APPENDIX G

Approach for Assessing Effects of Policy Element Alternatives on Upstream Passage and Spawning Habitat Availability

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APPENDIX G

APPROACH FOR ASSESSING EFFECTS OF POLICY ELEMENT ALTERNATIVES ON UPSTREAM PASSAGE AND SPAWNING HABITAT AVAILABILITY

This appendix describes the approach used to assess the protectiveness of Policy element alternatives on upstream passage and spawning habitat.

An assessment of protectiveness should consider scale-related variations in channel size, flow, and fish habitat availability. The importance of basin size to developing a protective instream flow Policy at the regional level can be evaluated via various levels of complexity and effort. At the greater data intensive level, habitat-flow and hydraulic geometry data could be collected extensively in a range of streams and used to develop a regional relationship that describes the variability in channel size, fish habitat, and instream flow needs (e.g., Arthington et al. 2006). Runoff records and habitat-flow relations could be developed for each sampled stream and results compared across basin size and hydrologic response (e.g., a flashy stream vs. one with a more sustained base flow). Such a study would take many years and involve a large number of streams, and hence, could not be conducted within the time frame allowed for the development of the Policy.

A simpler, yet still biologically meaningful approach was used to evaluate the level of protectiveness of the Policy element alternatives that restrict flow (diversion season, minimum bypass flow and maximum cumulative diversion) on upstream passage and spawning habitat needs for anadromous salmonids. For this, R2 and Stetson collected basic cross-section data in 13 validation streams within the Policy area in 2006 (called the 2006 validation sites in this report). The overall analysis process is depicted conceptually in Figures G-1 through G-3 and consisted of the following main steps:

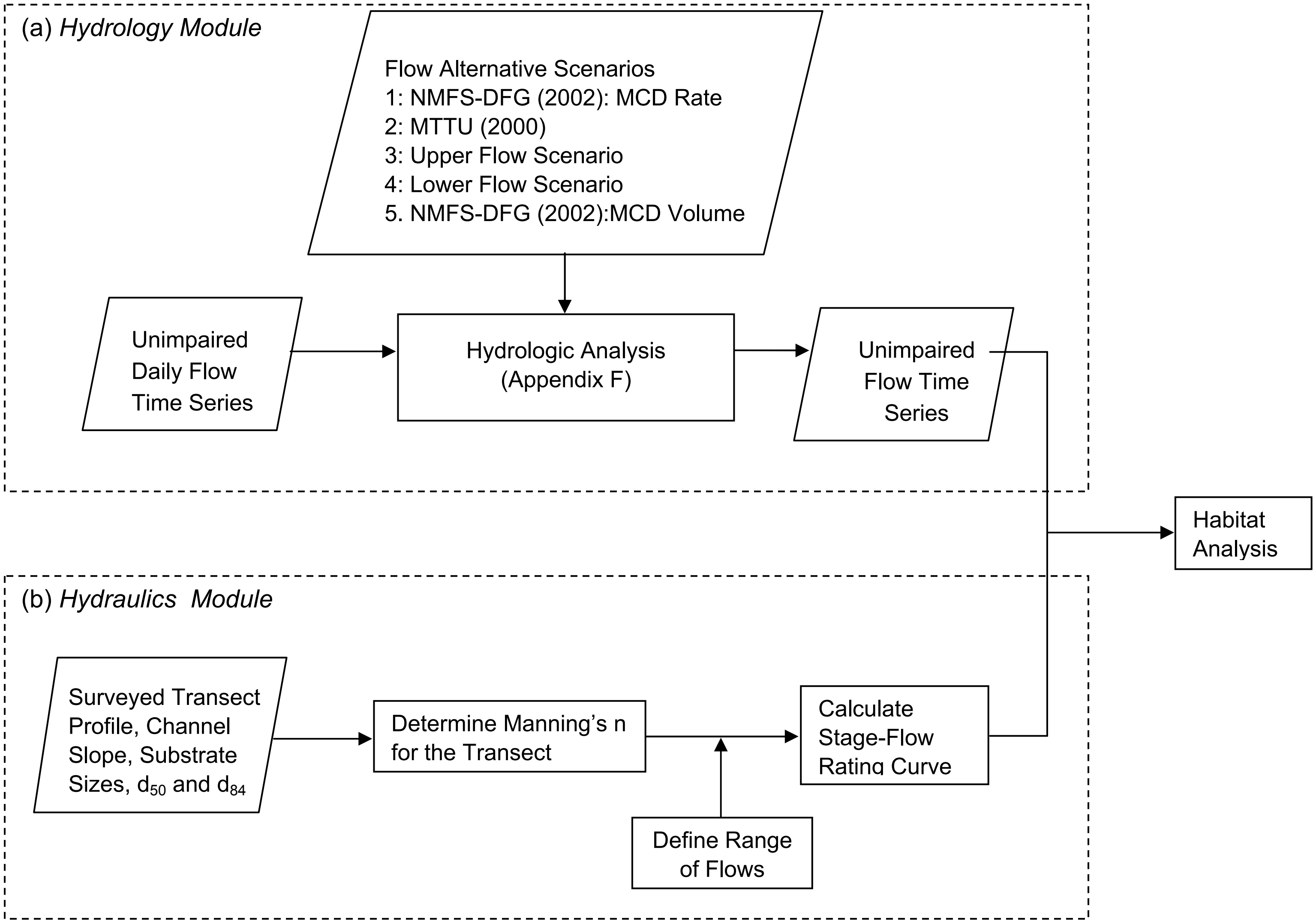

Figure G-1. Flow chart for hydrology module (upper portion) and hydraulic module (lower portion)

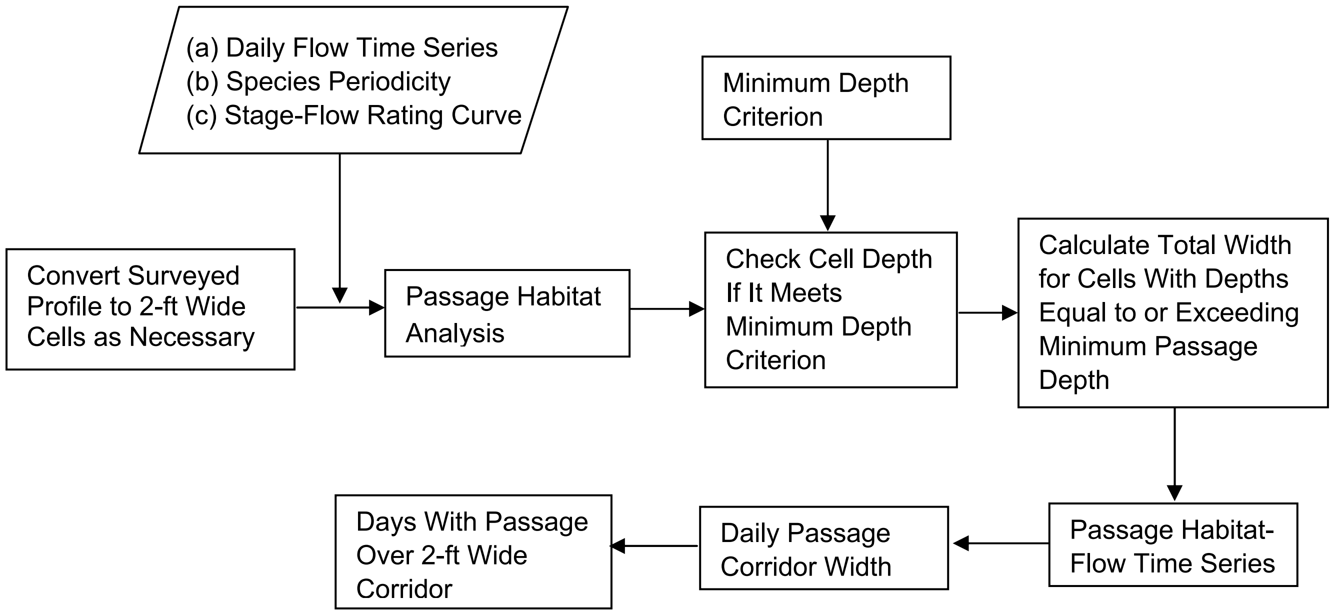

Figure G.2. Flow Chart for Passage Habitat Analysis

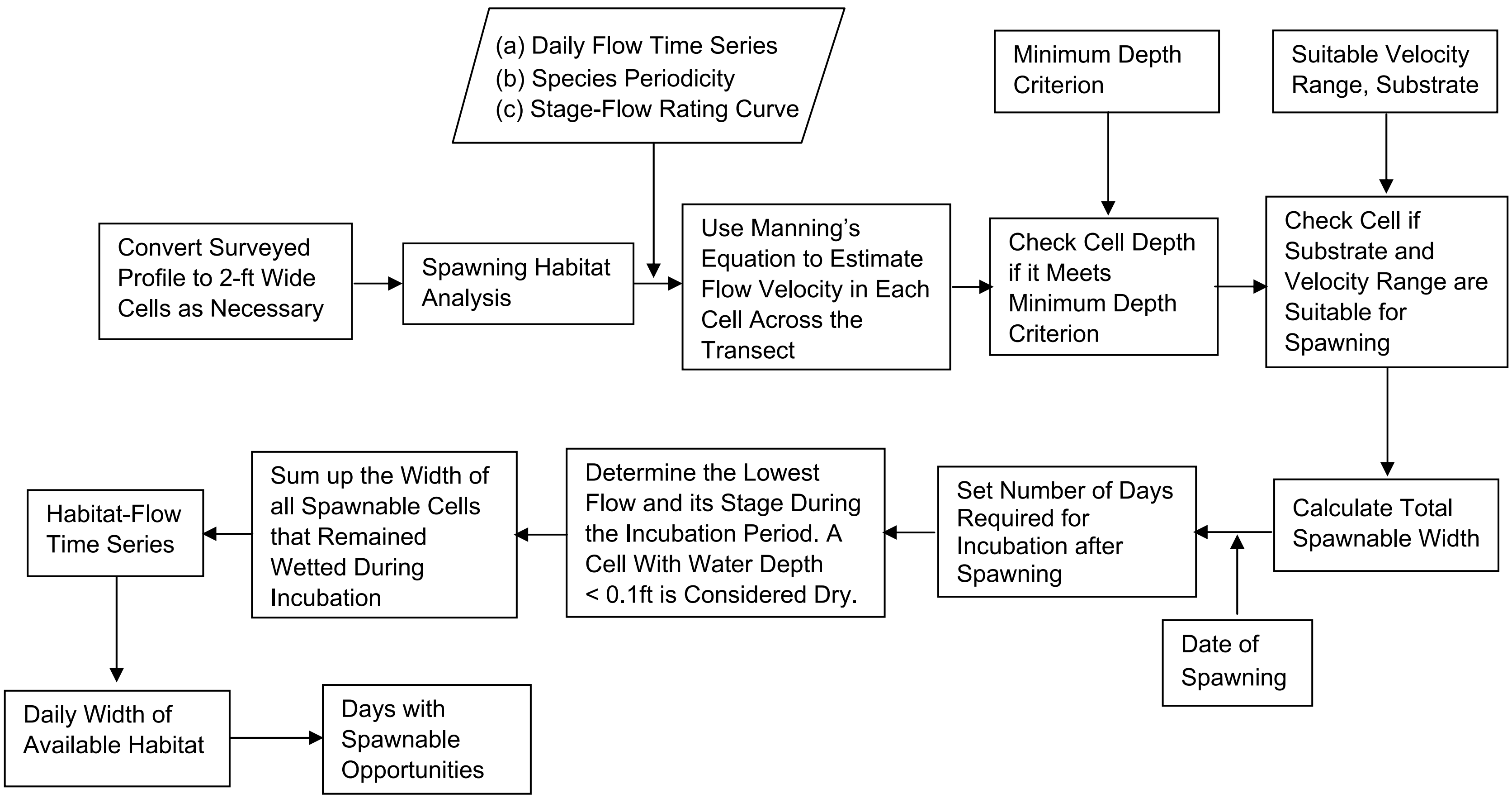

Figure G.3 Flow Chart for Spawning Habitat Analysis.

- Impaired daily times series of flows were calculated for Flow Alternative Scenarios 1 to 5 (described in Table 4-2) by withdrawing the maximum diversions allowed by the selected set of Policy element alternatives as described in Appendix F
- Cross-section data were collected to estimate hydraulic conditions at 1 to 2 passage locations and spawning habitats in each stream over a range of flows.
- The resulting estimated hydraulic conditions were compared with passage and spawning habitat suitability criteria derived from an extensive review of the literature to generate a set of simplified habitat-flow curves.
- The habitat-flow relations were then used to generate daily habitat time series for passage and spawning for the daily time series of flows for the estimated unimpaired condition and the five Flow Alternative Scenarios over the period of record. Habitat time series are useful for evaluating effective habitat availability over time frames important to various species and life stages (Bovee 1982).
- Passage and spawning/incubation timing were considered in the time series analysis, and the frequency with which each type of habitat was available was assessed directly for all years for which data were available.
- The resulting habitat time series were then compared between Flow Alternative Scenarios and against unimpaired flow conditions. The primary metric for assessing effects to passage and spawning habitat was the number of days that opportunities were available, in each water year. Protectiveness was judged based on relative differences in the average number of days per water year compared with unimpaired flow conditions. Differences were expressed in terms of number of days, and percent change from the number of days available under unimpaired flow conditions.

The resulting habitat time series were then compared between alternatives and against unimpaired flow conditions. The primary metric for assessing effects to passage and spawning habitat was the number of days that opportunities were afforded for each, in each water year. Protectiveness was judged based on relative differences in the average number of days/year compared with unimpaired flow conditions. Differences were expressed in terms of number of days, and percent change from the number of days available under unimpaired flow conditions.

The following sections describe specific components of the hydraulic and habitat analyses. Details on the hydrologic analyses are given in Appendix F.

G.1 FIELD DATA COLLECTION

Up to two passage and two spawning transects were measured in each site, with the number of transects depending on habitat availability within the reach sampled. Passage transects were placed at locations in each validation site that would require more flow than elsewhere in a reach to meet passage depth criteria; transects were typically placed over wide, shallow riffles or in a few cases where a limiting critical depth occurred in the hydraulic sense (e.g., Chow 1959). Spawning transects were located upstream of riffle crests in pool or run tails. These locations are typically used by steelhead and coho in small to mid-size streams (Shapovalov and Taft 1954). Spawning transects placed near riffle crests were generally located downstream of deeper cross-sections that provided spawning habitat. The sampled locations were selected to have a lower probability of egg pocket scour near the thalweg than deeper locations nearer the pool edge, based on potential for sediment transport rate imbalances that are the cause of deep scour (DeVries 2000). Alternatively, spawning transects were placed in riffle or run habitats depending on predominant spawning habitat characteristics. Pocket gravels behind boulders were avoided because they could not be easily modeled, and flows rendering such habitats suitable are less related to channel size.

The data collected included:

- Cross-section bed profiles and depth/velocity distributions, surveyed approximately every 2 ft, provided there was no major change in bathymetry or substrate type, (2 ft approximates the width of small steelhead and coho redds, and is roughly half the width of an average steelhead redd; Shapovalov and Taft 1954; 2 ft also affords a minimum passage lane);
- Visual assessment of substrate suitability for spawning across the channel based on dominant grain size (i.e., gravel of a broad size range suitable for spawning by both steelhead and coho);
- Grain size distribution characteristics across the transect based on pebble counts, or characterized visually when patches of spawning gravel were interspersed (for use in estimating the effects of relative roughness on predicted stage-discharge relations); and
- Longitudinal slope.

The data were collected in streams near current or historic gage locations within the Policy area, for which available flow records represented relatively unimpaired conditions, or for which unimpaired conditions could be reasonably estimated. Given that the DFG-NMFS (2002) Draft Guidelines were based on the results of existing habitat-flow studies in streams with drainage areas greater than about 15 mi^2, sampling efforts for this assessment focused primarily on smaller (less than 15 mi^2) stream channels. Analyses conducted by MTTU (2000) indicated that this range of channel sizes may exhibit the greatest variation in the ratio of instream flows to mean annual flow and other hydrologic flow frequency metrics. The validation sites and numbers of transects are presented in Table G-1; validation site locations are depicted in Figure G-4.

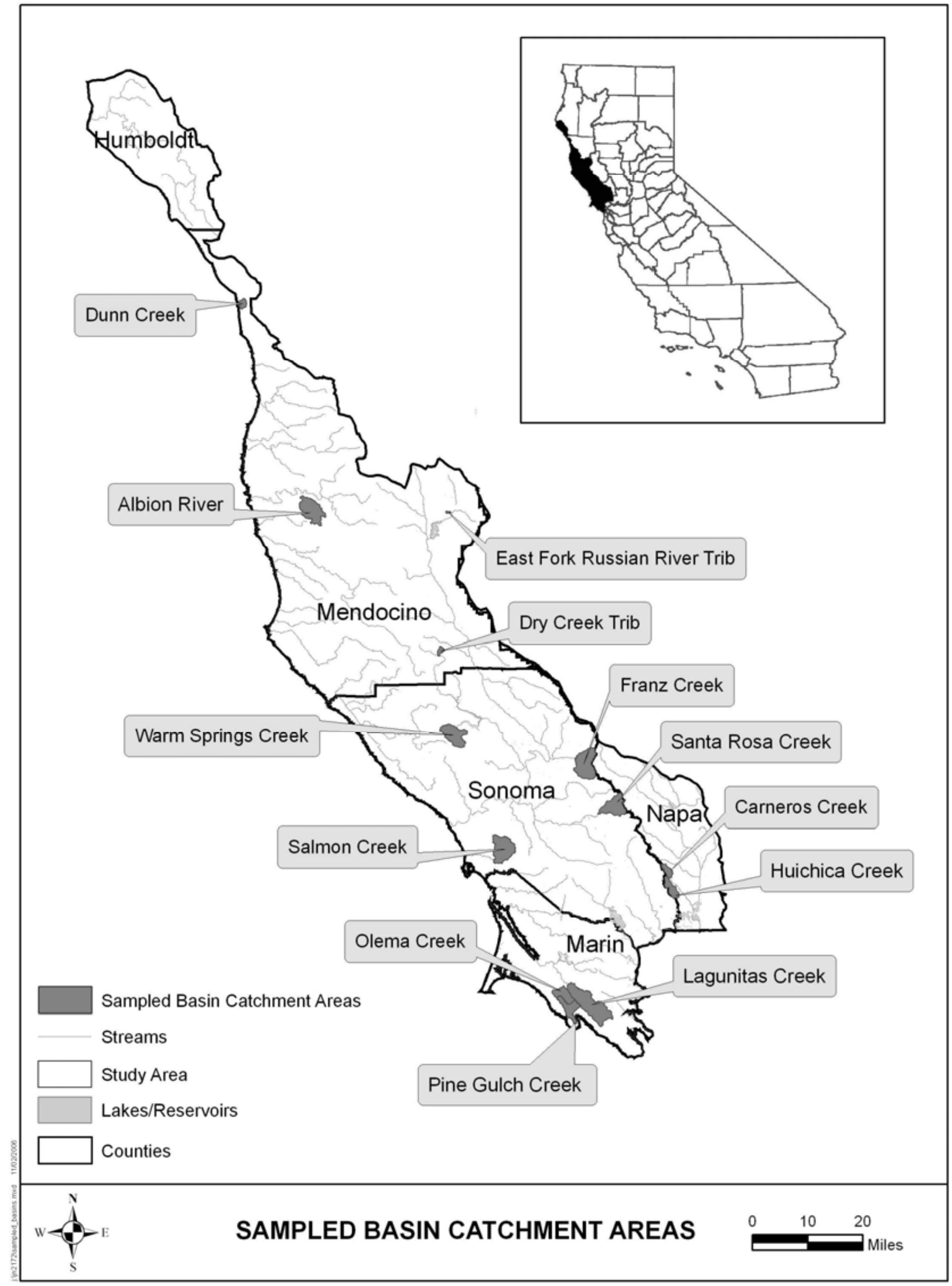

Figure G-4. Locations of validation sites sampled for passage and spawning transects that were evaluated for protectiveness of Policy element alternatives involving restrictions on flow.

Table G-1. Validation Sites Where Transects were Surveyed to Characterize Passage and Spawning Conditions Associated with Policy Elements Alternatives Regarding Restrictions on Flow.

Stream	Date Visited	Drainage Area (mi2)	Reach Slope (%)	Number of Transects		Water Years Analyzed
				Passage	Spawning	
Lagunitas Creek	8/28/2006	34.3	0.53	2	2	1956-1992
Olema Creek	8/28/2006	6.47	0.91	2	2	1987-2003
Pine Gulch Creek	8/28/2006	7.83	1.14	2	2	1999-2003
Huichica Creek	8/29/2006	4.92	0.79	1	1	2002-2005
Carneros Creek	8/29/2006	2.75	1.10	2	2	2002-2005
Salmon Creek	8/30/2006	15.7	0.69	2	2	1963-1975
Warm Springs Creek	8/30/2006	12.2	0.71	2	2	1974-1983
Dry Creek Trib	8/30/2006	1.19	2.04	1	1	1968-1969
Dunn Creek	8/31/2006	1.88	1.58	2	2	1962-1964
Albion River	8/31/2006	14.4	1.01	2	2	1962-1969
E. Fk. Russian River Trib	8/31/2006	0.25	2.50	1	0	1959-1961
Franz Creek	9/1/2006	15.7	0.29	2	2	1964-1968
Santa Rosa Creek	9/1/2006	12.5	1.37	1	2	1960-1970

G.2 HYDRAULIC ANALYSES

The transect cross-section stationing and bed elevation data were first reduced to a profile of uniformly spaced, 2 ft wide cells to approximate the minimum width of steelhead and coho redds and minimum passage lane width. This uniform discretization was applied primarily to model suitable width of habitat in increments corresponding to individual redds. This avoided predicting habitat being available at flows lower than those needed to support a redd. The resulting habitat-flow curves provided an order of magnitude characterization of habitat availability that could be directly converted to number of redds. In most cases, the survey data had been collected at 2 ft increments over spawning habitat, but smaller scale cross-channel variation in elevation and substrate suitability for spawning required finer resolution surveying in some cases. Figure G-5 depicts an example of how finer scale survey data were converted to 2-ft wide cells for subsequent use in hydraulic and habitat analysis.

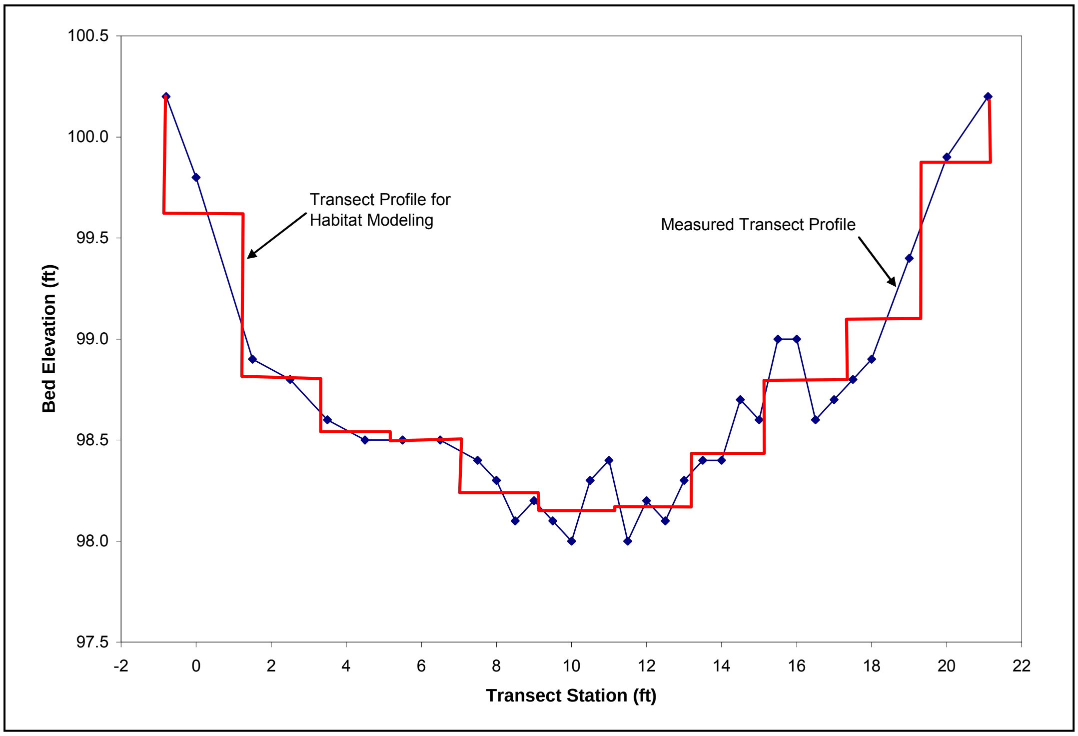

Figure G.5. Example of conversion of measured transect profile to 2-ft wide cells for subsequent hydraulic and habitat modeling.

Stage-flow rating curves were then developed for each cross-section. This required consideration of channel roughness. The average channel Manning's n coefficient magnitude was estimated using values recommended in Chow (1959) and reported in Barnes (1967). Photos taken during data collection were used to assist in deriving n values using these two references. The resulting n-value was then adjusted using the procedure developed by Cowan (1956) to take into account other channel characteristics not considered in the initial n-value. The final n-value was accordingly computed using:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5 \qquad \text{(G.1)}$$

where n_o was the primary roughness value derived initially, and n_1, n_2, n_3, n_4, m_5, were the correction factors to account for surface irregularities, shape of transect profiles, channel obstruction, presence of vegetation, and channel meandering, respectively.

At lower flows, Manning's n values will generally be larger due to greater relative roughness, where the size of roughness elements comprising the streambed become proportionally larger relative to the flow depth. Flow resistance was estimated for lower flow conditions using the relative roughness equation developed by Limerinos (1970):

$$n = \frac{0.0926R^{1/6}}{1.16 + 2.0\log(\frac{R}{D_{84}})} \qquad \text{(G.2)}$$

where R is the hydraulic radius and D_{84} is the particle size for which 84% of particles are smaller. The D_{84} was estimated from pebble counts when collected, or as a multiple of a visual estimate of D_{50} when a pebble count was not collected. The multiplier value was estimated to be 1.6 based on the pebble count data collected at the other sites. Table G-2 lists the estimated values of D_{50} and D_{84}.

To estimate the flow below which relative roughness would be predicted to increase most significantly, the n values calculated for a range of flows using Equation (G.2) were compared with the n-value computed using Equation (G.1). For flows above that resulting in comparable n-value, the Manning's n coefficient used to estimate stage was set equal to the constant Equation (G.1) value. For lower flows, Equation (g.2) was applied. For example: Franz Creek had an estimated D_{84} =1.4 inches and n value of 0.037 determined using photos and Equation (G.1). Inserting n = 0.037 into Equation (G.2) gave a value of R = 0.35 ft, which corresponded to the estimated hydraulic radius for 15.6 cfs. For flows below 15.6 cfs, the n coefficients were estimated using Equation (G.2), while the n coefficient was held constant at n = 0.037 for higher flows.

Stage-flow rating curves were then derived using Manning's equation applied to the adjusted cross-section geometry and surveyed slope:

$$Q = \frac{1.486}{n} R^{2/3} S^{1/2} A \qquad \text{(G.3)}$$

Where A = cross-sectional area. Velocity was estimated for each 2-ft wide cell to model the suitability of spawning habitat at each flow. In the absence of usable field velocity measurements because of low flows during the time of sampling, Manning's equation was used to also estimate the velocity for each cell. Velocity v_i in each cell *i* was calculated as:

$$v_i = \frac{1.486}{n} d_i^{2/3} S^{1/2} \qquad \text{(G.4)}$$

where d_i is cell water depth (ft), S is the channel slope assumed constant for all flow conditions. The total flow Q_C was calculated as:

$$Q_C = \sum_{i=1}^{i=p} v_i a_i \qquad \text{(G.5)}$$

where p is the total number of wetted 2-ft cells in the transect, and a_i is the cell flow area (equal to $2d_i$ ft^2). Because the resulting value of Q_C calculated using Equation (G.5) was generally not equal to the actual daily value of flow Q, adjustment to the velocity v_i was needed to meet the continuity condition. The adjustment was accordingly made using the ratio $\alpha = Q/Q_C$, where the adjusted velocity in each cell was:

$$v_{i,\alpha} = \alpha v_i \qquad \text{(G.6)}$$

The adjusted velocity $v_{i,\alpha}$ was then compared with habitat suitability criteria in the spawning habitat analysis.

Table G-2. Values of Substrate Grain Size Distribution Percentiles Used in the Modeling of Channel Roughness

Stream	D_{50} (inches)	D_{84} (inches)
Lagunitas Creek	1.6	2.6
Olema Creek	1.8	2.7
Pine Gulch Creek	0.8	1.2
Huichica Creek	1.2	1.9
Carneros Creek	0.5	0.8
Salmon Creek	1.1	1.6
Warm Springs Creek	0.8	1.4
Dry Creek	1.2	1.9
Dunn Creek	0.8	1.4
Albion River	0.8	1.2
E.F. Russian River Trib	2.4	3.5
Franz Creek	0.7	1.4
Santa Rosa Creek	0.7	1.1

G.3 PASSAGE AND SPAWNING HABITAT ANALYSIS

Habitat analyses were performed for upstream passage and spawning in two stages. First, habitat-flow curves were generated by comparing hydraulic characteristics at a given flow calculated for each 2-ft wide transect cell, with binary habitat suitability criteria specific to the species (steelhead, coho, and Chinook) and habitat attribute (passage and spawning). Usability was defined as an either/or condition, where a cell was either usable if its hydraulic characteristic(s) met suitability criteria, or unusable otherwise. The total width of usable habitat per transect was computed by summing all usable 2-ft wide cells. This was performed for a range of flows to generate habitat-flow relationships for each transect and habitat attribute. Habitat usability was defined for upstream passage using suitability criteria for depth alone. Habitat usability was defined for spawning using suitability criteria for depth and velocity, with suitability of the cell's substrate for spawning determined in the field. The resulting habitat-flow relationships are plotted for both upstream passage and spawning in Appendix H.

The habitat-flow relationships were then used to calculate a daily habitat time series for each of the six daily flow time series considered (i.e., unimpaired flow and five impaired Flow Alternative Scenarios). Periodicity information presented in Appendix B was used to identify the dates between which upstream passage and spawning could occur, for each of the three anadromous salmonid species. Methods differed slightly for upstream passage and spawning analyses (Figures G-2, G-3):

- For passage, a cell was considered usable on a given day when the depth for the flow occurring that day equaled or exceeded the minimum passage depth suitability criterion. The lowest flow resulting in the first usable cell on either transect equaled the minimum flow needed for upstream passage.

- For spawning, a cell with suitable spawning substrates was considered usable for spawning when the depth for the flow occurring that day equaled or exceeded the minimum spawning depth suitability criterion, and the velocity was between lower and upper suitability criteria. Spawning was considered successful if a cell was found to be wetted by a minimum depth criterion over the estimated duration of incubation. Only those cells that remained sufficiently wetted over the estimated incubation period were considered usable for spawning.

The number of days for which passage and spawning opportunities existed during the period each species could migrate and spawn was then summed over each water year. Protectiveness was assessed in terms of differences in the number of days/water year that habitat opportunities existed for each impaired Flow Alternative Scenario, compared with unimpaired flow conditions.

Details are provided on the development of suitability criteria, incubation duration estimation, and general analysis steps for upstream passage and spawning habitat in the following, respective sub-sections.

G.3.1 Development and Analysis of Upstream Passage Habitat Suitability Criteria

Successful passage of adult anadromous salmonids to upstream spawning grounds is critical to the perpetuation of the species. Physical barriers such as waterfalls, log jams, or dams are the most common types of upstream passage barriers. Water quality can sometimes lead to the blocking of adult salmonid migrations, in the form of temperature or chemical barriers. Water quantity also affects upstream passage success, at either low or high flows. Upstream passage barriers are generally location-specific, where analysis requires detailed knowledge of the barrier characteristics at specific flows.

There are generally two ways in which flow can lead to passage restrictions. At low flows, the stream becomes too shallow for successful navigation upstream, preventing passage because of excessive fish body size. At high flows, the velocities may become so severe that the fish encounters an energetic barrier. In the latter case, the migrating fish is usually able to swim upstream along the edge of the channel where the water is slower than in the middle of the channel, at any flow no matter how high. The only time velocity becomes an effective barrier is when the entire flow of the channel becomes concentrated into a fast chute, the length and speed of which combine to overcome the fish's swimming ability, and the structure of the barrier precludes the fish's ability to leap over it. Since minimum flows are the focus of water rights considerations, potential passage barriers due to high flow are not relevant here. The issue for the Policy area is mainly related to addressing to what extent depth can become a significant barrier or impediment to passage in streams with altered flows (McEwan and Jackson 1996).

Low flow barriers are less location-specific than velocity barriers, and can occur at many places throughout the stream. The main criterion for successful upstream passage at low flows is depth. Many minimum-depth criteria can be found in the literature for salmonids, varying with species and investigation. The majority of studies have focused on the design of fish ladders, culverts, spawning channels, and other man-made structures, emphasizing not only the conditions within the structure, but also at the entrance and exit (e.g., Chambers et al. 1955; Thompson 1970; Slatick 1975; Evans and Johnston 1980; Bell 1991). Fewer studies have evaluated fish passage conditions in natural channels (e.g., Mosley 1982; Thompson 1972).

G.3.1.1 Compilation of Upstream Passage Suitability Criteria

Various investigators have suggested different methods and criteria for minimum passage depth (Table G-3). The method of Thompson (1972) has been widely applied in flow - passage assessments; the method involves minimum depth criteria for adult trout and salmon coupled with an appropriate lane width for passage. Thompson (1972) established a curved transect that followed the shallowest contour across a stream channel. For each transect, the flow is selected which meets minimum depth and maximum velocity criteria on at least 25 percent of the total transect width and a continuous portion equaling at least 10 percent of its total width. The result averaged from all transects is the minimum flow recommended for passage. Mosley

(1982) noted that Thompson's (1972) criteria were based on fish body size considerations rather than on controlled observations of fish behavior, and could be considered conservative. Mosley (1982) further noted that salmonids have been regularly observed to move upstream in water "very much" shallower than the criteria over distances of "some" meters. However, Mosley (1982) also pointed out that the effects of movement in water shallower than the criteria could be associated with abrasion and loss of spawning condition, and that the number and extent of shallow water passages needed to cause an effect were unknown. Bell (1991) recommended a narrower minimum passage width of 1 ft for large bodied salmon in the design of fishways. In the design of culverts, he recommended a minimum passage depth equal to the body size of the largest adult salmonid expected. The distance fish must travel through shallow water areas is also a critical factor (Barnhart 1986). Lang et al. (2004) determined the limiting depth to be the shallowest point over a riffle following the thalweg in the stream wise direction. Snider (1985) used a similar approach in Brush Creek and observed that a limiting passage corridor depth of 0.45 ft extending 40 ft long in a critical passage riffle was associated with steelhead downstream but not upstream, from which blockage could be inferred.

Table G-3. Summary of Relevant Upstream Passage Depth Criteria for Adult Salmon and Steelhead.

Author(s)	Depth (ft)	Comments
Thompson (1970)	1.0-1.25	Weir design, salmon and steelhead
Thompson (1972)	0.6	Coho, steelhead
	0.8	Chinook
Evans and Johnston (1980)	1.0	Culvert design minimum for salmon
Powers and Orsborn (1985)	0.4	Minimum chute depth for coho, will not pass all fish
	0.75	Dane's (1978) culvert design minimum for salmon
	1.0	Weir design for salmon, various references
Snider (1985)	0.45	Observed to block steelhead passage in Brush Creek
Bell (1991)	0.5	Minimum depth over weir; design value for salmon
	0.53	Minimum culvert passage depth for steelhead, using assumed maximum body height for steelhead (see text; 1.0 ft recommended for salmon in 1986 edition)
MTTU (2000)	0.8	Minimum safe passage depth based on adult salmonid body height of 0.6 ft plus one inch clearance off bottom
DFG (2002)	0.33	Minimum passage depth for coho
	0.6	DFG preferred passage depth for coho

Two principles are important with respect to selecting minimum passage depth criteria. First, Powers and Orsborn (1985) emphasized that flow depth needed to be greater than body depth in passage designs for the fish to make full use of its propulsive power. Orsborn and Powers (1985) noted the general length to height ratio equaled 5 for fish. For older steelhead that reached a mean length of approximately 32 inches in Waddell Creek (Shapovalov and Taft 1954), this equates to a design body height of 0.53 ft. Younger fish with a length averaging around 22 inches would have a design body height of approximately 0.36 ft.

Second, Evans and Johnston (1980) emphasized that fish passage structures must be designed for the successful passage of all fish, not just the most fit. The ability of the fish to overcome barriers decreases over time and distance (Paulik 1959; Powers and Orsborn 1985). In addition, specific passage locations may require subsequent recovery time before the fish is sufficiently fit to continue upstream. For example, Paulik and DeLacy (1957) determined it may take 6 hours for a steelhead to recover from an exhaustive swimming effort. Effects of strenuous muscular exertion and delay on upstream migrant salmon are detrimental to survival and these effects may have a cumulative and delayed action (Paulik 1959). Lang et al. (2004) noted that the condition of salmon and steelhead can deteriorate substantially prior to spawning in coastal California streams, when the fish are forced to spend time holding until the next freshet. Accordingly, they recommended that passage criteria for culverts should reflect weaker swimming adult fish irrespective of the distance to the ocean.

G.3.1.2 Identification of Passage Depth Criteria for Use in the Protectiveness Analysis

The ideas above lead to the conclusion that an upstream passage design criterion should not be set at the absolute minimum depth at which only a percentage of the fish can move upstream. Rather, the ideal criterion should enable passage of all possible sizes of individual fish. In addition, under ideal conditions of suitability for passage, there should be sufficient clearance underneath the fish so that contact with the streambed and abrasion are minimized, assumed here to be approximately 0.1 ft. However, in applying passage depth criteria, it must be recognized that the occurrence of critical depth at riffle crests can limit the depths available for passage under unimpaired flow conditions, where fish are naturally forced to pass through sections shallower than desired based on conservative design criteria. In such cases, application of a minimum passable criterion can be used to evaluate the threshold for passage.

Given the above considerations and the criteria listed in Table G-3, threshold upstream passage depth criteria were identified for evaluating the protectiveness of alternative elements proposed for application under the Policy (Table G-4).

Table G-4. Minimum Upstream Passage Depth Criteria for Analyzing the Protectiveness of the Policy for Upstream Passage Needs.

Species	Minimum Passage Depth Criterion (ft)
Steelhead	0.7
Coho	0.6
Chinook	0.9

G.3.1.3 Times of Year When Upstream Passage Was Analyzed

Upstream passage conditions were evaluated for the following periods for each species, reflecting the intersection of periodicity information presented in Appendix C and the range of start and end dates proposed as Policy element alternatives for the winter diversion season[8]:

Steelhead: 11/1 – 3/31 (reflects most streams except mainstem Russian River)
Coho: 10/1 – 2/28 (reflects observations in Brush Creek)
Chinook: 10/1 – 1/31 (reflects proposed alternative start to diversion season)

The effects of Policy diversion season alternatives were evaluated as they intersected the above periods (results are presented in Chapter 4 and Appendices I and J). For example, passage conditions prior to December 15 were not different between unimpaired flow conditions and flow conditions resulting from implementation of the diversion season proposed in the DFG-NMFS (2002) Draft Guidelines, December 15 to March 31 (DS1) because flows during that period would not be impaired (i.e., there would be no new diversions permitted before December 15 under the DFG-NMFS Draft Guidelines).

G.3.2 Development and Analysis of Spawning and Incubation Habitat Criteria

Spawning habitat conditions were evaluated in terms of the availability of spawning habitat and whether potential redd sites remained inundated through emergence. Thus, the analysis required identifying criteria for suitable spawning habitat, and understanding and setting reasonable time periods that would encompass the duration of the spawning act (i.e., length of time a pair of adult salmonids require to complete spawning – from redd construction to egg deposition and redd covering), and the length of the incubation period (i.e., from time of egg deposition to fry emergence), as described below.

In this analysis, spawning habitat suitability was defined by combinations of depth, velocity, and substrate characteristics. Thus, if a section of streambed met certain spawning criteria (see

[8] The year-round diversion season alternative (DS2) proposed by MTTU (2000) is not protective of summer rearing habitat. Passage and spawning habitat was assessed over the full period of the remaining diversion season alternatives, from October 1 to March 31.

below), it was considered suitable for spawning, independent of its suitability for incubation. There are two ways of representing the suitability of each of these parameters for spawning. The first is to consider habitat suitability of a parameter as a continuous range of probability-of-use values between 0 and 1 (i.e., continuous habitat suitability index, or HSI curves; e.g., Bovee 1978; Snider 1985; Smith 1986; Sanford and Seppeler 1990). The second is to consider spawning habitat in a binary context where habitats are either useable or not (i.e., a threshold suitability index equal to 0 or 1 only; e.g., OSGC 1963; Rantz 1964; Thompson 1972; Collings et al. 1972b). For this analysis, the second approach was used to allow a first order evaluation of the effects of flows on spawning habitat suitability.

G.3.2.1 Compilation of Spawning Habitat Suitability Criteria

A variety of literature sources were compiled and reviewed to identify candidate suitability threshold criteria (Tables G-5, G-6). In addition, Smith (1986) applied Bovee's (1978) continuous depth and velocity HSI curves to an instream flow study in Lagunitas Creek; the curves reported by Smith (1986) were converted to threshold criteria for comparison. HSI curves are typically multiplied to generate a composite suitability index, assuming each parameter is selected independently by spawning salmonids. A composite depth-velocity suitability index equal to 0.5 was used as a cut-off point to generate a binomial condition, where composite values exceeding 0.5 (or, 50%) were assumed to be generally suitable, and lower values unsuitable. Accordingly, a depth or velocity magnitude was considered suitable if its HSI value exceeded 0.7 (i.e., a 0.7 HSI for depth times a 0.7 HSI for velocity results in a composite, or joint suitability of 0.49 ≈ 0.5).

In selecting threshold depth and velocity criteria, a variety of representations may be applied (Tables G-5, G-6). Where a range of depths or velocities have been reported to be used, the lower value of the range could be considered as the minimum acceptable or preferred. However, the actual value applied depends in part on the purpose for which the data will be used, and part on judgment. For example, even though Bell (1991) noted salmon generally spawn at a minimum depth of 0.75 ft, he recommended 1.5 ft for spawning channel design. Velocity was recommended to be less than sustained swimming speed, between 1.5-3.0 ft/s. DFG (2002) noted that coho salmon spawn mostly in small streams where flow is 2.9-3.4 cfs, and depths and velocities range between about 0.33-1.2 ft and 1 ft/s to 1.8 ft/s, respectively. Rather than selecting the lowest value of the depth range, DFG specified a minimum preferred depth of 0.6 ft (Table G-5). MTTU (2000) estimated steelhead and Chinook body heights as 0.6 ft and 0.8 ft, respectively. They evaluated minimum depth criteria at the deepest area in spawning habitat, and established a minimum depth criterion equal to 0.8 ft for adult salmonids based on body dimension and clearance above the streambed. OSGC (1963) developed threshold criteria based on data collected at numerous redds.

Table G-5. Summary of Minimum Depth Criteria Reported for Salmon and Steelhead Spawning.

Author(s)	Depth (ft)	Comments
		Steelhead
OSGC (1963)	0.6	Minimum depth
Thompson (1972)	0.6	Minimum depth
Swift (1976)	0.7	Preferred minimum depth
Smith (1986)	0.9	Lagunitas Creek HSI >0.70
Bratovich and Kelley (1988)	≥0.6	Spawning depths in Lagunitas Creek
Keeley and Slaney (1996)	0.85	Range minimum
	1.3	Mean value of range
Moyle (2002)	0.33	Minimum depth
SEC et al. (2004)	0.6	Preferred minimum depth
		Coho
OSGC (1963)	0.6	Minimum depth
Collings et al. (1972b)	1.0	Preferred minimum depth
Thompson (1972)	0.6	Minimum depth
Swift (1979)	0.5	Preferred minimum depth
Smith (1986)	0.43	Lagunitas Creek HSI >0.70
Bratovich and Kelley (1988)	≥0.5	Spawning depths in Lagunitas Creek
Keeley and Slaney (1996)	0.5	Range minimum
	0.8	Mean value of range
DFG (2002)	0.33	Range minimum in streams with flow 2.9-3.4 cfs
	0.6	Specified minimum depth
SEC et al. (2004)	0.6	Preferred minimum depth
		Chinook
OSGC (1963)	0.8	Minimum depth
Rantz (1964)	0.83	Favorable minimum depth
Collings et al. (1972b)	1.0	Fall Chinook preferred minimum depth
Thompson (1972)	0.8	Minimum depth
Swift (1979)	1.0	Preferred minimum depth
Keeley and Slaney (1996)	0.85	Range minimum
	1.3	Mean value of range
Moyle (2002)	0.8	Minimum typical depth

Table G-6. Summary of General Velocity Ranges Reported for Salmon and Steelhead Spawning.

Author(s)	Velocity (ft/s)	Comments
		Steelhead
OSGC (1963)	1.0-2.5	Proper range
Thompson (1972)	1.0-3.0	Suitable range
Swift (1976)	1.2-3.3	Preferred Range
Smith (1986)	1.4-2.6	Lagunitas Creek HSI >0.70
Bratovich and Kelley (1988)	0.7-2.0	Velocity range used in Lagunitas Creek
Keeley and Slaney (1996)	1.3 (0.9-2.3)	Mean value of range (range)
Moyle (2002)	0.65-5	Typical range
SEC et al. (2004)	2.0-3.8	Preferred range
		Coho
OSGC (1963)	1.0-2.5	Proper range
Collings et al. (1972b)	1.2-1.8	Preferred velocity range measured 0.4 ft above streambed
Thompson (1972)	1.0-3.0	Suitable range
Swift (1979)	0.25-2.5	Preferred Range
Smith (1986)	0.9-1.8	Lagunitas Creek HSI >0.70
Bratovich and Kelley (1988)	0.7-2.6	Velocity range used in Lagunitas Creek
Keeley and Slaney (1996)	0.8 (0.5-1.0)	Mean value of range (range)
DFG (2002)	1.0-1.8	Range in streams with flow 2.9-3.4 cfs
	1-3	Range used
SEC et al. (2004)		Preferred minimum depth
		Chinook
OSGC (1963)	1.0-2.5	Proper range
Rantz (1964)	1-3	Favorable range measured 0.3 ft above streambed
Collings et al. (1972b)	1.0-2.25	Fall Chinook preferred velocity range measured 0.4 ft above streambed
Thompson (1972)	1.0-3.0	Suitable range
Swift (1979)	1.0-3.0	Preferred Range
Keeley and Slaney (1996)	1.3 (0.9-2.8)	Mean value of range (range)
Moyle (2002)	1.0-2.6	Most spawning

G.3.2.2 Identification of Spawning Criteria for Use in the Protectiveness Analysis

The selection of depth and velocity criteria to be used in the spawning analysis was based on a review of similar criteria derived from a variety of investigators (Table G-5 and Table G-6). The review resulted in the selection of criteria presented in Table G-7. In general, the selected minimum depth criteria were about 0.2 ft greater than minimum reported values, and hence can be considered conservatively protective with respect to providing suitable depths for spawning. For velocity, the criteria proposed by Thompson (1972) typically exceed the range of values reported by other investigators for favorable or proper conditions. The Thompson (1972) criteria should therefore be conservatively protective of spawning habitats and were selected for analysis. The criteria were narrowed slightly for coho, reflecting their slightly smaller body size compared with steelhead and Chinook.

Potential spawning substrates were visually defined in the field as patches where the dominant substrate was judged to fall within the general range of D_{50} values used by steelhead and coho (Kondolf and Wolman 1993)(approximately 10-45 mm; Table G-7).

Table G-7. Minimum Depth, Favorable Velocity, and Substrate Spawning Criteria for Analyzing the Protectiveness of the Policy for Spawning Habitat Needs.

Species	Minimum Depth (ft)	Favorable Velocities (ft/s)	Useable Substrate D_{50} (mm)
Steelhead	0.8	1.0-3.0	12-46
Coho	0.8	1.0-2.6	5.4-35
Chinook	1.0	1.0-3.0	11-78

G.3.2.3 Identification of Incubation Habitat Depth Requirement

Successful incubation requires sufficient, continuous inundation by water to ensure delivery of oxygen, removal of metabolic wastes, and prevention of excessive warming or freezing (Bjornn and Reiser 1991). Steelhead and Chinook embryos can withstand periodic dewatering for a number of weeks following fertilization, provided the eggs remain moist and water temperatures are within acceptable limits for incubation (Reiser and White 1983). However, both egg growth and the size of alevins can be reduced when eggs are exposed to prolonged periods of dewatering (Becker et al. 1982; Reiser and White 1981). Embryos that are exposed for various periods of time may also prematurely hatch and emerge in response to elevated temperatures and accelerated development, resulting in increased mortality (Becker et al. 1982). Becker et al. (1982, 1983) noted that the egg phases were considerably more tolerant of temporary dewatering than the alevin phase, which has fully functioning gills. For example, advanced alevins are unable to withstand even one hour of repeated dewatering (Becker et al. 1982), and less than 6 hours of a one-time dewatering (Becker et al. 1983).

Egg burial depths for steelhead, coho, and Chinook generally exceed 0.5 ft (15 cm; DeVries 1997). In principle, a redd could withstand short term dewatering to this depth below the surface. However, intragravel velocities are likely to decrease, and gravel temperatures either increase or decrease depending on air temperature. Hence, to be protective of incubating eggs, the stream level should remain at or above the redd surface elevation for the duration of incubation. In addition, a minimal water depth is necessary so that alevins can emerge and move into the channel successfully. For this analysis, the minimum depth for incubation was assumed to be approximately 0.1 ft above the bed surface.

G.3.2.4 Redd Construction and Incubation Duration

It was assumed that for anadromous salmonid reproduction to be successful, water must be available throughout the duration of the spawning act and the period of incubation. An evaluation of the protectiveness of the Policy was completed by computing the amount of spawning habitat that remains continuously wetted over the combined redd construction and incubation period.

i. Duration of Redd Construction

Shapovalov and Taft (1954) noted that individual steelhead can take as little as approximately 12 hours or in some cases, more than a week to complete redd construction activities. Bratovich and Kelley (1988) noted that steelhead appeared to spawn quickly and left the redd soon after spawning. Trush (1991) observed redds completed within a 30 hour period, and considered 3 days as a conservative estimate of spawning duration in the small streams he surveyed. He noted that steelhead would ascend the channel, spawn, and emigrate back downstream all within the time frame of a single storm hydrograph. Gallagher (2000) estimated average stream residency of steelhead in the Noyo River, including pre- and post-spawning, to be 11 days. Shapovalov and Taft (1954) and Moyle (2002) both reported that coho can take a week or more to complete their spawning. Sandercock (1991) reported coho redd construction may take up to five days. Wydoski and Whitney reported that the average length of time spent on the spawning grounds by ripe coho is about 11 days for females and 12 to 15 days for males. Cook (2003) noted that Russian River Chinook begin spawning within a few days or weeks of arriving at the spawning ground. Healey (1991) noted that individual Chinook females spend at least 4 days defending a redd after spawning begins.

ii. Incubation

Water temperature controls the length of the incubation period, with the duration decreasing with increasing temperature. There are also inherent differences in the length of egg incubation between species, that likely reflect adaptations to their general life history periodicity and thermal environment over the incubation period (Quinn 2005). The literature indicates that incubation time for the same constant water temperature increases from steelhead to coho to Chinook (Figure G-6). Steelhead spawn in the spring and thus, must emerge before water temperatures reach summer levels. Coho spawn later and in smaller streams than Chinook, and both emerge earlier in the year than steelhead.

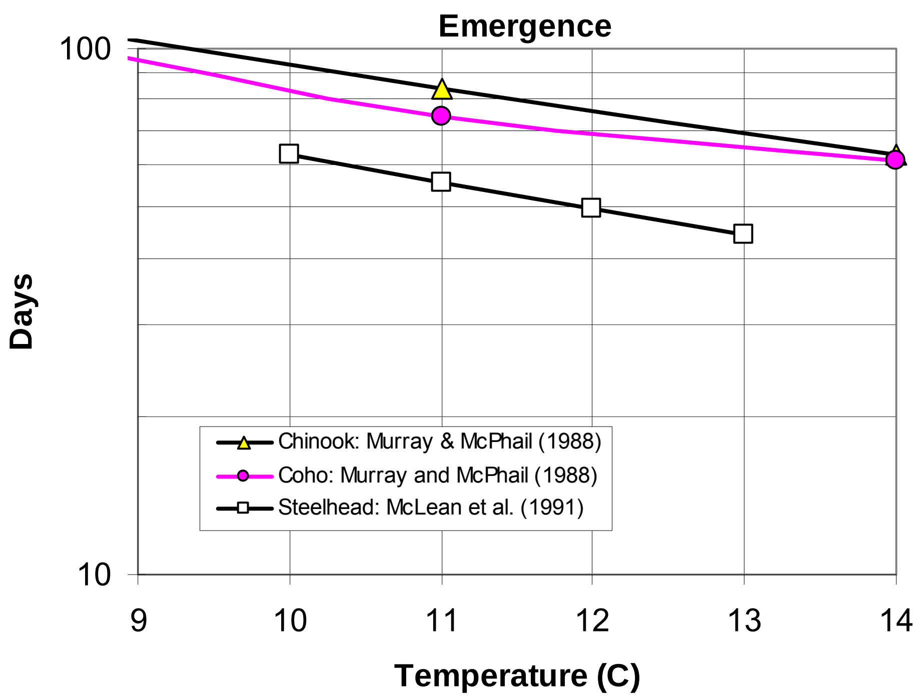

Figure G-6. Comparison of times from fertilization to emergence of steelhead, coho, and Chinook as a function of water temperatures commonly occurring in the Policy area during the winter and early spring.

Steelhead: Developing steelhead alevins may reside in the gravel for many weeks after hatching before emerging. For example, Leitritz and Lewis (1980) noted that the time to hatch for steelhead in California was about 30 days at 10.6ºC; Shapovalov (1937) noted that steelhead emergence from experimental gravel occurred between 49-64 days after fertilization at a temperature around 10.6ºC. Shapovalov and Taft (1954) noted the time to hatch in Waddell Creek was usually between 25-35 days, with emergence occurring 2-6 weeks post-hatch. The pre- and post-hatch stages differ in sensitivity to temporary dewatering as indicated above, where dewatering events occurring later in the development process are likely to be more detrimental than earlier dewatering events. Maintenance of sufficient instream flows may therefore become even more critical in March and April just as water availability decreases, than earlier in the winter period.

Crisp (1981) developed a model of median time to hatch for rainbow trout, which is applicable to steelhead, where:

$$\log(\text{days to 50\% hatch}) = -2.0961(\log(T + 6.0)) + 4.0313$$

McLean et al. (1991) developed a comparable model for steelhead emergence, where the number of days after fertilization (D) is:

$$D = \frac{922050}{(T + 14.20)^{3.01}}$$

These relations are plotted in Figure G-7 for comparison.

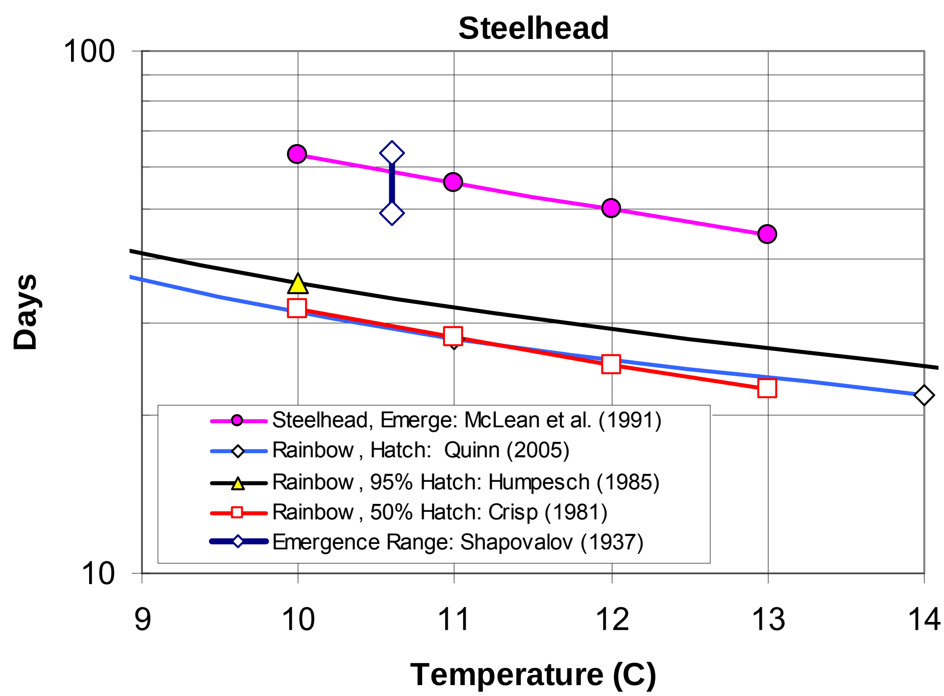

Figure G-7. Comparison of times from fertilization to hatching and emergence of steelhead as a function of water temperatures commonly occurring in the Policy area during the winter and early spring.

Coho: Developing coho alevins may reside in the gravel for many weeks after hatching before emerging. Shapovalov and Taft (1954) noted the time to hatch varied from about 38 d at 10.7ºC to 48 d at 8.9ºC. The time to hatch in Waddell Creek was observed to take from 35-50 days, with emergence occurring 2 to 7 weeks after hatching, depending on temperature and silt levels. Peak emergence occurred approximately 3 weeks post-hatch. DFG (2002) noted that coho embryos in California remain in the gravel between 2-10 weeks after hatching.

Beacham and Murray (1990) developed a model to compute the number of days to emergence (D) as a function of temperature:

$$ln(D) = 7.018 - 1.069 \ln(T + 2.062)$$

McLean et al. (1991) developed another model for coho, where the number of days to emergence after fertilization (D) is:

$$D = \frac{923367}{(T + 15.03)^{2.90}}$$

These relations are plotted in Figure G-8 for comparison.

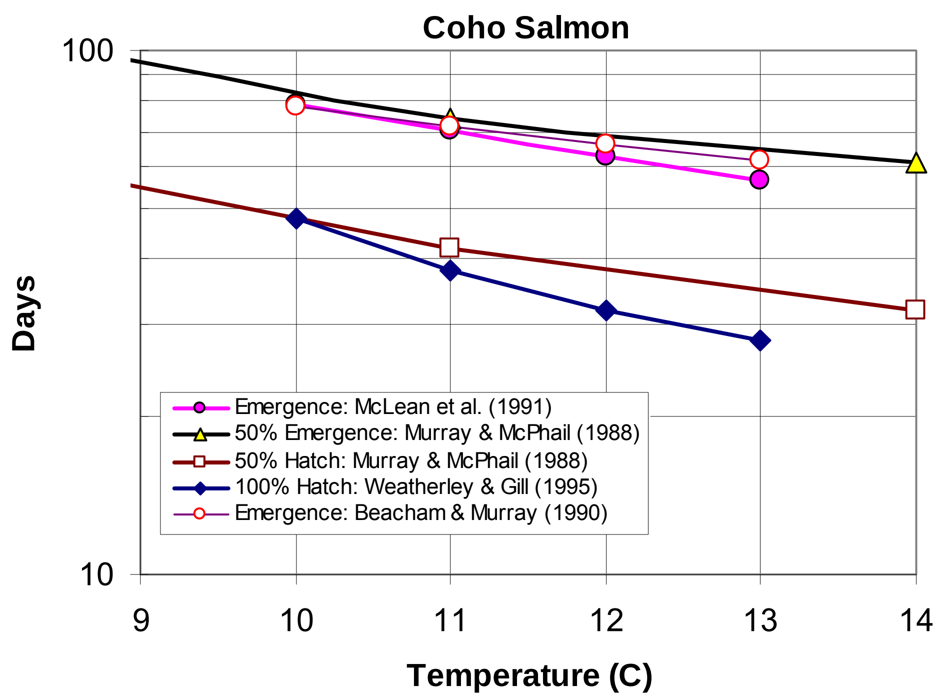

Figure G-8. Comparison of times from fertilization to hatching and emergence of coho as a function of water temperatures commonly occurring in the Policy area during the winter and early spring.

Chinook: A variety of incubation time data are available for Chinook (Figure G-9). Crisp (1981) developed a model of median time to hatch for Chinook salmon:

$$\log(\text{days to 50\% hatch}) = -1.8126 (\log(T + 6.0)) + 3.9166$$

Beacham and Murray (1990) developed a model for days to emergence (D) as a function of temperature:

$$ln(D) = 10.404 - 2.043\ ln\ (T + 7.575)$$

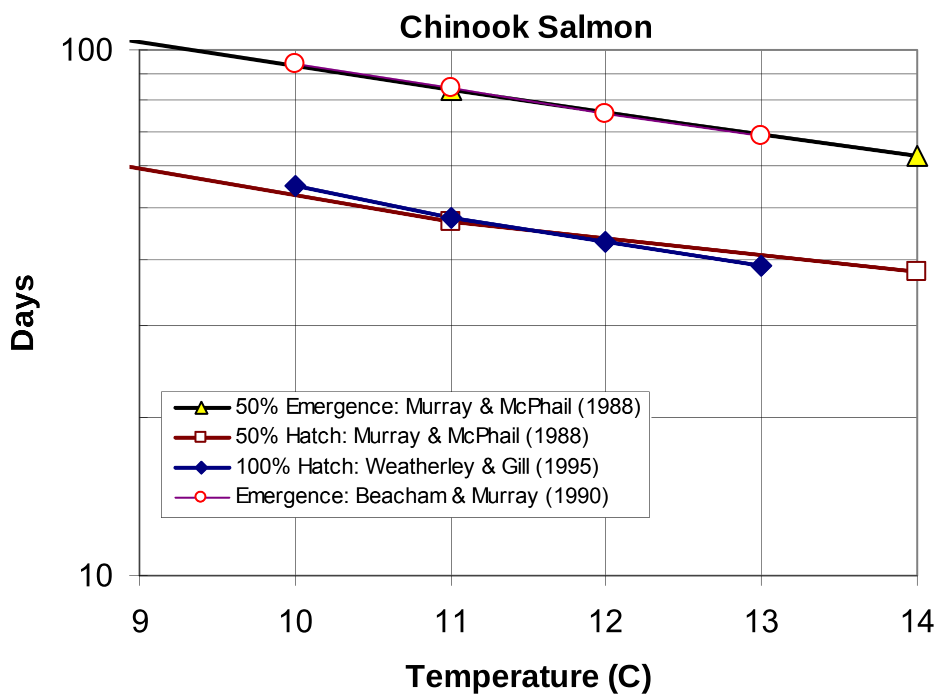

Figure G-9. Comparison of times from fertilization to hatching and emergence of Chinook as a function of water temperatures commonly occurring in the Policy area during the winter and early spring.

iii. Total Duration of Spawning and Intragravel Residence

Coho and steelhead may begin spawning as soon as they reach natal spawning grounds (Shapovalov and Taft 1954; NCRWQCB 2000; MTTU 2000). Available information for the Policy area generally indicates that the duration of spawning in small streams is shorter than in large streams, reflecting in large part, a shorter duration of elevated flows with decreasing channel size (MTTU 2000). However, smaller streams tend to have colder water temperatures than larger ones during the winter, which increases the incubation time. A review of recent USGS water temperature data for mid- to large size streams (drainage areas > 30 mi^2) in the Policy area indicates that water temperatures generally range around 10ºC to 11ºC during the December-February period, and around 12ºC to13ºC during the March-April period. Fong (1996) noted similar to slightly cooler temperatures in Redwood Creek, a small stream in Marin

County. This suggests applying two general seasonal criteria for incubation duration depending on date of spawning. The corresponding approximate times to emergence indicated in Figures G-7 to G-9 for these temperatures are presented accordingly for each species in Table G-8. In addition, it was assumed that a minimum of five days are needed for spawning in both large and small streams. Although spawning may occur in as little as one day in smaller flashier streams, the required incubation times may be longer due to cooler temperatures.

The duration of spawning and incubation used in the analysis varied depending on the date that spawning occurred and the species, reflecting the effect of water temperature. If the total duration specified in Table G-8 for a species spawning between November 1-February 28, exceeded the number of days calculated from the date of spawning to March 1, then the duration of incubation extending into the March 1- April 30 period was set to equal the larger value of either (i) the March 1-April 30 duration period (listed in Table G-8), or (ii) the number of days calculated between the start date and March 1. This "weighted" the longer incubation period associated with late winter spawning (and colder water temperatures), relative to the shorter incubation period associated with spring spawning (and warmer water temperatures).

Table G-8. Summary of Incubation Time, and Maximum Intragravel Residence Time from Initiation of Spawning to Emergence, for Anadromous Salmonids in the Policy Area. The Total Duration Numbers were Used in the Analysis.

	Approximate Time to Emergence From Fertilization (days)		**Total Duration of Vulnerability to Dewatering (days)**	
Species	**Nov 1–Feb 28**	**Mar 1–April 30**	**Nov 1–Feb 28**	**Mar 1–April 30**
Steelhead	60	47	65	52
Coho	75	62	80	67
Chinook	90	70	95	75

G.3.2.5 Times of Year When Spawning Was Analyzed

Spawning was considered possible over the following periods for each species, reflecting the intersection of periodicity information presented in Appendix C and the range of start and end dates proposed as Policy element alternatives for the winter diversion season:

Steelhead: 12/1 – 3/31 (excepts data from heavily regulated Lagunitas Creek)
Coho: 11/1 – 2/28 (excepts Mattole River – low risk of big diversion impact)
Chinook: 11/1 – 1/31 (based on Russian River system)

The effects of alternative variations in the Policy diversion season element were evaluated as they intersected the above periods (results are presented in Chapter 4 and Appendices I and J).