Information Structure of Ecosystem Diagnosis and Treatment (EDT) and Habitat Rating Rules for Chinook Salmon, Coho Salmon, and Steelhead Trout

by

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> *"…the challenge for stream ecologists, especially those who study fish, is to understand how these continuous, hierarchical and heterogeneous habitats are arrayed in space and time and are linked by fish movement to influence the persistence, abundance, and productivity of fish populations and communities along the riverscape."*
>
> (Fausch and others 2002)

SECTION 1. INTRODUCTION

Knowledge of how the quality and quantity of different habitats affect the performance of salmonid populations is a basic need of natural resources managers. Concerns about salmonid species and stocks at risk have prompted wide consideration of how land use practices affect aquatic habitats. While broad patterns of land use and environmental condition can generally be correlated with population abundance (Pess and others 2002, Feist and others 2003), such knowledge is often inadequate for the needs of decision makers and watershed planners.

For those charged with managing watersheds and fish populations, the need is for far more specific information about how fish populations might respond to various types and combinations of actions that could be taken in a watershed. Managers must prioritize actions to improve fish population performance; this requires information on spatial and temporal variation in habitat quality and quantity within a target watershed. This information can be used to evaluate outcomes of different strategies and actions. Managers must weigh trade-offs between different scenarios involving future development and devise scientifically accountable and cost effective solutions to management of freshwater systems.

Ecosystem Diagnosis and Treatment (EDT) was developed to provide such information for decision makers. EDT provides a diagnosis of current environmental constraints in a system and allows managers to explore alternative habitat restoration strategies. The method uses species-specific rules that relate environmental conditions in freshwater to life stage survival responses of salmonid fishes. The rules are one part of the modeling procedure to characterize habitat conditions in a stream and to assess how anthropomorphic changes to the environment constrain species performance. The general process for application of the EDT to watershed planning is explained in Lichatowich and others (1995). EDT species-habitat rules have been developed for most anadromous species of *Oncorhynchus* as well as several non-anadromous salmonid species. Using these rules, EDT has been successfully applied to most streams in the Columbia River and Puget Sound basins.

This document will explain the rules and information structure for EDT with specific application to the rules for Chinook salmon (*O. tshawytscha*), coho salmon (*O. kisutch*) and steelhead trout (*O. mykiss*). The document should be used in conjunction with the EDT Rules Viewer software that allows users to explore the effects of specific EDT rules using an EDT stream reach data set. This document will describe the structure of the rules and provide illustrations of the EDT rule concepts using these three species. Each of the habitat rules used in EDT for spring Chinook, fall Chinook, coho, summer steelhead and winter steelhead are illustrated in the EDT Rules Viewer.

The documentation of the EDT rules is intended to encourage a dialogue between EDT practitioners and scientists regarding species-habitat relationships for salmonid fishes. The rules in EDT are hypotheses based on the scientific literature and expert knowledge. Their utility to produce useful and accurate representations of salmonid habitat potential has been shown in numerous applications throughout the Pacific Northwest. However, continued dialogue, review and refinement of the rules and EDT structure are encouraged.

SECTION 2. ECOSYSTEM DIAGNOSIS AND TREATMENT THEORY AND INFORMATION STRUCTURE

A. Theory

EDT is a process to rate the quality and quantity of habitat in a stream for a particular species. To do this, EDT assumes that the biological capacity and productivity of a fish population are functions of the underlying environment and that conditions are reflected in the shape of the production function (Reisenbichler 1989). Specifically, we assume that habitat based estimates of capacity and productivity create a Beverton-Holt production function (Beverton and Holt 1957) that serves as an index of potential biological performance of the species in the modeled environment (Figure 1). Capacity defines the “size” of the environment with respect to a species while productivity is the survival rate without any density effects (density independent survival). Moussalli and Hilborn (1986) showed that a Beverton-Holt function for a population can be disaggregated into similar functions describing survival and capacity of the environment at different life stages. In EDT, capacity and productivity are calculated for each life stage at a stream reach scale and then integrated to estimate overall population capacity and productivity.

Productivity in EDT is equivalent to the concept of intrinsic productivity discussed in McElhany and others (2000) to describe viable salmonid populations with respect to the Endangered Species Act. It is survival without density dependence effects, i.e., the approximate rate that would occur when competition for resources is eliminated. As abundance increases, productivity is increasingly modified by density dependent factors of the environment to the point that the quantity of resources becomes limiting and abundance approaches the capacity. In Figure 1, productivity is the slope of the abundance curve at its origin. Productivity in EDT is a function of the quality of the environment.[1] The definition of productivity as applied here is consistent with its use by Hilborn and Walters (1992) in population dynamics modeling.

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[1] / Empirically measured productivity would also incorporate sex ratio, fecundity, and fitness.

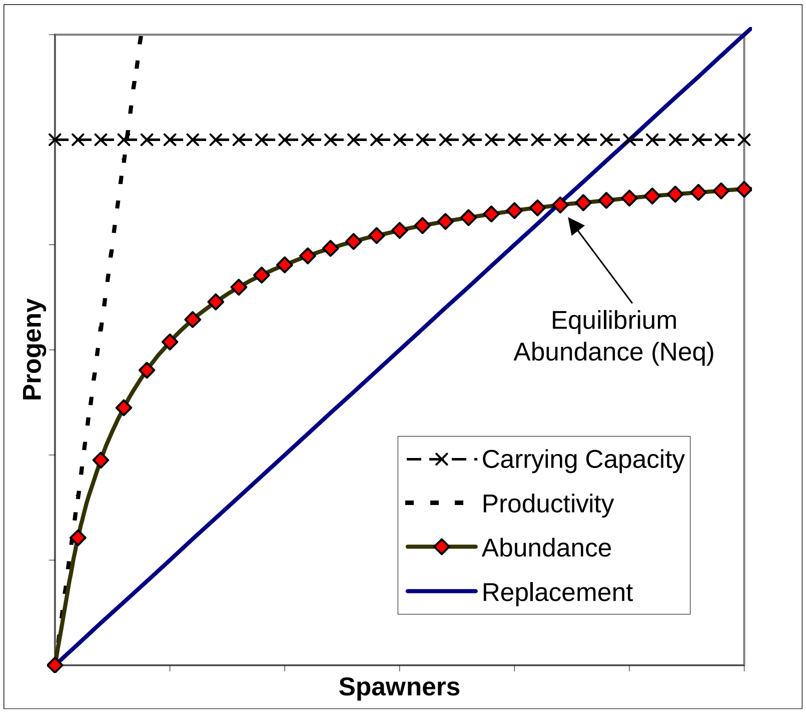

Figure 1. Features of a Beverton-Holt production function. Productivity is the density independent survival, which, along with density dependent factors of the environment, determines abundance limited by the total capacity of the environment. Replacement is the minimum number of spawners required to maintain a given abundance. Under steady-state environmental conditions, the population abundance equilibrates at Neq, the point where abundance crosses the replacement line.

Environmental capacity limits how large a population can grow given finite space and food resources, depicted by the asymptote in Figure 1. It controls the extent that density dependence is operative at different population (or density) levels. Capacity is a function of the quantity of key habitats and food resources available.[2] The term key habitat here refers to those habitat types that are the primary types utilized by the species in a life stage—they are the types that are preferred or required by the species in the life stage. Given steady-state condition, abundance will increase toward the capacity and will equilibrate at a point below capacity where the Progeny/Spawners is equal to 1.0 (Figure 1). This equilibrium abundance, or Neq, is a function of both capacity and productivity.

Using the recursive property of the Beverton-Holt function highlighted by Mousalli and Hilborn (1986), the population level production function is decomposed in EDT into similar functions for each life stage. Life stages for Chinook, coho and steelhead are provided in Appendix A. From the scientific literature we can describe optimal productivity (survival rate) and capacity (density) conditions under ideal conditions. We refer to these optimal survival and density values as reference benchmarks. Benchmarks provide us with a set of descriptions for performance under optimal conditions expressed as survival and maximum

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[2] / Environmental carrying capacity illustrated in the stock-production relationship is actually a function of both quantity of resources (ones that are competed for) and environmental quality—easily seen in a disaggregated production function, see Moussalli and Hilborn (Moussalli and Hilborn 1986) and pages 284-285 in Hilborn and Walters (Hilborn and Walters 1992).

densities for each life stage. Benchmarks are the theoretical natural limits on survival and density for a species. These conditions constitute what can be thought of as “as good as it gets” for survival of the species in nature. Benchmarks survival for Chinook, coho and steelhead in EDT are provided in Appendix B.

The biological rules are used to adjust the optimal benchmark performance to account for habitat conditions in a specific stream. The EDT rules adjust the theoretical benchmarks downward to reflect local conditions because conditions in any stream are inherently constrained by local geology, climate and biology independent of anthropogenic constraints. As a result, fish performance is always less than the benchmark optimal levels. The EDT rules provide a systematic way of quantifying survival conditions for any reach by computing performance in the local environment relative to the benchmarks. This procedure ensures that productivity and capacity values computed for each life history segment are: a) bounded by the biological limits of the species, b) scaled consistently across time, space, and life stage, and c) scaled consistently with the benchmark values. While the rules are based on knowledge contained in the literature, they should be thought of as hypotheses about how survival is affected by environmental conditions.

It is important to distinguish the benchmarks from the historic or pristine conditions (often referred to as the Template or Reference condition in EDT). Maximum performance of fish in a particular stream is almost always less than the benchmarks because even pristine conditions are not “perfect.” The benchmark descriptions serve as a point of reference for both the present-day and historic conditions and for all watersheds.

B. EDT Information Structure

Information used to derive biological performance parameters in EDT is organized through the hierarchical EDT Information Structure. It structures information through three levels of organization. Together, these levels can be thought of as an information pyramid in which each level of information builds on information from the lower level (Figure 2). As we move up through the levels, we take an increasingly organism-centered view of the ecosystem.

Levels 1 and 2 together characterize the environment as it can be described by different types of data (Figure 2). This provides the characterization of the environment needed to analyze biological performance for a species. Level 1 and Level 2 information is not specific to a species but instead forms a species-independent description of the aquatic environment. The Level 3 category of information, on the other hand, is a characterization of that same environment from a different perspective: “through the eyes of the salmon"(Mobrand and others 1997). This category describes biological performance in relation to the state of the environment described by the Level 2 information.

The Information Structure begins with a wide range of environmental data (Level 1 input data) such as flow, sediment load, temperature, physical habitat, land use and ownership, elevation, slope, and so on. Included is information on the spatial and temporal structure of the data (Figure 3). These data exist in a variety of forms and pedigrees. Some watersheds are data rich, others might be comparatively data poor. Level 1 information includes empirical measurements as well as conclusions of expert observers. These data are the basis for the more refined description of the environment in Level 2.

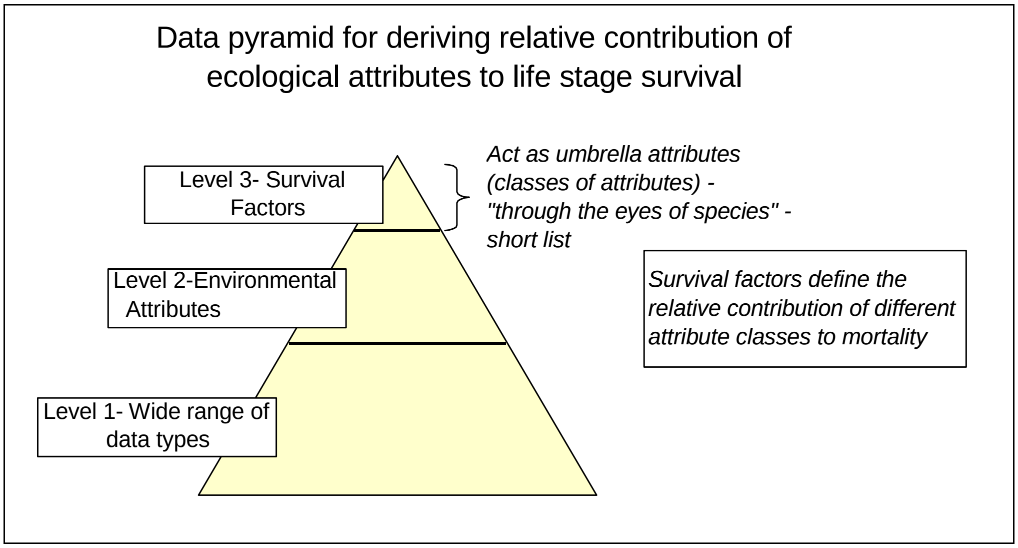

Figure 2. EDT Information Structure can be visualized as a "data pyramid." Information begins as raw data and observations (Level 1), is organized into a species-neutral description of the environment (Level 2) and then characterized as performance of a particular species (Level 3).

Level 2 factors are referred to as Environmental Attributes. Level 2 information creates a generalized depiction of the aquatic environment, essentially as a set of conclusions derived from the Level 1 information (Figure 3). Level 2 Environmental Attributes are <u>measurable</u> characteristics of the environment that relate to salmonid performance. Level 2 Environmental Attributes are the main input to EDT and is organized in the Stream Reach Editor application. EDT Environmental Attributes are similar to the concept of Environmental Attributes used by (Morrison and others 1998) to describe species-habitat relationships for terrestrial environments. The Level 2 Environmental Attributes are measurable physical and biological characteristics about the environment relevant to a salmonid view of the stream. In concept though, a set of Level 2 Attributes can be described for analyzing the environment with respect to any species. The EDT Environmental Attributes (Level 2) are defined more fully in Appendix C.

The Level 2 characterization describes conditions in the watershed at specific locations (reaches along a stream), times of year (specific months), and by scenario (template, current[3], or a future scenario). Thus values assigned for each Environmental Attribute represent conclusions about the stream by site, month, and scenario based on the Level 1 data and observations. These assumptions become operating hypotheses for these attributes under specific scenarios. Where Level 1 data are sufficient, Level 2 conclusions can be derived directly or through simple algorithms. However, where Level 1 data are incomplete, experts are needed to provide knowledge about geographic areas and attributes. Regardless of the types of information used to derive the Environmental Attribute ratings, the Level 2 Environmental Attributes are measurable characteristics of the environment that can be monitored and ground-truthed over time through an adaptive process.

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[3] The Current condition in EDT is often referred to as the Patient condition reflecting the terminology of Lichatowich and others (1995)

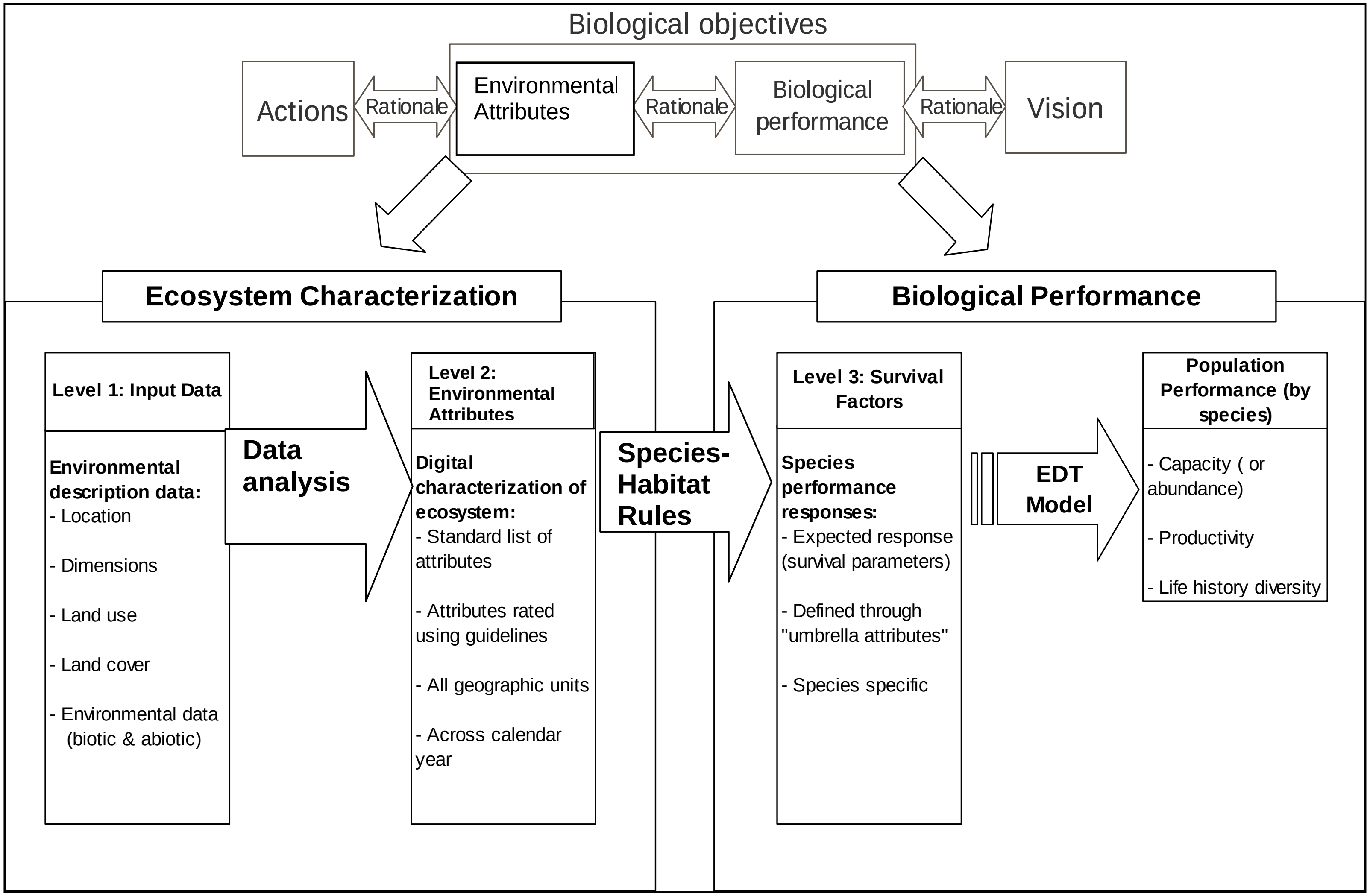

Figure 3. Ecological Information Structure. Species-Habitat rules relate characteristics of the environment to potential performance of the focal species.

Most Level 2 Attributes are characterized using ratings on a scale of 0 to 4, spanning a spectrum of conditions. Generally, there is a consistent direction to the attribute ratings, where 0 or low values will tend to correspond with pristine environmental conditions and higher values tend toward more degraded conditions. In these cases, a 0 corresponds to a condition of *no reduction of biological performance as a result of the attribute*, whereas a value of 4 is a *severe reduction in performance*. This pattern varies for several attributes, however. Table 1 gives examples of the index values for three Environmental Attributes, all addressing a different aspect of sediment load within the stream system. Integer values represent the midpoint of conditions for attributes when a range of conditions is associated with one value.[4] The indexing system allows users to specify either continuous or integer values for the attributes, depending on the appropriate level of precision for particular stream reach given the available data. Conditions associated with index values for all Level 2 Environmental Attributes are described in Appendix D.

Table 1. Rating indexes used for three Level 2 Environmental Attributes that address different characteristics of sediment load in a stream system.

Embeddedness	
Rating	Rating definition
0	≤ 10% embedded
1	> 10% and ≤ 25% embedded
2	> 25% and ≤ 50% embedded
3	> 50% and ≤ 90% embedded
4	> 90% embedded
Fine sediment (intragravel)	
Rating	Rating definition
0	≤ 6% fines < 0.85 mm
1	> 6% and ≤ 11% fines < 0.85 mm
2	> 11% and ≤ 18% fines < 0.85 mm
3	> 18% and ≤ 30% fines < 0.85 mm
4	> 30% fines < 0.85 mm
Suspended sediment (from SEV index – after Newcombe and Jensen 1996)	
Rating	Rating definition
0	≤ 4.5 scale of severity (SEV)
1	> 4.5 and ≤ 7.5 scale of severity (SEV)
2	> 7.5 and ≤ 10.5 scale of severity (SEV)
3	> 10.5 and ≤ 12.5 scale of severity (SEV)
4	> 12.5 scale of severity (SEV)

Some Level 2 Attributes do not use the rating scale of 0-4. Instead they employ the appropriate metric for the attribute. These attributes are wetted channel width (maximum and minimum width in feet), channel length (miles), channel gradient (proportion) and percent of the wetted area of a reach represented by specific habitat types (e.g. pools, riffles and glides).

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[4] When generating Level 2 attribute values for the basin, integer values frequently mean that only a broad categorical conclusion can be reached about an environmental attribute, as reflected in the range of values shown for the sediment examples. In these cases, the rule would interpret an integer to represent the midpoint.

The species-habitat rules translate the species-neutral Level 2 characterization of the environment into a species-specific depiction of habitat in terms of 1) Level 3 Survival Factors by life stage, 2) and Level 3 Key Habitat. A third aspect of Level 3, Food, affects both Productivity and Capacity. The EDT model then integrates the Survival Factors (including the Productivity aspect of Food) across life stages to estimate population Productivity and uses Key Habitat and the Capacity aspect of Food to estimate population Capacity (Figure 3). The rules linking these three Level 3 factors and the Level 2 Environmental Attributes are quite different and will be discussed separately.

SECTION 3. RULES FOR ESTIMATING PRODUCTIVITY

Productivity in EDT is a measure of the quality of the environment with respect to the focal species. We calculate productivity in terms of the Level 3 Survival Factors. The Level 3 Factors are listed and defined in Appendix E. The Survival Factors act as "umbrella attributes", grouping the effects of Environmental Attributes into broader synthetic concepts of habitat conditions for the species (Figure 4). The purpose of grouping effects of classes of attributes in this manner is to allocate mortality by the types of factors that biologists typically refer to in environmental analysis (e.g., limiting factors analysis). Table 2 illustrates general relationships between Level 2 Environmental Attributes and Level 3 Survival Factors. Specific associations of Level 2 Attributes and Level 3 Factors for Chinook are found in Appendix F, for coho in Appendix G, and for steelhead in Appendix G.

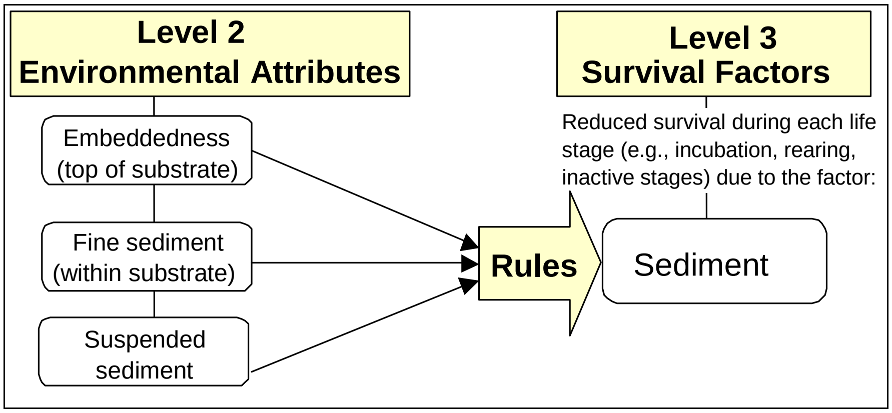

Figure 4. Concept of EDT rules relating Level 2 Environmental Attributes to Level 3 Survival Factors. Rules derive (as hypotheses) effects of Level 2 Attributes on species performance by life stage (example shows effects of sediment attributes on life stage productivity).

Table 2. Organization of Level 2 Environmental Attributes by categories of major stream corridor features. Salmonid Survival Factors (Level 3) are shown associated with groups of Level 2 attributes. Associations can differ by species and life stage. See Appendix F, G, and H for association matrices for Chinook, coho, and steelhead respectively.

Environmental Attributes (Level 2)		**Related Survival Factors**
1 Hydrologic Characteristics		
1.1 Flow variation	Flow - change in interannual variability in high flows	Flow Withdrawals (entrainment)
	Flow - changes in interannual variability in low flows	
	Flow - Intra daily (diel) variation	
	Flow - intra-annual flow pattern	
	Water withdrawals	
1.2 Hydrologic regime	Hydrologic regime - natural	
	Hydrologic regime - regulated	
2 Stream Corridor Structure		
2.1 Channel morphometry	Channel length	Channel length Channel stability Channel width Habitat diversity Key habitat Obstructions Sediment load
	Channel width - month maximum width	
	Channel width - month minimum width	
	Gradient	
2.2 Confinement	Confinement - hydromodifications	
	Confinement - natural	
2.3 Habitat type	Habitat type - backwater pools	
	Habitat type - beaver ponds	
	Habitat type - glides	
	Habitat type - large cobble/boulder riffles	
	Habitat type - off-channel habitat factor	
	Habitat type - pool tailouts	
	Habitat type - primary pools	
	Habitat type - small cobble/gravel riffles	
2.4 Obstruction	Obstructions to fish migration	
2.5 Riparian and channel integrity	Bed scour	
	Icing	
	Riparian function	
	Wood	
2.6 Sediment type	Embeddedness	
	Fine sediment (intragravel)	
	Turbidity (suspended sediment)	
3 Water Quality		
3.1 Chemistry	Alkalinity	Chemicals (toxic substances) Oxygen Temperature
	Dissolved oxygen	
	Metals - in water column	
	Metals/Pollutants - in sediments/soils	
	Miscellaneous toxic pollutants - water column	
	Nutrient enrichment	
3.2 Temperature variation	Temperature - daily maximum (by month)	
	Temperature - daily minimum (by month)	
	Temperature - spatial variation	
4 Biological Community		
4.1 Community effects	Fish community richness	Competition with hatchery fish Competition with other fish Food Harassment Pathogens Predation
	Fish pathogens	
	Fish species introductions	
	Harassment	
	Hatchery fish outplants	
	Predation risk	
	Salmonid carcasses	
4.2 Macroinvertebrates	Benthos diversity and production	

EDT rules are grouped into categories that describe the species-habitat relationships for different types of environments. Rule Categories relate to width of the stream and to the hydrologic regime (e.g. rainfed, glacial, spring-fed). The EDT Rules Viewer shows the appropriate Rule Category for each species-habitat rule based on the Level 2 input. In most cases, a single rule exists for one life stage-Level 3 Survival Factor combination. For example, the Level 3 Factor of Habitat Diversity is related to the Level 2 Attributes of Wood (large woody debris), Artificial Confinement and Gradient regardless of the size of the stream or the hydrologic regime. However, in some cases alternative forms of the rules exist for different Rules Categories to account for different biological responses to conditions in streams of different size (by channel width) and hydrologic regime (accounting for source of flow, e.g., groundwater vs. rain fed).

A. Structure of EDT Species-Habitat Rules for estimating productivity

The life stage productivity value associated with a specific stream reach is defined as the density independent survival rate expected if the entire life stage occurred under the conditions in that reach.[5]

The rules presented here assume that productivity, P , can be partitioned into a set of sixteen independent multiplicative survival factors F_i , i.e.

$$P = P_0 \cdot F_1 \cdot F_2 \cdot F_3 \cdots F_{16}$$

where $0< F_i <1$ are relative productivity values and P_0 is the benchmark survival (Appendix B and discussion above).. Each $F_i < 1$ acts to reduce P from the benchmark productivity due to habitat conditions that are less than optimal corresponding to that F_i in the given reach. When the reach has optimal conditions corresponding to all factors, i.e, $F_i = 1$ for all Level 3 factors, then $P = P_0$.

We then assume that each Level 3 Survival Factor F_i can be estimated as a function of the Level 2 Environmental Attributes for the reach. The EDT Rules Viewer calculates the individual F_i values based on a set of Level 2 inputs. These are seen in the right panel of the Viewer associated with each of the Level 3 Survival Factors. The functional form that we applied in formulating the present rule set assumes that a Level 3 Survival Factor will principally be driven by a single dominant, or primary, Level 2 Attribute, though other Level 2 Attributes can act to modify the overall effect. We refer to this rule structure as the **Synergistic Form**.

In this form for rule structure, we refer to the dominant Environmental Attributes as the **Primary Level 2** Attribute for that specific life stage-Level 3 factor. When the Primary Level 2 attribute (p) alone affects the Level 3 (i.e. there are no secondary Level 2 attributes in the rule) survival factor F_i , it is defined as:

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[5] / Differences in conditions between months are handled within EDT by modeling life history trajectories to capture how groups of fish experience changes in environmental conditions in space and time.

$$F_i = 1 - S_{P,i}$$

where $S_{P,i}$ is the sensitivity of survival of the species to the Primary Level 2 Attribute, here without other contributing Level 2 Attributes. The $S_{P,i}$ values for each rating (0 – 4) of the Primary Level 2 are estimated based on published studies, available data or where data is sparse, expert opinion. In the Rules Viewer, clicking first on a Level 3 Factor and then on a Level 2 Attribute will display a graph showing the shape of the relationship between an attribute rating (0-4) and $S_{P,i}$ value.

In most cases the sensitivity to the Primary Level 2 Attribute is affected by one or more **Modifying Level 2** Attributes. These attributes modify overall sensitivity associated with the Primary Level 2, either increasing it or, in some cases, decreasing it. The functional form used (unless otherwise specified) to capture this modifying effect is:

$$F_i = 1 - \left[\sum_j S_{j,i}{}^{g} \right]^{1/g}$$

where $S_{j,i}$'s are the sensitivities of all contributing Level 2 Attributes *j* (including the Primary) operating on factor *i*, and *g* is a "synergy parameter."

In all rules where this synergistic form is used the value of *g* is 0.4. This value of *g* derives from the way the 0 – 4 rating scale for Level 2 attributes was defined. The synergistic form shapes the overall combined effect of multiple Level 2 Attributes affecting a single Level 3 factor *i* consistent with the way in which ratings have been defined for Level 2 Attributes. In general, the rating system was devised so that values of 1 or 2 would have little effect on survival, whereas values between 3 and 4 tend to reflect severe conditions for survival. Use of *g* = 0.4 in the equation retains a minor effect on relative productivity when adding multiple Level 2 modifiers with low ratings, but rapidly increases sensitivity at higher values for modifying attributes. As more data and information become available this function should be tested against observations.

An alternative to the synergistic rule described above would be to assume that Level 2 Attributes operate independently of each other. The **Independent Form** of the rule would assume a simple multiplicative effect:

$$F_i = \prod_j (1 - S_{j,i})$$

None of the rules in the current EDT rule sets are structured using the Independent Form.[6] It is important to recognize that sensitivities ascribed to Level 2 Attributes for each factor *i* in the existing rules database were formulated using the synergistic form—which means that sensitivities of those Environmental Attributes identified as being "modifiers" are likely set too low to be used without adjustment with the independent form. If a rule structure was to

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[6] / A special set of rules have been developed for use in large lakes that use the Independent Form of the rules. This document does not address those rules.

be modified to follow the Independent Form, then many of these sensitivities would need to be adjusted upwards.

B. Examples of EDT Species-Habitat Rules and their application

Three examples (Table 3) are presented below to show how rules were formulated and how they function within EDT. The logic, approach, and key studies applied are described. Each example looks at how Level 2 Environmental Attributes are used to derive relative productivity associated with the Level 3 Survival Factor "Sediment Load" illustrated in Figure 4. The examples show how these Level 2 Attributes are used to project a total effect on productivity associated with this survival factor. They also illustrate that different levels of confidence or "proof" can be given to the rules depending on how much is known from documented empirical relationships.

Table 3. List of examples to illustrate how rules were formulated and function. Each example projects total sensitivity (1- relative productivity) ascribed to the Level 3 survival factor "Sediment Load."

Type of example (shown to right)	Example 1	Example 2	Example 3
	One Attribute affecting sensitivity – based on empirical relationship	Multiple Attributes affecting sensitivity – based on empirically derived index with added inferences	Multiple Attributes affecting sensitivity – inferred from empirical observations and qualitative conclusions
Life stage	Incubation (to emergence)	Resident rearing	Inactive (overwintering)
Primary Attribute	Fine sediment (intragravel)	Suspended sediment	Embeddedness
Modifying sediment Attribute	none adding sensitivity	none adding sensitivity	Suspended sediment
Other modifying Attributes	none adding sensitivity	Temperature (max)	none adding sensitivity

Example 1: Incubation life stage – one Environmental Attributes based on an empirical relationship

This example illustrates the use of a documented relationship between fine sediment within the substrate of riffles and pool-tailouts and survival from egg deposition to fry emergence. Only one Level 2 Attribute is used in this rule. Evidence for the effect of intra-gravel fine sediment (e.g., particles < 1mm in size, most often expressed as <0.85 mm) is well documented (e.g. Chapman and McLeod 1987, Bjornn and Reiser 1991, Kondolf 2000). The many studies that have documented effects of sediment on egg-to-fry survival typically link reduced survival to this single aspect of sedimentation.

Kondolf (2000) outlines a procedure to consider two size classes of intragravel sediment in assessing effects on egg-to-fry survival, based on analyses by Tapel and Bjornn (1983) and Chapman and McLeod (1987). In areas where excessive fines < 1 mm are present, the major determinant of STE would be based on this size class. The effect in this case occurs due to restriction of oxygenated flow passing incubating eggs with loss of gravel permeability as percent fines increases. In areas where somewhat larger particle sizes are excessive (i.e., sand sized, 3-6 mm), such as in the Idaho Batholith, this size is believed to have the dominant effect. In this case, sand size particles can entomb pre-emergent fry. Definitions used to describe the Level 2 Attribute for fine sediment provide an option for either using particle sizes <1 mm (as seen in Table 2) or particles between 3-6 mm in size (see Appendix D). Further discussion on how this Attribute is to be rated is provided in Lestelle (2004)

We employed the empirical relationship reported by Tagart (1984) for the effects of percent fine sediment (<0.85 mm) on survival to emergence for coho (Figure 5). We assumed the same relationship is applicable to chinook salmon and steelhead trout. Using a benchmark survival to emergence of 60% (assumed average survival under optimal conditions for chinook and coho), we can convert Tagart's survivals into sensitivity (as 1 minus survival divided by the benchmark) and plot the values against the appropriate Level 2 rating values on the x-axis (Figure 6). The resulting relationship forms the rule for sediment effects on the incubation life stage, except when the hydrologic regime is mainly characterized as groundwater fed.[7] In that case, upwelling associated with groundwater sources appears to largely protect embryos from deleterious effects of high fines (Bjornn and Reiser 1991, Waters 1995). This explains why salmonids can have high rates of reproduction in some streams despite excessive deposits of fine sediment (e.g., chum and sockeye salmon are known to spawn heavily in groundwater fed streams, even in areas of excessive fines). We therefore created a Rule Category for this hydrologic regime that maintained high survivals even at high levels of fine sediment.

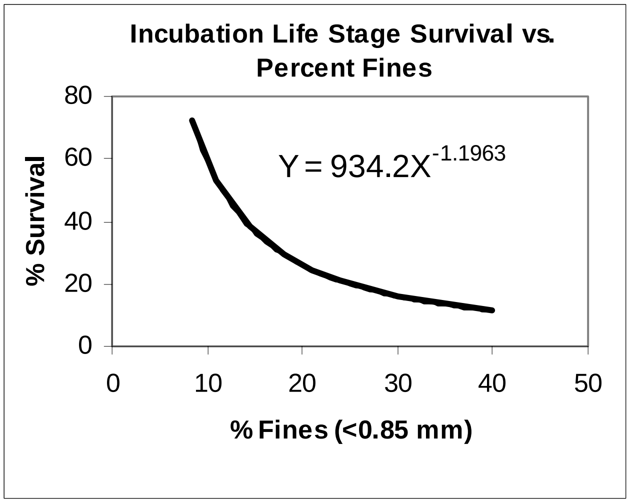

Figure 5. Relationship between percent fines and survival from egg deposition to emergence for coho salmon. Adapted from Tagart (1984)

It bears noting that there is some evidence suggesting that steelhead trout are more sensitive to sediment effects during egg incubation, particularly if the sediment particles are sand sized. Data collected by Irving and Bjornn (1984); also seen in (Bjornn and Reiser 1991)) suggest that steelhead are more sensitive, apparently due to a greater susceptibility to entombment

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[7] Hydrologic regime is a Level 2 Attribute. Five regimes are described through the ratings, of which one is predominately groundwater fed (see Appendix D).

associated with sand particles. The rules do not currently incorporate this difference; an update to the rules is expected sometime in the future.[8]

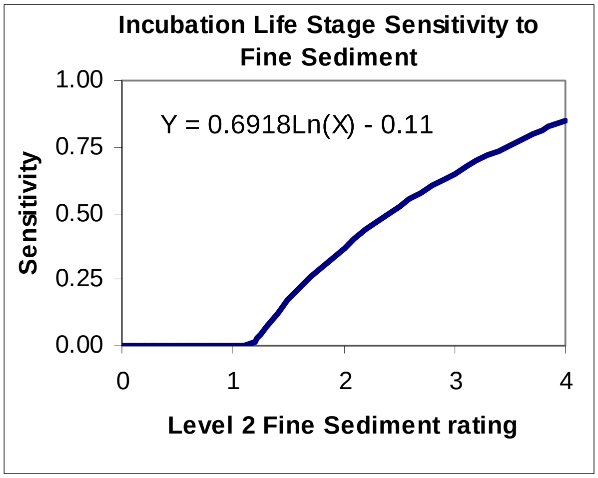

Figure 6. Relationship between ratings for Level 2 Fine Sediment and sensitivity of eggs and alevins, derived by converting the relationship in Figure 5.

Examples of results obtained by applying the rule described here for all hydrologic regimes except groundwater dominated are provided in Table 4.

Table 4. Example results obtained for the rule incubation-Level 3 Survival Factor "Sediment Load" for chinook and coho salmon.

Life stage: egg incubation						
Attribute		Example				
		A	B	C	D	E
Fine sediment (intragravel)(Primary)	Rating	0	1	2	3	4
	Sensitivity	0	0	0.370	0.650	0.849
Relative productivity		1.00	1.00	0.63	0.35	0.15
Benchmark survival		0.6	0.6	0.6	0.6	0.6
Absolute survival		0.60	0.60	0.38	0.21	0.09

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[8] / The rule for the effects of fine sediment is the same in the current set of rules whether the dominant particle size is <1mm or >1 and <6 mm. We formulated the breakpoints in the definitions that use sand sized particles by matching the effects of the larger particle sizes from Irving and Bjornn (Irving and Bjornn 1984) with those of Tagart (Tagart 1984) that used the size class <1mm.

Example 2: Resident rearing life stages – multiple Environmental Attributes based on empirically derived index with inferences for synergy

This example involves two Attributes acting synergistically to produce a total sensitivity associated with sediment during the active rearing stage. The rule is based on an empirically derived index for sensitivity to suspended sediment, the primary Environmental Attribute in this case, and an assumed synergistic effect with temperature. This example illustrates how some rules combine a well documented sensitivity relationship with more qualitative information to derive an overall effect ascribed to a single Level 3 Factor.

Effects of suspended sediment, either as turbidity or suspended solids[9], on fish are well documented (summarized in Bash and others 2001). Suspended sediments can affect fish behavior and physiology and result in stress and reduced survival. Temperature acts synergistically to increase the effect of suspended sediment (Newcombe and Jensen 1996, Bash and others 2001).

The severity of effect of suspended sediment increases as a function of both sediment concentration and exposure time, or dose (Newcombe and Jensen 1996, Bash and others 2001). Newcombe and Jensen (1996) performed a meta-analysis of data contained in 80 published and documented reports to assess the effects of dose on fish responses, including numerous studies involving salmonids. The analysis yielded empirical equations that relate biological response to duration of exposure and suspended sediment, including two that specifically address salmonids. The authors synthesized the results of their scale of severity (SEV) into likely outcomes for fish species (adapted in Table 4). We aligned our rating system of 0-4 to their scale, consistent with our intent to span the general range of effects across our rating scale as described earlier (Table 5).

We interpret Table 5 as seen in Figure 7 -- giving a relationship between life stage survival and SEV (based on discussion in Newcombe and Jensen, we assume these results apply to actively rearing fish, as well as adult prespawners). Figure 7 is then easily converted to a relationship between our rating scale of 0-4 and life stage sensitivity (Figure 8).

The SEV index is easily computed by expressing suspended sediment in mg/l (which can be estimated from turbidity NTUs) and making a reasoned assumption about the percent of time during the worst case month (on average) when that concentration is attained. Further discussion on how this Attribute is to be rated can be found in Lestelle (2004)

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[9] / The correlate suspended sediment is described either as turbidity or suspended solids, though the latter is preferred. Turbidity is an optical property of water where suspended solids, including very fine particles such as clays and colloids, and some dissolved materials cause light to be scattered. It is expressed typically in nephelometric turbidity units (NTU). Suspended solids represents the actual measure of mineral and organic particles transported in the water column, either expressed as total suspended solids or suspended sediment concentration—both as mg/l. Technically, turbidity is not normally considered as suspended sediment, but we treat them together since they are usually well correlated.

Table 5. Scale of severity (SEV) index of ill effects associated with excess suspended sediment (adapted from Newcombe and Jensen 1996) and corresponding Level 2 Suspended Sediment ratings used in rule formulation.

SEV	Description of effect	Level 2 SS rating
Nil effect		0
0	No behavioral effects	
Behavioral effects		
1	Alarm reaction	
2	Abandonment of cover	
3	Avoidance response	
Sublethal effects		
4	Short-term reduction in feeding rates; short term reduction in feeding success	1
5	Minor physiological stress; increase in rate of coughing;	
6	Moderate physiological stress	
7	Impaired homing	2
8	Indications of major physiological stress; long-term reduction in feeding rate; long-term reduction in feeding success; poor condition	
Lethal and paralethal effects		
9	Reduced growth rate; reduced fish density	
10	0-20% mortality; increased predation	3
11	>20 – 40% mortality	
12	>40 – 60% mortality	4
13	>60 – 80% mortality	
14	>80 – 100% mortality	

Although it is readily accepted that higher temperatures act through synergism to increase the effect of suspended sediment, the extent of the effect has not yet been quantified in a manner to be included directly in the SEV index (Newcombe and Jensen 1996). The authors of the SEV state that the effect probably has to do with temperature-related patterns of oxygen saturation, respiration rate, and metabolic rate of fishes. From our review, we conclude that a noticeable effect of synergy between suspended sediment and temperature is needed in the rule to recognize this effect. We therefore assumed what is likely a conservative synergistic effect, setting the sensitivity to temperature (maximum) in the rule to add approximately 20-25% greater effect with intermediate temperature ratings when they occur with intermediate suspended sediment ratings.

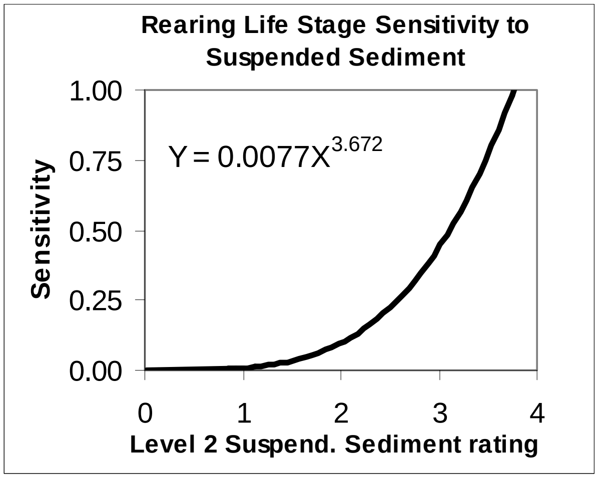

Figure 7. Relationship between scale of severity (SEV) index for suspended sediment (SS) and percent survival in rearing and prespawning life stages for salmonids – interpreted from Newcombe and Jensen (1996).

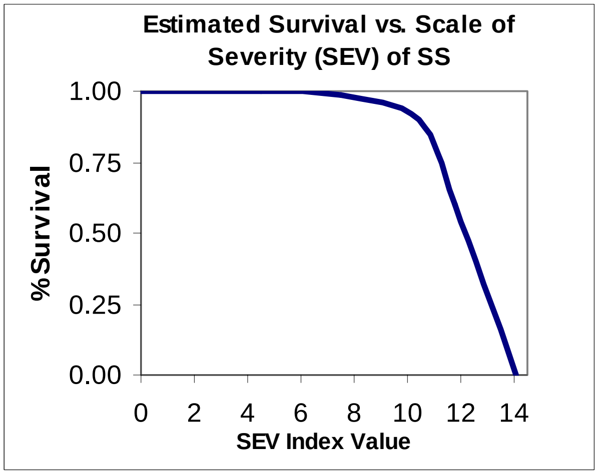

Figure 8. Relationship between ratings for Level 2 Suspended Sediment (SS) and sensitivity of salmonids during active rearing stages, derived by converting the relationship in Figure 7.

An additional note on the effect of sediment during the active rearing stage is warranted. Bjornn and Reiser (1991) summarize findings of several studies that suggest that embeddedness may further increase the effect of overall sedimentation during active rearing stages. Bjornn and Reiser conclude however that the effect likely occurs largely through reduced benthos as food for chinook. We concur with this interpretation—we address the effect of reduced benthos through the Level 3 factor food and not through sediment load.

Examples of results obtained by applying the rule described here are provided in Table 6.

Table 6. Example results obtained for the rule 0-age resident rearing-Level 3 Sediment Load for chinook and coho salmon and steelhead trout.

Life stage: 0-age resident rearing						
Attribute		Example				
		A	B	C	D	E
Suspended sediment (Primary)	Rating	2	2	3	3	3
	Sensitivity	0.098	0.098	0.436	0.436	0.436
Temperature (max)(Modifier)	Rating	0	2	0	2	3
	Sensitivity	0	0.001	0	0.001	0.005
Relative productivity		0.90	0.84	0.56	0.42	0.29
Benchmark survival		0.7	0.7	0.7	0.7	0.7
Absolute survival		0.63	0.59	0.40	0.29	0.20

Example 3: Inactive life stage – multiple Environmental Attributes based on a weight of evidence approach, including synergy

As in the previous case, this example involves two Environmental Attributes, assumed to act in synergy to produce a total sensitivity associated with sediment during the inactive rearing stage. The rule is based on a weight of evidence from several studies on the impact of substrate embeddedness on overwintering juveniles conducted over the past three decades. In addition, the rule incorporates a synergistic effect for suspended sediment, here acting as a modifying Attribute to embeddedness.

Embeddedness describes the extent that interstitial spaces between cobble and gravel on the substrate surface is filled with fine particles. Some species of salmonids use the voids between cobbles as hiding cover during the inactive (overwintering) life stage. It is well documented that the capability of the substrate to hold juvenile salmonids during winter diminishes as the substrate becomes more embedded (Bjornn and Reiser 1991)implying that overall habitat quality during this life stage declines with sedimentation. Further, the overall sensitivity to fine sediment during this stage can include effects of suspended sediment, as described above for the active rearing stages. Here, however, fish in the inactive stage are much less sensitive to suspended sediment (Noggle 1978), apparently because of reduced respiratory and metabolic requirements. We therefore allowed for some added effect of suspended sediment and assumed that it would operate to increase sensitivity identified with embeddedness in this case.

Efforts to quantify effects of embeddedness on overwintering juvenile chinook are based in large part on studies by Bjornn and others (1977). and Hillman and others (1987). Both studies reported that juvenile densities were reduced by more than half when cobble substrate became highly embedded. Juveniles are known to emigrate at the onset of winter from areas of high embeddedness and to keep moving until suitable substrate is found (Bjornn 1978). We are not aware of any studies in which mortality was specifically assessed in relation to embeddedness, though it is believed to increase under such conditions (Waters 1995). Presumably, some fish emigrate because survival of fish remaining in embedded substrates is lower than for migrants that successfully find better habitat. Moreover, if emigrants do not find suitable substrates (as must sometimes occur because the extent of sedimentation has increased over pristine conditions), their penalty might be an even greater reduction in survival than those that do not migrate from poor quality habitat.

Lacking a quantitative relationship to apply, we drew on Chapman and McLeod's (1987) interpretation of the Bjornn and others (1977) and Hillman and others (1987) studies. They concluded that a reduction in winter habitat must occur at embeddedness levels somewhere between 0% and 66% and at that level or higher that such areas would be made unusable by overwintering fish. They also stated: "We have no doubt that functional relationships exist between embeddedness and winter holding capacity of the substrate for salmonids, and that those relationships differ by fish size and perhaps by species."

We conclude from the foregoing that it is reasonable to hypothesize a functional relationship between the survival of fish that attempt to overwinter in embedded stream reaches and the degree of embeddeness. We hypothesize that the relationship between survival and embeddedness would show little effect up to about 66% embeddedness, and then exhibit a very rapid decrease in survival above that level (Figure 9). We recast the relationships in Figure 9 in terms of sensitivity corresponding to the Level 2 embeddedness ratings (Figure 10). We assumed that the sensitivities of chinook and steelhead to embeddedness during this life stage are the same. Chinook (Chapman and Bjornn 1969, Hillman and others 1987) and steelhead (Bjornn 1971, Bustard and Narver 1975, Everest and others 1986) both rely extensively on cobbles for overwintering cover.

In contrast to chinook and steelhead, coho use substrate for overwintering cover much less often, preferring undercut banks, rootwads, and off-channel habitat(Bustard and Narver 1975), Peterson and Reid 1984). When they do use substrate, they prefer unembedded cobbles to those that are embedded (Bustard and Narver 1975b). We conclude from this that coho are much less sensitive to embedded cobbles during winter than chinook and steelhead and formulated a rule accordingly (Figures 9 and 10).

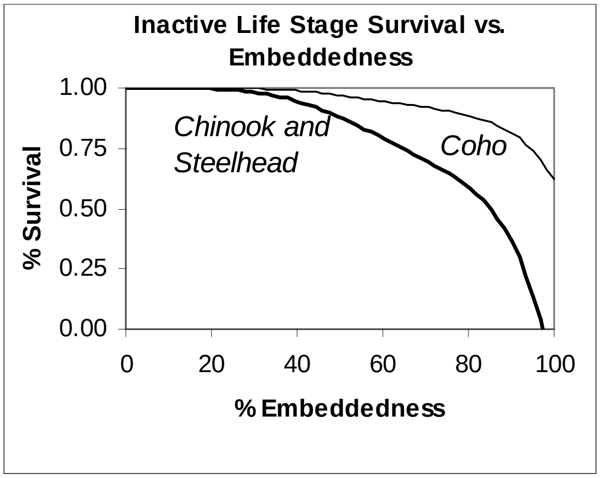

Figure 9. Relationships between survival and embeddedness for juvenile chinook, steelhead, and coho during the inactive (overwintering) life stage. The relationships are hypothesized based on general conclusions in Chapman and McLeod (1987).

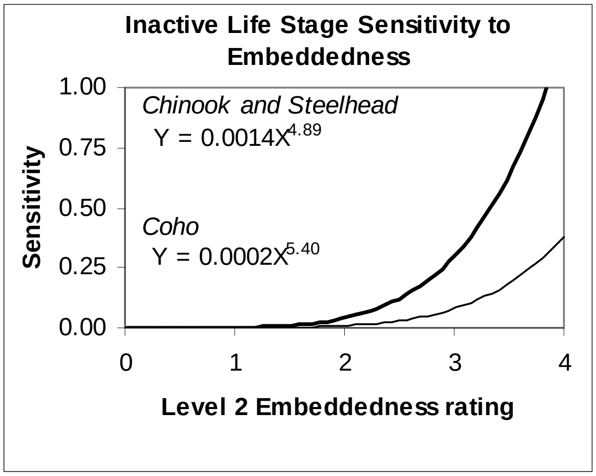

Figure 10. Relationships between ratings for Level 2 Embeddedness and sensitivity for juvenile chinook, steelhead, and coho during the inactive (overwintering) life stage—assumed based on general conclusions in Chapman and McLeod (1987). Coho sensitivity is shown with the thin line.

Additional mortality due to sedimentation could also occur if pulses of suspended sediment are sufficiently high. The tolerance of juvenile salmonids to suspended sediment during winter is known to be much higher than during periods of active rearing, likely due to a reduced state of activity. Still, some added effect associated with high SS doses is expected. We treat this potential effect as operating in a synergistic manner with embeddedness. If embeddedness is low, then the effect that might be ascribed to high suspended sediment doses should be much lower than if embeddedness is high, when fish should be more exposed to suspended sediment. We consider exposure here in the sense that fish would be more likely to enter the water column when embeddedness is high, instead of remaining in a resting state within the substrate when embeddeness is low. Hence a higher state of activity should make them more vulnerable to suspended sediment.

Examples of results obtained by applying the rule described here are provided in Table 7.

Table 7. Example results obtained for the rule inactive (overwintering)-Level 3 Sediment Load for chinook salmon.

Life stage: Inactive (overwintering)						
Attribute		Example				
		A	B	C	D	E
Embeddedness (Primary)	Rating	2	2	3	3	3
	Sensitivity	0.041	0.041	0.299	0.299	0.299
Suspended sediment (Modifier)	Rating	0	2	0	2	3
	Sensitivity	0	0.008	0	0.008	0.128
Relative productivity		0.96	0.86	0.70	0.44	0
Benchmark survival		0.7	0.7	0.7	0.7	0.7
Absolute survival		0.67	0.61	0.49	0.31	0

SECTION 4. RULES FOR ESTIMATING KEY HABITAT

Key Habitat is defined as the primary habitat type(s) utilized by a species during a particular life stage. Preference for habitat types changes with life stages. Some life stages, like egg incubation, occur almost entirely within three habitat types (i.e., pool-tailouts, glides and riffles), while other life stages, like actively migrating fish, use all habitat types.

The use of habitat types by individual life stages is not necessarily "all or nothing", however. For example, resident rearing by 0-age juvenile chinook does not occur equally in those habitat types that are utilized, some types that show use appear to be more preferred than others, while other types show almost no use.

The rules for Chinook and coho salmon and for certain life stages for steelhead trout were formulated by assigning weights to each habitat type to represent relative levels of preference based on patterns reported in the literature and in consultation with knowledgeable biologists. In addition, a different type of rule was applied to estimating key habitat for rearing juvenile steelhead, described later in this section. Literature used in formulating conclusions on habitat utilization are listed below:

- Chinook: Everest and Chapman (1972), Healey (1991), and Hayman and others (1996)
- Coho: Bisson and others.(1988b), Sandercock (1991), Nicklelson and others (1992a, 1992b)
- Steelhead: Hartman (1965), Bisson and others (1988a), Johnson and others (1988), Bjornn and Reiser (1991)

Percent Key Habitat (*%KeyHab*) for any life stage (except as noted below) was computed to be the sum of the weighted percentages of habitat types *i* within a geographic unit, as follows

$$\%KeyHab = \sum \%HabType_i * Weight_i$$

where $\%HabType_i$ is the percent of wetted channel surface area comprised of habitat type *i* and $Weight_i$ is the preference weight for habitat type *i* in the appropriate life stage. The habitat weights are easily derived from densities measured empirically for different habitat types, such as data on fish per square meter obtained by electrofishing in different seasons.

The format for the presentation of rules for the Level 3 Key Habitat attribute is shown in Figure 11.

In contrast to chinook and coho salmon, juvenile steelhead are known to use all habitat types for rearing. We therefore employed a relationship described by Johnson and others (1988) to compute a factor for adjusting downward percent key habitat, assuming that the percent key habitat is 100% at the maximum possible density (benchmark density) for each rearing life stage. The relationship estimates the rearing density of steelhead juveniles based on stream flow (or width in the absence of flow data) and channel gradient.

Level 3 -- Key Habitat
Species: Chinook Life Stage: Incubation

Definition: The relative quantity (%) of the primary habitat type(s) utilized by the focus species during a life stage; quantity is expressed as percent of wetted surface area of the stream channel. Environmental quality attributes characterize the quality of this habitat for the focus species.

Rule: The quantity of Key Habitat in a stream reach is computed from reach channel length, channel width, and percent of Key Habitat within the reach. Percent Key Habitat is estimated from habitat type composition based on a weighted sum of seven Level 2 Environmental Attributes (see table below) that quantify stream habitat types.

Contributing Level 2 attributes:

Level 2 attribute	Abbrev.	Weight	Rationale	Level of Proof
Habitat type - backwater pools	HbBckPls	0.00	Eggs placed by spawners; weighting same as for Spawning. Chinook spawning does not occur in backwater pools.	1
Habitat type - beaver ponds	HbBvrPnds	0.00	Eggs placed by spawners; weighting same as for Spawning. Chinook spawning does not occur in beaver ponds.	1
Habitat type - large cobble/boulder riffles	HbLrgCbl	0.00	Eggs placed by spawners; weighting same as for Spawning. Substrate size typically too large for chinook spawning in large cobble/boulder riffles.	2
Habitat type - primary pools	HbPls	0.00	Eggs placed by spawners; weighting same as for Spawning. Chinook spawning does not typically occur in pools.	2
Habitat type - small cobble/gravel riffles	HbSmlCbl	0.60	Eggs placed by spawners; weighting same as for Spawning. Chinook spawn heavily on riffles with substrate sizes suitable for nest building.	1
Habitat type - glides	HbGlide	0.40	Chinook spawn in swifter areas of glides, similar to pool-tailouts in characteristics.	1
Habitat type - pool tailouts	HbPlTails	0.80	Chinook spawning densities are typically greatest on pool-tailouts.	1

Examples:	Example 1			Example 2			Example 3		
Level 2 attribute	Percent of reach	Weight	Weighted percent	Percent of reach	Weight	Weighted percent	Percent of reach	Weight	Weighted percent
Habitat type - backwater pools	10	0.00	0.0	5	0.00	0.0	0	0.00	0.0
Habitat type - beaver ponds	10	0.00	0.0	0	0.00	0.0	0	0.00	0.0
Habitat type - large cobble/boulder riffles	5	0.00	0.0	20	0.00	0.0	50	0.00	0.0
Habitat type - primary pools	40	0.00	0.0	32	0.00	0.0	20	0.00	0.0
Habitat type - small cobble/gravel riffles	15	0.60	9.0	35	0.60	21.0	25	0.60	15.0
Habitat type - glides	10	0.40	4.0	4	0.40	1.6	2.5	0.40	1.0
Habitat type - pool tailouts	10	0.80	8.0	4	0.80	3.2	2.5	0.80	2.0
Sum	100		21.0	100		25.8	100		18.0

Figure 11. Example of the use of Key Habitat in EDT for the Incubation life stage of Chinook salmon. The Weight is an assumption about the relative preference of the habitat types for the life stage. The lower box shows an example of the weighted percent Key Habitat given a description for a stream reach: $\%KeyHab = \sum \%HabType_i * Weight_i$

The rearing density for yearling parr *ParrDensity* is calculated from the equation

$$ParrDensity = 26.335 \times Flow^{-0.25} \times \%Gradient \times e^{(-0.1447 \times \%Gradient)}$$

where *Flow* is the low flow in cfs and *%Gradient* is the channel slope. The assumed maximum possible parr density was computed at a gradient of 4%. The adjustment factor *KeyHabAdj* to key habitat then is simply

$$KeyHabAdj = ParrDensity \div BenchmarkDensity$$

where *BenchmarkDensity* is the benchmark density for the appropriate life stage.

SECTION 5. RULES FOR ESTIMATING FOOD

Food is a Level 3 factor that modifies both productivity and capacity. In EDT, food affects survival through both density-dependent and density independent effects and is an essential element of both habitat quantity and quality. For this reason, Food appears in the Rules Viewer as both a habitat quality factor affecting Productivity (Food re: productivity) and a habitat quantity attribute affecting Capacity (Food re: capacity).

A. Food (re:Capacity)

The importance of food to population performance is a truism so evident that it is often ignored in analyzing salmonid population response to environmental change. The nascent understanding of the role of salmon carcasses in affecting basic stream productivity and food abundance for juvenile salmonids (Cederholm and others 2001, Stockner 2003) has emphasized the need to include food when modeling salmonid response to habitat change.

The effects of food in EDT are based in large measure on work by Ptolemy (1993). We use the Ptolomy relationship to scale the Benchmark densities (Appendix B) to account for local conditions associated with food availability. Ptolomy developed equations for estimating maximum salmonid densities in fluvial habitats based on fish size and nutrient indicators in British Columbia streams considered to be at or near full seeding and with little or no environmental disturbance. Further studies since his original publication continue to validate the equations (Ron Ptolemy, personal communications).

Ptolemy's work is built on Allen's (1969) observations that the maximum density of a life stage of stream-dwelling salmonids within in an area of stream is a function of fish size. Allen's concept was further developed by Grant and Kramer (1990) who concluded that fish size explained 87 percent of the variation in territory size. For a given size of fish, the density that can be supported in an area of habitat would be limited by the amount of aquatic food available. Mason and Chapman (1965) and Chapman (1966) hypothesized that the spatial requirements of fish limit their density below ceilings *set by the food supply*. Mason (1976) found proof of such food limitation for juvenile coho in a field study where he supplemented the natural food abundance in a stream. Subsequent work in British Columbia with nutrient enrichment of streams has produced strong evidence for food limitations (Stockner 2003).

While the concept relating food in streams to maximum fish density is well established, a quantitative relationship linking food and density is not available. To get around this, we assume that there is a relationship between stream alkalinity and food. We then use the relationship between alkalinity and fish density developed by Ptolomy (1993) to calculate maximum fish density for different life stages. The key concept in our use of Ptolomy's equation is that while he related stream alkalinity to fish density, the actual relationship is between food and fish density. In other words, alkalinity itself has no direct impact on fish density, but rather it has an indirect impact due to its control on general stream productivity and, therefore, on food. In streams with conditions less optimal than those studied by Ptolomy, food is also affected by the health of the benthic invertebrate population, quantity of salmon carcasses and the amount of allochthanous inputs from the riparian zone in addition to stream alkalinity. Because of this, we develop a term for use in Ptolomy's equation that incorporates a broader definition of food, and we assume that this food term affects fish density in the manner portrayed by Ptolomy for alkalinity alone in the pristine streams he studied. Ptolemy's equation for the relationship between fish density for a life stage and alkalinity is:

$$Fish\_Density = 3300 \times ALKA^{0.5} \times SIZE^{-3}$$

where *Fish_Density* is measured in fish per m^2 of habitat, *ALKA* is alkalinity and *SIZE* is fork length in cm.[10] In EDT, an index of food based on Level 2 Attributes is converted to an alkalinity term (*ALKA*) and used in Ptolomy's equation to estimate maximum fish density for a life stage. The EDT index of alkalinity based on food attributes for use in Ptolomy's equation is created in two steps: first, development of a food index based on Level 2 Attributes, and second, creating a relationship between this food index and the stream alkalinity term in Ptolomy's equation.

The index of food availability in EDT incorporates four Level 2 Environmental Attributes:

- Alkalinity—use of this attribute is based on knowledge that alkalinity affects primary and secondary productivity of streams;
- Benthic Community Richness—this attribute describes benthic diversity and is a measure of how land use affects food availability, measured by the B-IBI;
- Riparian Function—this attribute reflects potential contributions of terrestrial insects to fish food availability;
- Salmon Carcasses—this attribute defines the relative quantity of salmonid carcasses within the area.

EDT incorporates these four Attributes to derive a FOOD index for each stream as:

$$FOOD = 4 - \left[\sum_j (a_j \bullet ATT_j^{\,b_j}) \right]$$

where *a* and *b* are rule parameters for the Level 2 Attributes of alkalinity, benthos, riparian function, and salmon carcasses (ATT_j). This results in an index for Food that is scaled from 0-4 with a 0 indicating a lack of food and a 4 indicating a super abundance of food (note that this is opposite of the categorical ratings for most attributes). We then associate the range of alkalinity seen across the Pacific Northwest to our scale of 0-4 for food ratings (Figure 12). This relationship results in a value of "alkalinity" for use in Ptolomy's equation that incorporates a broad measure of food controls applicable to streams with significant anthropogenic constraints on environmental conditions. Using Ptolomy's equation with this food term, we calculate a maximum fish density for a given environmental condition.

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[10] / The equation differs slightly for coho for reasons given in Ptolemy (1993).

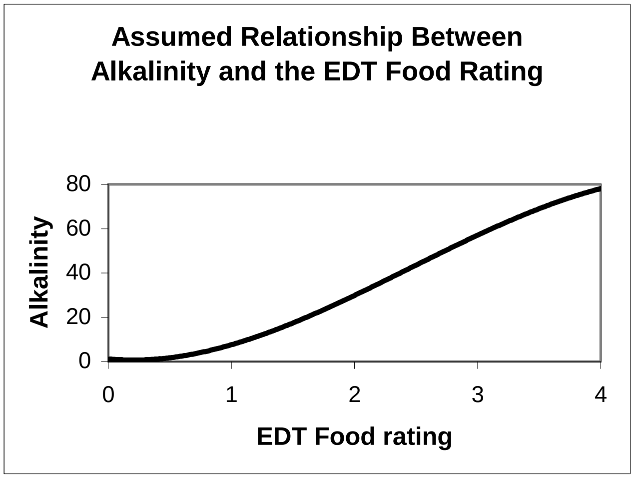

Figure 12. Assumed relationship between food rating and total alkalinity, based on the range of alkalinity values applied by Ptolemy (1993). Alkalinity here is used as a surrogate of total food availability in a stream to juvenile salmonids.

The last step in calculating the fish density is to use the density derived above, which accounts for the food availability in the stream, to adjust the Benchmark densities in Appendix B and derive the final fish density for the stream. To do this, we compute a scalar between 0 and 1 that reflects the adjustment described above to the Ptolomy estimate of density as a result of food abundance in the stream:

$$Food\_Scalar = Fish\_Density / Max\_Density$$

where, *Fish_Density* is the fish density adjusted for food conditions in the stream that comes from the Ptolomy equation, and *Max_Density* is the fish density from the Ptolomy equation when all the food attributes are set to their maximum (best) value. Finally, *Food_Scalar* times the Benchmark density in Appendix B gives the adjusted fish density that is used to compute capacity in the stream.

B. Food (re:Productivity)

To this point in the food discussion, the results are applied in a manner that affects how food abundance affects Capacity. We also apply the food rating to adjust Productivity, consistent with evidence that suggests that food characteristics affect survival at very low population densities, i.e., in the absence of density effects. Ward and others (2003) and Wilson and others (2003) found that enrichment of food resources in oligotrophic rivers of British Columbia using fertilizers containing marine derived nutrients significantly increased survival even when populations were extremely depressed. This suggests that the quality of food resources can be enhanced in such a manner that it affects survival even when competition for food should be minor.

To estimate the effect on productivity, we apply the attribute ratings in the **Synergistic Form** of the productivity equation presented earlier. The shape of the relationship between Level 2 Attributes and Food (re:productivity) can be viewed in the Rules Viewer. The resulting survival factor F_i is allocated equally across the number of relevant life stages for the species (four life stages for Chinook and coho each and seven life stages for steelhead).

Although much research is now being focused on improving understanding about what affects food abundance in streams and how it is utilized by fish, there remains considerable uncertainty (Stockner 2003). Results of EDT incorporating effects on both capacity and productivity, however, produce results that compare favorably with how coho and steelhead populations have been found to respond to stream enrichment studies in streams in British Columbia (Ward and others 2003, Wilson and others 2003). We tested the rules by looking at how additions of salmon carcasses affect population performance. Modeling results showed that Productivity and Capacity were increased significantly by adding salmon carcasses where depleted and to an extent comparable to the findings from British Columbia.

SECTION 6. LEVEL OF PROOF

The species-habitat rules in EDT are working hypotheses based on a synthesis of existing knowledge of salmonid biological in streams of the Pacific Northwest. The existing knowledge that goes into the rules comes from a variety of sources including published, peer reviewed literature, “grey” literature that comes from contract report or other unpublished sources and from conclusions from recognized experts in the field. As a result, some of the rules are firmly grounded in existing science while others may be more speculative. To recognize this range of certainty associated with the existing scientific knowledge base, we have established four levels of proof for each Attribute Rule (Table 8). Almost all rules in EDT are currently rated a 1 or 2 proof level. This is not to say that even rules with a level of proof of 1 will not be refined as knowledge improves. Ultimately, all aspects of EDT and the rules are open to discussion and refinement. EDT is intended to be a “knowledge capture tool”—a vehicle for assembling a collective statement about how salmonid fishes experience the environment. EDT is not designed to prove anything but rather to apply existing knowledge to important watershed problems. In this way we believe that the region can make the best decisions possible at a point in time, recognizing that scientific and social uncertainties dictate the need for an adaptive approach.

Table 8. Levels of proof assigned to the use of Level 2 Environmental Attributes in EDT Species-Habitat rules.

Level of proof	Evidence
1	Thoroughly established, generally accepted, good peer-reviewed empirical evidence in its favor
2	Strong weight of evidence in support but not fully conclusive
3	Theoretical support with some evidence from experiments or observations
4	Speculative, little empirical support

SECTION 7. LITERATURE CITED

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