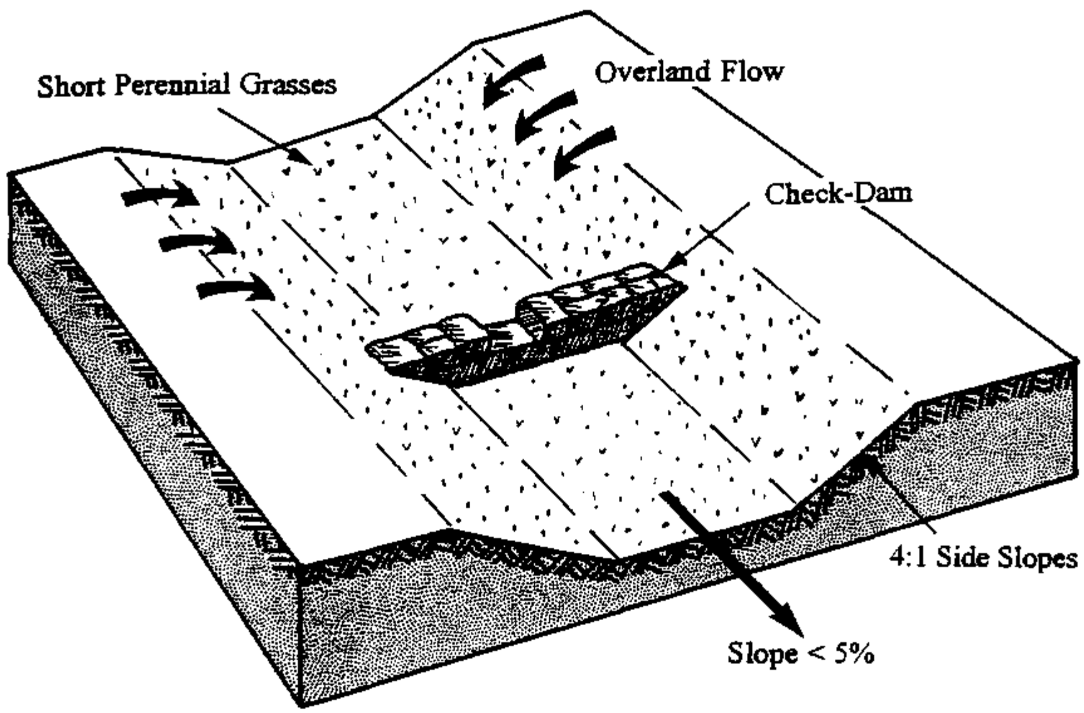
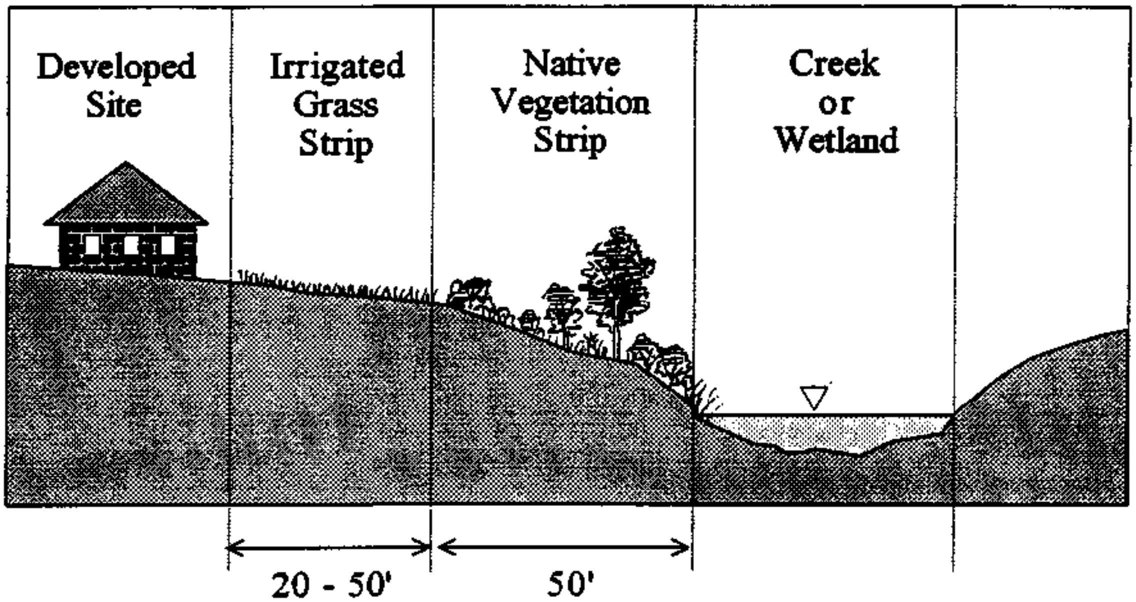
Water Quality Sampling
Station Locations

Figure
13



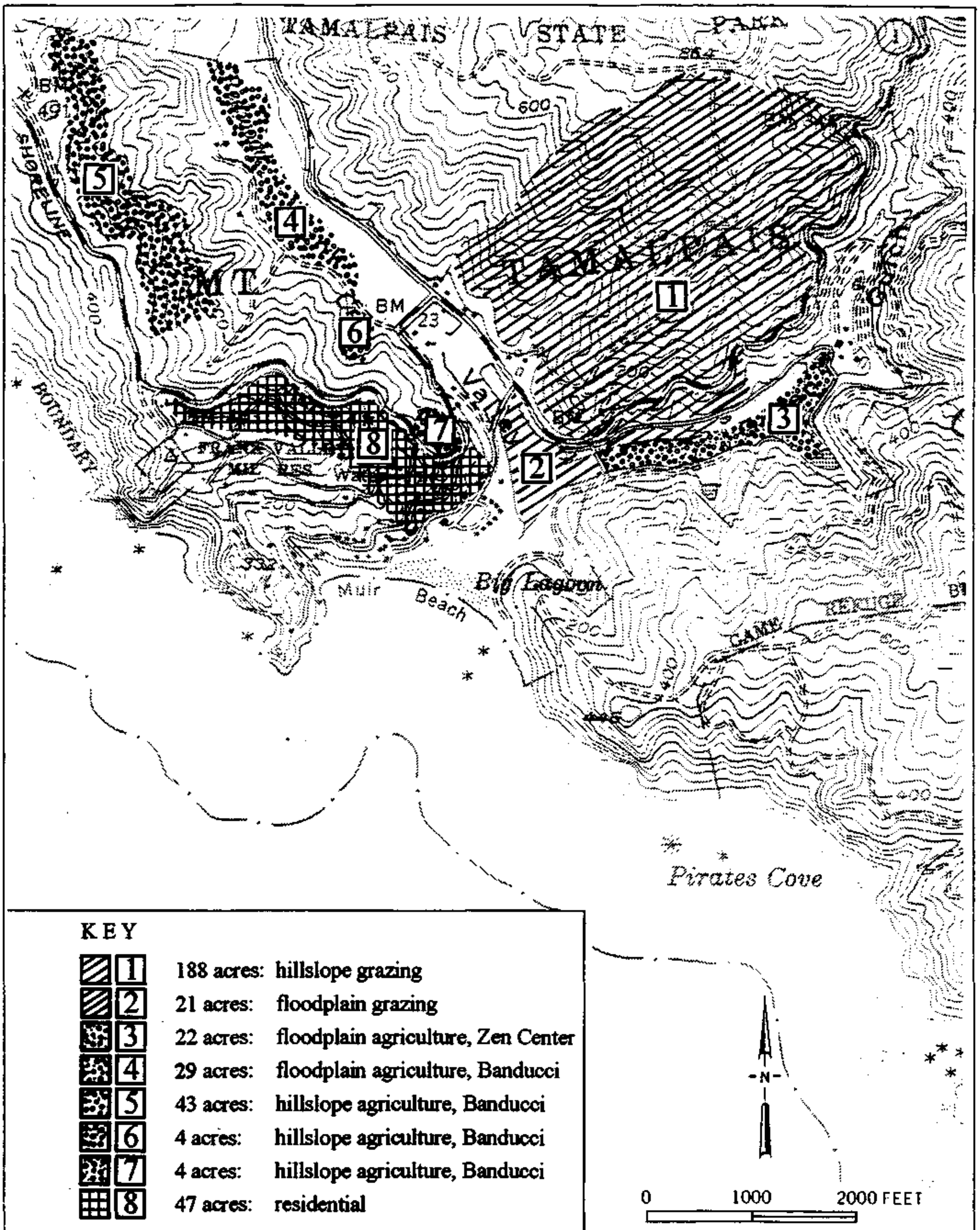
- Shallow flow depths
- Design for 2-year storm
- Check dams to dissipate energy and retain flow

cross-section



Biofilter Strip for Water Quality Control

Figure 15



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Land Use in Frank Valley and Green Gulch Valley

Figure 16

TABLES

TABLE 1

MEAN MONTHLY RAINFALL AND EVAPORATION

Month	Mean Precip (in)	Mean Evap (in)	Mean PET (in)	Available Water (in)
OCT	2.49	2.39	1.67	0.82
NOV	6.24	0.98	0.69	5.55
DEC	4.74	0.53	0.37	4.37
JAN	5.73	0.39	0.27	5.46
FEB	5.62	0.84	0.59	5.03
MAR	5.68	2.68	1.88	3.80
APR	2.39	3.71	2.60	0.00
MAY	0.39	5.53	3.87	0.00
JUN	0.26	6.42	4.49	0.00
JUL	0.20	7.30	5.11	0.00
AUG	0.16	5.68	3.98	0.00
SEP	0.53	3.91	2.74	0.00
TOTAL	**34.43**	**40.36**	**28.25**	**25.03**

Notes

Precipitation data from Muir Woods daily records

Evaporation Data from Lagunitas Reservoir Pan

Potential Evapotranspiration (PET) Computed from Pan Evaporation using a pan coefficient of 0.7

TABLE 2

HISTORICAL FLOW DATA ON REDWOOD CREEK AND GREEN GULCH

Date	Location	Agency	Conditions	Instantaneous Flow (cfs)
02/13/62	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	880
10/13/62	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	800
01/20/64	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	100
01/06/65	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	410
01/04/66	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	1300
01/21/67	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	295
01/30/68	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	630
12/15/68	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	1040
01/21/70	Redwood Creek at Frank Valley Road	USGS	Annual Storm Peak	1780
08/74	Lower Redwood Creek	NPS	Dry Weather	0.56
09/74	Lower Redwood Creek	NPS	Dry Weather	0.31
01/31/86	Redwood Creek at Muir Woods	USGS	Winter	51
01/31/86	Redwood Creek at Pacific Way	USGS	Winter	86
01/30/86	Green Gulch Creek	USGS	Winter	9.9
06/26/86	Redwood Creek at Muir Woods	USGS	Summer	0.77
06/26/86	Redwood Creek at Pacific Way	USGS	Summer	0.66
06/25/86	Green Gulch Creek	USGS	Summer	0.01
02/13/87	Redwood Creek at Muir Woods	USGS	Winter	114
03/13/87	Redwood Creek at Pacific Way	USGS	Winter	30
03/13/87	Green Gulch Creek	USGS	Winter	1.2
06/10/87	Redwood Creek at Muir Woods	USGS	Summer	0.62
06/12/87	Redwood Creek at Pacific Way	USGS	Summer	0.68
06/12/87	Green Gulch Creek	USGS	Summer	0.01
01/05/88	Redwood Creek at Muir Woods	USGS	Winter	42
01/05/88	Redwood Creek at Pacific Way	USGS	Winter	73
03/23/88	Green Gulch Creek	USGS	Winter	0.04
06/07/88	Redwood Creek at Muir Woods	USGS	Summer	0.7
06/07/88	Redwood Creek at Pacific Way	USGS	Summer	0.78
06/02/88	Green Gulch Creek	USGS	Summer	0.01
09/04/88	Redwood Creek at Frank Valley Road	NPS	Dry Weather	0.06

TABLE 3

SUMMARY OF FLOW MEASUREMENTS ALONG REDWOOD CREEK

	MEASURED SURFACE FLOW (CFS)						
DATE	**Site l at Pacific Way**	**Site 2 Above HWY1**	**Site 3 Between Banducci Wells**	**Site 4 Above Banducci Wells**	**Site5 Above Muir Beach CSD Well**	**Site 6 Below Muir Woods**	**COMMENTS**
06/18/93	2.38	2.16	2.10	2.29	1.58	1.81	
07/02/93	1.37	1.19	1.28	1.27	1.19	1.20	
07/15/93	0.80	0.79	0.76	0.88	1.03	1.08	
08/02/93	0.45	0.41	0.45	0.54	0.65	0.80	
08/13/93	0.49	0.63	0.71	0.64	0.63	0.71	Banducci wells not operating
08/28/93	0.34	0.28	0.42	0.36	0.38	0.49	Banducci wells not operating
09/13/93	0.11	0.09	0.18	0.25		0.24	
10/04/93	0.08	0.05	0.10	0.14	0.18	0.14	
06/05/94	0.75	0.65	0.80	0.80	0.80	0.79	Banducci wells not operating
07/22/94	0.37	0.31	0.50	0.39	0.39	0.59	Banducci wells not operating

Description of Sites:

Site 1	Bridge near the Pelican Inn
Site 2	+/- 75 yards upstream of HWY 1 crossing (off of Banducci driveway)
Site 3	Mid-way between Banducci pumps, directly across from first house on Banducci driveway. Accessed from road, near sharp bend.
Site 4	Mid-way between U/S Banducci pump and community pumps. Accessed from community pump house area.
Site 5	+/- 50 yards upstream from old USGS gaging station
Site 6	Directly below bridge at D/S boundary of Muir Woods

TABLE 4
SUMMARY OF WATER QUALITY DATA FOR REDWOOD CREEK AND GREEN GULCH

Location	Date	Q (cfs)	Conduct (us/cm)	pH	Temp. (C)	D.O. (mg/l)	Fecal Colif. (#/100ml)	NO2&3 (mg/l)	Phos (mg/l)	Turb. (NTU)	NH3	TSS (mg/l)	Data Source
Muir Woods	01/31/86	51	136	7	12	10.4	77	<.l	0.01				USGS
Muir Woods	06/26/86	0.77	212	7.3	14	9.8	290	<.l	0.01				USGS
Muir Woods	02/13/87	114	118	7.9	12.5	10.4	46	0.14	0.08				USGS
Muir Woods	06/10/87	0.62	215	7.5	14	8.7	5	<.l	<.l				USGS
Muir Woods	01/05/88	42	148	7.8	10	11.1	27	0.22	0.01				USGS
Muir Woods	06/07/88	0.7	225	7.9	13.5	9.2	34	0.1	<.l				USGS
Above Banducci	11/14/90			7.5	9		30	<.05		0.7			MBCC
Above Banducci	12/11/90			7.6	9		23	<.05		3			MBCC
Above Banducci	01/22/91			7.8	6		2	0.1		0.2			MBCC
Above Banducci	02/05/91			7.8	9		130	0.55					MBCC
Above Banducci	02/20/91			7.8	10		4	0.32		0.9			MBCC
Above Banducci	03/04/91			7.7	10		110	0.35		13			MBCC
Above Banducci	03/13/91			7.7	9		30	0.23		9.5			MBCC
Above Banducci	03/27/91			7.5	9		30	0.32		16			MBCC
Above Banducci	08/31/93						23	<012	<.01		<.05		PWA
Above Banducci	08/31/93						33	<.012	<.01		<.05		PWA
Above Banducci	08/31/93						49	<.012	<.01		<.05		PWA
Above Banducci *	12/13/93	20						0.51	0.03			<5	PWA
Above Banducci *	12/14/93	110					1600	0.56	0.19			120	PWA
Below Banducci	08/31/93						240	0.011	<.01		<.05		PWA
Below Banducci	08/31/93						140	<012	<01		<.05		PWA
Below Banducci	08/31/93						540	0.021	0.094		<.05		PWA
Below Banducci *	12/13/93	20						0.62	0.28			<5	
Below Banducci *	12/14/93	110					>2400	0.55	0.17			210	
Pacific Way	01/31/86	86	155	7.2	12	10.2	870	0.19	0.01				USGS
Pacific Way	06/26/86	0.66	226	7.4	14	8.8	110	<.l	0.01				USGS
Pacific Way	03/13/87	30	178	7.3	11.5	10.7	8000	0.1	<.01				USGS
Pacific Way	06/12/87	0.68	228	7.8	12.5	8.6	280	<.l	<01				USGS
Pacific Way	01/05/88	73	176	7.5	10.5	10.8	50	0.58	0.02				USGS
Pacific Way	06/07/88	0.78	242	7.9	12	9.4	110	0.39	<01				USGS
Pacific Way	08/31/93						>2400	0.021	0.013		<.05		PWA
Pacific Way	08/31/93						>2400	0.015	<.01		<.05		PWA
Pacific Way	08/31/93						920	<.012	<.01		<.05		PWA
Pacific Way *	12/13/93	20						0.46	0.14			24	PWA
Pacific Way *	12/14/93	110					540	0.55	0.45			250	PWA
Tinker Drain *	12/13/93							1.4	4.8			990	PWA
Tinker Drain *	12/14/93						>2400	1.3	0.61			78	PWA

-continued-

TABLE 4 (continued)

SUMMARY OF WATER QUALITY DATA FOR REDWOOD CREEK AND GREEN GULCH

Location	Date	Q (cfs)	Conduct (us/cm)	PH	Temp. (C)	D.O. (mg/l)	Fecal Colif. (#/100ml)	NO2&3 (mg/l)	Phos (mg/I)	Turb. (NTU)	NH3	TSS (mg/l)	Data Source
Upper Green Gulch	01/30/86	9.9	202	7.2	12.5	10.1	370	1	<.01				USGS
Upper Green Gulch	06/25/86	0.01	463	7.4	15.5	7.4	13	<.l	0.02				USGS
Upper Green Gulch	03/13/87	1.2	261	7.4	14	10.2	500	0.68	<.01				USGS
Upper Green Gulch	06/12/87	0.01	518	7.4	13.5	6.4	23	0.54	<.01				USGS
Upper Green Gulch	03/23/88	0.04	434	7.6	12.5	7.5	10	0.82	<.01				USGS
Upper Green Gulch	06/02/88	0.01	461	7.6	13	6.3	3	<.l	<.01				USGS
Upper Green Gulch *	12/13/93							1.6	0.29			130	PWA
Upper Green Gulch *	12/14/93						>2400	1.5	0.15			14	PWA
Lower Green Gulch *	12/13/93							1.1	0.19			6	PWA
Lower Green Gulch *	12/14/93						>2400	1.4	0.3			20	PWA
Lower Green Gulch	08/31/93						240	<.012	<.01		<.05		PWA
Lower Green Gulch	08/31/93						110	<012	<.01		<.05		PWA
Lower Green Gulch	08/31/93						130	<.012	0.02		<.05		PWA
Backwater Pond *	12/13/93							0.67	0.12			410	PWA
Backwater Pond *	12/14/93						1600	0.7	0.22			140	PWA

* = sample associated with a storm event

TABLE 5

SUMMARY OF WATER QUALITY DATA

		Mean Concentration (*)			
Location	Season	Fecal Coliform (#/100ml)	Nitrate and Nitrite (mg/l as N)	Total Phosphates (mg/l)	TSS (mg/l)
Above Banducci	Winter	279	0.32	0.10	60
Below Banducci	Winter	2400	0.59	0.23	105
Pacific Way Bridge	Winter	540	0.51	0.30	137
Backwater Pond near Footbridge	Winter	1600	0.70	0.17	275
Above Banducci	Summer	35	0.004	<0.01	NA
Below Banducci	Summer	307	0.012	0.030	NA
Pacific Way	Summer	1907	0.014	0.004	NA
Backwater Pond near Footbridge	Summer	160	0.012	0.007	NA
Objectives for Water Contact Recreation		<200	NA	NA	NA
Objectives for Drinking Water		<20	<10	NA	NA

* Mean of data collected by PWA in 1993 and Harding-Lawson in 1991. Does not include pre-1989 data when the Muir Woods Leach Field was operating.

** Water Quality Objectives from the San Francisco Bay Basin Plan, SF Regional Water Quality Control Board, 1990.

TABLE 6

ESTIMATES OF SEDIMENT YIELD FOR REDWOOD CREEK

Method		Source
Nearby		
	135 tons/square mile/year	Lehre (1982)
	50 to 72 tons/square mile/year	Reseau(1988)
Big Lagoon Sedimentation Study		
	270 tons/square mile/year	PWA (1994)
PSIAC Method		
	390 to 980 tons/square mile/year	PWA (this study)
USLE		
	Riding Rings, Paddocks = 1,200 tons/square mile/year	PWA (this study)
	Banducci Farms =152 tons/square mile/year	
	Green Gulch Farms =152 tons/square mile/year	
	Pasture = 50 tons/square mile/year	
	Natural Condition = 1 ton/square mile/year	

TABLE 7

UNIVERSAL SOIL LOSS EQUATION FACTORS

	R	K	LS	C	P	A (tons/acre/yr)	A (tons/mi2/
Bare Soil	50	0.37	0.1	1.0	1.0	1.85	1200
Floodplain Agricultural	50	0.37	0.1	0.16	0.80	0.237	152
Floodplain Pasture	50	0.37	0.1	0.42	1.0	0.0777	50
Natural Floodplain	50	0.37	0.1	0.11	0.10	0.002	1

TABLE 8

ESTIMATED SEDIMENT YIELD FROM LOWLAND AGRICULTURE AND PASTURES

	Area (acres)	Total Sediment Yield (tons/yr)
Floodplain Agriculture, Green Gulch	22	5.2
Floodplain Agriculture, Banducci	29	6.9
Floodplain Pasture	21	1.6
TOTAL	72	14
Natural (undeveloped) Conditions	72	0.14

Note: Total Redwood Creek Watershed Yield apprx. 1,200 tons/year