Preservation Ranch Limiting Factors Analysis

FINAL REPORT

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1 INTRODUCTION

1.1 Introduction

This report presents the results of studies conducted by Stillwater Sciences to analyze factors potentially limiting steelhead (*Oncorhynchus mykiss*) production in the Buckeye Creek and Wheatfield Fork sub-basins (the Study Area) of the Gualala River basin. This study was funded by Buckeye Ranch LLC as part of an effort to assess factors limiting steelhead production within the Gualala River basin.

This study was designed to assess basin-wide current conditions and to identify the factors that are most likely limiting the population of steelhead in the Study Area , using an iterative process of hypothesis development and testing,. The focus of this study was to understand factors that limit steelhead production under current conditions. The results are expected to inform decisions regarding land management in the study sub-basins.

1.2 Approach

We employed a limiting factors analysis approach to evaluate factors that may be currently limiting steelhead production. By identifying these factors, we can focus future management activities, help prioritize actions, and refine our current understanding of steelhead population dynamics in these sub-basins. Preliminary hypotheses regarding potential limiting factors for steelhead were developed using a conceptual model that identifies the habitat constraints most likely affecting the success of each life stage. We then used an iterative process of hypothesis development, testing, and refinement to evaluate the potential effectiveness of proposed studies in the Study Area. This approach mirrors that used by Stillwater Sciences for the 2006 Upper Penitencia Creek Limiting Factors Analysis (Stillwater Sciences 2006), as well as a similar study conducted by Stillwater Sciences and the University of California, Berkeley for the Napa River watershed (Napa County) (Stillwater Sciences 2002). Similar approaches are currently being used in other California coastal watersheds, including Lagunitas Creek (Marin County) and Sonoma Creek (Sonoma County).

The Limiting Factors Analysis (LFA) was a five-step process:

Step 1. Acquire and Review Available Information. We acquired and reviewed relevant existing information and queried local experts to characterize the physical and biological attributes of the Study Area and identify key issues of concern. This step included developing various Geographic Information System (GIS) layers to display watershed conditions in a map-based format. This allowed us to stratify the channel network for developing hypotheses and selecting study sites.

Step 2. Develop and Refine Conceptual Model, Hypotheses, and Work Plan for Focused Studies. We created a conceptual model that describes the habitat requirements and potential constraints for each steelhead life stage in the Study Area using available information and spatial data developed in Step 1. Using this conceptual model, we began developing hypotheses regarding current habitat conditions and potential limiting factors for steelhead. We then conducted initial reconnaissance of the watershed to begin refining hypotheses and identify priorities for focused studies.

Step 3. Conduct Focused Studies. We began conducting focused studies to test the most likely hypotheses regarding factors limiting steelhead production in the Study Area. Focused studies conducted to date include field assessments of overwintering habitat, steelhead distribution and abundance (via direct observation [snorkel] surveys and electrofishing) and spawning gravel permeability.

Step 4. Conduct Limiting Factors Analysis. This step involved reviewing and synthesizing the results of the focused studies and literature sources to evaluate the factors most likely limiting steelhead production in the Study Area under current conditions. Steelhead population modeling was used to reject, accept, or refine hypotheses based on the results of the focused studies, and to identify key uncertainties that might affect management of aquatic ecosystems in the Study Area.

Step 5. Develop Recommendations. Based on available information, hypotheses developed during these studies, and testing of hypotheses with a population model, we identified recommendations for future studies to further understand factors limiting steelhead production in the Study Area.

2 BASIN CHARACTERIZATION

2.1 Physical Setting

The Gualala River, located in northern California, drains a watershed of approximately 771 km^2 (298 mi^2) along the coast of southern Mendocino and northern Sonoma counties before flowing into the Pacific Ocean near the town of Gualala (Klamt et al. 2002) (Map 1). The Gualala River comprises five major sub-basins: North Fork Gualala River, South Fork Gualala River, Rockpile Creek, Buckeye Creek, and Wheatfield Fork and runs 52 km (32 mi) in a north-south direction along the San Andreas rift zone. The entire basin lies within 32 km (20 mi) of the Pacific Ocean, and the major sub-basins are largely fault-controlled, flowing through gorge-like valleys with narrow floodplains. The Study Area for this limiting factors analysis is the Buckeye Creek and Wheatfield Fork sub-basins, which are adjacent to one another and cover approximately 40% of the Gualala River basin area.

Population centers are concentrated along the Pacific coastline and include the towns of Gualala, Annapolis, Sea Ranch, and Stewarts Point, which are accessed by Highway 1, running North and South, and Skaggs Springs Road, running East and West. Ninety-five percent of the watershed is held in private ownership (Klamt et al. 2002).

2.2 Climate and Hydrology

The Gualala River basin has a Mediterranean climate influenced by coastal fog near its mouth and warmer air within the interior (Klamt et al. 2002). Near the coast, winter and summer temperatures tend to range from 4 to 16°C (40 to 60°F), while summer daytime temperatures inland may be as high as 27 to 32°C (80 to 90°F), and below freezing in the winter. Precipitation is higher in inland areas than at the coast. The majority of annual precipitation occurs as rainfall in the winter and early spring, with 90% occurring in November through March (Klamt et al. 2002). The mean annual precipitation ranges from 84 cm (33 in) near the coast to 168 cm (66 in) in the eastern portion of the basin. Two nearby precipitation gages, located in Fort Ross and

Cloverdale, have been in long-term operation and indicate trends in regional rainfall. The mean annual precipitation recorded at the Fort Ross gage from 1876 to 2000 was 110 cm (43 in), ranging from a low of 41 cm (16 in) recorded in 1977 to a high of 239 cm (94 in) in 1878, while the Cloverdale gage, in continuous operation since 1903, has recorded a mean annual precipitation of 104 cm (41 in), ranging from 36 cm (14 in) in 1924 to 200 cm (79 in) in 1983.

A USGS streamflow gage in the town of Annapolis along the South Fork Gualala River was in operation from 1950 to 1971. The two highest recorded flows occurred in December 1955 (55,000 cfs) and January 1966 (47,800 cfs), with seven other flows exceeding 30,000 cfs (~2.5 yr recurrence interval) during the period of record (Table 2.2-1). Other regional gages suggest flows above this threshold may have occurred in 1974, 1983, 1986, 1993, 1995, and 1997 (Klamt et al. 2002, Appendix A.1).

Table 2.2-1. Largest recorded peak flows in the South Fork Gualala River, 1951–1971.

Water Year (Oct–Sept)	Peak Flow/Discharge (cfs)
1956	55,000
1966	47,800
1962	37,700
1954	35,900
1970	35,800
1958	35,400
1951	34,100
1953	33,900
1960	33,700
1952	29,500
1969	29,100
1967	28,900
1971	27,900

Source: USGS Annapolis Gage #11467500

The hydrologic setting during the study period (October 2005 to September 2006), can be described using the Navarro River near Navarro stream gage (USGS Gage # 11468000), located ~42 km (26 mi) north of the town of Gualala. We examined the mean daily discharge for the study period and found that the three highest values occurred on 31 December 2005, 6 March 2006, and 12 April 2006, consistent with observations of O'Connor (2006, unpublished data) for the Study Area over the same time period. Peak flow data for the Navarro River near Navarro stream gage also show that the peak discharge on 31 December 2005 was second highest recorded over the period of record (WY 1951-2006).

2.3 Land Use and Cover

The primary anthropogenic activities influencing sediment dynamics and current geomorphic conditions in the Gualala River basin are timber harvest, road building, and livestock grazing.

Timber harvest within the Study Area has occurred over three general time periods (Klamt et al. 2002, Appendix A.3). The earliest period centers around 1900, when old-growth coastal redwoods were harvested along low-gradient alluvial reaches of the Gualala River and its tributaries. From the 1950s to the early 1970s, harvest targeted old-growth conifer stands in the central Gualala River basin. The greatest harvest intensity occurred from 1952 to 1960 when 22,000 hectares (54,000 acres) were effectively clearcut. Intensity declined from 1960 to 1973, with harvest progressing to higher elevation areas near the basin divide. During the most recent period, from 1990 to 2001, harvest of second-growth conifers occurred along low-gradient alluvial reaches, many of which had been harvested in the early 1900s.

The road network within the Gualala River basin is extensive, made up mainly of private roads with some larger public roads, such as Highway 1 and Skaggs Springs Road. The private roads were built primarily to support timber operations; most were constructed during the period from the 1950s to 1970s. Some of these roads were abandoned as timber harvest intensity decreased, and others were replaced by more modern roads located away from streambanks near ridgelines and upslope areas.

Grazing is the second most dominant land use within the basin, behind timber harvest, and occurs mainly in the eastern portion of the basin on dry, high-elevation sites (Klamt et al. 2002, Appendix A.3).

2.4 Geologic Setting

2.4.1 Wheatfield Fork

Geologic formations and units within the Wheatfield Fork are described in Table 2.4-1 and shown in Map 2. Wheatfield Fork is the largest sub-basin in the Gualala River watershed, comprising 180 km^2 (112 mi^2) of mostly privately owned property and 0.7 km^2 (0.3 mi^2) of public land (Klamt et al. 2002, Appendix A.2). Major land uses include timber production, grazing, vineyards, and some rural subdivisions. Wheatfield Fork is bounded to the north by the Buckeye Creek sub-basin and to the west by the South Fork Gualala River sub-basin. A stream gage was installed near the Wheatfield Fork's confluence with the South Fork Gualala River in 2001.

The watershed is dissected in the east by the dormant Tombs Creek Fault and in the west by the San Andreas Fault. Both are strike-slip faults which have sheared the Franciscan siltstones that comprise most of the watershed, resulting in frequent and abundant landslides The eastern, headwater region of the Wheatfield Fork is composed of mélange of the Central Terrane Franciscan formation, bounding the Tombs Creek Fault to the east. Most of the watershed is dominated by oak woodland and grassland with rolling ridgetops and steep, incised stream channels. The Tombs Creek Fault and ancillary faults have created parallel, northwest-trending, east-facing ridgelines that prevent drainage from the eastern to western portions of the watershed. This, coupled with stream deflection along the fault zones, has created a highly disordered drainage. The Wheatfield Fork trends west, then south around Oak Ridge until it resumes its western course to the South Fork Gualala. The downstream portion of Wheatfield Fork parallels Gualala Ridge, running northward along the San Andreas fault to its confluence with the South Fork Gualala. The Coastal Terrane Franciscan supports coniferous vegetation in the western portion of the Wheatfield Fork basin, while the flat-topped ridgelines capped with the young marine sediments of the Ohlson Ranch Formation support oak woodland. Contact zones between the Ohlson Ranch Formation and surrounding Central and Coastal belt Franciscan Formation are relatively unstable, especially in the steeper incised channels, resulting in abundant slumps and earth flows along the lower Wheatfield Fork. This lower portion, underlain with tectonically crushed and highly sheared mélange, produces frequent deep-seated, intermittently active landslides. Along the San Andreas Fault zone, debris slides and debris flows are abundant. The lower reaches of the Wheatfield Fork are mainly bedrock-controlled within moderately steep valleys, with narrow floodplains in the lowermost 3 km (2 mi) of stream.

Table 2.4-1. Geologic units within the Study Area.

Geologic Formation	Lithology	Area		Total (%)
		km^2	mi^2	
Central Belt Franciscan	Cretaceous green stone and Greywacke	38.06	14.78	9.68
Coastal Belt Franciscan	Tertiary marine siltstone and sandstone, chert	271..02	104.68	68.92
Ohlson Ranch Formation	Quaternary conglomerate and siltstone	27.37	10.57	6.96
	Older Alluvium	0.1	0.04	0.03
River terrace and stream channel deposits	Quaternary River terrace deposits, stream channel deposits, undifferentiated stream channel deposits	1.92	0.74	0.49
Undifferentiated Central Belt Franciscan	Cretaceous siltstone and serpentinite	46.24	17.86	11.76
Undifferentiated Franciscan Complex	Cretaceous greenstone, sandstone and metamorphic	8.54	3.30	2.17
Totals		**393.24**	**151.89**	**100.00**

2.4.2 Buckeye Creek

The Buckeye Creek sub-basin is the fourth largest in the Gualala River watershed, covering an area of 65 km^2 (40 mi^2). The descriptions and extent of the geologic formations and units within Buckeye Creek are described in Table 2.4-1 and shown in Map 2. The basin is bounded to the north by the Rockpile Creek sub-basin and to the south by the Wheatfield Fork. The watershed is held entirely in private ownership primarily for timber production, grazing and vineyards (Klamt et al. 2002). Buckeye Creek runs east to west until it reaches the confluence with the South Fork Gualala River. Three major tributaries to the Buckeye Creek sub-basin are Flat Ridge, Osser and Grasshopper creeks.

The uppermost portion of Buckeye Creek lies in the eastern rolling ridgetops of the Central Terrane Franciscan formation. The upper extent is dominated by Oak woodland forest and grassland, with large areas of active earthflow and steep headwater streams (Klamt et al 2002, Appendix A.2). Tombs Creek fault dissects this upper portion. The NW-WNW trending strike-slip faults have undergone extensive movement, shearing the green stones and siltstones of the Central and Coastal Terrane Franciscan complexes. Drainages have offset along this fault zone forming twinned patterns like Osser, Roy and Flat Ridge Creeks. Moving westward of the Tombs Creek shear zone, the vegetation changes to mixed conifer-hardwood, Douglas fir and eventually reaching the redwoods in the lower reaches of the Buckeye basin. The marine sandstone of the Coastal Terrane Franciscan dominates the western portion of the watershed and characteristically produces abundant debris slides The unconsolidated siltstone and conglomerates of the Ohlson Ranch Formation exist as flat ridgetops in the western portion of the watershed, whose correlated contact zone with Franciscan complexes are landslide prone especially along the steepened slopes adjacent to streams.

2.4.3 Mass wasting

Geologic mapping indicates multiple active hillslope processes occurring throughout the Gualala River basin (Klamt et al. 2002 Appendix A.2). The intense regional uplift and faulting has weakened the already fragile Franciscan complex, contributing to landsliding and debris flows. Sediment delivery to stream channels is also facilitated by the episodic rainfall characteristic of the area's Mediterranean climate and influenced by the orographic effects of storm clouds being forced over the Coast Ranges. Landslides within the basin range from very large rotational and earthflow complexes concentrated along fault zones or within geomorphic terranes to smaller debris slides and debris flows found along steep to moderate slopes. Inner gorge landslides are also found within incised reaches throughout the basin. The most commons landslides are shallow failures within the Coastal Terrane and small to very large earthlow complexes in moderate and steep slopes of the Central Pickett Peak, Rio Nido, and Yolla Bolly Terranes.

Several previous studies have examined mass wasting within the Gualala basin. A sediment source analysis, within the technical support document for the Gualala River total maximum daily load for sediment (North Coast Regional Water Quality Control Board [NCRWQCB] 2001), mapped landslides and estimated sediment yield from bank erosion and roads. The analysis examined anthropogenic (e.g., from road building and timber harvest) and natural sources of sediment. Debris slides, debris flows, deep seated landslides, earthflows, roadcuts, and road crossing failures were identified on 1:24000 aerial photographs from 1989 and 1999/2000 to estimate the change in sediment input. The survey did not include landslide features <10,000 ft^2 as they were difficult to identify on the aerial photographs. Estimates of sediment delivery from these smaller elements were developed from field measurements. A random sample of features identified from the aerial photographs was verified in the field as to type and size of the landslide. The analysis found that natural sediment yield (i.e., mass wasting and bank erosion) accounted for only one-third of the sediment load within the basin, while anthropogenically caused sediment delivery accounted for two thirds, or 200% of the natural yield (NCRWQCB 2001).

The California Geologic Survey mapped landslides as part of North Coast Watershed Assessment Program (Klamt et al. 2002). Landslides were identified on 1:24000 aerial photographs from 1984 to 1999/2000, and verified with limited field survey. The study differed from the previous survey by mapping smaller features (>100-ft diameter) and by using the results to produce basin-wide maps of geologic and geomorphic features related to landsliding. The survey found that 34% of the basin was underlain by large, dormant, deep-seated landslides and that 40% of smaller landslides (<100-ft diameter) occur within these larger features (Klamt et al. 2002).

2.5 Fish Community Composition

Six native fish species have been documented in the Study Area, including federally listed steelhead (*Oncorhynchus mykiss*) and its resident form rainbow trout (Cox 1989, as cited in Klamt et al. 2002) and coho salmon *(Oncorhynchus kisutch)* (CDFG, unpublished data, as cited by Klamt et al. 2002), as well as Pacific lamprey (*Lampetra tridentata*), Coast Range sculpin (*Cottus aleuticus*), prickly sculpin (*Cottus asper*), riffle sculpin (*Cottus gulosus*) (R. Kaye, as cited in Klamt et al. 2002), threespine stickleback (*Gasterosteus aculeatus*), and Gualala roach (*Lavinia symmetricus parvipinnis*), a regional subspecies of California roach (Klamt et. al. 2002, Appendix A.5). Historical anecdotal information also reports that Sacramento sucker (*Catostomus occidentalis*) (Spacek 1997, as cited by Higgins 1997) and Chinook salmon (*Oncorhynchus tshawytscha)* may have occurred in mainstem reaches, and euchalon (*Thaleichtys pacificus*) in the Gualala estuary (Higgins 1997). Starry flounder (*Platichthyes stellatus*), surf smelt (*Hypomesus pretiosus*), Pacific herring (*Clupea pallasii*), Pacific staghorn sculpin (*Lentocottus armatus*), and green sunfish *(Lepomis cyanellus)* are found in the lower reaches of the estuary and in the lagoon (ECORP 2005, Higgins 1997, Klamt et. al. 2002, Appendix A.5).

Anecdotal evidence indicates that coho salmon and steelhead were historically abundant throughout the Gualala River basin, including in the Study Area, but populations of both species declined sharply prior to the 1960s (Klamt et al. 2002). The Gualala River lies within the Central California Coast coho salmon Evolutionary Significant Unit (ESU), which is listed as endangered under the Endangered Species Act (NMFS 2005). Critical habitat includes all river reaches and estuarine areas accessible to coho salmon within the ESU's geographic area (NMFS 1999), including coastal drainages from the Punta Gorda in northern California south to and including the San Lorenzo River in central California, the drainages of San Francisco and San Pablo bays, excluding the Sacramento-San Joaquin River basin. Populations within the Central California Coast coho ESU have generally been declining since the 1980s (Klamt et al. 2002). Although 10,000 to 20,000 coho salmon fry were planted annually in the Gualala River basin from 1969 through 1999, electrofishing surveys conducted by the California Department of Fish and Game (CDFG 2001, as cited in Klamt et. al. 2002) do not indicate the presence of a self-supporting population. In 2002, small numbers of coho salmon were observed in Dry Creek during snorkel surveys, and electrofishing surveys recorded coho salmon in Doty Creek and Little North Fork Creek. All three of these streams are at the northern edge of the Gualala basin and are not within the Study Area.

Steelhead in the Gualala river basin are part of the Northern California steelhead Distinct Population Segment (DPS) and are listed as threatened under the Federal ESA (NMFS 2006). Annual planting of steelhead occurred from 1972 through 1976 (83,220 fish planted), and from 1983 through 1990 (343,070 planted) (Klamt et al. 2002). In 1993, the Gualala River Steelhead Project began relocating juveniles from streams that dried during the summer. The steelhead were held in a hatchery over summer and released into the North Fork sub-basin and mainstem Gualala River following significant fall rain events that provided more favorable conditions for the juveniles. This continued from 1993 to 1997 and from 1999 to 2000, with over 20,000 steelhead being rescued and released over all years (Klamt et al. 2002). The Gualala roach has replaced steelhead as the dominant species in most areas of the basin as a result of increased water temperatures (Klamt et al. 2002, CDFG unpublished data, 2002). Accurate adult steelhead population estimates for the Gualala River basin, and the Buckeye and Wheatfield Fork sub-basins, are not available. In general, steelhead stocks throughout California have declined substantially. The most current estimate of the population of steelhead in California is approximately 250,000 adults, which is roughly half the adult population that existed in the mid-1960s (McEwan and Jackson 1996). A summary of the life history and habitat requirements of steelhead is provided below and the general steelhead life cycle is presented in Figure 3-1.

3 ANALYSIS SPECIES

One of the premises of the limiting factors analysis (LFA) was that a selected analysis species could be used for evaluating the impacts of watershed activities on a range of native aquatic species found within the basin. An analysis focused on the life history and habitat requirements of a certain species allows us to improve our understanding of the relative importance of various watershed processes and habitat features, identify factors currently limiting the distribution and abundance of the species in the watershed, and evaluate the degree to which watershed-level management strategies may benefit the species. Additionally, assessing the factors that may be limiting production of an analysis species at each freshwater life stage helps evaluate the impact of a specific stressor (e.g., sediment) at multiple temporal and spatial scales.

Steelhead (*Oncorhynchus mykiss*) was chosen as the analysis species for the Preservation Ranch LFA because this species: (1) has special regulatory status (the Northern California Distinct Population Segment [DPS] of steelhead is listed as threatened under the federal Endangered Species Act (NMFS 2006), (2) has high economic and public interest value, (3) has relatively narrow life stage specific habitat requirements that together encompass a wide range of habitats and habitat components, (4) is dependent on habitats that have likely been reduced in quality and quantity from historical conditions because of anthropogenic land use within the basin and elsewhere, (5) is in decline locally and regionally, and (6) has habitat requirements that generally represent the needs of a suite of native coldwater fish species. Steelhead, and its resident form rainbow trout, are the only salmonids currently present in the Study Area (Klamt et al. 2002 Appendix A.5). Coho salmon are also known to occur within the Gualala River basin within the North Fork sub-basin, but have not been observed within the Buckeye Creek or Wheatfield Fork sub-basins since the 1970s (Klamt et al. 2002).

3.1 Steelhead Life History Overview

Steelhead is the term commonly used for the anadromous life history form of rainbow trout. In the Gualala River basin, both resident and anadromous life histories are present (Cox 1989), although detailed information on the relative proportion of each life-history type not available. For convenience, we use the term steelhead throughout this report to describe all *O. mykiss* in the Gualala River basin. The relationship between anadromous and resident forms of this species is the subject of ongoing research. Evidence suggests that the two forms are capable of interbreeding and that either life history form can produce offspring that exhibit the alternate form (i.e., resident rainbow trout can produce anadromous progeny and vice-versa) (Shapovalov and Taft 1954, Burgner et al. 1992, Hallock 1989). The fact that little to no genetic differentiation has been found between resident and anadromous life history forms inhabiting the same basin supports this hypothesis (Busby et al. 1993, Nielsen 1994, as cited in Zimmerman and Reeves 2000).

Steelhead return to spawn in their natal stream, usually at age 4 or 5 years, with males typically returning to freshwater at a younger age than females (Shapovalov and Taft 1954, Behnke 1992). A small percentage of steelhead may stray into streams other than their natal stream. Based on variability in the timing of their life histories, steelhead are broadly categorized into winter and summer reproductive ecotypes. The winter ecotype (winter-run) occurs in the Gualala River basin. Winter-run steelhead generally enter spawning streams from late-fall through spring as sexually mature adults, and spawn January through March (Roelofs 1985, Bjornn and

Reiser1991, Behnke 1992), but spawning may begin as early as late December and extend through May (Hallock et al. 1961).

Female steelhead construct redds in suitable gravels, often in pool tailouts and heads of riffles, or in isolated patches in cobble-bedded streams. Steelhead eggs typically incubate in the redds for 25–30 days, depending on water temperatures (Shapovalov and Taft 1954, Barnhart 1991). After hatching, alevins remain in the gravel for an additional 2–5 weeks while absorbing their yolk sacs, and then emerge in spring or early summer (Barnhart 1991).

After emergence, steelhead fry move to shallow-water, low-velocity habitats, such as stream margins and low-gradient riffles, and forage in open areas lacking instream cover (Hartman 1965, Fontaine 1988). As fry grow and improve their swimming abilities in late summer and fall, they increasingly use areas with cover and show a preference for higher velocity, deeper mid-channel areas near the thalweg (the deepest part of the channel) (Hartman 1965, Everest and Chapman 1972, Fontaine 1988).

Juvenile steelhead (parr) rear in freshwater before outmigrating to the ocean as smolts. The duration of time parr spend in freshwater appears to be related to growth rate, with larger, faster-growing members of a cohort smolting earlier (Peven et al. 1994). Steelhead in warmer areas, where feeding and growth are possible throughout the winter, may require a shorter period in freshwater before smolting, while steelhead in colder, more northern, and inland streams may require three or four years before smolting (Roelofs 1985).

Juvenile steelhead occupy a wide range of habitats, preferring deep pools as well as higher velocity riffle and run habitats (Bisson et al. 1982, Bisson et al. 1988). During periods of low temperatures and high flows that occur in winter months, steelhead prefer low-velocity pool habitats with large rocky substrate or woody debris for cover (Hartman 1965, Raleigh et al. 1984, Swales et al. 1986, Fontaine 1988). During high winter flows, juvenile steelhead seek refuge in interstitial spaces in cobble and boulder substrates (Bustard and Narver 1975).

Juvenile emigration typically occurs from March through June. Emigration appears to be more closely associated with size than age, with a total length of 15–20 cm (6–8 in) being the most common size for downstream migrants. Depending partly on growing conditions in their rearing habitat, steelhead may migrate downstream to estuaries as age 0+ juveniles or may rear in streams for up to four years before outmigrating to the estuary and ocean (Shapovalov and Taft 1954). Steelhead migrating downstream as juveniles may rear for one month to a year in the estuary before entering the ocean (Shapovalov and Taft 1954, Barnhart 1991).

3.2 Steelhead Life History and Habitat Use Conceptual Model

In this section, we describe a conceptual model of linkages between physical habitat and the life history of steelhead. We then briefly discuss how existing steelhead abundance data and results from population surveys conducted during this study were used to screen the initial list of potential limiting factors to develop a list of hypotheses specific to the Study Area.

Generally speaking, a wide range of factors may limit the size and growth potential of a population of organisms. While a variety of factors may serve as the primary limiting factor for a given life stage under specific circumstances, our goal was to identify the factor or factors that appeared to be limiting the population of steelhead under current conditions in the Gualala River basin. The primary aim of this analysis was to use knowledge of various potential limiting factors combined with information gathered from focused studies to examine the importance of sediment- and flow-related impacts relative to other potential limiting factors.

Steelhead can smolt at a variety of ages, but most frequently smolt at ages 1+ and 2+[1]. Because juvenile steelhead must spend at least one summer and winter in freshwater prior to outmigrating to the sea, they tend to establish territories[2] in suitable rearing habitat soon after emergence from the gravel (as opposed to fall Chinook, chum, pink, and sockeye salmon, which only spend a few days, weeks, or months within their natal stream). The maximum densities of oversummering age 0+ steelhead that a reach of stream can support are determined by territorial/agonistic behavior, both intraspecific and interspecific with other salmonids when they are present. Aggressive displays such as gill flaring, fin extensions, charges, and attacks are used to actively defend individual territories. This behavior results in density-dependent emigration or mortality of juvenile steelhead that do not successfully establish and defend territories.

The size of steelhead territories may vary from location to location or between seasons as a function of food availability and temperature, becoming smaller when habitats are more productive or when they are colder. Whether territories are relatively large or small, the forming of territories during freshwater rearing provides an important mechanism for partitioning a finite food resource among individuals and regulating the growth of juvenile steelhead. If territories were not established and defended by individuals, the result would either be mortality of many juveniles due to starvation or the production of a large number of small smolts that, as we discuss below, would have very poor ocean survival.

Steelhead smolts tend to have much greater survival to adulthood if they outmigrate as age 2+ or older smolts because the older fish are generally larger. Although they are sometimes common, age 1+ smolts may contribute little to the numbers of returning adults[3]. This differential survival is likely due to the advantages that larger fish have in evading predation, either through superior swimming ability or by surpassing the gape size of potential predators. In considering steelhead life histories, it is important to distinguish between age 1+ smolts and age 1+ downstream migrants. It is a common life history strategy for juvenile steelhead to migrate downstream in the spring but rear for an additional year before smolting in an estuary when one is present. This is true of all age classes of juvenile steelhead but especially common at age 1+. Age 1+ steelhead that rear in the estuary will then smolt at age 2+ the following spring and, because they may be larger as a result of greater food supply in the estuary, they may experience similar if not higher survival to adults as stream-reared age 2+ smolts. Therefore, both in instances of stream rearing and estuary rearing, production of adult steelhead depends greatly on the size of the smolts produced and advantageous smolt size is most often reached by age 2+.

The relatively extended freshwater rearing of steelhead has important consequences for its population dynamics. The maximum number of steelhead that a stream can support is limited by food and space through territorial behavior, and this territoriality is necessary to produce

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[1] We follow conventional methods for assigning fish ages to year classes. Age 0+ refers to fish in their first year of life, sometimes called young-of-the-year; age 1+ to fish in their second year of life, and so on. A fish changes from age 0+ to age 1+ based on the time of hatching, which in the case of steelhead occurs in the spring.

[2] We use the term territory and territory size not only in its traditional sense—as a particular defended area —but also in cases where defense of a particular area may not occur but agonistic behavior by dominant individuals (e.g., nips, fin extensions, charges) effectively determine the maximum density of rearing juvenile steelhead in an area.

[3] Patterns described here are typical of North Coast and Central Valley populations, but may not necessarily reflect life histories of steelhead in southern California. South of San Francisco Bay, where warmer stream temperatures and longer photoperiods may lead to higher steelhead growth opportunities in some seasons, fish may achieve a suitable size for smolting at age 1+.

steelhead smolts that are large enough to have a reasonable chance of ocean survival. Because of these habitat requirements, the number of age 0+ fish that a reach of stream can support is typically small relative to the average fecundity of an adult female steelhead. For example, a female steelhead may produce, on average, about 5,000 eggs. Typical age 0+ densities in some of the most productive California steelhead streams (e.g., tributaries to South Fork Eel River) have been around 1.1 fish/m^2 (0.10 fish/ft^2) (Connor 1996). Consequently, reproductive effort may have little effect on the next generation's adult population size (although it may influence how many offspring from a particular female will occupy the finite number of territories within a stream). Because of this, spawning gravel availability and egg mortality (e.g., as a result of poor gravel quality, redd dewatering, fungal infections, redd scour) may not have an important effect on steelhead population dynamics. In other words, any density-dependent mortality that might result from redd superimposition or density-independent mortality resulting from redd scour and poor gravel quality (among other factors) may be irrelevant because, despite these sources of mortality, far more fry are typically produced than can be supported by the available rearing habitat. Therefore, the availability of suitable juvenile rearing habitat (either in the summer or winter) is the factor that usually governs the number of steelhead smolts produced from a stream. Consequently, we would expect that, even with small escapements and high egg mortality, available summer habitat will usually be well seeded with steelhead fry.

Within the freshwater rearing stages of their life histories, the physical habitat requirements for different age classes of steelhead are relatively similar, except that as fish age and grow their requirements for space tend to become more restrictive. We postulate that age 0+ steelhead rearing habitat, both summer and winter, did not typically limit steelhead production under historical conditions and does not currently do so. Age 0+ steelhead can use shallower habitats and finer substrates (e.g., gravels) than age 1+ steelhead, which, because of their larger size, need coarser cobble-boulder substrate for velocity cover while feeding and escape cover from predators. Because age 0+ steelhead can generally utilize the habitats suitable for age 1+ steelhead, but age 1+ steelhead can not use shallower and/or finer substrate habitats suitable for age 0+ steelhead, it is unlikely that summer habitat will be in shorter supply for age 0+ than age 1+ steelhead. There may be stream systems or reaches where all available habitat is suitable for both age 0+ and age 1+ steelhead, but even in these cases the density of age 0+ steelhead that the habitat will support will be higher than for the larger age 1+ steelhead simply due to allometric increases in territory size. In situations where summer habitat is suitable for both age classes, competition for space between age 0+ and age 1+ steelhead may restrict the numbers of age 0+ steelhead that the habitat will effectively support. But in general, a reach of stream would commonly support far fewer age 1+ than age 0+ steelhead in the summer.

Cobble-boulder rearing habitat complexes may occur within discrete portions of the channel network according to reach-scale sediment supply and transport capacity, channel confinement, and local hillslope processes. Cobble-boulder rearing habitats are supported by channels with adequate stream power to maintain a bed composed of larger particles (>90 mm), are confined, encouraging in-channel deposition of cobbles and boulders, and are coupled to hillslopes so hillslope processes are a proximal source of large particles. Using the conceptual framework of Montgomery and Buffington (1997), which describes a downstream sequence of channel types based on longitudinal trends of sediment transport capacity and supply, with transport capacity decreasing downstream with slope and supply increasing downstream with drainage area, cobble-boulder rearing habitats are most likely to occur in step-pool channels. Step-pool channels are characterized by clast-formed longitudinal steps separated by pools that act as temporary storage sites for transient fine sediment. Step-pool channels have steep gradients (~3–7%), and typically flow through confined valleys with active hillslope processes. Sediment transport capacity exceeds sediment supply, leaving a channel composed of large clasts, potentially within the cobble-boulder size range. Discharge is occasionally great enough to rearrange bed material, but even after such events, the material will still self-organize into discrete step-forms. Farther upstream are cascade channel types (Montgomery and Buffington 1997), which are also steep with confined valleys, but with bed material that is disorganized and likely not predisposed to forming cobble-boulder habitat complexes. Farther downstream, sediment transport capacity decreases with channel gradient while relative fine sediment supply increases, leaving channels comprised of median sediment sizes that are smaller than cobble-boulder. Cobble-boulder substrates may occur locally, but tend not to be organized into discrete complexes and are embedded in finer sediment.

Step-pool reaches are also relatively confined and deep enough to contain cobble-boulder substrates within their wetted channel. A channel should be at least as deep as the smallest cobble grains within a cobble-boulder habitat complex to be usable as juvenile fish rearing habitat. Confinement also restricts the cobble-boulder substrates to the wetted channel. Wider reaches found lower along the continuum, such as plane-bed and pool-riffle not only lack the gradient to support discrete, unembedded cobble-boulder habitat complexes, but are also flanked by gravel bars over which cobbles and boulders may distribute rather than remaining in the center of the channel.

The formation and persistence of cobble-boulder habitat complexes may also depend on a proximal source of large particles, favoring channels that are coupled with hillslopes and active hillslope processes (Coulombe-Pontbriand and Lapointe 2004). Along the continuum of channel types, the degree of channel-hillslope coupling decreases in the downstream direction, with step-pool channels tightly coupled with the adjacent hillslopes, but with the degree of coupling reducing as alluvial floodplains develop (Montgomery and Buffington 1997). The adjacent hillslopes may provide numerous, chronic and episodic, sources of coarse sediment to step-pool channels.

As with summer habitat, a reach of stream will typically support far fewer age 1+ than age 0+ steelhead in the winter. In watersheds where temperatures become cold in winter (i.e., < 7°C (45°F)), predation risk becomes much greater because the fish become slower, sluggish, and less able to escape predators. Refuge from high flows requires a similar type of habitat as concealment cover, but may require access deeper into the streambed to avoid turbulent conditions that exist near the surface or even within the first layer of substrate. During winter juvenile steelhead will often hide within the substrate (or other cover) during the day, emerging only at night. In colder regions, juvenile steelhead may remain concealed in the substrate all winter. Because steelhead tend to spawn in higher gradient reaches (i.e., >3%) with confined stream channels, off-channel water bodies such as sloughs and backwaters are typically rare. As a result, steelhead show less propensity than other species (e.g., coho salmon) for using off-channel slackwater habitats in winter, and a greater propensity for using in-channel cover provided by cobble and boulder substrates, which are typically common and usually immobile at all but the highest flows in these areas. Because age 0+ steelhead are smaller and can utilize a wider range of substrate than age 1+ steelhead, it will often be the case that there is more winter habitat available for age 0+ than for age 1+ fish.

In watersheds where, as a result of anthropogenic disturbance, there are increased inputs of coarse and fine sediment to the stream channel and decreased large woody debris, the disparity between the amount of summer habitat for age 0+ steelhead and age 1+ steelhead is often increased. Pool frequency is reduced with the removal of large woody debris, especially in forced pool-riffle and plane-bed stream reaches. The remaining pools may become shallower as a result of aggradation and the lack of scour-forcing features such as large woody debris. The filling of interstitial spaces of cobble-boulder substrates by gravels and sand can affect summer habitat for both age 0+ and age 1+ steelhead. But because of the larger size and more secretive nature of age 1+ steelhead, their habitat will be more affected by embeddedness than age 0+ steelhead.

Likewise, in the winter, habitat may often become unsuitable for age 1+ steelhead at lower levels of finer sediment deposition than for age 0+ steelhead. At higher levels of embeddedness, substrate will become unsuitable for both summer and winter rearing, but it will often be more limiting in winter because refuge from entrainment during winter freshets typically occurs deeper within the substrate.

4 FOCUSED STUDIES

The focused studies concentrated filling information gaps and testing hypotheses regarding physical and biological factors that may limit the distribution and abundance of steelhead in the Study Area. The studies involved gathering data to identify and refine our understanding of the links between physical processes and steelhead population responses, and ultimately improve our process-based conceptual model for steelhead in the Study Area.

4.1 *O. mykiss* Abundance

4.1.1 Population assessment

Fish population monitoring in the Gualala River has been limited in scope and the resulting data provide an incomplete view of trends in steelhead abundance. Information on historical fish community composition and species distributions in the Gualala River is limited. Available data and results of recent field studies provide “snapshots” of a dynamic system in which various factors may influence steelhead populations. Available information suggests that steelhead and coho salmon were abundant in the basin up until the 1940s (Higgins 1997). Steep declines in steelhead abundance were observed in the mid-1960s, and coho salmon have not been observed in recent years (Klamt et al. 2002). Several past surveys have documented the presence and distribution of steelhead in the Gualala River, but only recently have there been efforts to quantify steelhead abundance.

Examination of available steelhead data (

Table 4.1-1) for the Buckeye Creek and Wheatfield Fork basins reveals significant information gaps. First, no surveys have been conducted to document steelhead presence or habitat conditions in the middle and upper elevations of the Study Area watersheds. Second, the methods used to collect the data were insufficiently rigorous to allow estimation of the proportion of age 0+, 1+, or 2+ steelhead present at any given time. Variability with regard to seasonal timing of sampling, along with methods used and level of effort, also preclude estimating survival of various age classes between years. Finally, all steelhead data collected in Gualala basin streams have been collected in the period from mid-summer to early fall, apart from limited spawning surveys (DeHaven 2001 and 2002). No data are available on juvenile steelhead distribution, habitat use, or abundance in the winter or spring.

Table 4.1-1. Steelhead monitoring site location, year, and method of collection. (All snorkel surveys were single-pass, with single or multiple divers; all electrofishing was single-pass, with no blocking net employed.)

Site ID	Date of data collection	Method
Buckeye Creek sub-basin		
223	1998–2002	Snorkel Survey[1]
223	2003, 2004	Electrofishing[1]
Wheatfield Fork sub-basin		
224	2003	Electrofishing[1]
226	1998, 2002	Snorkel Survey [1]
226	2003	Electrofishing[1]
227	2003	Electrofishing[1]
97-01	2000	Electrofishing[2]
97-01	2001, 2002	Snorkel Survey[2]
97-02	2000, 2001	Electrofishing[2]
97-03	2000, 2001	Electrofishing[2]
97-04	2000, 2001, 2002	Electrofishing[2]
97-05	2000, 2002	Electrofishing[2]
97-05	2001	Snorkel Survey[2]
97-06	2000, 2001	Electrofishing[2]
97-07	2000, 2001, 2002	Electrofishing[2]
97-08	2000, 2001, 2002	Electrofishing[2]
97-09	2000, 2001	Electrofishing[2]
97-10	2000, 2001, 2002	Electrofishing[2]
97-11	2000, 2002	Electrofishing[2]
97-11	2001	Snorkel Survey[2]
97-12	2000, 2001	Electrofishing[2]
97-13	2000, 2001, 2002	Electrofishing[2]
97-14	2000, 2001, 2002	Snorkel Survey[2]
97-15	2000, 2001	Electrofishing[2]

[1] Source: Gualala Redwoods Company (unpublished data, 2005)
[2] Source: Mendocino Redwood Company (unpublished data, 2002)

The primary source of steelhead abundance information is from direct observation surveys conducted in 2006 for the purposes of this study. Eight reaches in the Study Area were sampled in late winter/early spring (March and May), 11 reaches in early summer (June), and six in early fall (September) 2006 (Map 1, Table A1-1). Age-specific juvenile steelhead densities were estimated from direct observation using the "Method of Bounded Counts," described in Hankin and Mohr (2005) and Appendix A.1. The limited data on "juvenile" steelhead densities (not separated by age class) collected during late winter, early summer, and early fall represents a sparse but necessary starting point for analyzing steelhead population dynamics in the basin. As described in our general conceptual model, we believe the production of age 2+ or older smolts is essential to the success of the population and that the habitats required for producing them, such as deep, large woody debris (LWD) formed pools and unembedded cobble-boulder substrates, were limited under historical conditions, and are likely even more limited under current, disturbed conditions. Therefore, the initial focus was on evaluating ratios of abundance between different life stages. This approach led to the following hypotheses.

1. If the number of age 1+ steelhead is high during the early summer relative to the number of age 1+ during the late summer/fall (i.e., if abundance of age 1+ fish declines over the summer), then it would indicate that summer habitat for age 1+ fish is limiting.

2. If the late summer/fall abundance of age 0+ steelhead is high relative to age 1+ steelhead the following late winter, then winter habitat for age 0+ fish is likely limiting (of course, this would also imply a limitation of age 1+ winter habitat, indicating that increasing age 0+ winter habitat, without also increasing age 1+ winter habitat, would not result in an increase in age 2+ smolts).

The precision of both conceptual and parameterized numerical population models depends on the quantity and quality of available information. For the analyses described below, we limited our discussion to the seven reaches that were sampled during our three sample periods in 2006 (Flat Ridge, Franchini, Fuller, Grasshopper, North Fork Fuller, Redwood, and Tombs Creeks; see Appendix A.1 for complete results). Not all of the reaches were sampled in all periods due to weather, access, and timing constraints. Because of the lack of historical population information for the Gualala River basin, results must be considered preliminary and subject to considerable uncertainty until more information becomes available to test the assumptions on which the models are based. Nevertheless, the existing information provides a starting point for examining the two hypotheses above.

4.1.2 Population modeling

An assessment of current habitat conditions for steelhead in the Study Area was conducted within the framework of a population dynamics model. This assessment relies on fundamental concepts in population dynamics, particularly stock-production analysis. The assessment performed here was based on results from field studies conducted by Stillwater Sciences and is intended only to provide a preliminary, and conservative, indication of the degree to which steelhead smolt production may be limited by current channel conditions.

The salmonid population modeling approach used in this analysis is based on stock-production theory (Ricker 1976). Stock-production theory characterizes the number of individuals of one life stage at one time (the production) as a function of the number in the same cohort of an earlier life stage at an earlier time (the stock). This approach is particularly well suited to situations where physical habitat is believed to be limiting, and where population dynamics can be plausibly separated into density-independent and density-dependent components, such as productivity (the ratio of stock to production that would be expected if there were no limits on population density) and carrying capacity (the maximum number of individuals of a given life stage that the habitat can support for the duration of that life stage). A detailed description of the population modeling approach is described in Appendix A.2.

Mortality occurs at every steelhead life stage due to factors that may vary by season and development (i.e., age and size) of fish. When considered in isolation, these mortality factors may not elucidate habitat factors affecting steelhead population growth. For example, in some streams, improving summer rearing habitat may increase summer carrying capacity, but if winter habitat is more limiting, no population growth will occur. Our goal in this study was to assess factors limiting the growth of the steelhead population, rather than the abundance of steelhead at any given life stage. To that end, data resulting from selected focused field studies were used as input for preliminary modeling efforts to test our hypotheses.

4.2 Spawning Gravel Permeability

The availability and quality of spawning gravel is a key factor influencing the spawning success of anadromous salmonids. Successful spawning and incubation requires gravel of appropriate size, in appropriate locations, and without excessive fine sediment. Gravel must also be distributed in patches large enough to allow redd construction, and must be deep enough to allow excavation of an egg pocket by the spawning fish. The key factor determining survival of salmonids during egg incubation through fry emergence is sufficient flow of cool, oxygenated water through the spawning gravels to ensure adequate delivery of dissolved oxygen and removal of metabolic wastes. When fine sediment is deposited in or on the streambed, gravel permeability[4] can be substantially reduced. Gravel permeability and hydraulic head together determine the rate of interstitial flow. Reduced gravel permeability results in progressively less oxygen and greater concentrations of metabolic wastes around incubating eggs and alevins (newly hatched fish larvae, or sac-fry) as they develop in the pore spaces between gravels, resulting in higher mortality (McNeil 1966, Cooper 1965, Platts 1979, Barnard and McBain 1994).

We hypothesized that fine sediment in Buckeye Creek and Wheatfield Fork has increased from historical levels based on a review of existing information (i.e., Klamt et al. 2002) and reconnaissance-level field assessments made by Stillwater Sciences in October 2005, during which we observed that patches of suitably-sized spawning gravels were frequently embedded with fine and coarse sand. Depending on the extent of sand and depth of spawning gravels, permeability could be poor in these areas, indicating that, regardless of the amount of spawning habitat available, survival to emergence may be poor.

Spawning habitat quality was assessed using standpipe gravel permeability measurements that provide a rapid and cost-effective indicator of both gravel quality and egg survival (Terhune 1958, Barnard and McBain 1994). Permeability is preferred as a descriptor of spawning gravel quality because (1) it is the descriptor most directly related to salmonid survival during egg incubation through fry emergence, and (2) it is directly affected by fine sediment deposition. Permeability measurements can be converted to predicted survival-to-emergence rates using relationships derived from field observations of redds with differing permeabilities (Tagart 1976) and studies where the permeability of artificial redds was manipulated experimentally (McCuddin 1977) (Figure 4-1). Detailed methods are described in Appendix A.3.

The relative importance of egg survival to steelhead population dynamics, as affected by spawning gravel permeability, was evaluated using a population model that incorporates data from focused field studies and values for habitat- and life-stage-specific fish densities and survival rates reported in the literature (discussed in further detail in Appendix A.2). The model was run using survival-to-emergence values ranging from 0 to 100%. The results of varying survival rates were expressed in terms of the fraction of smolts produced at a given survival rate relative to maximum potential smolt production assuming 100% egg survival (see Figure 4-2 and discussion below).

We focused our spawning habitat studies in five tributary reaches that represented the geographic range of spawning distribution within the Study Area: Flat Ridge Creek, Grasshopper Creek, Franchini Creek, Redwood Creek, and Fuller Creek. The most relevant findings of the spawning gravel analysis are discussed below. Detailed methods and results are presented for the permeability studies in Appendix A.3.

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[4] Our use of the term 'permeability' (expressed in units of length/time), is consistent with the established convention in fisheries biology. However the property being measured is more accurately termed 'hydraulic conductivity,' as defined in the hydraulics literature.

Spawning gravel patches as small as 2 ft^2 (0.18 m^2) may be used by resident rainbow trout (Bjornn and Reiser 1991). Values reported in the literature for average steelhead redd sizes are as high as 50 ft^2 (4.64 m^2) in large alluvial rivers (Bjornn and Reiser 1991), but patches as small as 4 ft^2 (0.37 m^2) may be used, especially in streams where spawning gravel occurs in small isolated patches (W. Trush, pers. comm., 2004).

Based on permeability measurements recorded at 43 potential steelhead spawning sites, median predicted survival to emergence was 38%, with three of the 43 sites having predicted survival rates lower than 25% and no sites having predicted survival rates greater than 72% (Figure 4-3, Appendix A.3). The highest average survival to emergence was found in Franchini Creek (51%), while the lowest was found in Flat Ridge Creek (36%). These were also the only two sites that were significantly different at the 95% level ($p = 0.031$).

Shapovalov (1937, as cited in Shapovalov and Taft 1954) found that survival to emergence of steelhead was 29.8% “in the presence of considerable silting” and 79.9% in the absence of silting. Shapovalov and Taft (1954) hypothesized that under favorable conditions, survival to emergence is high (70–85%) for steelhead. From these results, we concluded that our original hypothesis—that gravel permeability at potential spawning sites was insufficient to support high egg-to-emergence survival—is correct, and that elevated fine sediment concentrations in the subsurface of the channel bed may be adversely affecting egg-to-emergence survival in the Study Area.

The relative importance of egg-to-emergence survival to steelhead population dynamics, as compared with factors such as the availability of rearing habitat for juveniles, was assessed via population modeling using data from the permeability assessment and other focused field studies. The results of the sensitivity analysis are illustrated in Figure 4-2. The analysis demonstrates that increases in smolt production can be expected relative to increases in egg survival only when egg survival is very low to begin with (e.g., lower than 10%). The response of a population to increased egg survival diminishes rapidly, and even 10% egg-to-emergence survival is sufficient to produce nearly 100% of the maximum number of smolts expected under optimum spawning habitat conditions (i.e., maximum [100%] permeability) for sites in the Study Area. Similarly, no increases in smolt production would be expected by increasing spawning gravel quantity, since population modeling indicated that greatly increasing fry production results in only very small increases in smolt production. These results strongly suggest that, despite relatively low predicted survival-to-emergence rates, steelhead production is not likely limited by spawning habitat quality or quantity in the Study Area.

Despite predictions of low egg-to-emergence survival, our spring, summer, and fall 2006 fish surveys indicate that juvenile steelhead are common to abundant in Buckeye Creek and Wheatfield Fork. This is consistent with the results of our population modeling that indicate only limited spawning habitat is needed to effectively seed available rearing habitat in the Study Area. These findings are also consistent with empirical and theoretical evidence presented in our conceptual model for steelhead in Section 3. The relative importance of reduced permeability as compared with factors such as the availability of rearing habitat for juveniles is discussed further in Section 5.

4.3 Summer Habitat Suitability

Water temperature is a particularly relevant parameter for understanding constraints on steelhead because steelhead rear as juveniles in freshwater for one or more years. Steelhead may experience several summer seasons while rearing, during which they may be exposed to warm water temperatures and the resulting thermal stresses. The direct impacts of high temperatures may include both acute and chronic effects. Acute effects tend to involve decreased or disrupted enzyme function, which may compromise a wide range of physiological functions and result in total incapacitation and death. Chronic effects involve physiological changes that slowly degrade the condition of the fish, such as increased metabolic rate (which beyond a certain threshold reduces growth efficiency), reduced immune system function (which increases susceptibility to disease), or reduced energy (which reduces foraging efficiency). Indirectly, high temperatures may affect coldwater fish such as steelhead by reducing dissolved oxygen (the dissolved oxygen capacity of water is inversely related to temperature), or by changing the behavioral or physiological characteristics that affect the competitive balance among species, and hence may result in a shift in fish species composition or relative abundance. In addition, because steelhead are sensitive to increases in temperature, any additional factors that might increase physiological stress, such as disease, food limitations, elevated turbidity, or increased competition between species, have the potential to exacerbate the effects of elevated temperatures.

The amount of direct solar radiation reaching the water surface is the primary factor influencing water temperature. Removal of riparian vegetation that would otherwise shade the stream surface can increase the exposure of the water surface to solar radiation, resulting in warmer water temperatures. In addition, alterations of channel geomorphology that lead to an increased width to-depth ratio increase water surface area per unit flow volume, thus increasing the potential for solar heat gain. Portions of the Study Area have likely aggraded and become wider and shallower due to land use impacts over the last century (timber harvest, grazing, etc), which has likely led to an increase in the width-to-depth ratio. Groundwater inputs to streams typically have a local cooling effect, at least during the summer months, and may be of particular importance for providing local pockets of cold water within the generally warmer stream network. Actions that reduce groundwater inputs into the stream channel during summer months can therefore affect the thermal environment of salmonids and other aquatic organisms.

We characterized existing temperature patterns in the Study Area using continuous recording thermographs (set to record temperature at 15-minute intervals) deployed at 23 sites (Map 3). The thermographs were deployed in early June 2006 and retrieved in late September 2006. Five of the thermographs were deployed in mainstem Buckeye Creek, nine were placed in the mainstem of Wheatfield Fork, and the remainder in tributaries.

High summer water temperatures in portions of the Study Area may result in low summer steelhead growth rates. Maximum weekly average water temperatures (MWATs) at nine sites along the Wheatfield Fork (including the confluence with Tombs Creek) were close to or exceeded lethal limits reported for steelhead and rainbow trout (24–27°C [75–80°F]; Hokanson et al. 1977, Bell 1991, Bjornn and Reiser 1991, Myrick and Cech 2001). In general, mainstem Wheatfield Fork had higher MWATs, greater daily mean, maximum, and minimum temperatures, and greater daily temperature fluctuations than any other reach (Appendix A.5**)**, with a trend toward progressively higher temperatures and greater temperature fluctuations in an upstream direction in response to reduced canopy cover and greater insolation within the oak woodlands that are found in upper reaches. Temperatures were slightly lower at RM 26.2, possibly due to the influence of springs or groundwater inputs, or channel narrowing that increases channel shading. Consequently, summer conditions in the mainstem Wheatfield Fork may be limiting to steelhead populations.

In addition to an overall trend of increasing average temperatures and greater temperature fluctuations in an upstream direction in mainstem (Buckeye Creek and Wheatfield Fork) reaches, there were differences in MWATs, and daily mean, maximum, and minimum temperature among tributary sites. Franchini and Grasshopper Creeks had the lowest MWATs and daily mean temperatures with very little fluctuation, most likely due to the dense coniferous riparian and upland vegetation shading the stream channel (Appendix A.5). Conversely, Tombs Creek had the highest MWAT of any tributary with large, regular fluctuations about the daily mean temperature, which were likely due to low topographic and riparian shading of the channel.

Table 4.3-1. Maximum weekly average temperatures (MWATs) recorded within the Study Area. See Map 3 for datalogger locations.

Site	Abbreviation	Week Ending Date (2006)	MWAT (°C)
Buckeye Creek (RM 10.3)	BU 10.3	7/26	21.8
Buckeye Creek (RM 10.4)	BU 10.4	7/26	22.5
Buckeye Creek (RM 13.4)	BU 13.4	7/26	22.9
Buckeye Creek (RM 15.8)	BU 15.8	7/26	23.3
Buckeye Creek (RM 15.9)	BU 15.9	7/26	23.6
Flat Ridge Creek (RM 0.0)	FL 0.0	7/26	23.2
Franchini Creek (RM 0.0)	FR 0.0	7/26	17.4
Fuller Creek (RM 2.4)	FU 2.4	7/27	19.3
Grasshopper Creek (RM 3.4)	GR 3.4	7/26	17.3
North Fork Buckeye Creek (RM 0.1)	NFBU 0.1	7/26	21.7
North Fork Fuller Creek (RM 0.1)	NFFU 0.1	7/26	19.8
Redwood Creek (RM 0.0)	RE 0.0	7/27	20.9
Tombs Creek (RM 0.0)	TO 0.0	7/27	24.7
Wheatfield Fork (RM 7.9)	WH 7.9	7/26	23.9
Wheatfield Fork (RM 9.2)	WH 9.2	7/26	24.5
Wheatfield Fork (RM 9.3)	WH 9.3	7/26	25.1
Wheatfield Fork (RM 15.8)	WH 15.8	7/26	26.8
Wheatfield Fork (RM 20.7)	WH 20.7	7/26	26.2
Wheatfield Fork (RM 20.9)	WH 20.9	7/26	26.5
Wheatfield Fork (RM 26.2)	WH 26.2	7/27	24.9
Wheatfield Fork (RM 26.5)	WH 26.5	7/27	25.1
Wheatfield Fork (RM 27.3)	WH 27.3	7/27	25.1

The first step in our analysis of steelhead population dynamics is to examine whether the density of age 1+ steelhead was high during early summer relative to the density of age 1+ fish during the early fall. If so, this may indicate that age 1+ summer habitat is limiting. In five out of the seven observed reaches, densities of age 1+ and older fish increased from early summer to early fall 2006, suggesting that summer habitat is not limiting steelhead populations in these areas (Figure 4-4). These reaches had cool water temperatures during the summer, as shown by Maximum Weekly Average Temperatures (MWATs) recorded by temperature dataloggers deployed throughout the study area (Table 4.3-1). Temperatures did not exceed 21°C (70°F), except for in Flat Ridge Creek, which had an MWAT of 23 °C (74°F). Tombs Creek, with the highest recorded MWAT over the summer (24.7°C [76°F]), showed a decrease in age 1+ steelhead density, suggesting that it was too warm to support juvenile steelhead and that age 1+ summer habitat may be limiting within this reach. Tombs Creek is located in the oak woodland zone of the Study Area (Map 4), which generally possesses sparser riparian bank cover and greater insolation (solar radiation) rates during the summer, resulting in higher water temperatures (Table 4.3-2). Age 1+ steelhead density also decreased over the summer in Redwood Creek, which flowed through the oak woodland zone, but was steeper (3–7 % channel gradient) and narrower, with greater riparian shading (lower insolation rates) than Tombs Creek, resulting in a lower summer MWAT and greater early fall densities of juvenile steelhead. If we assume that the observations in Tombs Creek apply to similar reaches within the basin, and that these densities are typical for juvenile steelhead within these reaches, then this suggests that summer habitat is limiting in wider, lower-gradient (0–1%) reaches with less riparian shading (greater insolation rates) within the oak woodland zone. This summer habitat limitation also applies to the mainstem Wheatfield Fork, which flows through the oak woodland zone for much of its length and where the highest MWATs (24°C to 27°C [75°F to 80°F] within the Study Area were recorded. Streams flowing through the conifer zone (Map 4) have greater bank cover, lower rates of insolation, and lower water temperatures, and populations of age 1+ steelhead occurring in these portions of the Study Area are not likely limited by summer habitat.

Table 4.3-2. Percent bank cover and summer insolation, as measured

Tributary	Forest Type	% Cover Bank	Avg % Sun	June % Sun	July % Sun	Aug % Sun
Franchini Creek	Redwood	78	16	19	18	12
Buckeye Creek	Oak Woodland	58	28	55	28	0
Grasshopper Creek	Mixed Conifer	83	12	14	15	7

The summer increases in the aforementioned age 1+ densities in study reaches may signify the redistribution of juvenile steelhead from reaches that are too warm for rearing (>24°C; [75°F]; Hokanson et al. 1977, Bell 1991, Bjornn and Reiser 1991, Myrick and Cech 2001), to cooler reaches able to support summer growth. Fidelity to cooler reaches can also be seen in age 0+ steelhead. Densities of age 0+ steelhead in Grasshopper Creek and Franchini Creek, the coolest of our study reaches, increased or remained about the same from early summer to early fall 2006 (Figure 4-5). Both age 1+ and age 0+ fish may be remaining in or redistributing to cooler portions of the Study Area during the summer.

4.4 Winter Habitat Suitability

The availability and quality of overwintering habitat is an important factor influencing juvenile survival in many streams and thus the production of steelhead smolts. Because steelhead generally rear for more than one year in their natal stream, they are subject to harsh environmental conditions during winter high flows. Despite the difficulties posed by winter stream conditions, extended freshwater rearing may increase the chances of successful outmigration and ocean survival. Research has shown that although age 1+ smolts may represent a substantial portion of outmigrating steelhead, their survival is poor and they often contribute little to the numbers of returning adults (Shapovalov and Taft 1954, Kabel and German 1967). Survival of steelhead smolts tends to be much greater if outmigration occurs at age 2+ or 3+ at a larger size. Persistence of a steelhead population is therefore highly dependent on the quantity and quality of habitat for older age classes of juvenile fish (i.e., age 2+ and, to a lesser extent, 3+ and 4+). Because larger fish have greater requirements for space and other resources, however, habitat for age 1+ and older fish is usually more limited than for age 0+ fish.

Although features such as large woody debris jams may provide some value as winter refuge for steelhead, cover consisting of interstitial spaces in cobble or boulder substrate is the key attribute defining winter habitat suitability for juvenile steelhead (Hartman 1965, Chapman and Bjornn 1969, Meyer and Griffith 1997). As stream temperatures fall below approximately 45°F (7°C) in the late fall to early winter, steelhead enter a period of winter inactivity spent hiding in the substrate or closely associated with instream cover, during which time growth may cease (Everest and Chapman 1972). Winter hiding behavior of juveniles reduces their metabolism and food requirements and reduces their exposure to predation (Bustard and Narver 1975). In streams where winter storms bring periodic high flows, juvenile steelhead also use coarse substrate as a refuge from high velocity flows that can cause downstream displacement to less suitable habitat. Velocity refugia may occur deeper within the streambed than concealment cover typically used during winter base flows. Initial observations from experiments conducted by Redwood Sciences Laboratory and Stillwater Sciences in artificial stream channels indicate that juvenile steelhead respond to high flows by seeking cover deep within cobble and boulder substrate. These experiments suggest that steelhead will seek refuge at least 1–2 times the depth of the median particle size (d50) in unembedded cobble/boulder substrate (Redwood Sciences Laboratory and Stillwater Sciences, unpublished data). Therefore, in streams subject to frequent high flows, the area and depth of unembedded substrate may be a primary determinant of the stream's winter carrying capacity for juvenile steelhead.

Rearing densities for juvenile steelhead overwintering in high-quality habitats with cobble-boulder substrates in California streams are estimated to range from approximately 0.24 fish/ft^2 (2.58 fish/m^2 [W. Trush, pers. comm., 1997]) to 0.69 fish/ft^2 (7.42 fish/m^2 [Bjornn et al. 1977]). The density of fish that cobble and boulder substrate can support during the winter declines when fine sediments fill the interstitial spaces of the substrate. Bjornn et al. (1977) measured the densities of age 0+ steelhead (mean total length = 4.5 in [11.4 cm]) remaining in laboratory stream channels with different substrates to evaluate the effects of sedimentation on winter habitat quality. At flows equivalent to winter base flow, fine sediments were added to pools and riffles to embed the cobbles and boulders from 0 to 100%. Densities were between 0.65 and 0.74 fish/ ft^2 (7 and 8 fish/m^2) when cobbles and boulders were completely free of fine sediment. Steelhead densities decreased to between 0.09 and 0.18 fish/ ft^2 (0.97 and 1.94 fish/m^2) when embeddedness increased to 50%. Densities declined further to 0.05 to 0.06 fish/ ft^2 (0.54 to 0.64 fish/ m^2) when cobble and boulder substrate were fully embedded. Similarly, Chapman and Bjornn (1969) found that approximately twice as many juvenile steelhead remained in artificial stream channels with coarse substrate ("rubble") than in stream channels with gravel substrate when stream temperatures were below 50ºF (10ºC). Meyer and Griffith (1997) found that the number of age 0+ rainbow trout (2.2–6.1 in total length [5.6–15.5 cm]) remaining in stream enclosures during the winter was higher when the arrangement of cobble and boulder substrate provided the most refuge cover.

Observations conducted under conditions similar to high winter flows provide a clearer understanding of the importance of interstitial velocity refuge. Results of preliminary experiments by Redwood Sciences Laboratory and Stillwater Sciences in an artificial stream channel show the effect of coarse substrate embeddedness on the use of interstitial space by age 0+ juvenile steelhead during high flows. At flow velocities of 3–4 ft/s, densities of 0.65 fish/ft^2 (7 fish/m^2) were observed when cobbles were unembedded (Table 4.4-1.) (Redwood Sciences Laboratory and Stillwater Sciences, unpublished data). When cobbles were at least 30% embedded in sand and finer particles, a lack of sufficient interstitial space precluded use by juvenile steelhead of coarse substrates for refuge (i.e., a fish density of 0). Comparison of results from this flume study and other studies conducted under stable winter baseflow regimes suggests that completely unembedded coarse material provides similar carrying capacities during both base and storm flows. However, with increasing fine sediment inputs, carrying capacities for habitats subjected to high flows decrease much more quickly than in habitats subject to stable winter base flow.

Table 4.4-1. Winter 0+ juvenile steelhead density (fish/ft^2) in an artificial stream channel with different levels of coarse substrate embeddedness.

Embeddedness	Steelhead Density (fish/ft^2)
0%	0.65
10%	0.33[a]
20%	0.16[a]
≥30%	0

Source: Redwood Sciences Laboratory and Stillwater Sciences, unpublished data

[a] interpolated (not observed).

These studies demonstrate that winter carrying capacity for juvenile steelhead depends primarily on the amount of space located within the interstices of coarse substrate. Considerable uncertainty remains regarding the rate at which winter habitat degrades with increasing fine sediment loading. For example, results from Redwood Sciences Laboratory and Stillwater Sciences (unpublished data) indicate that fish use declines to zero at embeddedness levels as low as 30% (Table 4.4-1.). However, it is not known if the decline in habitat capacity between zero and 30% embeddedness is linear or takes the form of some other function.

We examined the quantity and quality of cobble-boulder habitat complexes within the Study Area using methods developed in conjunction with UC Berkeley and the Redwood Sciences Laboratory (Appendix A.4). Laboratory methods were applied in the field to reaches within three channel gradient ranges (0–1%, 1–3%, and 3–7%) and two inner gorge hillslope gradient ranges (<60% and >60%) to determine the effect of channel network position and potential proximal sources of cobble- and boulder-sized particles on the quantity and quality of steelhead winter habitat. Based on the conceptual model of cobble-boulder habitat complex formation detailed in Section 3.2, we hypothesized that cobble-boulder habitat complexes were likely to form and be maintained in reaches occurring within the 3–7% gradient range and/or near hillslopes that are able to contribute cobble-boulder-sized particles (hillslopes >60%), and as such these reaches would support high densities of age 1+ steelhead (Table 4.4-2, Map 5).

Table 4.4-2. The gradient range of reaches surveyed for cobble-boulder abundance and quality, their proximity to hillslopes >60%, the area (m^2) of cobble-boulder >15 cm vertical depth, and late winter/early spring age 1+ steelhead density (fish/m^2). (See Map 5 for reach locations.)

Reach	Gradient range	Proximal to hillslopes >60%	Area (m^2) of cobble-boulder with vertical depth >15 cm	Late winter/early spring 1+ steelhead density (fish/m^2)
Fuller Creek	0–1%	No	0.7	0.033
Flat Ridge Creek	1–3%	No	2.3	0.070
Tombs Creek	1–3%	No	2.8	0.073
N Fork Fuller Creek	1–3%	Yes	1.8	0.068

Reach	Gradient range	Proximal to hillslopes >60%	Area (m^2) of cobble-boulder with vertical depth >15 cm	Late winter/early spring 1+ steelhead density (fish/m^2)
Franchini Creek	3–7%	Yes	1.2	0.055
Grasshopper Creek	3–7%	Yes	0.7	0.064
Redwood Creek	3–7%	Yes	2.1	0.069

We found a positive relationship between the reach-wide area of cobble-boulder habitat complexes >15 cm vertical depth (from the surface of the embedding matrix to the top of the cobble-boulder framework grains) and late winter density of age 1+ steelhead (Figure 4-6). Based upon previous flume studies (Redwood Sciences Laboratory and Stillwater Sciences, unpublished data) and subsequent evaluation of bed substrate used for hydraulic cover (this study), vertical depth was determined to be the best indicator of cobble-boulder winter habitat quality, specifically, the area of cobble-boulder habitat with >15 cm vertical depth. The relationship suggests that an increase in the area of cobble-boulder habitats will increase age 1+ steelhead densities. Still, reaches predicted to have abundant winter habitat and high age 1+ steelhead densities (Franchini, Grasshopper, and Redwood creeks) had less habitat area and/or lower densities than reaches predicted to have scarce winter habitat and low age 1+ steelhead densities (Flat Ridge and Tombs creeks). The difference between observed and predicted winter habitat area and age 1+ steelhead densities may be a result of incorrect assumptions about winter habitat formation and maintenance, poor winter habitat (interstices filled with fine sediment, reducing vertical depth to <15 cm), or poor winter habitat quantity (interstices not filled with fine sediment but few cobble-boulder habitat complexes) in Franchini, Grasshopper, and Redwood creeks.

If the early fall abundance of age 0+ steelhead is high relative to age 1+ steelhead in late winter, winter habitat for age 0+ fish may be limiting production of age 1+ steelhead. For this comparison, we used our fall 2006 estimates of densities of age 0+ steelhead and compared them to the late-winter estimates of age 1+ and older juvenile steelhead (Figure 4-7). Due to the timing of the study, we were not able to compare the same cohort from late fall 2005 to late winter 2006 in our assessment of winter habitat usage. Instead, we compared different cohorts within the same year under the assumption that the densities were near typical capacity for both seasons. We found that densities of age 0+ and 1+ steelhead decreased from early fall to late winter in six out of seven reaches (Figure 4-3). These are the same reaches that are refuge for age 0+ during the summer and into fall, yet they provide poor refuge during the winter. If we assume that the late-winter densities of age 1+ steelhead observed during this study were near carrying capacity for fish during their first winter (i.e., if age 1+ abundance provides a minimum estimate of the number of age 0+ fish surviving through their first winter), then our data suggests that winter habitat for age 0+ fish limits the production of age 1+ steelhead. As described in our conceptual model for steelhead (Section 3), a limited amount of winter habitat for age 1+ steelhead also implies a limitation for age 2+ steelhead, since older age classes presumably have more restrictive habitat requirements.

The relative importance of winter habitat quality to steelhead population dynamics, as compared with factors such as the quality of spawning habitat, was assessed with population modeling incorporating habitat data from the results of our focused studies. The relative importance of winter habitat quality to steelhead population dynamics, assessed over a range of winter habitat densities, is illustrated in Figure 4-8. The purpose of this analysis was to determine the sensitivity of steelhead populations to a range of winter habitat conditions relative to habitat quantity as a constraint on population growth. The results of these variations in fish density were expressed as the fraction of smolts produced at a given winter fish density relative to the maximum potential production of smolts, given a high fish density. The analysis demonstrated that increases in the quantity or quality of winter habitat are expected to result in dramatic increases in smolt production when habitat quality is low to begin with. For example, increasing winter habitat rearing densities for age 1+ steelhead from 0.07 to 0.2 fish/m^2 (0.007 to 0.02 fish/ft^2) results in an approximately 55% increase in smolt production (assuming densities of age 0+ steelhead increase proportionally). These results also indicate that if our current estimate of winter rearing densities is reasonable, any decrease in winter habitat quality could result in substantial reductions in steelhead production. However, we urge caution in applying this preliminary modeling analysis, which is based on assumptions about survival rates, fish densities, and habitat use in the Study Area. Studies to more accurately estimate juvenile densities at the beginning and end of winter over several seasons would be very useful in validating our assumptions and the modeling results.

4.5 Riparian Vegetation and Large Woody Debris

Riparian zones provide several critical functions for stream systems and their inhabitants. Some of the most important of these functions include providing shade to moderate stream temperatures, supplying organic matter for the aquatic food web, providing large woody debris (LWD) inputs that affect channel form and sediment storage, stabilizing stream banks, and filtering nutrients and fine sediments from incoming ground and surface water (Flosi et al. 1998, Gregory et al.1991, Naiman et al. 2000).

Shade from riparian vegetation has been demonstrated to reduce water temperatures as well as reduce the magnitude of diurnal temperature fluctuations (Cafferata 1990). The amount of radiation to reach the stream varies with vegetation type and canopy density, as well as abiotic characteristics such as channel aspect, channel gradient, and valley hillslope gradient. Incident radiation has greater effects on water temperatures in smaller, shallow reaches, since a higher proportion of the stream is exposed. Exposure to direct sunlight generally increases downstream with stream width. Therefore, inputs of cool water from well-shaded, low-order streams can be critical for maintaining cooler water temperatures downstream (Tate et al. 2005). Channels with steep adjacent hillslopes will often have a shorter season of maximum sun exposure than those bordered by low-gradient hillslopes. Similarly, south-facing reaches are more exposed to solar radiation than north-facing ones, and require more canopy shade in order to maintain cool water temperatures. More solar radiation is blocked by shade from hillslopes than from vegetation, and shade from conifers is denser than from most deciduous species. Thus, the type and distribution of riparian vegetation has important effects on stream temperatures in both the upper and lower reaches of the watershed. Conversion of upland forest types from conifer to hardwood, or from dense forests to more open woodland can increase the amount of solar radiation that reaches the channel. Similarly, shifts in the height of surrounding upland trees alter the degree of shading they provide to the channel.

Large woody debris includes logs and root wads that have fallen into or adjacent to the channel. In-channel LWD affects channel type (e.g., increasing the frequency of pool-riffle sequences), channel bedform and roughness, sediment storage, and bank erosion (Bilby and Bisson 1998). Log jams can create upstream reservoirs that retain coarse sediment and create downstream plunge pools. Single logs can deflect scour and form backwater pools. Logs and root wads can also become lodged along channel banks, fortifying these areas against erosion while creating pool habitat. In low-gradient alluvial reaches, LWD can affect channel morphology by creating areas of low shear stress that can promote sediment deposition and colonization by riparian vegetation (Naiman et al. 2000). In steep as well as low-gradient channels, LWD may influence channel movement and meander by creating cut-offs and back channels (Keller and Swanson 1979). The spatial and temporal variations in channel form and migration induced by LWD helps to create and maintain important in-channel habitat for aquatic species, as well as diversity of riparian habitat for amphibious and terrestrial plants and animals.

Large woody debris is recruited to the channel from riparian vegetation as well as adjacent upland forests and woodlands. LWD can enter the channel through windthrow, landslides and debris flows, floods, or erosive undercutting of banks. The effectiveness of in-channel LWD depends on piece size (dbh and length) in relation to channel width and depth (Gregory et al. 2003). Longevity of LWD in the channel varies by species. For example, Naiman et al. (2000) infer that conifer LWD stay in channel longer than hardwood LWD, since the former are more frequently observed in stream channels when compared to their upland frequency than are the latter. Clearing streams and upland areas of LWD reduces stream habitat diversity and alters patterns of channel erosion and sediment transport (Boon et al. 1992). Many of the channels in the Wheatland and Buckeye basins were completely cleared of LWD as part of a historical management approach (Morse 2002).

We examined riparian vegetation within the Study Area using a combination of aerial photographic interpretation and field investigation to characterize canopy cover and potential LWD input to the stream channels. Canopy cover was lowest in mainstem Buckeye Creek and Wheatfield Fork, which also had the greatest stream temperatures (Appendix A.5), and were located in oak-woodland-dominated portions of the Study Area (Map 4)The recruitment of LWD within the Study Area was found to be insufficient to maintain or improve current channel conditions based on the diameter and height of trees along the riparian corridor (Table 4.5-2). The current load of instream LWD reflected this low recruitment potential, with only 4 out of 15 surveyed reaches exceeding a standard of 13 pieces >50 cm (20 in) dbh per 30 m (100 ft) of stream channel (Beechie and Sibley 1997).

Table 4.5-1. Percent bank cover and summer insolation as measured in the field at the fifteen field sites, presented by tributary and vegetation type. Sites with bank cover below 80% target levels are highlighted.

Tributary	Forest Type	% Bank Cover	Avg % Sun	June % Sun	July % Sun	Aug % Sun
Franchini Creek	Redwood	90	5	0	7	7
Grasshopper Creek	Mixed Conifer	60	23	25	26	19
Grasshopper Creek	Redwood	95	23	31	24	15
Grasshopper Creek	Redwood	83	6	9	6	3
Wheatfield Fork	Oak Woodland		31	30	31	33
Wheatfield Fork	Redwood	45	60	60	61	59
Redwood Creek	Oak Woodland	83	12	8	8	18
Redwood Creek	Oak Woodland	80	17	14	17	19
Tombs Creek	Oak Woodland	45	61	72	64	47

Tributary	Forest Type	% Bank Cover	Avg % Sun	June % Sun	July % Sun	Aug % Sun
Tombs Creek	Oak Woodland	85	13	11	16	11
Tombs Creek	Oak Woodland	13	28	29	29	25

Table 4.5-2. Field measurements of tree size (height and dbh) within 22 m (75 ft) of the channel. Fifty cm (20 in) dbh is the likely minimum LWD dbh needed to be stable within the channel and create effective log jams. These measurements indicate that the trees are generally too small to make effective log jams.

Tributary	Conifer dbh (cm)	Conifer height (m)	% conifer stems
Franchini Creek	no data	19	no data
Grasshopper Creek	30	25	63
Wheatfield Fork	48	26	36
Redwood Creek	50	26	3
Tombs Creek	28	25	8
Average	**38**	**25**	**37**

5 LIMITING FACTORS SYNTHESIS

In conducting the limiting factors analysis we attempted to: (1) systematically review steelhead life history requirements, (2) identify the full range of potential factors that might be limiting to steelhead populations in the Buckeye Creek and Wheatfield Fork basins, (3) screen these potential limiting factors using available information and initial observations on current watershed conditions to develop hypotheses about those factors thought to be of greatest importance in the basin, and (4) test and refine hypotheses using the focused studies described above. Time and funding constraints for this project, however, limited our ability to address some key uncertainties about potential limiting factors. Because of limitations in our understanding of current conditions and how limiting factors have operated in the basin, there are varying degrees of uncertainty associated with our identification and ranking of key limiting factors. Future studies, including collection of additional data on steelhead habitat use and carrying capacity in the Study Area for use in supplemental population modeling, have been proposed in Section 6 to address what we feel are the most important uncertainties related to the conservation and management of steelhead and other aquatic resources in the basins. A synthesis of the conceptual models, hypotheses, and findings developed during this study is provided below.

Review of available information and analysis of limiting factors for steelhead in the Gualala River basin suggests that, despite land use activities (Section 2.3) in the Study Area, watershed impacts have not seriously compromised the potential of the system to support a self-sustaining population of steelhead. The primary impact to steelhead in the Study Area is hypothesized to be a general simplification of the channel, resulting in somewhat reduced quantity and quality of habitat for spawning and rearing life stages. Due to the lack of data describing the pre-disturbance (i.e., reference) conditions in the watershed, however, this hypothesis remains largely unverified.

Currently, the Buckeye Creek and Wheatfield Fork sub-basins support juvenile steelhead in the area from the estuary at the mouth of the Gualala River and throughout mainstem and tributary reaches. To help synthesize the information collected on steelhead habitat conditions and juvenile abundance in the Study Area, we conducted a population dynamics modeling exercise based on fish and habitat data collected during this study (Appendix A.2).

Our studies suggest that summer habitat limits age 1+ steelhead abundance in low-gradient reaches (0–1%) within the oak woodland zone and within the mainstem Wheatfield Fork. The analysis of summer water temperature, although limited to observations from only one summer (June to September 2006), suggests that temperatures within the mainstem Wheatfield Fork may be unsuitable for juvenile steelhead rearing. Maximum weekly average water temperatures (MWATs) at nine sites in the Wheatfield Fork (including at its confluence with Tombs Creek) were close to or exceeded lethal limits reported for steelhead and rainbow trout (24–27°C [75–80°F]; Hokanson et al. 1977, Bell 1991, Bjornn and Reiser 1991, Myrick and Cech 2001). Reaches within the conifer zone appear to provide summer temperature refuge for juvenile steelhead as evinced by the increased densities in these areas from early summer to late fall. This increase may be a result of a redistribution of fish from warmer reaches to cooler reaches that are better able to support juvenile steelhead growth. The degree to which temperatures limit juvenile growth during warmer periods is unknown, but if other factors such as food availability, turbidity, and flow are affecting growth, elevated temperatures may exacerbate such effects.

The gravel permeability study indicates that spawning gravels in the Study Area have low to moderate permeability, probably due to fine sediment intrusion. Although the survival of steelhead eggs and alevins is likely reduced by low permeability of spawning gravels, our analysis suggests that this factor is not sufficient to reduce steelhead smolt production. The quantity and quality of spawning habitat throughout Buckeye Creek and Wheatfield Fork likely provide spawning and incubation conditions sufficient to fully seed the available rearing habitat. Population modeling suggests that under current conditions we would not expect significant changes in smolt production even if egg-to-emergence survival was increased by improving spawning gravel quality. Similarly, the quantity of spawning gravel is not likely limiting the steelhead population.

Our analysis of winter rearing habitat suggests that highly embedded cobble and boulder substrates may limit winter carrying capacity for juvenile steelhead in the Study Area. The abundance of cobble-boulder habitat complexes may vary according to position within the channel network and proximity to steep hillslopes (which are a source of large particles), but intrusion of sediment into interstitial spaces may still reduce the area available for juvenile steelhead concealment and velocity refuge during high winter flows. Despite observations that sediment ranging in size from silt to small gravel is embedding coarser substrates and reducing interstitial space, existing evidence was not sufficient to determine whether a significant fraction of the sediment load in the Study Area is derived from past land use. The naturally erosive underlying geology, steep topography, local seismic activity, and intense, episodic winter rainfall characteristic of the study area, combine to produce naturally high sediment loads in the Gualala River basin. Results from population modeling suggest that modest gains in the density of age 1+ steelhead will result in larger gains in smolt production (Figure 4-9), and potential increases in adult escapement and spawning.

The riparian analysis found that mainstem and low-gradient reaches (0–1%) within the oak woodland zone had the least amount of riparian bank cover, the greatest insolation rates (Section 4.5), and the warmest water temperatures (Section 4.3, Appendix A.5). Data from field surveys show that age 1+ steelhead density decreased from early summer to early fall 2006 in Tombs Creek (Figure 4-4); if similar conditions are assumed to occur in similar reaches within the basin, and these densities are typical for 1+ steelhead within these reaches, then this suggests that summer rearing habitat is limiting in low-gradient reaches (0–1%) flowing through the oak woodland zone. The assessment also found low instream LWD loads within the Study Area and low LWD recruitment potential from the riparian and upland forest, likely reducing channel heterogeneity and reducing the number of wood-formed pools.

In summary, spring and fall 2006 population densities suggest that summer habitat limits the production of age 1+ and older steelhead in low-gradient (0–1%) reaches within the oak woodland zone of the Study Area, but is not limiting in other areas. Juvenile fish may remain in or redistribute to cooler tributaries within the Study Area, but the available information indicates that winter habitat for age 1+ and 2+ steelhead in these same tributaries limits production of steelhead during freshwater rearing stages, which is consistent with our conceptual model (Section 3). These conclusions are based on sampling conducted within a single year and they should be interpreted with caution. The conceptual model and preliminary evaluation of existing population data provide a tool for prioritizing focused studies and a context for interpreting their results. The following sections present the results of focused studies that attempt to link the hypothesized population dynamics described above to current habitat conditions within the Study Area.

The lack of detailed historical information on fish populations and habitat conditions and the extensive period of human use in the Gualala River watershed make it difficult to characterize pre-disturbance conditions. Nevertheless, we have used currently available information to analyze the current habitat conditions within the watershed in relation to likely historical conditions. Our current hypotheses regarding changes from historical conditions and their likely effects on various life stages of steelhead are summarized in Table 5-1.

Table 5-1. Summary of conceptual models and hypotheses regarding historical and current conditions in the Study Area and their potential effects on different life stages of steelhead.

Life History Stage	Hypothesized Historical Condition	Current Condition
Upstream migration	Steelhead accessed the Gualala River each year after the onset of winter rains that breached the barrier beach at the estuary. Natural hydrologic fluctuation delayed steelhead passage during dry years but, besides low flow, there were probably no significant in-channel barriers or impediments to upstream migration of adults. Steep stream gradients (>7%) and natural waterfalls within the Study Area were the upstream limits of anadromous fish distribution. LWD formed deep pools, providing holding habitat for anadromous adult	The majority of the drainage area remains relatively undeveloped. The duration and frequency of winter high-flow events remains similar to historical conditions. Upstream passage by steelhead remains relatively unimpeded up to the natural waterfalls. Reductions in LWD may have resulted in fewer deep pools, reduced holding habitat for spawners, and reduced spawning gravel storage.

Life History Stage	Hypothesized Historical Condition	Current Condition
	salmonids and storage of spawning gravels..	
Spawning and incubation	Spawning gravel was relatively abundant throughout the study area, but gravel quality may have been reduced by naturally high fine sediment loads originating from the erosive Franciscan Formation parent material. Localized bed mobility may have occurred at high flows, especially in areas where steep, narrow canyon walls or bedrock outcrops concentrated stream flow. Redd scour was probably rare, however, because suitable quantities of spawning gravel were not likely to occur in areas with extremely high bed mobility.	Spawning habitat quality is relatively low, as evidenced by low to moderate permeability. This likely results in reduced survival of steelhead eggs and alevins (larvae). Spawning habitat, however, is believed to be sufficient to fully seed rearing habitat under current conditions.
Juvenile rearing	Juvenile rearing was limited to reaches that were well shaded with riparian forest and had suitably cool stream temperatures. Pools with complex structural habitat and relatively cool water likely provided the primary summer rearing habitat in the Study Area. Well developed native riparian forests in the upper watershed probably provided moderate to high amounts of LWD, leading to frequent pool development. Abundant coarse substrate likely provided a high amount of potentially suitable overwintering habitat. Natural sediment may have chronically reduced overwintering habitat quality (but actual quality is unknown). The Gualala River estuary was important for juvenile steelhead rearing. The estuary likely provided nursery habitat for juvenile fish, allowing them to grow to optimum size before emigrating to the ocean, and acted as a transition zone where fish could acclimatize to ocean salinity. Juvenile steelhead may have spent several days or several months in the estuary before entering the ocean.	Juvenile rearing is restricted to tributaries within the conifer zone and cool mainstem reaches. Juvenile steelhead likely redistribute form warm mainstem reaches and low gradient reaches within the oak woodland zone, to cooler conifer shaded reaches in the summer. Cobble-boulder habitats used by overwintering steelhead are limiting, but it is unclear whether these habitats are naturally scarce within the Study Area or are degraded. The stream channel likely has fewer pools and pool quality is reduced due to a reduction in instream LWD and recruitment potential. Water temperatures are likely warmer due to a decrease in bank cover and an increase in insolation rates caused by historic timber harvest and conversion of conifer to oak woodland. The Gualala River estuary is still important for juvenile steelhead, but it is unclear whether its role has expanded to include thermal refuge from potentially lethal (>24°C [75°F]) water temperatures along mainstems and oak woodland reaches.

Life History Stage	Hypothesized Historical Condition	Current Condition
Outmigration	During wet years smolt outmigration occurred over a wide time period from late winter to early summer, with the peak likely occurring in April and May. During dry years, interruption of smolt outmigration likely occurred when reaches dried during the spring or flows were too low to breach the estuary at the mouth of the Gualala River.	Outmigration is likely similar to historical patterns, although it is unclear how altered vegetation patterns and historical and current land uses have affected hydrology and consequent channel drying and estuary breaching, thereby influencing ocean entry.
Summary of steelhead production potential	Steelhead production would have been high, in general, within the Study Area. Production would have been limited occasionally during drought years, but the availability of suitable spawning habitat would have spread risks and reduced the odds of substantial year class failures.	Steelhead production remains sufficient to maintain a population although as substantially reduced level compared to historical conditions. Summer survival of steelhead appears limited by warm water temperatures, a limitation that may be caused by a change in vegetation patterns from conifer to oak woodland in the upper portions of the Study Area. Reduction in the frequency of deep pools, caused by LWD removal and a reduction in streamside recruitment, may also have reduced the carrying capacity of juveniles. Overwintering habitat, in particular cobble-boulder habitat complexes, is scarce and likely limits survival and production of age 1+ and older steelhead smolts.

6 CONCLUSIONS AND PROPOSED STUDIES

The limiting factors analysis was based on the best available existing information and the results from each of the focused studies. Consistent with the limiting factors approach, key findings are summarized by steelhead life stage in Table 6-1. For each life stage we have described important information needs that were identified based on currently available information and hypotheses and these needs are presented as recommended future studies.

The recommendations for additional studies presented below may be implemented as individual studies or integrated with existing and/or proposed programs. We expect that local knowledge and experience, conveyed through input from local landowners, resource managers, and stakeholders, will enhance and bring specificity to the recommendations provided herein prior to implementation. The results of this study and future studies, including those currently underway or planned, should be used to develop a better understanding of priorities for the Study Area.

Table 6-1. Summary of conclusions and recommended studies.

Life history stage	Conclusion	Potential studies to reduce uncertainties	One-time or ongoing study?	Potential importance to steelhead population dynamics	Current relative uncertainty	Potential reduction in uncertainty	Relative priority ranking
Upstream migration	Reductions in LWD may have resulted in fewer deep pools, reduced holding habitat for spawners and reduced spawning gravel storage.	Conduct detailed habitat surveys to determine the relationship between LWD (i.e. abundance and volume) and pool depth, pool frequency, and spawning gravel storage.	One-time	Low	Moderate	High	11
Spawning and incubation	Results of gravel permeability and other analyses strongly suggest that steelhead production is not limited by spawning habitat quality or quantity in the Study Area. Predicted survival of steelhead eggs and alevins is relatively low, due to low-moderate permeability of spawning gravels. The degree to which that this is attributable to anthropogenic disturbance or a naturally high sediment load is unknown. Under existing conditions, improved spawning gravel permeability and increased egg-to-emergence survival would not be expected to increase smolt production because of population limitations at other life stages.	None recommended.	NA	NA	NA	NA	NA

Life history stage	Conclusion	Potential studies to reduce uncertainties	One-time or ongoing study?	Potential importance to steelhead population dynamics	Current relative uncertainty	Potential reduction in uncertainty	Relative priority ranking
Juvenile rearing	*Summer Rearing*: Results of instream temperature monitoring (Section 4.3 and Appendix A.5) suggest that mainstem reaches and tributaries within the oak woodland zone are too warm to support juvenile rearing. Results of summer habitat suitability study (Section 4.3) suggest that juvenile steelhead likely redistribute from warm mainstem reaches and low gradient reaches within the oak woodland zone, to cooler conifer shaded reaches in the summer. The Gualala River estuary is still important for juvenile steelhead, but it is unclear whether its role has expanded to include thermal refuge from potentially lethal (>24°C [75°F]) water temperatures along mainstems and oak woodland reaches.	Monitor stream temperatures year-round at multiple locations in the Study Area for several years to improve our understanding of seasonal and annual variability in stream temperatures that might adversely affect steelhead and other aquatic organisms. The need for stream temperature data is especially critical in tributary reaches, where most rearing likely takes place.	Ongoing	Moderate	Moderate	Moderate–High	8
		Monitor juvenile steelhead populations in established sample reaches twice annually (spring and fall) to collect habitat-specific population data and determine summer (and winter) carrying capacity within mainstem and tributary reaches to determine distribution and importance of thermal refugia within the study area.	Ongoing	High	High	High	3

Life history stage	Conclusion	Potential studies to reduce uncertainties	One-time or ongoing study?	Potential importance to steelhead population dynamics	Current relative uncertainty	Potential reduction in uncertainty	Relative priority ranking
		Use individual marking (passive integrated transponder (PIT) tags or dye marks) to track movement and growth of individual juvenile steelhead to determine distribution in relation to water temperature and potentially identify effects of water temperature on growth. Study would also determine whether summer growth is limited by water temperatures, food, and flow, and whether potential low or negative summer growth can be offset by growth during the spring and fall.	Ongoing (≥2 yrs)	High	High	Moderate-High	6
		Conduct annual outmigrant trapping in Buckeye Creek and Wheatfield Fork during spring and summer to determine smolt size, abundance, outmigration timing, and potential use of Gualala Estuary as rearing habitat and thermal refuge.	Ongoing	High	High	High	4

Life history stage	Conclusion	Potential studies to reduce uncertainties	One-time or ongoing study?	Potential importance to steelhead population dynamics	Current relative uncertainty	Potential reduction in uncertainty	Relative priority ranking
		Conduct detailed LWD budget to determine the current volume, abundance, and approximate age of LWD to determine current condition and recovery potential of channels within Study Area to support and maintain rearing habitat.	One-time	High	High	High	5
	Winter Rearing- Cobble-boulder habitats used by overwintering steelhead are limiting, but it is unclear whether these habitats are naturally scarce within the Study Area or are degraded. Preliminary modeling suggests that an increase in the quantity or quality of winter refuge habitat would likely increase smolt production.	Perform intensive field studies to more accurately characterize the hydraulic and geomorphic conditions under which cobble-boulder habitats form and are maintained in order to develop detailed conceptual model. The conceptual model would be used to develop a combination of: 1) physical experiments at UC Berkeley flume to test hypotheses generated by the detailed conceptual model, 2) an experimental restoration plan designed to further test hypotheses generated by the conceptual model and physical experiments.	One-time	High	High	High	1

Life history stage	Conclusion	Potential studies to reduce uncertainties	One-time or ongoing study?	Potential importance to steelhead population dynamics	Current relative uncertainty	Potential reduction in uncertainty	Relative priority ranking
		Additional population surveys in late winter/early spring over successive years would provide the data necessary to document winter survival and carrying capacity. Spring densities of age 1+ or greater steelhead obtained from surveys in the same reaches surveyed in 2006 would greatly aid in determining whether winter rearing habitat is limiting smolt production. If conducted in conjunction with recommended fall population monitoring (see *Summer Rearing* above), this information would greatly aid in determining the relative importance of winter habitat as a limiting factor for steelhead.	Ongoing	High	High	High	2
		Monitor juvenile steelhead populations in established sample reaches twice annually (fall and spring) to collect habitat-specific population data and determine winter (and summer) carrying capacity.	Ongoing	Moderate	High	Moderate–High	3 (same study as for summer rearing)

Life history stage	Conclusion	Potential studies to reduce uncertainties	One-time or ongoing study?	Potential importance to steelhead population dynamics	Current relative uncertainty	Potential reduction in uncertainty	Relative priority ranking
		Conduct detailed LWD budget to determine the current volume, abundance, and approximate age of LWD to determine current condition and recovery potential of channels within Study Area to support and maintain rearing habitat.	One-time	High	High	High	5 (same study as for summer rearing)
Outmigration	Outmigration is likely similar to historical patterns, although it is unclear how altered vegetation patterns and historical and current land uses have affected hydrology and consequent channel drying and estuary breaching, thereby influencing ocean entry.	Conduct summer field surveys to determine the extent and timing of any drying along mainstem channels.	One-time	Moderate	Moderate	Moderate	9
		Monitor estuary to determine timing and hydrologic conditions of estuary breaching.	Ongoing	Moderate	Moderate	Moderate	10
		Conduct annual outmigrant trapping in Buckeye Creek and Wheatfield Fork during spring and summer to determine smolt size, abundance, outmigration timing, and potential use of Gualala Estuary as rearing habitat and thermal refuge	Ongoing	High	High	High	4 (same study as for summer rearing)

Life history stage	Conclusion	Potential studies to reduce uncertainties	One-time or ongoing study?	Potential importance to steelhead population dynamics	Current relative uncertainty	Potential reduction in uncertainty	Relative priority ranking
		Snorkel or other surveys within the Gualala estuary, prior to breaching, to determine the importance of the estuary for rearing by juvenile steelhead at each pre-smolt age class (0+, 1+, and 2+).	One time (1-2 yrs)	Moderate-High	High	High	7

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Appendix A

Focused Studies

A.1 Steelhead Population Estimation

Direct observation dives were conducted to estimate the total juvenile steelhead population in Buckeye Creek and Wheatfield Fork in spring and fall 2006. To develop the population estimate we used the most recent iteration of the two-phase ratio estimation design (Hankin and Mohr 2005). This method estimates total fish abundance in small streams using the following components: (1) habitat typing of the entire stream channel, (2) stratified random selection of habitat units to receive at least a single-pass diver count, (3) estimation of fish abundance in a stratified random selection of these units using the method of bounded counts, based on four independent diver counts and multiple-pass electrofishing. This last step calibrates the first phase (step 2) counts of fish by divers using a more intensive, second phase of repeated diver counts or electrofishing.

A.1.1 Methods

Study reaches were habitat typed in February (eight reaches), and June (11 reaches) 2006. The number and location of reaches differed between the two sampling dates due to weather conditions and access restrictions. Instream habitat within study reaches was characterized according to McCain et al. (1990), classifying morphological units into run, riffle, pool, and cascade habitat types. The length of each reach varied, with a focus on representing the character of that reach. Reach lengths ranged from 400-1,000 meters, and habitat area (length and width of units) was measured within these reaches. Habitat units for fish sampling were selected from those observed during habitat surveys. However, only pool and run habitats were snorkeled. These selected units were used to extrapolate observed densities to the entire stream network.

A two-phase approach was used to survey the pool and run strata. Phase I sampled 50 % of these strata through direct observation techniques. Phase II adjusted diver counts through unit abundance estimation by either repeated dive counts (bounded counts) or 3-4 pass electrofishing in 50% of those units selected in Phase 1.

Snorkel surveys focused on detecting salmonids, and were conducted at night with divers working in an upstream direction when feasible. Prior studies by Stillwater Sciences (Stillwater Sciences 2006) indicate that night counts provided consistently higher counts of fish ≥ age 1+, as compared to daytime surveys. Nighttime surveys were therefore selected as the method to be used for population estimates in the Preservation Ranch LFA. A critical assumption of the bounded counts approach is that all individuals have a chance of being observed. Hankin and Mohr (2005) found that their survey designs were suitable for coho salmon, but they were not confident about applying their methodology to steelhead juveniles because the fish's secretive nature may violate the assumption that all fish have an observation probability > 0. It is therefore possible that our surveys underestimated the steelhead population. Sampling at the night helped increase observation probabilities, since juvenile steelhead are less oriented towards cover and less apt to flee from divers at night. Another result from the day/night snorkeling comparison is that, in contrast to age 1+ fish, detection of age 0+ fish declined dramatically during the night. Our observations indicated that these small fish may have moved into shallow habitats along the margins of pools and runs, or into very shallow riffles—areas that, in general, were too shallow to snorkel. Therefore, we believe that spring snorkeling may have underestimated the abundance of age 0+ steelhead.

Steelhead surveys were conducted during in late winter/early spring (March/May), early summer (early June), and early fall (late-September) 2006 at sample sites located throughout the tributaries and main stems of Buckeye Creek and the Wheatfield Fork. During the fall, we shifted our sampling effort to include only sample sites in the tributaries to Buckeye Creek and Wheatfield Fork, and excluded the mainstem reaches as Klamt et al. (2002) found summer MWATs along Wheatfield Fork and upper portions of Buckeye Creek to be unsuitable for salmonids (>20 °C [67 °F])

During snorkel surveys, divers conducted fish counts in each selected habitat unit. The divers entered the lower end of each habitat unit and proceeded upstream to the top of the unit. The number of fish were counted and identified to species, and were classified into young-of-the-year (<50, 70, and 100 mm for late winter/early spring, early summer, and early fall, respectively), or age 1+ and older fish (>50, 70, and 100 mm). This size break was determined by examining length frequency histograms after each successive fish survey.

Single-pass dive counts were calibrated to estimate the "true" abundance of fish using the method of bounded counts (MBC) in a subsample of habitat units. At sites chosen for repeat sampling, a total of four dive counts were made.

Hankin and Reeves (1988) showed that snorkel counts are poorly correlated with accurate estimates of fish numbers in riffles. Our observations also suggest that riffles are too shallow to snorkel effectively. Therefore, riffle strata were not sampled through diving methods. Instead, two to four riffle habitat units in each reach were electrofished during Phase II. Electrofishing methods were based on 3- to 4- pass techniques, and were conducted during the daylight hours. Electrofishing surveys were completed within 48 hours of the direct observation survey in any given reach. Two to four riffles, randomly selected in Phase I as described above, were electrofished in each reach. In addition, all Phase I dive units where more than 20 juvenile steelhead were captured and were also selected for Phase II were sampled by electrofishing methods.

A fourth electrofishing pass was conducted if one of the following applies:

3. The number of steelhead caught on the 2nd pass exceeded the number of steelhead caught on the 1st pass.
4. The number of steelhead caught on the 3rd pass was greater than or equal to 25 percent of number caught on the 2nd pass.

A.1.2 Results

Table A.1-1 shows the late winter/early spring, early summer, and late fall population estimates by age class and reach.

Table A.1-1. Population densities (fish/m^2) of juvenile steelhead by age class, reach, and sampling period.

Basin	Reach	Late winter/early spring 0+	Late winter/early spring 1+	Early Summer 0+	Early summer 1+	Early fall 0+	Early fall 1+
Buckeye	Franchini Cr	0.000	0.055	0.378	0.004	0.348	0.228
	Grasshopper Cr	0.000	0.064	0.069	0.057	0.295	0.127
	Flat Ridge Cr	0.021	0.070	0.479	0.055	0.187	0.081
	Buckeye Cr	0.065	0.115	0.324	0.075	---	---
Wheatfield	Fuller Cr	0.128	0.033	0.436	0.065	0.100	0.090

Basin	Reach	Late winter/early spring 0+	Late winter/early spring 1+	Early Summer 0+	Early summer 1+	Early fall 0+	Early fall 1+
	L Wheatfield Fk	---	---	0.054	0.044	---	---
	M Wheatfield Fk	---	---	0.038	0.031	---	---
	NF Fuller	0.026	0.068	0.311	0.197	0.136	0.295
	Redwood Cr	0.000	0.069	0.659	0.311	0.540	0.181
	Tombs Cr	0.018	0.073	0.466	0.150	0.048	0.018
	U Wheatfield Fk	---	---	0.155	0.084	---	---
Total (fish/m^2)		**0.044**	**0.081**	**0.120**	**0.055**	**0.162**	**0.106**

The density of age 0+ steelhead increased from later winter/early spring to early summer, but generally declined from early summer to early fall, with the exception of Grasshopper Creek, where early fall densities increased (Table A.1-1, Figure A.1-1). Reaches with lower MWATs (Table 4.3-1) from early summer to late fall tended to have high densities of age 0+ in the early summer and relatively high densities in the early fall, indicating that these reaches were used as thermal refuge by juvenile steelhead.

The density of age 1+ steelhead increased from late winter/early spring to early summer to early fall in most reaches with the exception of Redwood and Tombs Creeks, which were within the oak woodland zone (Figure A.1-2, Map 1). Redwood Creek still maintained high densities of age 1+ fish in the early fall compared to Tombs Creek, and the third highest observed density during the early fall sampling period. Tombs Creek had the lowest density of age 1+ fish and also had the highest MWAT (Table 4.3-1) and daily maximum temperatures (Appendix A.4) of all study reaches observed during early fall 2006, indicating a limitation of summer habitat.

On a unit-by-unit basis, the overall trend was for habitat unit-specific densities of age 1+ and older steelhead to increase in run and pool habitats from spring to fall, with decreases in Redwood and Tombs Creeks, although Redwood still maintained relatively high densities in pools in early fall (Table A.1-2).

Table A.1-2. Population densities (fish/m^2) of juvenile steelhead by age class, reach, and sampling period.

Basin	Reach	Habitat types (N= run, P = pool, R = riffle, SP = step-pool)	Late winter/early spring 0+	Late winter/early spring 1+	Early Summer 0+	Early summer 1+	Early fall 0+	Early fall 1+
Buckeye	Franchini Creek	N	0.000	0.047	0.455	0.000	0.345	0.158
		P	0.000	0.114	0.349	0.009	0.350	0.296
		R	0.000	0.012	0.349	0.000		
		SP	0.000	0.164				
	Grasshopper Creek	N	0.000	0.058	0.069	0.023	0.353	0.100
		P	0.000	0.220	0.034	0.135	0.258	0.144
		R	0.000	0.026	0.099	0.014		
	Lower Flat Ridge	N	0.027	0.079	0.284	0.158	0.292	0.243
		P	0.015	0.162	0.477	0.109	0.453	0.255
		R	0.014	0.029	0.494	0.022	0.107	0.025
	Upper Buckeye	N	0.078	0.137	0.225	0.133		
		P	0.000	0.167	0.293	0.070		
		R	0.170	0.108	0.479	0.018		
		SP	0.006	0.067				
Wheatfield	Fuller Creek	N	0.005	0.010			0.272	0.109
		P	0.005	0.048	0.373	0.102	0.089	0.178
		R	0.616	0.031	0.528	0.010	0.061	0.016
	NF Fuller Creek	N	0.022	0.061	0.283	0.155	0.243	0.256
		P	0.000	0.066	0.310	0.269	0.113	0.518
		R	0.000	0.024	0.318	0.033	0.042	0.000
		SP	0.131	0.169	0.478	0.615	0.205	0.547
	Redwood Creek	N	0.000	0.057	1.416	0.286	0.934	
		P	0.000	0.111	0.414	0.410	0.481	0.355

Basin	Reach	Habitat types (N= run, P = pool, R = riffle, SP = step-pool)	Late winter/early spring 0+	Late winter/early spring 1+	Early Summer 0+	Early summer 1+	Early fall 0+	Early fall 1+
		R			0.937	0.020	0.439	
		SP	0.000	0.048	0.360	0.410	0.531	0.161
	Tombs Creek	N	0.008	0.053	0.203	0.202	0.041	0.021
		P	0.012	0.140	0.644	0.206	0.116	0.037
		R	0.038	0.024	0.682	0.052	0.000	0.000
		SP						
	Lower Wheatfield	N			0.029	0.042		
		P			0.062	0.057		
		R			0.107	0.025		
	Middle Wheatfield	N			0.030	0.032		
		P			0.028	0.017		
		R			0.102	0.071		
	Upper Wheatfield	N			0.156	0.066		
		P			0.146	0.133		
		R			0.169	0.040		
Total both basins		**N**	**0.026**	**0.078**	**0.068**	**0.048**	**0.214**	**0.099**
		P	**0.008**	**0.113**	**0.128**	**0.074**	**0.210**	**0.220**
		R	**0.114**	**0.049**	**0.247**	**0.038**	**0.079**	**0.015**
		SP	**0.016**	**0.093**	**0.377**	**0.439**	**0.472**	**0.230**

A.2 Steelhead Population Dynamics Modeling

A preliminary assessment of current habitat conditions for steelhead populations in the Study Area was conducted within the framework of a population dynamics model. This assessment relies on fundamental concepts in population dynamics, particularly stock-production analysis. The assessment performed here was based on results from habitat surveys completed in late winter/early spring and early summer 2006 and is only intended to provide a preliminary, and conservative, indication of the degree to which steelhead smolt production may be limited by current habitat conditions.

The population modeling exercise involved three basic steps: (1) analyzing habitat-specific information regarding habitat quality and quantity from a suitable reach within the area of interest; (2) assigning density-independent survival and habitat-specific carrying capacity values for each salmonid life stage; and (3) integrating these values into a system of equations to express the impact of current salmonid habitat conditions on potential steelhead production. These three steps are described in further detail below (in reverse order).

A.2.1 Methods

A.2.1.1 Population modeling

The salmonid population modeling approach used in this analysis is based on stock-production theory (Ricker 1976). Stock-production theory characterizes the number of individuals of one life stage at one time (the production) as a function of the number in the same cohort of an earlier life stage at an earlier time (the stock). This approach is particularly well suited to situations where physical habitat is believed to be limiting, and where population dynamics can be plausibly separated into density-independent and density-dependent components, such as productivity (the ratio of stock to production that would be expected if there were no limits on population density) and carrying capacity (the maximum number of individuals of a given life stage that the habitat can support for the duration of that life stage).

The population model uses the following relationships between a stock S and a production P. In the equations below, the parameter r can generally be interpreted as the intrinsic productivity (e.g., a density-independent survival rate, or in the case of reproduction, a fecundity). The parameter K is interpreted as the carrying capacity for the production stage. In practice, both of these can vary from year to year in response to varying environmental conditions, although such refinements were not used in the present analysis. All of these relationships are asymptotic to the two lines $P = rS$ and $P = K$. There are three basic types of functional relationships that are used in this model:

Truncated Linear: $P = \max(rS, K)$

Modified Beverton-Holt: $P = \dfrac{rKS}{\left((rS)^{\gamma} + K^{\gamma}\right)^{1/\gamma}}$

Superimposition: $P = K\left(1 - \exp(-rS/K)\right)$

The truncated linear relationship is often used when no natural carrying capacity is evident; in this case *K* is set to some very large value, or simply omitted. The parameter γ of the modified Beverton-Holt relationship controls the "stiffness" of the relationship: $\gamma = 1$ is the usual Beverton-Holt relationship; larger values yield curves which make more abrupt transitions between the two asymptotes $P = rS$ and $P = K$. The superimposition relationship was derived from analytical models of habitat selection.

A.2.1.2 Collecting habitat specific information

Habitat-specific information for this population modeling exercise was collected during late winter/early spring and early summer 2006 (see Appendix A.1). Basic habitat types (i.e., pool, riffle, run, and cascade) were delineated within study reaches according to standard habitat mapping descriptions. Mean length, width, and depth were estimated for each habitat unit, and maximum depth was measured within each unit. The area of potential steelhead spawning habitat was estimated from observations made during the spawning gravel permeability focused study (Appendix A.3).

A.2.1.3 Assigning steelhead life history parameters

Steelhead life history was separated into discrete stages having identifiable, and to some extent overlapping, habitat requirements. As discussed above, the population dynamics modeling approach that we used requires two biological parameters for each stage: (1) a carrying capacity (*K*), which describes the ultimate limits imposed by crowding and competition; and (2) an intrinsic productivity (*r*), which describes the expected dynamics under conditions for which the effects of crowding and competition can be ignored. The model was parameterized using values obtained from focused field studies (e.g., permeability measurements) that related physical habitat measurements to survival (*r*) or density-related carrying capacities (*K*). Existing information for the Study Area was not available for some life stages so professional judgment was used to determine when literature based values fish densities were reasonable surrogates for Buckeye Creek and Wheatfield Fork. Tables A2-1 and A2-2 summarize the *K* and *r* parameters used in the analysis, and the derivations of these values.

Table A.2-1. Structure and parameters for modeling of Upper Penitencia Creek steelhead population dynamics.

Life history segment	Stock-production relationship	r (fish/fish)	K (fish)
Spawning and superimposition (spawner to effective eggs)	Superimposition	2,751.5[a]	182,484,983[b]
Egg and alevin rearing (effective egg to spring fry)	Truncated Linear	0.39[c]	(NA)
Early fry rearing (spring fry to 0+ summer)	Modified Beverton-Holt ($\gamma = 2$)	1	634,048[d]
Summer rearing, first year (0+ summer to 0+ fall)	Truncated Linear	1	119,850[e]
Winter rearing, first year (0+ fall to 1+ spring)	Modified Beverton-Holt ($\gamma = 2$)	1	37,807[f]
Summer rearing, second year (1+ spring to 1+ fall)	Modified Beverton-Holt ($\gamma = 2$)	1	29,780[g]
Winter rearing, second year (1+ fall to 2+ smolt)	Modified Beverton-Holt ($\gamma = 2$)	1	14,296[h]

Life history segment	Stock-production relationship	r (fish/fish)	K (fish)
Outmigration, ocean life, and return (2+ smolt to spawner)	Truncated Linear	0.05[i]	(NA)

a. 0.5 females/total spawners × 5,503 eggs/female (estimated from Shapovalov and Taft 1954)
b. 6,426 ft^2 spawning habitat × 0.2 redds/ft^2 × 5,503 eggs/redd.
c. Derived from permeability samples (Appendix A.3).
d. See Table A2-2.
e. Derived from age 0+ and older steelhead densities from early summer 2006 fish surveys.
f. Derived from late winter/early spring estimates of age 1+ and older steelhead in 2006.
g. Derived from age 1+ and older steelhead densities from early fall 2006 fish surveys.
h. Derived from age 0+ winter carrying capacity scaled for larger age 1+ steelhead in 2006.
i. Shapovalov and Taft (1954).

Table A.2-2. Derivations of carrying capacities used in the model.

Life history segment	Habitat type	Habitat area (ft^2)[a]	Density (fish/ft^2)	K (fish)
Early fry rearing	Pool	3,894,468[b]	0.0101[j]	634,048
	Riffle	4,505,850[c]	0.1139[k]	
	Run	3,145,180[d]	0.0259[l]	
Summer rearing, first year	Pool	3,063,568[e]	0.0123[n]	119,850
	Riffle	2,836,163[f]	0.0229[o]	
	Run	2,740,915[g]	0.0063[p]	
Winter rearing, first year	All	5,046,316[h]	0.0075[m]	37,870
Summer rearing, second year	Pool	1,040,632[i]	0.0074[n]	29,780
	Riffle	2,836,163[c]	0.0035[o]	
	Run	2,740,915[d]	0.0045[p]	
Winter rearing, second year	All	5,046,316[h]	0.0028[q]	14,296

a. Area estimates based on estimates made from late winter and early summer 2006 habitat surveys.
b. Total area of all pools in Study Area, estimated from late winter 2006 habitat surveys.
c. Total area of riffles in Study Area, estimated from late winter 2006 habitat surveys.
d. Total area of runs in Study Area, estimated from late winter 2006 habitat surveys.
e. Total area of all pools in Study Area, estimated from early summer 2006 habitat surveys.
f. Total area of riffles in Study Area, estimated from early summer 2006 habitat surveys.
g. Total area of runs in Study Area, estimated from early summer 2006 habitat surveys.
h. Area of cobble/boulder substrate in Study Area allocated to specific steelhead age classes estimated from channel area of 3-7% gradient reaches and 1-3% reaches adjacent to hillslopes >60% (see Section 4.3 and Appendix A.4).
i. Pools with summer maximum depth of at least 2 ft
j. Weighted average (total # of fish observed/total area of pools observed during February 2006 habitat survey) of observed age-specific density in pools in reaches sampled during late winter/early spring 2006 fish surveys
k. Weighted average (total # of fish observed/total area of riffles observed during February 2006 habitat survey) of observed age-specific density in riffles in reaches sampled during late winter/early spring 2006 fish surveys
l. Weighted average (total # of fish observed/total area of runs observed during February 2006 habitat survey) of observed age-specific density in runs in reaches sampled during late winter/early spring 2006 fish surveys
m. Derived from observed late winter/early spring 2006 age 1+ population densities (Appendix A.1).
n. Weighted average (total # of fish observed/total area of pools observed during June 2006 habitat survey) of observed age-specific density in pools in reaches sampled during early summer 2006 fish surveys.
o. Weighted average (total # of fish observed/total area of riffles observed during June 2006 habitat survey) e of observed age-specific density in riffles in reaches sampled during early summer 2006 fish surveys.
p. Weighted average (total # of fish observed/total area of runs observed during June 2006 habitat survey) of observed age-specific density in runs in reaches sampled during early summer 2006 fish surveys.
q. Ratio of age 0+ to age 1+ fish length was used as a scaling factor to approximate the degree to which fewer larger fish can fit in a given habitat area. Fish size was estimated from data collected in late winter/early spring and early fall 2006.

A.3 Spawning Gravel Permeability

A.3.1 Methods

To determine the quality of streambed gravels for salmonid egg incubation and larval (alevin) rearing, substrate permeability (i.e., hydraulic conductivity) was measured using a modified Mark IV standpipe (Terhune 1958, Barnard and McBain 1994). Prior to standpipe sampling, gravels at potential spawning sites were mixed to a depth of 0.95 feet to simulate mixing and sorting conditions that would occur during redd construction by a spawning salmonid (see Kondolf and Wolman 1993 for more information on this topic). The standpipe used was 46.5 inches long, with a 1.0 in inside diameter and a 1.25 in outside diameter. The standpipe had a 2.75 in-long band of perforations and was driven into the substrate so that the band of perforations extended in depth from approximately 0.60 to 0.86 ft below the bed surface. To reduce the potential for water 'slippage' down the outside of the pipe, the standpipe was held, but not forced in any direction, during the driving process.

Permeability was measured by using a Thomas vacuum pump (Model 107CDC20, powered by a 12-volt rechargeable battery) to siphon water out of the standpipe to maintain the water level inside the standpipe exactly one-inch lower than the surrounding water. By measuring the volume of water siphoned out of the standpipe over a measured time interval, it was possible to determine the recharge rate of the water level in the standpipe under a standard one-inch pressure head. At each spawning patch assessed, the standpipe was driven in once and five consecutive permeability measurements were taken. We used the median permeability value from this series of measurements for further analysis.

The recharge rate (units of volume per time) data measured in the field were converted into permeability (units of length per time) using an empirically derived rating table (Barnard and McBain 1994) and adjusted with a correction factor that accounts for temperature related changes in water viscosity that can affect permeability results (Barnard and McBain 1994).

We then used published empirical relationships between permeability and survival-to-emergence for anadromous salmonids (McCuddin 1977, Tagart 1976) to estimate survival based on our permeability measurements. The following simple linear regression defines this relationship:

$$\text{Survival} = 0.1488 * \ln(\text{Permeability}) - 0.8253$$

where permeability is in units of cm/hr.

During field studies we observed several redds constructed in the tails of pools. When we encountered a redd we measured the maximum width and total length of the pit and tail. The area of each redd was then approximated by calculating the area of an ellipse using the width as the short axis and the total redd length as the long axis.

A.3.2 Results

The results of the permeability analysis and the survival index calculation are given in Table A.3-1. Discussion of the results is provided in Section 4.2 of the main report.

Table A.3-1. Summary of permeability sampling in the Buckeye Creek and Wheatfield Fork sub-basins.

Reach	Site ID	Date	Permeability (cm/hr)	Predicted survival-to-emergence
Franchini Creek	A	4/10/2006	4,303	0.42
	B	4/10/2006	2,354	0.33
	C	4/10/2006	8,442	0.52
	D	4/10/2006	32,663	0.72
	E	4/10/2006	25,355	0.68
	F	4/10/2006	8,403	0.52
	G	4/10/2006	2,805	0.36
	H	4/10/2006	4,154	0.41
	I	4/10/2006	13,340	0.59
Grasshopper Creek	A	4/26/2006	9,657	0.54
	B	4/26/2006	12,117	0.57
	C	4/26/2006	1,867	0.30
	D	4/26/2006	2,967	0.36
	E	4/26/2006	2,828	0.36
	F	4/26/2006	2,221	0.32
	G	4/26/2006	1,335	0.25
	H	4/26/2006	2,856	0.36
	I	4/26/2006	4,498	0.43
Flat Ridge Creek	A	4/27/2006	3,292	0.38
	B	4/27/2006	2,720	0.35
	C	4/27/2006	3,937	0.41
	D	4/27/2006	1,0093	0.55
	E	4/27/2006	2,377	0.33
	F	4/27/2006	7,098	0.49
	G	4/27/2006	1,939	0.30
	H	4/27/2006	2,072	0.31
	I	4/27/2006	619	0.13
Fuller Creek	A	4/27/2006	5,790	0.46
	B	4/27/2006	1,799	0.29
	C	4/27/2006	2,929	0.36
	D	4/27/2006	3,649	0.40
	E	4/27/2006	1388	0.25
	F	4/27/2006	2,203	0.32
	G	4/27/2006	8,027	0.51
	H	4/27/2006	4,269	0.42
	I	4/27/2006	10,622	0.55
Redwood Creek	A	4/26/2006	3,300	0.38
	B	4/26/2006	3,169	0.37

Reach	Site ID	Date	Permeability (cm/hr)	Predicted survival-to-emergence
	C	4/26/2006	10,219	0.55
	D	4/26/2006	1,933	0.30
	E	4/26/2006	7,210	0.50
	F	4/26/2006	6,947	0.49
	G	4/26/2006	6,50	0.14

A.4 Winter Habitat Suitability

A.4.1 Methods

Study reaches were chosen based on channel gradient to select between potential step-pool channel types (3-7%) that are likely to support the formation of cobble/boulder habitat complexes and lower gradient reaches (0-1% and 1-3%) that likely do not support the formation of cobble/boulder habitat complexes, and hillslope gradient to predict steep inner gorges (hillslopes > 60%) that are potential source areas for cobble/boulder substrates. Within each study reach, the frequency of cobble/boulder habitat complexes was determined and compared to the above predictions. The quality of cobble/boulder habitat complexes was also evaluated in a two step procedure where a metric was developed from laboratory studies and then applied in the field. The density of steelhead across a range of cobble/boulder habitat complex frequencies was determined using direct observation and electrofishing (**Appendix A.1**).

A.4.2 Laboratory Study

The objective of this exploratory research was to develop a method to measure the in-situ quality of cobble-boulder overwintering habitat. On a practical level, in-situ evaluation of cobble-boulder habitat is difficult without destructive sampling of the habitat. This research was intended to produce a method that allows rapid, non-destructive sampling of cobble-boulder habitat. The method was then refined ex-situ and applied to field sites within the Study Area. The laboratory and field research was conducted in collaboration with scientists at the University of California, Berkeley, who have conducted a pilot level study on the abundance of flow refugia crevices within cobble-boulder substrates along a mountain stream channel (Cover et al. 2006). The research also built on observations on the usage of cobble-boulder substrates by juvenile steelhead during high flow. Redwood Sciences Laboratory and Stillwater Sciences (2004 unpublished data) found that fish used unembedded to partially embedded bed material as hydraulic refuge during increased flow within a flume.

Cobble-boulder substrates in three size distributions ranging from 45 to 512 mm (measured along the intermediate axis), to match the range of sizes used in Redwood Sciences Laboratory and Stillwater Sciences (2004 unpublished data), were arranged in two horizontal layers within a 1 m by 1 m box. The depth of usable interstitial pore space for juvenile steelhead was probed using lengths of 5, 10, and 15 mm (outside diameter) flexible vinyl tubing cut at a 45 degree angle to simulate the inter-orbital width and shape of the anterior end of age 0+, 1+, and 2+ juvenile steelhead. The angled end of each piece of vinyl tubing was inserted into a surface pore and probed downward into the cobble-boulder substrate until resistance was met. The insertion distance of each probe was recorded as the distance from the angled end of the tubing (within the substrate) to a horizontal plane formed by the outer edge of the surface layer of cobble-boulder substrate. The plane was perpendicular to the vector of the vinyl tubing and was created by placing a ruler across the surface of two particles forming the probed pore space. The depth of surface pores was measured to the nearest centimeter.

A.4.3 Field Study

The laboratory research produced a repeatable method of measuring the apparent quality of cobble-boulder habitat complexes that was correlated with fish densities observed during late spring fish surveys. The laboratory method was revised to include only 15 mm (outside diameter) tubing and the definition of a cobble-boulder habitat complex was narrowly defined as a collection of two or more particles >90 mm and < 512 mm (b-diameter) arranged in at least two strata (layers). While collections of smaller and larger particles arranged in a single strata may provide cover for overwintering juvenile steelhead, the focus of this study was to characterize discrete complexes of cobble-boulder habitat, thus a narrow definition was developed. Cobble-boulder habitat complexes were surveyed in twelve study reaches in June 2006; seven were reaches that were surveyed in late winter/early spring, allowing a comparison between 1+ steelhead density and area of cobble-boulder habitat (Figure 4-6). The following data were collected at each reach: 1) the number and size of particles >90 mm and < 512 mm, 2) the degree of embeddedness of the bottom layer, 3) the number and length of each pore as measured with the vinyl tubing, and 4) the vertical depth from the surface of the embedding matrix to the top of the framework grains that make up the complex. As discussed in Section 4.4, based upon previous flume studies (Redwood Sciences Laboratory and Stillwater Sciences, 2004 unpublished data) and subsequent evaluation of bed substrate used for hydraulic cover (this study), vertical depth was determined to be the best indicator of cobble-boulder winter habitat quality, specifically the area of cobble-boulder habitat with >15 cm vertical depth.

A.4.4 Results

The reach-level characteristics of cobble-boulder habitat complexes are given below in Table A.4-1. Discussion of the results is provided in Section 4.4 of the main report.

Table A.4-1. Summary of cobble-boulder habitat complex characteristics.

Reach	# of cobble-boulder	Mean embeddedness of bottom layer (%)	Mean insertion length (cm)	Mean vertical depth (cm)	Area (m^2) of cobble-boulder with vertical depth >15 cm
Franchini Cr	39	35	12.1	19.5	0.7
Fuller Cr	17	32	11.7	26.4	2.3
Grasshopper Cr	9	37	8.4	20.9	2.8
Flat Ridge Cr	33	30	14.7	21.3	1.8
N Fork Fuller	31	43	14.9	27.0	1.2
Redwood Cr	38	44	14.5	22.6	0.7
Tombs Cr	71	42	10.8	17.1	2.1

A.5 Temperature Monitoring

A.5.1 Methods

To determine whether water temperature in the Gualala River and its' tributaries might be high enough to cause chronic or acute impacts on salmonids, extensive temperature monitoring was undertaken at 23 sites throughout the Buckeye Creek and Wheatfield Fork sub-basins. Automatically recording thermographs were deployed at nine sites in tributaries throughout the Gualala River basin and 14 sites in the main stems of Buckeye Creek and Wheatfield Fork. Sites were selected to represent a wide variety of drainage areas, channel gradients and geologic land types present in the system (see Map 3) and to correlate with biological sampling reaches. Thermographs used were Stowaway TidBits manufactured by Onset Computer Corporation (Pocasset, MA).

Thermographs were first deployed in early June 2006. All thermographs were set to record water temperature at 15-minute intervals and final retrieval occurred in late September 2006. One of the thermographs experienced out-of-water conditions, due to human tampering, over the course of the summer.

A.5.2 Results

Figures A.5-1a to A.5-1w show the results of temperature monitoring for each station. The plots show daily mean (bold line), maximum (dashed line), and minimum (dotted line) temperatures associated with each logger. The locations are noted in Map 3. Section 4.3 discusses the biological implications of observed temperature patterns.

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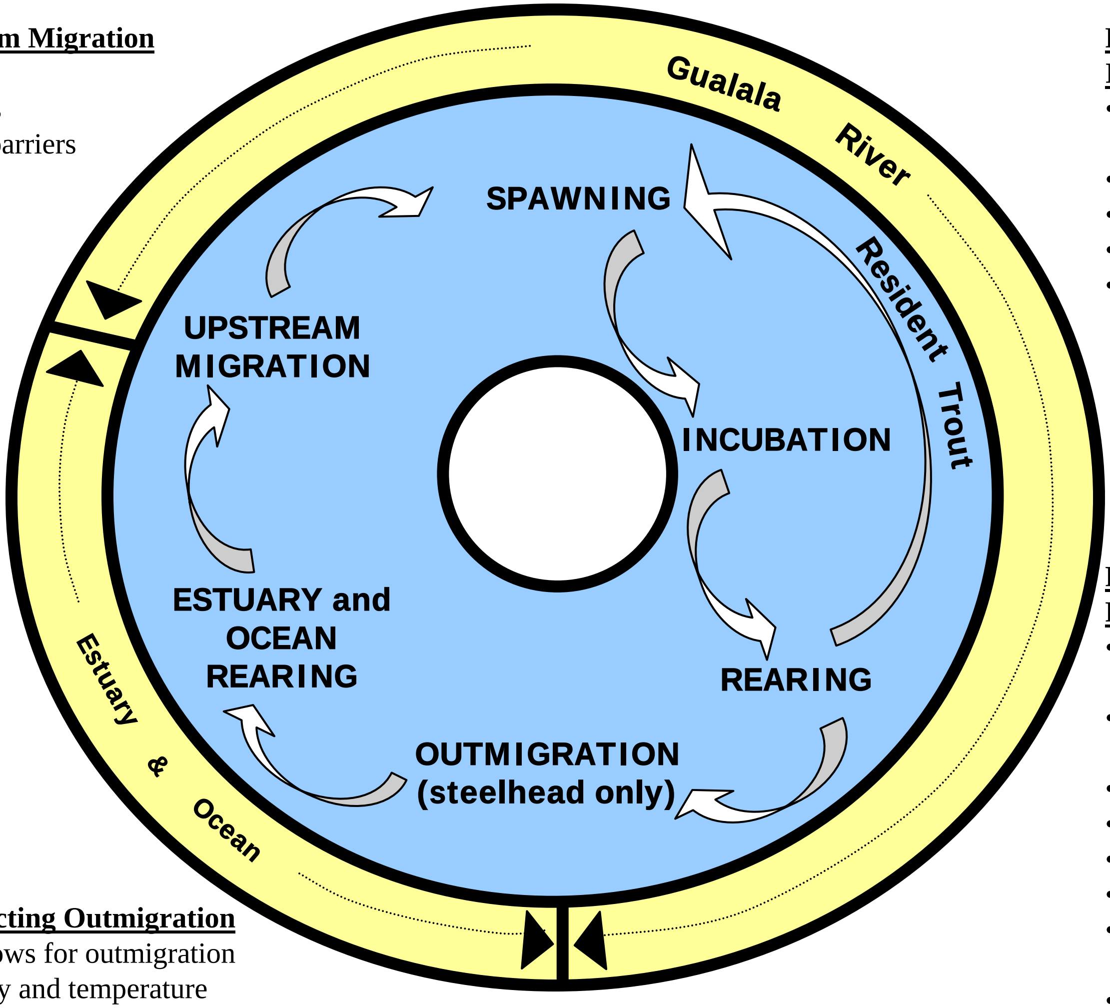
Figures



Factors Affecting Upstream Migration
- Attraction flows
- Physical migration barriers
- Environmental migration barriers
- Migration corridor hazards

Factors Affecting Spawning and Incubation
- Spawning gravel quantity and redd superimposition
- Spawning gravel quality
- Water quality and temperature
- Substrate mobility/scouring
- Redd dewatering

Factors Affecting Estuary and Ocean Rearing
- Loss of estuarine rearing habitat
- Water quality and temperature
- Harvest
- Ocean conditions
- Predation

Factors Affecting Juvenile Rearing
- Availability of summer rearing habitat
- Availability of overwintering habitat
- Stranding by low flows
- Displacement by high flows
- Predation
- Food availability
- Interspecific interactions between native species
- Competition with introduced species
- Water quality and temperature

Factors Affecting Outmigration
- Adequate flows for outmigration
- Water quality and temperature
- Predation
- Diversion hazards

Figure 3-1. Steelhead and resident rainbow trout life cycle and potential factors thought to affect the abundance of various life stages.

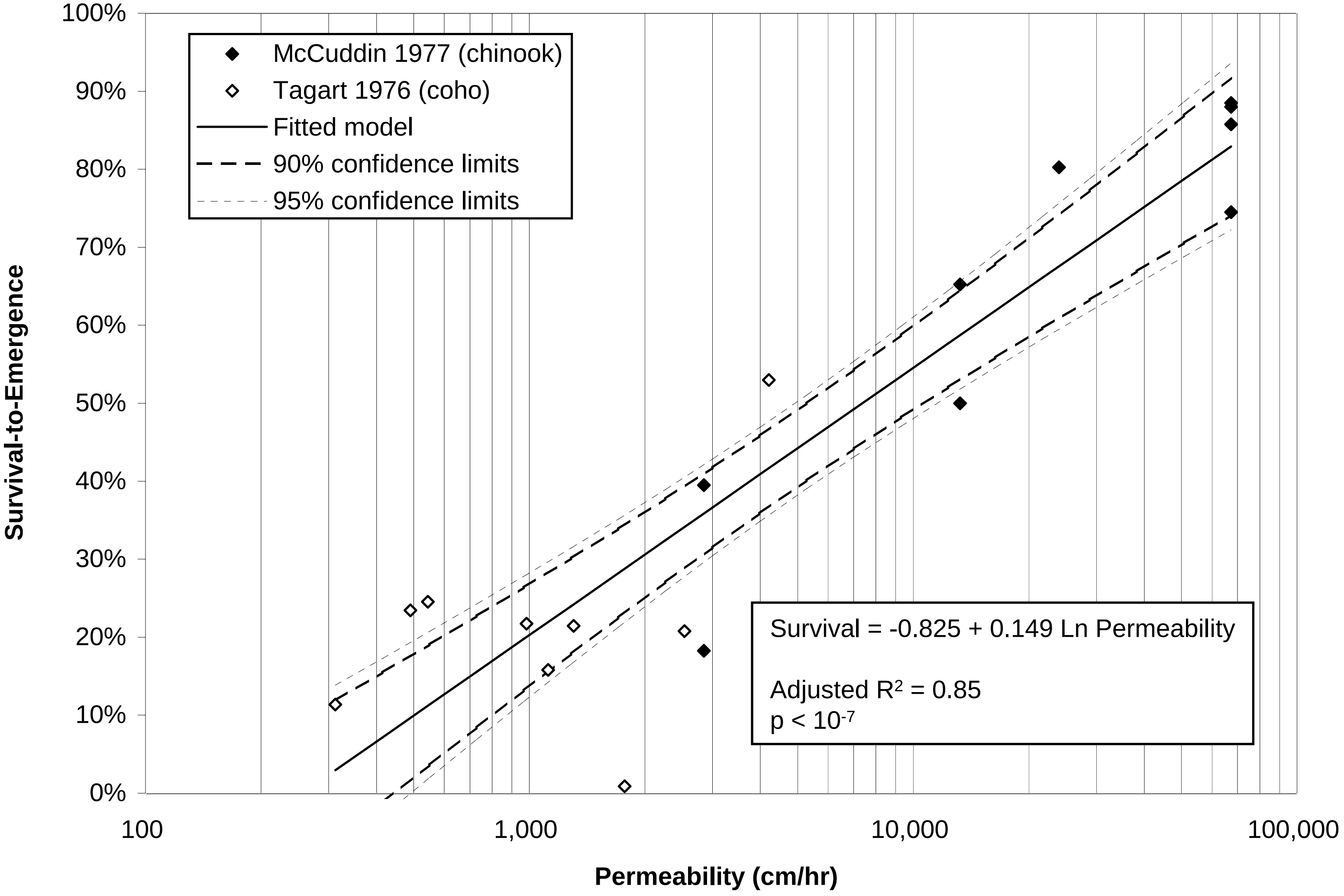


Figure 4-1. The egg survival-to-emergence index used to interpret the relative impact of measured permeability on steelhead production is based on the regression derived from data collected by Tagart (1976) for coho salmon and McCuddin (1977) for Chinook salmon.

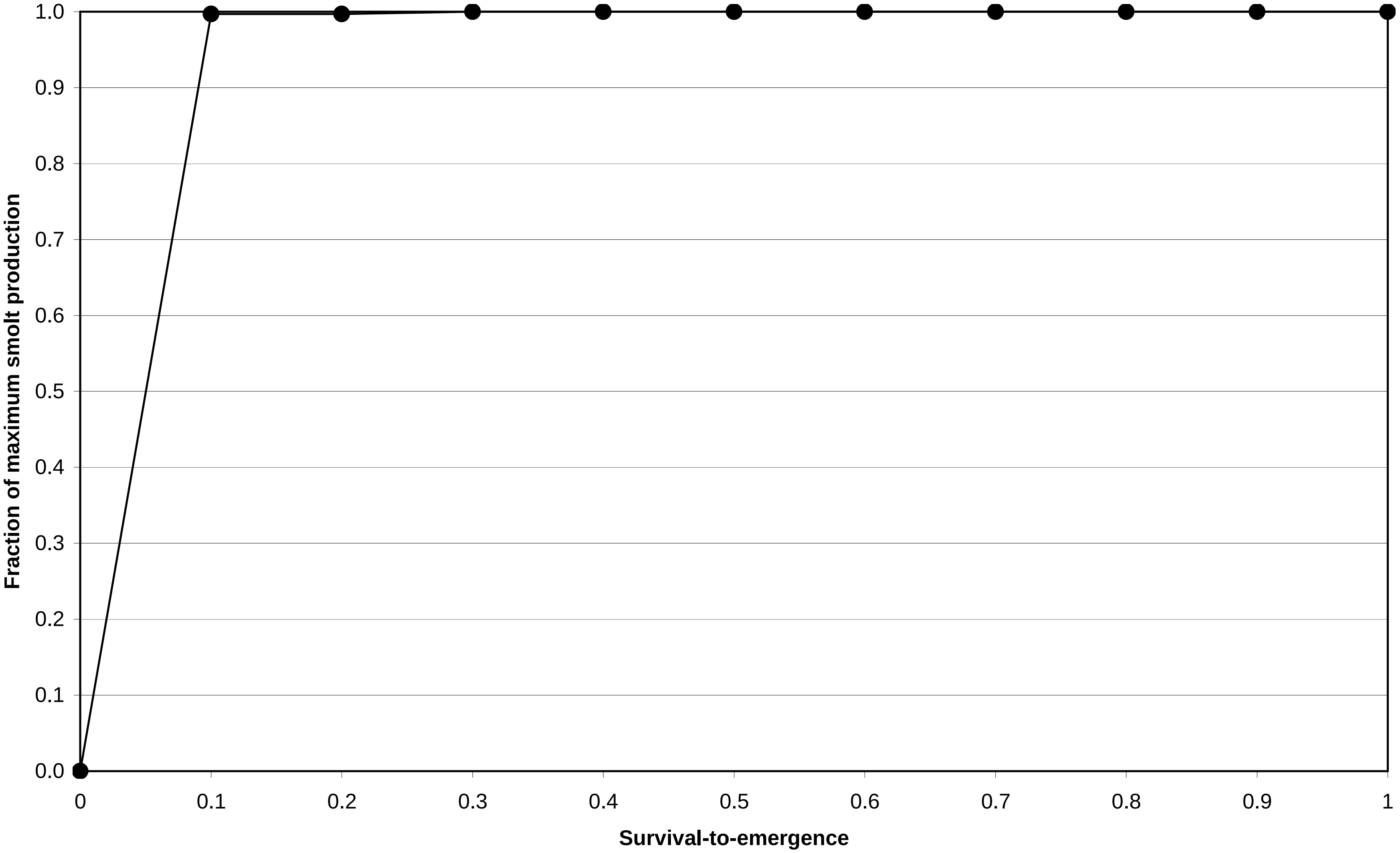


Figure 4-2. Expected potential smolt production as a function of emergence survival.

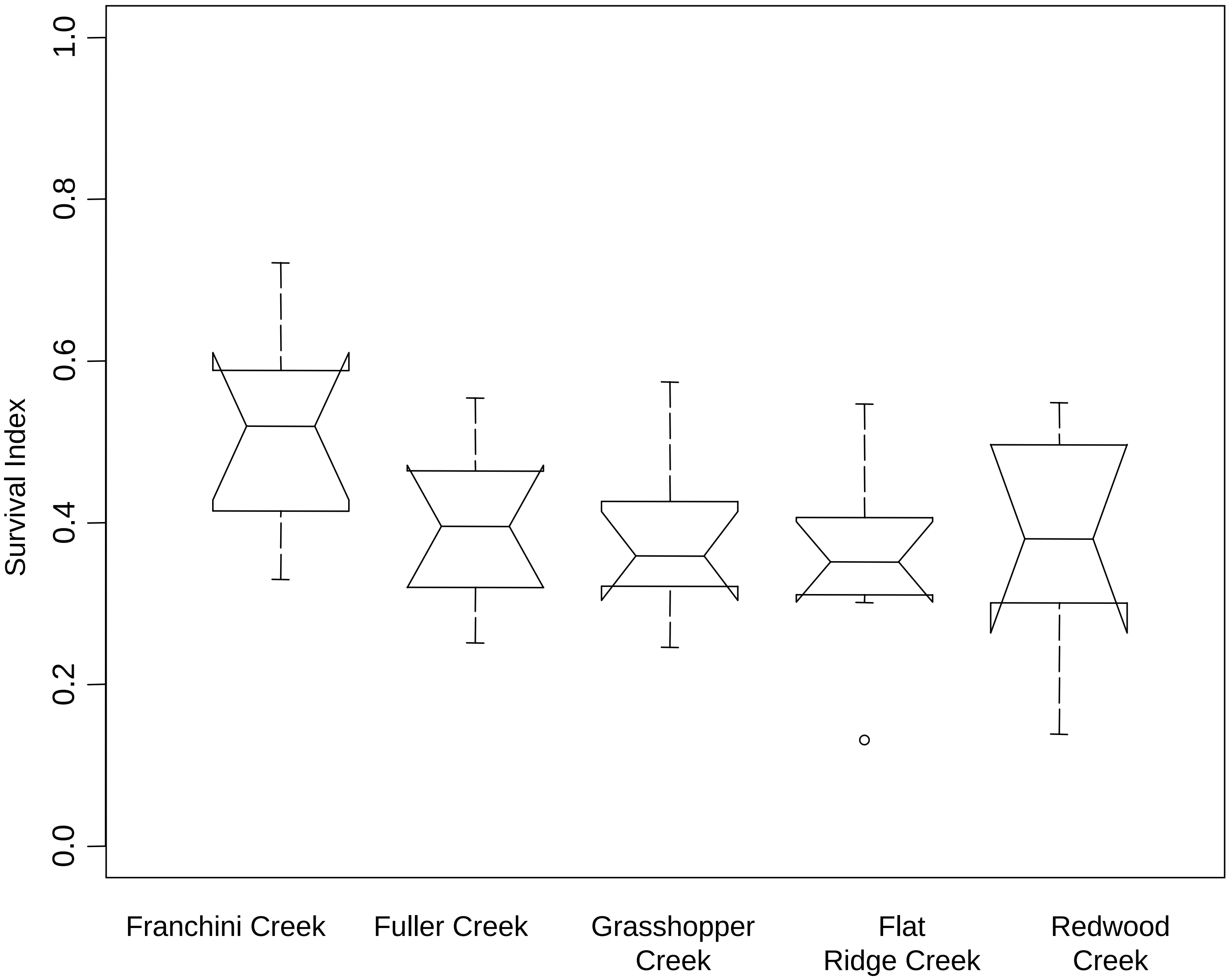


Figure 4-3. Box plots for survival to emergence (survival index) by reach. Each box extends from the first to third quartile of the data, with a horizontal bar at the median. Each whisker extends to the nearest values not beyond a standard span of the quartiles; values more extreme than this are plotted individually. The notches give 95% confidence intervals for the median, calculated from the quartiles.

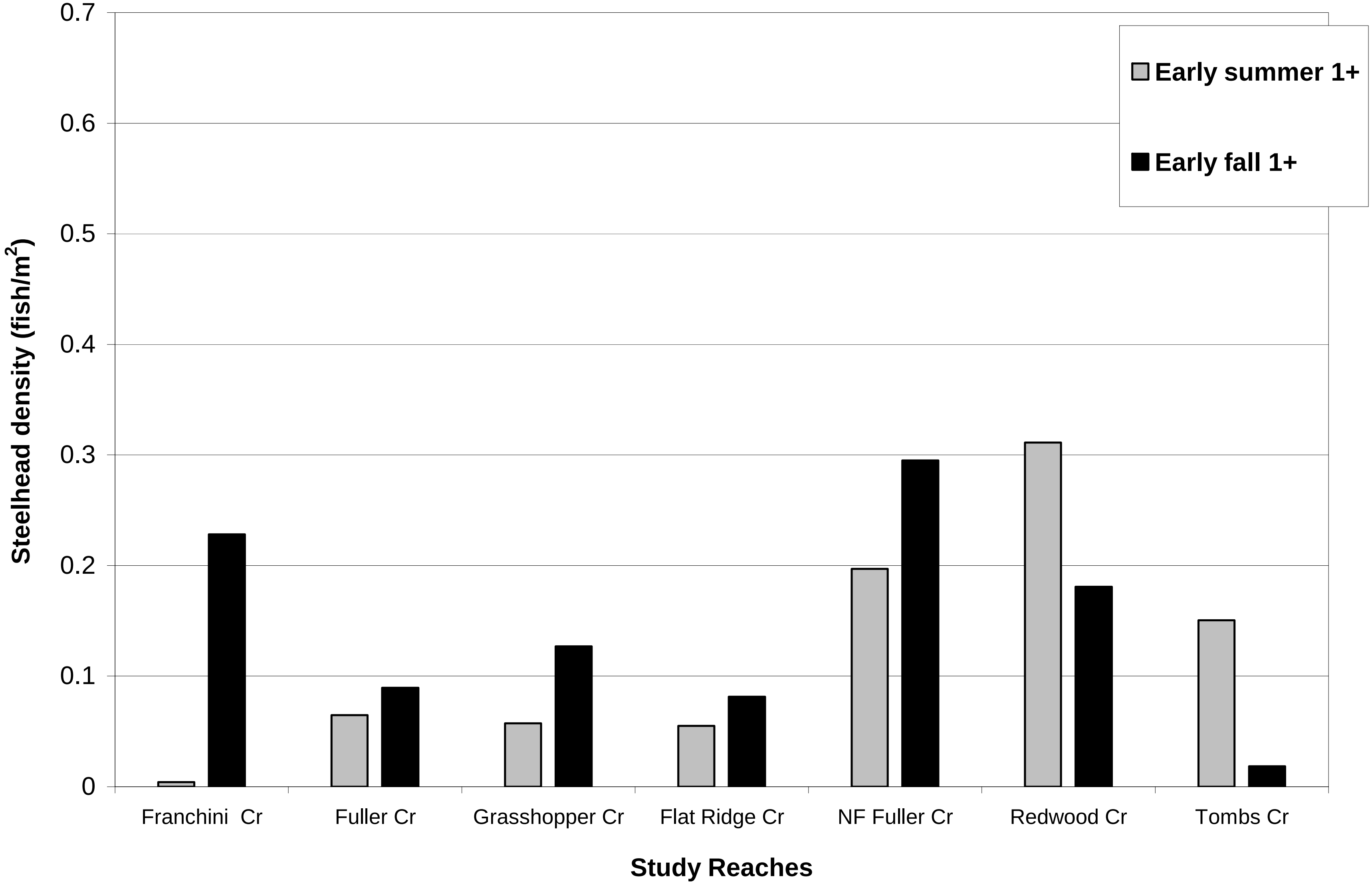


Figure 4-4. Early summer and late fall 2006 densities of age 1+ *O. mykiss*.

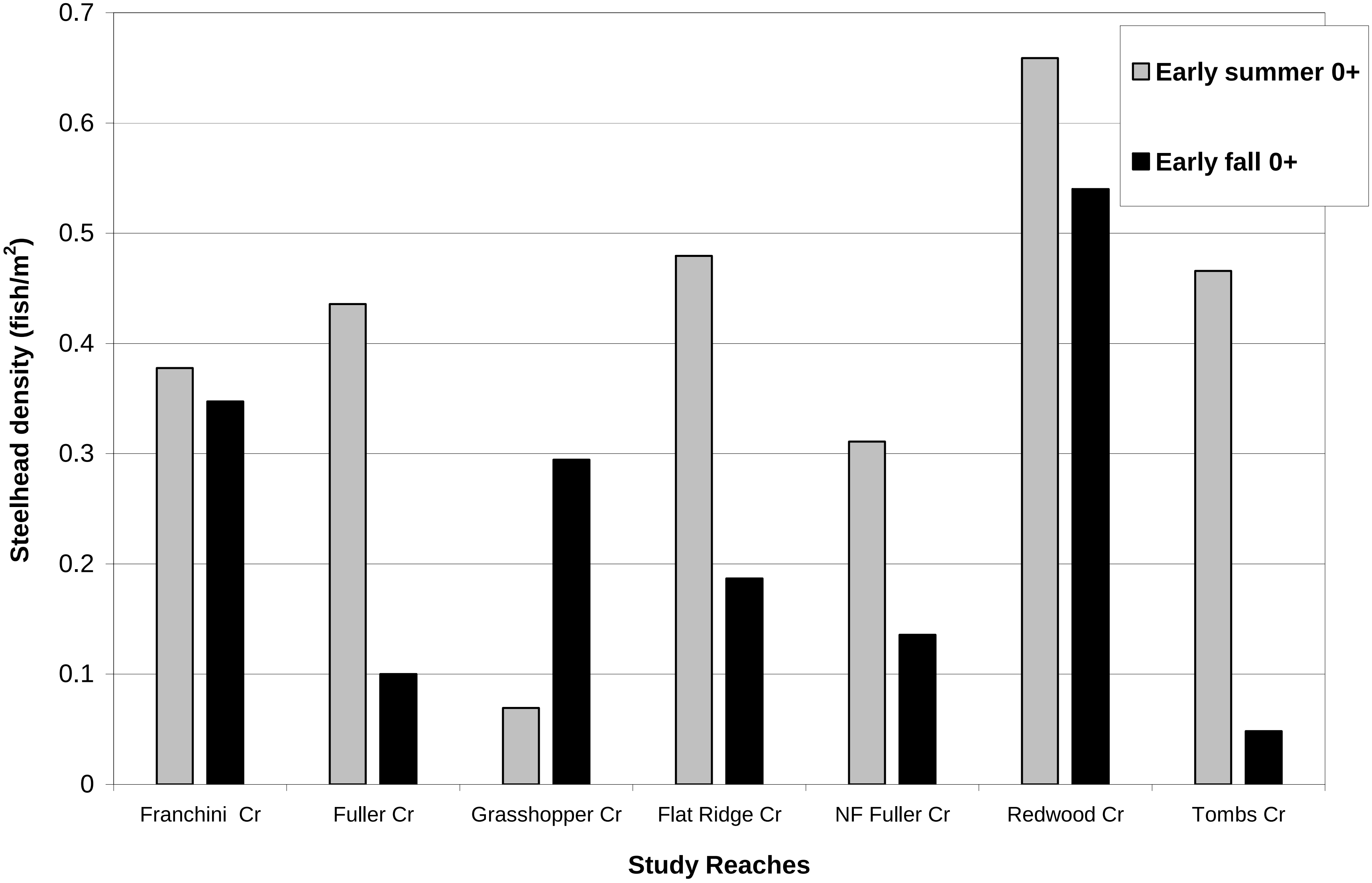


Figure 4-5. Early summer and late fall 2006 densities of age 0+ *O. mykiss*.

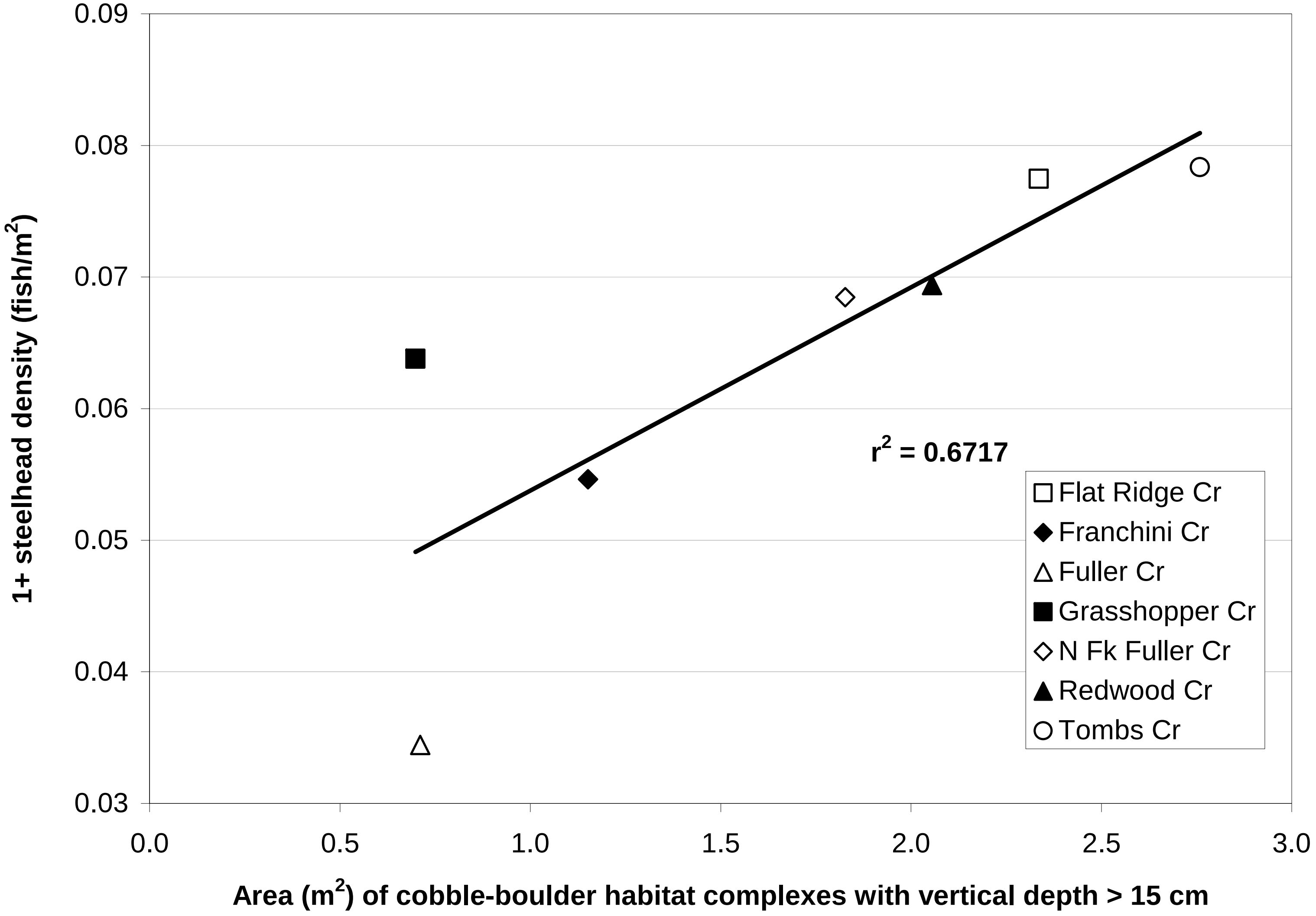


Figure 4-6. The relationship between 1+ steelhead density and area (m^2) of cobble boulder habitat.

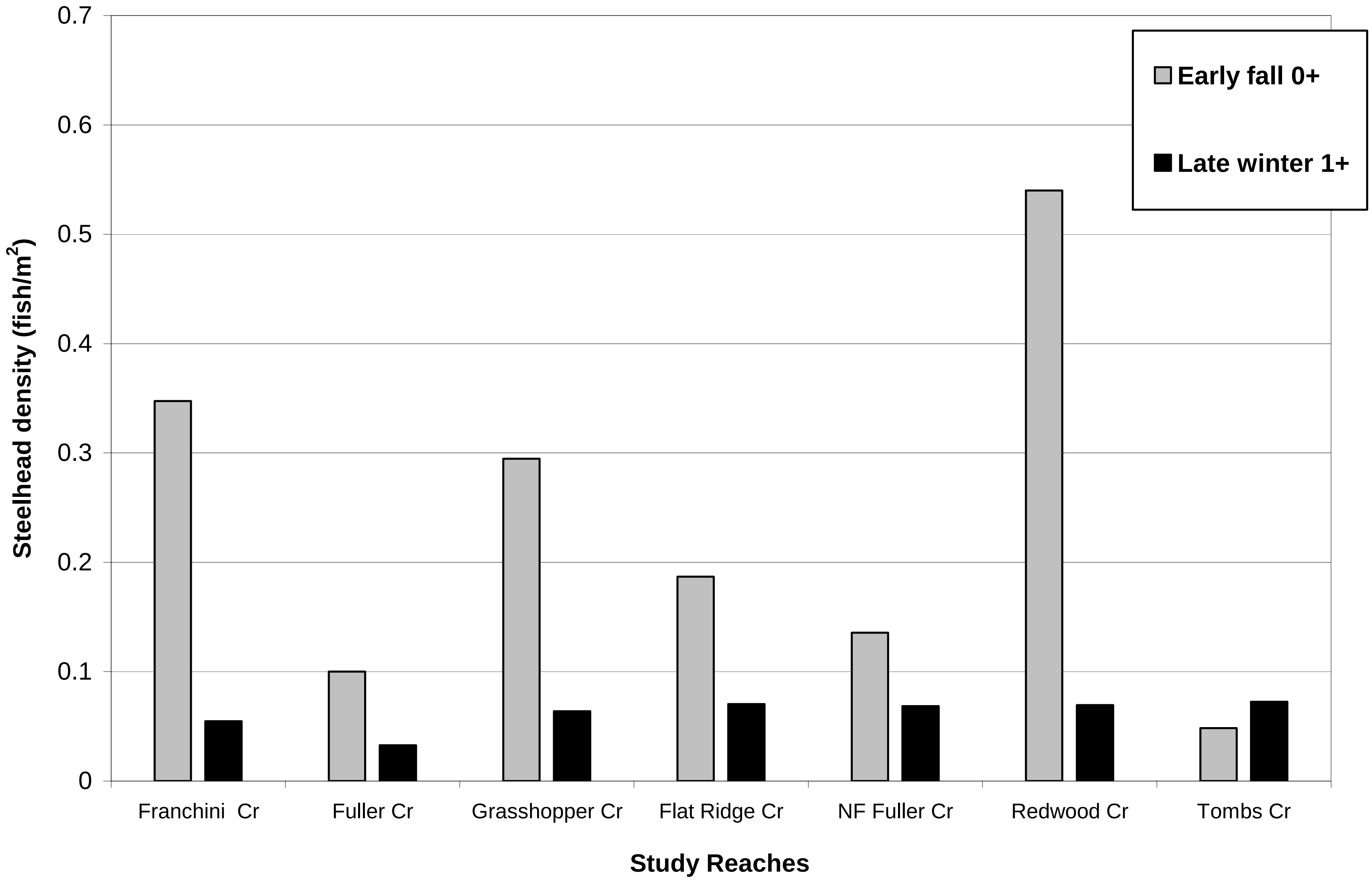


Figure 4-7. 2006 early fall age 0+ and late winter age 1+ densities of *O. mykiss*.

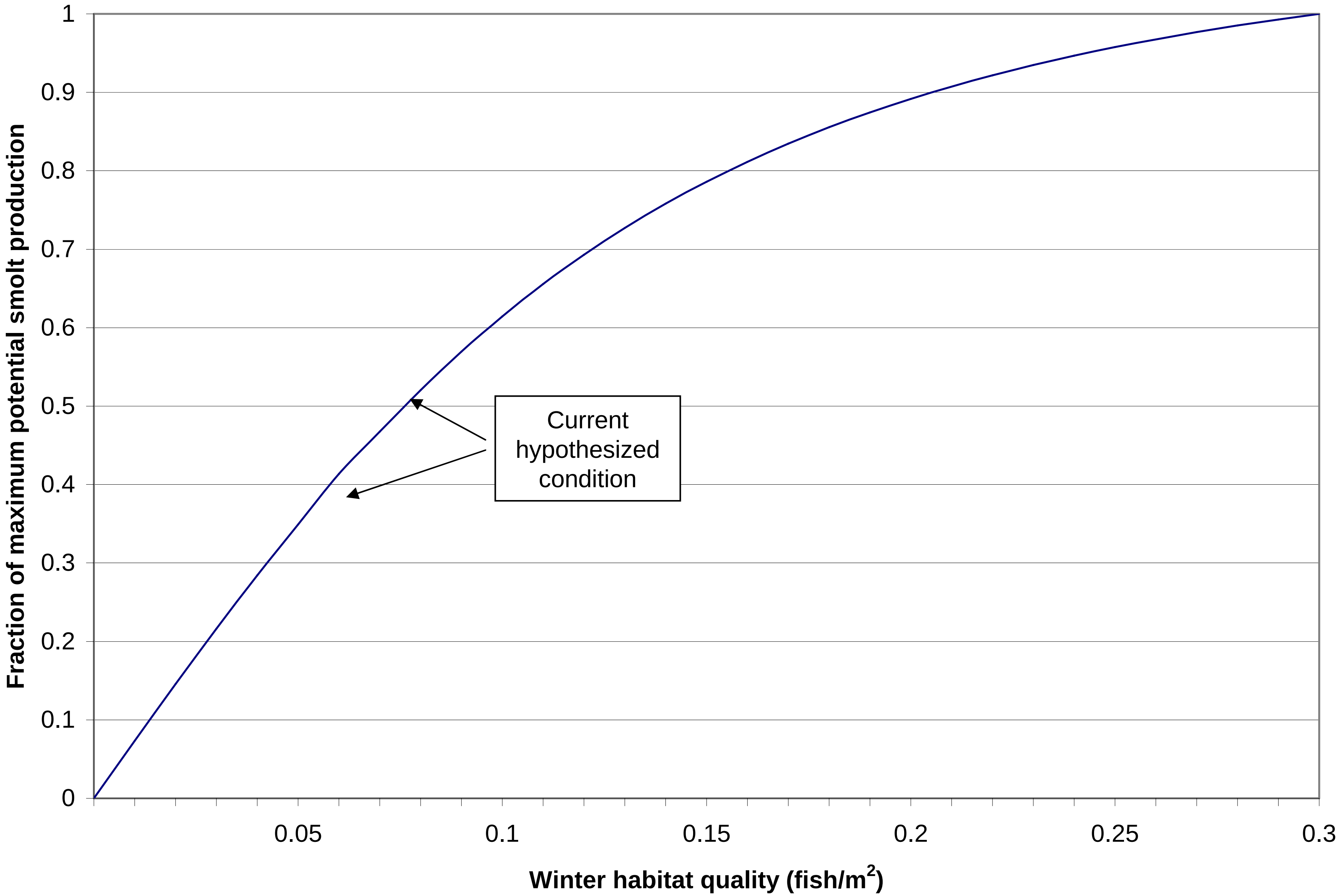


Figure 4-8. Expected smolt production as a function of overwintering habitat quality (i.e., fish density).

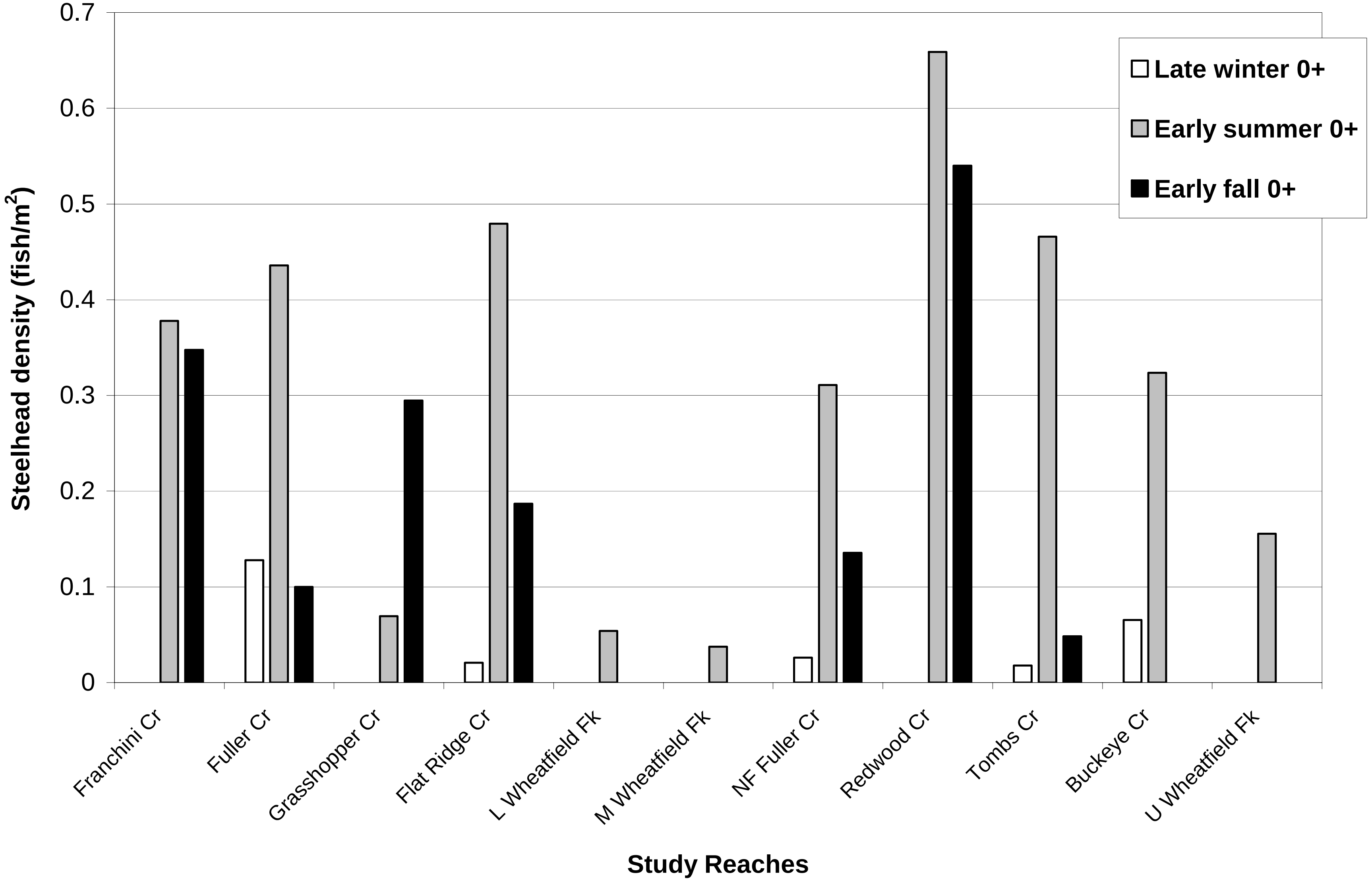


Figure A.1-1. 2006 Late winter, early summer, and early fall densities of age 0+ *O. mykiss*.

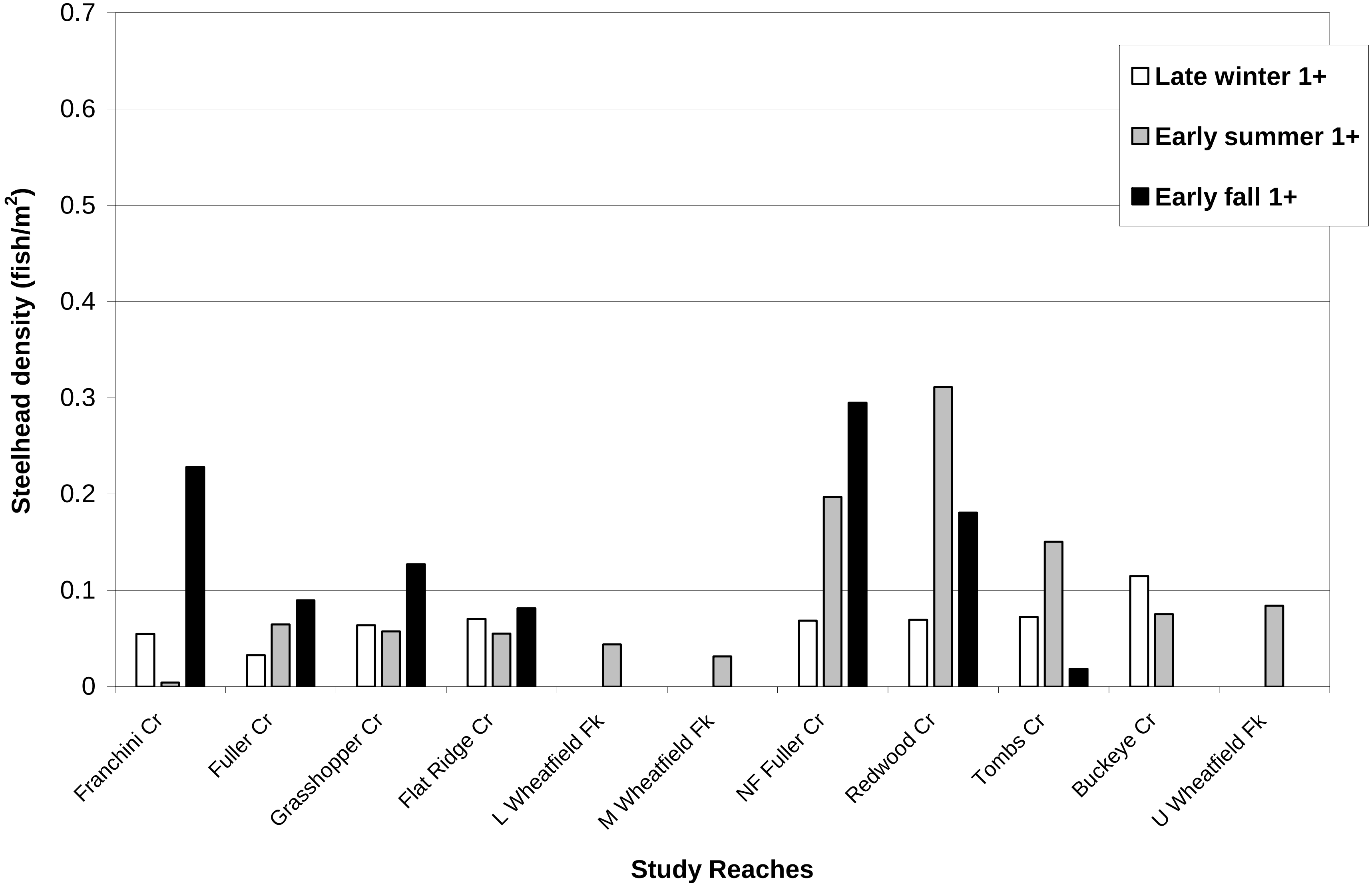
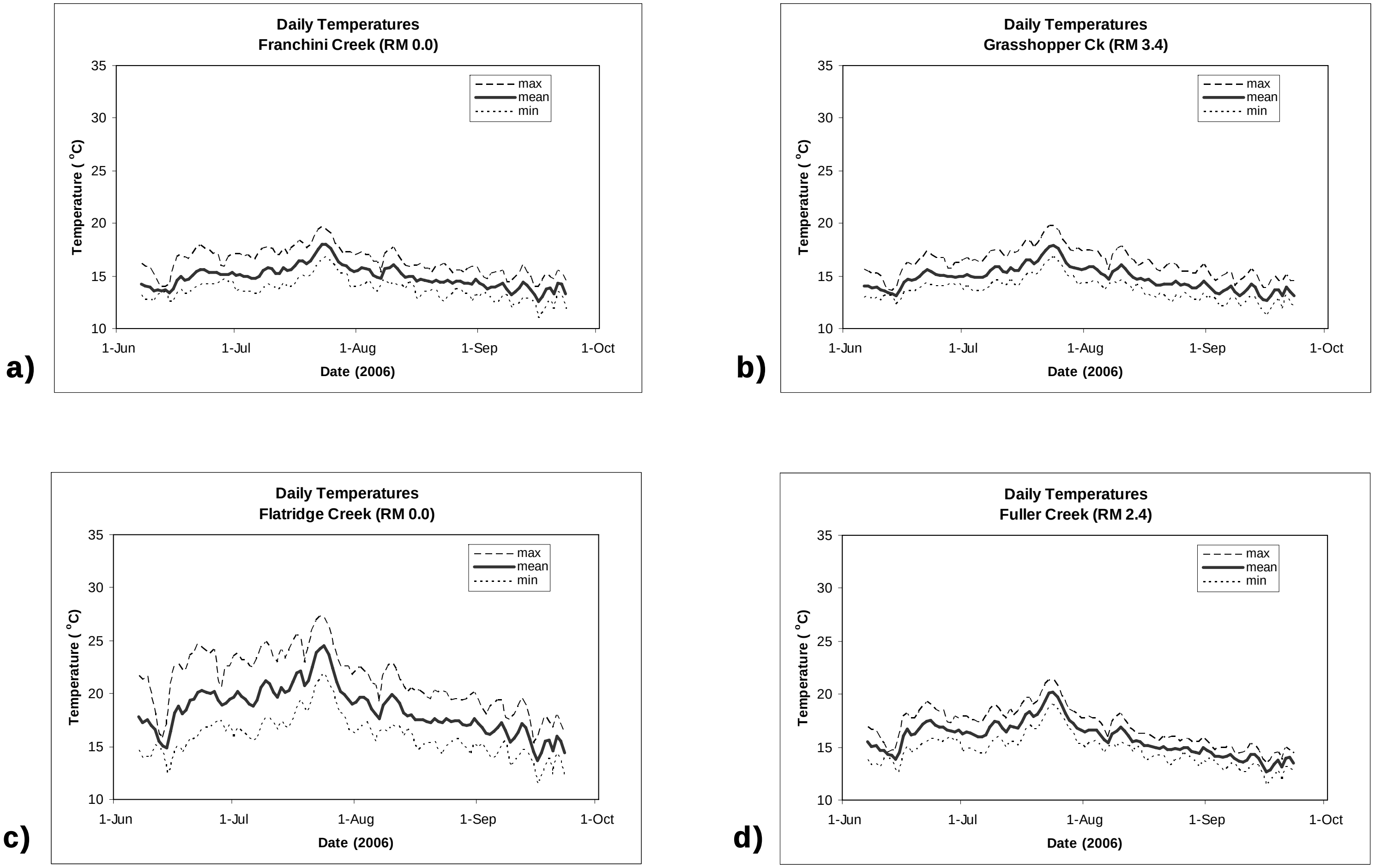
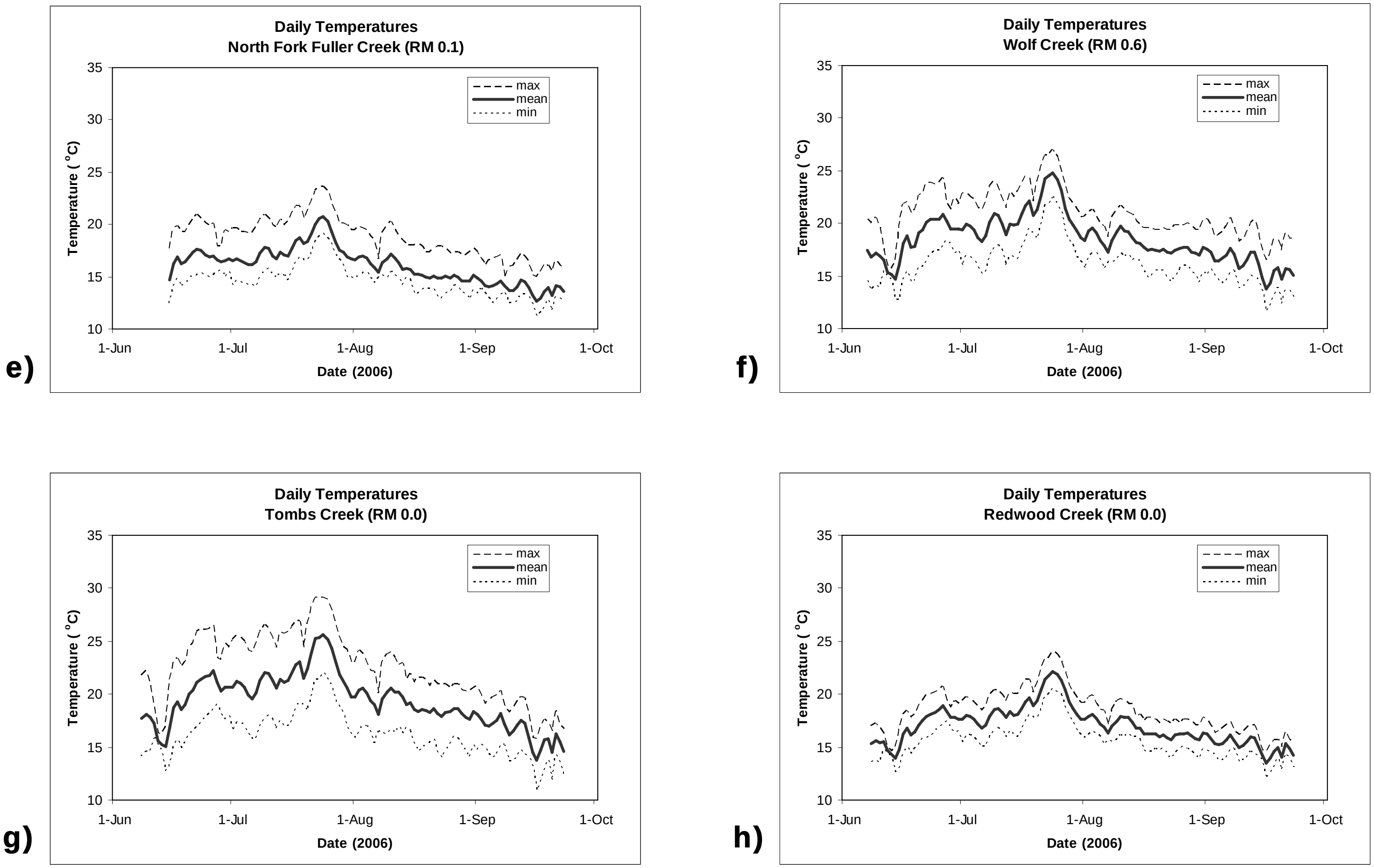


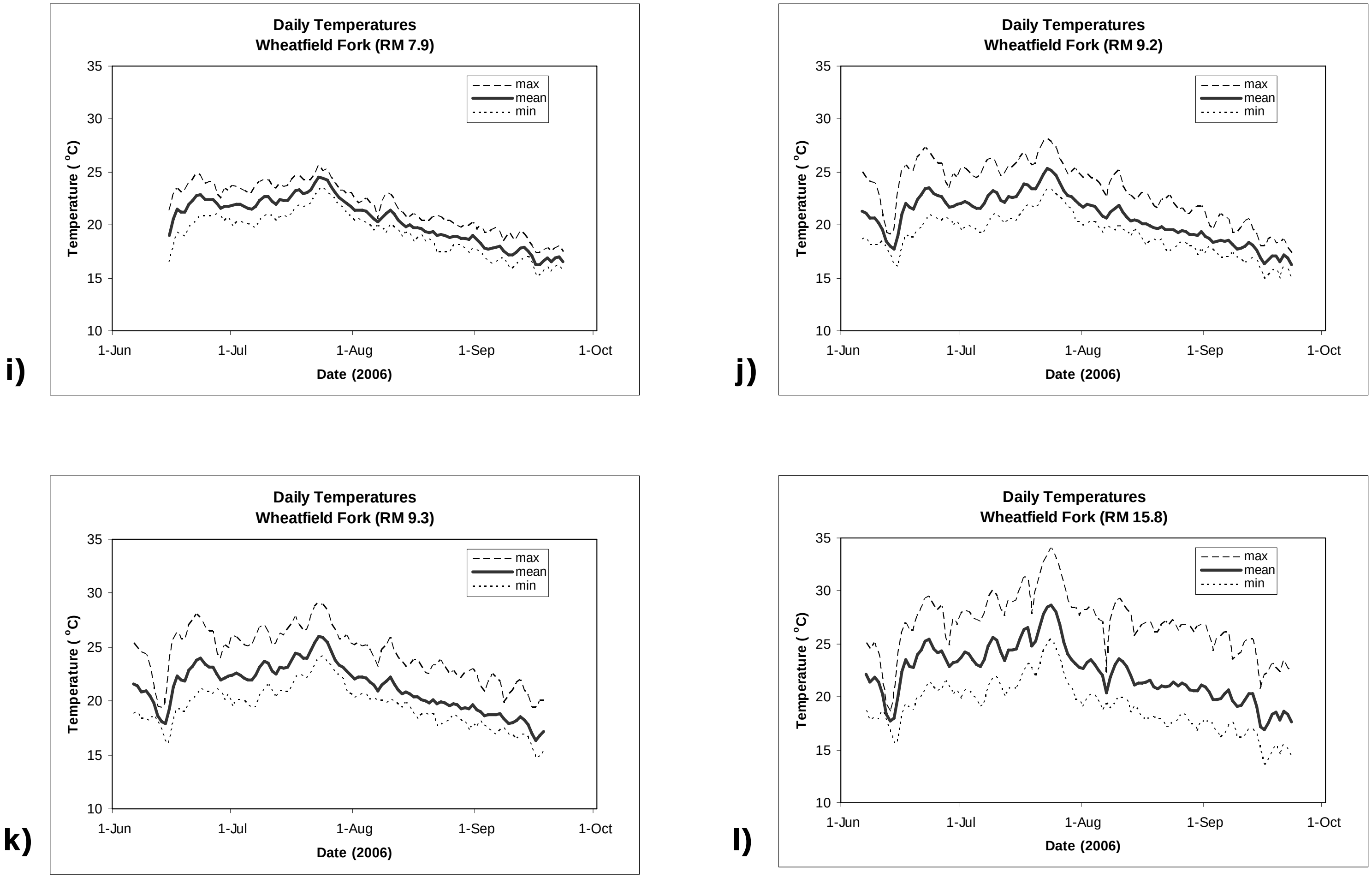
Figure A.1-2. 2006 Late winter, early summer, and early fall densities of age 1+ *O. mykiss*.



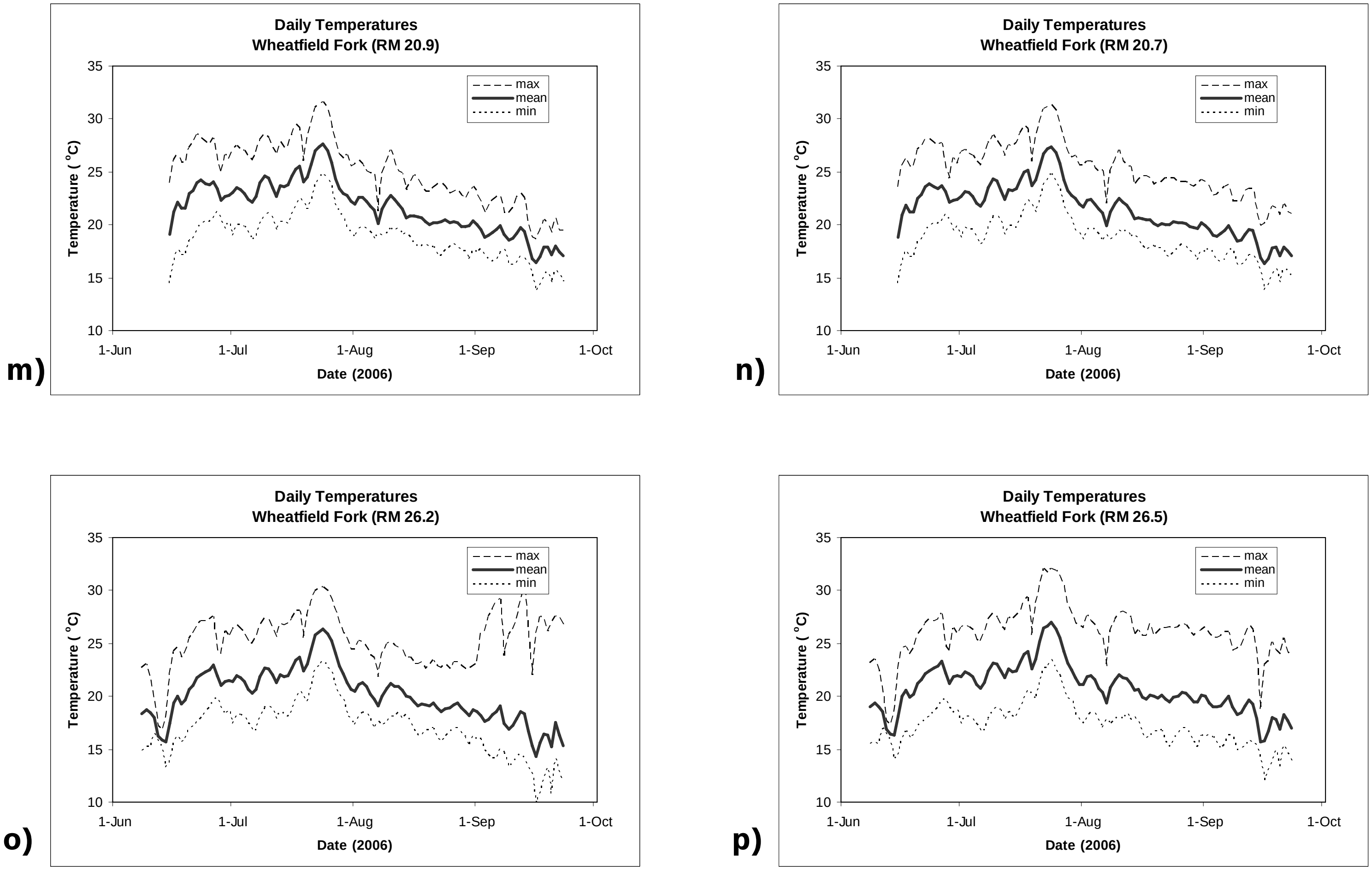
Figures A.5-1 a-d. Daily Average, maximum, and minimum water temperatures recorded at Stillwater Sciences monitoring locations in 2006. See Map 4 for data logger locations.



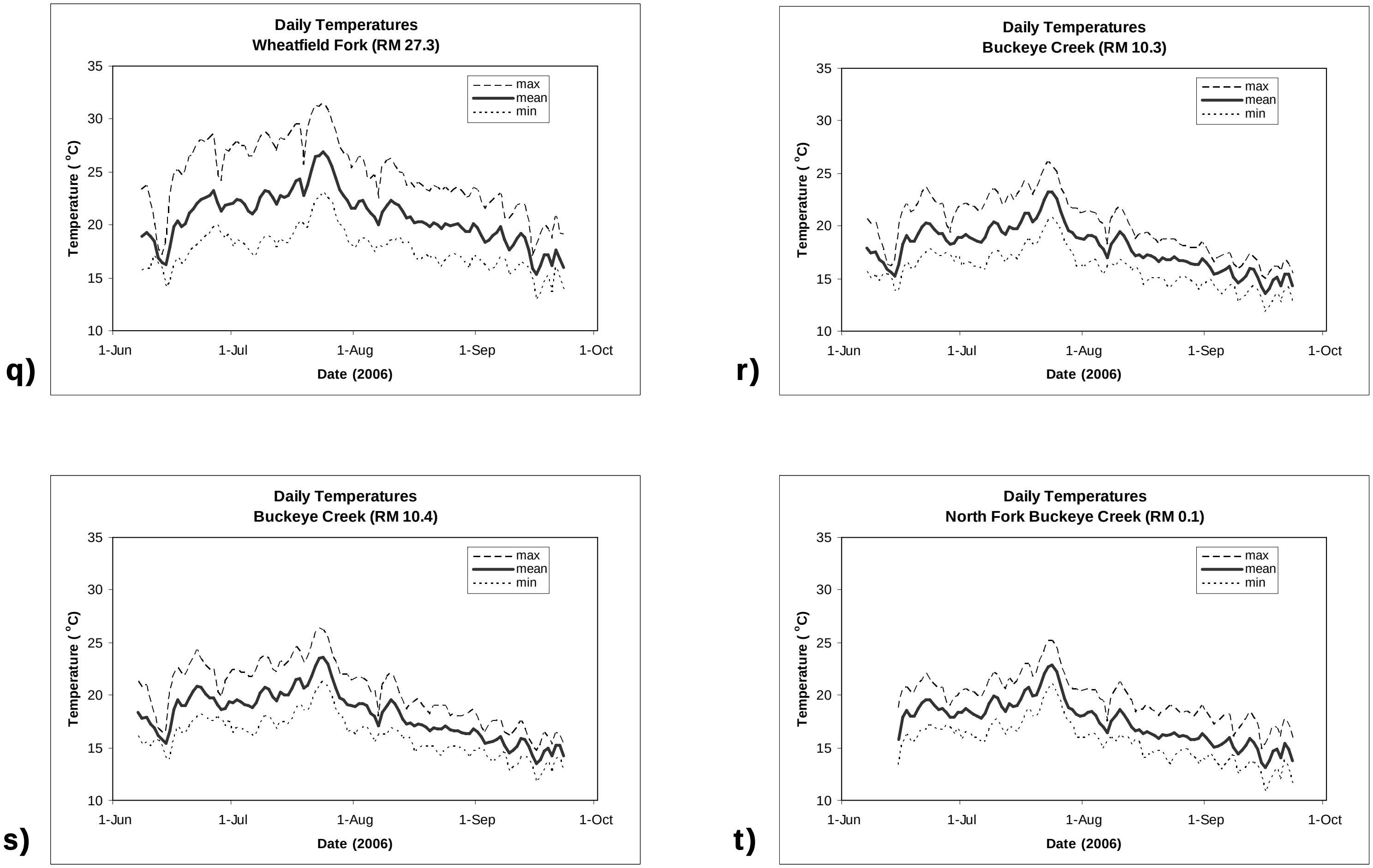
Figures A.5-1 e-h. Daily Average, maximum, and minimum water temperatures recorded at Stillwater Sciences monitoring locations in 2006. See Map 4 for data logger locations.



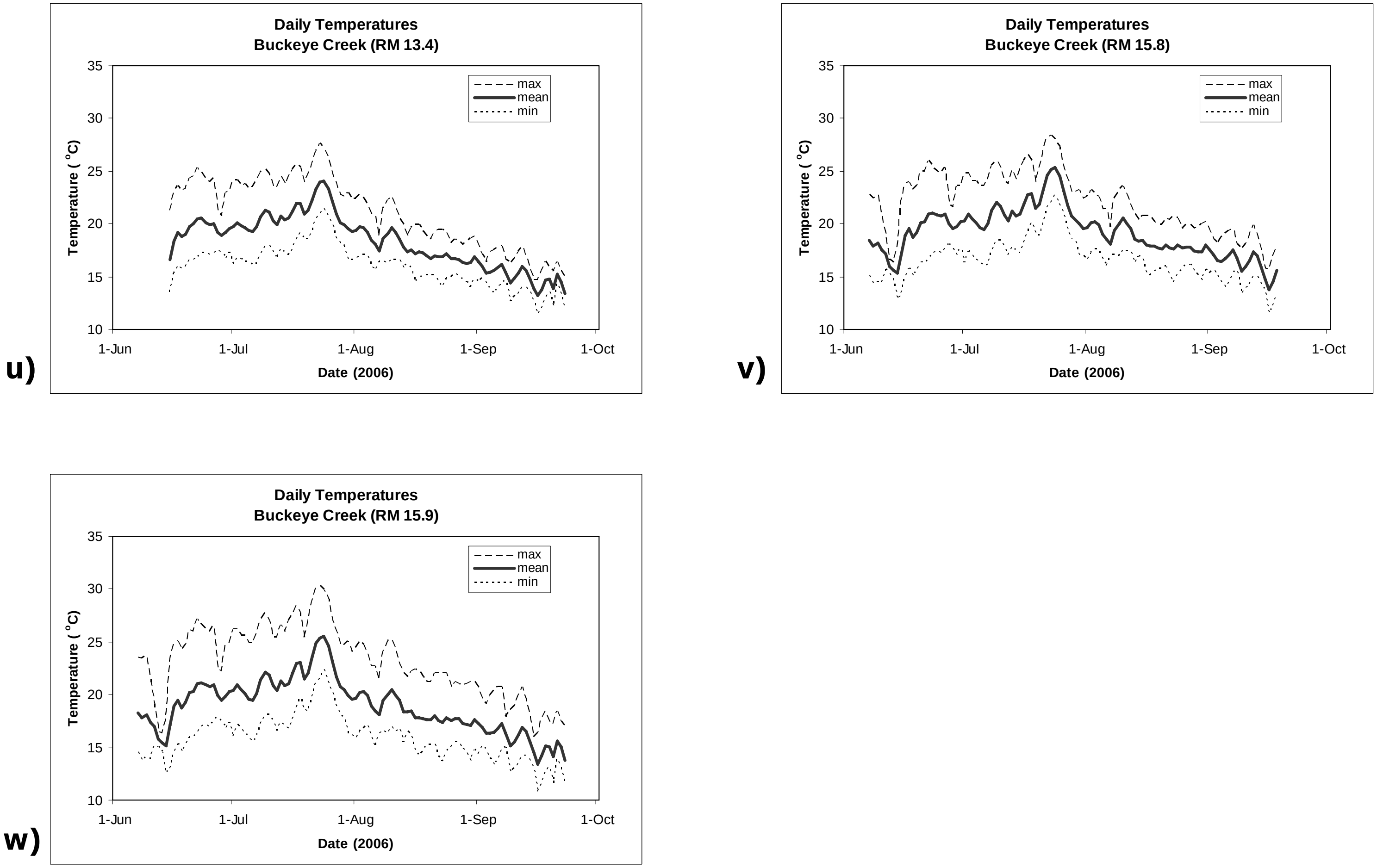
Figures A.5-1 i-l. Daily Average, maximum, and minimum water temperatures recorded at Stillwater Sciences monitoring locations in 2006. See Map 4 for data logger locations.



Figures A.5-1 m-p. Daily Average, maximum, and minimum water temperatures recorded at Stillwater Sciences monitoring locations in 2006. See Map 4 for data logger locations.

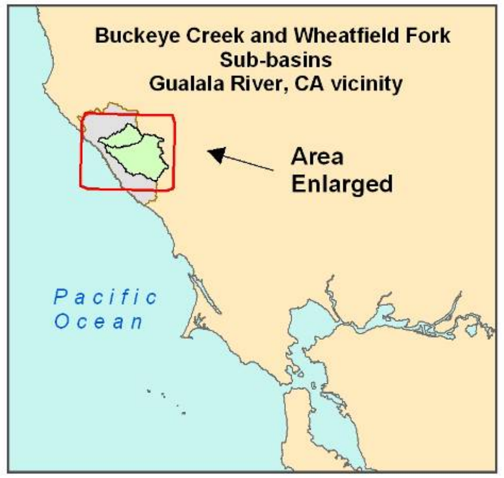


Figures A.5-1 q-t. Daily Average, maximum, and minimum water temperatures recorded at Stillwater Sciences monitoring locations in 2006. See Map 4 for data logger locations.



Figures A.5-1 u-w. Daily Average, maximum, and minimum water temperatures recorded at Stillwater Sciences monitoring locations in 2006. See Map 4 for data logger locations.

Maps



Map 1. Base Map
Study Area, Buckeye Creek & Wheatfield Fork Sub-basins, Gualala River, California

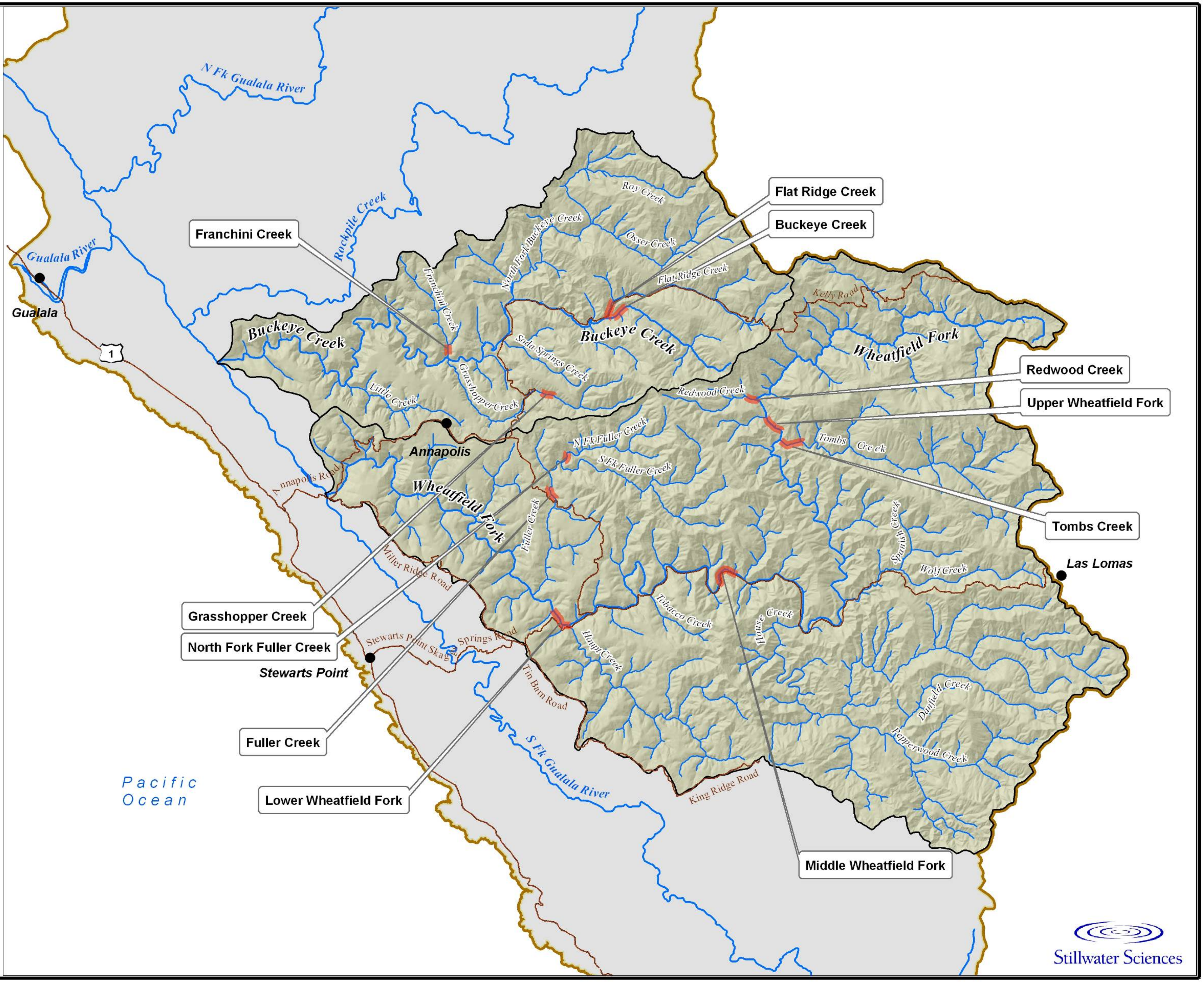
Legend

- ● Towns
- 🟥 Study reaches
- — Main roads
- — Streams
- ☐ Sub-basin boundaries
- ☐ Gualala River basin boundary

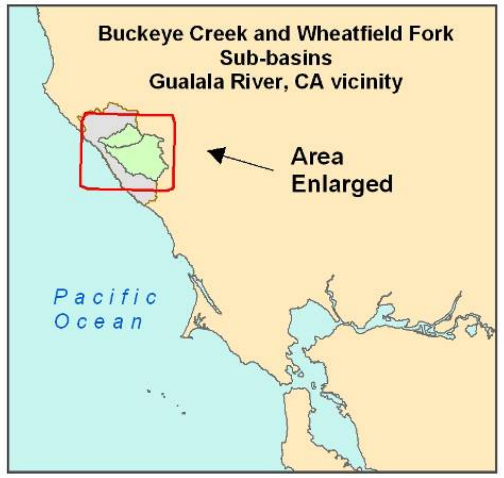
0 1 2 3 4 Km

Data Sources:
Roads: BLM, 1:100,000,
Streams & channel gradients: 10m USGS DEM.

1/16/2007



Stillwater Sciences



Map 2. Geology
Study Area, Buckeye Creek & Wheatfield Fork Sub-basins, Gualala River, California

Legend

- ● Towns
- — - Major faults
- — Streams
- ▨ Active landslides
- ▨ Dormant landslides
- ☐ Sub-basin boundaries
- ☐ Gualala River basin boundary

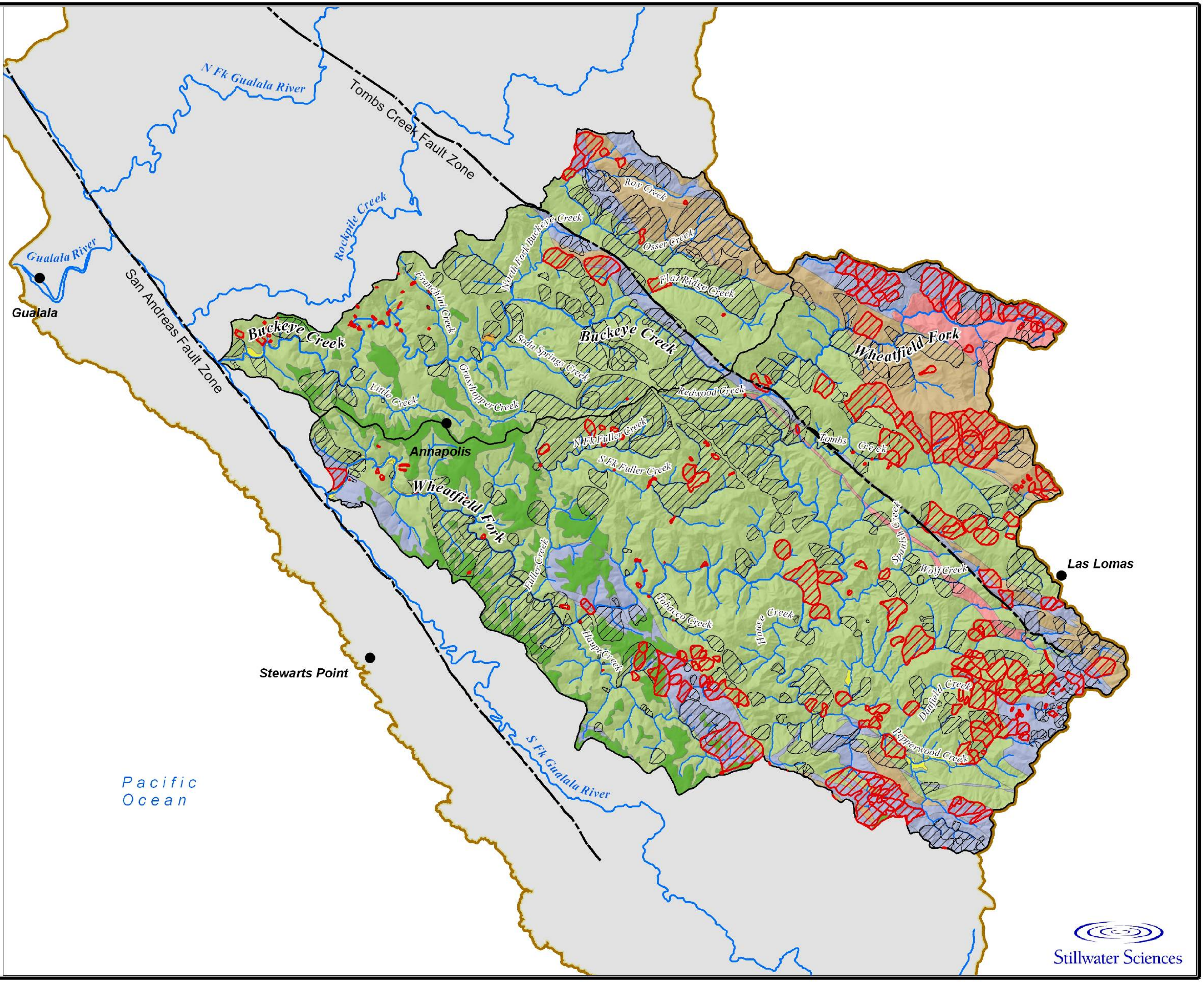
Geology

- 🟫 Central Belt Franciscan (KJfm, gs, gwy)
- 🟩 Coastal Belt Franciscan (TKfs, TKfss, ch)
- 🟩 Ohlson Ranch Formation (Qtor, Qtorc, Qtors)
- 🟨 River terrace and stream channel deposits (Qrt, Qsc1, Qscu)
- 🟧 Older Alluvium (Qoal)
- 🟦 Undiff. Central Belt Franciscan siltstone, serpentinite (KJfs, sp)
- 🟥 Undiff. Franciscan Complex (Kfgs, Kfss, m)

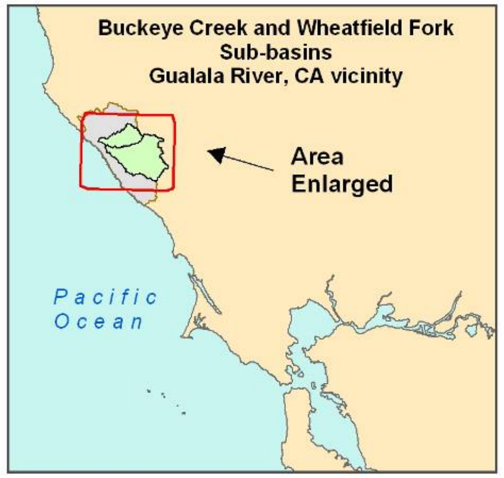
0 1 2 3 4
Km

Data Sources:
Roads: BLM, 1:100,000,
Streams & channel gradients: 10m USGS DEM.

1/11/2007



Stillwater Sciences



Map 3. Temperature Data Logger Locations, Study Area, Buckeye Creek & Wheatfield Fork Sub-basins, Gualala River, California

Legend

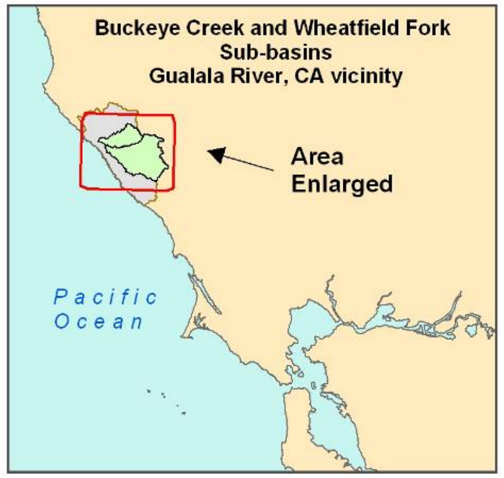
- ● Tidbit locations
- ● Towns
- Streams
- Main roads
- ☐ Sub-basin boundaries
- ▨ Gualala River basin boundary

0 1 2 3 4 Km

Data Sources:
Roads: BLM, 1:100,000,
Streams & channel gradients: 10m USGS DEM.

1/11/2007

Stillwater Sciences



Map 4. Vegetation types and Channel Gradient, Study Area, Buckeye Creek & Wheatfield Fork Sub-basins, Gualala River, California

Legend

- 🟩 Study reaches
- — Streams
- ☐ Basin boundaries
- ▨ Gualala River basin boundary

Vegetation type

- 🟥 Redwood
- 🟩 Conifer/mixed hardwood
- ▨ Oak woodland
- ▨ Agricultural land

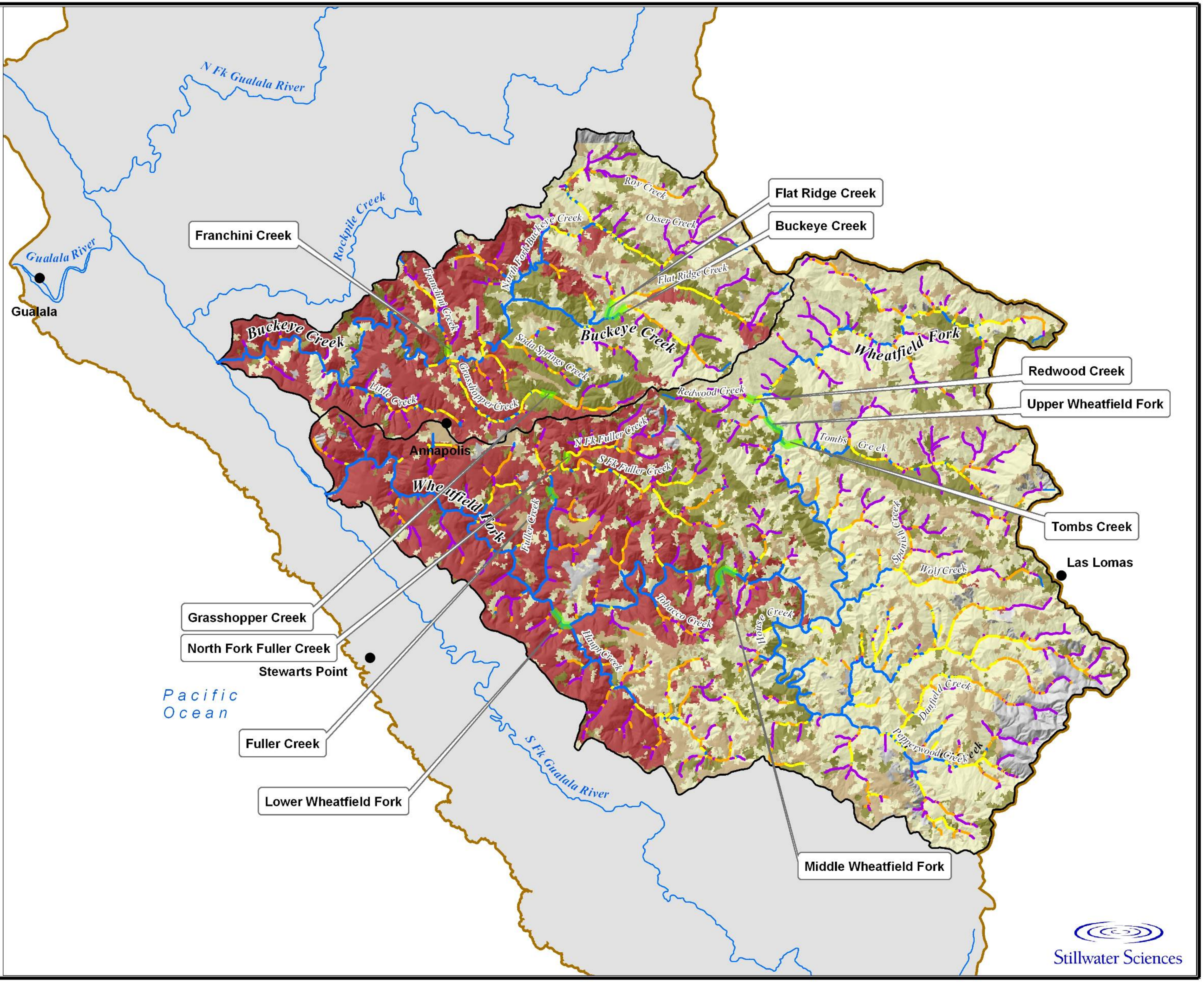
Channel Slope (%)

- — 0 - 1
- — 1 - 3
- — 3 - 7
- — > 7

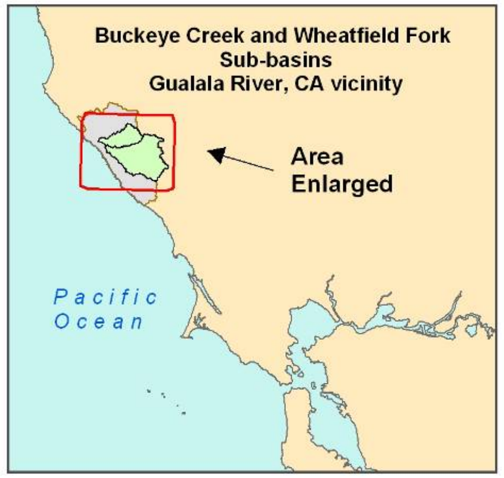
0 1 2 3 4
Km

Data Sources:
Roads: BLM, 1:100,000,
Streams & channel gradients: 10m USGS DEM.

1/18/2007



Stillwater Sciences



Map 5. Channel Gradient and Hillslopes of >60% Gradient, Study Area, Buckeye Creek & Wheatfield Fork Sub-basins, Gualala River, California

Legend

- ● Towns
- 🟩 Study reaches
- — Main roads
- — Streams
- 🟥 Hillslopes >60% gradient
- ☐ Sub-basin boundaries
- ▨ Gualala River basin boundary

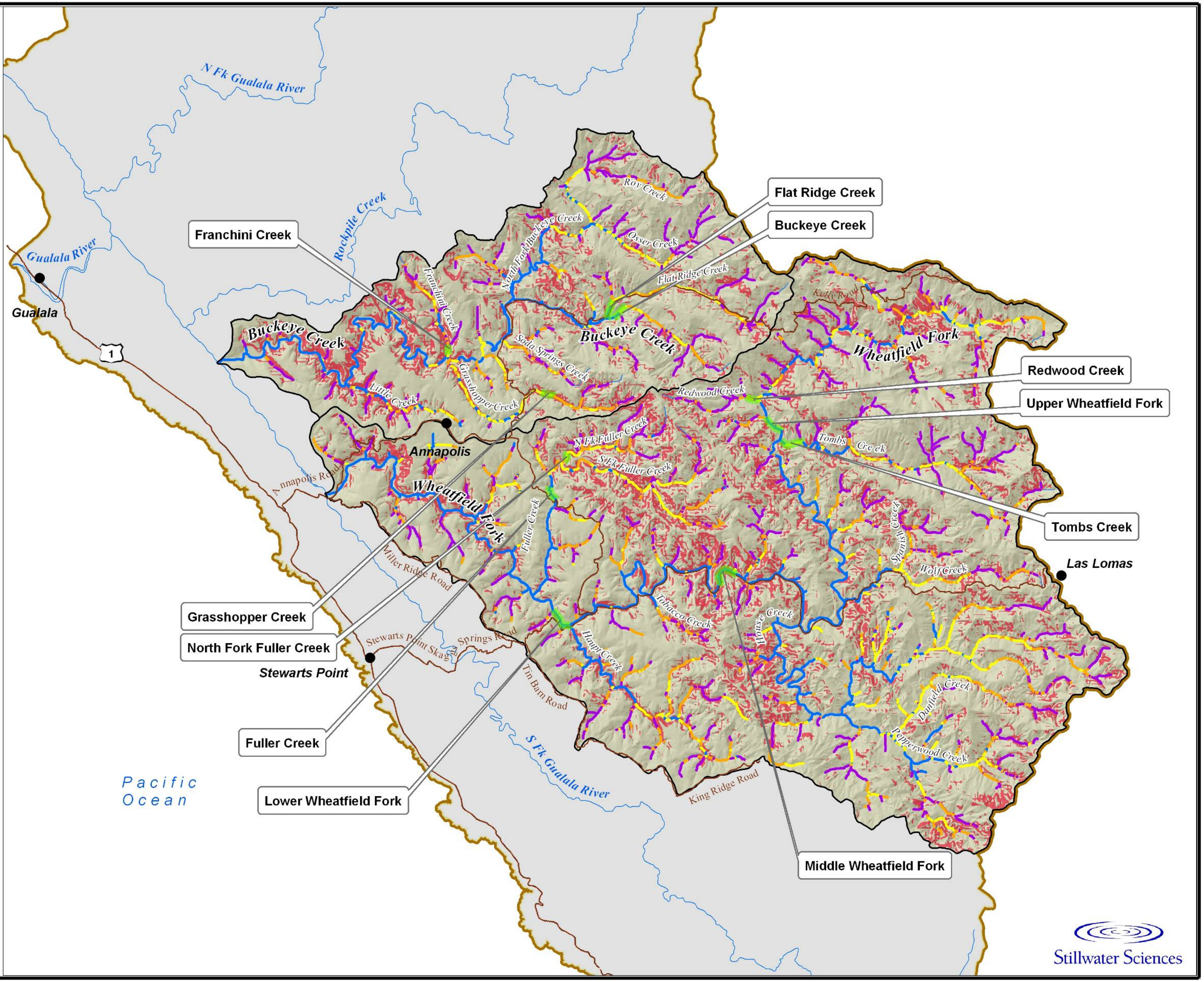
Channel Slope (%)

- — 0 - 1
- — 1 - 3
- — 3 - 7
- — > 7

0 1 2 3 4 Km

Data Sources:
Roads: BLM, 1:100,000,
Streams & channel gradients: 10m USGS DEM.

5/7/2007



Stillwater Sciences