

Technical Memorandum

Evaluating Water Temperature and Turbidity Effects on Steelhead Life History Tactics in Alameda Creek Watershed



March 22, 2011

Evaluating Water Temperature and Turbidity Effects on Steelhead Life History Tactics in Alameda Creek Watershed

Prepared for:

Alameda Creek Fisheries Restoration Workgroup

Prepared by

Kristine Atkinson

California Department of Fish and Game (CDFG)

Josh Fuller

National Marine Fisheries Service (NMFS)

Chuck Hanson

Hanson Environmental

Bill Trush

McBain & Trush, Inc. (M&T)

March 22, 2011

1 INTRODUCTION

Steelhead population recovery in Alameda Creek Watershed (Gunther et al. 2000) will require the repair of key steelhead life history tactics (LHTs) identified in the Final Study Plan (McBain & Trush 2008). Each channel segment within each LHT will have specific, assigned expectations for sustaining good and abundant habitat for steelhead spawning and egg incubation, fry and juvenile rearing, and/or pre-smolt/smolt outmigration. Favorable water temperatures within a channel reach often will dictate whether a given LHT should be expected to contribute significantly to population recovery. The Alameda Creek Fisheries Restoration Workgroup assigned a sub-committee to consider criteria and explore methodologies for assessing water temperature effects on LHTs. Members of this Water Temperature Sub-Committee are: Kristine Atkinson (CDFG), Josh Fuller (NMFS), Chuck Hanson (Hanson Environmental, consultant to the ACWD), and Bill Trush (McBain & Trush, consultant to the Fisheries Workgroup). Dr. Jerry Smith from San Jose State University provided many valuable comments and edits. Another effort has been underway by a different Fisheries Workgroup sub-committee to model annual hydrographs and annual thermographs in the Alameda Creek Watershed, under unimpaired and impaired streamflows, needed for the Number of Good Days (NGD) analysis outlined in the Final Study Plan (McBain & Trush 2008).

This technical memorandum specifies an analytical framework for evaluating promising LHTs by assessing likely water temperature effects on habitat availability and quality. Steelhead trout exhibit highly flexible life history strategies. Any NGD evaluation of steelhead habitat potential must provide ample opportunities for steelhead to persist, rather than dismiss – outright – channel reaches that might initially compute as unsuitable. Without the benefit of observing and measuring steelhead in the basin near-term, a healthy skepticism of modeling results will be warranted.

2 A POPULATION PERSPECTIVE

Consequences of detrimental water temperature effects differ between an individual steelhead and its population. Death or poor health of the individual does not mean death of the population. Yet many existing water temperature criteria, if not most, focus on the physiological condition and/or behavior of the individual. Mortality should be (death is expected in the population) incorporated (i.e., acceptable to recognize some mortality) into water temperature criteria when assessing duration and frequency of water temperatures, as well as magnitude. For example, daily average water temperatures exceeding 21°C (69.8°F) usually provide considerably poorer growth environments for steelhead juveniles than lower daily averages. But what does poorer growth mean to the population and prospects for recovery? An evaluation of a >21°C (69.8°F) effect on the population, and therefore of a LHT's viability, requires more information and more thresholds. Annual thermographs are needed to characterize the duration and frequency of 25°C (77.0°F) occurrences. Exceedence of three episodes of 25°C, with each episode occurring three days and lasting six continuous hours in each of the three days, should give a failing grade to a channel reach for a specific LHT requiring steelhead fry rearing. Rather than a single threshold for temperature magnitude (i.e., >21°C (69.8°F)),

population-oriented water temperature criteria can have, and generally will require, additional temperature thresholds for magnitude, duration, frequency, and/or timing.

Unfortunately, the scientific literature and regulatory frameworks do not provide sufficient information to be as prescriptive (i.e., specifying allowable magnitude, duration, and frequency) in defining water temperature criteria for evaluating population effects. Sullivan et al. (2000) succinctly summarizes water temperature thresholds for potential effects ranging from acutely lethal to chronic (Figure 1). The Fisheries Restoration Workgroup will need to focus on the likely chronic water temperature effects on steelhead population recovery.

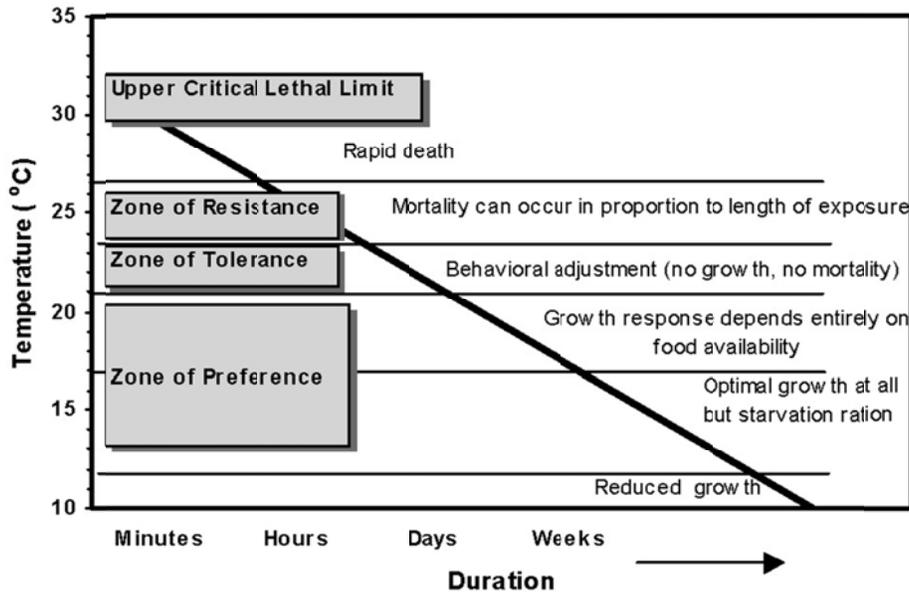


Figure 1. General biological effects of temperature in relation to duration and magnitude of temperature (reproduced from Sullivan et al. 2000).

3 ANALYTICAL APPROACHES FOR EVALUATING WATER TEMPERATURE EFFECTS ON STEELHEAD TROUT

The Water Temperature Sub-Committee considered the following analytical approaches: (1) craft water temperature criteria (functioning as thresholds) from the scientific literature (including classic dose-response studies), (2) develop annual thermographs under unregulated streamflow conditions to establish baselines (e.g., How often did 25°C (77.0°F) episodes, as defined above, occur in Dry water years from March through early-May along mainstem Alameda Creek in Sunol Valley?) for evaluating present and future annual thermographs for high priority LHTs, and (3) construct a simplified bioenergetic approach that does not rely entirely on temperature thresholds. Each approach contributed to the recommended analytical framework. Approach (1) has not been exhausted, including further discussions with experts. Approach (2) will have considerable uncertainty depending on how well water temperatures can be modeled, but nevertheless should produce extremely useful information for developing future water temperature criteria. Additionally, major land and water use changes in the Alameda Creek Basin have made some historical temperature goals impossible to achieve, even if quantifiable.

Approach (1) combined with Approach (2) might serve best as screening tools, whereas Approach (3) will be the workhorse for evaluating channel segments for each LHT.

3.1 APPROACH NO.1: USING THRESHOLDS TO ASSESS WATER TEMPERATURE

Water temperature criteria (derived from Approaches (1) and (2)) can be broadly categorized as follows: ‘Death to the Individual’, ‘Death to the Population’ (failure of a channel segment for a given LHT), and ‘Life for the Individual.’ A fourth category, ‘Life/Recovery for the Population’, will be addressed by Approach (3). The following key water temperature criteria should be considered for evaluating each channel segment within prioritized LHTs:

3.1.1 Death/Severe Stress to the Individual

An hourly temperature greater than 26°C (78.8°F) for 6 or more continuous hours (i.e., an ‘episode’) (Sullivan et al. 2000) is a threshold defining a ‘Bad’ day for juvenile salmonid rearing (i.e., an NBD, or Number-of-Bad-Days).

3.1.2 Death/Severe Stress to the Population

Three episodes of an hourly temperature greater than 26°C (78.8°F) for 6 or more continuous hours (i.e., an episode) in a given year is a threshold disqualifying a specific channel reach as juvenile salmonid rearing habitat for a given LHT. The evaluation should not rely on pockets of thermal refugia to sustain viability within a channel reach of a given LHT, but should recognize possible tolerance (physiological and/or behavioral) to warmer temperatures by steelhead in more southern and/or inland populations (Spina 2007). This temperature magnitude/duration/frequency threshold (criterion) should not be interpreted too conservatively. Most steelhead biologists in California can recall a stream where this temperature threshold was exceeded yet juvenile steelhead were observed. However, the purpose of this temperature analysis is to identify LHTs that will have the most influence on population recovery, not simply to predict fish presence or absence.

3.1.3 Life/Growth for the Individual

Daily average water temperatures between 12°C (53.6°F) and 21°C (69.8°F) are suitable for juvenile steelhead growth. However, the specific growth (SPGR) curves indicate that temperatures exceeding 19°C (66.2°F) will require high ration levels to expect high specific growth rates (Sullivan et al. 2000).

3.1.4 Pre-Smolts and Smolts Scooting Downstream

Many headwater LHTs will require good late-winter through early-summer rearing farther downstream, i.e., migrating and growing as smolts and pre-smolts. The alternative will not be conducive to recovery. If 2+ smolts and large 1+ smolts must rely on growth in the headwaters to reach 150 mm FL to 175 mm FL (a minimum length with a reasonable chance of returning as an adult), the number of large smolts (> 175 mm) entering SF Bay will remain small. Dr. Jerry Smith (2008) in his comments to the Study Plan notes:

“In any case, smolts in some of the central coast streams (like the Pajaro River tributaries or Penitencia Creek as a tributary to Coyote Creek and the Bay) that have warm downstream reaches do apparently pass through stream sections that should reverse smolting or rear rather late in warming stream sections before beginning their migrations. The downstream passage through unsuitable habitat (warm, turbid) is apparently very quick, and, since it occurs primarily at night, exposure to high daytime water temperatures may be limited. The prolonged migration and growth period hypothesized for some growth strategies of Alameda Creek may turn out to be more of a “grow in place and then dash” strategy that fits the environmental conditions. This dash may limit the ultimate size of the smolts (and their survival), unless Bay entrance is relatively benign or they are able to growth substantially in the mouth of the creek. There is likely to be severe selection pressure against reversing the smolting and staying another year, since the large smolt-size fish would have high absolute food demands that would be unlikely to be met in another year in warm water; metabolic costs would be too high for survival.”

Therefore, LHTs that require over-summer juvenile rearing and significant growth (e.g., where a 1+ juvenile steelhead grows through the summer), such as in Niles Canyon, might not be considered keystone LHTs in the overall recovery plan, especially initially. But these same reaches must provide good habitat for downstream migrating ‘headwater’ smolts and pre-smolts.

‘Scooting’ is a good descriptor for juveniles and pre-smolts swiftly swimming through these lower mainstem reaches with the objective of not being any worse off. Thermal refugia may be important, but would not be available during the well-mixed higher flows of spring and possibly early-summer. Also important would be ample large juvenile rearing habitat (for fast-water feeding stations) and productive BMI riffle habitats (for more benthic macroinvertebrate prey). Scooting between daily average water temperatures ranging from 21°C (69.8°F) to 24°C (75.2°C), with cooler nighttime temperatures (e.g., below 20°C), should be evaluated to assess the likely success of headwater LHTs contributing to, if not sustaining, small headwater populations. Afternoon water temperatures exceeding 24°C (75.2°F) will often cause steelhead to ‘hunker-down’, except to seek thermal refugia, rather than migrate. Thermal criteria for ‘good juvenile scooting’ may require a minimum continuous period (of hours) with cooler nighttime temperatures below 22° C (71.6°F) from mid-March through June. Smolts likely require lower scooting temperatures to prevent reversed smoltification, but there are no definitive references for recommending an upper water temperature magnitude or duration threshold. A closer examination of SFPUC’s annual downstream migrant trapping (e.g., in Arroyo Hondo) might provide an initial estimate. Given uncertainty likely will remain, the Water Temperature Sub-Committee recommends applying a range of water temperature magnitudes and duration in a sensitivity analysis before requiring greater resolution.

3.1.5 Steelhead Smolting Temperature Criteria

Several LHTs require smoltification in the upper watershed. The following NGD criteria for successful smoltification are: (1) a 'good' day occurs when the daily average temperature is between 6°C (42.8°F) and 12°C (53.6°F) and (2) a 'fair' day occurs when the daily average temperature ranges between 12°C (53.6°F) and 14°C (57.2°F), and (3) a 'bad' day when 16°C is exceeded. The scientific literature offers many estimates within this good range of water temperatures (Myrick and Cech 2001; Myrick and Cech 2004), but data for central coast steelhead are limited. Regional adaptation (physiological and behavioral) to higher smoltification temperatures may be occurring, though to what extent is unknown. In addition, north to south differences are likely due to seasonal "cluing", rather than to physiological requirements. Unfortunately the scientific literature provides poor guidance for selecting smolting thresholds in a diurnally fluctuating stream.

These NGD and NBD (number of bad days) criteria address individual smolts. For the population, there should be a minimum number of good smoltification days per water year during a specified smolt out-migrant season for evaluating whether a channel segment for a given LHT would be considered a successful smoltification channel reach (i.e., for computing number of good years (NGY)). An initial baseline for frequency of NGD per smoltification season and channel each will be estimated by modeling NGD from the unimpaired annual thermographs.

3.1.6 Benthic Macroinvertebrate Productivity

Rearing juvenile salmonids eat benthic macroinvertebrates (BMI). BMI riffle habitat is being habitat-mapped in Upper Alameda Creek by the Fisheries Workgroup to establish a quantitative relationship between streamflow and BMI riffle habitat abundance (including a velocity requirement of 1.5 ft/sec or greater). Fish eat the standing crop of benthic macroinvertebrates, not their productivity. But high BMI productivity is necessary to achieve high standing crop, that later will be available as juvenile salmonid food even when streamflows warm above a range conducive to high productivity for most EPT species (mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Trichoptera)). However, midges, blackflies, some mayflies, and some caddisflies can be productive at higher water temperatures. The scientific literature offers extremely limited information on the range of water temperatures necessary for high BMI productivity (Vieira et al. 2006). Water temperatures from 5.5°C (41.9°F) up to 15.5°C (59.9°F) are conducive to high BMI productivity for most EPT taxa and should be used for computing NGD. More thermally tolerant BMI taxa can be highly productive past 21°C, approaching or passing (depending on which study or investigator is being referenced) the upper boundary for significant juvenile steelhead growth sustained by a high ration level (e.g., 80%). By establishing a preferred temperature range and quantifying the range of streamflows (with riffle velocities exceeding 1.5 ft/sec) providing abundant BMI riffle habitat and fast-water feeding habitat by steelhead, the NGD of productive BMI habitat can be computed and evaluated for unimpaired or regulated flow regimes. Given the sensitivity of specific growth to ration level, managing for productive BMI riffle habitat will help offset negative temperature effects on juvenile steelhead growth in evaluating viable LHTs.

The Water Temperature Sub-Committee remains divided as to the contribution of BMI productivity during warm water temperatures on high juvenile salmonid specific growth rates. However, an analytical framework has been established, combining BMI habitat abundance with BMI habitat quality, which should help resolve this uncertainty objectively. An important initial step will be to compute NGDs using a wide range of threshold water temperature criteria for high BMI productivity (and ration level in the SPGR curves) to quantify consequences surrounding this uncertainty. For example, would a threshold temperature of 23°C for high warm water BMI productivity (with expected ration levels of 40% up to 60% for rearing juvenile steelhead) result in a viable LHT determination that otherwise would be considered unviable? If the consequences are far-ranging, then empirical field studies would be warranted.

3.1.7 Emergent Steelhead Fry Temperature Criteria

Adult steelhead will be migrating up Alameda Creek from late-December through March or even later into April to spawn. Those redds constructed later in the spawning season may require fewer incubation days (approximately 50 days for the eggs to incubate and for the fry to emerge the channelbed). But emergent fry from late spawners could be susceptible to excessively warm water temperatures. Spawner risk assessment will require knowing when/if emerging fry will encounter stressful and/or life-threatening water temperatures. A 'good' day for fry emergence occurs when the daily average water temperature is between 6°C (42.8°F) and 12°C (53.6°F) and a 'bad' day occurs when the daily average temperature exceeds 15°C (59.0°F). The transition from 12°C (53.6°F) through 15°C (59.0°F) will cause some mortality, but may not require a separate NBD analysis.

3.2 APPROACH NO.2. USING UNIMPAIRED ANNUAL THERMOGRAPHS TO ASSESS WATER TEMPERATURE

Approach 2 follows the logic that the unimpaired annual hydrograph was necessary to sustain steelhead populations prior to diversions. This logic has merit, even if flawed (steelhead needed more than streamflows to be successful). In the NGD analysis, the water temperature criteria adopted in Approach 1 can be applied to the unimpaired annual hydrograph and thermograph. This will create one baseline condition and will help identify those LHTs that once sustained the basin's steelhead population and could be recovered.

Even more importantly, Approach 2 can provide a quantitative population perspective missing from Approach 1. The water temperature criteria always specify a magnitude, occasionally a duration, but rarely a frequency. Regional adaptations will influence magnitude (e.g., Are southern inland steelhead smolts physiologically or behaviorally adapted to smolt effectively at higher temperatures than their northern counterparts?), although to what extent is a 'hot' debate! But the duration of a particular temperature's magnitude, and particularly its frequency, will be highly regional for a given channel reach. If 'pre-disturbance' annual water temperatures in Sunol Valley frequently exceeded Approach 1 criteria for NBD juvenile rearing (i.e., episodes happened more

often than three times annually) yet headwater LHTs flourished upstream, there are several possible explanations. The Fisheries Workgroup invested in modeling water temperature to explore these explanations for the purpose of better understanding how steelhead populations relied on, and could have adapted to, the watershed.

In summary, modeling annual water temperature under unimpaired and present-day streamflows in Approach 2 will help quantify the duration and frequency for Approach 1 temperature criteria, improving an NGD analysis.

3.3 APPROACH NO.3: USING STEELHEAD JUVENILE GROWTH TO EVALUATE WATER TEMPERATURE EFFECTS ON LHTS

Approaches 1 and 2 combined could be used to assess LHTs basinwide. However, application of thresholds would limit the NGD analysis. Assuming 19°C provides ‘good’ juvenile steelhead growth under modestly high ration levels, would 19.1°C really be measurably ‘less than good’ considering all the complexity of other important interacting habitat variables? Unlikely. Approach 3 explores the use of thermographs and bioenergetics, rather than water temperature thresholds, for assessing LHT viability.

Approach 3 contradicts nothing in Approaches 1 or 2, while offering these improvements to the NGD analysis and LHT evaluation: (1) many magnitude and duration thresholds in the water temperature criteria can be assessed as continuous variables and (2) more analytical capability is created for assessing population response without relying on actual population modeling by adopting population thresholds dependent on juvenile and smolt growth potential (and when there are steelhead in Alameda Creek Basin, on measured lengths and weights). Rather than count the ‘good’ or ‘bad’ days water temperatures meet specific criteria, estimate how much a juvenile or smolt could have grown instead. Next compare this potential growth to exceeding a growth threshold (actually, a minimum juvenile or smolt size) necessary for an LHT’s success. Therefore, Approach 3 integrates individual growth with population success and, in doing so, constructs a direct linkage between water temperature and LHT viability.

To accomplish Approach 3, juvenile steelhead growth must be modeled from the annual thermographs, targeting minimum desired juvenile and smolt sizes necessary to sustain a LHT. Hayes et al. (2008) note smolts less than 150 mm from Scott Creek (a small coastal stream, without a suitable spring estuary for feeding by smolts near Santa Cruz) entering the Pacific Ocean are unlikely to survive. Smolts entering the Pacific Ocean at 175 mm FL and greater have a much better chance of returning to spawn (SAR = smolt to adult return). Trush has been using an SAR curve derived from experimental hatchery data since the mid-1980’s (Figure 2). The Water Temperature Sub-Committee can do an extensive literature search and write-up on SAR curves, if requested by the Fisheries Workgroup. However, the Sub-Committee considers these two smolt threshold sizes a good foundation for the NGD analyses: 150 mm FL as a threshold for minimally acceptable smolt SAR and 175 mm FL for a good SAR for smolts leaving Niles Canyon. This provision, ‘on exiting’ Niles Canyon, keeps the NGD analysis independent of the mainstem downstream of Niles Canyon. At least for now. Maybe a pre-smolt or smolt

130 mm could grow to 150 mm in the Flood Control Channel before reaching San Francisco Bay. The estuary at the mouth of Alameda Creek could grow smolts, perhaps significantly, but no one really knows. Once steelhead begin returning to Alameda Creek, focused monitoring can reveal the true growth potential in both aquatic environments. Also for the future, an SAR curve can be adopted that would allow modeling SAR as a continuous variable dependent on smolt length or weight. The importance of considering smolt size in evaluating steelhead LHTs cannot be overstated.

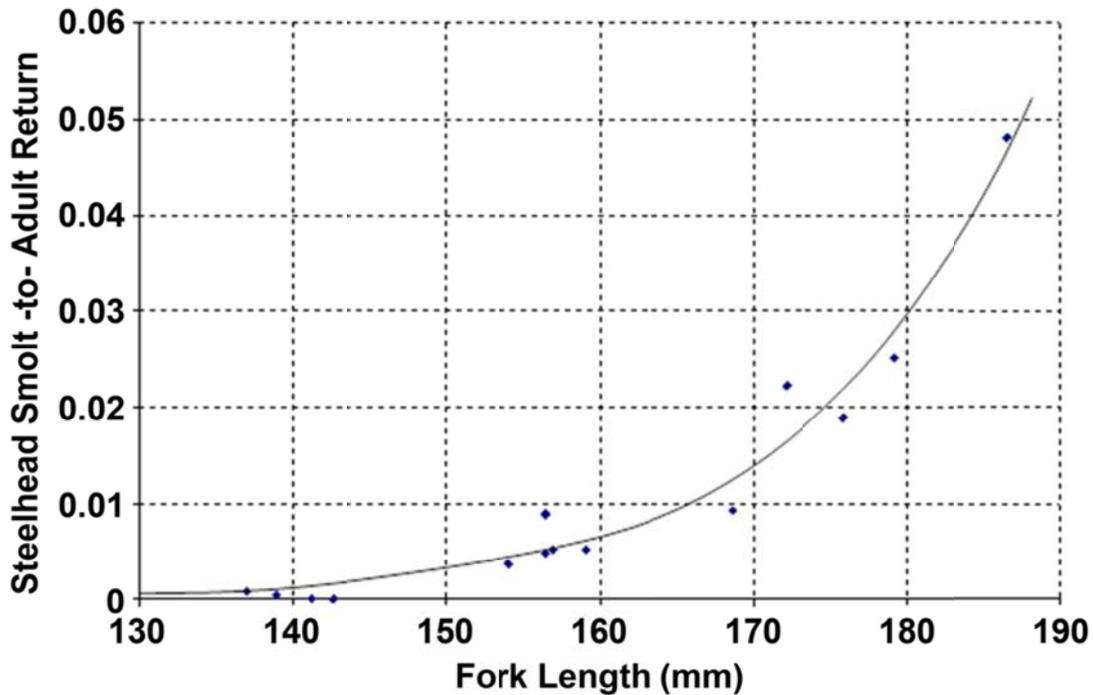


Figure 2. Smolt-to-Adult Return (SAR) curve for steelhead smolts constructed from data published in Kabel and German (1967) and presented in Klein et al. (2008).

Specific growth rate (SpGR) curves are essential for modeling juvenile steelhead growth. A classic SpGR curve has water temperature on the X-axis and specific growth rate on the Y-axis. Specific growth rate is expressed typically as the weight or length gained per weight or length per day (i.e., g/g/day). As with quantifying processes in nature, such as fish growth, there are many variables exerting influence. The aim will be to keep modeling simple; modeling can quickly become the goal rather than a tool. Sullivan et al. (2000) provide a good introduction to the topic and Fisheries Workgroup members can use this reference as a good refresher course. A SpGR curve by Brett et al. (1969) for sockeye salmon fry (Figure 3) illustrates the effect of water temperature on specific growth, as well as the importance of food availability (ration size) on specific growth. Using the 7% excess daily ration by body weight as equivalent to 100% ration and the 6% curve as approximately 80% ration level in Figure 3, the maximum specific growth rate shifts towards the left (from the 100% to 80% ration curve) by approximately 2°C. As ration level decreases further, effects are significantly more pronounced.

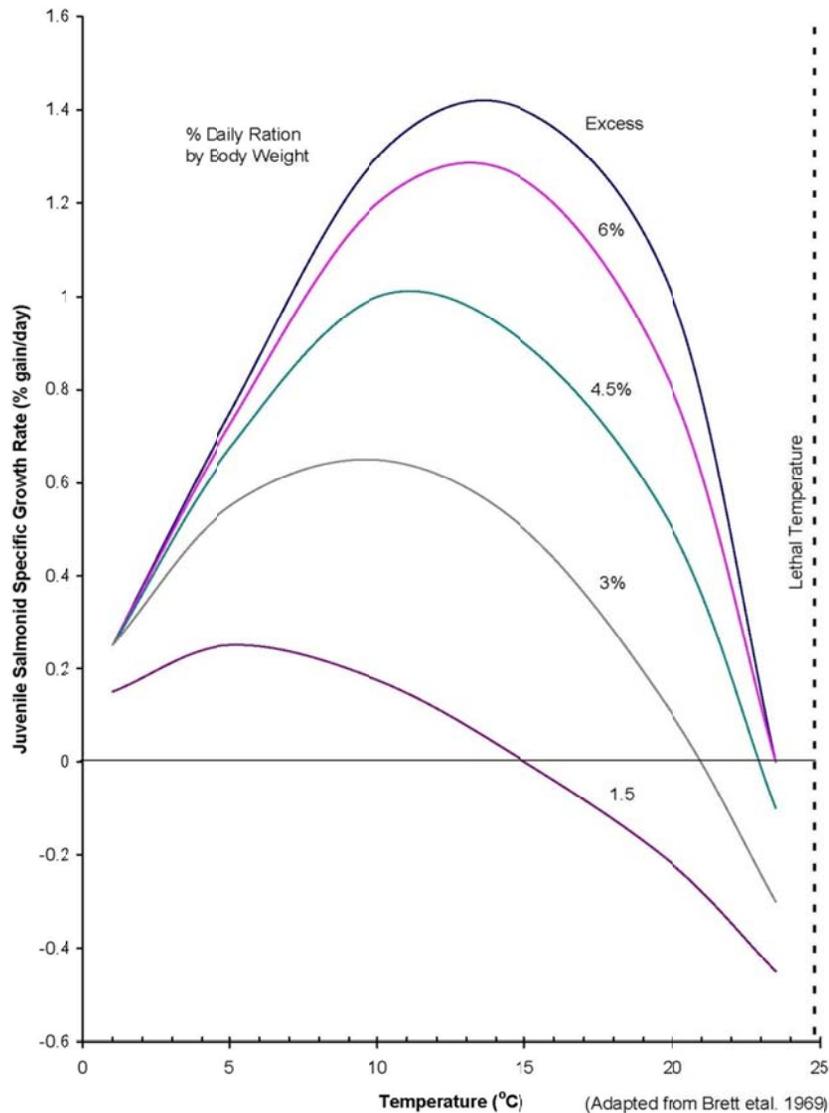


Figure 3. SpGR curves for sockeye salmon fry at different ration levels reproduced from Brett et al. 1969.

Surprisingly, SpGR curves for steelhead and rainbow trout are uncommon (Wurtsbaugh and Davis 1977a, 1977b). A good all-purpose candidate curve is Figure 4, taken from Figure 5.4 and Table 5.2 in Sullivan et al. (2000). This SpGR curve is recommended for the NGD analysis. SpGR curve selection could become important in differentiating channel reaches providing marginal growth potential at higher temperatures. SpGR curve selection could become important in differentiating channel reaches providing marginal growth potential at higher temperatures. Assumptions over ration level also will be important. Given the curves' importance, sensitivity analyses are recommended. Railsback and Rose (1999) provide a SpGR curve for rainbow trout at 40% ration level that also can be used in the NGD analysis. The Railsback/Rose curve shifts optimal specific growth farther to the curve's right than the SpGR curve presented in Sullivan et al. (2000) (refer to Railsback (1997) for growth modeling). Finally, SpGR curves used by Huber (2006) in the Navarro River could be used in the sensitivity analyses as well.

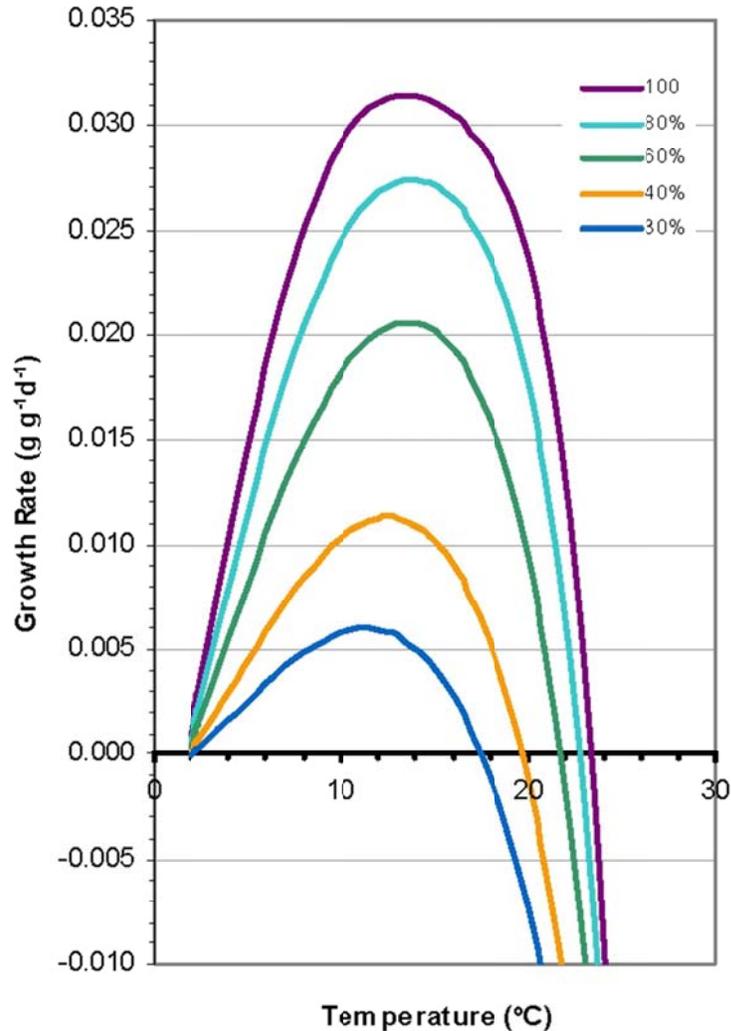


Figure 4. SpGR curves at variable ration levels for juvenile steelhead trout (reproduced from Sullivan et al. 2000).

Applying the SAR size thresholds and SpGR curves (at different ration levels), how would the NGD evaluation of LHTs be performed? Take Sunol valleybottom and floodplain as an example. Using 175 mm as the threshold for good SAR upon entering San Francisco Bay, could a 150 mm pre-smolt swimming down from upper Alameda Creek on March 1 grow to 175 mm by May 15 while residing within the Sunol Valley mainstem? The SpGR curve and ration level would be used to grow this 150 mm long cyber-smolt based on the daily average water temperature in the annual thermographs over the March 1 to May 15 period for a range of different WY types under past, present, proposed future annual flow/thermal regimes. By achieving a 175 mm length by May 15, a smolt's chance for survival significantly improves (refer to Figure 2). Consequently, a headwater LHT that requires significant smolt growth in the Sunol Valley would be possible and deserve priority consideration in the recovery plan.

A similar analytical pathway for 0+ and 1+ juvenile rearing will be needed to evaluate stream segments of selected LHTs. A stream segment expected to provide overwintering habitat for 0+ juveniles (approaching their first winter) will need to promote growth and provide abundant habitat for juveniles to have a reasonable chance for surviving and growing in the next leg of their downstream journey the following spring. Therefore, not only will smolt-sized juveniles be entering Sunol Valley from the Upper Alameda Creek headwaters, but several age classes of smaller juveniles as well (refer to Casagrande (2010) on juvenile steelhead data for nearby Uvas Creek). Each could be important for recovery. If a redd is built and fry emerge at the base of Little Yosemite Canyon, could those fry migrate to the Sunol Valley mainstem and grow through the summer, eventually achieving a minimum juvenile size likely to survive their first winter? Could Sunol Valley mainstem grow 1+ 120 mm juveniles (arriving April 1) to 175 mm pre-smolts/smolts by June 1? If so, these smolts could then scoot through lower Alameda Creek without requiring additional growth. This would address the viability of another LHT (i.e., produce 1+ juveniles upstream, but on Sunol Valley to grow these juveniles into smolts). Several key variables must be estimated. To forecast size by June 1, we need a time period (April 1 to June 1), a percentage ration estimate (e.g., 60%), a starting FL (120 mm), an ending FL (175 mm for 'good'), a streamflow range providing abundant physical rearing habitat for small and large juvenile steelhead, an acceptable SpGR curve, and annual hydrographs/thermographs (spanning all water year (WY) types for unregulated, regulated, and proposed streamflows) for April 1 through May 31. A stream segment that decisively fails this test would eliminate that LHT. This test is somewhat generic out of necessity: presently there are no fish (but a clear pathway for real adaptive management stretches ahead). The analysis also requires considerable sensitivity analyses for key model variables (e.g., using a range of ration level). If a segment passes only if ration level is high (80%), then productive BMI riffle habitat must be abundant as well, fast-water feeding habitat available and the water temperatures favorable for much (how much?) of the time period (in this example, April 1 to June 1). Note that habitat abundance is integrated with water temperature in this example. They could be kept separate (i.e., consider only water temperature and not the streamflow range for abundant physical habitat). If the stream segment passes, based on temperature alone, the possibility of physical habitat improvement might be considered.

4 RATION LEVEL EFFECTS ON JUVENILE GROWTH

To evaluate the potential for higher SpGR at warmer temperatures, by relying on more abundant prey, juvenile steelhead growth will be computed over a wide range (30% to 80%) of ration levels. Railsback and Rose (1999) conclude from their growth modeling that:

“This analysis indicates that assessments focused on effects of summer temperature may be misleading. The effects of temperature on summer growth at our sites were small, with growth being much more dependent on food consumption. Apparent growth rates were higher and more dependent on temperature during fall–spring.”

An analysis of juvenile growth potential should not rely on a juvenile steelhead requiring more than an 80% ration level to attain a given minimum size threshold. Targeted SpGRs - to achieve desired juvenile and smolt sizes - can be monitored effectively by estimating growth from otolith analyses as done on the Navarro River (Johnson et al. 2002 and Huber 2006).

Note that modeling growth essentially accounts for the cumulative effect of multiple days providing good growth temperatures. Rather than count the number of days that specific growth potentially exceeds a specified minimum or greater rate, modeled juvenile/smolt length at the end of the life stage period becomes the analytical metric in the NGD analysis. Harvey et al. (2006) quantify a trend between streamflow and trout growth that could be indirectly measuring the influence of ration size.

As adult steelhead return to spawn, and their progeny repopulate the basin, all the thresholds should be re-examined, especially the size thresholds and time periods for each life stage. SpGR curves should be adjusted based on empirical evidence and ration level can be back-calculated with some reliability (Huber 2006). These adjustments provide a clear pathway to substantive adaptive management and cost effective monitoring. A clear step will be to compare NGDs and growth computed from historical thermal regimes in Approach 2 with the growth results predicted under Approach 3.

5 MODELING TURBIDITY EFFECTS ON SPECIFIC GROWTH RATES

Newcombe and MacDonald (1991) and Newcombe and Jensen (1996) took the scientific literature and distilled thresholds for evaluating turbidity effects on stream organisms and ecosystems (refer to Bash and Berman (2001) for a general turbidity review and Cummins and Madej (2004) for a stream health perspective). Anderson (1975) was ahead of his time in considering cumulative impacts measurable by turbidity monitoring. The excerpt of Klein et al. (2008) below proposes three turbidity thresholds for assessing cumulative effects on anadromous salmonids:

“Background Stream Ecosystem Stress: 10 NTU Threshold

No natural environment is stress-free. Even in pristine watersheds of north coastal California, winter storms generate turbidities that can negatively affect aquatic plants and animals. The ecological significance of low-level turbidities, up to 10 NTU, will depend on the duration of exposure. ODEQ (2004) provides an excellent literature review of turbidity and suspended sediment effects on stream biota and anadromous salmonids. The following effects/responses are included: 1) ≥ 10 NTU: salmonid reactive distance is decreased by approximately 0.5 with potential change to active feeding strategy (Table 7 and Figure 5 in ODEQ 2004), 2) \geq median 10 NTU: steep reduction in BMI densities (Figure 6 in ODEQ 2004), and 3) \geq median 10 NTU: steep reduction in periphyton productivity (Figure 9 in ODEQ 2004). Many eastern US states consider 10 NTU the upper cutoff for “trout” streams (e.g., North Carolina). Also in the eastern US, Waters et al. (2001) identify a 10 NTU threshold for fish biotic integrity in 30 Piedmont streams. While 1) and 3) are directly attributable to the magnitude of turbidity, the

other effects are a product of magnitude and duration of turbidity. Given the difficulty in assigning ecological effects to daily turbidities less than 10 NTU, we used 10 NTU and greater as a biological threshold for causing background ecological effects. A one-day exceedence of 10 NTU very likely has a net negative effect on overall stream ecosystem productivity by reducing primary and secondary production. However the effect of exceeding 10 NTU for one day would be extremely difficult to measure in the field and would not be significant within the context of an entire water year.

Moderate Stream Ecosystem Stress: 25 NTU Threshold

In the extensive review by ODEQ (2004), the following trends were provided: 1) decreased weight and length of juvenile salmonids (Table 3 in ODEQ 2004), 2) brook trout switch from passive drift feeding to active searching (Table 3 in ODEQ 2004), 3) 13% to 50% reduction in primary productivity (Figure 11 in ODEQ 2004), 4) approaching low asymptote in salmonid reactive distance (Figure 4 and Figure 5 in ODEQ 2004), 5) approaching low asymptote in benthic macroinvertebrate (BMI) densities (Figure 6 in ODEQ 2004), and (6) approaching low asymptote in periphyton productivity (Figure 9 in ODEQ 2004). Berg and Northcote (1985) observed juvenile coho moving closer to the channelbed (within 4 inches), to help maintain their holding position, when exposed to turbidities exceeding 30 NTU. Anderson (1975, p.348) identifies turbidities at 25 NTU and higher as causing significantly greater and more intense impacts to stream biota. Anderson (1975, p. 348): “In this paper, turbid water is separated from non-turbid water at 27 mg/liter; at 27 mg/liter water has been characterized as “not drinkable,” catch of fish drops to one-half, no increased mortality of fish; fish production drops less than 10 percent (Cordone and Kelley)(18).” We used 25 NTU and greater as a biological threshold for causing much greater effects on overall stream productivity and fish health/behavior, compared to the background productivity effects expected from exceeding the 10 NTU biological threshold.

Severe Stream Ecosystem Stress: 50 NTU Threshold

Bash and Berman (2001) in their literature review found that: 1) juvenile salmonid behavioral changes occur by 60 NTU (Table 2 in Bash and Berman 2001) and 2) juvenile coho can be displaced at 40 to 50 NTU (Table 2 in Bash and Berman 2001). An ongoing laboratory/field study reports that juvenile salmonid feeding remained efficient (amphipods as prey) up to 40 NTU, but that there was almost no feeding by 70 NTU (Cummins and Madej 2004). Field observations of feeding were curtailed above 40 NTU because juvenile fish were no longer visible. Forced emigration of juvenile salmonids is a severe stressor. Bisson and Bilby (1982) found: “Juvenile coho salmon (*Oncorhynchus kisutch*) were subjected to experimentally elevated concentrations of suspended sediment and did not avoid moderate turbidity increases when background levels were low, but exhibited significant avoidance when turbidity exceeded a threshold that was relatively high (>70 NTU) and was varied according to previous suspended sediment exposure.” We used 50 NTU and greater as a biological threshold for causing much greater effects to overall stream productivity and immediate fish

health/behavior changes that threaten fish survival, compared to the background productivity effects expected from exceeding the 10 NTU biological threshold and potential physiological effects to fish and benthic macroinvertebrates from exceeding the 25 NTU biological threshold.”

Another excerpt from Klein et al. (2008) explains how daily turbidity effects can be evaluated on juvenile steelhead growth:

“One physical factor that can diminish juvenile salmonid growth is turbid streamflow (Newcombe and MacDonald 1991). A critical step in devising a conservative yet realistic CWE model was selection of a quantitative function between turbidity and juvenile salmonid growth. Rosenfeld (2002) reviews quantitative relationships that have been measured for a juvenile salmonid’s reactive distance to capturing prey as a function of turbidity. Reactive distance shortened as turbidity increased. Rosenfeld (2002) fits this averaged reactive distance curve to the reviewed studies: $PMR = 100 - 44.8 \log_{10}(NTU + 1)$, where PMR = percent of reactive distance at 0 NTU.

A consequence of shorter reactive distance would be less efficient foraging (more energy expended per prey captured) and therefore reduced growth. Laboratory and flume studies have demonstrated a negative turbidity effect on growth at discrete turbidities (Henley and others 2000). To estimate daily growth effects from fluctuating turbidity, as occurs in an annual turbidigraph, our model computes daily changes in specific growth rate proportional to Rosenfeld’s (2002) relative reactive distance curve (Figure A). One modification in applying the Rosenfeld equation for estimating juvenile steelhead growth was made.

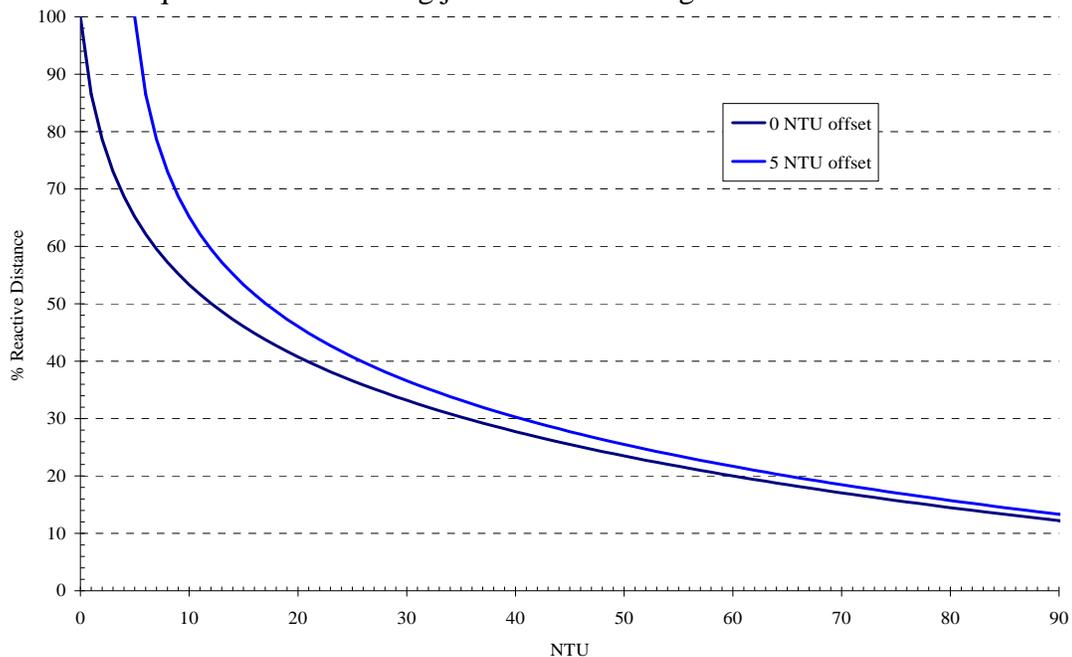


Figure A. Reactive distance curves as a function of turbidity, with and without a 5 NTU off-set.

Reactive distance is highly sensitive to low turbidity. Relative reactive distance at 10 NTU is 53%, and at 5 NTU is 65%. Harvey and Railsback (no date) assumed < 5 NTU did not affect reactive distance to drifting prey (ODEQ 2004). In streams with chronically high NTU, the specific growth rate likely begins dropping at extremely low NTUs (e.g., 5 NTU or lower), whereas in a pristine stream the specific growth rate probably doesn't begin dropping until reaching 10 NTU or higher. This is because all other effects associated with chronic turbidity will also contribute to lowering the specific growth rate (Henley and others 2000) even at very low NTUs (e.g., greater channelbed embeddedness will reduce benthic macroinvertebrate habitat capacity). However our modeling isolated and assessed just one potential effect of high turbidity, and not other related geomorphic effects. For our model, the Rosenfeld reactive distance curve was off-set 5 NTU as in Figure A, thus the modeled specific growth rate was unaffected by turbidities less than 5 NTU. Though the specific growth rate was significantly reduced (below 30%) in the model at higher turbidities, growth still occurred at 50 NTU and higher."

Rosenfeld (2006, Figure 2) reports declines in specific growth rates of brook trout as follows: (1) at 10 NTU, 10% decline, (2) at 25 NTU, a 30% decline, and at 50 NTU, a 60% decline. Percentage declines in reactive distance (estimated similarly from the graph above) exceed Rosenfeld's declines. Smith and Li (1983) provide an energetic – foraging relationship that could be highly impacted by reduced reactive distance.

6 A CONSERVATIVE NGD APPROACH FOR INTEGRATING WATER TEMPERATURE TURBIDITY EFFECTS FOR EVALUATING JUVENILE/SMOLT GROWTH

Turbidity data are being collected on several mainstem segments of Alameda Creek. The Workgroup has supported modeling annual hydrographs and thermographs. A similar effort to model annual turbidigraphs may not be warranted, modeling could not replace actual daily measurements, but a quantitative, conservative assessment of turbidity effects can nevertheless be attempted.

All turbidity measurements, regardless of whether measurements were taken winter or summer, or rising limb versus falling limb of a storm hydrograph can be graphed on one scatterplot. Variability at any given streamflow can be substantial, as shown in Figure 5 (using FTU rather than NTU). The regression line would provide a poor predictor for modeling NTU levels in a real annual hydrograph to create a realistic annual turbidigraph. However, the lower edge of the scatterplot, called the 'Lower Bound Line' by Klein et al. 2008, is well-defined at winter baseflows and lower.

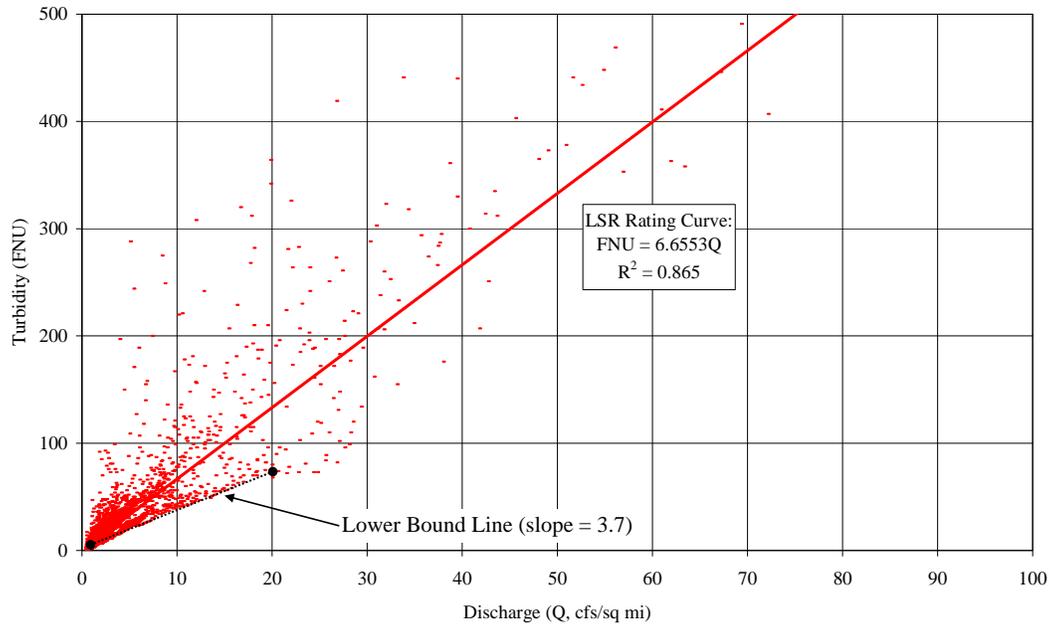


Figure 5. Example of Lower Bound Curve for a turbidity rating curve from Jacoby Creek, near Arcata, California (Klein et al. 2008).

This Lower Bound Line can be used to conservatively associate a daily average streamflow in an annual hydrograph with a minimum NTU value. Conservative declines in specific growth rate or ration level can be quantitatively linked to NTUs. This could be done via thresholds (as considered in Approaches 1 and 2 for water temperatures) or treated continuously as in Approach 3. If daily average turbidity exceeds 25 NTU (i.e., a threshold approach), then the daily predicted specific growth rate in the NGD analysis could be dropped 10% to 30% (the range constituting a sensitivity analysis). An NTU would be assigned (modeled) for each daily average streamflow using the Lower Bound Line. Or, the reactive distance curve (shown above) could be used to model a continuously changing specific growth rate at each daily streamflow and temperature. For a sensitivity analysis, the offset on the reactive curve could range 5% (as shown) up to 20%. Because the true ration level and specific growth rate curve are unknown for any mainstem reach in Alameda Creek, a model (the reactive distance curve shown above) modifying daily specific growth rates would be an assumption modifying an assumption. But initial sensitivity analyses would indicate whether turbidity could be an extreme limiting factor for some mainstem reaches, and therefore for some LHTs.

A watershed management goal would be to reduce the intercept of the Lower Bound Line. A first step for Alameda Creek, therefore, would be to compile the several sources of turbidity data and identify Lower Bound Lines.

7 INCORPORATING A SMOLT DECISION POINT INTO THE WATER TEMPERATURE EVALUATION

UC Santa Cruz and NMFS have identified a critical time in a juvenile's life. This recent research has not yet been incorporated into the proposed analytical framework, but

consideration is clearly warranted (Hayes et al. 2008 and Sogard et al. 2009 are good summaries and perspectives of recent steelhead life history interactions). This excerpt is from Mangel's grant proposal (2004):

“Experimental studies have elucidated the importance of early growth rates and the position of an individual along an expected growth trajectory in shaping the probability of early maturation and/or migration, as well as the timing of emigration for anadromous individuals, with the following general sequence for Atlantic salmon (outlined in Thorpe et al. 1998). In the spring, a maturation switch occurs in which current energetic state (lipid reserves) and the rate of change in state are compared with a genetically determined maturation threshold. Individuals exceeding the threshold adopt a pathway of early maturation. Near the end of their first summer, juveniles enter a second decision window of assessment of internal state (body size) and its rate of change (i.e., growth rate). If the threshold is exceeded, the individual adopts a migratory pathway and continues to feed and have high activity levels during the winter in preparation for smolting in the spring. If the threshold is not attained, the individual adopts a non-migratory pathway, reducing its activity and thus its vulnerability during the winter. Following this decision, the population in general will divide into two size modes as fish on the emigrating pathway continue to increase in size relative to the non-emigrating mode. Fish that have adopted the maturation pathway do not initiate the emigration process. As a consequence of these life history decisions, fast growing age-0 individuals with high lipid accumulation may mature as parr, individuals growing at moderately fast rates are likely to undergo smolt transformation in the spring and emigrate at age 1, and the slowest growers remain in the stream for another year, again entering the maturation and emigration decision windows at their respective times.

The relevance of this framework for steelhead populations has not been previously assessed. There is evidence of at least moderate heritability of early maturation, smolting timing, and growth in steelhead (Thrower et al. in press), providing support for the concept of varying genetic thresholds for life history transitions. Here we focus on the environmental factors underlying the expression of different pathways. Although steelhead and Atlantic salmon share a similar repertoire of life history strategies and variability in those strategies, we believe the situation of steelhead in California is different. Atlantic salmon on a life history pathway of delaying emigration until age 2 reduce activity and feeding in winter, presumably as a means of reducing predation risk during a period of poor growth opportunity due to cold temperatures and low food availability. A similar response is evident in steelhead populations of Vancouver Island, where fish reduce growth rates in winter even when provided with elevated temperatures and unlimited food (Johnsson et al. 1993). Johnsson et al. (1993) suggested that high feeding activity in winter was maladaptive due to the associated risk and costs. However, for some California populations it is winter, rather than summer, that is the good growing season and summer may be the harshest season, from the perspective of growth (Merz 2002, Fig. 2). Thus, the timing of life history

decisions in southern populations of steelhead is not necessarily comparable to Atlantic salmon, despite their similarity of plasticity in life histories. Models developed for Atlantic salmon may be more applicable in current form to northern populations of steelhead, which experience much harsher winter conditions. Furthermore, steelhead populations within California may experience very different biogeographic conditions. For example, preliminary studies of the four systems to be examined in this study found extreme differences in early growth rates and likely proportions of age-1 emigrants between the central coast and Central Valley. Development of appropriate life history models will require detailed comparisons of contrasts between the two regions. Most of our knowledge of steelhead ecology has been derived from northern populations. However, local adaptation of steelhead appears to be extensive; high levels of genetic differentiation among stream systems have been observed for both the Central Valley (Nielsen et al. 2003) and along the entire coast of California (Garza 2004).

Thus, we expect to see many contrasts between California steelhead and northern residents, as well as contrasts among streams within California. The central role of early growth in determining life history trajectories provides a tractable means of generating the empirical data necessary to develop life cycle models for California steelhead and for using these models to understand the effects of water policy on steelhead population dynamics. Our overall focus is to understand the mechanisms underlying variability in potential growth rates and how different factors impact growth and consequent life history pathways. As outlined below, we believe management decisions affecting the growth environment, including habitat availability, food delivery via drift, and physical conditions such as temperature, can dramatically alter the natural distribution of life history patterns exhibited in steelhead populations. Development of appropriate, well-supported life history models for steelhead will be useful for both improved management of water resources for threatened populations and improved predictive capabilities for future environmental impacts such as global warming and drought regimes.”

The Fisheries WorkGroup can refer to Satterthwaite et al (2009) to get acquainted with the concept.

8 SUMMARY

The Water Temperature Sub-Committee explored several analytical approaches for integrating water temperature into the NGD analyses. A threshold approach, using water temperature magnitude, duration, and/or frequency criteria, can differentiate good from bad days. These threshold criteria would then be applied to specific channel reaches and annual thermographs to compute NGDs and ultimately to evaluate LHT viability. However, the NGD analysis still must offer some mechanism for determining how many good days are enough. ‘Enough’ demands another threshold: if the NGD for pre-smolt growth in WY2000 during spring outmigration (e.g., March 15 to June 15) through Niles Canyon was 25 days, but could have been 45 days under a new Calaveras flow regime,

would 45 days qualify Niles Canyon mainstem as acceptable for LHTs requiring good pre-smolt growth through Niles Canyon? NGDs computed for water temperatures in an unimpaired hydrograph could provide one baseline functioning as the 'enough' threshold. In Wet WY's, every day between March 15 and at least June 1 could have offered good growth temperatures. But in Dry WY's, likely not. Historical, unimpaired annual NGD baselines, however, may never be attainable. The Water Temperature Sub-Committee explored another approach, complementing threshold criteria, but better addressing what might be considered 'enough' for evaluating LHTs. Using the example above, an LHT relying on significant pre-smolt growth through Niles Canyon needs a smolt exiting Niles Canyon that will be sufficiently big to have a good chance of returning as a spawning adult. The 'enough' threshold becomes fish size rather than NGD of good growth temperatures. Two minimum smolt threshold sizes have been recommended: 150 mm FL for acceptable SAR and 175 mm FL for good SAR.

Specific growth rate curves under different ration conditions will be needed to grow these cyber-juveniles. The SpGR approach in Approach 3 also offers diverse management options. The most obvious is recommending instream flow needs. But with SpGR highly dependent on ration, among many other complicating factors, management to improve food availability can partially compensate for unfavorably high water temperatures ... up to a point. The SpGR approach also will forecast effects of turbidity (more turbid water slows growth and reduces food availability) by decreasing specific growth rates with increasing turbidity, thus affecting the NGD analysis.

The Water Temperature Sub-Committee has adopted Approach 3 for evaluating water temperature effects on prioritized life history tactics identified in the study plan (McBain and Trush 2008). Water temperature will be incorporated into the NGD analysis by applying a specific growth rate curve to each channel reach expected to rear juvenile steelhead. Beginning with a targeted initial juvenile length and date (e.g., a 120 mm pre-smolt entering Niles Canyon on March 1), the daily specific growth rate will model growth until a projected exit date (May 15), or if water temperatures begin producing a negative specific growth rate, or if water temperatures begin exceeding a smoltification temperature threshold. A good year (NGY) will occur if the 120 mm pre-smolt beginning March 1 attains a 175 mm fork length before emigrating as a smolt. Growth modeling will proceed under unregulated and regulated annual thermographs to evaluate the viability of future high-priority LHTs.

9 REFERENCES

- Anderson, H.W. 1975. Sedimentation and turbidity hazards in wildlands. Pp. 347-375, in *Watershed Management Symposium Proceedings, Irrigation and Drainage Division*, Am. Soc. Civil Engineers, New York.
- Bash, J. and C. Berman. 2001. *Effects of Turbidity and Suspended Solids on Salmonids*. Final Research Report, Research Project T1803, Task 42, Effects of Turbidity on Salmon. Center for Streamside Studies, University of Washington, Seattle, WA 98195. 66 p. with appendices.
- Brett, R.J., Shelbourn, J.E., and C.T. Shoop. 1969. Growth rate and body composition of fingerling sockeye salmon, *Oncorhynchus nerka*, in relation to temperature and ration size. *J. Fish. Res. Bd. Canada* 26:2363-2394.
- Casagrande, J.M. 2010. *Distribution, Abundance, Growth, and Habitat Use of Steelhead in Uvas Creek, CA*. Master Thesis. San Jose State University. 160 p.
- Cummins, K. and M. A. Madej. 2004. *Update on evaluating the composition of suspended load as a measure of stream health*. January 2004 Monitoring Study Group Meeting Minutes. California Board of Forestry and Fire Protection. http://www.fire.ca.gov/CDFBOFDB/pdfs/MSG_January_2004.pdf
- Gunther, A. J., Hagar, J., and P. Salop. 2000. *An Assessment of the Potential for Restoring a Viable Steelhead Trout Population in the Alameda Creek watershed*. Prepared for the Alameda Creek Fisheries Restoration Workgroup. February 07, 2000.
- Harvey, B.C., Nakamoto, R.J., and J.L. White. 2006. Reduced streamflow lowers dry-season growth of rainbow trout in a small stream. *Trans. Am. Fish. Soc.* 135:998-1005.
- Hayes, S.A., Bond, M.H., Hanson, C.V., Freund, E.V., Smith, J.J., Anderson, E.C., Ammann, A.J., and R.B. MacFarlane. 2008. Steelhead growth in a small Central California watershed: upstream and estuarine rearing patterns. *Trans. Am. Fish. Soc.* 137:114-128.
- Huber, E.R. 2006. *Limitations in Nature Intensify Sublethal Thermal Stress Experienced by Juvenile Steelhead Trout (Oncorhynchus mykiss): Current Estimates and Future Predictions*. M.S. Thesis, University of California, Davis, CA, 2006.
- Johnson, M. L., Pasternack, G., Florsheim, J., Werner, I., Smith, T.B., Bowen, L., Turner, M., Viers, J., Steinmetz, J., Constantine, J., Huber, E.R., and O. Jorda. 2002. The impact of abiotic and biotic stressors on salmonids in the Navarro River watershed, Vols I-III. *Report CTSW-RT-02-040 to the Division of Environmental Analysis*, California Department of Transportation.

- Kabel, C.S. and E.R. German. 1967. Some aspects of stocking hatchery-reared steelhead and silver salmon. *Marine Resources Branch Administrative Report No. 67-3*. California Department of Fish and Game.
- Klein, R., Trush, W., and M. Buffleben. 2008. *Watershed condition, turbidity, and implications for anadromous salmonids in North Coastal California Streams*. A Report to the California North Coast Regional Water Quality Control Board, Santa Rosa, CA . May 21, 2008 89 p.
- Mangel, M.S. 2004. *Life history variation in steelhead trout and the implications for water management*. Submitted to CalFed Science Program 2004.
- McBain & Trush. 2008. *Alameda Creek Population Recovery Strategies and Instream Flow Assessment for Steelhead Trout, Final Study Plan*. Prepared for: Alameda Creek Fisheries Restoration Workgroup. 56 p.
- Myrick, C.A. and J.J. Cech, Jr. 2001. Temperature Effects on Chinook Salmon and Steelhead: A Review Focusing on California's Central Valley Populations. *Bay Delta Modeling Forum, Technical Publication 01-1*. 57 p.
- Myrick, C.A. and J.J. Cech, Jr. 2004. Temperature effects on juvenile anadromous salmonids in California's central valley: what don't we know? *Reviews in Fish Biology and Fisheries* 14:113-123.
- Myrick, C. A. and J. J. Cech. 2005. Effects of temperature on the growth, food consumption, and thermal tolerance of age-0 Nimbus-strain steelhead. *North American Journal of Aquaculture* 67:324-330.
- Newcombe, C.P. and D.D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. *No. Am. J. Fish. Management* 11:72-82.
- Newcombe, C.P. and J.O.T. Jensen. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. *No. Am. J. Fish. Management* 16:693-727.
- ODEQ. 2004. *Draft Technical Basis for Revising Turbidity Criteria*. Water Quality Division, Oregon Department of Environmental Quality. February 12, 2004 by Rosetta, T.
- Railsback, S.F. 1997. Guidance for Using a Bioenergetics Model to Assess Effects of Stream Temperature. Prepared for: Technical and Ecological Services, Pacific Gas and Electric, *Report No.001.8-97.8*, December 1997.
- Railsback, S.F. and K.A. Rose. 1999. Bioenergetics modeling of stream trout growth: temperature and food consumption effects. *Trans. Am. Fish. Soc.* 128:241-256.

- Rosenfeld, J. 2005. *Sustainability indicators for turbidity impacts on stream ecosystems*. Ann. Tech. Report, BC Forest Science Program. FP Number: Y051112, 14 p.
- Satterthwaite, W.H., Beakes, M.P., Collins, E.M., Swank, D.R., Merz, J.E., Titus, R.G., Sogard, S.M., and M. Mangel. 2009. *Steelhead life history on California's Central Coast: Insights from a state-dependent model*. I. 139:532-548.
- Smith, J. 2008. *Comments on the Alameda Creek Recovery Strategy and Instream Flow Assessment for Steelhead*. January 7, 2008.
- Smith, J.J. and H.W. Li. 1983. Energetic factors influencing foraging tactics of juvenile steelhead trout, *Salmo gairdneri*. Pp. 173-180 in D.L.G. Noakes et al. (eds.), *Predators and Prey in Fishes*. Dr. W. Junk Publishers, The Hague.
- Sogard, S.M., Williams, T.H., and H. Fish. 2009. Seasonal patterns of abundance, growth, and site fidelity of juvenile steelhead in a small Coastal California stream. *Trans. Am. Fish. Soc.* 138:549-563.
- Spina, A.P. 2007. Thermal ecology of juvenile steelhead in a warm-water environment. *Environ. Biol. Fish* 80:23-34.
- Sullivan, K., Martin, D.J., Cardwell, R.D., Toll, J.E., and S. Duke. 2000. *An analysis of the effects of temperature on salmonids of the Pacific Northwest with implications for selecting temperature criteria*. Sustainable Ecosystems Institute, Portland, OR. December 2000.
- Vieira, N.K., Poff, N.L., Carlisle, D.M., Moulton, S.R. II, Koski, M.L., and B.C. Kondratieff. 2006. A database of lotic invertebrate traits for North America. *U.S. Geological Survey Data Series 187*, Reston, VA <http://pubs.water.usgs.gov/ds187>.
- Wurtsbaugh, W. A. and G. E. Davis. 1977a. Effects of fish size and ration level on the growth and food conversion efficiency of rainbow trout, *Salmo gairdneri* Richardson. *Journal of Fish Biology* 11:99-104.
- Wurtsbaugh, W. A. and G. E. Davis. 1977b. Effects of temperature and ration level on the growth and food conversion efficiency of *Salmo gairdneri*, Richardson. *Journal of Fish Biology* 11:87-98.