POOL SPACING **IN** SAN GREGORIO CREEK, CALIFORNIA

A Thesis submitted to the faculty of
San Francisco State University
In partial fulfillment of
the requirements for
the Degree

Master of Science
In
Geographic Information Science

by

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August 2015

CERTIFICATION OF APPROVAL

I certify that I have read Pool Spacing in San Gregorio Creek, California by Joseph Maxwell Issel, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Geographic Information Sciences at San Francisco State University.

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Pool Spacing in San Gregorio Creek, California

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Field surveys in pool-riffle channel types within mainstem San Gregorio Creek show that pool formation is driven in large part by flow obstructions that were exposed as a result of channel incision and widening, such as exposed bedrock outcrops and undercut banks hardened with exposed root systems. The depth, cover and complexity of these pools are generally much lower than the pools formed by Large Woody Debris in the study reaches. The pool spacing for the three sites is relatively high, averaging 3.5 pools per channel width which can be attributed in part to the low LWD frequency which averages 0.06 LWD pieces per meter across the three sites. When observed pool spacing and LWD frequency values in San Gregorio Creek are compared with those predicted using a regression equation based on a variety of Washington and southeast Alaskan stream channel types, the pool spacing is overestimated and LWD frequency is underestimated by a factor of roughly 3. This is due in part to the high proportion of often low quality pools formed by obstructions rather than LWD.

I certify that the Abstract is a correct representation of the content of this thesis.

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Chair, Thesis Committee   Date

PREFACE AND/OR ACKNOWLEDGEMENTS

I would like to thank my thesis advisors Jerry Davis and Leonhard Blesius for their guidance and wisdom throughout my education at San Francisco State University; Matt Baldzikowski and the Midpeninsula Open Space District for their participation in funding this thesis project, providing access to their properties to conduct field research, and gather background information on the study sites; the private landowners wo provided access to their properties to conduct field research; John Klochak at the US Fish and Wildlife Service Coastal Program for his advisement; Kellyx Nelson, Jarrad Fisher and the rest of the staff at the San Mateo County Resource Conservation District for advisement, general assistance and participation in funding this research; and my family and friends who supported me in too many ways to list.

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INTRODUCTION

Few watersheds in the Central California Coast still provide Coho salmon (*Oncorhyncus kisutch*) and steelhead trout (*O. mykiss*) the capacity for self-renewal. These species are listed in the federal and California Endangered Species Acts as endangered and threatened, respectively (CDFG, 1996a and 2004; NMFS, 2007 and 2012). The Evolutionarily Significant Unit of Central California Coast coho salmon and Distinct Population Segments (DPS) of steelhead trout range from Monterey County in the south, to Mendocino County in the north (NMFS, 2007; NMFS, 2012). San Gregorio Creek is located in coastal San Mateo County, and represents an anchor watershed for the southern region of the steelhead DPS (Becker et al., 2010). San Gregorio Creek still supports a threatened independent population of steelhead trout (Becker et al., 2010), while coho salmon are observed only in small numbers (Stillwater, 2010).

Based on a limiting factor analysis for salmonid habitat conditions and instream flows in San Gregorio Watershed, over-wintering refuge and low summertime streamflow are identified as principal limiting factors for steelhead and coho, and summer rearing habitat was identified as a limiting factor for age 1+ juvenile steelhead. Physical habitat features such as deep pools, especially those with cover, can mitigate the negative impacts of low streamflow (Stillwater Sciences 2010; 2014).

Individual pieces of Large Woody Debris (LWD), especially with rootwads attached, and log jams made up of LWD have been shown to create critical habitat features for salmonids, including over-wintering refuge and deep pools (Cederholm et al., 1997; Buffington et al., 2002; Stewart et al., 2009; Roni et al., 2013). LWD can generate areas of low-velocity refuge during high-flow events which can prevent fish from getting swept downstream and create opportunities for high-value terrestrial feeding grounds. LWD also creates areas of flow convergence which can scour deep pools that are more likely to

provide cool water temperatures. Salmonids must have access to this habitat type during the summertime when water levels are low and temperatures are at their highest (Everest, 1972; Shirvell, 1990; Stillwater Siences, 2010)

In the fall of 2012, American Rivers completed a Large Woody Debris (LWD) inventory and assessment along 16.7 km out of the 20km of mainstem San Gregorio Creek (Alford, 2013). The study recorded the location and attributes of each piece of wood large enough to be considered LWD (> 30cm diameter measured anywhere along the log and >2m long) under California Department of Fish and Wildlife guidelines (CDFW; until 2013 was named California Department of Fish and Game [CDFG]; Flosi et al., 2010). The frequency of LWD (number of LWD pieces/meter of stream channel) in the mainstem of San Gregorio Creek is 0.05 pieces/m over the 16.7 km surveyed. This value is towards the lower extreme found in Northern California streams, and has been shown to lead to higher pool spacing (reach length/number of pools/average bankfull channel width) and a less divers and productive habitat (Buffington et al. 2002; Carroll and Robinson, 2004). Higher pool spacing means there are less frequent pools which provide critical habitat for salmonids, especially during the summertime when deep pools provide critical cold-water refuge and feeding grounds. While the LWD assessment did record which LWD pieces were associated with pools, no recent assessment in San Gregorio Creek has recorded locations or attributes of pools not formed by LWD (CDFW, 1996b; Stillwater, 2010).

The low amounts of LWD in San Gregorio Creek can be tied to a variety of factors ranging from historic logging operations, removal of wood from streams, and disconnection of the stream to the floodplain where LWD is often recruited (Alford, 2013). Projects which augment natural recruitment of LWD in San Gregorio Creek have been initiated by the San Mateo County Resource Conservation District (RCD) in partnership with the Midpeninsula Open Space District, Peninsula Open Space Trust, California State Coastal Conservancy, California Department of Fish and Wildlife (CDFW), U.S. Fish and Wildlife Service Coastal Program and the National Oceanic and

Atmospheric Administration Restoration Center. While there exists no specific target in San Gregorio creek for how many pieces of LWD are necessary to address this limiting factor, Montgomery et al. (1995) compared pool spacing with LWD frequency for low-gradient streams (slope < 0.3) and observed that pool spacing consistently reach a lower limit of 0.2 channel widths per pool when LWD frequency is high (>0.1 pieces/m), and an upper limit as high as nine channel widths per pool when LWD frequency is low (<0.03 pieces/m). LWD frequency observed in streams with intact old growth forests and little evidence of channel modification or LWD removal ranged from 0.4 in the Pacific Northwest to 0.24 in Northern California (Montgomery et al., 1995; Caroll and Robinson, 2004). Montgomery et al. (1995), Caroll and Robinson (2004) and other studies referenced in this study provide a basis for comparing conditions in San Gregorio creek with similar systems.

Objectives of this study include (1) quantifying the abundance of pool habitat, associated mechanisms of pool formation (LWD, boulders, bedrock outcrop), stream channel type (pool-riffle, forced pool-riffle, and plane-bed), and land use changes (e.g. confinement with levees, bank hardening) which affect channel morphology and response to LWD in San Gregorio creek; (2) comparing and contrasting relationships between pool locations, pool-forming mechanisms (e.g. LWD, bedrock outcrops, boulders) and stream channel morphology in mainstem San Gregorio creek with those developed in previous studies of Pacific northwest and northern California streams; and (3) developing a target and rough cost estimate for the amount of LWD needed increase the abundancy and frequency of pools and areas of refuge from high flows necessary to address limiting factors for salmonid recovery.

LITERATURE REVIEW

Variables for studying LWD and Pool Habitat

Channel morphology measurements included in studies investigating relationships between LWD and pool formation all record a useful set of fundamental measurements including channel gradient, bankfull channel width, residual pool depth, pool forming mechanisms, variations of LWD geometry, and classification of stream reaches (Montgomery and et all., 1995; Beechie and Sibley, 1997; Carroll and Robinson, 2004; Wohl et al., 2010). From these measurements a variety of metrics can be derived to further investigate relationships between LWD and channel morphology. Instruments used in these studies range from hand levels, surveyors levels, to total stations. Methods for measuring stream channel topography and classification also varied based on the scale and focus of the particular study.

Bryant et al. (2004) investigated which habitat measurement variables were among the most precise with regards to the signal (i.e. variance among streams) to noise (measurement variance between repeat stream visits) ratio. Eight habitat response variables have been demonstrated in previous literature to be the most precise: (1) Width-to-depth ratio, (2) total large wood pieces/meter, (3) total key (dominant) pieces of large wood/meter, (4) pools/kilometer, (5) pool spacing, (6) average residual pool depth/average channel bankfull width, (7) median particle size, and (8) pool length/meter (Bryant et al., 2004).

Other variables associated with LWD include: the decay status; stability; species; dimension of the wood submerged in relation to flow stage; function of the wood in relation to sediment storage or scour; accumulation mechanism; and whether there is a root wad attached (Wohl et al., 2010). The SG LWD Inventory followed CDFW guidelines which include a standardized form to record many of the most common

variables recorded in woody debris studies (Flosi et al. 2010). The chosen length of stream channel reach surveyed in the LWD studies referenced here varied from minimum distances (e.g. >100m, or >1,000m), to using lengths of average bankfull channel widths (e.g. >3, or between 10 to 24 channel widths), and surveying near entire stream segments (Montgomery et al. 1995 & 1997; Beechie and Sibley, 1997; Rosenfeld and Huato, 2003; Alford, 2013).

Measurements and Definitions of Pools

Among the most precise metrics for describing and comparing pool habitat among stream reaches are the number of pools, their length and width, and the mean residual pool depth (Kaufmann et al. 1999). Pool to pool spacing is defined as the reach length divided by both the number of pools and the reach-average channel width (Montgomery et al., 1995). This yields a pool-to-pool spacing in channel width units, or the number of channel widths between pools. This metric can be compared with LWD loading for different stream channel types (forced pool-riffle, pool-riffle, and plane-bed). Additionally, pool spacing can be analyzed as a function of LWD frequency, and percent pool (total pool area/(average channel width * channel length) (Beechie and Sibley, 1997; Rosenfeld and Huato, 2003).

Table 1 lists definitions of LWD used by several different LWD studies. As with LWD, pools are also characterized differently among studies, but are not always as clearly defined as LWD. Montgomery et al. (1995) recorded all morphologically distinct pools which typically had water depths many times greater than the median bed surface grain size, residual depths of at least 25% of bankfull depth and a length or width of at least 10% of the channel width. Beechie and Sibley (1997) referenced Bisson et al. (1982) when providing a basis for defining pools. Bisson et al. (1982) defined six types of

Table 1 . Definitions of LWD and pools

References	LWD Diameter	LWD Length	Pools
O'Neill and Abrahams, 1984	N/A	N/A	Compares the absolute value of elevation changes in reach against a threshold value to determine if the channel bed form of the reach was a pool or riffle. This method is called the bed form differencing technique.
Montgomery et al., 1995	>10cm	>1m	Recorded all morphologically distinct pools (estimated at 25% bankfull depth and length or width of 10% of channel width.
Beechie and Sibley, 1997	>10cm	>2m	Secondary channel pools, backwater pools, trench pools, plunge pools, lateral scour pools and dammed pools (see Bisson et al., 1982)
Bryant et al., 2004	>10cm	>1m	N/A
Carroll and Robinson, 2004	>10cm	>2m	Pools defined by channel size: minimum residual depth was 25% of mean bankfull depth. Minimum pool length was half bankfull width.
Rosenfeld and Huato, 2003	>15cm	>1m	Pools were counted that spanned the entire width of the channel.
Flosi et al., 2010 (CDFW guidelines)	>30cm	>2m	Level I Habitat Types: Main, scour and backwater pools

pools: Secondary channel pools, backwater pools, trench pools, plunge pools, lateral scour pools and dammed pools. Rosenfeld and Huato (2003) defined pools that spanned the entire width of the channel in order to ensure consistency with a study of fish abundance. CDFW guidelines (Flosi et al., 2010) breaks pools into three Level I Habitat Types: main channel pool, scour pool and backwater pools; and further breaks these down into fifteen Level II Types. In order to best compare results with Montgomery et al. (1995), pools in San Gregorio Creek were identified as having residual depths of at least 25% average bankfull depth (> 0.35 m) and a length/width > 10% average bankfull width (> 1.62m). Pool habitat considered of good quality for steelhead trout has a residual depth of at least 0.35 m (1 foot; Everest and Chapman, 1972; Shirvell, 1990).

Measurements and Definitions of LWD

Studies which investigated the relationship between wood and channel morphology typically recorded wood pieces with a mean diameter greater than 10cm and 1m in length (**Table 1**). The smallest pieces of wood recorded to form a pool by Beechie and Sibley (1997) had a mean diameter of 12cm in a small channel (bankfull width 4.3m) and 75cm in the largest stream channel (bankfull width 22.1m); and in the SG LWD Inventory (2013) the smallest log that formed a pool was between 30cm and 60cm wide and <2m long. CDFW's guideline for measuring LWD indicates that the diameter of a downed log should be the largest diameter anywhere along the log (Flosi et al. 2010). Wohl et al. (2010) identify the need to make a minimum of two measurements to better estimate the volume of wood. The suggested measurements include recording both the entire length of the wood piece and the portion within the bankfull channel.

As a general rule, projects installing LWD without anchoring hardware use logs 1.5 times the average bankfull width in order to help ensure logs remain in place (Flosi et al. 2010). This is not possible to achieve in channels wider than the tallest available conifer trees.

Debris jams spanning wide channels like the Willamette River in Washington (215m-365m) were observed prior to debris clearing efforts for navigation purposes. The Willamette has channel widths many times greater (155-205m) than the tallest available conifer trees (60m). The influence of LWD on pool formation depends on channel width, flood flows, river management (debris removal), and composition of the riparian tree species. In smaller channels where the average channel width is less than the median wood piece length CDFW guidelines for LWD can generally be achieved. In medium (channel width is greater than the majority of wood pieces) and large channels (channel width is greater than all wood pieces), other factors must be considered when determining the minimum side of a wood piece to influence channel morphology and the formation of pools (Gurnell et al., 2002).

The orientation of LWD is shown to be a significant driver of pool formation (Hilderbrand et al., 1998; Buffington et al., 2002) and should be recorded in LWD surveys. Buffington et al. (2002) describes five types of obstruction types which LWD can form, but does not include channel spanning log jams. Each obstruction type is associated with different mechanisms for forcing scour which also depends on channel characteristics. The channel gradient, width to depth ratio, relative submergence (ratio of flow depth to gran size), and the caliber (i.e. size) and input rate (i.e. bedload transport rate) of bed material size all act as controls on the relative effectiveness of obstructions to induce scour. Methods for recording the horizontal and vertical angles and positions of wood pieces vary among studies, and typically include the angle of the wood with respect to overall flow direction at bankfull (Hilderbrand et al., 1998; Buffington et al., 2002; Wohl et al., 2010).

Stream Channel Classification Systems

Methods used for watershed-scale assessments of stream channel types can be separated into two groups: form based (e.g. Rosgen, 1994); and process based methods (e.g. Montgomery and Buffington, 1997; Montgomery and MacDonald, 2002). The form based classification system presented by Rosgen (1994) identifies seven major and 42 minor hierarchical stream channel types which are separated using descriptive topological classifications based on channel form (e.g. slope bed material, entrenchment ratio, sinuosity, width to depth ratio, and geomorphic environment).

Form based methods rely on reference channels that are assumed to be in a stable state and reflect the pre-disturbance conditions (Niezgoda and Johnson, 2005). Reference channels must be able to transport the upstream inputs of water and sediment while limiting streambed and bank erosion. The relationship between the morphology of reference reaches and stream function are then used to predict channel conditions and potential responses to changes in similar watershed systems. Reference reaches are used as comparisons to model restoration designs for disturbed channel reaches. This is often called the "natural channel design method" and references the work of Rosgen (1994, 1997) among others (additional form-based methods are listed in Niezgoda and Johnson, 2005). Form based classification and restoration methods are used in federal (e.g. Harrelson et al., 1994) and California state guidance documents (Flosi et al., 2010). Rosgen's (1994) stream classification system for natural rivers assumes that bankfull discharge is the dominant channel forming discharge when the existing channel is in a stable state. Bankfull is defined as the dominant channel forming flow that creates a stable alluvial channel form. In a stable alluvial channel, the bankfull flow is located at the top of the bank, where water would begin to overflows onto adjacent floodplains. Bankfull flows occur on average every 1.5 to 2 years (Rosgen, 1994; Florsheim et al., 2013).

Montgomery and MacDonald (2002) present a diagnostic, process based approach for stream channel assessments monitoring, and Montgomery and Buffington (1997) present stream channel classifications for seven distinct morphologies in mountain drainage basins. The areas investigated in this study are considered natural landscapes dominated by forestlands in the Pacific Northwest. Each alluvial channel reach morphology type is separated by examining the following relationships: (1) the relationship between channel slope (S) and the drainage area (A):

$$S = KA^{-m/n} \tag{1}$$

where K, m, and n are empirical variables that incorporate basin geology, climate, and erosion processes, (2) the ranges of slope most likely to occur amongst each channel type (e.g. <0.015 ≈ pool-riffle, 0.015-0.03 ≈ plane-bed, 0.03-0.065 ≈ step-pool, >0.065 ≈ cascade) , (3) the relative roughness (the ration of the ninetieth percentile grain size to the bankfull flow depth [d90/D]) compared to channel reach slope, and 3) reach-average bankfull shear stress compared with channel type (Montgomery and Buffington, 1997).

Montgomery and Buffington (1997) show that channel types are distributed along a continuum from transport limited to supply limited reaches based on the ratio of sediment supply (Qs) to transport capacity (Qc). For example, pool riffle channels lean slightly towards the transport limited side, while plane bed channels resemble a semi-equilibrium state. Pool riffle channels will tend to be located in downstream reaches below 1.5% slopes. Forced pool-riffle channels can be forced in steeper stream channels by bedrock outcrops and Large Woody Debris (LWD).

Process based classification systems like the one developed by Montgomery and Buffington (1997) separate channel-reach classes based on channel-reach processes and their spatial location within the watershed (drainage area), combined with external influences like sediment inputs, confinement, riparian vegetation and flow obstructions (LWD, boulders, bedrock-outcrops). Montgomery and Buffington (1997) present three

primary channel-reach classes based on substrate (bedrock, alluvium, and colluvium), of which alluvium are broken into five distinct morphologies (cascade, step pool, plane bed, pool riffle, and dune ripple). Each channel type can be identified by unique channel-bed morphology which allows field surveyors to rapidly classify stream channel reaches through visual observations.

The use of form based classification schemes has been criticized by Simon et al. (2007), suggesting that it ignores the open system of alluvial streams and the adjustments made to altered inputs of energy and material. It is argued by Montgomery et al (1997) that Rosgen's classification system lacks basis in channel processes, and that it combines reach morphologies that may have very different response potentials. Niezgoda and Johnson (2005) highlight that Rosgen's methodology assumes all streams with comparable measureable forms will act in similar ways, or that the rivers behavior can be predicted by its appearance. Niezgoda and Johnson (2005) suggests that process-based classification systems are better suited for studying altered watershed systems, because in urban environments it can be difficult to locate stream channels that have returned to a stable state after urbanization. Streams that are influenced from changing upslope land use conditions impacting sediment and water input regimes typically exist in a state of incising, widening, or aggradation. Streams which are subject to these irregular conditions can experience variations in the dominant channel forming discharge. In these situations it is necessary to adjust classification schemes for urban watersheds and modify regional curves to fit bankfull determinations where stable urbanized streams do exist (Niezgoda and Johnson (2005).

Florsheim et al. 2013 discusses the concept of "effective flow," which is the flow necessary to mobilize sediment in a stream channel, and can be used in lieu of bankfull elevation in highly altered systems (e.g. incised channels). In such systems bankfull elevations that represent the dominant channel forming flow can be difficult to interpret. Effective flow can be determined when bar formations in incised channels represent an

estimate of the elevation of effective flow. Bar formations in stable channels are shown to be roughly 71% of the bankfull depth. To help identify when a channel is incised, a "relative incision" metric is provided which is defined as terrace height (h_t) / effective flow depth (d_e; Florsheim et al., 2013). A stable alluvial channel without incision would have a relative incision value of 1. Stream channels with values above 1 would be considered incised.

In this study, the stream studies surveyed are relatively similar and would likely fall into a single class in most classification systems. The descriptions of channel types provided by Montgomery et al. (1995) are used to define the stream channel types included in this study. In general, the mainstem of San Gregorio Creek is considered to be an altered and incised pool-riffle channel type (Stillwater Sciences, 2010). Hydrologic analysis at one of the study sites (DR) shows that 10 year storms are contained almost entirely within the incised stream channel, and only inundate low lying floodplains within the incised channel or in the few low lying floodplains that still remain. Similarly, the 100 year storm event is contained within much of the stream channel, but does overtop its banks onto the historic floodplain in some areas (Stillwater Sciences, 2015). Given the incised state of mainstem San Gregorio Creek, a processed based classification scheme would be more accurately characterize the stream channel processes at play.

Channel morphology and gradient

Low-gradient (slope ~0.01) plane-bed channels are described by Montgomery and Buffington (1997) as having morphologies that encompass common fish habitat types, including glides (runs) and riffles. Booth et al. (1997) characterized plane bed channels as roughly straight channels with featureless beds, and in an idealized watershed occur between stream gradients of 0.01 to 0.03. In circumstances when low-gradient plane-bed channels have large substrate size they tend to exhibit a greater transport capacity than

sediment supply, preventing scouring of pools until discharge exceeds a threshold typically at or above bankfull width (Montgomery and Buffington, 1997, Buffington et al., 2002). A key characteristic of plane-bed channel types described by Montgomery and Buffington is the lack of significant lateral flow convergence to develop pool-riffle morphology given the lower bankfull width to depth ratio and high relative roughness. Pool spacing was observed to range from 2 to over 13 channel widths in the Montgomery et al. (1995) study.

Pool-riffle channels tend to occur at lower stream gradients (0.001 and 0.02) than plan-bed channels (Booth et al. 1997). In free-formed pool-riffle channels, an oscillating pattern of flow convergence on the inside of bends result in the scour of pools and downstream flow divergence results in sediment accumulation on discrete bars (Montgomery and Buffington, 1997). Montgomery et al. (1995) found that pool-riffle channel types in forested streams had pool spacing's of 2 to 4 channel widths, even when LWD loading was low (<0.03 pieces/m^2). Pool-riffle and plane-bed reaches where pool spacing has been shortened due to increased obstructions such as LWD, bedrock or boulder outcrops can be classified as forced pool-riffle channel types (Montgomery et al., 1995; Buffington et al., 2002).

In a disturbed watershed, such as San Gregorio, current channel morphology may not reflect the typical channel morphology which would be found for a reach with the same gradient in a natural setting. For example, where multi-threaded or free-formed pool-riffle channel sequences with a gradient ≤0.01 were once likely to occur prior to disturbance, channel confinement, removal of LWD, and increased coarse sediment inputs can lead to increased pool spacing and the formation of a plane-bed channel morphology (Booth et al., 1997; Buffington et al. 2002; Cluer and Thorne, 2013).

Pool-Forming Mechanisms

In a study by Buffington et al. (2002) controls on pool forming mechanisms are discussed in detail and their results indicate that controls on pool formation depend on a variety of interacting factors, including obstructions (e.g. woody debris, boulders and bedrock outcrops), coarse and fine sediment inputs, bank disturbance and channel widening. Each factor was observed to be more or less important based on the channel morphology and location within the watershed. Pool formation in plane-bed channel types were found to be highly influenced by the supply of wood and other obstructions; moderately influenced by coarse sediment inputs, bank disturbance and channel widening; and fine sediment inputs had a low influence on pool scour. Pool-riffle channel types were found to be highly influenced by the supply of wood and other obstructions, coarse sediment inputs, bank disturbance and channel widening; and were moderately influenced by fine sediment inputs (Buffington et al., 2002).

LWD influence on pool formation

The proportion of LWD that has a dominant influence on forming pools tends to be around 40% of LWD pieces (Montgomery et al. 1995; Beechie and Sibley, 1997; Alford; 2013). Beechie and Sibley (1997) reported free-formed pools accounted for an average of 23% of pools in low-slope channels (slope $0.001 \leq 0.02$), and an average of only 9% in moderate-slope channels ($0.02 < $ slope $ < 0.05$), while LWD forced pools accounted for an average of 48% in both slope classes in northwestern Washington streams. Montgomery et al. (1995) similarly recorded LWD obstructions having the largest influence on pool formation, where 73% of 471 pools recorded were observed to be forced by LWD, compared to 18% being self-formed. Montgomery also reported that in general up to 40% in-channel LWD exerted dominant influence on pool formation. A similar ratio was

recorded by Alford (2013) in mainstem San Gregorio Creek with 45% of in channel LWD acting as a primary driver of pool formation.

The influence of channel width has a significant impact on the relationship between LWD loading (pieces/m^2) and pool frequency (channel widths/pool; the inverse of pool spacing).   Wider channels have more pools per channel width than narrower pools down to 4m wide. Below 4m wide channels, pool frequency is independent of LWD loading. Wider channels have more pools than narrower channels because multiple pools can form with a single piece of LWD, and in a small channel a piece of LWD often only forms a pool at one location (Montgomery et al. 1995).

LWD frequency (number of LWD pieces/meter of stream channel) accurately incorporates influences from both channel width and LWD loading (number of LWD pieces in a reach/reach length/bankfull width, or LWD/m^2; Montgomery et al., 1995). Furthermore, the proportion and total number of pools formed by LWD increases with increasing LWD frequency. This results in a roughly inverse relationship between pool spacing and LWD abundance. When LWD abundance is plotted against pool spacing, it shows that this relationship asymptotically approaches a lower limit of about 0.2 channel widths at the highest LWD abundance (**Figure 1.**). When LWD spacing approaches 0.2 channel widths, the interference between zones of forced flow convergence and divergence at high LWD loading limits the ability of the channel bed to form additional morphologically distinct pools at each LWD piece or structure. The proportion of in-channel LWD influencing pool formation was independent of LWD loading (LWD/m^2) above 0.03 pieces/m^2, where LWD loading resulted in the same proportion of pool forming LWD pieces (roughly 40%; Montgomery et al., 1995; Beechie and Sibley, 1997).   While this proportion remained constant, the total number of pool forming LWD pieces did increase until LWD spacing reached 0.2 channel widths (Montgomery et al. 1995).
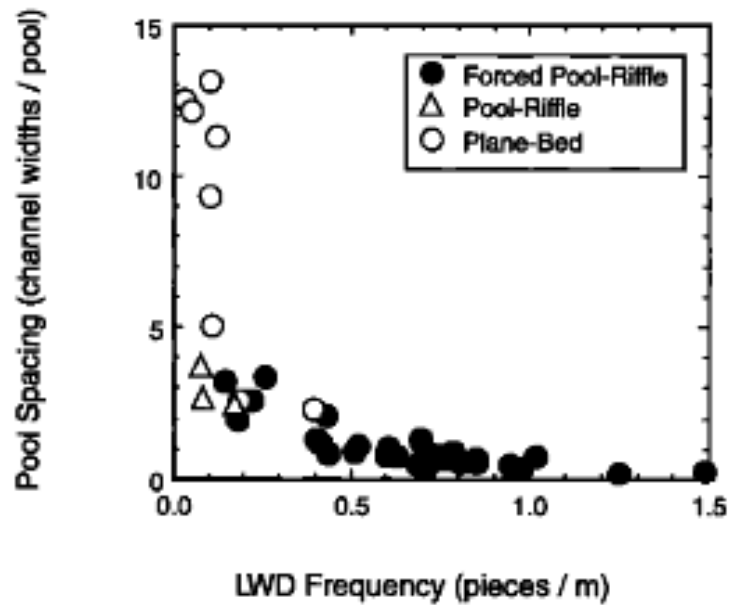
Figure 1. LWD frequency versus pool spacing for pool-riffle, plane-bed, and forced pool-riffle reaches (From, Montgomery et al., 1995).

STUDY AREA

The San Gregorio Watershed Management Plan (Stillwater Sciences, 2010) provides detailed background information on the San Gregorio Watershed. Much of the information provided below can be found in the Watershed Plan and original sources in greater detail. What is included here is intended to provide the reader with the necessary background information to best appreciate the discussion on pool spacing in mainstem San Gregorio Creek.

Climate

The San Gregorio Watershed is characterized by a Mediterranean climate, where the majority of the rainfall occurs during the late fall and winter (November – April) and remains mostly dry the rest of the year. Most storm systems come off the Pacific during the cooler winter, delivering up to 91.5cm of rain in the higher elevations and predominately on steep western facing slopes. Lower elevations typically receive 66.04cm (Rantz, 1971; Saah and Nahn, 1989). Average annual temperatures recorded in the town of La Honda - approximately in the middle of the watershed - fluctuate between 4.5^{o}C and 21.5^{o}C (Brady et al., 2004).

Geology

San Gregorio Creek lies in a geologically active area with the San Andreas Fault located 3km to the east and several smaller faults intersect the watershed. The location of rock units and stream channels are heavily influenced by the location of these faults and the geologic structure (Brabb et al., 1998). The four major geologic assemblages are comprised of sandstone, siltstone, and shale assemblages which are considered to be moderately to highly erodible (Brown 1973). Sediment delivery is dominated by landslides caused by movement along fault lines and saturated soils from heavy winter storm systems (Balance Hydrologics 2006). The steep hillslopes in the higher elevations contain both highly erodible Lambert Shale and Vaqueros Formation, in addition to relatively resistant Monterey and Mindego Basalt Formations (Brabb et al., 1998). In the lower portion of mainstem San Gregorio Creek the Montara Mountains and Pigeon Point assemblages are composed of alluvial deposits, and to a lesser degree siltstone and fine-grained sandstone (Stillwater Sciences, 2010).

Geomorphology

The morphological characteristics of the hillslopes and stream channels in the San Gregorio Creek Watershed are typical of central coast California Watersheds and the western slope of the Santa Cruz Mountain range. In the higher elevations steep canyons dominated by conifer forests and shallow soils form the tributaries. Mid-elevations are characterized as having rolling hills, with convex upland ridges which are dominated by coastal scrub and oak woodland vegetation. Much of this mid-elevation area is used as rangeland for cattle, where dry-land flax farming once dominated the landscape.   The lower elevations contain mainstem San Gregorio Creek which runs through a low-gradient floodplain where row-crop agriculture dominates the landscape (Stillwater Sciences, 2010). The riparian corridor has been confined with levees in some stretches, leading to a single meandering single thread channel which is entrenched and disconnected from much of its historic floodplain (Brady et al., 2004; Stillwater Sciences, 2010).

Land Use

Current land use in the San Gregorio Creek Watershed includes a mix of zoning designations which include resource management, open space, timberland, agriculture and limited residential. The entire watershed is an unincorporated area of San Mateo County, 53% of which is in private lands, with the remaining 47% in a combination of open space preserves, land trusts and parks. Private property dominates the borders of the lower and middle mainstem San Gregorio Creek, while open space, land trusts and parks dominate the major tributaries and portions of upper mainstem San Gregorio Creek. The surrounding landuse at the AO reach is dominated by rangelands used for grazing cattle; at the DR site there is a mix between an equestrian center, open space, and an

event center; and at the RP reach the surrounding landuse is split between row-crop agriculture and rangelands (Stillwater Sciences, 2010).

The Costanoan Indians were the original inhabitants of the San Gregorio Creek Watershed and were first displaced by the Spanish missionaries around 1776. From 1822 to 1846 the area was officially part of Mexico and was used for cattle ranching, dairies and farming. During the gold rush in the mid-19th century, large numbers of settlers arrived in California which included San Gregorio Watershed. The redwood and conifer forest was heavily harvested to supply the large demand for lumber. Intense dryland flax farming during World War II took place on the coastal ranges and led to displacement of a large portion of the cattle operations. Since then, cattle and farming operations have dominated what working landscapes remain (San Mateo County, 1986).

This combinations of land use resulted in increased sediment delivery, reductions in woody debris recruitment, loss of floodplain connectivity to San Gregorio Creek and its tributaries. The combination of decreased vegetation cover and logging roads led to increased erosion and delivery into stream channels. LWD recruitment was decreased directly from logging activities in the riparian corridor where most LWD is naturally recruited. Natural LWD recruitment was further reduced as a result of incised channels which disconnected streams from floodplains where LWD is typically washed into the stream channel during flood events. Stream channel incision resulted from a combination of land use changes including confining stream channels with constructed levees effectively disconnecting the stream from floodplains, removal of LWD, armoring streambanks with boulders or concrete to protect roads and other infrastructure, and increased impervious surfaces directing a larger portion of water into streams during storm events (Stillwater Sciences, 2010). As a result, the current stream channel configuration in mainstem San Gregorio Creek and the low-gradient reaches of its tributaries are more entrenched and less complex, reducing the overall quantity and quality of salmonid habitat (Alford, 2013).

Location

The San Gregorio Creek watershed is located along the western slope of the Santa Cruz Mountains and is the second largest catchment in coastal San Mateo County. The roughly 135 km^2 watershed contains approximately 72 km of stream channel. The focus of this study is along three low gradient reaches of mainstem San Gregorio Creek and its tributaries (**Figure 2.**). Reach AO is the furthest upstream reach in the study, and is 17.5 km upstream from the lagoon. Reach DR is in the middle reach, and is located 14.7km upstream. Reach RP is the furthest downstream reach, located 5.8 km upstream from the lagoon. For the purposes of this study, low gradient reaches will be defined as having a slope of 0.01 or less. Analysis using Geographic Information Systems (GIS) software shows that the slope is 0.01 for the majority of mainstem San Gregorio Creek below the confluence of La Honda Creek.   Significant portions of the tributaries have stream channel gradients between 0.01 and 0.03. Coho salmon and steelhead trout distribution from 1998 typically overlaps with the low gradient reaches found in mainstem San Gregorio Creek (**Figure 2.**, CDFG, 1996b).

Stream Morphology

Mainstem San Gregorio Creek runs approximately 20 km upstream from the lagoon through a low-gradient alluvial valley roughly 0.29 km wide. The channel has incised 4-6m below the valley floor at the location of the USGS stream gage (#11162570). The majority of the sediment transported in this reach is from upland sources. Streambank erosion is limited by infrequent flow events large enough to promote channel migration and streambank erosion, however destabilization due to channel incision is observed as a significant contributing factor to sediment loading (Stillwater Sciences, 2010).
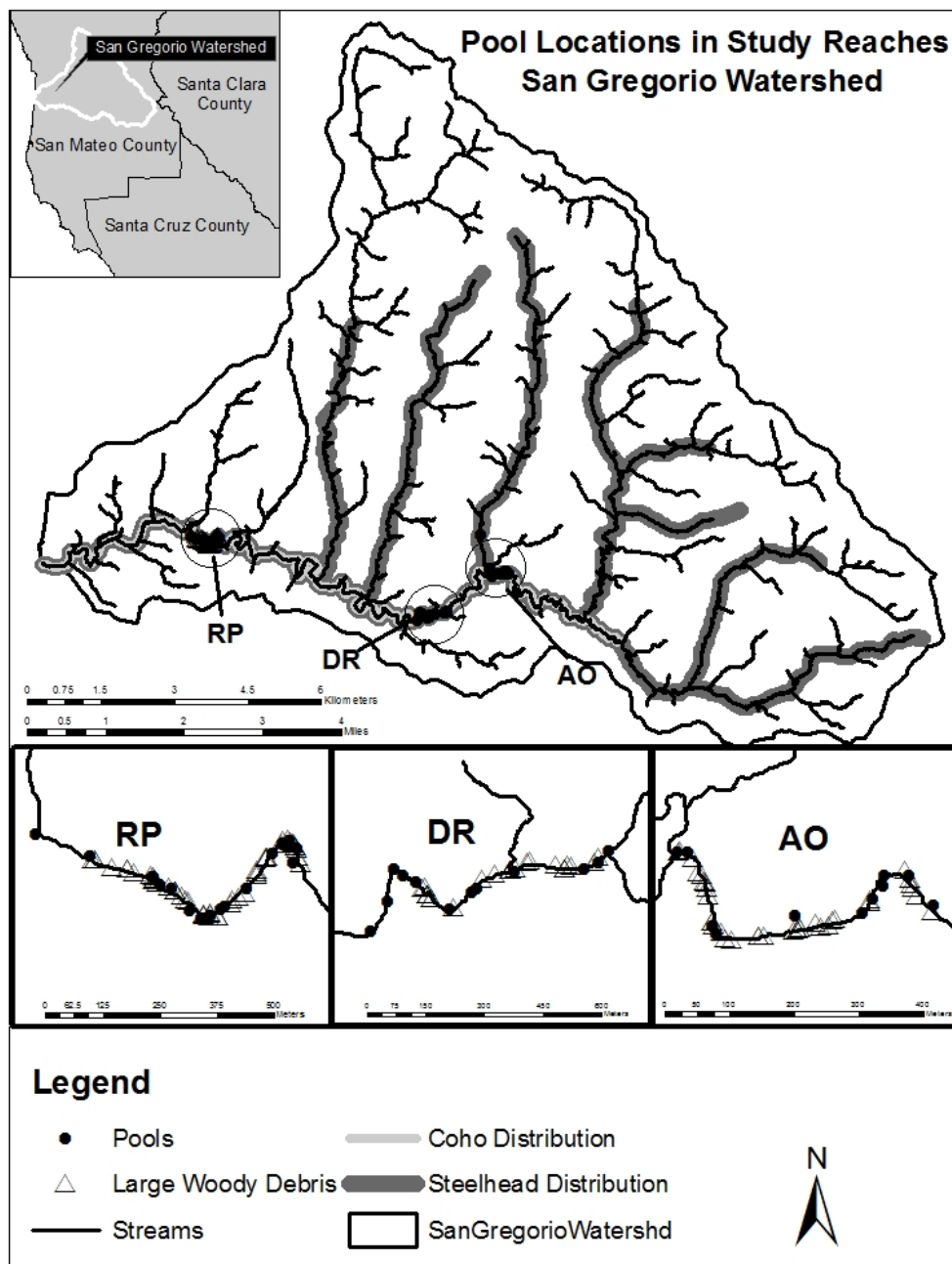
Figure 2. San Gregorio Creek study reaches, and coho and steelhead distribution.

Mainstem of San Gregorio creek is a 4th order stream and has been classified as an F4 channel by CDFW (CDFG, 1996b) using the stream channel classification scheme proposed by Rosgen (1994). The F4 channel has a slope of less than 2%, and is considered a low-gradient meandering pool/riffle channel that has a Rosgen (1994) entrenchment ratio (flood-prone width/bankfull width) less than 1.4, a sinuosity (stream length/valley length or valley slope/channel slope) of greater than 1.4, a width to depth ratio (bankfull width/bankfull mean depth) less than 1.2. The San Gregorio mainstem has a slope of less than 0.01 downstream of the confluence of La Honda and Alpine Creek, and has characteristics where pool-riffle channel types ideal for Coho salmon are most likely to occur (CDFG, 1996b).

Pool-riffle channel types occurred on all three project reaches. However, the pool, riffle, run sequence contained very long runs. Montgomery et al. (1995) found that pool-riffle channel types in forested streams had pool spacing's of 2 to 4 channel widths, even when LWD loading was low (<0.03 pieces/m^2). With an average pool spacing of 3.53 channel widths across the tree study reaches, the existing LWD and bedrock formed pools have decreased the pool spacing. In 1996 CDFW surveyed mainstem San Gregorio Creek and recorded the distribution of habitat types by percent length where pools made up 28%, riffles 25%, and flatwater 47% (CDFG, 1996b).

Hydrology and Limiting Factors to Salmonid Recovery

The large winter storms typically observed from December to March drive the high flow events which are important for bringing water levels high enough to allow for adult Coho and steelhead trout to migrate upstream, and for smolt outmigration (**Figure 3.**, Stillwater Sciences, 2014). The target flow rates for adult steelhead passage is a minimum water depth of 0.21m, and when 25% of the average total wetted width and 10% of the average continuous wetted width is usable, this occurs at 38ft^3/s (1.08 m^3/s), and 18ft^3/s (0.51

m^3/s), respectively (Stillwater Sciences, 2014). Adult passage flows are estimated to occur 30% of the time during the winter in mainstem San Gregorio Creek (**Figure 4.**).
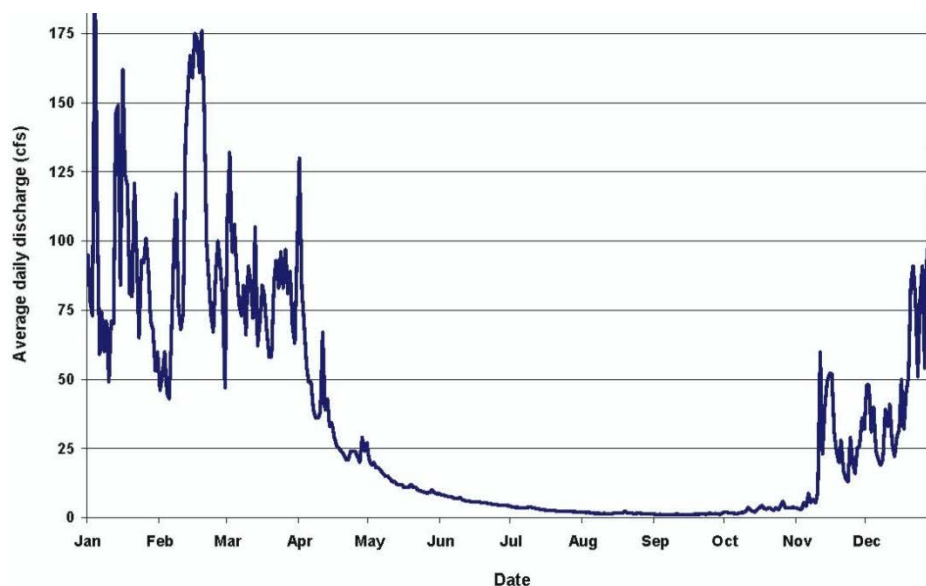
Figure 3. Average Daily Discharge recorded at the USGS stream gauge (#11162570) for water years October 1970 to September1994, May 2001 to September 2005, and July 2007 to September 2008 (From, Stillwater Sciences, 2010).

During the high flows and especially the peak of the high flow events, fish must find refuge in low-velocity areas typically found along banks, backwater areas and floodplains. Fish of all age classes use these areas to rest, avoid getting washed downstream, injured by debris flows, and for access to high value feeding opportunities on terrestrial grounds which are only accessible during these flows (Cederholm et al. 1997; Alford, 2013).

Refugia from high-flows and access to floodplain areas is currently lacking in San Gregorio Creek and has been identified as a primary limiting factor to the Coho salmon and steelhead trout (Stillwater Sciences, 2010; Alford, 2013). Much of the historic
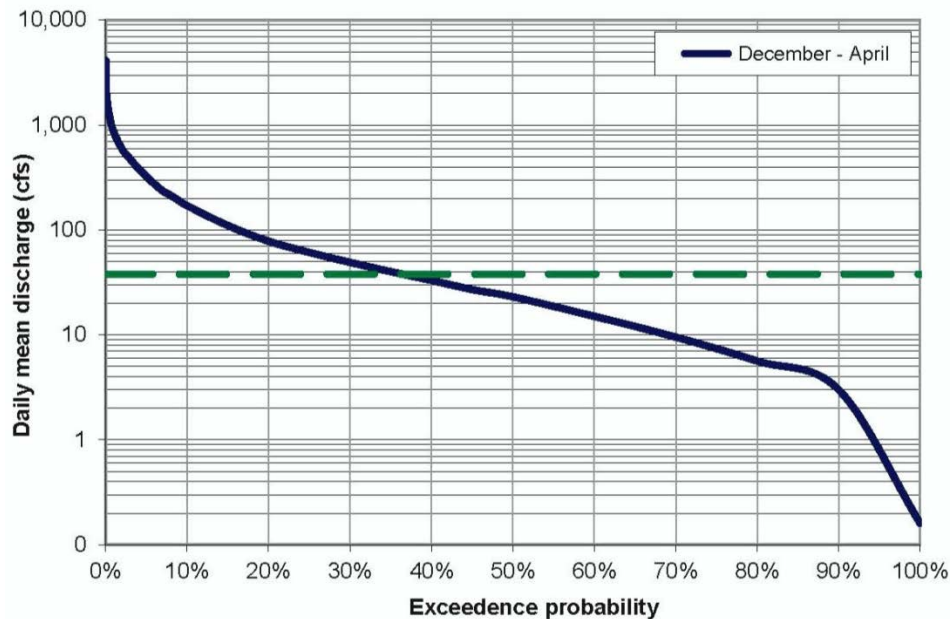
Figure 4. Mean daily discharge observed winter-spring (December-April) measured at USGS gauge #11162570 from 1970-2009, San Gregorio Creek. Adult steelhead passage criteria target >38ft^3/s (1. 8 m^3/s) shown in dashed green line (From, Stillwater Sciences, 2014).

floodplains are no longer hydrologically connected to the stream channel which has incised in many locations, and no longer is inundated at more frequent flow frequencies as they were historically. At the USGS stream gage in lower San Gregorio Creek, it is estimated that the stream channel has incised 4-7m (Stillwater Sciences, 2010).

In order to increase access to, and create floodplain or backwater channel habitat which salmonids can access during high flows, portions of creek-side properties must be allowed to flood. This often conflicts with current land use in suitable floodplain areas. Cluer and Thorne (2013) present a channel evolution model showing that incised channels can eventually widen when banks fail and inset floodplains will begin to form. Laying back stream channel banks and creating in-set floodplain habitat would help keep

mainstem San Gregorio Creek in a confined state under more frequent flood events and likely be a more accepted practice by the stream-side landowners.

Another way to create low-velocity refuge during high flows is to install Large Woody Debris (LWD) structures which had naturally occurred in much greater frequency throughout San Gregorio Creek (Cederholm et al. 1997; Alford, 2013). In addition to creating low-velocity refuge during high flow events, LWD obstructs flows and concentrates energy which can scour deep pools (Montgomery et al. 1995; Beechie and Sibley, 1997). Flow obstructions like LWD can push water towards a bank and increase the frequency of inundation from a given storm event. In areas where there exist low impacts to streamside infrastructure and land use, the stream channel can be built up with channel-spanning LWD structures. This will increase water surface elevations locally and inundate connected floodplain areas on a more frequent basis.

Another primary limiting factor to salmonid recovery highlighted in the San Gregorio Creek Watershed Management Plan (Stillwater Sciences, 2010) is low flows during the summer (July-September, **Figure 3.**). The target flow rates for juvenile steelhead (age 1+, from year 1 of age until sexual maturity) migration is a minimum water depth of 0.1m and when 25% of the average total wetted width and 10% of the average continuous wetted width is usable, this occurs at $6ft^3/s$ ($0.17 \ m^3/s$) and $1ft^3/s$ ($0.03 \ m^3/s$) respectively (Stillwater Sciences, 2014). This is estimated to occur less than 10% of the time during the summer in mainstem San Gregorio Creek. This limiting factor can be partially mitigated by frequent deep pools and cover structures (e.g. woody debris, bedrock outcrops) which provide cooler water temperatures.

Low summer flows in San Gregorio Creek are due in large part to the 331 groundwater wells (estimated) and 258 known points of diversion (Stillwater Sciences, 2010). San Gregorio Creek is a fully adjudicated watershed, which demonstrates that the need for water exceeds availability especially during the dry season and during drought years.

Physical habitat improvements such as installation of LWD structures have been shown to create deep pools and cover for salmonids during the summer rearing period for fry (age 0+, born within the past year) and parr fish (age 1+, from 1 year of age until smolt stage when adapted for the marine environment). These improvements are listed as high priority restoration actions in the San Gregorio Creek Watershed Management Plan and salmonid recovery plans to address this limiting factor to salmonid recovery (CDFG 1996a; 2004; NMFS, 2007; 2012; Stillwater Sciences, 2010).

San Gregorio Creek LWD Inventory and Assessment

An inventory and assessment of LWD in mainstem San Gregorio Creek was completed by American Rivers in the fall of 2012 (Alford, 2013). The inventory covered roughly 16.7 km out of the 20km miles of San Gregorio Creek and was broken into 4 reaches based on dominant vegetation. Reach 4, the uppermost reach, is dominated by conifers. Reach 3 is dominated by a mix of coast live oak, Douglas fir, and mixed riparian species. Reach 2 contains a narrow band of oak, alder, willows and other deciduous hardwood trees. Reach 1, the furthest downstream reach, has a narrow band of vegetation similar to reach 2 and coastal chaparral and grassland/shrub just outside the bankfull channel width. The reaches surveyed in this study occur in reach 4 (AO), reach 3 (DR), and reach 2 (RP).

All occurrences of large wood pieces or large wood accumulations (i.e. log jams) were recorded that met the minimum size requirements consistent with CDFW (Flosi et al. 2010), and recommends classifying LWD pieces in this way: diameter of 1-2ft (0.3-0.61m), 2.1-3ft (0.62-0.91m), 3.1-4ft (0.92-1.22m) or >4ft (1.22m) and lengths of <6ft (1.8m, only for root wads), 6-20 (1.8-6.1m), or >20ft (6.1m).   In all, 1,002 LWD pieces were recorded in the 16.7 km of San Gregorio Creek that were within 15.25m of the bankfull channel. This distance was used to represent the recruitment zone for LWD

pieces which are likely to enter the stream channel at some point. Each LWD piece was classified by the type (e.g. with or without root wad attached), species (redwood, other conifers, and hardwood), location (e.g. left bank, right bank, or stream channel), position (e.g. in-low flow channel, in low-flow channel and bankfull channel, etc.), pool association (e.g. pool formed by LWD, pool associated with LWD, no pool), key piece classification (i.e. stable piece of wood within bankfull channel that could accumulate debris or other wood, typically 1.5 times bankfull width), decay status (a live tree was rated 0 and a rotted through piece of wood was rated 8), debris jam classification (i.e. whether the LWD piece was associated with a debris jam that had at least one key piece), along with a few other variables, some of which are not included in the report.

Most of the redwood and conifer LWD pieces occurred in reach 4 and 3, and steadily decreased through reach 2 until their numbers increased again in reach 1. This trend reversed with regards to hardwood species. Reach 1 included the lagoon which has a wider stream channel width, lower bankfull height and connected flood plains and terraces. In reaches 2 through 4, no more than 8% of the LWD occurred outside the bankfull channel, whereas large portions of the LWD in Reach 1 was located outside the bankfull channel. While reach 3 was longer than reach 4, it had both the greatest occurrence (378) of LWD and the greatest frequency (108 per mile). Many of these pieces were located in log jams formed as a result of landslides.

Much of the naturally occurring LWD has been removed over the years in efforts thought to prevent flooding or damage to infrastructure. Today there is still ample evidence of woody debris being cut in the mainstem of San Gregorio Creek (Alford, 2013). Most of the large trees that could have provided LWD to the stream were removed during the past logging operations, and despite the protected status of much of the remaining intact conifer stands it will take decades to increase LWD abundance to historic levels.

METHODS

Data collection and analysis methods are adapted from previous studies examining LWD's influence on pool formation within stream channel types (e.g. Montgomery et al., 1995; Beechie and Sibley, 1997; Bryant et al., 2004; Carroll and Robinson, 2004; Flosi et al., 2010). Study reaches are located in wadable reaches of mainstem San Gregorio creek well upstream of the tidally influenced lagoon. Study reaches were visually classified into pool-riffle, forced pool-riffle and plane-bed channel types (Montgomery and Buffington, 1997) which generally provides habitat for anadromous salmonids (Beechie and Sibley, 1997).

For each stream channel reach the following measurements were recorded:

1) The slope and reach length was measured at two sites (AO and DR) using a combination of total station and LiDAR data. Elevations at the RP reach was derived from a Light Detection and Ranging (LiDAR) digital elevation model (HJW GeoSpatial, 2005. For this data set the Root Mean Squared error is 0.332ft (0.1m) and accuracy (95%) is 0.651ft (.2m; Kelly and Loecherbach, 2006). This dataset was also used to generate a stream layer throughout the project reach to determine the length. For the purposes of this study, anything under a slope of 0.01 is considered low gradient.

2) Bankfull widths and depths were measured in straight segments of reaches with minimum obstructions using a tape to the nearest 0.1m.

3) All morphologically distinct pools were recorded that had depths of at least 25% of bankfull depth and a length or width of at least 10% of the channel width (Montgomery et al., 1995; Caroll and Robinson, 2004). Depth was recorded as residual pool depth, or maximum pool depth - depth of downstream riffle crest). Observed pool forming mechanisms were recorded as self-formed, associated or

forced by an obstruction. Obstructions were recorded as boulders, bedrock-outcrops, and LWD. A global positioning system (code phase, 5m accuracy) unit was used to provide a spatial location for each pool.

RESULTS AND DISCUSSION

Three reaches (AO, DR, RP; **Figure 2**) were surveyed along mainstem San Gregorio Creek during the fall and winter of 2014/15, a summary of the data collected can be found in **Tables 2A** and metrics calculated from this data in **Table 2B**.   Comparisons between pool pacing and LWD frequency are shown in **Figure 7**, and include data from similar studies. In San Gregorio Creek, LWD frequency was amongst the lowest in any of study reaches included in **Figure 5**. However, this did not lead to as high of pool spacing as in some of the other reaches. Out of the 40 pools surveyed, 17 were formed by LWD, 12 by bedrock outcrops, 4 in the corners of meanders, 4 by undercut banks hardened with live root systems, 2 by boulders, and 1 mid-channel pool where willow trees heavily constricted the channel width.

Averages between the three study reaches yields a reach length of 732m and a slope of 0.005. The number of LWD pieces at least partly within the bankfull channel ranged from 52 in the furthest downstream reach (RP), to 37 in the furthest upstream reach (AO). The DR reach was the longest reach and had the fewest LWD pieces at a count of 30. The number of pools ranged from 11 at the AO reach to 17 at the RP reach. The maximum residual pool depth in any of the three reaches was 1.5m at the RP reach.

Pool spacing, LWD frequency and channel type
The RP reach had the lowest pool spacing (2.4 channel widths/pool), but also had the highest LWD frequency (0.07, **Table 2B**).   The DR and AO reaches had almost twice

the pool a spacing (4.2 and 4.0) with slightly lower LWD frequencies (0.03 and 0.06). The number of LWD pieces associated with pools was twice as high in the RP reach (30), than in either the AO reach (15) or the DR reach (9). The reach with the highest percent LWD that was the dominant pool forming mechanism was the RP reach (58%) and was lower in the AO (42%) and DR (30%) reaches. Average pool spacing in San Gregorio Creek is 3.5 compared with 3.7 across all referenced study reaches shown in **Figure 5.** However, the median pool spacing for all referenced studies is 2.2. Average LWD frequency for all studies is 0.29 and the median is 0.33, compared to an average and median of 0.06 in San Gregorio Creek.

Montgomery et al. (1995) found that pool-riffle channel types in forested streams had pool spacing's of 2 to 4 channel widths, even when LWD loading (LWD/m^2) was low (<0.03 pieces/m^2). With an average pool spacing of 3.5 across the tree study reaches and an average LWD frequency of 0.06, the existing LWD and bedrock formed pools have decreased the pool spacing well below what would be considered a plane-bed channel type.

Reach Morphology, AO reach example

The stream morphology of the three study reaches resembled a pool-riffle morphology that contains sequences of pools, riffles, and long, roughly uniform runs that mirror higher gradient plane-bed reaches. The portion of the AO study reach with plane bed morphology begins with large cobble dominating the stream substrate and is armored along the left bank with large boulders that appear to be part of a streambank stabilization project associated with Hwy 84 which runs along the top of the left bank. The stream

Table 2A. Pool, stream channel and LWD measurements

Issel, 2015. Central California, San Gregorio Creek	Reach Length (m)	# Pools	Bankfull Width (m)	Drainage Area (km^2)	LWD Pieces	Max Depth (m)	Slope (m/m)	Channel Type*
RP Reach	746	17	18.2	120.00	52.00	1.52	0.002	PR
DR Reach	867	12	17.2	72.00	30.00	1.20	0.006	PR
AO Reach	582	11	13.3	68.00	37.00	1.28	0.007	PR
Average	**732**	**13.3**	**16.2**	**86.7**	**39.67**		**0.005**	

Table 2B. Pool and LWD metrics

Issel, 2015. Central California, San Gregorio Creek	Pool Spacing (Length/ Width/ #pools)	LWD Frequency (LWD/RL)	LWD Loading (LWD/m^2)	LWD Pieces Associated w/Pools	% Dominant LWD
RP Reach	2.4	0.07	0.004	30.00	0.58
DR Reach	4.2	0.03	0.002	9.00	0.30
AO Reach	4.0	0.06	0.005	15.00	0.41
Average	**3.5**	**0.06**	**0.004**	**18.00**	**0.43**

L = reach length,

substrate transitions to very fine sediments below a log spanning 85% of the channel.
This log has formed a scour pool and appears to act as a grade control, retaining much of
the large substrate upstream. This is the only pool in the 225 m plane-bed section of the
AO study reach. The channel is highly confined in this location and according to a

hydrologic and hydraulic analysis completed for the RCD in 2013 and the 100 year flood frequency event is contained within the stream channel. The entire plane-bed section is roughly straight until the creek takes a hard turn at a clump of redwood trees. The remaining portions of the AO reach exhibit pool-riffle morphology with point and side bars.

Comparisons of the AO reach with other studies

Out of the 11 pools in the 528m AO reach, only 3 are formed by LWD, the rest are formed by bedrock outcrops (3), corner pools at meander bends (4), and undercut banks hardened with live roots (1). Pool spacing in the AO reach is 4, meaning on average pools are separated by 4 times the average channel width.

The equation generated from the study by Montgomery et al. (1995) which describes a roughly inverse proportionality between pool spacing and LWD frequency is shown below, where Ps is pool spacing and LWDf is LWD frequency. After using this equation to compare predicted values versus measured values at both the San Gregorio sites and the measurements given in the Montgomery et al. (1995) study, it appeared initially that the model over-fit the high LWD frequency vales, creating a poor prediction of pool spacing for low LWD frequency values. When the original coefficient (0.05) was changed to 0.5 (equation 3) the measured and predicted values closely aligned. It is believed this was a typo.

$$Ps = 0.05 LWDf^{-26/25} \tag{2}$$

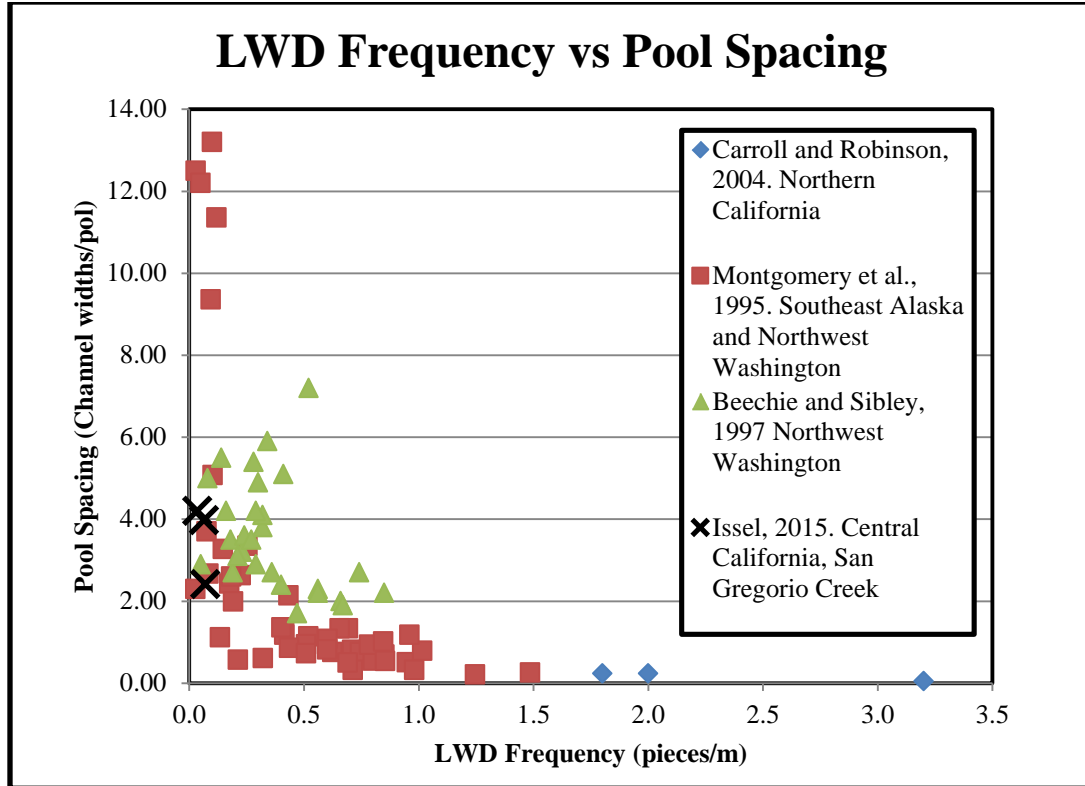<div align="center">or</div>

$$LWDf = 0.05^{25/26}/Ps^{25/26}$$

$$Ps = 0.5 LWDf^{-26/25} \tag{3}$$

<div align="center">or</div>

$$LWDf = 0.5^{25/26}/Ps^{25/26}$$

Figure 5. LWD Frequency vs Pool Spacing measured in four studies

Using equation (3), we can compare the study sites in San Gregorio with measurements reported in other studies (**Figure 7**). According to this inverse relationship between pool spacing and LWD frequency at the AO reach, the calculated LWD frequency is 0.14, when it is measured at 0.06 (**Table 3**). Based on the existing LWD frequency, the calculated pool spacing is 8.8, when it is measured at 4.0. The predicted values for pool spacing and LWD frequency are roughly double what are measured at the AO reach. Average calculated pool spacing and LWD frequencies for all three study sites is 3.2 and 2.7 (respectively) times larger compared with measured values. Average calculated number of LWD pieces is 118.5 compared to an average 39.7 recorded pieces. This is roughly a 3.0 fold difference. Finally, average calculated number of pools is 4.39

Table 3. Calculated Pool and LWD metrics

Issel, 2015. Central California, San Gregorio Creek	$cLWDf = 0.05^{25/26}/mPs25^{25/26}$	cLWD= cLWDf*L	$cPs = 0.5(mLWDf^{-1.04})$	cP= L/(W*cPs)
RP Reach	0.22	164	8.0	5
DR Reach	0.13	112	16.5	3
AO Reach	0.14	79	8.8	5
Average	**0.16**	**118.48**	**11.10**	**4.39**

cLWDf = calculated LWD frequency),   mPs = measured pool spacing,

cLWD = calculated # of LWD,   L = reach length,

cPs = calculated pool spacing,   mLWD = measured # LWD,

cP = calculated # pools,   W = Avg Bankfull width P = # pools

compared to an average of 13.3 recorded pools; also a roughly 3.0 fold difference. Based on these results, equation (3) is underestimating the number of pools and subsequently returning higher pool spacing than what was measured; and overestimates the amount of wood and subsequently returns a higher LWD frequency than what was measured. This could be due to the bedrock and self-formed corner pools present in the San Gregorio Study reaches which equation (3) does not account for. Based on field observations, it appears that channel incision has exposed some bedrock in the stream channel which is forming pools in locations that would likely have been covered in bedload under pre-disturbance conditions. Similarly, banks hardened with a network of root systems have been exposed due to channel incision. These root hardened banks have been undercut and form a significant number of fairly good quality lateral scour pools. Along with the occasional bedrock outcrop and hardened bank formed pools, self-formed

pools like corner pools are a natural part of pool-riffle channel types. Any model for the interaction between LWD frequency and pool spacing should take into account for these pool types not formed by LWD.

The cost of LWD augmentation

In the pristine old grown forest streams included in the Montgomery et al. (1995) study pool spacing reached a lower limit of 0.2 when LWD frequency was very high (~1 to 1.5 LWD/m). Stream reaches in old growth forests of the Pacific Northwest and California had LWD frequency greater than 0.24 (northern California) and 0.4 (Pacific Northwest). Assuming a minimum of 0.4 pieces per meter as a target for stream restoration, that would yield a pool spacing of 1.3 using equation (3). At the AO reach, that would yield an additional 23 pools to the existing 11. With a current LWD frequency of 0.06 at the AO reach, it would require 196 additional pieces of LWD to bring the LWD frequency to 0.4 using equation (3).

Designs were prepared at the AO reach to augment LWD recruitment by installing 13 LWD structures. The 13 structures composed of 24 LWD pieces are designed to create 8 additional pools and enhance 5. This would roughly double the LWD frequency to 0.1 and lower the pool spacing to 2.3. There were only a few opportunities to install additional LWD structures to create pools in appropriate locations, but were not taken due to risks of streambank stabilization and construction related issues. According to project engineers, project biologists, and federal and state resource agency staff, the designs for the AO reach satisfied the need for additional pools in the reach. A pool spacing much lower than that proposed by the designs could diminish other valuable habitat types utilized by salmonids during various live stages. The higher LWD frequency of 0.4 pieces per meter found in the old growth streams surveyed in the Montgomery et al. (1995) study may not reflect conditions in San Gregorio prior to

disturbance activities resulting in the removal of LWD in the channel and recruitment zone. Raising the level of LWD frequency to 0.4 and achieving a self-maintaining system of LWD recruitment and retention might not be possible or desirable from the standpoint of maximizing beneficial salmonid habitat.

The cost for constructing LWD structures has been analyzed in a study by Carah et al. (2014) which compared the costs of accelerated recruitment methods versus traditional anchored LWD structures. Unlike the traditional anchored LWD pieces, structures or log-jams, accelerated recruitment techniques do not use anchoring hardware and rely on large, long logs (1.5 times the length of the average bankfull width) to self-anchor in the channel. The majority of these long logs were available on-site, that is not always the case in LWD projects. The Carah et al. (2014) study recorded an average retention rate of 92% with this method. The range in construction cost to install one log for the accelerated recruitment method was $95 to $511, and $748 to $1,625 for anchored logs. At the AO and DR reaches, designs have been prepared to install 26 LWD structures with up to 80 logs. The direct construction related costs to install each log is on average $1,774. It should be noted that the per log total project cost, which includes permitting, project management, and monitoring is approximately $1,600 to $1,860. Costs for installing LWD structures can vary greatly depending on the location.

Installing an additional 80 pieces of LWD would raise the combined LWD frequency in the AO and DR reaches to 0.1 pieces per meter. The LWD frequency in the 17.7km of mainstem San Gregorio Creek is 0.05. Assuming this holds roughly true when including the unsurveyed 2.3km and average bankfull width of the three study reaches (16.2m), an additional 997 logs would be required bring the LWD frequency to 0.1 in the entire 20km of mainstem San Gregorio Creek. This would cost an estimated $1,770,000. To bring the LWD frequency to 0.4 it would require an additional 6,997 pieces of LWD at an estimated cost of $12,400,000. LWD projects can be designed to help recruit naturally generated LWD from the riparian forest and help keep it in the system. It is cost

prohibitive to install enough LWD to bring LWD spacing up to the levels found in old growth forests, but it is feasible to double the LWD frequency in mainstem San Gregorio Creek from 0.05 pieces per meter to 0.1.

CONCLUSION

Designs for installing LWD structures at the AO and DR reaches would yield an average pool spacing of 2.6 and LWD frequency of 0.1, which would greatly improve the overwintering and summer rearing habitat for salmonids compared to current conditions. Assuming that a pool spacing of 2.6 is adequate throughout mainstem San Gregorio Creek, the calculated LWD frequency using equation (3) would be 0.21, roughly the same LWD frequency found in old growth streams surveyed in Northern California (Caroll and Robinson, 2004), half that of the old growth streams in the Pacific Northwest (Montgomery et al., 1995), and double what would result from the project designs at the AO and DR reaches. A LWD frequency of 0.1 comprised of additional LWD structures all designed and constructed with the intention of creating pools may be able to bring the pool spacing down to 2.6, with roughly half the amount of LWD that equation (3) would calculate is required. Furthermore, the pools created would likely be of much higher quality in terms of depth and cover than the majority of pools currently in mainstem San Gregorio Creek.

Pool habitat in mainstem San Gregorio Creek is formed by several factors and LWD plays a dominant role in pool formation in 32% of the pools within the study sites. Of the LWD recorded partially or entirely within the low flow stream channel, 45% of pieces were observed to be primary drivers of pool formation (Alford, 2013). This rate is comparable with the rate reported in the Montgomery et al. (1995) study (~40%).

The predictive power of the inverse relationship model (equation 3) between pool spacing and LWD frequency is reduced at low LWD frequencies. This limits the usefulness of this equation in impaired watersheds like San Gregorio which has low amounts of LWD. If resource managers were to use equation (3) to predict the quantity of LWD in a given reach within mainstem San Gregorio Creek based on existing pool spacing, the amount of LWD would be overestimated by an average factor of ~3. Alternatively, if resource managers were to use equation (3) to predict the number of pools in a given reach based on existing LWD frequency, the number of pools would be underestimated by an average factor of ~3. Some of this inaccuracy can be attributed to the altered state of mainstem San Gregorio Creek, where exposed bedrock outcrops and undercut banks hardened by networks of roots form a significant number of pools. However, equation (3) is useful for comparison purpose between different watersheds and highlights the significance of pool forming mechanisms other than LWD. Given that likely none of the LWD recorded in the Montgomery et al. (1995) study was purposefully placed in a position to create a pool, it is understandable that equation (3) overestimates the LWD frequency necessary to bring pool spacing 1.3 since each new piece of LWD would be constructed to create or enhance an existing pool.

REFERENCES

Alford, C., 2013. San Gregorio Creek Large Woody Debris Inventory and Assessment Report. A technical report of the Alford California Conservation Program, Publication No. AR-CA-2013-01, 44pp.

Balance Hydrologics, Inc., 2006. Streamflow and sediment monitoring, El Corte de Madera Creek, water year 2006, El Corte de Madera Creek Open Space Preserve, San Mateo County, California. Prepared for Midpeninsula Regional Open Space District, Los Altos, California.

Becker, G.S., Smetak, K.M., and Asbury, D.A., 2010. Southern Steelhead Resources Evaluation: Identifying Promising Locations for Steelhead Restoration in Watersheds South of the Golden Gate. Center for Ecosystem Management and Restoration. Oakland, CA.

Beechie, T.J., and Sibley, T.H., 1997. Relationships between Channel Characteristics, Woody Debris, and Fish Habitat in Northwestern Washington Streams, Transactions of the American Fisheries Society 126:2, 217-229

Bisson, P. A., Nielsen, J. L., Palmason, R. A., and Grove, L. E., 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. Pages 62-73 In N. B. Armantrout, editor. Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Western Division. Bethesda, Maryland. Proceedings of asymposium held 28-30 October, 1981, Portland, Oregon. Western Division, American Fisheries Society, Bethesda, Maryland, USA.

Booth, D.B., Montgomery, D.R., and Bethel, J.P., 1997. Large woody debris in urban streams of the Pacific Northwest: in Roesner, L.A., ed., Effects of watershed development and management on aquatic ecosystems: Engineering Foundation Conference, Proceedings, Snowbird, Utah, August 4–9, 1996, pp. 178-197.

Brady, R. H. III, Pearce, S., McKee, L., Overton, S., and Striplen, C., 2004. Fluvial geomorphology, hydrology, and riparian habitat of La Honda Creek along the Highway 84 transportation corridor, San Mateo County, California. A technical report of the Watershed Program, San Francisco Estuary Institute (SFEI), Oakland, California. SFEI contribution No. 78.

Brown, W. M. 1973. Erosion processes, fluvial sediment transport, and reservoir sedimentation in a part of the Newell and Zayante Creek basins, Santa Cruz County, California. USGS Open File Report 73-0035.

Bryant, D.M., Caouette, J.P., Wright, B.E., 2004. Evaluating Stream Habitat Survey Data and Statistical Power Using an Example from southeast Alaska. North American Journal of Fisheries Management 24:1353-1362

Buffington, J.M., Lisle, T.E., Woodsmith, R.D. and Hilton, S. 2002. Controls on the Size and Occurrence of Pools in Coarse-Grained Forest Rivers. River Research and Applications 18: 507-531

Brabb, E. E., Graymer, R.W., and Jones, D. L., 1998. Geology of the onshore part of San Mateo County, California: A digital database: U.S. Geological Survey Open-File Report 98-137, U.S. Geological Survey, Menlo Park, California. http://pubs.usgs.gov/of/1998/of98-137/ [Accessed August, 2015].

Carah, J.K., Blencowe, C. C., Wright, D.W., and Bolton, L.A. 2014. Low-Cost Restoration Techniques for Rapidly Increasing Wood Cover in Coastal Coho Salmon Streams, North American Journal of Fisheries Management 34:5, 1003-1013

Carroll, S. and Robison, G. 2004. The Effects of Large Wood on Stream Channel morphology on Three Low-Gradient Stream Reaches in the Coastal Redwood Region. Presented at the Redwood Science Symposium. Humboldt State University. Humboldt, CA.

California Department of Fish and Game (CDFG), 2004. Recovery Strategy for California Coho Salmon. California Department of Fish and Game, Sacramento, CA

California Department of Fish and Game (CDFG), 1996a. Steelhead Restoration and Management Plan for California, California Department of Fish and Game, Sacramento, CA

California Department of Fish and Game (CDFG), 1996b. Stream Inventory Report, San Gregorio Creek. San Mateo County, California.

Cederholm, C. J., Bilby, R. E., Bisson, P. A., Bumstead, T. W., Fransen, B. R., Scarlett, W. J. & Ward, J. W., 1997. Response of Juvenile Coho Salmon and Steelhead to Placement of Large Woody Debris in a Coastal Washington Stream, North American Journal of Fisheries Management, 17:4, 947-963, DOI:

Cluer, B. and C. Thorne, 2013. A Stream Evolution Model Integrating Habitat and Ecosystem Benefits. River Research and Applications. Wiley Online Library, DOI: 10.1002/rra.2631

Everest, F. H., and Chapman, D. W., 1972. Habitat selection and spatial interaction by juvenile Chinook salmon and steelhead trout in two Idaho streams. Journal of the Fisheries Research Board of Canada 29: 91–100.

Florsheim, J. L., Chin, A., Gaffney, K., Slota, D., 2013. Thresholds of stability in incised "Anthropocene" landscapes. Anthropocene 2:27-41

Flosi, G., Downie, S., Hopelain, J., Bird, M., Coey, R., and Collins, B., 2010. California Salmonid Stream Habitat Restoration Manual. Fourth Edition. State of California Resources Agency, Department of Fish and Game Wildlife and Fisheries Division.

Gurnell, A. M., Piègay, H., Swanson, F. J., Gregory, S. V. 2002. Large wood and fluvial processes. Freshwater Biology 47:601-619

Harrelson, C.C, Rawlins, C.L., Potyondy, J.P., 1994. Stream channel reference sites: an illustrated guide to field technique. Gen. Tech. Rep. RM-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station 61 p.

Hilderbrand R.H., Lemly, A.D., Dolloff, C.A., Harpster, K.L. 1998. Design Considerations for Large Woody Debris Placement in Stream Enhancement Projects. North American Journal of Fisheries Management 18:161-167.

HJW GeoSpatial, 2005. San Mateo County LiDAR Data Acquisition. October 2005 & January 2006

Kaufmann, P.R, Levine, P., Robison, E.G., Seeliger, C., and Peck, D.V., 1999. Quantifying Physical Habitat in Wadeable Streams. EPA/620/R-99/003. U.S. Environmental Protection Agency, Washington, D.C.

Kelly, D., and Loecherbach, T., 2006. Challenges and successes in photogrammetric approaches to LiDAR-derived products. MAPPS/ASPRS Fall Conference, San Antonio, Texas, November 06 -10, 2006 15p.

Montgomery, D. R., Buffington, J. M., Smith, R. D., Schmidt, K. M., and Press, G., 1995. Pool spacing in forest channels. Water Resources Research, 31(4):1097-1105.

Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:5, 596-611

Montgomery, D.R. and MacDonald, L.H.. 2002. Diagnostic Approach to Stream Channel Assessment and Monitoring. American Water Resources Association 38(1):1-16.

National Marine Fisheries Service (NMFS), 2007. Federal Recovery Outline for the Distinct Population Segment of Central California Coast Steelhead, National Marine Fisheries Service. Santa Rosa, CA

National Marine Fisheries Service (NMFS), 2012. Recovery Plan for Evolutionarily Significant Unit Central California Coast Coho Salmon, National Marine Fisheries Service, Southwest Region, Santa Rosa, CA

Niezgoda, S.L. and Johnson, P.A., 2005. Improving the Urban Stream Restoration Effort: Identifying critical Form and Processes Relationships. Environmental Management 35(5): 579-592.

O'Neill, M.P., and Abrahams, A.D., Objective Identification of Pools and Riffles. 1984. Water Resources Research 20(7):921-926.

Rantz, S. E. 1971. Mean annual precipitation depth-duration-frequency data for the San Francisco Bay Region. U.S. Geological Survey, basic data contribution 32.

Rosenfeld, J. S., Huato, L., 2003. Relationship between Large Woody Debris Characteristics and Pool Formation in Small Coastal British Columbia Streams. North American Journal of Fisheries Management 23:928-938.

Roni, P., Press, G., and Beechie, T. 2013. Fish-Habitat Relationships & Effectiveness of Habitat Restoration. Unpublished. NOAA Fisheries, Northwest Fisheries Science Center, Fisheries Ecology Division, Watershed Program. Seattle Washington 98112.

Rosgen, D.L., 1997. A Geomorphic Approach to Restoration of Incised Rivers. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision ISBN 0-937099-05-8.

Rosgen, D.L., 1994. A classification of natural rivers. Catena 22:169–199.

Saah, A. D., and Nahn, C. E. 1989. Mean annual precipitation map for San Francisco and Monterey Bay region. Santa Clara Valley Water District, hydrology open file report.

Shirvell, C.S., 1990. Role of instream rootwads as juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*) cover habitat under varying streamflows. Canadian Journal of Fisheries and Aquatic Sciences 47: 852–861.

San Mateo County, 1986. San Mateo County general plan. Prepared by the environmental Services Agency, Planning and Building Division, San Mateo County, California.

Stewart, G.B., Bayliss, H.R., Showler, D.A., Sutherland, W.J., Pullin, A.S. 2009. Effectiveness of engineered in-stream structure mitigation measures to increase salmonid abundance: a systematic review. Ecological Applications 19(4):931-941

Stillwater Sciences, 2010. San Gregorio Creek Watershed Management Plan, Natural Heritage Institute, San Francisco, CA

Stillwater Sciences. 2014. Ecological assessment of flows in San Gregorio Creek. Appendix to: San Gregorio Creek watershed management plan. Final report. Prepared by Stillwater Sciences, Morro Bay, California for Alford, Nevada City, California.

Stillwater Sciences. 2015. San Gregorio Creek Habitat Enhancement Project—Basis of Design Report. Prepared by Stillwater Sciences, Berkeley, California for San Mateo County Resource Conservation District, Half Moon Bay, California.

Wohl, E., Cenderelli, D.A., Dwire, K.A., Ryan-Burkett, S.E., Young, M.K. and Faush, K.D., 2010. Large in-stream wood studies: a call for common metrics. Earth Surface Process and Landforms 25:618-625.