



**RIPPLE**  
**A Digital Terrain-Based Model for Linking Salmon  
Population Dynamics to Channel Networks**

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## MODEL OVERVIEW

RIPPLE is a process-based, integrative, adaptive modeling framework incorporating state-of-the-art science and tools for understanding how habitat and ecosystem processes affect salmon populations. The model couples geomorphological information with biological and aquatic habitat data. RIPPLE is made up of three sub-models: (1) a physical model (“GEO”), (2) a habitat carrying capacity model (“HAB”), and (3) a population dynamics model (“POP”).

One of the guiding principles of RIPPLE is the assumption that physical processes and the resulting environment—specifically topography, geology, climate, drainage area, channel gradient, channel longitudinal profile—are essentially time-invariant compared with ecosystems and the animal and plant populations supported by these ecosystems. This assumption enables us to construct a model that establishes a physical template composed of such information as topographic data, channel networks, and geology. The physical template exerts important controls on the distribution and abundance of salmonid life stages that occupy different parts of the watershed (GEO). RIPPLE uses the physical template to predict reach-specific historical, current, and potential future salmon habitat (HAB). RIPPLE then employs a multi-stage, stock-production model (POP) that is spatially explicit; e.g., adult and juvenile salmon can migrate through the watershed in search of available habitat.

## 1 GEOMORPHIC LANDSCAPE UNIT CLASSIFICATION

A landscape-scale stratification or classification is necessary before one can apply RIPPLE. The goal of such classification systems is to identify relatively homogenous regions, or units, for which a single set of characteristics can be developed and then applied without need to verify their accuracy at every site. Ideally, a relatively small number of units in a given region, each of which spans a relatively large area, can be identified and characterized. The physical attributes of a geomorphic landscape unit (or “GLU”) are what the GEO component uses to provide the physical template for RIPPLE.

There is no single “best” method for classifying and subdividing a landscape—the approach will depend on the area being considered and the use to which the classification will be put. As input to RIPPLE, our classification objectives will be to identify relatively homogenous “subregions” where:

1. channel-size parameters provided to RIPPLE are consistent, so that relationships between drainage area, channel depth, and sediment transport are accurate despite the heterogeneity of the landscape;
2. any limitations on sediment delivery of a given grain size (a consequence of the underlying lithology not producing those sediment sizes) are recognized;
3. runoff and sediment-delivery processes are relatively homogenous (and distinct from other GLUs);
4. channel classification based on slope, grain size, confinement, and drainage area are applicable over the entire area; and
5. habitat quality and quantity (adjusted for drainage area) associated with a given channel type is relatively consistent.

“Ecoregions” and “process domains” are two of the most widely applied landscape classification approaches. Ecoregions are contiguous areas that “generally exhibit similarities in the mosaic of environmental resources, ecosystems, and effects of humans” (Omernik 1995, p. 49). Their delineation depends on geology and soils, topography, climate and hydrology, vegetation and wildlife, and human factors. They are also scale-dependent; the U.S. Environmental Protection Agency defines several “levels” of ecoregions, of which “Level 2” covers all of the coterminous United States at a relatively coarse scale, and “Level 3,” where defined, discriminates between finer subdivisions. At this level, classes are delineated on the basis of geomorphology, lithology, soils, vegetation, fauna, climate (annual means and seasonality of precipitation and temperature), surface water, natural disturbances, land use, and human modification of the landscape.

Process domains are a conceptual framework within which “spatial variability in geomorphic processes governs temporal patterns of disturbances that influence ecosystem structure and dynamics” (Montgomery 1999). As with ecoregions, process domains are spatially hierarchical; unlike ecoregions, however, physical attributes dominate in terms of characterizing homogeneous regions, while biological conditions are treated as simple dependent variables. Human factors are not typically considered in this approach. The coarsest spatial scale (“geomorphic provinces”) is defined by topography, climate, and tectonic setting; the next finer scale (“lithotopo units”) is determined by differences in geology and topography.

The tasks involved in defining GLUs within a study area include:

1. Compiling available literature and data on regional geology, climate, and other landscape-scale parameters to make a preliminary determination of distinct GLUs;
2. Using a combination of scientific literature and new field-based measurements to establish GLU-specific and/or regional empirical relationships, including:
  - relationships among drainage area, bankfull width/depth, winter base flow, and summer low flow;
  - relationship between channel slope and channel type, to assign a modified Montgomery and Buffington (1993) classification;
  - grain-size limitations imposed by underlying geology;
  - potential for significant groundwater losses or additions, as a result of either geologic controls or anthropogenic conditions;
  - any particular conditions that may render stream channels susceptible to unusual heat loadings from the adjacent landscape.
3. Using the results of Task 2, refining the number of distinct GLUs to be used in subsequent modeling and management evaluations.

## **2 THE GEO MODEL**

The GEO model comprises several tools, procedures, and semi-empirical and physically-based algorithms implemented within a GIS framework, which are used to assemble and parameterize watershed-scale fluvial geomorphic, channel network, and hydrologic information. Combined, these data represent the physical environment template upon which all subsequent habitat modeling and population dynamics are performed.

Because of its importance to running GEO, a detailed discussion of channel network generation and parameter attribution is included before discussing the GEO model proper. Accurately and

consistently assembling and attributing the geomorphic and hydrologic data is an essential precursor to the GEO model. A RIPPLE-ready channel network needs to have three fields before starting the model:

- **ARC\_ID:** This is the key field. It defines a unique ID for each arc from which GEO, HAB and POP output tables are linked to the channel network shapefile. Each Arc segment is defined by the intersection of a channel network arc with elevation contours or by the confluence of two channels.
- **SLOPE:** RIPPLE defines slope as the drop in elevation between the intersections of a channel arc with the two contiguous elevation contours, divided by the length of the arc.
- **FROMAREA:** The drainage area to the upstream extent of an arc in the channel network (node in ARCINFO terms).

The units of the channel network need to be in meters. Habitat carrying capacity and population tables are processed assuming the coordinate units are meters. Results are presented in units/meter.

A simple approach to obtaining a RIPPLE-ready channel network is to use EPA's NHD+ hydrography, adding the three fields shown above, creating a unique arc-id for each arc and converting slope and drainage area values to those required by RIPPLE (e.g. 100% slope is be 1 and drainage area values need to be in square meters). NHD+ hydrography does not represent well lower order streams and slopes are taken from the USGS 30m DEM but it will be easily set for training purposes.

The time and effort invested in assembling and parameterizing an accurate, reliable stream channel network directly affects all subsequent habitat computations and population dynamics modeling. The quality and resolution of the input data to GEO is important, but equally if not more important are the methods used to process, assemble, and parameterize input data. This section describes Stillwater Sciences' approach to assembling fluvial geomorphic and channel network information in GEO and compares our approach to some of the more commonly applied strategies. The section also lists and describes the source data required to operate GEO.

Accurately quantifying channel gradient and drainage area for entire channel networks is a formidable challenge. Several approaches apply automated or semi-automated techniques toward quantifying these attributes, but many if not most of these approaches have serious flaws. Stillwater Sciences has adopted an alternative "hybrid" approach that combines several tools and algorithms with which to extract and attribute the channel network, along with incorporating pre-processing and manual editing in order to extract the best available channel network.

Source data resolution affects the quality and consistency of the stream classification system. The time invested in generating a reliable, consistent channel network demands that input data be resolved at scales commensurate with the extra effort required to process that data (minimum 1:24,000). This is not the case for coarser resolution data (e.g., USGS 30-meter DEM or 1:100,000 blue-line hydrography). Applying the GEO to individual or multiple basins requires both local data and information as well as more regional information. For example, hydraulic geometry (bankfull and summer lowflow widths and depths) can be computed using regional hydraulic geometry formulae—typically organized according to largely uniform lithologic-topographic units.

## 2.1 Preparing the channel network for GEO

RIPPLE assumes that geology and topography are fundamentally immutable over the time frames relevant for modeling biological responses, e.g., <1,000 years. In effect, the GEO model defines a time-invariant, physical template over which biological habitat is stratified and species population dynamics modeling are conducted.

### 2.1.1 Channel network generation

Accurately characterizing the full spatial extent of the stream channel network is fundamental to effectively implementing the GEO model. Generating a reliable, comprehensive channel network consumes most of the data processing, and manual editing and revision effort. In contrast, most other network generation approaches adopt one of two strategies, both of which are considerably less labor-intensive. One is an automated threshold-area approach that uses only a DEM as input. These automated channel extraction techniques apply several rule-based algorithms to route flow down throughout the watershed, and apply flow orientation information to define a channel when it equals or exceeds a predefined (typically defined by the user) threshold area. The other major strategy extracts the channel network using only stream channel data freely available from the USGS (usually 1:24,000 or 1:100,000 digital line graph hydrography).

While both approaches have their merits, they are both flawed in different, but significant ways that severely limit their applicability. Threshold-area routines perform satisfactorily where there is sufficient relief to guide the channel-routing algorithms. In low-lying, floodplain areas with little change in relief, the algorithms perform poorly, often substantially so. The extracted channel network for these low-lying areas is highly prone to error. Routinely, the extracted network barely matches that which is observed.<sup>1</sup> Channel artifacts generated by threshold-area techniques can translate into significant errors when computing channel gradient and drainage area.

By contrast, USGS 1:24,000 blueline hydrography data (typically digitized from 7.5-minute USGS quadrangles) accurately depict the higher order, perennial channel network. However, USGS bluelines omit many of the smaller, low-order channels within the network. As a result, USGS bluelines significantly underestimate drainage density, especially during the wet season. From the perspective of fish population modeling, the limitations of using a channel network generated solely from USGS bluelines data are mostly related to (under) estimation of overwintering habitat.

The chief limitations of these two network generation approaches suggest adopting a third approach that combines the best of the each and eliminates (or significantly reduces) the worst. Stillwater Sciences has developed a suite of tools and algorithms that combine the USGS blueline channel network with a threshold-area channel network creating an ‘aggregate’ or ‘extended’ channel network that more accurately depicts the watershed in low-relief, floodplain areas (the USGS blueline network), while capturing most of the small, low-order channels in the headwaters (channels generated by automated, threshold-area techniques). Combining the USGS blueline channel network with the threshold-area channel network is far from straightforward, however. The majority of the GIS pre-processing effort prior to running GEO is devoted to generating and manually editing the merged (or extended) stream channel network and ensuring that it is correctly georeferenced to local topography (contours).

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<sup>1</sup> By “observed” we mean the channel network as defined by digitized USGS bluelines, typically resolved at a scale of 1:24,000.

## 2.1.2 Channel network parameter attribution

### 2.1.2.1 Channel gradient

Stream channel gradient is computed using a contour-based approach relying on vector contour data (preferably USGS digital line graph hypsography, but if these are unavailable, contours interpolated from the DEM will suffice). Algorithms developed by the UC Berkeley Geomorphology group, the University of Washington Department of Geology, and Stillwater Sciences compute channel gradient using a procedure that involves the intersection of stream channels with contours. Where a stream intersects a contour, a node is created and that node is attributed with the elevation value from the contour with which it intersects. This is a key feature of our approach and distinguishes it from most other strategies, which typically use only a DEM to attribute channels. The latter approach is especially problematic for lower-gradient reaches, where there is little change in elevation over long stretches, and hence where the potential for attributing incorrect elevations increases significantly (calculated negative channel gradients are not uncommon when applying DEM-based channel attribution strategies). Significantly, these low-lying, low gradient areas are often of critical importance as fish habitat, and thus, flawed channel attribution routines may significantly under- or overestimate available habitat. Lunetta et al. (1997) attempted to circumvent this problem by resampling 30-meter DTM data into 150-meter units (5 x 5 grid cells) and averaging across the resampled distance. While this method does reduce the likelihood of elevational artifacts it results in significant overgeneralization of the elevational field and introduces artifacts by the process of generalization itself.

By exclusively using vector channel data and 1:24,000 digital line graph contours, we ensure that we are using the best available data for calculating channel gradient and eliminating the artifacts introduced by using a generated digital terrain model.

### 2.1.2.2 Drainage area

The Arc/Info GRID module includes several hydrologic functions that can be used to compute drainage area for entire basins. A flow routing algorithm takes an elevation DEM and applies a “steepest-descent” criterion to define direction of flow. For a nine-cell neighborhood, with the center-cell being the cell of interest, the algorithm searches for the maximum elevational drop between itself and one of the eight adjacent cells. If there is no unique maximum elevation drop, then flow direction remains undefined. In this instance, the grid cell is considered a “sink”—there are several techniques used in Arc/Info and also developed by the U.C. Berkeley Geomorphology laboratory and Stillwater Sciences, to fill these (typically artificial) sinks.

Accumulated flow uses the flow routing information computed above, and calculates the number of upstream cells or pixels that flow into any given pixel. Arc/Info-derived drainage area is then simply the product of the number of upstream cells and the area of the cell.

The procedures for calculating drainage area correspond, necessarily, to those for generating the calculated, threshold-area network described above. As mentioned above, however, Stillwater’s extended channel network approach integrates both the blueline network and the threshold-area network. This requires that we adopt an alternative approach to computing drainage area.

The principal channels depicted by USGS bluelines best represent main channel planform position. However, these mainstem bluelines, particularly in low-gradient floodplain reaches, rarely match the computed threshold-area channels generated using Arc/Info’s hydrologic

routines. The chief reason for the discrepancy is insufficient elevation information in the DEM to guide the routing algorithms. Our approach to accurately attributing drainage area involves several steps that are conceptually straightforward (e.g., “entrenching” the river network by dropping its elevation by a uniform value, and then re-running the Arc/Info FLOWDIRECTION and FLOWACCUMULATION algorithms), but computationally cumbersome and very time-consuming. However, the net result is a channel network accurately and consistently attributed with drainage area for each reach.

### **2.1.3 Definition of a stream reach for use in GEO**

A stream reach in GEO is defined as a channel delimited either by contour intersections or tributary junctions (Figure A-1). As noted above, where contours cross the channel, a node is created and an elevation assigned to that node. Nodes are also created at tributary confluences. The result is a vector channel network discretized into reaches that are delimited either by contour intersections or tributary junctions. This represents the reach-scale analysis used in RIPPLE and hence the finest resolution of analysis performed. We recognize that neither contour data nor channel networks are evenly distributed across a basin and thus reach lengths will vary—shorter in steep, incised terrain, and considerably longer (up to tens of kilometers) in low-gradient, floodplain areas.

## **2.2 GEO Source Data Requirements**

As discussed in Section 2 of this report, a RIPPLE-ready channel network requires three fields prior to starting the model: ARC\_ID, SLOPE, and FROMAREA. With those fields in hand, the GEO model can be initiated.

Source data required by the GEO model includes topographic data and a digital channel network. These data should be resolved at scales no smaller than 1:24,000.

GEO input data requirements include:

1. Digital elevation data: 10-m minimum resolution. (e.g., USGS 10-m DEM).
2. Stream channel network (e.g., USGS digital line graph hydrography [bluelines]).
3. Vector-based contours, if available (e.g., USGS 1:24,000 digital line graph hypsography). If vector contour data are not available, contours need to be generated from the DEM.

High-resolution topographic (LIDAR, IFSAR) data and remotely sensed imagery (NAIP, hyperspectral, DOQQs, etc.) are becoming more widely available. While these data may be substituted for coarser resolution data, the techniques that are described in this section are not appropriate for high-resolution data. LIDAR data, for example, acquires elevational information sufficient to characterize the full two-dimensional structure of the channel network. However, the tools and algorithms described in this section are only appropriate for one-dimensional channel networks. Stillwater Sciences’ approach and algorithms for LIDAR data are described elsewhere.

## 2.3 Predicted Geomorphic Variables

### 2.3.1 Bankfull and summer lowflow hydraulic geometry

River channel systems are organized, hierarchical features that systematically collect and transport water and sediment down through the system. Considerable empirical support (e.g., Leopold and Maddock 1953, Leopold et al. 1964) demonstrates that with increasing discharge, channel geometry (width and depth) and velocity systematically increase according to well constrained power law functions:

$$w = aQ^b, d = cQ^f, \text{ and } v = kQ^m$$

where  $w$  is width,  $d$  is depth,  $v$  is velocity,  $Q$  is discharge, and  $a, b, c, f, k,$  and  $m$  are coefficients. Drainage area scales with discharge according to power law relationships, so the common practice is to substitute drainage area for discharge in places where there is sparse discharge data. This means that hydraulic geometry relationships can be generated using field-surveyed hydraulic geometry measurements acquired from only a handful of sites selected throughout a basin or Geomorphic Landscape Unit (GLU).<sup>2</sup>

### 2.3.2 Predicted median grainsize ( $D_{50}$ )

A prediction of bed surface material size is implemented in GEO. Theory and empirical observation support the notion that, for gravel-bedded rivers, transport of significant amounts of bedload sediment will occur primarily during flows at or about the bankfull stage (Parker 1978, Leopold et al. 1964). The median grainsize under such conditions can be predicted from the Shield's shear stress equation, which assumes incipient particle motion when the driving forces (fluid stresses) equal and exceed resisting, tractive (grain weight resistance) forces per unit area of bed (Raudkivi 1990). Rearranged, it can predict the median grainsize under conditions of bankfull flow:

$$D_{50} = \frac{\rho h S}{(\rho_s - \rho) \tau_c^*}$$

where,  $D_{50}$  is the median grainsize,  $g$  is gravitational acceleration,  $\tau_c^*$  is the critical Shield's stress,  $\rho_s$  and  $\rho$  are sediment and fluid densities respectively,  $S$  is channel slope, and  $h$  is bankfull depth. Cast in this form, the only variables are channel slope and bankfull depth, both of which have been computed for every stream channel arc throughout the network (Buffington et al. 2004).

### 2.3.3 Channel confinement

Channel confinement is defined as the ratio of valley width (VW) to bankfull channel width (BW) (Montgomery and Buffington 1993), and provides a guide for identifying channels with different frequencies and magnitudes of ecologically relevant disturbance processes. For confined channels, bed shear stress increases with increasing flow depth, and as discharge increases above bankfull stage in confined channels, depth continues to increase, generating greater bed shear stresses and sediment transport capacity. For unconfined channels, flow can

<sup>2</sup> Geomorphic landscape units (GLUs) circumscribe areas of relatively homogenous lithology and topography and climate. By stratifying a region of interest into lithotopo units, a suite of regionally-based hydraulic geometry relationships can be developed and applied to basins which fall within the same GLU.

spread across the floodplain above bankfull stage, moderating increases in depth and sediment transport capacity and depositing sediment on the floodplain. Montgomery and Buffington (1993) suggest three confinement categories: (1) confined ( $VW < 2 BW$ ), (2) moderately confined ( $4 BW > VW > 2 BW$ ), and (3) unconfined ( $VW > 4 BW$ ). A recently developed and fully implemented, GIS-based algorithm can now be used to automatically attribute confinement to the entire channel network (previously it had been assigned only to channels where independent methods (e.g., aerial photographic interpretation) had been used to stratify confinement classes).

Quantifying channel confinement for entire channel networks is important because it is an indicator of available salmonid habitat. In mountainous areas, unconfined reaches can represent locally unique sites where channel gradient and sediment transport capacity are locally decreased, gravel substrates are abundant (in contrast to the cobble-boulder substrates characteristic in steep, confined channels), low-velocity overwintering habitats are available in side-channel or floodplain areas, and production potential for salmonid populations may be high.

Table 1. Channel attributes generated prior to and during GEO model.

<p>Morphometric and topologic channel arc attributes (generated prior to RIPPLE)</p>	<ul style="list-style-type: none"> <li>• Shreve stream ordering scheme (Shreve 1966)</li> <li>• Strahler ordering scheme (Strahler 1952)</li> <li>• Elevation at upstream arc end</li> <li>• Elevation at downstream arc end</li> <li>• Channel gradient</li> <li>• Drainage area</li> </ul>
<p>Derived or predicted channel arc attributes (generated in RIPPLE)</p>	<ul style="list-style-type: none"> <li>• Predicted median grain size (<math>D_{50}</math>) on the bed</li> <li>• Bankfull width and depth</li> <li>• Summer low flow width and depth</li> <li>• Channel confinement (currently calculated outside RIPPLE)</li> </ul>

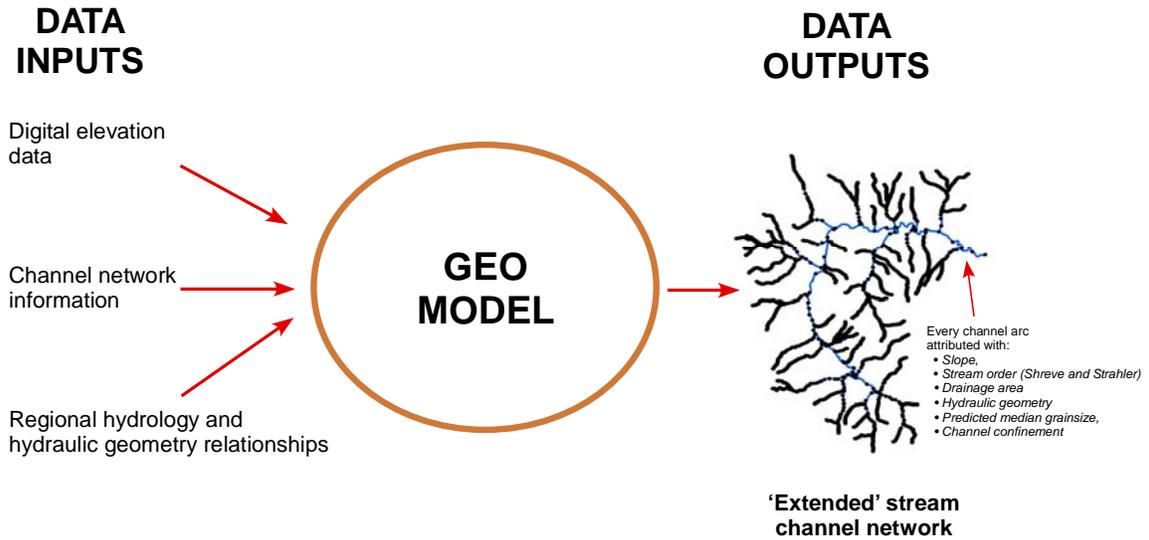


Figure 1. GEO model.

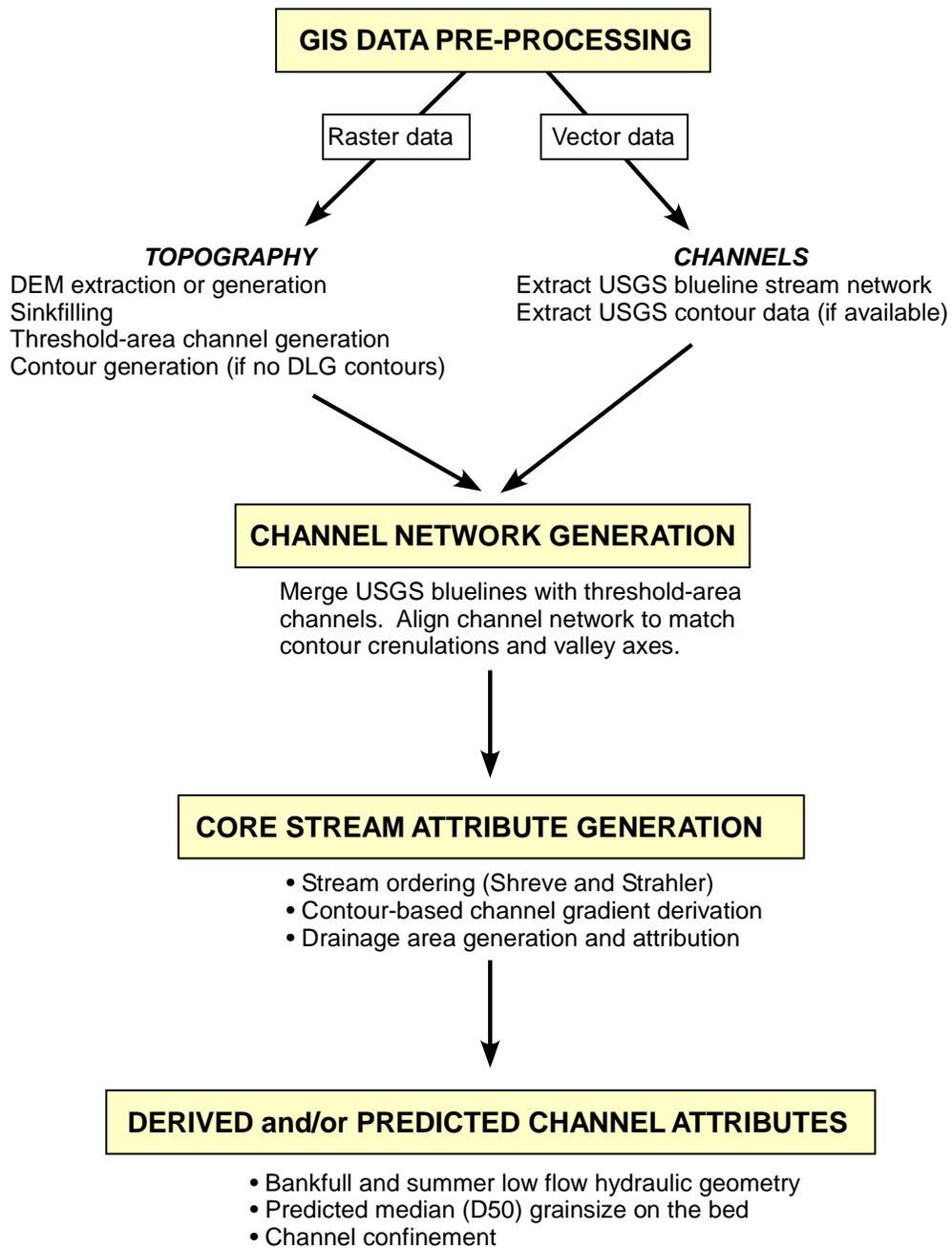


Figure 2. GEO model workflow.

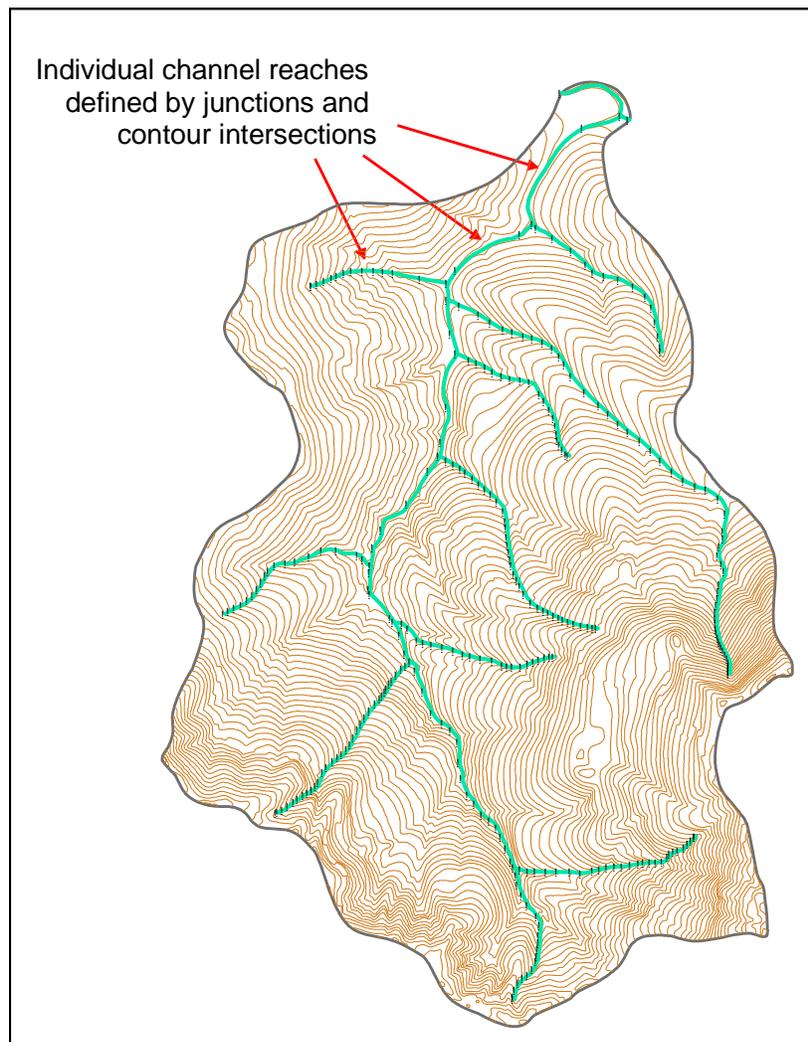


Figure 3. Channel reaches defined in the GEO model.

### 3 THE HAB MODEL

The HAB model uses the attributed channel network developed in the GEO model as a framework for defining habitat quality and quantity for different salmonid life stages.

The primary goal of the HAB model is to calculate life-stage-specific carrying capacity. Carrying capacity is the maximum number of individuals of a given life stage that the available habitat can be expected to support. To further refine carrying capacity estimates, habitat criteria thresholds can be used to identify channel reaches for analysis. Threshold parameters include channel gradient, habitat surface area, and channel width and depth at various stream flows. Thus, estimates of carrying capacities can reflect seasonal differences in channel width and estimates of available habitat that were empirically determined at the reach scale from running the RIPPLE GEO model component. In this way, minimum width and depth thresholds are used to preclude some areas of the channel network as useable fish habitat at the reach scale.

#### 3.1 Methodology

##### 3.1.1 Channel type determination and channel classification for different geomorphic landscape units

Once physical processes have been evaluated and geomorphic landscape units have been delineated, the next step is to determine how channel morphology (in particular, those aspects that create and maintain habitat for the various life stages of the target species) varies as a function of channel gradient, confinement, and drainage area for each GLU. Classifying channel types stratifies a channel network into logical groups of channel segments that exhibit similar geomorphic characteristics and habitat features for the species and life stages of interest. Natural variability within a channel type is to be expected, and habitat values used describe channel types generally reflect average conditions.

A channel classification system modified from Montgomery and Buffington (1997) is used to define channel types for each GLU. Channel types refer to functional units of the channel network that have similar channel and floodplain morphology. This channel classification scheme stratifies the channel network by gradient and confinement categories to define channel types. Channel gradient strongly controls transport processes (e.g., fluvial transport vs. debris flow), bed shear stress, the ratio of sediment transport to sediment supply, and grain size (in loose boundary channels). Channel morphology therefore varies directly with gradient. Channels formed at steeper gradients ( $>0.03$ ) typically have step pool and cascade morphologies, while channels formed at lower gradients typically have plane bed and pool riffle morphologies. Channel gradient in a drainage basin channel network generally decreases in the downstream direction and is often closely related to confinement, where steeper channel gradients are typically more confined.

Channel confinement controls width-to-depth ratio and unit stream power, limits changes in channel width and sediment storage, and maximizes channel response to increased discharge (Montgomery and Buffington 1997). Confinement in a drainage basin channel network typically decreases in the downstream direction. Mountain channel reaches are commonly confined by a resistant boundary (e.g., bedrock or large immobile clasts) or by colluvial deposits where hillslope processes (e.g., mass wasting) deliver sediment directly to the channel, while valley reaches may be confined by colluvial or alluvial terrace deposits. Confined channels typically

have high unit stream power, lower gravel and cobble entrainment thresholds for a given drainage area, supply-limited mass balance, and limited accommodation space for sediment deposition. These factors contribute to bedrock, cascade, step pool, and plane bed morphologies where gravel and cobble deposition is limited to patches associated with large roughness elements (e.g., boulders, bedrock outcrops, and large wood), planform curvature, and local backwater effects from channel width contraction or expansion. Riparian habitat and supply of large wood from riparian areas is typically limited in confined channels. Conversely, unconfined channels typically exhibit plane bed and pool riffle morphologies with low unit stream power, smaller grain sizes per unit drainage area, more accommodation space for sediment deposition in active channel bars and floodplains, and more riparian habitat.

While Montgomery and Buffington (1993) gradient categories correlating to channel bed morphologies provide useful guidelines, and may be used as a default in the absence of site-specific information, in practice, channel gradient and confinement categories used to define channel types within the HAB model should be developed separately for each geomorphic landscape unit (GLU) and should correlate with biologically important habitat characteristics for the species of interest. This is because the abundance and distribution of different salmonid species and life stages will vary among channel types according to a given species' preferences for particular habitat characteristics. For example, coho salmon tend to spawn and rear in small- or mid-size streams in reaches with moderate gradients (<3%), and the coarse cobble and boulder substrates that are often used as winter cover by other salmonids, such as steelhead and coastal cutthroat trout, are frequently not available. Overwintering coho salmon, therefore, are often found in slower velocity habitats such as floodplains, sloughs, off-channel water bodies, beaver ponds, and complex in-channel habitats associated with large woody debris jams. Conversely, steelhead tend to spawn in higher gradient reaches (>3%) with confined stream channels where off-channel water bodies such as sloughs and backwaters are typically rare. As a result, steelhead show less propensity than coho for using off-channel slackwater habitats in winter, and a greater propensity for using in-channel cover provided by cobble and boulder substrates, which are typically common and usually immobile at all but the highest flows in these areas. Therefore, the life histories and habitat use of different salmonid species are differentially influenced by characteristics of gradient and confinement and channel type delineations should correlate to these preferences.

Similarly, for a given species, a particular life stage may be distributed across several channel types within a basin, but the abundance of that life stage may vary according to differences in habitat characteristics between channel types. For example, juvenile coho salmon show a strong preference for rearing in low velocity habitat provided by pools, but pool morphology differs between channel types. As gradient increases above three to four percent (depending on the GLU), and stream channels change from forced pool-riffle to step-pool morphologies, pool habitats tend to become more turbulent. For juvenile coho salmon, the proportion of usable area within a pool may decrease in higher gradient channels, and, therefore, the biological value of a channel type for that lifestage (expressed as fish density) will decline.

Table 2. Example of channel type classification.

	Unconfined (VW >4 x BW)	Moderately-confined (2xCW <VW <4 x BW)	Confined (VW <2 x BW)
<1%			
1–3%			
3–6%			
6–12%			
>12%			

Channel network segments in GEO are grouped (or binned) according to channel type.

### 3.1.2 Applying filters

The foundation of the HAB model is a base map (GIS channel network) including all reaches within the study area having potentially suitable habitat for the species and life stages of interest, from which portions of the basin are “filtered” out from consideration, based on field observations, local knowledge, and review of existing information. For example, entire subbasins may appear to contain suitable spawning and rearing habitat for Pacific salmon based on channel classification, but in fact are not suitable due to high water temperature, or large substrate particle-size characteristics. The final HAB model uses external data in GIS overlays as filters to assign a carrying capacity of zero for all portions of the basin excluded in basin-wide carrying capacity estimates, as described in specific examples below.

To apply filters, habitat criteria for each species and life stage are determined. A process of filtering for all species and life stages is then used to determine the final life-stage-specific carrying capacity from the HAB model. For example, suitable habitat for Chinook salmon spawning within a subbasin may ultimately be restricted to accessible stream reaches where: (1) drainage area exceeds 15 km<sup>2</sup>, (2) predicted median substrate size (D50) is between 20 and 80 mm, and (3) water temperatures are less than 60.8°F (16°C).

#### 3.1.2.1 Migration barriers

Dams, waterfalls, debris jams, and excessive water velocities may impede fish access into otherwise suitable habitat. Identifying locations of human-made barriers (e.g., dams, culverts) is straightforward, since most structures are well documented. However, assessing whether or not a natural obstruction (e.g., falls, cascade, chute) is a barrier is challenging. Falls that are insurmountable at one time of the year may be passed at other times under different flows (Bjornn and Reiser 1991). Classifying natural features as barriers requires empirical observations of fish distribution (i.e., no fish observed above barrier), or extensive observations of fish failing to pass a particular feature. The knowledge of experts in the basin can be very useful for identifying known barriers. If such information is not available, detailed surveys of the feature can be conducted. Powers and Orsborn (1985) reported that the ability of salmonids to pass over barriers is dependent on the species and life-stage-specific swimming and jumping ability of the fish, the horizontal and vertical distances to be jumped, and the angle to the top of the barrier. Surveys of features in the field often provide species and life-stage-specific estimates of how often, and under what flow conditions features are barriers. Another option in the HAB model is to use gradient/distance relationships to filter out channels that have a long distance (e.g., >1 mile) of high gradient (e.g., >15%) channel. Once the information on barriers (natural or otherwise) is compiled, it can be used to filter out portions of the basin where particular life-stages of specific fish species will be excluded (carrying capacity = zero), despite predictions of habitat suitability.

Reaches could be removed from the network of potentially suitable spawning habitat if they occurred above barriers to fish migration, including permanent barriers (geologic waterfalls) and more ephemeral barriers (decadent beaver dams).

### 3.1.2.2 Drainage area and channel size thresholds

Channel size thresholds are used to restrict the extent of habitat considered suitable based on physical constraints to species utilization.

Pacific salmon tend to be spatially segregated with a basin, partially by selecting different channel sizes. For example, steelhead will often use tributary and upper watershed habitat for spawning where it is available (Briggs 1953, Reavis 1995, while fall Chinook salmon often prefer to spawn in the mainstem or lower portions of large tributaries (Yoshiyama et al. 1996). Channel size requirements also differ between life stages, with some species (e.g., coho salmon) spawning in tributaries with small drainage areas, and rearing in larger mainstem rivers. Data is available in the scientific literature to establish species and life-stage specific channel size thresholds; e.g., Sebastian et al. (1991) for steelhead; Holsinger and Pess (2003) for Chinook salmon; Burnett (2001), Nemeth et al. (2004), and Beechie et al. (2005) for coho salmon; and Rosenfeld et al. (2000) for cutthroat trout. Channel size, or geometry, can be predicted for GLUs in the Geo model based on deriving best-fit power functions of channel width as a function of drainage area drainage area to bankfull width relationships, most often calibrated by empirical data (i.e., cross sections) (see Section 3). Typically the relationships are used to predict portions of the basin with channel sizes that are below the threshold of use for each species life stage included in the analysis. For example, small (and often steep) tributaries and upper watershed habitat will not be considered suitable for Chinook salmon spawning, whereas very little habitat would be excluded as suitable for cutthroat trout with the same filter.

### 3.1.2.3 Predicted bed particle size thresholds

Substrate particle size composition has been shown to have a significant influence on intragravel flow dynamics (Platts et al. 1979). Pacific salmon may therefore have evolved to select redd sites with specific particle-size criteria that will ensure adequate delivery of dissolved oxygen to their incubating eggs and developing alevins. In addition, salmon are limited by the size of substrate that they can physically move during the redd building process. Substrates selected likely reflect a balance between water depth and velocity, substrate composition and angularity, and fish size. The useable range of  $D_{50}$  values (the median diameter of substrate particles found within a redd) for Pacific salmon have been well documented (e.g., Kondolf and Wolman 1993). The importance of coarse substrate with interstitial space for rearing of some salmon species has more recently become recognized, and could possibly be used as a filter for rearing habitat of some species (e.g., Rosenfeld et al. 2000).

Data to support filtering out portions of the basin can be based on estimated particle size distribution from the GLU model, as well as site-specific pebble counts, or other field data. Particle size distribution is then overlaid with other HAB model results to filter out unsuitable reaches. For example, a reach that meets gradient requirements for Chinook salmon spawning may be filtered out based on substrate particles that are either too fine or too coarse for suitable spawning.

#### 3.1.2.4 Water temperature thresholds

Most fish maintain body temperatures that closely match their environment. As a result, temperature has a strong influence on almost every life history stage of Pacific salmon and steelhead, including metabolism, growth and development, timing of life history events such as adult migration and emergence from the redd, and susceptibility to disease (Groot et al. 1995). Extensive data exists in the literature defining thermal tolerances of Pacific salmon for all life stages, from incubation, rearing, migration, to spawning. In many basins, stream reaches or entire tributaries may be predicted to contain suitable habitat based on parameters in the GLU and HAB models, but do not have suitable temperatures for one or more life stages.

Data with which to make temperature determinations within a basin can come from a variety of sources, including long-term temperature monitoring at specific locations or Forward Looking Infrared Red (FLIR) data (e.g., Torgersen et al. 2001). In basins where detailed temperature data is not available, other sub-models, such as BasinTemp or SNTemp can be used to predict annual temperature regimes. Temperature data can then be used as a filter to exclude some species and/or life stages from portions of the basin. For example, some reaches may be excluded as spring Chinook spawning habitat due to high temperatures during fall, while remaining suitable for other life stages. In some stream reaches, temperatures may be outside thermal tolerances for all life stages, and thus the entire reach may be excluded as habitat for all life stages.

#### 3.1.3 Channel reach delineation and habitat attribution

Channel reaches are spatially explicit groups of channel network segments (from GEO) defined by channel type (gradient and confinement) and composed of habitat units. Channel reaches are the functional unit for which carrying capacity is calculated. The channel network segments comprising a channel reach are attributed with the same HAB-specific parameters (i.e., habitat type proportion, density by species and life stage, and usability by species and life stage). Each channel network segment contains unique physical attributes such as length and width (from GEO) that are used to calculate habitat area, and ultimately, carrying capacity.

Each channel reach is composed of habitat units that vary in size and suitability. The different types of habitat units defined reflect channel features that vary in their value and use by different salmonid species and life stages. RIPPLE currently uses a classification of four habitat types including pool, riffle, and run habitats where each channel type within a GLU is composed of a similar proportion of these habitat units. Although the proportion of habitat units is similar between reaches of the same channel type, the quantity of habitat within a channel reach is not. Habitat area is calculated based on channel size using a drainage area relationship (from GEO) according to the location of the reach within the drainage basin.

Habitat unit classification systems were developed to standardize terminology and facilitate comparative analysis of aquatic habitats. These systems generally rely on a hierarchical organization of unit types (Bisson et al. 1982, Hawkins et al. 1993, Frissell et al. 2005) where an appropriate level of habitat type specificity can be used based on the application. These classification systems generally depend on physical channel features [e.g., channel gradient, geometry, and position (side channel vs. main channel, off channel)], local hydraulics (width, depth, velocity, surface turbulence), substrate characteristics (bed particle size), and habitat-forming mechanisms (LWD, boulders, bedrock) to define habitat types. The number of habitat unit types used in RIPPLE to define habitat characteristics within a GLU can be adjusted depending on regional differences in habitat composition and/or their relative value and use by different species and life stages.

Fish density by species and life stage are derived for each habitat type (i.e., pool, riffle, run, and cascade) and channel type from literature values and focused field studies as described above. These densities relate directly to usability, and the relationship between usability and density is usually determined by the available data. For example, if suitable spawning habitat (i.e., gravel patches) data is available, the percent usable area can be limited only to that area which is suitable. This, in turn, correlates to a higher density than would be used if gravel patch data were unavailable. Conversely, suitable winter habitat data is rarely available and winter densities are frequently determined in spring for entire habitat units compared with determining the area and density for habitat used during winter as refuge. Under this scenario, the percent useable would be 100%, and density would be far less than would be expected for refuge habitat alone.

RIPPLE currently uses four habitat types (pool, riffle, run, and cascade) to describe habitat composition within a channel type. Differences in the value and use of these habitat types by different salmonid species and life stage varies based on channel type (gradient and confinement) and the various filters used (described below).

In order to determine the appropriate habitat types to use to define habitat in RIPPLE, the following aspects should to be considered (1) the composition of habitat types by channel type in the basin, (2) the biological value of each habitat type by channel type, species and life stage, and (3) the available information for applying biological value to each habitat type. We currently believe that defining habitat using pool, riffle, run, and cascade habitat types provides the broadest application and has the strongest support in the literature regarding associating usability and density to specific habitat types. RIPPLE can be modified to incorporate a more elaborate system of classifying habitat types or add additional habitat types. Expanding the number of habitat classifications could be beneficial in large river systems with complex low-gradient reaches.

Habitat units in RIPPLE are represented as the proportion of total channel area (or length) for a given channel type. Currently, spatial information (i.e., the relative position of the segment within the watershed or assessment area) is not incorporated into the model. Segments within each channel reach are attributed with relative proportion of pool, riffle, run, and cascade habitat by area (or length). The number, sequence, or relative location of individual units are not currently used. The proportion of pool, riffle run, and cascade habitat types within a channel type is generally empirically derived from literature or field work.

The existing habitat types represent a partition of the in-channel habitat into disjoint categories. In the future, an additional habitat type will be added to represent habitat outside the main channel (e.g., floodplains, side-channels, or backwaters). This “floodplain” habitat will be calculated from an arc-specific “floodplain width”, assigned separately from the existing channel width measures (e.g., bank-full width and summer low-flow width). This will be multiplied by the full length of the arc (rather than some fraction of the length, as the in-channel habitat), to yield an area. Floodplain area will then be converted into floodplain carrying capacity by means of usability and density factors, just like the other habitat types. We do not have a simple model for predicting floodplain width, such as the hydraulic geometry relationships used to set the other channel width measures. Instead, floodplain widths will be assigned directly by the user.

RIPPLE can incorporate site-specific habitat data by reach by applying the appropriate proportion of habitat unit area to the reach. In the future, reaches will be able to be attributed with real habitat unit data, where the sequence and relative location of habitat units can be maintained. This will allow life history and bioenergetic factors to be evaluated with greater precision. For

example, use of spawning habitat by spring Chinook salmon may be correlated to distance from preferred holding pools in which habitat in close proximity to these holding pools has higher utilization. For another example, riffle length upstream of pools may correlate to food delivery, where very short riffles may not provide sufficient drift for maximum rations.

### 3.1.3.1 Determining habitat suitability/applying usability and density

In order to account for differences in the amount of a habitat useable by a species or life history stage, a “useable area” parameter is incorporated into the model. Fish density values reported in the scientific literature are typically determined by dividing the number of individuals observed by the total habitat area, implying that 100% of a given habitat area is useable (i.e., density is calculated based on 100% of the habitat area). Fish are often concentrated in only a portion of a specific habitat unit, however, suggesting that carrying capacities should be based on useable area of each habitat, rather than total area. For example, usually only the tails of pools are appropriate for spawning, given gravel distribution and hydraulics. Spawning density is therefore most accurate and useful when calculated as the number of individuals spawning as a function of pool tail area.

Because some juvenile salmonids smolt at age 1+ or older, and must spend at least one summer and winter in fresh water prior to outmigrating to the sea, they tend to establish territories<sup>3</sup> in suitable rearing habitat soon after emergence, whereas others (such as fall Chinook, chum, pink, and sockeye salmon) only spend a few weeks or months in the rearing stream (Mason 1966). Territories ensure access to sufficient food supply (Kalleberg 1958). The role of territories in regulating individual growth is an important mechanism for partitioning a finite food resource among juvenile salmon (especially in summer when low stream flows reduce invertebrate production and higher temperatures increase metabolic demand). Larger salmon smolts may have a higher probability of returning as adults, especially when ocean conditions are less than optimal (Holtby et al. 1990). If territories were not established and defended by individuals, theoretically the result would be either mortality due to starvation or a large number of small smolts that would have very poor ocean survival. The size of individual territories (and thus rearing density) may vary from location to location as a function of food availability and temperature, with territories becoming smaller in more productive or physically complex habitats or colder streams (Mason 1976, Dill et al. 1981).

The maximum densities of overwintering age 0+ steelhead that a reach of stream can support are determined by territorial/agonistic behavior, both with conspecifics and with other salmonids when they are present. For example, age 0+ steelhead and age 0+ coho salmon are potential competitors for space in streams where both species are found. Their behavioral interactions are primarily determined by fish size, with larger fish having a competitive advantage. In contrast to coho salmon, which spawn in the late fall and emerge early in the spring, peak steelhead spawning typically occurs in March (Shapovalov and Taft 1954) with emergence occurring in late spring. Consequently, steelhead fry emerge later in the year than coho salmon and are typically at a size disadvantage to juvenile coho salmon, which have had weeks or months of exogenous feeding within the stream prior to steelhead emergence. Since coho salmon prefer pool habitat over other habitat types and are competitively dominant over steelhead of the same year class, they tend to displace or reduce the density of age 0+ steelhead within pools. Therefore, in years

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<sup>3</sup> We use the term territory and territory size not only in its traditional sense—as a particular defended area—but also in cases where defense of a particular area may not occur but agonistic behavior by dominant individuals (e.g., nips, fin extensions, charges) effectively determine the maximum density of rearing juvenile coho in a pool.

of low juvenile coho density the density of age 0+ steelhead in pools may increase as the density of coho declines. A clear example of this come from fish surveys in Devil’s Gulch, a tributary to Lagunitas Creek, Marin County, California. In this stream, the abundance of age 0+ steelhead appears to respond positively to increased space available in pools during years of lower juvenile coho abundance and negatively in years of high juvenile coho abundance.

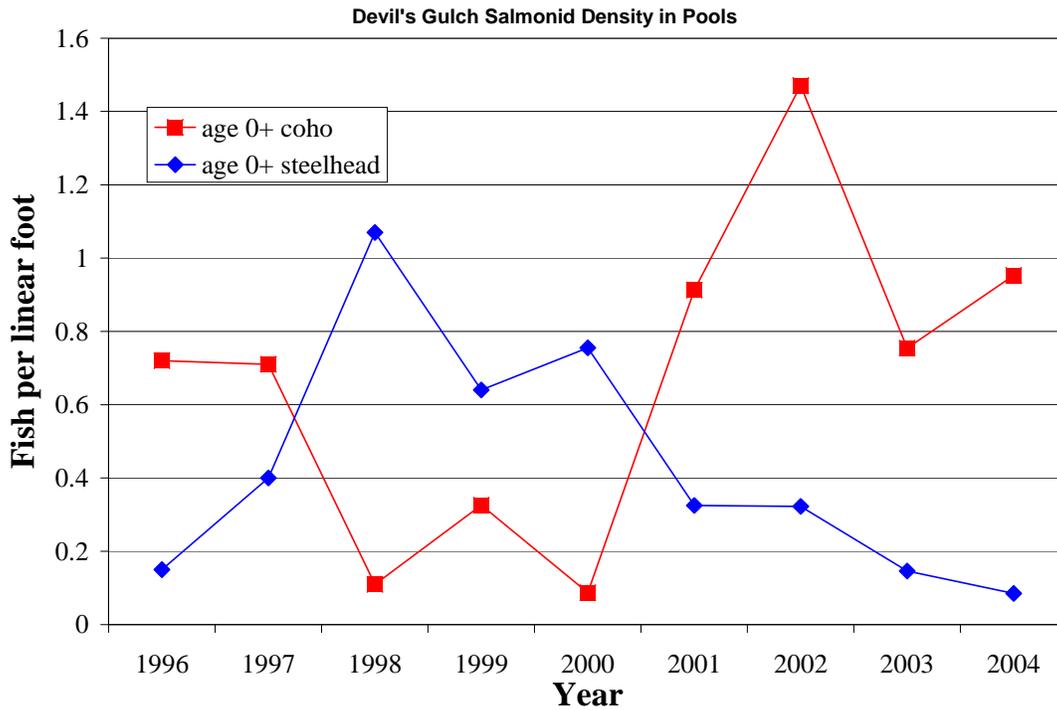


Figure 4. Age 0+ Coho and steelhead density in Devil’s Gulch, Marin County, CA

### 3.1.3.2 Calculating carrying capacity

Carrying capacities pertain to the maximum number of individuals the available habitat is expected to support in the *absence* of any constraints imposed by population dynamics for a given species. Habitat carrying capacity is calculated for each stream segment and summed by reach. Fish habitat carrying capacities at the reach scale is calculated as:

$$C_R = A_T [(AUD)_p + (AUD)_r + (AUD)_g + (AUD)_c]$$

where:  $C_R$  = reach-scale carrying capacity,  $A_T$  = total reach area, and  $AUD_{p,r,g,c}$  = product of habitat area (A), usability (U) and species density (D) for pool, riffle, glide, or cascade habitat units. Habitat carrying capacity for reaches can then be summed for specific subbasins or for the entire watershed. Total predicted carrying capacity is the sum of reach-specific estimates. As specified in the above formula, channel reaches were subdivided into the representative proportions of pool, riffle, glide, and cascade habitat areas anticipated for current and historical conditions.

“Effective” or actual carrying capacity may be less than predicted carrying capacity due to constraints on life stage distributions. For example, if fry habitat is present upstream of, or in a location where no spawning habitat is present, it would not be considered useable (or effective).

### 3.2 Data Requirements

Source data required by the HAB model includes physical characteristics developed by GEO model including the digital channel network, gradient predictions, channel geometry (bankfull width and depth), drainage area, and bed particle size predictions. Other data requirements include:

- habitat typing data
- density information by species and life stage for different channel types
- usability information by species and life stage for different channel types

Methods used to estimate parameter distributions vary, depending on the population. First, it is necessary to identify the data available for each population. For parameters for which no local data are available, we may rely on values from the scientific literature. For many parameter distributions, values derived from a review of published and unpublished literature are sufficient and appropriate. In other cases, contact with experts actively involved in local research may be necessary. For each parameter, we use the best available data from which to develop distributions, as determined through review by experienced Stillwater Sciences staff or discussions with other scientists. Whenever possible, we use data specific to the population of interest to estimate parameter distributions. When these are not available, we extrapolate using data from populations as similar as possible to the population of interest. Standard statistical approaches are employed, such as calculating means and variances where appropriate. For some carrying capacity estimates, bootstrapping techniques may be used to form confidence intervals.

Freshwater survival rates are based on local information where possible. Beyond the emergent fry life stage, freshwater survival is assumed to be governed by both density-dependent and density-independent factors. Typically, density-dependent factors play a larger role in determining survival than density-independent factors; the modeled numbers of fish produced at each life stage are typically greater than the estimated number that the habitat can support. Due to this dominance (or high model sensitivity to carrying capacity values), efforts focus on estimating the uncertainty associated with carrying capacity parameters.

## 4 THE POP MODEL

“The POP model” is actually a family of closely-related models, one for each population of interest. The present notes describe a generic representative of this family.

The design of POP represents a balance between the desire for transparency and the desire for realism. The model is kept as simple as feasible, so that the model assumptions are visible and explicit to users, and in particular so that unusual or unexpected results can be traced back to specific assumptions. On the other hand, a model is of use to managers only to the extent that it can inform management decisions: this requires that physical or biological processes be represented with a degree of fidelity appropriate to the questions expected to arise.

The intended users of RIPPLE can be expected to ask questions about the consequences of land-use proposals which require the model to make use of geographically specific habitat information, and to represent the effects of these data on fish with an equal degree of geographic specificity.

### 4.1 Model Architecture

POP is organized as a so-called “generalized stock-production model” in the sense of Baker (in press).

In the stock-production style of population modeling, calculations are organized around life stages (discrete landmarks in individual development, such as hatching or smoltification) and stage-to-stage relationships. The model’s highest-order abstractions represent groups of individuals sharing a common stage of development (rather than, say, a common location in time and space), and the basic computational steps are transitions between stages (rather than advancement in time).

The life stages of POP typically mark fundamental changes in the way fish interact with habitat. Emergent fry cease to be constrained by subsurface gravel conditions; end-of-summer juveniles mark the transition from a summer emphasis on growth to a winter emphasis on riding out high flow events, and so on. The basic motivation is that each stage-to-stage transition should be associated with a particular dimension of physical habitat.

#### 4.1.1 Life stage representations

In “classical” stock-production models, each life-stage is represented by a single number (the total number of organisms occupying that stage), and stage-to-stage relationships are simply functions, generally chosen from a very small library of standard forms such as Beverton-Holt, hockey stick, or Ricker functions.

This is inadequate for the needs of RIPPLE users, however. GEO and HAB assign attributes to individual arcs of a channel network, and users can be expected to take an interest in the relationships between local changes in habitat conditions and local responses of fish to these changes.

Inland life stages of the model are therefore represented primarily by arrays, reporting abundance at each arc of the network. Arc abundances are stored as a linear densities (fish/m), facilitating

GIS display of fish distributions. The total abundance (obtained by multiplying densities by arc lengths and summing over the network) is also calculated and stored as a life-stage attribute.

#### 4.1.2 Stage-to-stage relationships

The stage-to-stage relationships of POP determine the values associated with the representation of one life stage from the values associated with those of parent life stages.

These relationships are implemented by model subroutines which may become quite complicated. For example when the life stages involved are all inland stages, the stage-to-stage relationships must create a spatial pattern of abundance for some stage using the spatial patterns of abundance of the parent stages. Typically, this will require the model to consider the character and distribution of habitat throughout the channel network, and movement of fish from one part of the network to another.

In classical stock-production theory, when life stages are represented as simple numbers, stage-to-stage relationships are simply functions. One of the great attractions of classical stock-production theory is that the forms most often used for these functions are characterized by just two parameters. For example, a function  $y$  of  $x$  is in Beverton-Holt form if it can be written as

$$y = rKx / (rx + K)$$

for some values of  $r$  and  $K$ . Moreover, the parameterizations can be chosen in such a way that the parameters have natural biological interpretations: one (usually called “ $r$ ”, as above) can be interpreted as an intrinsic survival or productivity rate under conditions in which competition or crowding can be ignored; the other (usually called “ $K$ ”) can be interpreted as a carrying capacity. There is an extensive body of knowledge about the relationship of intrinsic productivities and carrying capacities to physical habitat data: the stock-production paradigm provides a simple and natural way to apply this literature to population modeling.

The clarity and simplicity of the “ $r$ - $K$ ” approach are very attractive, and in fact such relationships form the heart of POP. A typical stage-to-stage relationship looks like this:

1. Redistribute fish of the first life stage through the channel network, assessing mortality associated with fish movement as appropriate and keeping track of the numbers of fish leaving the system entirely.
2. For each arc, use  $r$  and  $K$  parameters appropriate to that arc to calculate the number of fish of the second life stage in that arc.

#### 4.1.3 Redistribution rules

It is helpful to distinguish between “major migrations”, associated with turning points in life history, in which fish travel significant distances in response to more or less mysterious internal drives, and “minor migrations”, occurring during a period of rearing between two life stages, in which fish may move around in a strictly local search for food or habitat.

##### 4.1.3.1 Major migrations

Major migrations include the run of adults upstream, from the mouth of the system to arcs containing spawning habitat, and the run of smolting juveniles downstream, from their rearing habitat towards the ocean.

The seaward migration of smolting juveniles is implemented in a straightforward manner. Juveniles are simply transferred from each arc to the arc immediately downstream, while assessing a mortality based on the length of the arc traversed and accounting for additional problems at barriers (barriers are discussed below). The survival of migrants is assumed to decay exponentially with distance traveled: this is equivalent to assuming that all fish traversing a given arc will experience the same chance of death, regardless of how they reached that arc. The migration survival parameter is expressed in “half-life” form, that is, as the migration distance over which expected survival would be 50%. Logically, this is an arc-specific value, which could depend on conditions in the arc, however it is currently treated as a single user-provided parameter.

#### 4.1.3.2 Minor migrations

The other category of migration considered in the model is movement of rearing animals in response to local habitat conditions. POP makes several fundamental simplifying assumptions.

First, the decision of fish to remain in an arc or to attempt migration to another arc is based solely on habitat conditions and population density in that arc. Specifically, the stock-production relation specific to that arc is used to calculate an expected survival at the current population density; fish are forced to outmigrate until this expected survival rises to an acceptable level. This assumption reflects the desire for model clarity and simplicity. In particular, alternatives seem to require fish to somehow make use of information about conditions in other parts of the stream network, or for model users to provide large amounts of geographically-specific empirical information. This treatment of redistribution requires only a single user-provided parameter (the minimum acceptable expected survival), and is rooted in a simple model of fish psychology.

Second, each stage-to-stage redistribution is assumed to be strictly downstream or strictly upstream. This is primarily for computational convenience, since it allows redistribution to be calculated with a single pass through the network.

Finally, the survival of migrants is assumed to decay exponentially with distance traveled. This is also a matter of computational convenience; it is equivalent to assuming that all fish traversing a given arc will experience the same chance of death, regardless of how they reached that arc. The migration survival parameter is expressed in “half-life” form, that is, as the migration distance over which expected survival would be 50%. Logically, this is an arc-specific value, which could depend on conditions in the arc; however, it is currently treated as a single user-provided parameter.

#### 4.1.3.3 Barriers

In the future, the model will be able to explicitly address migration barriers. A barrier is a feature which prevents or inhibits otherwise expected movement of fish. Examples of barriers include cascades, culverts, and dams. A feature may be a barrier to one life stage but not another (because of seasonal changes in the nature of the barrier, or the different needs of different life stages), or may impede passage in different directions to different degrees. RIPPLE users can be expected to ask questions about the likely consequences of adding, removing, or modifying such features, so POP represents barriers in a flexible and general way. Each barrier record applies to a single life stage, and can control movement in a single direction; multiple barrier records can be associated with a single arc. A barrier record specifies what fraction of fish otherwise expected to cross the arc boundary will attempt to pass the barrier, and of these, what fraction will survive the passage.

## 4.2 Data Requirements

POP requires data of several different kinds.

- In order to account for fish movement, POP requires “topological” information about the channel network, that is, information about how arcs are connected together. This takes the form of a database table with one record per arc. These data are identical with those used in the input data to the GEO model.
- Information about barriers is provided by a database table with one record per barrier.
- POP requires arc-specific “K” values for each arc of the channel network for each inland life stage of the modeled population; in some cases, arc-specific “r” values are needed as well. These data are normally obtained as the output of the HAB model.
- Finally, biological parameters of POP not associated with particular arcs, such as minimum acceptable survival values, and many “r” values such as fecundities, are provided by a database table with one record per parameter.

## 4.3 Model Operation and Reporting

POP is implemented as a free-standing executable file, compiled from platform-independent C++ source code. It is possible to invoke POP directly from a command line, but it is more naturally and conveniently called from within RIPPLE’s graphical user interface. This interface allows model parameters to be viewed and changed via dialog boxes, and generates graphical displays of model results. It also provides some management of module dependencies (for example, it sees to it that HAB is run before POP), and keeps track of alternate versions of parameter files.

The model generates two kinds of output: static spatial patterns of long-term average abundance for each inland life stage, and time-series of total abundance for each life stage. The former can be displayed on a map; the latter used to generate graphs, or to digest the entire GEO/HAB/POP assumptions about the system into a single number, such as “long-term average escapement” for purposes of assessment or comparison.

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