# Forest Management and Coho Salmon Population Dynamics in Southeast Alaska's Staney Creek Watershed

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# EXECUTIVE SUMMARY

In an effort to better understand physical conditions and the biological health of the Staney Creek Watershed, this report provides an overview of historical land use, detailing human-induced watershed disturbances and the benefits of conserving old growth forests. Coho salmon were selected as an indicator of ecosystem health and used to enumerate the biological benefits of alternative future scenarios. As one of five Pacific salmon species documented in the Tongass National forest, coho salmon exhibit an extended freshwater residency which provides a year round barometer of watershed health.

Following the overview of coho life history and population trends, a population dynamics model was developed for coho salmon in the Staney Creek Watershed. The spatially explicit model was used to quantify the distribution and abundance of coho salmon under current conditions (Current Conditions), three scenarios of a restored future (Restored Forest, Restored Passage, and Restored Forest and Passage scenarios) and one scenario of a degraded future (Degraded Forest Scenario). These scenarios considered varying levels of simulated forest management, habitat restoration, and removal of barriers to fish passage that may occur in the Staney Creek Watershed. Primary findings from this study include:

- Winter rearing habitat capacity is currently more limiting than summer rearing habitat capacity
- Large, low gradient streams, typically found in mainstem habitat, produce the highest winter density of juvenile coho
- Small, high gradient streams support lower winter densities of juvenile coho per unit measure, but cumulatively provide highly significant rearing habitat
- Barrier removal of six impassible redpipes provides a slight increase in the equilibrium level of returning adult coho (1%) relative to current conditions
- Forest restoration actions are capable of providing a large increase in the equilibrium level of returning adult coho (144%) relative to current conditions with the greatest increase occurring when forest restoration and barrier removal are combined
- Degraded forest conditions in the absence of effective forest management could result in a 63% decline in returning adult coho relative to current conditions

Understanding the population-level impacts to coho salmon from varied land use activities and potential restoration scenarios will help resource managers understand, prioritize, and maintain conditions essential to supporting healthy coho salmon populations. Not all actions have the same cost, or the same potential benefit. This study advances our knowledge base in Staney Creek Watershed by identifying important salmon habitats within the watershed and by evaluating species response to a range of management alternatives. The quantitative linkage between land use, fish habitat carrying capacity and population response serves as an effective management tool for decision makers.

# 1 INTRODUCTION

Coho salmon (*Oncorhynchus kisutch*) support important commercial, sport, and subsistence fisheries in southeast Alaska. Moreover, during the freshwater portions of their life cycle, they, along with other anadromous species, provide marine-derived nutrients to otherwise nutrient poor streams. By offering a valuable food resource for numerous aquatic predators and invertebrates and terrestrial vertebrate predators and scavengers, they form a critical link between the aquatic and terrestrial ecosystems (Houston 1983, Cederholm et al. 1989, Willson and Halupka 1995). Declines in coho salmon may therefore result in deleterious cascading effects through food webs in both aquatic and adjacent terrestrial ecosystems.

Because they are anadromous, and thus occupy freshwater, estuarine, and ocean habitats during different stages of their life cycle, coho salmon are exposed to impacts from a variety of factors, including natural or man-made habitat alterations, ocean and freshwater fishing, and climate change. Degradations of freshwater spawning and rearing habitat are speculated to be the most important factors causing long-term declines of coho productivity and adult escapement (Pearcy et al. 1992, Halupka et al. 2000). Land management activities can dramatically affect the capacity of coastal streams for the production of coho salmon because such actions can cause changes in fine sediment loads, stream cover, and channel morphology that can have pronounced effects on habitat quantity and quality. The adverse impacts of such activities, particularly timber harvest and road construction, were highlighted by the Tongass Land Management Plan (USDA Forest Service 2008a) and prompted the Wilderness Society to fund this analysis of habitat conditions and coho salmon populations. In this report, we characterize and quantify current conditions in the Staney Creek watershed, a watershed within the Tongass National Forest (TNF) of Southeast Alaska (Figure 1-1), both from a broad, stream ecosystem perspective, and by evaluating impacts to coho salmon habitat and populations. We also simulate the effects of further intensive forest harvest on coho salmon habitat and populations, as well as the potential benefits of restoration actions.

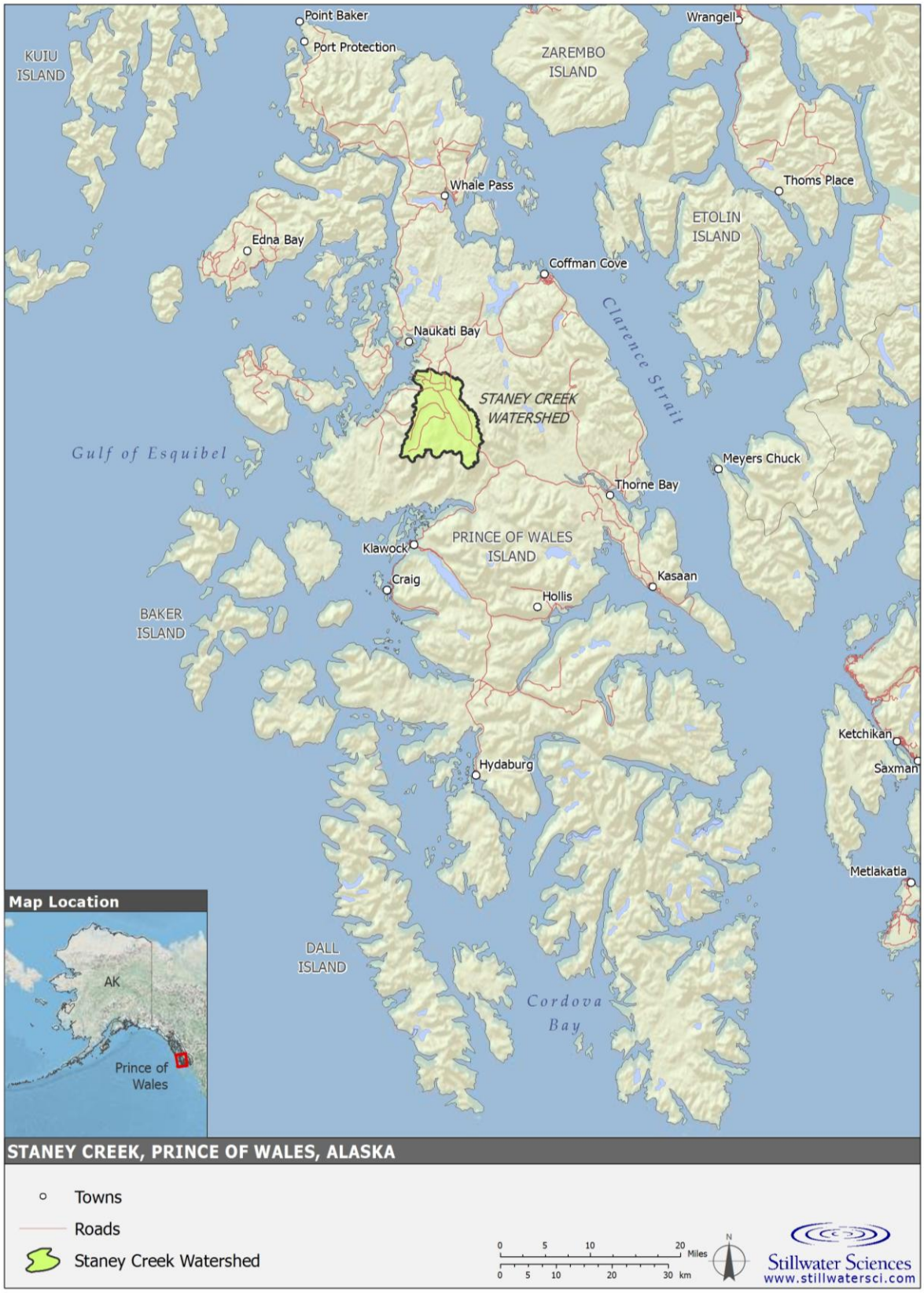


**Figure 1-1.** Regional map of the Staney Creek watershed.

# 2 COHO SALMON

## 2.1 Life History

Coho salmon, also referred to as silver salmon, are one of five species of Pacific salmon (*Oncorhynchus spp*.) found in southeast Alaska, the others being Chinook (*O. tshawytscha*), sockeye (*O. nerka*), pink (*O. gorbuscha*), and chum salmon (*O. keta*). Of these species, pink, chum, and coho salmon, and in very low numbers Chinook salmon, spawn and rear in Staney Creek (USDA Forest Service 2008b). Steelhead (O. *mykiss*), cutthroat trout (O. *clarki*), and Dolly Varden (*Salvelinus malma*) are also present, as are stickleback and sculpin species (USDA Forest Service 2008b). The following sections describe the life history of coho salmon.

### 2.1.1 Adult migration and spawning

The majority of coho salmon in southeast Alaska spend about 16 months in the ocean before returning to freshwater to spawn (Sandercock 1991); though a small number of individuals spend 28 months (Halupka et al. 2000). In addition, spawning runs of coho usually include males that return after spending only four to six months at sea; these males are commonly referred to as jacks (Nielsen et al. 1991, Halupka et al. 2000). After attaining sexual maturity in the summer, coho salmon in southeast Alaska typically return to the vicinity of their natal streams in July and August and enter freshwater in September and October. Most spawning occurs in late October and November. Some runs enter freshwater as early as mid-July and hold for several months before spawning (Sandercock 1991, Halupka et al. 2000). Coho salmon populations do not enter the stream system all at once, but instead arrive throughout the spawning season in a pattern that reflects the occurrence of storms that increase stream flow in the spawning streams (Shapovalov and Taft 1954). Most adult coho migrate upstream during daylight hours (Sandercock 1991), with peak activity usually occurring at dawn and sunset (Fraser et al. 1983). Homing of coho salmon to their natal streams is well-documented. Coded-wire-tag recoveries of wild adult coho indicate that rates of straying into non-natal stream may be in the range of 0.1%–2.0% (Sandercock 1991, Labelle 1992). Salmon that are blocked from access to their natal tributary may die before choosing an alternate location to spawn (Ricker and Robertson 1935, Hartman and Raleigh 1964).

Most spawning occurs in small low-gradient tributaries, in areas with groundwater seepage or high inter-gravel flow rates (Halupka et al. 2000). Females select a nest site after arriving on the spawning ground, and defend the area against other females. Redd construction behavior is similar to that displayed by other salmonid species, with the female excavating a depression in the gravel by turning on her side and using her body and tail to displace the gravel downstream. Digging activity may last as long as five days, during which time the female will dig up to seven egg pockets in succession, progressing in an upstream direction (Shapovalov and Taft 1954, Tautz 1977, van den Berghe and Gross 1984, Sandercock 1991). The average number of eggs deposited per egg pocket ranges from 300 to 1,200 (Sandercock 1991). Total fecundity and egg size generally increase with female size (Stauffer 1976, Beacham 1982). Fecundity can range from 1,000–7,600 eggs per female (Beacham 1982, Sandercock 1991), and generally increases with increasing latitude (Nemeth et al. 2005). Fecundity in southeast Alaska is commonly 4,000–5,000 (Sandercock 1991).

Two separate tactics may be used by male coho in fertilizing the eggs laid by a female, depending whether the male is a jack or older adult (Gross 1985). Adult males are adapted for fighting other males to achieve dominance and the opportunity to fertilize a defended female's eggs. Jacks

employ a sneaking tactic, using refuges such as rocks, LWD, or shallow areas near females that are constructing redds and rushing in to fertilize some of the eggs during the act of spawning between a female and a dominant male. Because jacks have a shorter marine residence they do not spawn with their cohort, and therefore can increase genetic variation in the population (Young 1999). The eggs of a female may often be fertilized by more than one male (Gross 1984, Sargent et al. 1987). Fertilization rates under natural conditions appear to be very high, close to the percentages of eggs found fertilized under ideal conditions existing in hatcheries (Shapovalov and Taft 1954). Hobbs (1937) found that various species of salmonids had average fertility rates of over 99% under natural conditions. Females continue to guard the redd and prevent superimposition by other females until they are too weak to maintain position in the current (Briggs 1953). Both males and females die soon after spawning.

### 2.1.2 Egg incubation and fry emergence

Following deposition in redd gravels, coho salmon eggs incubate for approximately 30–60 days at temperatures of approximately 8–14°C (46.4–57.2°F), with incubation time being inversely related to water temperature (Murray and McPhail 1988). After hatching, young salmon (alevins) remain in the gravel while undergoing further development and absorption of the yolk sac. Emergence from the gravel begins 2–5 weeks after hatching, and may continue for an additional 2–7 weeks (Shapovalov and Berrian 1940, Murray and McPhail 1988). Alevins typically emerge from the gravel in April (Halupka et al. 2000). Many alevins emerge at night (Shapovalov and Taft 1954), which presumably decreases vulnerability to predation (Mason 1976, Godin 1980). Egg-to-emergence survival estimates for coho salmon range from approximately 10% (Tagart 1984) to 85% (Shapovalov and Taft 1954). Factors which affect egg survival include fine sediments, temperature, permeability, dissolved oxygen, gravel mobilization during high flow events, low flows, freezing, bird and insect predation, and fungal infections (Sandercock 1991).

### 2.1.3 Juvenile freshwater rearing

Upon emergence from the redd gravels, coho fry seek low velocity areas along shallow stream margins (Shapovalov and Taft 1954). As they grow, juvenile coho move to deeper habitats, although they continue to prefer low-velocity habitat throughout the freshwater rearing period. Juvenile coho establish territories or form hierarchical groups in pools based on optimal foraging positions (Dolloff and Reeves 1990, Fausch 1993). During the winter, when water temperatures are low (<7°C [<44.6°F]), aggressive territorial behavior and feeding is reduced (Shapovalov and Taft 1954).

Coho salmon populations are generally believed to be limited by density-dependent mechanisms operating within the freshwater environment (Allen 1969, Chapman 1962, 1966, McFadden 1969, Marshall and Britton 1990, Meehan and Bjornn 1991). The availability of suitable winter rearing habitat, is believed to be the limiting factor that usually governs the number of coho salmon smolt that can be produced from a stream system (Larkin 1988; Chapman 1962, 1966), which, in turn, sets the upper limit for the number of adults that can return to spawn. Optimum winter rearing habitat for coho juveniles is typically located in smaller streams, beaver ponds, lakes, and off-channel portions of larger streams (Bryant 1985, Gray and Marriott 1986, Bramblett et al. 2002). These areas all feature a complex habitat structure with abundant aquatic and riparian cover. Juvenile coho salmon, including individuals in Staney Creek, commonly move from mainstem rearing locations into off-channel habitat and smaller tributaries during fall freshets, presumably to seek refuge from high flows (Cederholm and Scarlett 1982; Tschaplinski and Hartman 1983; Bramblett et al. 2002; B. Wright, USDA Forest Service, pers. comm.).

Numerous studies have shown that deep pools with substantial cover in the form of LWD are the most important habitat elements used by juvenile coho in the winter (Hartman 1965; Bustard and Narver 1975a, 1975b; Tschaplinski and Hartman 1983; Murphy et al. 1984; Bisson et al. 1985, 1988; Everest et al. 1986; Glova 1986; Heifetz et al. 1986; Swales et al. 1986; Hartman and Brown 1987; Cederholm et al. 1988; McMahon and Hartman 1989; Shirvell 1990; Nickelson et al. 1992b). Although juvenile coho use pools in all seasons, in the winter they show a preference for pools that provide cover and refuge from high water velocities, which are essential for protection against displacement by high flows (Bustard and Narver 1975a, Mason 1976b, Hartman et al. 1982).

Coho salmon in southeast Alaska, spend at least 1 year rearing in freshwater before outmigration to the ocean, and most rear in freshwater for 2 years. A smaller fraction of the population may remain in freshwater for three or four years (Sandercock 1991, Halupka et al. 2000). This timing contrasts with coho salmon stocks in southern British Columbia and the Pacific Northwest, where most juveniles spend only one year in freshwater (Shapovalov and Taft 1954, Sandercock 1991). Because coho salmon populations in southeast Alaska spend such a significant portion of their life history rearing in freshwater habitats, they can be especially vulnerable to impacts from logging and road building.

### 2.1.4 Smolt outmigration and estuarine rearing

Following fall and winter peak flows, juvenile coho salmon feed heavily to grow in size in preparation for downstream migration. Coho smolt outmigration generally occurs in the spring. In the Staney Creek watershed, Bramblett et al. (2002) captured smolts in Tye and Twiw creeks from April to June. The mean length of two year old smolts in southeast Alaska is approximately 100 mm (Halupka et al. 2000). Bramblett et al. (2002) reported individuals from 70 to 142 mm fork length.

Photoperiod, temperature, stream flow, and lunar or tidal phase are among the environmental factors that may influence smoltification and downstream movement (Parry 1960; Hoar 1965; Wagner 1974; Clarke et al. 1978, 1981; Wedemeyer et al. 1980; Clarke and Shelbourn 1981). Coho smolt outmigration may be influenced by local factors which signal favorable conditions for rearing downstream within estuaries. Holtby et al. (1989) found that variability in stream temperatures during spring accounted for 60% of the variability in the median date of coho emigration in Carnation Creek. They hypothesized that this timing/temperature relationship and the timing of adult spawning were adaptations for synchronizing outmigration with windows of opportunity or advantageous conditions in the ocean or estuarine rearing environment.

During smoltification, territories may be defended less vigorously and coho may migrate downstream in small schools, presumably an adaptation for life in the sea (Hoar 1951, Shapovalov and Taft 1954, McMahon and Holtby 1992). After reaching the estuary, coho salmon may remain for a few months of residency prior to entering the ocean environment. McMahon and Holtby (1992) found that coho smolts remained in the Carnation Creek estuary for about 2 months (April and May). A similar period of estuarine residency was found for coho in an Oregon estuary (Myers and Horton 1982). Even a short period of estuary rearing may result in enhanced ocean survival as growth appears to be very rapid in this habitat. For this reason, estuary habitat quality may play a key role in the number of adults returning to spawn. Rapid growth during estuary rearing may reduce vulnerability to nearshore predators, which are believed to be a major source of ocean mortality for coho salmon (Holtby et al. 1990).

## 2.2 Population Trends

USDA Forest Service (2008b) reports that the Staney Creek watershed was historically one of the largest producers of fish for commercial, sport, and subsistence fisheries on Prince of Wales Island. However, very little quantitative information is available to evaluate the coho salmon population size in the watershed and how it has changed over time (USDA Forest Service 2008b), especially in recent years. Annual counts of adults migrating past a weir in the lower watershed from 1929–1932 ranged from 2,046–20,398, with a mean of 9,101 (USDA Forest Service 2008b). By the period of 1982–1988, weir counts had declined substantially, ranging from 4–1114, with a mean of 264 (USDA Forest Service 2008b). More recent adult data from Staney Creek is not available.

USDA Forest Service (2008b) summarized juvenile coho density data collected by USDA Forest Service in various Staney Creek tributaries sampled beginning in the mid-1970s. These data indicate that juvenile densities were highly variable within streams and between seasons and years, but do not indicate any clear population trends for the watershed.

# 3 HISTORICAL LAND USE IN STANEY CREEK WATERSHED

Past timber harvest within the Staney Creek watershed has been extensive. Approximately 37.5% (14,736 acres) of the 39,298 acre watershed has been logged, with clear-cutting ("even age harvest") comprising the vast majority of harvest (Howell et al. 2008, USDA Forest Service 2008b). Industrial timber harvest began in the 1960s and 48% of the total harvest occurred from 1970–1979 (Figure 3-1). This logging was concentrated in the lower elevations of the watershed and comprised large, contiguous blocks of cleared land (Howell et al. 2008).

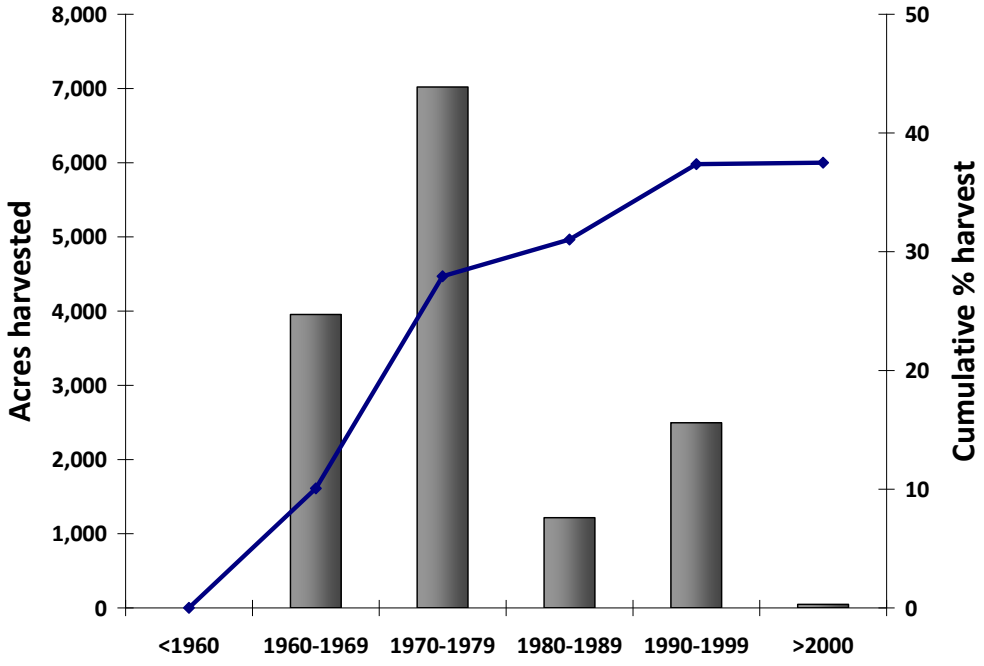


**Figure 3-1.** Old growth timber harvest by decade and cumulative percent of the Staney Creek watershed harvested. Data from Howell et al. (2008).

In addition to widespread clear-cutting, riparian zones have been substantially altered in the watershed. Anderson (2008) noted that timber harvest has commonly occurred adjacent to streams, with little to no buffer retained. Thirty-two percent of the designated riparian management area has been harvested in the Staney Creek watershed, and is particularly concentrated in the Northern and Main Middle Fork sub-watersheds (Howell et al. 2008, USDA Forest Service 2008b, Figure 3-2). Logging has markedly changed the composition of the riparian area, resulting in domination by alders and a paucity of large conifers (USDA Forest Service 2008b). Moreover, removal of large woody debris (LWD) from many stream channels has occurred (Bryant 1982, USDA Forest Service 2008b).

Pre-commercial thinning (thinning in young stands that were previously harvested) has also been widespread in the Staney Creek watershed (Howell et al. 2008). Since 1983, 11,575 harvested acres in the watershed have been thinned (Howell et al. 2008).

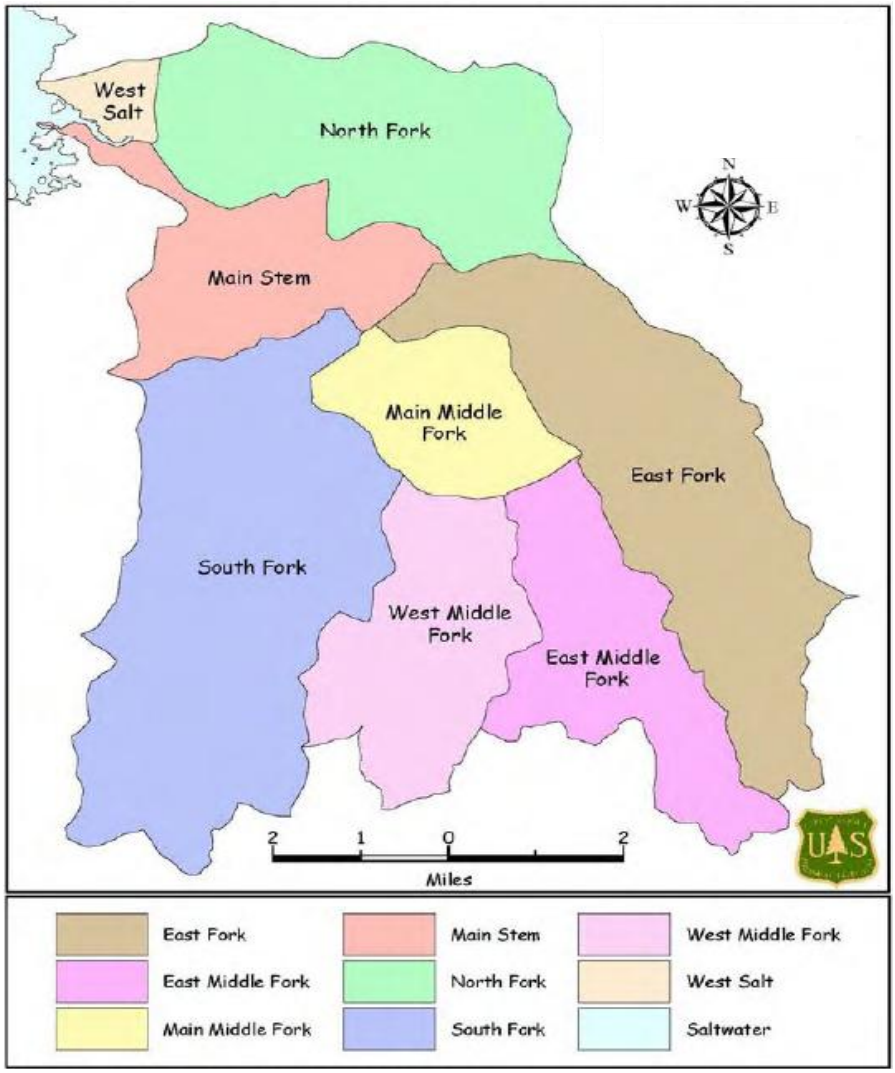


**Figure 3-2.** Sub-watersheds in the Staney Creek watershed. Map source: USDA Forest Service (2009). Note: the East Fork sub-watershed is locally referred to by some as "North Fork", but we refer to it hereafter as East Fork, in keeping with USDA Forest Service (2009).

Logging roads built to support the extensive timber harvest are also widespread in the watershed. Staney Creek has approximately 150 miles of logging roads and a road density of 2.4 linear miles of road per square mile of area (Albert et al. 2008, Figure 3-3). These roads have numerous culverts that impede fish passage into important spawning and rearing reaches (designated as "red pipes") in both Class I[1] and Class II[2] streams (USDA Forest Service 2008a, b). In addition, numerous areas prone to erosion and associated landslides and stream sedimentation have been identified by the Forest Service (USDA Forest Service 2008b). Areas with the highest risk of erosion and landslide failure are generally found along roads that are in disrepair and/or located on steep gradients.

[1] Class I streams contain anadromous or adfluvial fish or fish habitat, or high quality resident fish waters or habitat above fish migration barriers known to provide reasonable enhancement opportunities for anadromous fish.
[2] Class II streams contain resident fish or fish habitat—generally steep channels 6 to 25 percent or higher gradient—where no anadromous fish occur, and otherwise do not meet Class I criteria (USDA Forest Service 2008b).

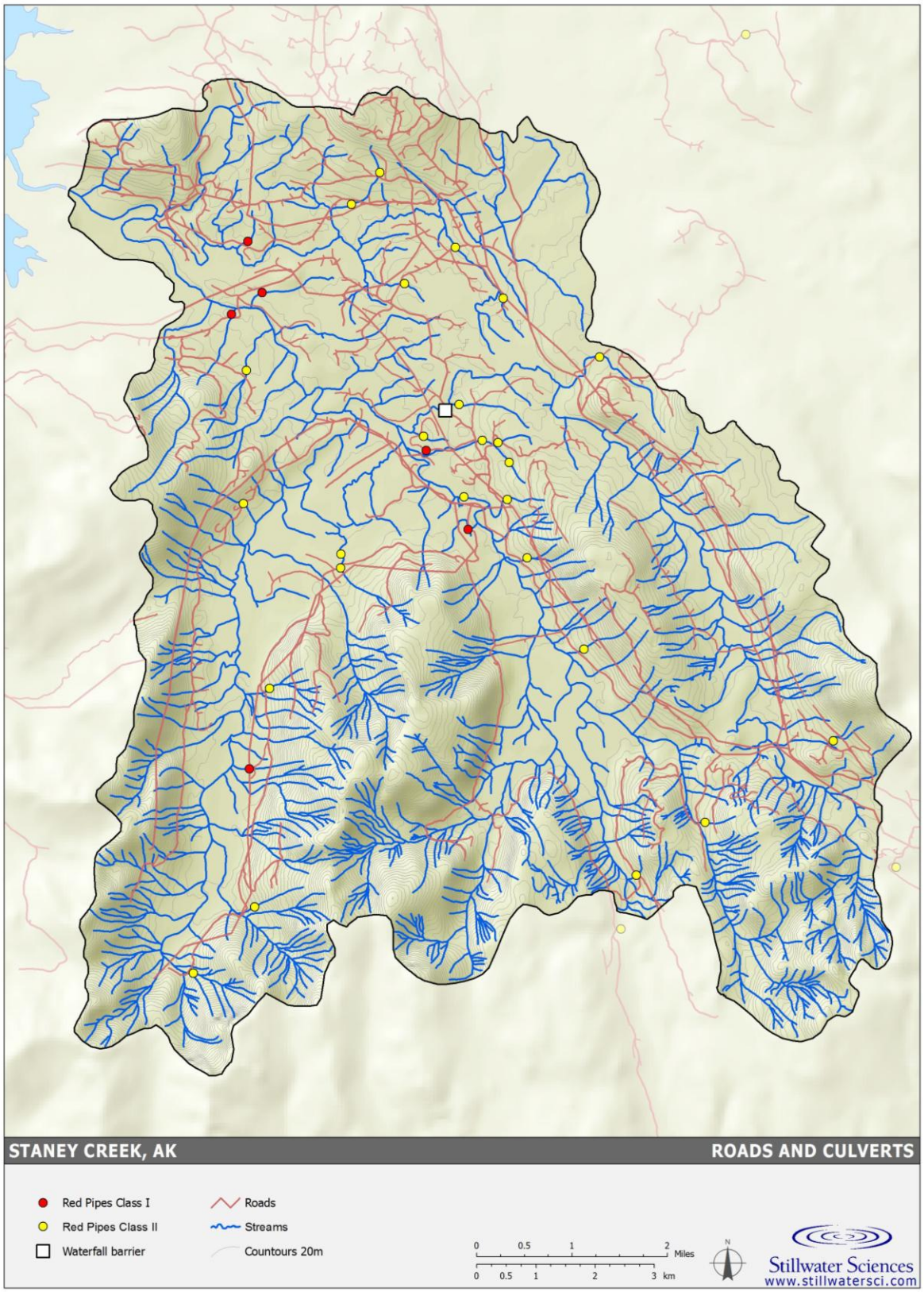


**Figure 3-3.** Locations of roads and culvert barriers to fish (red pipes) on Class I and Class II streams in the Staney Creek watershed.

# 4 ANTHROPOGENIC WATERSHED DISTURBANCES

Timber harvest and associated activities in the Staney Creek watershed have altered fisheries and wildlife resources through the loss and fragmentation of old-growth forest habitat and alteration of stream habitats and ecosystem function (Figure 4-1). Although considerable efforts are being made to reduce adverse impacts from timber harvest practices (USDA Forest Service 2008a), the remnant effects from past practices persists and future logging and road building will further exacerbate habitat problems. This section reviews the potential impacts to the stream ecosystem and coho populations resulting from past management in terms of the direct, indirect, and cumulative effects of timber harvest, road building, and related disturbances. The subsequent section describes the potential ecosystem benefits of conserving old growth and the use of logging practices other than clear-cutting.

Loss of stream habitat is widely acknowledged as the single biggest cause of declines of anadromous salmonids in the Pacific Northwest and southeast Alaska, particularly of coho salmon populations, which are vulnerable due to their extended residence in freshwater (Tschaplinksi and Hartman 1983, Nehlsen et al. 1991, Reeves and Sedell 1992, The Wilderness Society 1993). Most habitat loss in southeast Alaska has resulted from watershed disturbances associated with logging, mining, and the construction of forest roads (Bryant 1982, Murphy et al. 1986, Halupka et al. 2000). These activities typically result in the loss of complex stream habitat that is characteristic of coho salmon streams (Tschaplinksi and Hartman 1983, Shirvell 1990, Sandercock 1991), particularly due to reductions in LWD and an increase in fine sediment input to streams.

The negative impacts of timber harvest and associated road building on ecosystem function, channel condition, and fish populations have been well documented (e.g.: Sedell and Luchessa 1982, Johnson et al 1986, Kostow 1995, Hartman et al. 1996, Halupka et al. 2000), including several examples from streams within the Staney Creek watershed (e.g.; Bryant 1982, Swanson et al. 1984, Murphy et. al.1986). Below we characterize the impacts of past degradation due to timber harvest activities with respect to watershed processes, stream habitat conditions and fish populations. Key issues impacting ecosystem integrity and fish populations in the Staney Creek watershed include altered riparian vegetation composition, increased in-stream sedimentation, and a lack of LWD.

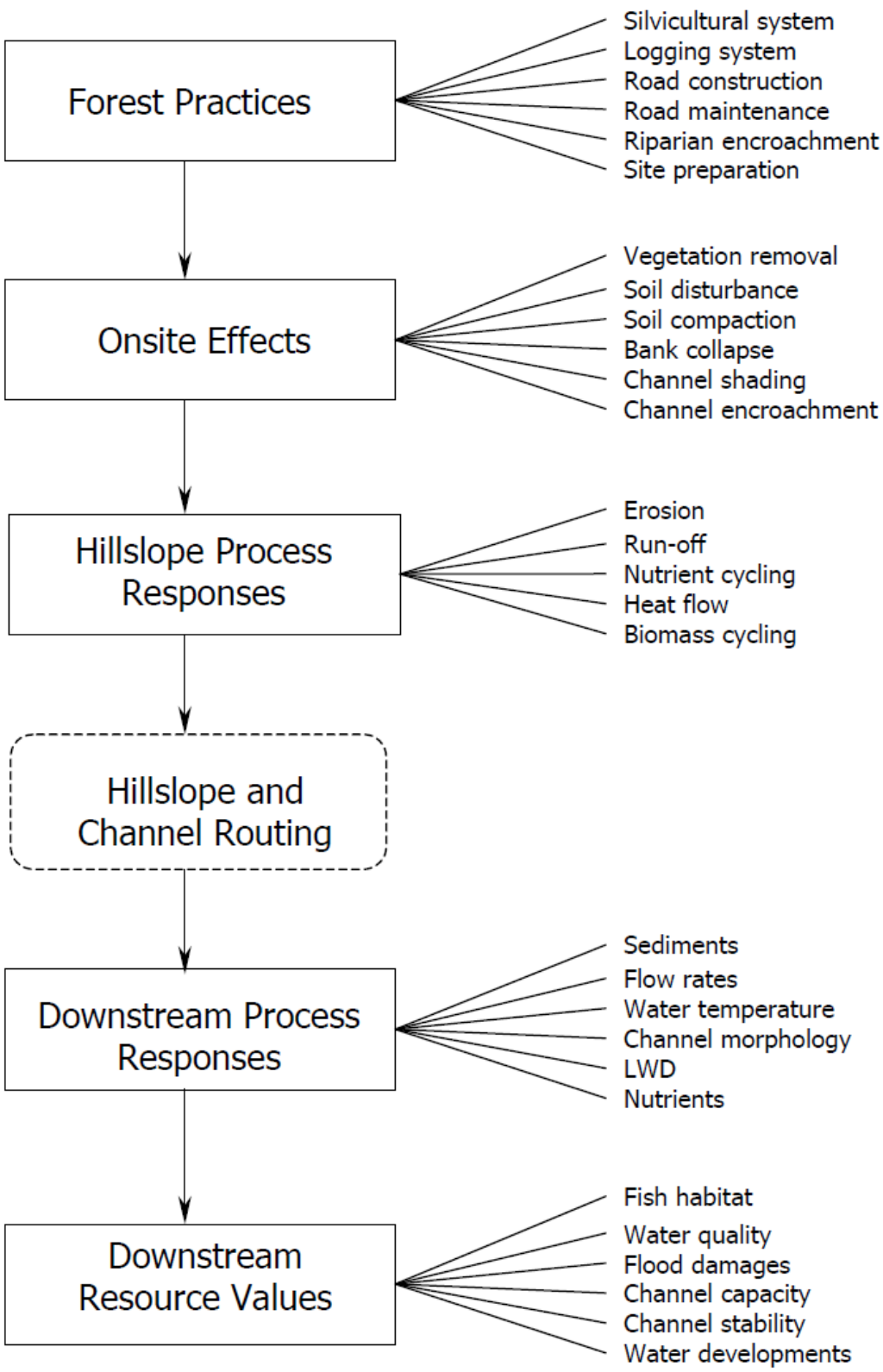


**Figure 4-1.** Effects of forest practices on ecosystem processes and values.

## 4.1 Hydrologic Regime and Channel Processes

Impacts to channel dynamics resulting from logging and associated roads are attributed to (1) changes in forest hydrology; (2) changes in sediment dynamics; and (3) changes in the form and function of in-channel LWD. Hydrologic responses include increased average runoff, increased peak flow magnitude, and advances in timing of floods. This change in delivery of water to the stream channel alters several characteristics of the hydrologic regime, and subsequently the ability of the river to transport sediment, as well as the amount of sediment available for transport. Stream flow alterations can also potentially alter the sediment being supplied from channel banks, the morphological character of rivers, and the ecological processes in the channel and riparian corridor.

Clearcutting and associated road building can significantly alter annual runoff and discharge patterns by reducing evapotranspiration and increasing surface flow (Jones and Grant 1996, Keppler 1998, Keppler et al. 2003, Grant et al. 2008). Changes in forest hydrology result in changes in sediment transport dynamics on the hillslopes and in the channel. Surface runoff controls fluvial geomorphology and any change in hydrology resulting from timber harvesting and road building will have both direct and indirect effects on geomorphic processes. Logging roads increase storm runoff and advance the timing of floods, with potentially detrimental effects on sensitive salmonid life stages such as incubating eggs and rearing juveniles. Because timber harvest and the associated road development can increase the amount and velocity of water to soil and streams, streamflow is increased and slope failures are induced.

Altered discharge patterns can impact channel processes and sediment transport dynamics and impair coho salmon habitat quality (Keppler et al. 2003). Although clearcutting has been shown to actually increase summer base flows in some coastal watersheds (Keppler 1998, Grant et al. 2008), it can also result in significant increases in the magnitude of peak flows during storm events, in some cases by as much as 300% (Lewis et al. 2001, Grant et al. 2008). Ziemer (1998) showed that peak stream flows were greater in fully clear-cut watersheds than in partially clear-cut watersheds. Similarly, it has been speculated that peak flows can be reduced to some extent in watersheds with riparian buffers by reducing hydrologic connectivity betweens roads, compacted areas, and streams; though this effect is expected to be less pronounced in steeper, mountainous watersheds (Grant et al. 2008). Larger peak flow events resulting from clear-cutting and roads can have deleterious effects on coho salmon and other fish species by scouring stream channels of spawning gravels, thereby decreasing spawning opportunities. Increased peak flows also reduce survival of eggs and alevins through displacement if gravels are mobilized. Importantly, magnitude and quality of overwinter rearing habitat are key factors controlling coho smolt production in many streams (Shirvell 1990, Crouse et al. 1981, Bustard and Narver 1975, Mason 1976, Hartman et al. 1982). For this reason, increased winter peak flows are predicted to have a direct, deleterious impact on coho salmon populations, since increased velocities are expected to displace a greater number of individuals (Tschaplinksi and Hartman 1983, Nickelson 1998, Shirvell 1990).

The impact of logging can be directly related to the magnitude of alteration in the hydrograph and sediment flux of the river system. Riparian vegetation in turn influences geomorphic processes by altering bank resistance, sediment deposition, and hydraulic roughness along the channel boundaries (Simon et al., 2000, Simon and Collision, 2002, Pollen and Simon, 2005*)*. Logging can indirectly impact streams by increasing hillslope runoff and causing excessive erosion, and may also result in direct scouring of channels when streams are used as a conduit to move logs downstream ("splash damming"). The impact of a reduction in LWD accumulation and resupply impacts channel form, water and sediment routing characteristics, and habitat complexity and

availability. The reduction in roughness associated with the removal of LWD pieces in the channel results in a loss of channel steps and leads to an increase in water velocities. Morphological complexity and bed substrate variability is ultimately reduced due to a decrease in hydraulic heterogeneity. Reduction of LWD can simplify width and depth characteristics, and there is a tendency for the pool area to decline and riffle area to increase as released sediment fills the pools (Bisson and Sedell 1984, Hogan 1987). Channel parameters consistently impacted include width-to-depth ratios, density and spacing of key LWD pieces, and the spacing and abundance of pools (USDA Forest Service 2008b). In Western Washington, Bisson and Sedell (1984) found that juvenile coho abundance was lower in drainages that have experienced timber harvest as compared with old growth watersheds. They attributed the decline in abundance to the loss of pool volume and the loss of cover associated with LWD.

## 4.2 Sediment Dynamics

The Staney Creek watershed has a high density of roads and associated mass wasting and gully erosion, which has altered sediment dynamics in the watershed and degraded fish habitat (Albert et al. 2008, USDA Forest Service 2008b). Timber harvest and associated road building often cause increased levels of sediment delivery to stream channels, especially when buffer strips are inadequate to prevent soil runoff (Barton and Taylor 1981, Hartman and Scrivener 1990, Keppler et al. 2003), as is the case in much of the Staney Creek watershed (Howell et al. 2008). Increased fine sediments can cause increased water turbidity, filling of pools, and reduction of rearing habitat quality and quantity for juvenile coho salmon and other aquatic species (Cederholm et al. 1981). High turbidity levels may have lethal or sub-lethal effects on salmonids. These effects include physiological stress such as gill trauma and decreased osmoregulatory ability, and behavioral changes such as delayed migration, decreased feeding rates, and altered prey selection (Bash et al. 2001). Embeddedness of gravel with fine sediments can also reduce fish production, primarily by reducing egg-to-emergence survival and aquatic invertebrate production (Crouse et al. 1981). Streambed aggradation from increased sediment deposition may reduce habitat complexity and result in less stable spawning gravels and mortality of eggs and embryos due to gravel mobilization during freshets (Nawa et al. 1990). Gravel instability may also affect colonization of the streamside areas by riparian vegetation and extremely aggraded streams may have reduced or absent surface flows during low flow periods (CDFG 1994). Furthermore, large accumulations of sediment may block juvenile and adult migrations where tributaries join main rivers (Payne and Associates 1989). Intrusion of fine sediments from logging activities into areas such as pool tails can cause profound effects on spawning gravel permeability and reduce spawning success (McNeil and Ahnell 1964, Peters 1965, Moring 1975).

Cederholm et al. (1981) studied the production of fine sediment from logging roads, increases in the portion of fine sediment in spawning gravels downstream from logging roads, and the effect of fine sediment on survival-to-emergence of coho salmon and cutthroat trout in the Clearwater River, Washington. They concluded that logging roads increased fine sediment (<0.85 mm) in streams, and that elevated levels of fine sediment lowered survival-to-emergence of coho salmon and cutthroat. When fines exceeded 20% the range of survival rates was reduced, and was significantly affected by further increases in fines. In addition, they found a significant positive relationship between road area in the watershed and percent fines in downstream spawning gravels. The authors concluded that when road area exceeded 2.5% of the watershed area, fine sediments begin to accumulate in downstream spawning gravels. In general, they concluded that logging roads are a significant source of fine sediment in spawning gravels.

## 4.3 Large Woody Debris Dynamics

LWD plays a key role in maintaining numerous physical and biological processes important for small stream ecosystems and is a crucial habitat feature for juvenile coho salmon during all life-stages of their freshwater residency. McMahon and Reeves (1989) postulated that LWD could be considered a keystone habitat feature for salmonids because of its overwhelming influence on channel morphology (e.g., pool formation, bank condition), sediment and organic matter retention, water velocity, and cover availability. Streams lacking instream LWD generally have insufficient escape cover for coho salmon summer rearing and do not provide ample refuge from high winter flows. LWD is a key habitat component, not only because it provides escape cover, but because it increases overall habitat complexity, facilitates sediment storage, and forms scour points that create and maintain deep pools (Harmon et al. 1986).

Removal of LWD generally leads to loss of those habitat features most important to rearing juvenile coho and a decline in salmonid abundance (Bryant 1980, Toews and Moore 1982, Lestelle and Cederholm 1984, Dolloff 1986, Elliott 1986, Fausch and Northcote 1992). Stream channels tend to become simpler and less stable after the removal of LWD, and the habitat complexity that provides substrate diversity, refuges from high current velocity, and cover used by spawning, feeding, and resting salmonids is lost (McMahon and Reeves 1989, Shirvell 1990). Several studies have shown that removal of LWD results in wider and shallower channels with little pool volume available at low flows (Bilby 1984, Bisson and Sedell 1984, Heifetz et al. 1986). Cutting of streamside forests and LWD removal has been observed to decrease frequency and area of important pool habitats and increase riffle area (Bryant 1980, Everest and Meehan 1981, Bisson and Sedell 1984). In clearcuts, Bisson and Sedell (1984) observed that, while the volume of riffles increased, the frequency of both pools and riffles appeared to decline, suggesting that the normally stepped stream profile had changed to a steeper gradient.

Juvenile coho survival and carrying capacity is often substantially reduced in disturbed streams when compared with undisturbed streams. Many studies have documented reductions in rearing habitat as a result of the removal of LWD (Tschaplinski and Hartman 1983, Bisson and Sedell 1984, Koski et al. 1984, House and Boehne 1987). The number of overwintering coho is low in stream reaches where debris abundance has been reduced by removal associated with stream clearing, streamside logging (Tschaplinski and Hartman 1983, Murphy et al. 1986), or other disturbances (Martin et al. 1986). Tschaplinski and Hartman (1983) and McMahon and Holtby (1992) found that the estimated carrying capacity of streams for coho smolts was reduced in clear-cut reaches of their study areas, and debris volume and smolt abundance were significantly lower than in reaches bordered by a forested buffer strip. Nickelson et al. (1992a) found that pool habitat that had been enhanced by the addition of LWD supported significantly higher coho densities than pools without LWD. The addition of woody debris to artificially-dammed pools increased the density of juvenile coho inhabiting the pools to levels found in naturally dammed pools. Larger juvenile coho appear to benefit most from availability of deeper pools and cover. A study in a British Columbia stream found that the standing crop of age 1+ coho was significantly greater in pools with complex cover and was positively correlated to pool volume in a given section of stream (Fausch and Northcote 1992).

Various studies have documented a reduction in coho salmon juvenile densities in streams lacking LWD. On two Staney Creek tributaries, Bryant (1982) showed an apparent reduction in coho densities after removal of woody debris from streams following logging. Management activities such as splash damming, stream cleaning, and timber harvesting have resulted in the loss of LWD in streams and reduced LWD recruitment from valley slopes throughout the

Northwest and southeast Alaska, including the Staney Creek watershed (McMahon and Reeves 1989, Bryant 1982, Lisle 1986, Murphy et al. 1986, USDA Forest Service 2008b).

As described in Section 3, logging has markedly changed the composition of riparian areas in the Staney Creek watershed, resulting in domination by alders and a paucity of large conifers (USDA Forest Service 2008b). Clear-cutting can change LWD dynamics within streams by altering recruitment of large logs from hillslopes and through the removal of wood from streams following logging (Sedell and Luchessa 1982, Dolloff 1986, Harmon et al. 1986, Murphy et al. 1986). LWD greatly influences stream habitat, channel form, and sediment dynamics. Timber harvest activities increase the frequency of relatively small, unstable pieces of debris and removes large stabilizing elements. In a heavily logged stream section, House and Boehne (1987) found that the reduction of large conifers in the riparian zone resulted in only 0.4 pieces of LWD large enough to influence channel morphology per 100 m of stream, compared with 18 such pieces of LWD per 100 m in a relatively undisturbed section. Lisle (1986) reported a 50% reduction in wood debris dam frequency 10 years after a watershed was clear-cut but otherwise undisturbed.

The consequences of forest harvest on fish habitat are expected to become more severe many years after harvest, since it may take 20 years or more for existing large, stable LWD structures to decay and break up (Swanson et al. 1984). The USDA Forest Service (2008b) compared volumes of woody debris in two second growth and two old growth streams in Staney Creek from 1977 and 1997. They found that volumes of wood per meter within the near-stream corridor of old growth streams increased over the twenty years by an average of 21%, while volumes in the second growth streams had decreased by an average of 43%. The adverse impacts of clear-cutting to ecosystem complexity and channel function are anticipated to occur over a much shorter timeframe in streams where LWD and other logging debris has been removed (Lisle 1986). Such removal has occurred in many streams, including from some logged areas in the Staney Creek watershed (Bryant 1982, Lisle 1986, Howell et al. 2008).

## 4.4 Stream Temperature and Water Quality

Coho salmon populations, like other anadromous salmonids, show population-specific patterns of variation in incubation rate, emergence timing, and growth that appear to be adapted to local thermal regimes (Beacham and Murray 1990, Halupka et al. 2003). Logging practices that result in increased stream temperatures, such as removal of canopy shade, can threaten survival and reproduction by cold water species (Moore et al. 2005). Removal of riparian canopy cover exposes more of the stream channel to direct solar radiation, increasing summer water temperatures. Increased fine sediment inputs can also cause increased stream temperatures by replacing the reflective gravel substrate with darker sediment that could store more solar radiation (Hagans et al. 1986). In addition, sedimentation can reduce intragravel flow, thereby exposing more of the water column to solar radiation (Hagans et al. 1986). Higher temperatures during the incubation period can cause coho and other fall spawning species to emerge earlier and be displaced by winter freshets (Scrivener and Anderson 1984). Increased water temperature may increase fish growth in some colder streams, but inhibit it in warmer streams (Murphy et al. 1986, Keith et al. 1998, Moore et al. 2005). In addition, faster growing juveniles may smolt and migrate to sea before the spring plankton bloom, leading to poor ocean survival (Holtby et al. 1989). In addition to its effects on stream temperatures, removal of the riparian canopy also results in reduced input of terrestrial invertebrates and allochthonous material that is critical to stream productivity. Many coho salmon populations in southeast Alaska use small tributaries for spawning and rearing (Gray and Marriott 1986), and because of their small size, these streams may be particularly vulnerable to logging induced alteration of their thermal regimes.

Increased water temperatures may also directly or indirectly lead to pre-spawning mortality of adult salmon. Large die-offs of adult salmon have been documented in lower Staney Creek in recent years, mostly of pink and chum populations, but also coho (USDA Forest Service 2008b). Salmon die-offs in Staney Creek and other southeast Alaska streams appear to be triggered by a combination of several factors, including stream temperature, tidal height, stream flow, and fish density (Murphy 1985).

## 4.5 Physical Barriers to Migration and Movement

Although there are no dams in the Staney Creek watershed, construction of logging roads has led to numerous culverts and stream crossings of varying size and type (Flanders and Cariello 2000). In addition to blocking adult access to spawning areas, culverts can alter channel morphology, sediment dynamics, and hydrologic processes. Of the 112 stream crossings identified in Staney Creek, 33 (30%) inhibit or completely block adult passage (Anderson 2008). Scientists have also expressed concern that culverts and other stream crossing structures may block movement of juvenile fish and result in a long term reduction in available rearing habitat (Dunlap 1997).

## 4.6 Commercial and Recreational Coho Salmon Harvest

No data on commercial or recreational ocean harvest of the Staney Creek coho salmon stock is readily available (Wood 1991, Shaul 1994, Halupka et al. 2000, Volk et al. 2009). However, commercial harvest of coho salmon must be considered when evaluating the potential impacts to Staney Creek coho populations. Collection of stock-specific harvest data is difficult because the coho salmon fishery is a mixed-stock fishery, with fish originating from numerous watersheds in southeast Alaska. For this reason, management of coho salmon in southeast Alaska has typically relied on analysis of catch-per-unit-effort data for the entire fishery and the use of "indicator" stocks, which are assumed to be representative of nearby watersheds (i.e., they experience similar environmental conditions, have similar migration patterns, and incur similar exploitation rates) (Shaul 1994). Nevertheless, available data from the fishery indicates that a substantial amount of harvest pressure has been exerted on southeast Alaska coho salmon stocks—likely including the Staney Creek stock—with the fishing pressure increasing in recent years (Wood 1991, Shaul 1994, Halupka et al. 2000, Volk et al. 2009). Coho salmon harvest from southeast Alaska during the late 1980s and early 1990s averaged over 2 million fish per year, nearly double the average annual harvest for the previous 30 years (Halupka et al. 2000, Figure 4-2). In the period from 1998–2007, coho harvest averaged nearly 2.8 million fish, higher than the long-term average (since 1959) of 2.1 million fish (Volk et al. 2009).

The harvest rate for Hugh Smith Lake, the indicator stock closest to Prince of Wales, averaged 66% from 1982–1990, but was between 81% and 82% during 1989 and 1990 (Shaul 1994). These results indicate that coho salmon spawner abundance can be influenced by commercial harvest patterns (Halupka et al. 2003).

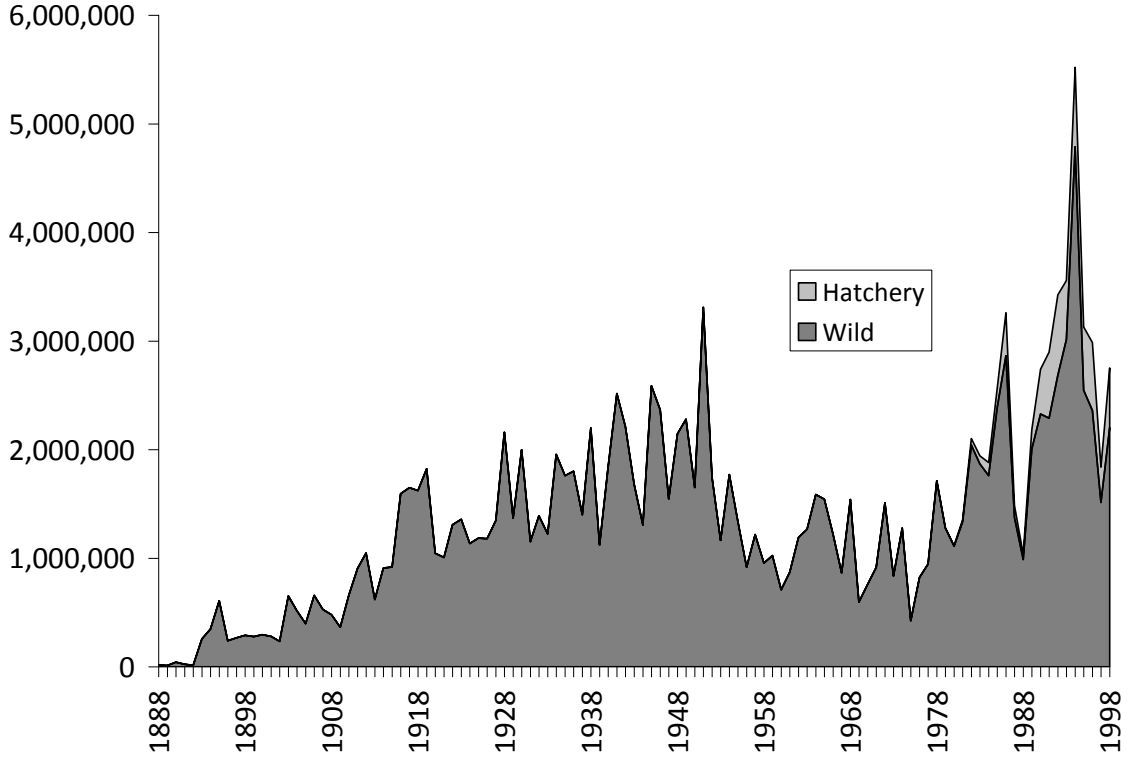


**Figure 4-2.** Annual commercial harvest of hatchery and wild coho salmon in southeast Alaska, 1888–1998 (Source: PSC 2002).

## 4.7 Hatcheries

No hatcheries are located on Staney Creek; however impacts of abundant hatchery coho salmon could occur in the form of ocean competition, diseases, and loss of genetic integrity resulting from straying hatchery fish (Steward and Bjornn 1990, Hindar et al. 1991, Shaul 2010). The genetic integrity of many native coho salmon stocks has been affected by the introduction of large numbers of hatchery fish in southeast Alaska. Differences in the genetic structure of native and hatchery stocks can potentially lead to lower survival of subsequent hybrid generations compared with pure wild fish (Steward and Bjornn 1990, Hindar et al. 1991). The interaction of hatchery and native stocks also increases disease potential, since native stocks may be exposed to disease organisms originating from hatcheries that they would not be exposed to under normal conditions. For example, some hatchery coho stocks are known to harbor Bacterial Kidney Disease (BKD), a chronic and slow developing infection that can have adverse effects on coho smolts (CDFG 1994, NMFS 1995).

The genetic integrity of native coho salmon stocks has been affected by the introduction of large numbers of hatchery fish and transplants of different stocks. Nehlsen et al. (1991) suggest that native coho stocks have a high probability of introgression with hatchery stocks. Bartley et al. (1992) noted that transplants of different stocks may have effects such as disruption of locally adapted gene complexes, swamping and homogenization of native gene pools, and transmittal of nonadaptive traits from hatchery stocks to native stocks. Studies have shown lower survival of juvenile coho that were offspring of hatchery strays or hatchery-wild hybrids (Smith et al. 1985,

Chilcote et al. 1986). Hatcheries have not proven successful in the restoration of native coho stocks (Withler 1982, Solazzi et al. 1983, Nickelson 1986).

# 5 BENEFITS OF CONSERVING OLD GROWTH

Old growth forest maintains an ecosystem and physical structure that is both dynamic and resilient. The natural system is dominated by ecosystem processes in dynamic equilibrium, episodically punctuated by disturbances. To be resilient, natural communities must be of sufficient quality and maintain appropriate processes to withstand both natural and human perturbations. To safeguard against unpredictable events, communities in a watershed should be redundant, with a sufficient quantity and quality of habitat for terrestrial and aquatic species to persist following major perturbations. Old growth forests provide a range of conditions that support a diverse array of flora and fauna that are lacking in even-age stands. The primary drivers of resiliency are functions and processes, not necessarily species, so the maintenance of these processes is a critical component of population viability.

The conservation of the remaining old growth forest is paramount in the maintenance of high quality habitat and hydrologic function. Forests must have significant habitat connectivity to maintain the necessary sequence of habitats in varying stages of forest succession to meet the life history needs of each species that utilizes the watershed, from headwater drainages to the lower river and estuary. Watershed processes that form critical habitats include hydrologic connectivity between floodplains, side channels and active channels, riparian community succession, sediment and nutrient flow, habitat connectivity, LWD recruitment to the stream channel, and natural disturbance regimes. In 1994, the TNF contained an estimated 14% of the world's total acreage of coastal temperate rainforest, and 29% of the remaining unlogged acreage (Knoder 1994). The value of conserving the remaining old growth relates not only to economic value, but also to different ecological levels of biodiversity and to specific complementary relationships– between species, between elements of ecological structures, and between ecological functions. To appreciate the full benefit of old growth forests, it is important to look at varying spatial scales, from the watershed as a whole to stream reaches and to aquatic habitat.

## 5.1 Hydrology and Sediment Supply

In an old growth forest there is a functioning hydrologic connectivity between floodplains, side-channels, and active channels. Old growth forests mediate the timing, volume and maximum rate of runoff resulting from precipitation. The presence of old growth diversity and structure improves evapotranspiration, soil infiltration capacity, soil cohesion and reduces overland flow and runoff potential. The benefit provided from evapotranspiration decreases the total water yield during storms and can increase summer low-flow (Ziemer 1987). The presence of a diverse and robust forest structure also allows for high soil infiltration rates that reduce the frequency and magnitude of high flows. Following logging, most of the increase in annual water yield has been shown to occur during the high runoff season and during wetter years (Keppeler and Ziemer 1990, Ziemer 1987). In an unlogged old growth basin, the upper watershed avoids deleterious effects from the presence of roads and maintains lower rates of sediment supply to stream channels. Hillslopes of old growth forest remain relatively stable, avoiding erosive conditions that can contribute substantial amounts of sediment to stream channels where extensive road networks are present.

## 5.2 Riparian Zones

In synchrony with the physical alterations to a watershed, the ecological functions of riparian zones can be significantly altered by timber harvest activities. The removal of riparian forests and other vegetation changes stream shading and temperature regimes, reduces the supply of LWD, and alters the supply of nutrients (Hicks et al. 1991). The conservation of old growth forest and a complex riparian corridor ensures that physical processes remain in equilibrium and, at the reach scale, the dynamic nature of the channel contributes to greater complexity of habitat structure and species biodiversity.

Specifically, high rates of LWD loading in and along streams provide increased habitat structure, abundant pools, increased hydraulic complexity and increased storage of spawning gravels and other sediment. These complexities in habitat structure are key elements of providing adequate and diverse habitat for aquatic species. Large pieces of wood tend to persist in streams for longer amounts of time and the structural integrity of old growth pieces resist decay and contribute to the persistence of the wood. These large pieces enhance local scour of the channel, creating deeper and more persistent pools. The presence of wood and complex hydraulic forces also enhances the retention of gravels, most importantly those of suitable size for use in redd building by spawning salmon. LWD in channels also reduces flow velocities during storms and high flows, reducing flushing flows that often denude channels of gravels and habitat diversity. Lower transport capacity in channels due to the abundance of roughness elements such as LWD also creates low-velocity conditions in the adjacent channels and increased refuge from predators. Woody pieces in the stream channel provide forage for macroinvertebrates, a key food source for salmon and other aquatic species. In Staney Creek specifically, volumes of wood per meter within the near stream corridor of old growth streams increased by an average of 21% between 1977 and 1997 while volumes in the second-growth streams decreased by an average of 43% during the same time period (Alexander 1999).

Streams are a major supplier of LWD to estuarine habitats. The LWD, most of it transported to the estuary during high flows, creates a diverse and spatially complex habitat. The wood provides a food source for macroinvertebrates, a refuge for salmon in tidal rivers and sloughs, and also affects sediment accumulation by stabilizing sand bars and mud banks and creating diverse habitats. Estuaries may be particularly important as juvenile salmon make a physiologic adjustment to a saline environment while experiencing substantial changes in habitat and food resources.

Riparian vegetation can be important in regulating stream water temperature as well. The temperature of water entering headwater streams in forested ecosystems is typically close to that of the subsoil environment. As this water flows through the stream system, water temperature becomes increasingly influenced by solar radiation and ambient air temperature (Burns 1972, Beschta and Platts 1986 1987). Where stream shading and LWD loading is high, the canopy contributes to a decreased susceptibility to high water temperatures. Water temperature is an important habitat parameter for coho salmon, steelhead, and many amphibians, aquatic macroinvertebrates, and other organisms, potentially influencing reproductive success and survival during all freshwater life stages (e.g., Bjornn and Reiser 1991).

## 5.3 Instream Habitat

The high rates of LWD loading associated with old growth forest structures and intact riparian areas generally leads to increases of those habitat features important to many salmonid species

and an increase in salmonid abundance (Bryant 1980, Toews and Moore 1982, Lestelle and Cederholm 1984, Dolloff 1986, Elliott 1986, Fausch and Northcote 1992). Abundant LWD increases the frequency, depth, and complexity of pool habitats used by rearing juvenile and resting adult migrating salmon, and results in overall increases in reach-scale habitat diversity (e.g., pool-riffle sequences) (Bryant 1980, Everest and Meehan 1981, Bisson and Sedell 1984). High densities of LWD may especially increase the carrying capacity for the older age classes of juvenile salmonids, which typically prefer deeper habitats (Bisson et al. 1988). Stream channels tend to be more complex and more stable with increasing volumes of LWD, and the structural complexity that provides substrate diversity, low-velocity refugia during high flows, and cover from predation is also improved as compared with those conditions lacking abundant LWD (McMahon and Reeves 1989). Reduced LWD may also limit formation of backwater pools and the complex stream margin habitat used by emergent fry (McCain 1992). Other benefits of high LWD loading may include decreased bank and bed erosion, increased retention of spawning gravels, and increased retention of organic materials important for maintaining communities of macroinvertebrate that are a food resource for juvenile salmonids.

Low-velocity stream habitats preferred by juvenile coho salmon include pools and off-channel habitats such as side channels, backwaters, and tributaries on floodplains and terraces (Everest et al. 1986, Glova 1986, Taylor 1988, Bugert and Bjornn 1991). In an analysis of 262 stream reaches, Paustian (1992) revealed multiple parameters that showed consistent difference between managed and unmanaged watersheds: channel width/depth ratio, key woody debris, pool frequency, pool size and a normalized measure of residual pool depth. These changes appeared strongest in floodplains and moderate gradient sections of channels. These features are important for rearing and overwintering fish.

## 5.4 Old Growth and Salmon

Salmon in Southeast Alaska are of particular ecological and economic importance, with salmon supporting over 10% of regional employment and contributing roughly $1 billion to the southeast Alaska economy (USDA 2012). Key habitat conditions for salmon, including coho (e.g., cool water temperatures, LWD, and associated pools), are expected to also represent habitat conditions favored by other sensitive aquatic and semi-aquatic species. For example, habitats preferred by rearing salmonids, such as pools, backwater areas, and off-channel habitat, also provide important habitat for various amphibian species. Murphy et al. (1986) studied 18 streams in southeast Alaska and found negative correlations between clear-cut areas (vs. old growth and buffer) and fish density and habitat. Additionally, if LWD had been removed from the stream reaches, fish densities also decreased. Murphy found that clear-cutting may increase parr abundance in summer months by increasing primary production, but during the critical overwintering period the abundance of parr was reduced if debris in the channel was removed.

Stream reaches where the channel is relatively unconfined and unentrenched (i.e., where the channel can migrate laterally within the valley) provide important rearing and overwintering habitat for coho and other fish due to the greater availability in these areas of off-channel habitat and areas of low water velocity during high flows. Pool characteristics (e.g., frequency, area, depth, and volume), LWD spacing, reach-level bed substrate $D_{50}$ (geometric mean diameter), and the amount of available refuge habitat, such as alcoves and backwaters, are other habitat features of potential importance to rearing and overwintering survival.

The quality of spawning gravel is influenced by several factors affecting the success of spawning salmonids and the survival of incubating eggs and emerging fry. These factors include the size of

the gravel, the size and location of available spawning areas, the proportion of fine sediment in the gravel at the time of spawning, and subsequent deposition of fine sediment in the redd during incubation and development (Beschta and Jackson 1979, Grost et al. 1991, Peterson et al. 1992). All of these parameters are influenced by, and generally improved by, the existence of old growth forest adjacent to the channel and encompassing the hillslopes of the watershed.

During the freshwater portions of their life cycle, salmon may act as a keystone food resource for terrestrial vertebrate predators and scavengers, and thus they form a critical link between the aquatic and terrestrial ecosystems (Houston 1983, Cederholm et al. 1981, Willson and Halupka 1995). Declines in anadromous fish species such as coho salmon may therefore result in cascading effects through the trophic system.

# 6 RIPPLE MODEL

The past and current land use practices and coho population data described in the preceding sections suggest that adverse effects to ecosystem health and fish populations have occurred in the Staney Creek watershed. The importance to fish populations of maintaining old growth forests and restoring intact riparian ecosystems have also been highlighted (Tschaplinksi and Hartman 1983, Nehlsen et al. 1991, Reeves and Sedell 1992, The Wilderness Society 1993). Understanding the population-level impacts of various land use activities and potential conservation and restoration scenarios will help resource managers to understand, prioritize, and maintain conditions essential to supporting healthy coho salmon populations. However, a clear quantitative linkage between land use and fish habitat carrying capacity and population levels has not been established. Such data are critical to informing management decisions and prioritizing restoration alternatives within the watershed.

Accordingly, we used RIPPLE, a spatially explicit, predictive population dynamics model, to quantify the distribution and abundance of coho salmon under simulated current conditions (Current Conditions), three restored conditions scenarios (Restored Forest, Restored Passage, and Restored Forest and Passage scenarios) and one degraded conditions scenario (Degraded Forest Scenario). These scenarios considered varying levels of forest management, habitat restoration, and removal of barriers to fish passage that may occur in the Staney Creek Watershed. In addition to modeling restored and degraded conditions, we applied RIPPLE for each scenario to model low, medium, and high coho salmon ocean survival in order to evaluate the population-level impacts of variable ocean conditions and commercial harvest.

Using a model such as RIPPLE allows the development of hypotheses about current and future controls on the coho salmon population in the Staney Creek watershed. Furthermore, it improves understanding of the relative impact of various management scenarios on the population, which can in turn be used to guide future data collection efforts and improve management decisions. The future scenarios are not specifically tied to current practices. Instead they reflect hypothetically broad-scale improvements and reductions in basin-wide forest health. Information provided by the model will serve to inform future fish habitat protection, restoration, and monitoring efforts in the watershed.

In the succeeding sections we describe the methods used to model coho habitat distribution and production potential in the Staney Creek watershed and present population-level results of various future scenarios. Importantly, this is a Phase 1 application of the model, which will benefit greatly

from review by local biologists, model validation, and refinement. Nonetheless, application of the RIPPLE model will greatly expand the knowledge base of where important salmon habitats occur within the watershed and aid in understanding relative population responses to various management and restoration actions.

## 6.1 RIPPLE Model Overview

RIPPLE is a powerful analytical tool that uses an ecological process-based approach to model the effects of historical, current, and potential future watershed conditions as they affect salmonid habitat and populations. The model is a collaborative product of the National Science Foundation-funded National Center for Earth Surface Dynamics (NCED) and Stillwater Sciences. In addition to comparing watershed conditions and fish populations across time and restoration scenarios, it can provide a systematic, reliable characterization of habitat "hot spots" for salmon productivity within a watershed, thereby ensuring that those locations receive an appropriate level of protection.

RIPPLE can function at spatial scales from individual stream reaches to small watersheds to whole regions or landscapes. It was specifically developed for use in conditions where limited data exists, and relies on digital elevation data and empirical relationships to estimate reach-specific habitat throughout a channel network. The model uses population dynamics models to estimate spatially-explicit populations for each salmonid life stage. By changing these relationships, or inserting data from reach-specific field observations in the model, it is possible to model changes in habitats and examine how a restoration program might affect overall productivity through improvements in carrying capacity and survival during one or more life stages. Variable marine survival and ocean harvest can also be incorporated to understand the impact of these factors on population dynamics.

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"). The model is open-source and public domain, and a coho life history version can be downloaded from the NCED website at http://www.nced.umn.edu/RIPPLE2.html. Future advancements in the model will be uploaded to the website.

One of the guiding principles of the model is the assumption that physical processes and the resulting environment—specifically topography, geology, drainage area, channel gradient, and channel longitudinal profile—are relatively unchanging. This assumption permits construction of a digital model of terrain features that establishes a physical "template" based on available data for topography and channel network characteristics. This physical template dictates the characteristics of habitats, which in turn can be used to predict reach-specific historical, current, and potential future salmon habitat and thus the potential distribution and abundance of salmon and life stages in different parts of the watershed.

RIPPLE includes a multi-stage stock-production model that links habitat conditions to population productivity attributable to specific stream reaches or watersheds. Conceptually, the model allows adult and juvenile salmon to migrate through the watershed in search of available habitat, which they occupy at densities specified by the user. Its main virtue is that it allows the user to project how changes over time in habitat quality and quantity will affect multiple generations of salmon in terms of overall population performance. The model allows the user to explore various outcomes by changing habitat abundance and quality.

Refer to the following link for additional detail on model structure and theory
http://www.stillwatersci.com/resources/RIPPLE_overview.pdf

### 6.1.1 Channel network development and attribution

Using and developing a robust channel network is key to the implementation of the model because physical attributes such as channel gradient and drainage area will have direct influence on the spatial distribution and amount of aquatic habitat.

Stillwater used an enhanced 1:24,000 vector channel network provided by the Tongass National Forest (TNF) and a 2-arc second National Elevation Dataset (NED) DEM (digital elevation model) projected onto a 10-m DEM, from which 10-m elevation contours were interpolated.

The TNF channel network was overlaid onto current imagery and selected over channel networks derived directly from the 2-arc second NED DEM or from a 30-m Aster-based DEM. Channels derived from both DEMs were disconnected because of the hummocky terrain in the lower, flatter areas of the watershed derived from kettle glacier topography. To address this problem both sets of channels were automatically corrected; however the alignment of the channels did not correspond well with streams depicted in digital images and current ground conditions. Therefore, the TNF vector channel network was identified as the preferred data set for the analysis.

The TNF vector channel network was detailed and extended upstream to first order watersheds mostly in the southern portion of the watershed. It was part of the original dataset provided by TNF and was most likely derived from more detailed TNF surveys of the southern portion of the watershed. Although the drainage densities are higher in the southern part of the watershed, this has no effect in the output of RIPPLE given that these first order channels are too steep to provide salmon habitat.

#### 6.1.1.1 Channel gradient

Channel gradient was calculated by intersecting the TNF channel network with the 10-m elevation 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. Channel gradient for individual reaches was therefore calculated by taking the elevation difference between contour intervals divided by the length of channel for that reach.

By exclusively using vector channel data and the 10-m 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 (DTM). Figure 6-1 shows the channel network for Staney Creek showing calculated channel gradient.

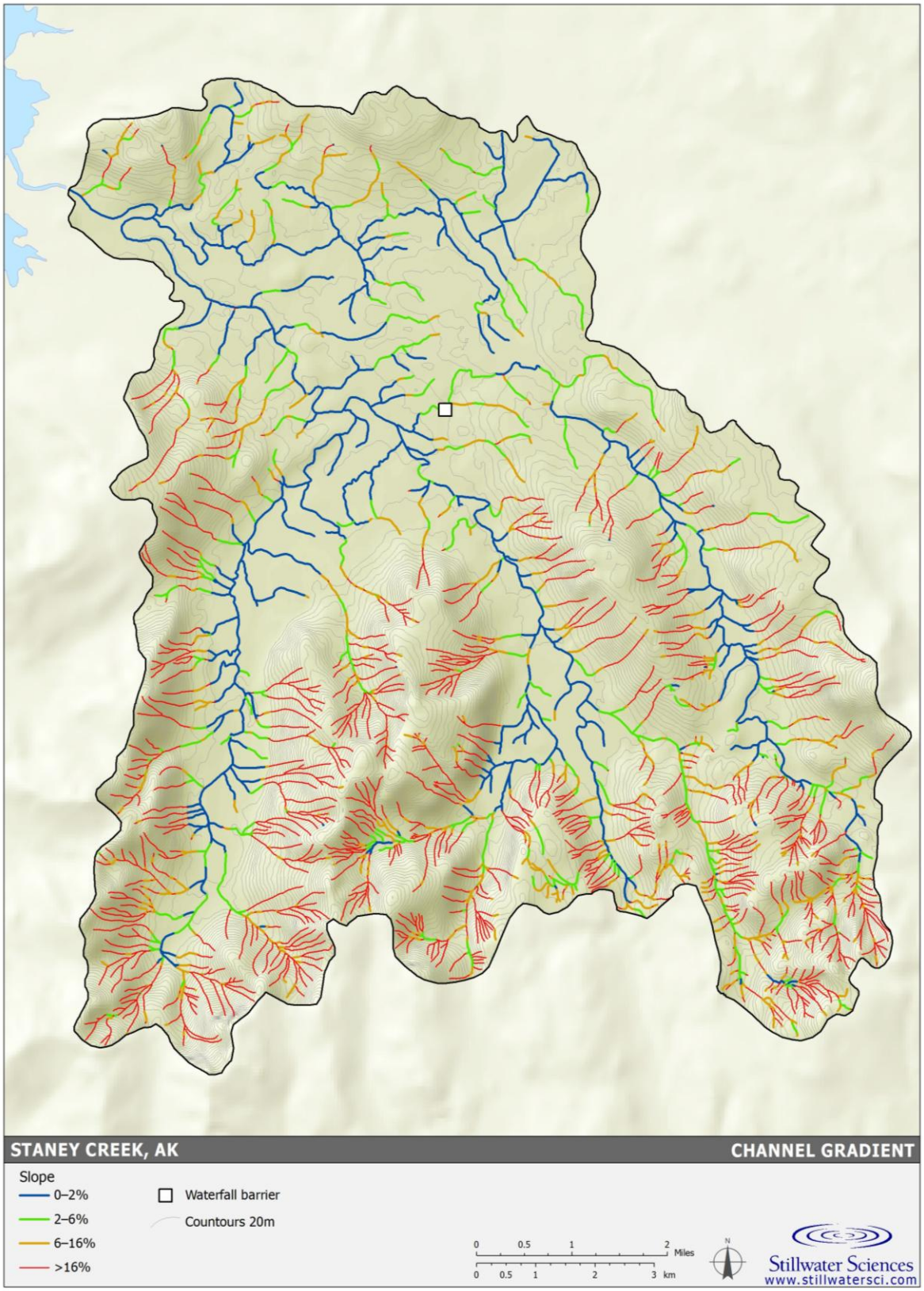


**Figure 6-1.** Channel gradient in the Staney Creek watershed.

#### 6.1.1.2 Drainage area

Drainage area was calculated by obtaining the contributing area to the 10 m grid-cell and overlaying arc ends and tributary junctions on the contributing area grid. This was done using several hydrological functions in ESRI's ARCINFO that allow artificial depressions in the DEM to be filled and route water following the steepest elevational drop in the terrain. Since sometimes the steepest drop in the DEM does not follow the channel alignment, channels were "burned" or incised in the DEM forcing the flow into them. Once the "burned" grid with the contributed areas was created, the endpoints and junctions of the arcs were used to extract the contributing area values from the cells they overlay. Figure 6-2 shows the channel network for Staney Creek showing calculated drainage area.

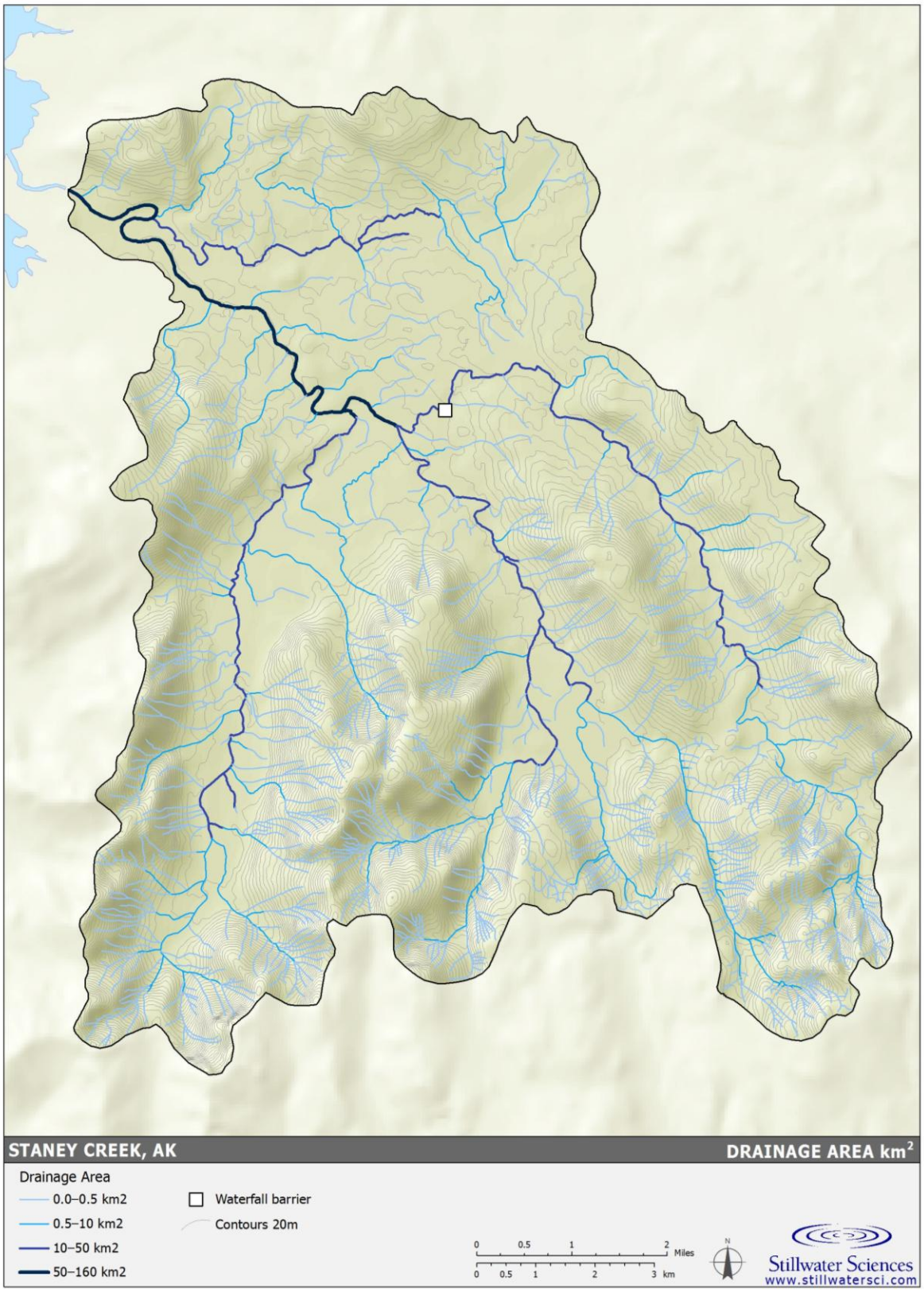


**Figure 6-2.** Drainage area in the Staney Creek watershed.

#### 6.1.1.3 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. These segments, or arcs, define the scale of the analysis used in RIPPLE and hence represent the finest resolution of analysis performed. We recognize that neither contour data nor channel networks are evenly distributed across a watershed and thus reach lengths will vary—shorter in steep, incised terrain, and considerably longer (up to tens of kilometers in the absence of tributaries) in low-gradient, floodplain areas.

## 6.2 Hydraulic Geometry (GEO)

The GEO module, the first of three RIPPLE sub-models, stratifies the physical template (e.g., channel network and fluvial geomorphology) upon which all subsequent modeling of aquatic habitat and population dynamics are performed. GEO input data include digital elevation data (e.g., USGS 10-m DEM), stream channel network (e.g., USGS digital line graph hydrography), vector-based contours (e.g., USGS 1:24,000 digital line graph hypsography), and hydraulic geometry relationships. The quality and resolution of the available input data affect all subsequent model estimates.

GEO sub-model implementation assumes that topography and geomorphology do not change during the time scale over which biological responses are modeled (e.g., <1,000 years). Physical channel parameters predicted by the GEO sub-model include the following:

- Shreve stream order (Shreve 1966)
- Strahler stream order (Strahler 1952)
- Stream channel elevations at arc endpoints
- Drainage area
- Channel gradient
- Width and depth at bankfull flow
- Width and depth at summer low flow
- Width and depth at winter base flow

Detailed methods and sources of information used to develop hydraulic geometry relationships used to predict channel widths and depths for the Staney Creek GEO module are presented in Appendix A.

### 6.2.1 Results and discussion

Hydraulic geometry relationships developed for bankfull flow, summer low flow, and winter base flow are summarized in Table 6-1. These functions are implemented in GEO to predict the width and depth at bankfull flow, winter base flow, and summer low flow for each arc (i.e., reach) in the channel network. The predicted channel widths at bankfull flow shown in Figure 6-3 are one important example of the GEO sub-model products that are used as input to the habitat capacity and population dynamics components of RIPPLE and may be independently used for other aquatic resource management objectives. Similar results are available for each of the GEO output parameters.

**Table 6-1.** Summary of GEO hydraulic geometry relations for the Staney Creek watershed.

| Parameter | Function | $R^2$ | Source |
|---|---|---|---|
| Bankfull width | $W_{bf} = 0.0483\ A^{0.3334}$ | 0.91 | Bankfull width and depth at COMIS sites in Staney Creek; bankfull width and depth data at 13 sites surveyed by Emmett (1972) |
| Bankfull depth | $D_{bf} = 0.0157\ A^{0.2111}$ | 0.88 | Bankfull width and depth at COMIS sites in Staney Creek; bankfull width and depth data at 13 sites surveyed by Emmett (1972) |
| Summer low flow width | $W_{lf} = 0.5174\ W_{bf} + 0.4806$ | 0.30 | Wetted width and bankfull width at COMIS sites |
| Summer low flow depth | $D_{lf} = 0.1653\ D_{bf} + 0.0417$ | 0.17 | Wetted depth and bankfull depth at COMIS XS sites. |
| Winter base flow width | $W_{wb} = 0.9319\ W_{bf} – 0.3095$ | 0.97 | Active bed width and bankfull width from CTV sites in floodplain and moderate gradient process groups, bottom of bank width and bankfull width from COMIS sites. |
| Winter base flow depth | $D_{wb} = 0.5033\ D_{bf} – 0.0117$ | 0.54 | Bottom of bank depths and bankfull depths from COMIS sites. |

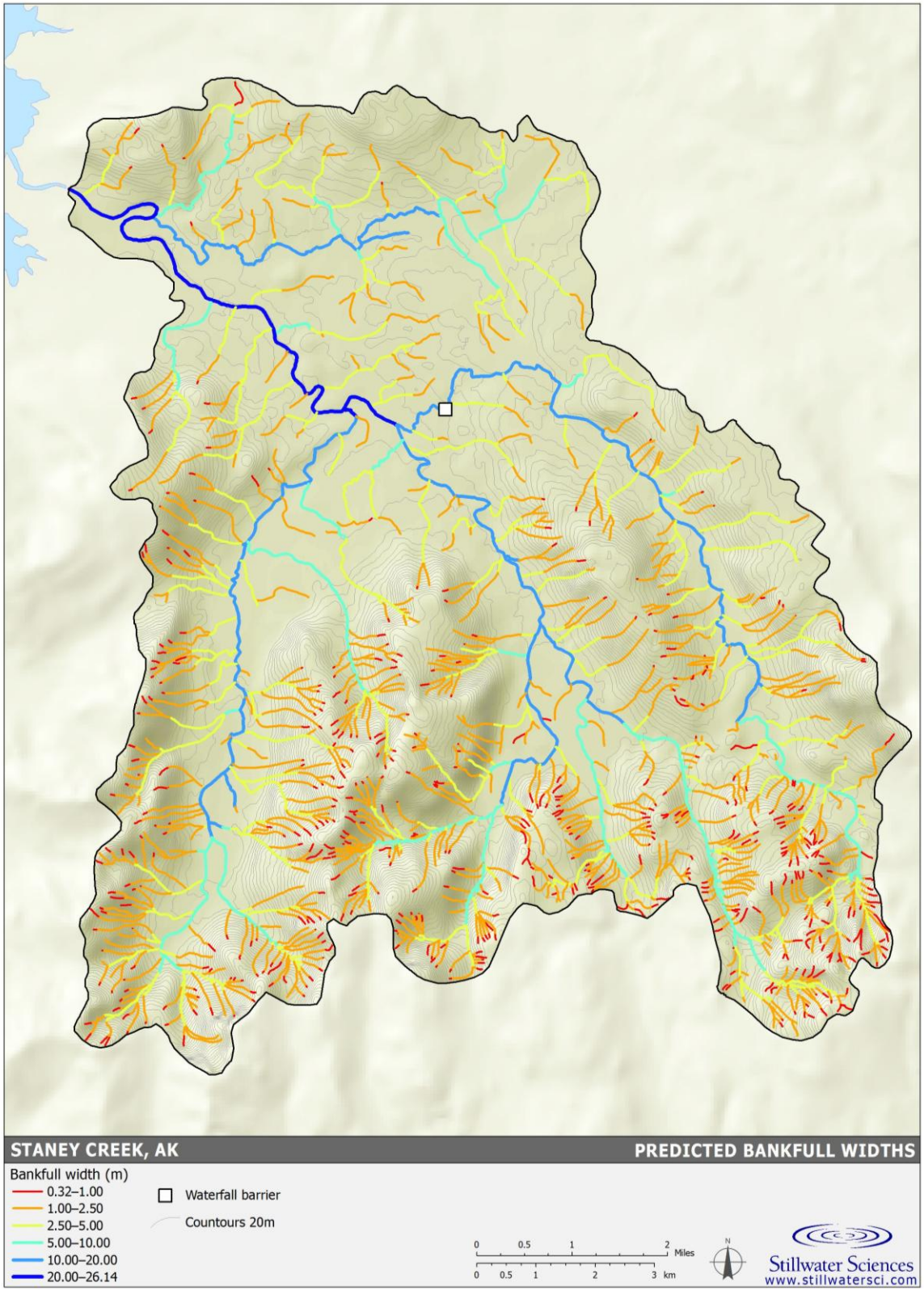


**Figure 6-3.** GEO output map showing predicted channel widths at bankfull flow in the Staney Creek watershed.

GEO output parameters are sensitive to the quality and resolution of the available input data, including digital elevation, channel network, and hydraulic geometry data. Data describing channel geometry in the Staney Creek watershed was limited to a small number of sites with a narrow range of small contributing drainage area. Hydraulic geometry relationships were therefore developed using the available data from Staney Creek and data describing stream channel geometry in watersheds throughout southcentral and southeast Alaska that, based on existing available information, are assumed to have similar controls (e.g., geology, geomorphology, base-level control, and climate) governing fluvial processes and channel geometry. Variations in the controls between watersheds where these data were collected leads to some uncertainty in model predictions, particularly for portions of the channel network with drainage areas unrepresented by data collected within Staney Creek. Correlation coefficients are relatively high for bankfull and winter base flow relationships but relatively low for low flow relationships. This is typical and to be expected in channel networks where low flow is a small fraction of the channel-forming bankfull flow and winter base flow.

## 6.3 Habitat Capacity (HAB) and Population Dynamics (POP)

The primary goal of the HAB sub-model is to calculate life-stage-specific carrying capacity, or the maximum number of individuals of a given coho salmon life stage that the available habitat can support. HAB uses the attributed channel network developed in the GEO sub-model as a framework for defining habitat quality and quantity for each life stage. For example, channel width predicted for each reach by the GEO sub-model is used to calculate habitat area, which is then used in conjunction with life-stage-specific fish density values to calculate carrying capacity in that reach. GEO-predicted width is also used to restrict spawning and rearing to channels of a certain size.

The POP sub-model uses the reach-specific carrying capacities generated by HAB to predict life stage-specific population size for the watershed. The sub-model simulates mature adults migrating to stream reaches with available spawning habitat. Once the spawning carrying capacity of a reach is filled, then subsequent spawners can look for available habitat in other reaches. Likewise, when fry emerge and fill a reach's carrying capacity for summer juveniles, excess fry will look for available habitat in other reaches. Similarly, juveniles in excess of a reach's winter carrying capacity will search for unsaturated habitat in other reaches.

RIPPLE is based on stock-recruitment functions that result in equilibrium population predictions for each life stage. It is a deterministic, mechanistic model, as opposed to a statistical model. As a result, statistical uncertainty in the form of confidence intervals or distributions are generally not appropriate. It is mathematically possible to construct confidence intervals for model outputs using Monte Carlo methods if we have statistical distributions for model parameters, however that is not the case. A more appropriate next step would be to use sensitivity analysis to better calibrate model input parameters and demonstrate the sensitivity of the model predictions to certain parameters. This is recommended for future model development.

### 6.3.1 Methods

As described in Section 5.1, coho salmon in southeast Alaska can display a diversity of life history strategies. In particular, time spent rearing in freshwater varies from one to four years (Halupka et al. 2000). In the RIPPLE model, we assumed the predominant coho salmon life history type in Staney Creek spends two years in freshwater and parameterized the model

accordingly. We acknowledge that all Staney Creek coho rearing for two years is a mathematical simplification of the likely biological diversity, and in fact some fraction of the population likely follow different life history timing; however, given the available data, the model assumptions reflect freshwater rearing duration for the majority of the population as reported by Sandercock (1991) and Halupka et al. (2000). We applied and documented other such model assumptions based on the best available data.

The version of the RIPPLE model applied was designed to model juvenile carrying capacity during two freshwater life stages, for which we selected the first summer and winter spent in freshwater. To model summer carrying capacity, we used fry density data collected in the summer. To model winter carrying capacity, we used parr density data collected in the summer following the first winter spent in freshwater. These data reflect potential carrying capacity during the first winter. A key assumption of the model structure is that carrying capacity of juveniles in their first winter is more limiting than in the second winter, since individuals that make it through one winter are expected be stronger swimmers and outcompete the smaller age-0 individuals in limited low-velocity winter habitat during their second winter. In the POP sub-model, we accounted for two years of density-independent survival by using the product of estimated survival values from the first and second summer to parameterize summer survival and the first and second winter to parameterize winter survival.

#### 6.3.1.1 HAB sub-model

The HAB sub-model requires the input of data on relative composition of habitat types, fish density, and suitable channel widths, depths, substrate sizes and barriers for each life stage across a range of channel gradient classes. Table 6-2 describes the parameters required for input into HAB.

**Table 6-2.** Parameters required for input into the RIPPLE HAB sub-model.

| HAB parameters | Description |
|---|---|
| Habitat type composition | Fraction of pool, riffle, and glide habitat units (by channel length) in each channel gradient class in the study watershed or similar geomorphic region. |
| Usable fraction | Expected fraction (in stream length) of each habitat type potentially available for use by a specific life stage (e.g., spawner, fry, or parr) in each gradient class. |
| Fish density | Number of individuals per square meter for a given life stage in each habitat type and channel gradient class combination. |
| Channel width and depth thresholds | A width or depth threshold can be assigned to filter out portions of the stream network that have a predicted width or depth less than or greater than that usable by a given life stage |
| Grain size ($D_{50}$) thresholds | Minimum and maximum grain sizes can be assigned to filter out portions of the stream network that have a predicted $D_{50}$ less than or greater than that usable by a given life stage |

Appendix B details the methods and data sources used to parameterize the HAB sub-model.

#### 6.3.1.2 POP sub-model

The POP sub-model requires reach-specific carrying capacity values for each life stage, which are generated and supplied by the HAB sub-model for the entire channel network. These carrying capacity values are used in conjunction with biological parameters to produce life-stage-specific stock-production curves, the forms of which are user-selected. The stock-production curves are used in the POP sub-model to estimate equilibrium population sizes of fry, juveniles, smolt-ready juveniles, smolts, and returning adults for individual reaches and for the entire watershed. The equilibrium population is reached after multiple iterations of the model (e.g., 1,000) until the stable long-term average population is reached. Table 6-3 lists the POP sub-model parameters applied in Staney Creek for Current Conditions and describes how they were selected. Where possible, biological parameters specific to coho populations in southeast Alaska were used.

**Table 6-3.** Biological parameters input into the POP sub-model for Current Conditions.

| POP parameters | Value | Source/Rationale |
|---|---|---|
| Fraction female | 0.49 | Mean of 26 populations of coho salmon returning to weirs in southeast Alaska (Halupka et al. 2000, Table 10). |
| Eggs per female | 4,300 | Value for unknown southeast Alaskan population (Nemeth et al. 2005, Figure 10). Intermediate between more northern and southern populations. |
| Embryo background survival[1] | 0.253 | Average survival from egg deposition until emergence from redd reported by Quinn (2005, pg. 254, Table 15-1) for numerous populations. |
| Summer background survival[1] | 0.86 | Product of survival values from two summers of survival (0.9x0.95). Assumes relatively high summer survival once carrying capacity is reached and higher survival during second summer. Based on professional judgment and comparison of spring and fall densities of sites within southeast Alaska. |
| Winter background survival[1] | 0.86 | Product of survival values from two winters of survival (0.9x0.95). Assumes relatively high winter survival once carrying capacity is reached and higher survival during second winter. Based on professional judgment and comparison of spring and fall densities of sites within southeast Alaska. |
| Smolt background survival[1] | 0.95 | Assumes relatively high smolt survival during migration to the ocean. Professional judgment. |
| Ocean survival | 0.10 | Mean smolt-to-adult survival value from seven coho salmon populations in southeast Alaska (Halupka et al. 2000, Table 11). |
| Stock-production curve form | Varies by life stage | Redd superimposition model to simulation spawning, coupled with a density dependent Hockey Stick model to reflect summer and winter stock production. |

[1] Background survival values account for density-independent mortality such as predation or disease.

#### 6.3.1.3 Future scenarios

In addition to modeling coho salmon habitat and population size under current watershed conditions, we modeled the population level impacts of four hypothetical future scenarios for the watershed. With the exception of the red pipe removals simulated by restored passage, the future scenarios are not directly tied to specific forest practices or proposed changes. Instead the scenarios reflect a broad range of basin-wide physical and biological conditions that could occur under active forest management practices. These scenarios are outlined in the succeeding sections and in Table 6-4.

**Table 6-4.** Changes to RIPPLE parameters and passage in restored and degraded future scenarios relative to Current Conditions.

| Parameter | Restored Passage | Restored Forest | Restored Forest and Passage | Degraded Forest |
|---|---|---|---|---|
| Barriers (red pipes) | Fix/remove redpipes on Class I streams | Redpipe barriers present on Class I streams | Fix/remove redpipes on Class I streams | Redpipe barriers present on Class I streams |
| Habitat type composition (pools/riffles) | Same as current | Increase pools/decrease riffles | Increase pools/decrease riffles | Decrease pools/increase riffles |
| Juvenile densities | Same as current | Increase summer and winter rearing densities | Increase summer and winter rearing densities | Decrease summer and winter rearing densities |
| Summer background survival | Same as current | Increase | Increase | Decrease |
| Winter background survival | Same as current | Increase | Increase | Decrease |
| Embryo background survival | Same as current | Increase | Increase | Decrease |
| Smolt background survival | Same as current | Increase | Increase | Decrease |
| Channel width thresholds | Same as current | Increase maximum width for winter rearing | Increase maximum width for winter rearing | Decrease maximum and increase minimum width for winter rearing |

**Restored Passage**

In the Current Conditions scenario, we utilized GIS datasets (provided by D. Albert, The Nature Conservancy), to exclude the stream network upstream of six specific man-made barriers to coho salmon migration in Class I streams. Of the eight road-stream crossings in the Staney Creek watershed that have been identified as inhibiting or completely blocking adult salmon (USDA 2008b), these six barriers have been identified as having the greatest impact on anadromous fish passage. The time frame for this scenario was 1–2 years. In the Restored Passage scenario, we modeled the population-level impact of removing these barriers and allowing upstream passage into suitable habitat by including the entire stream network upstream of these barriers. All RIPPLE model parameters for this scenario were identical to Current Conditions.

**Restored Forest**

The purpose of this scenario was to simulate the long-term population level impacts of conserving old-growth forests and actively restoring currently degraded coho habitat basin-wide to a level approaching the historical, pre-harvest conditions. The time frame for this scenario was 100 or more years to actively promote mature conifer stands capable of generating natural wood recruitment into the stream channel. Passive restoration was assumed to occur in this scenario. Other restoration actions could occur in a significantly shorter timeframe (5 or more years). We did not directly specify the scale, precise location or specific type of restoration actions (e.g., LWD placement, riparian thinning, road decommissioning), but rather focused on the degree of potential improvements to habitat capacity and survival with a target of historical coho population levels. Our goal was to demonstrate the maximum habitat capacity and freshwater production potential likely to occur in historical, pre-harvest conditions.

As described in Section 4, watersheds in old growth forests generally have greater channel stability, pool volume, riparian cover and overall habitat complexity than harvested watersheds of similar size, all of which are important for maintaining healthy coho salmon populations. A fundamental component of this complexity is the size, stability, and recruitment rate of LWD to the channel. Logs and debris jams large enough to withstand high winter flows and help connect the main channel to off-channel winter rearing habitats are crucial for coho overwinter survival. Riparian canopy cover is also a beneficial element, buffering summer high and winter low temperatures. In addition to improving complexity through forest restoration, this scenario assumes a parallel decrease in fine sediment input due to decommissioning of defunct roads and culverts in the watershed.

A primary assumption of the Restored Forest scenario is that an increase in quantity, size, and stability of LWD structures due to forest regeneration and restoration will improve the ability of coho salmon to overwinter in wider channels, such as the lower mainstem of Staney Creek, compared with Current Conditions. This increased distribution was modeled in the HAB sub-model by increasing the maximum winter baseflow width threshold for winter rearing from 21.7 m to 23.8 m; thus allowing rearing in a substantially greater portion of the lower mainstem compared with Current Conditions (Figure 6-4). The extent to which winter rearing distribution was increased was based approximately on the recently documented summer juvenile coho salmon distribution in the watershed and assumes that relatively high numbers of fish will be able to successfully overwinter in the lower mainstem, rather than migrate into tributaries or be displaced by high flows (Bramblett, et al. 2002; B. Wright, USDA Forest Service, pers. comm.).

A second prevailing assumption of this scenario is that more and large LWD and a decreased supply of fine sediments (from fewer roads, more stable hillslopes, and a more intact riparian zone) will result in an increase in formation and maintenance of the pool habitat preferred by coho salmon. To reflect increased pool habitat the Restored Forest model was parameterized with the median of pool fraction values for old growth watersheds in southeast Alaska (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright), which was substantially higher than that measured in harvested watersheds. Appendix C, Table 1 shows habitat type composition values used in the RIPPLE model for the Restored Forest scenario and other scenarios modeled.

In addition to increasing pool fraction, both fry and parr rearing densities were increased in the model to reflect an increase in suitable rearing habitat expected to result from the greater habitat complexity of a restored watershed. Density and usable fraction values used for fry and parr in the HAB sub-model for Restored Forest and other scenarios are shown in Appendix C, Tables 2 and 3.

Summer, winter, and smolt background survival values were also increased in the POP sub-model to reflect decreased predation due to increased escape cover resulting from the overall increase in habitat complexity. Finally, embryo survival, which is correlated to spawning gravel permeability (Tagart 1976) was increased due to diminished inputs of fine sediment expected following road decommissioning and forest restoration Appendix C, Table 4).

The effect of channel width as a threshold condition restricting winter rearing in the various scenarios is illustrated by Figure 6-4.

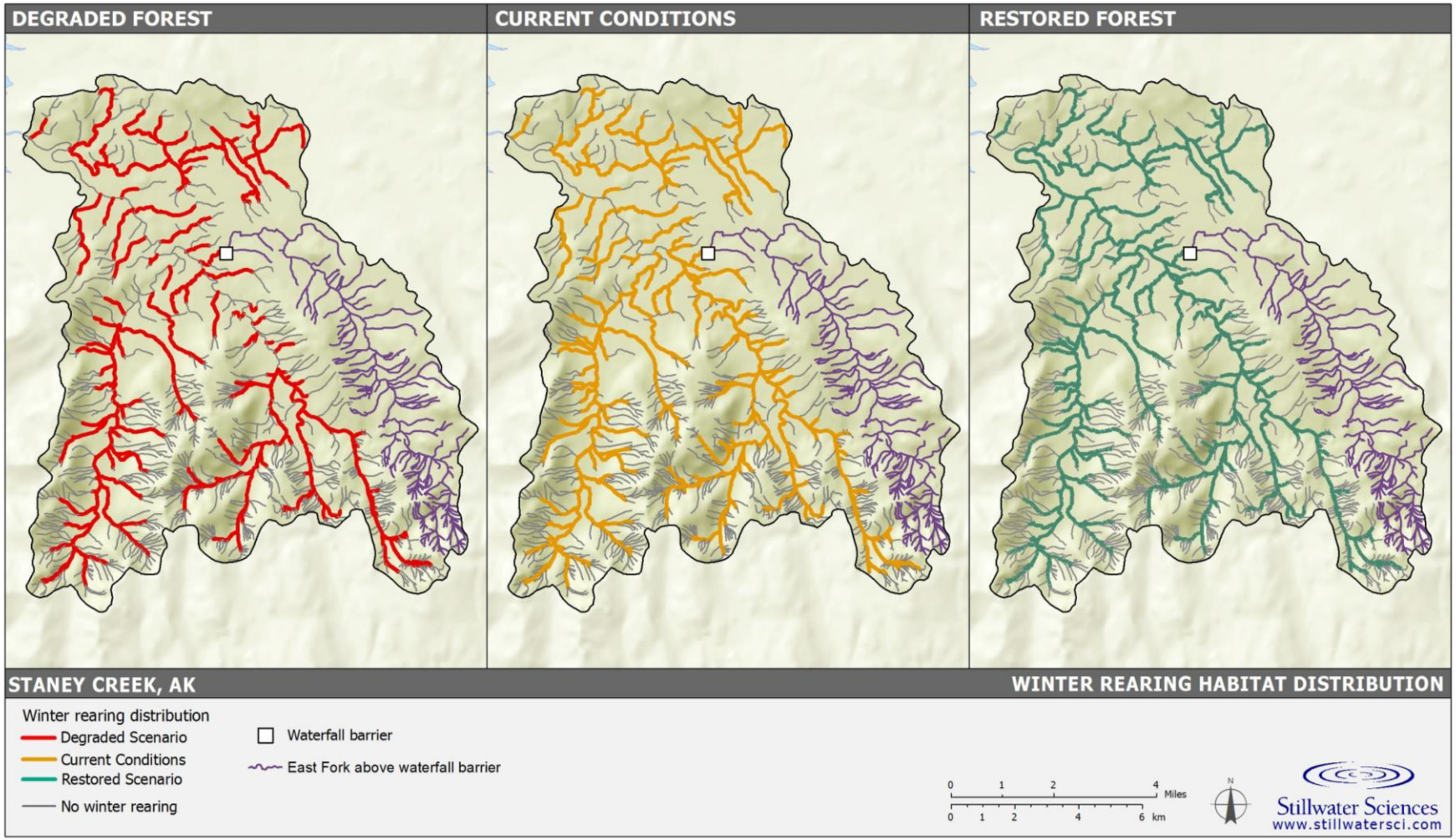


**Figure 6-4.** Comparison of the winter rearing distribution of juvenile coho salmon in the Staney Creek watershed between scenarios resulting from modifying channel width thresholds in the HAB sub-model. Note: to aid in comparison, this projection does not account for differences in upper distribution between scenarios related to culvert barriers.

**Restored Forest and Passage**

The intent of the Restored Forest and Passage scenario is to evaluate the combined benefits of forest restoration and passage improvements in terms of coho population response. The timeframe for this scenario was 100 or more years and was modeled by combining the elements described in the Restored Forest and Restored Passage scenarios above.

**Degraded Forest**

The purpose of the Degraded Forest scenario is to simulate the long-term population level impacts of additional old growth harvest basin-wide in the absence of proactive forest conservation and restoration measures. The timeframe for this scenario was 10 or more years. This reflects sufficient time to conduct extensive harvest throughout the basin. However, as stated previously, this is not based on exact U.S. Forest Service plans for the watershed and instead represents more of a hypothetical worse-case scenario. Our model development was focused on the degree of change in habitat conditions and life stage specific survival, rather than a direct quantification of harvest (e.g., % forest harvested). A key assumption of this scenario is that over longer time periods much of the LWD currently present in streams in heavily harvested portions of the watershed, either from logging debris or naturally recruited, will either decay and break-up or be carried out of the channel by large floods. We also assume that intensive logging of the hillslopes will continue, diminishing future recruitment of LWD in the watershed and eliminating riparian canopy cover. Even if no additional logging occurs in these watersheds, recruitment of the important large conifer logs to the stream channel is expected to greatly diminish for many years (B. Wright, USDA Forest Service, pers. comm.; Lisle 1986) and coho carrying capacity is expected to decline in response. As described above, these large logs are crucial for maintaining habitat complexity and providing preferred coho habitat. Thus, this scenario is effectively the inverse of the Forest Restoration scenario and was parameterized accordingly.

In the Degraded Forests scenario, lack of recruitment of large, stable LWD and pool filling resulting from increases in fine sediment inputs are expected to reduce the ability of coho salmon to overwinter in Staney Creek, especially larger mainstem channels, compared with the Current Conditions scenario (Figure 6-4). This decreased distribution was modeled in the HAB sub-model by decreasing the maximum channel width threshold for winter rearing from 21.7 to 14.0 m, which restricted coho winter rearing to a shorter reach of the mainstem and South Fork. This restriction of winter rearing habitat was based on the professional judgment that reduced availability and size of LWD under the Degraded Forest Scenario would alter habitat composition in the mainstem channel. Likewise, a reduction in channel complexity was assumed to decrease suitability of spawning and rearing habitats at the upstream extent of coho distribution.

In response to decreased LWD and complexity associated with a degraded watershed, pool fraction, rearing densities, and background survivals were all decreased to levels below Current Conditions. Refer to Appendix C for parameter values used in the Degraded Forest scenario.

#### 6.3.1.4 Ocean conditions and harvest

Ocean conditions and harvest levels can exert influence on the number of returning adult coho salmon (Section 3.6). In RIPPLE, the combined influence of ocean conditions and harvest are accounted for in the ocean survival parameter of the POP sub-model. For the Current Conditions model and each of the four future scenarios described above, we assumed moderate ocean survival and thus selected the mean of the ocean survival values (10%) reported by Halupka et al. (2000). However, in order to help understand the relative impacts of ocean conditions and harvest levels on adult equilibrium populations, we also ran each model scenario with the lowest (3.7%)

and highest (16.5%) coho salmon ocean survival values reported by Halupka et al. (2000) for southeast Alaska.

### 6.3.2 Results

Model results for current conditions and future scenarios are summarized according to summer and winter carrying capacities and an equilibrium level of smolt and adult coho (Table 6-5). The predictions illustrate that winter conditions are more restrictive than summer rearing capacity and that the various management scenarios result in a wide range of smolts (8,983 - 59,726) and returning adults (898 - 5,973).

**Table 6-5.** RIPPLE-predicted summer and winter juvenile coho salmon carrying capacity and smolt and adult equilibrium populations at 10% ocean survival for the Staney Creek watershed under Current Conditions and Future Scenarios.

| Model output metric | RIPPLE sub-model | Current Conditions | Future Scenarios | | | |
|---|---|---|---|---|---|---|
| | | | Restored Passage | Restored Forest | Restored Forest and Passage | Degraded Forest |
| Summer carrying capacity | HAB | 67,920 | 68,728 | 135,231 | 136,936 | 22,163 |
| Winter carrying capacity | HAB | 26,658 | 26,961 | 64,765 | 65,593 | 11,407 |
| Smolts | POP | 24,216 | 24,496 | 59,139 | 59,726 | 8,983 |
| Adults | POP | 2,422 | 2,450 | 5,914 | 5,973 | 898 |

#### 6.3.2.1 Current Conditions scenario

The HAB sub-model predicted summer and winter juvenile carrying capacities for the Current Conditions scenario of approximately 67,900 and 26,700, respectively (Table 6-5). The POP sub-model predicted an annual equilibrium population of approximately 24,200 smolts and 2,400 returning adults (Table 6-5).

Appendix D, Figure 1 provides a graphical representation of the POP sub-model output map for number of redds, age-0 juveniles (fry that have survived through their first summer), and smolt-ready juveniles (individuals that have survived two winters and are preparing to outmigrate to the ocean) predicted per meter of channel under Current Conditions. Spawning and smolt-ready-juvenile production did not occur in the mainstem downstream from the confluence of the South Fork, but occurred in upstream channels and tributaries with winter baseflow widths larger than 2 m. Age-0 juvenile production occurred in the mainstem nearly as far downstream as the confluence of the North Fork with the mainstem. The difference in distribution between age-0 and smolt-ready-juvenile, which reflects winter habitat carrying capacity, highlights the shortage of winter habitat compared with summer habitat. Within the expected distribution of each life stage, numbers of redds and juveniles produced generally increased with channel size and were higher in lower gradient channels, which have greater carrying capacities. Finally, spawning and juvenile production did not occur upstream of the six Class I culvert barriers, labeled as "redpipes", in the Current Conditions scenario. Appendix D, Figure 1 also demonstrates the relative amount of production of each life stage, and the inaccessible area lost due to the presence of these barriers.

Appendix D presents similar graphical results for the restored and degraded scenarios.

#### 6.3.2.2 Restored Passage scenario

Removing the six "redpipe" barriers on Class I streams would allow access to approximately 2.1 miles of potential spawning and juvenile rearing habitat predicted by the model. This additional habitat is estimated to produce an additional 28 adults (a 1.2% increase) compared with the Current Conditions scenario assuming like habitat conditions (Table 6-5). Appendix D, Figure 2 shows the relative amount of additional production of redds and juveniles expected to occur upstream of these barriers under the Restored Passage scenario assuming current habitat conditions. It should be noted that this is a model-approximation of the actual miles of anadromous fish habitat that would be opened up by removing these barriers based on channel width and gradient.

#### 6.3.2.3 Restored Forest scenario

Under the Restored Forest scenario, the HAB sub-model predicted summer and winter juvenile carrying capacities of approximately 135,200 and 65,600, respectively (Table 6-14). POP predicted an equilibrium population of approximately 59,100 smolts and 5,900 returning adults annually, nearly 2.5 times more adults (a 144% increase) than under Current Conditions (Table 6-5).

Appendix D, Figure 2 shows the POP output map for number redds and smolt-ready juveniles predicted per meter of channel under the Restored Forest Scenario. In this scenario, spawning distribution was the same as Current Conditions, but the number of redds per meter was substantially higher for all reaches, which was largely due to an increased fraction of pools (which have more usable area of for spawning) in the Restored Forest scenario (Appendix C, Table 1).

In this scenario, production of smolt-ready juveniles occurred in the mainstem downstream to the confluence with the northern watershed, reflecting greater suitability of winter rearing habitat in larger channels than under Current Conditions (Appendix D, Figures 1 and 2). In addition to increased winter rearing distribution, the number of smolt-ready juveniles produced per meter was substantially higher for all reaches as a result of increased pool habitat, higher densities, and higher survival values than for Current Conditions. As with Current Conditions, no redd or juvenile production occurred upstream of Class I culvert barriers. Appendix D, Figure 2 shows the relative amount of redd and juvenile production lost to the population upstream of each barrier.

#### 6.3.2.4 Restored Forest and Passage scenario

The Restored Forest and Passage scenario simulated the removal of the six culvert barriers on Class I streams under the Restored Forest Scenario. Appendix D, Figure 3 shows the distribution and relative quantity of redds and smolt-ready juveniles under this fully restored scenario. As with restoring passage under Current Conditions (modeled by the Restored Passage scenario), 2.1 miles of potential coho salmon spawning and rearing habitat was made accessible. An additional 59 returning adults were estimated to be produced upstream of the removed barriers assuming restored habitat conditions, which is 31 more than restoring passage assuming current habitat conditions (Table 6-5). This increased production results from the greater quantity and higher quality of spawning and rearing habitat in the Restored Forest Scenario. The number of adults returning under the Restored Forest and Passage scenario represents an estimated 1% increase above the Restored Forest scenario and a 147% increase above Current Conditions.

#### 6.3.2.5 Degraded Forest scenario

Under the Degraded Forest scenario, the HAB sub-model predicted summer and winter juvenile carrying capacities of approximately 22,100 and 11,400, respectively (Table 6-5). POP predicted an equilibrium population of approximately 9,000 smolts and 900 returning adults, a 63% decline from Current Conditions (Table 6-5) based on assumed changes to habitat capacity and survival discussed in Section 6.3.1.3.

Appendix D, Figure 4 shows the POP sub-model output map for number of redds and smolt-ready juveniles per meter under the Degraded Forest scenario. The downstream boundary of spawning distribution was the same as for Current Conditions, but the upstream bounds of spawning was restricted to channels larger than 2.4 m winter baseflow width. Number of redds per meter was considerably lower than for Current Conditions in all reaches due to a decrease in fraction of pools in the Degraded Forest scenario (Appendix C, Table 1). Production of smolt-ready juveniles in the mainstem was restricted to considerably smaller channels compared with Current Conditions and the restored scenarios (Appendix D, Figures 1-3), and the number of smolt-ready juveniles per meter was significantly lower for all reaches compared with Current Conditions. The predicted reduced distribution and abundance is due to the paucity of large, stable LWD pieces and jams and degraded winter habitat in the mainstem. As with Current Conditions, no production occurred upstream of the six culvert barriers on Class I streams.

#### 6.3.2.6 Ocean Conditions and Harvest

Table 6-6 demonstrates the impact of varying ocean survival levels on the returning adult population for each scenario modeled. Within each scenario, the equilibrium population size of returning adults increased in proportion to ocean survival.

**Table 6-6.** RIPPLE-predicted adult equilibrium populations for Staney Creek at the lowest, mean, and highest ocean survival values reported for southeast Alaska (Halupka et al. 2000, Table 11).

| Model scenario | Ocean survival | | |
|---|---|---|---|
| | 3.7% | 10.0% | 16.5% |
| Current Conditions | 896 | 2,422 | 3,996 |
| Restored Passage | 906 | 2,450 | 4,042 |
| Restored Forest | 2,188 | 5,914 | 9,758 |
| Restored Forest and Passage | 2,210 | 5,973 | 9,855 |
| Degraded Forest | 319 | 898 | 1,482 |

### 6.3.3 Discussion

As with any mathematical representation of nature, model results are predictions, subject to uncertainty, anthropogenic influences and environmental variation. The population estimates produced by a model such as RIPPLE are point values that incorporate a range of variability and uncertainty from all parameter sources. As such, the point estimates are best used to characterize broad physical and biological trends within the system, limiting conditions and relative points of comparison between alternative conditions. Such information can be a powerful aid in the decision making process.

#### 6.3.3.1 Key reaches

RIPPLE output maps for Current Conditions generally indicate the highest production of smolt-ready juveniles per meter in larger, low gradient channels within the expected winter distribution of juvenile coho in the Staney Creek watershed. These reaches include the mainstem upstream of the South Fork and its main branches, as well as the mainstems of the North and South Forks. The greater production predicted for these larger channels is due in part to the larger overall habitat area of these reaches. Importantly, this pattern should not overshadow the value to the population of the numerous, smaller tributaries. While fewer juveniles per meter are expected from each of the smaller channels, the combined production from these channels contributes significantly to the overall production of coho salmon in the watershed and should be considered in management decisions.

#### 6.3.3.2 Comparison of scenarios

The RIPPLE model outputs demonstrate the relative magnitude of the impacts of the various forest management and fish passage alternatives on the coho salmon population. Model results indicate that forest restoration (Restored Forest scenario) would have a much greater impact on the population than passage restoration (Restored Passage scenario) alone (144% and 1.2% increase in returning adults over Current Conditions, respectively), but that combining forest and passage restoration would yield the greatest increased percentage of returning adults. However, it is important to consider that a Restored Forest scenario assumes full forest restoration to near historical conditions of LWD recruitment and channel stability, which, if approached passively, could require hundreds of years of forest regeneration. However, there are active restoration actions which could significantly expedite the process of restoring coho habitat and increasing fish production such as: LWD placement, riparian thinning, in-channel pool creation and the improvement or decommissioning of roads and culverts.

The scenario results from the RIPPLE model do not prescribe the specific amount, type, or location of riparian restoration actions needed. Rather, the scenario results illustrate the effects on coho salmon populations that come from different forest management practices and their subsequent changes to coho salmon habitat features in the Staney Creek watershed. These results and the RIPPLE model, however, can be combined with local restoration practices and knowledge to produce restoration prescriptions for specific locations within the watershed. Additionally, a comparison of scenarios clearly demonstrates the adverse impacts of old growth timber harvest and road building on coho salmon habitat features.

Results of the Restored Passage and Forest scenario indicate that forest restoration would have a greater overall benefit to fish production than improving passage. Notably, though, this scenario underscores the importance of implementing fish passage projects in concert with stream habitat restoration. The same 2.1 miles of stream within the expected coho salmon distribution above the Class I barriers, is predicted to produce over twice as many returning adults if habitat conditions are restored, compared with current habitat conditions (59 assuming restored habitat compared with 28 assuming current habitat).

#### 6.3.3.3 Population constraints

In the modeled scenarios, carrying capacity of juvenile coho salmon is predicted to be between 2 and 2.5 times higher in the summer than in the winter. Even, under the Restored Forest scenarios, where the spatial distribution of winter rearing habitat is equivalent to that of summer rearing

habitat, summer carrying capacity is substantially higher. These results indicate that the quantity and quality of winter habitat limits the size of the coho salmon population in the Staney Creek watershed. These findings are consistent with numerous studies that emphasize the importance of winter habitat to coho salmon populations (e.g., Bustard and Narver 1975a and 1975b, Mason 1976, Crouse et al. 1981, Hartman et al. 1982, Shirvell 1990) and suggest that stream restoration actions aimed at improving coho salmon winter habitat (such as active placement of LWD structures in degraded stream channels) will result in the greatest benefit to the population.

While winter habitat carrying capacity likely limits the number of smolts that can be produced from the watershed, model results also clearly demonstrate the relatively large impact ocean conditions and commercial harvest can have on adult returns. For example, decreasing ocean survival to the lowest reported value under Current Conditions results in 1,526 fewer returning adults, or a 63% decline—the same relative impact as the Degraded Forest scenario.

#### 6.3.3.4 Model challenges

A fundamental confounding factor that arises when evaluating the impacts of intensive forest harvest on coho salmon habitat is the difficulty in detecting shorter term responses of important habitat features (such as LWD quantity, complexity, and pool frequency) to harvest. For example, after riparian areas in the Staney Creek and Shaheen Cr. watersheds were clear-cut during the 1960s and 1970s, a three-fold greater volume of woody debris was found in small stream channels in clear-cuts than in channels in unharvested areas (Swanson et al. 1984). Likewise, Lisle (1986) reported a greater number of debris jams and more pool habitat in the same first- and second-order tributaries within 6–10 year old clear-cut forests (in which logging debris was not cleared from streams) than in forested tributaries. In our preliminary analyses of USFS 2003–2005 coho monitoring data from 26 sites in southeast Alaska (USDA Forest Service, unpubl. data provided by B. Wright) we did not find significant differences in various LWD or pool frequency metrics between streams in harvested and unharvested watersheds. These findings can be explained in part by the persistence of existing LWD features many years after logging and by the input of additional woody debris associated with clear-cutting the hillslopes (Swanson et al. 1984; Lisle 1986; Lisle 1986; B. Wright, USDA Forest Service, pers. comm.). Swanson et al. (1984) found many LWD features that had changed little in 20 to 30 years. They attributed this persistence to the slow decay of large conifers, stable orientation in the channel, partial burial by fine sediments, and binding by tree roots growing on and around the features.

In modeling the Degraded Forest scenario, we assumed much of the LWD currently present in previously clear-cut watersheds in Staney Creek will decay and break-up or be carried out of the channel by large flood events before significant recruitment of large conifer logs to the stream channels can occur. Likewise, if intensive timber harvest practices continue on hillslopes throughout the watershed, the future recruitment of LWD to stream channels will be significantly diminished and coho salmon winter carrying capacity is expected to decline in response (Lisle 1986). As discussed in Section 3.3, these assumptions are supported by studies showing reductions in LWD in small streams in second growth forests (including many of the same streams studied by Lisle 1986) compared with streams flowing through unharvested reaches after approximately 20 years following harvest (House and Boehne 1987, Lisle 1986, USDA Forest Service 2008a). Over longer time periods, differences in LWD recruitment and coho habitat quality between harvested and old-growth watersheds are expected to become more pronounced.

The expected time lag between clear-cutting and re-growth of large trees and their recruitment as LWD has implications for forest and stream restoration as well. In our Restored Forest scenario, we assume that it will be many years before substantial recruitment of LWD occurs in harvested

reaches of Staney Creek. Consequently, in the interim, active introduction of LWD into reaches where it has been depleted could be used to create pools and help connect the main channel to off-channel habitats.

An important distinction exists between the response of small channels (such as the first- and second-order streams studied by Lisle 1986) and larger channels (such as the mainstem of Staney Creek and its forks) to clear-cut logging. Logging slash and smaller, younger riparian trees might be stable and create suitable coho salmon rearing habitat in small streams, but not in larger channels. Larger channels, which regularly experience high, scouring flows, require much larger/older logs to create stable, pool- and habitat-forming LWD features than do small channels (Gurnell et al. 2002). Because LWD jams are flushed out of larger channels more frequently, they require a greater supply of logs from upstream to maintain suitable winter coho habitat. For this reason, under an intensive forest harvest regime, such as the Degraded Forest scenario, where the size and frequency of large logs is greatly diminished, we expect that only channels smaller than a certain size are able to maintain sufficient LWD features to support coho salmon rearing through the winter.

#### 6.3.3.5 Model validation and uncertainties

The RIPPLE model output of the equilibrium population size for adult coho salmon returning to the Staney Creek watershed under Current Conditions was relatively close to, but somewhat higher than the most recent empirical data. RIPPLE estimated from 896–3,996 adults depending on ocean survival; whereas weir counts on lower Staney Creek from 1982–1988, a period of high ocean harvest (Figure 3.2), ranged from 4–1,114, with a mean of 264. The higher RIPPLE estimates may reflect improved conditions since the 1980s or could be due to an inexact representation of winter rearing carrying capacity, which limits population size in the model. We used the same parr density values in the HAB sub-model to predict winter carrying capacity, but clearly the maximum winter density that a reach of stream can support varies greatly depending on local conditions. For example, it is likely that coho parr densities in wider, mainstem channels—where most low velocity winter rearing habitats are located on the margins—are effectively lower than in the smaller tributaries, where a great portion of the channel area contains suitable winter rearing habitat.

The RIPPLE coho model is also sensitive to changes in background survivals in the POP module (density-independent after carrying capacity is reached). We assumed that background survival rates of rearing juveniles and outmigrating smolt were relatively high under Current Conditions. However, no quantitative data on predation for each life stage in southeast Alaska were available, and it could be higher than we assumed. Decreasing background survival values would result in reduced adult returns. For example, lowering smolt survival from 95% to 75% in the Current Conditions model at 10% ocean survival results in approximately 500 fewer returning adults.

The Restored Forest and Passage scenario, aimed at simulating fully restored or historical conditions, also generated adult estimates in the range of available weir counts from 1929–1932, a period expected to represent near historical conditions. RIPPLE predicted 2,210–9,855 returning adults and weir counts ranged from 2,046–20,398, with a mean of 9,101. Even under the highest ocean survival, the RIPPLE model did not generate adult numbers as large as the highest 1920s weir counts. A likely explanation for this result is that the parr density data used in the model to predict winter rearing carrying capacity was the 75$^{th}$ percentile of density data collected in recent years (2003–2005), which may not truly represent maximum juvenile densities that the stream could support under fully restored conditions. Unfortunately, historical density data were not available; but increasing parr density values in the HAB sub-model would have a

significant effect on the number of returning adults. For example, increasing parr densities in pools in 0–2% and 2–6% gradients from approximately 0.10 fish/$m^2$ to 0.15 fish/$m^2$ would result in approximately 3,750 additional returning adults at 16.5% ocean survival.

Another difficulty in modeling coho salmon populations is that juveniles occupy a wide range of habitats, and seasonal use of habitats varies (e.g., Bryant 1984, Swales et al. 1986, Nickelson et al. 1992a). For example, they may move from main channel habitats into off-channel habitats, beaver ponds, and small tributaries during the fall and rear there in the winter (Bryant 1984, Swales and Levings 1989, Bramblett et al. 2002) and may even use lakes for rearing (Bryant et al. 1996). The version of the RIPPLE model applied to Staney Creek did not account for these off-channel habitats in predictions of winter carrying capacity since habitat area was based on length and width of each stream reach predicted from hydraulic geometry relationships (refer to Section 6.2). The Staney Creek watershed contains numerous off-channel features including large beaver ponds and small lakes. Since the beaver ponds and other off-channel habitats provide important coho salmon overwinter habitat and increase survival (Bryant 1984, Pollock et al. 2004, B. Wright, USDA Forest Service, pers. comm.), it is reasonable to assume that our estimates of smolt production and adult returns may be low. However, it is likely that the smolt production not accounted for in off-channel habitats was offset by an artificially high production modeled in larger channels, resulting from the use of higher densities measured in small channels. Stillwater Sciences is refining the development of an updated version of the coho RIPPLE model that accounts for off-channel habitat area. That, coupled with density data collected in larger channel for more accurate model parameterization could resolve these model uncertainties.

A further uncertainty in the application of the RIPPLE model is defining the upstream-most distribution of spawning and rearing. For each scenario, a single minimum width threshold was applied to define the upper extent of the distribution. However, it is likely there are barriers to fish passage resulting from long high gradient reaches and other unknown barriers may exist downstream of the assumed upper limit of spawning and rearing. Using a single threshold likely allows spawning and rearing in some channels upstream of where it actually occurs. Likewise, it likely restricts rearing in some channels downstream of where it actually occurs.

#### 6.3.3.6 Recommendations for model refinement

Refining the RIPPLE model predictions using data from field validation is an important component of a successful model implementation, particularly for the most sensitive model parameters. Whenever possible, we utilized locally collected data to parameterize the model; yet, as described above, uncertainties in data accuracy remain. For this reason, we recommend the following key steps to better understand and refine the model predictions:

- Review of the model parameter inputs and results by local fisheries biologists familiar with the Staney Creek watershed. This review should focus on parameters that the model results are most sensitive to, such as those affecting winter rearing distribution and winter carrying capacity.
- Collect habitat type-specific juvenile density data across the Staney Creek watershed, in small tributaries, larger channels, and in off-channel habitats. These data could be used in future model runs to parameterize larger channels and off-channel habitats separately from tributaries to account for varying densities expected between these habitats.
- Collect parr density data in the winter or early spring to obtain a better estimate of winter carrying capacity prior to spring movement and dispersal.

- Quantify off-channel juvenile rearing habitat area provided by features such as beaver ponds. Utilize these data in the new version of the RIPPLE model that incorporates off-channel habitat area into estimates of carrying capacity.

In addition to refinement of model parameters, we believe it would be beneficial to simulate two additional future scenarios: (1) the effect of specific timber harvest plans and locations in the watershed based on the prescriptions set forth in the Tongass Land Management Plan (USDA 2008a) and (2) restoration actions at specific locations within the watershed. To do so would require input from silvicultural growth and yield models as well as a LWD recruitment model to serve as input data for the RIPPLE modeling.

Models are mathematical simplifications of complex and often poorly understood ecological systems. As such, there is always room for improvement. We acknowledge this universal challenge and have sought to address it with a transparent model framework, careful documentation of model parameters and sources, and a limited exploration of model sensitivity. Despite this inherent challenge, the quantification of habitat capacity and coho salmon population levels under variable conditions in Staney Creek Watershed provides valuable insight into limiting conditions within the system and the relative benefits of alternative forest management practices.

RIPPLE is best employed as a working tool for resource managers. It can be further refined with additional data and specific management actions at known locations. To do so with an existing model structure already developed would be a relatively streamlined process. Although there may be future applications of the model, at the time of this publication, we anticipate the predicted ecological consequences simulated by the enclosed model scenarios will be paired with economic impacts evaluated in Hjerpe's 2010 publication, *Seeing the Tongass for the Trees*.

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# Appendices

# Appendix A

# Methods and Sources of Information Used to Develop Hydraulic Geometry Relationships for the GEO Module

The following Appendix provides detailed methods and sources of data used to develop the RIPPLE GEO module for Staney Creek Watershed.

The stream channel network in a drainage watershed systematically increases in size with increasing drainage area and discharge. Channel hydraulic geometry (width and depth) systematically changes with increasing discharge according to the following power law functions (Leopold and Maddock 1953, Leopold et al. 1964):

$w = aQ^b$ $\qquad$ $d = cQ^f$ $\qquad$ $v = kQ^m$

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, such that drainage area can be substituted for discharge where discharge data are sparse or unavailable. The GEO sub-model implements power law functions relating bankfull hydraulic geometry (width and depth) to drainage area. Drainage area must be known at each bankfull measurement site in order to develop the power law relationship for bankfull hydraulic geometry. The GEO sub-model implements linear functions relating hydraulic geometry at other flows (i.e., winter base and low flow) to the same hydraulic geometry variable at bankfull flow (e.g., $W_{lf} = m\ W_{bf} + b$). Drainage area is not required to develop these linear relationships if hydraulic geometry data for winter, bankfull, and low flows are available over a large area where the computationally intensive process of developing channel networks (and calculating drainage area) is infeasible. Empirical hydraulic geometry relationships are typically developed from field measurements of channel width and depth acquired from sample sites stratified by channel gradient and drainage area throughout a watershed or terrain type. Data describing hydraulic geometry at bankfull flow, winter base flow, and summer low flow is often incomplete within a study watershed. In these cases, hydraulic geometry relationships developed in nearby watersheds or terrain types with similar characteristics governing fluvial processes and geomorphology may be used as input for GEO modeling.

Three data sources describing channels in southeast and southcentral Alaska were available for developing hydraulic geometry relationships applicable to GEO modeling in Staney Creek:

1. COMIS cross section data surveyed over an extensive area during 2003–2005 as part of monitoring coho habitat conditions (B. Wright, USDA Forest Service, pers. comm., 22 December 2010);
2. Channel type verification (CTV) data surveyed over an extensive area and compiled by the USDA Forest Service (E. Tucker, Hydrologist, TNF, pers. comm., 4 October 2010); and
3. Channel sites surveyed by Emmett (1972) to characterize channel and flow characteristics along the trans-Alaska pipeline corridor south of the Yukon River.

Bankfull hydraulic geometry relations were developed using data from 3 COMIS sites in the Staney Creek watershed (Aha, Threetenths, and Tye) and the 13 sites surveyed by Emmett (1972) in southcentral Alaska (Figure A-1). The 3 COMIS sites have small drainage areas (0.24–0.54 $km^2$) while the 13 sites surveyed by Emmet (1972) have large drainage areas (52–53,000 $km^2$).

The computationally intensive process of developing channel networks and calculating drainage area was infeasible for COMIS sites outside the Staney Creek watershed. Survey data at COMIS sites included channel type, channel gradient, width and depth at bankfull stage and low flow, dominant substrate, and pebble counts. Data at the Emmet (1972) sites included drainage area and the width, depth, and discharge at bankfull stage.

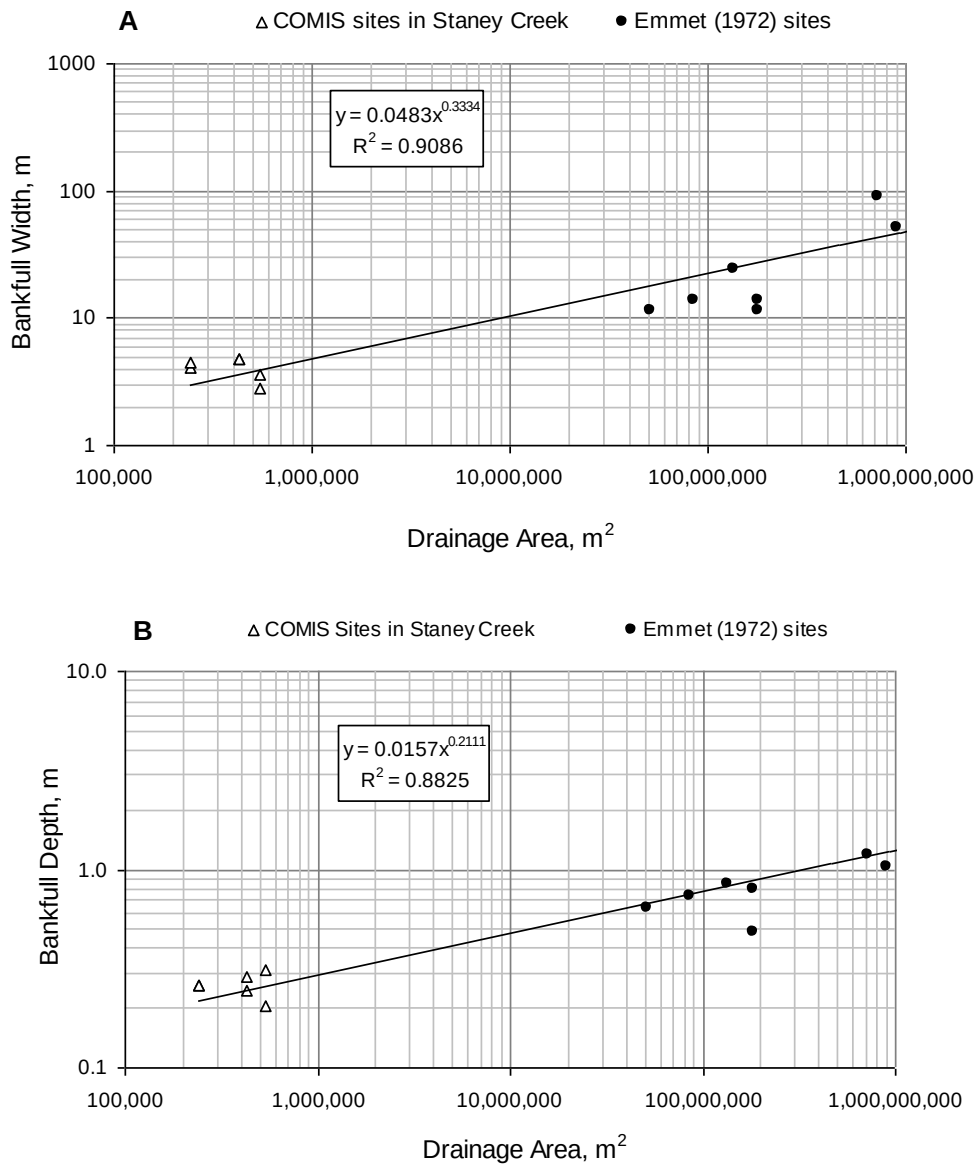


**Figure A-1.** Hydraulic geometry relationships for bankfull width (A) and bankfull depth (B).

Summer low flow hydraulic geometry relationships were developed using data from 50 COMIS sites (Figure A-2). These linear functions relate wetted width and depth at summer low flow to width and depth at bankfull flow. Because drainage area was not required to develop these relationships, data from a larger number of COMIS sites were used.

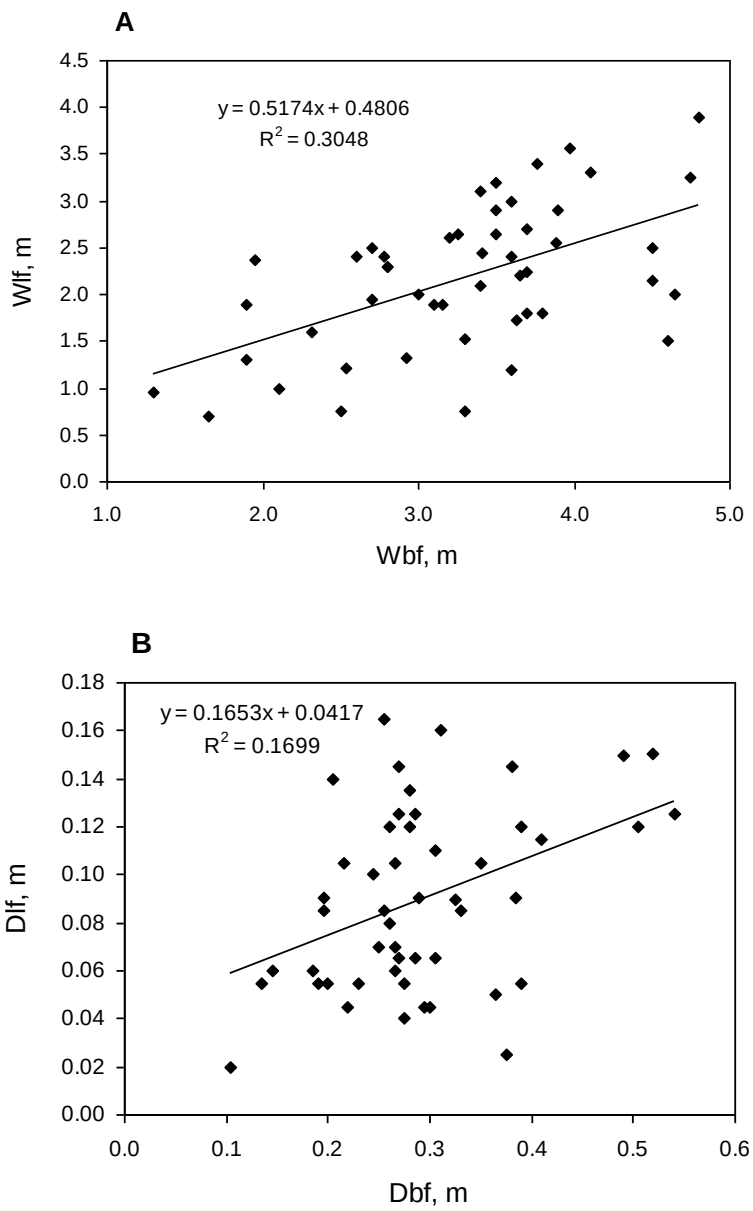


**Figure A-2.** Hydraulic geometry relationships for summer low flow width (A) and summer low flow depth (B).

A hydraulic geometry relationship for width at winter baseflow to bankfull width was developed using data from 376 CTV sites and 53 COMIS sites (Figure A-3). The CTV sites were selected from the Floodplain (n=261) and Moderate Gradient (n=115) process groups. Process groups are defined according to the USDA Forest Service Region 10 Channel Type Classification system (Paustian 1992). Channel gradient in the Floodplain (0–2%) and Moderate Gradient (2–6%) process groups encompasses the range of channel conditions where coho salmon are most commonly found in southeast Alaska. The linear function relates the active channel bed width (at CTV sites) and the bottom of bank width (at COMIS site) to bankfull width. It was assumed that the winter base flow inundates the active bed width to the bottom of the banks. The active bed typically includes the portion of the channel that is scoured frequently enough and inundated long

enough to prohibit establishment and/or persistent growth of woody riparian vegetation within alluvial deposits.

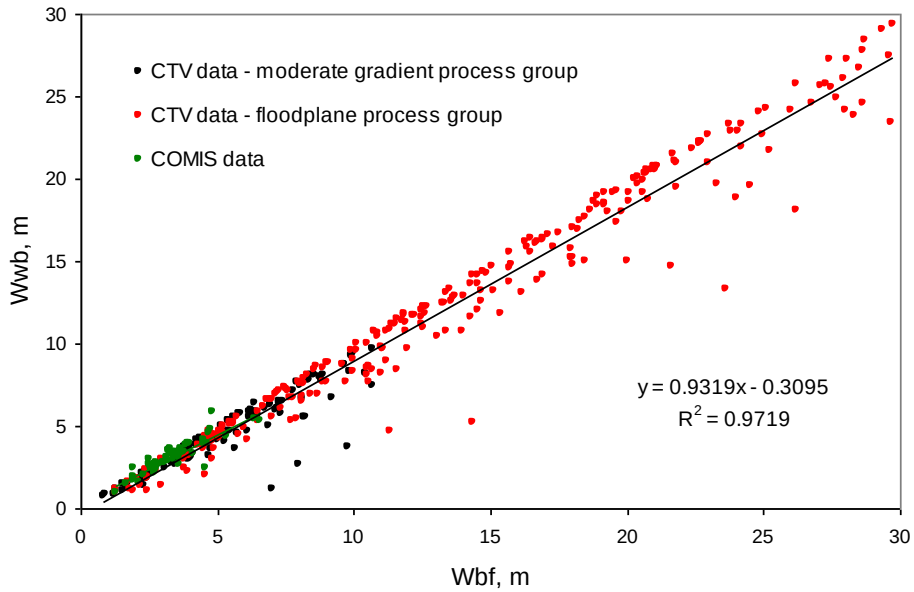


**Figure A-3.** Hydraulic geometry relationship between the width at winter base flow and bankfull width.

A hydraulic geometry relationship for depth at winter baseflow to bankfull depth was developed using cross section data from 50 COMIS sites (Figure A-4). The CTV data did not contain depth information to develop a relationship between winter baseflow depth and bankfull depth. This linear function relates the depth at which flow fills the channel between the bottom of the banks (referred to in the COMIS data as the bottom of bank depth) and the depth at bankfull flow. It was assumed that the winter base flow typically fills the channel to the bottom of the banks and that winter base flow depth is approximately equal to bottom of bank depth.

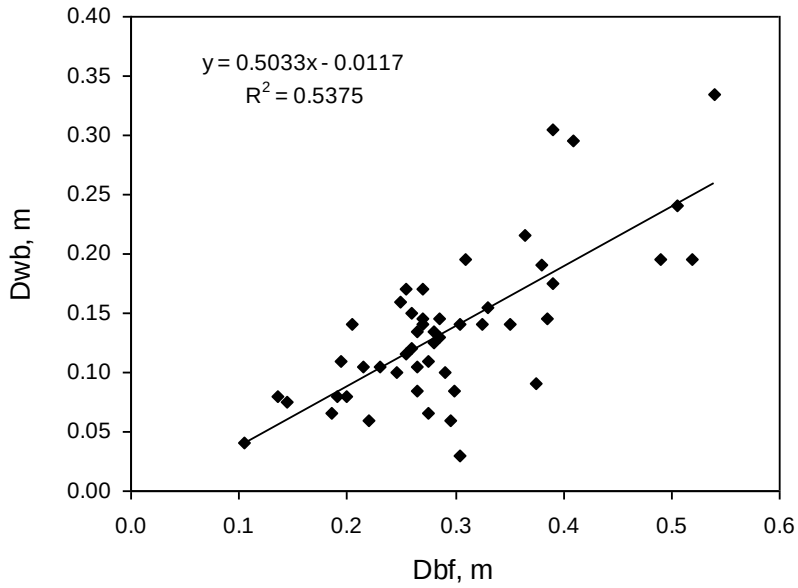


**Figure A7-4.** Hydraulic geometry relationship between the depth at winter base flow and bankfull depth.

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# Appendix B

# Methods and Sources of Information Used to Parameterize the HAB Module

The first step in applying HAB is to determine the stream channel gradient breaks that separate reaches with different morphology and, consequently, differing habitat quality and quantity for the study species. For the Staney Creek model application, gradient categories were selected to correspond largely with three of the most common broad Process Groups defined by the USDA Forest Service Region 10 Channel Type Classification system (Paustian et al.1992;) (Table B-1). Selecting these gradient classes allowed for seamless incorporation of USDA Forest Service coho density and habitat data—collected from sites classified by Process Group—during model parameterization. We assumed that coho salmon in southeast Alaska do not use channels with gradients greater than 16% (Bryant et al. 2004) and parameterized the model accordingly.

**Table B-1.** Channel gradient classes used in the RIPPLE HAB sub-model and corresponding process groups used by in the USDA Forest Service Region 10 Channel Type Classification System.

| RIPPLE gradient class | USDA Forest Service process group | Abbreviation |
|---|---|---|
| 0–2% | Flood Plain | FP |
| 2–6% | Moderate Gradient Mixed Control | MM |
| 6–16% | High Gradient Contained | HC |
| >16% | n/a | n/a |

The next step in the HAB sub-model is to assign the relative fraction of different habitat types (pools, riffles, and glides) for each gradient category used by coho salmon. We evaluated numerous sources of habitat type fraction data from across southeast Alaska, including peer review literature (e.g., Bryant et al. 1998, Keith et al. 1998) and raw data provided by USDA Forest Service. We used a combination of two datasets provided by USDA Forest Service: 2003–2005 coho monitoring data from 26 sites in southeast Alaska (USDA Forest Service, unpubl. data provided by B. Wright); and stream habitat survey data for 82 sites in southeast Alaska (USDA Forest Service, unpubl. data provided by E. Tucker) to parameterize habitat type fraction in the model. Habitat type fraction values used in the model for Current Conditions are presented in Table B-2.

**Table B-2.** Habitat type fraction for each channel gradient category used to parameterize the RIPPLE HAB sub-model for Current Conditions.

| Channel gradient | Pool | Riffle | Glide |
|---|---|---|---|
| 0–2% | 0.470[a] | 0.410[c] | 0.120[c] |
| 2–6% | 0.351[a] | 0.600[c] | 0.049[c] |
| 6–16% | 0.224[b] | 0.776[d] | 0 |

[a] Median of pool fraction values from partially harvested watersheds (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright)

[b] Assumed 20% less than median of pool fraction from unharvested watersheds in HC process group (USDA Forest Service habitat survey data provided by E. Tucker).

[c] Relative fraction of riffle and glide (USDA Forest Service habitat survey data provided by E. Tucker) multiplied by *1 - pool fraction* to estimate riffle and glide fraction.

[d] Assumed riffle fraction = *1 – pool fraction*.

Once the relationships between gradient and the relative fraction of habitat types have been established, each combination of channel gradient and habitat type (e.g., 0–2% pools) was assigned a density and usable fraction for each life stage (e.g., spawning, fry, parr). "Density" is the number of individuals per square meter for a given life stage. "Usable fraction" is the fraction of the total habitat unit area that is, on average, usable for a given life stage. If population surveys report fish numbers for the entire habitat unit, rather than just the portion being used, then the entire habitat unit is treated as usable and the assigned usable fraction is 1.

Quantitative data on coho salmon spawning density and usable fraction of spawning habitat in southeast Alaska were not available; therefore spawning densities were based on Lestelle et al. (1996). Usable fraction of spawning habitat assigned to each combination of gradient category and habitat type were based on measurements of suitable coho spawning gravels collected in Rock Creek, Oregon (Stillwater Sciences, unpubl. data in support of the relicensing of the North Umpqua Hydroelectric Project). It is possible that these values are not an accurate representation of spawning habitat availability in southeast Alaska and the Staney Creek watershed. However, spawning habitat quantity generally does not limit the size of coho salmon populations (Nickelson et al. 1992a**;** Larkin 1988; Chapman 1962, 1966) and estimates of production of smolts and returning adults in the RIPPLE model are not sensitive to even relatively large changes in spawning habitat parameters. For this reason, we assumed that data collected from an Oregon stream was sufficient for the purposes of this analysis. This assumption was evaluated by doubling the usable fraction for spawning, which only increased the predicted number of fry produced, but did not affect later life stages (parr, smolt, or adults), since each has a much lower carrying capacity than fry. Spawning density and usable fraction values used in the model are listed in Table B-3. The same values were used for all future scenarios.

**Table B-3.** Values used to parameterize the RIPPLE HAB sub-model for female spawning density and fraction of the channel usable for spawning for each habitat type and channel gradient combination.

| Channel gradient | Pool | | Riffle | | Glide | |
|---|---|---|---|---|---|---|
| | Density (females/m$^2$) | Usable fraction | Density (females/m$^2$) | Usable fraction | Density (females/m$^2$) | Usable fraction |
| 0–2% | 0.22[a] | 0.132[b] | 0.22[a] | 0.062[b] | 0.22[a] | 0.022[b] |
| 2–6% | 0.22[a] | 0.064[c] | 0.22[a] | 0[e] | 0.22[a] | 0.012[c] |
| 6–16% | 0.22[a] | 0.032[d] | 0.22[a] | 0[e] | 0.22[a] | 0[e] |
| >16%[f] | 0 | 0 | 0 | 0 | 0 | 0 |

[a] Assumes one female per redd with an average size of 4.54m$^2$.
[b] Equals the mean of usable fractions estimated for the 0–1% and 1–2% gradients in Rock Cr., Oregon (Stillwater Sciences unpubl. data).
[c] Equals the usable fraction estimated for the 2–4% gradients in EF Rock Cr., Oregon (Stillwater Sciences unpubl. data).
[d] Assumes usable fraction in pools in the 6–16% gradient class equals 50% of the 2–6% gradient class.
[e] Assumes no spawning in riffles with gradients above 2% or in glides with gradients above 6%.
[f] Assumes no coho spawning above 16% based on professional judgment.

Several potential sources of juvenile rearing density data for coho salmon fry and parr were evaluated for parameterizing the Staney Creek model. Data collected in 26 TNF streams from 2003–2005 during development of a coho monitoring protocol (Bryant et al. 2008; USDA Forest Service data provided by B. Wright) were used as the basis for assigning juvenile densities in the model for each gradient class. These data were not reported by habitat type (pool, riffle, glide); thus they were proportioned among habitat types based on habitat-type-specific density data

reported by Bryant et al. (1998). Density and usable fraction values used for fry and parr in the model for Current Conditions are presented in Table B-4 and Table B-5. Since juvenile density data were collected on the reach scale, a usable fraction of 1 was assigned for both age-0 and age-1+.

**Table B-4.** Fry density and usable fraction values for each habitat type and channel gradient combination used to parameterize the RIPPLE HAB sub-model for Current Conditions.

| Channel gradient | Pool | | Riffle | | Glide | |
|---|---|---|---|---|---|---|
| | Density (fish/m$^2$) | Usable fraction | Density (fish/m$^2$) | Usable fraction | Density (fish/m$^2$) | Usable fraction |
| 0–2% | 0.211[a,b] | 1 | 0.041[a,b] | 1 | 0.007[a,b] | 1 |
| 2–6% | 0.220[b,c] | 1 | 0.043[b,c] | 1 | 0.007[b,c] | 1 |
| 6–16% | 0.011[d] | 1 | 0.002[d] | 1 | 0.0003[d] | 1 |
| >16%[e] | 0 | 0 | 0 | 0 | 0 | 0 |

[a] Median of fry density values from the FP process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright).
[b] Median density proportioned by habitat type based on Bryant et al. (1998).
[c] Median of fry density values from the MM process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright).
[d] Assumes fry density in 6–16% gradients is 5% of that in 2–6% gradients, based on Bryant et al. (2004, Figure 3).
[e] Assumes coho salmon do not rear in gradients above 16% based on Bryan et al. (2004).

**Table B-5.** Parr density and usable fraction values for each habitat type and channel gradient combination used to parameterize the RIPPLE HAB sub-model for Current Conditions.

| Channel gradient | Pool | | Riffle | | Glide | |
|---|---|---|---|---|---|---|
| | Density (fish/m$^2$) | Usable fraction | Density (fish/m$^2$) | Usable fraction | Density (fish/m$^2$) | Usable fraction |
| 0–2% | 0.0671[a,b] | 1 | 0.0132[a,b] | 1 | 0.0022[a,b] | 1 |
| 2–6% | 0.0580[b,c] | 1 | 0.0114[b,c] | 1 | 0.0019[b,c] | 1 |
| 6–16% | 0.0058[d] | 1 | 0.0011[d] | 1 | 0.0002[d] | 1 |
| >16%[e] | 0 | 0 | 0 | 0 | 0 | 0 |

[a] Median of parr density values from the FP process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright)
[b] Median density proportioned by habitat type based on Bryant et al. (1998).
[c] Median of parr density values from the MM process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright).
[d] Assumes parr density in 6–16% gradients is 10% of that in 2–6% gradients, based on Bryant et al. (2004, Figure 3).
[e] Assumes coho salmon do not rear in gradients above 16% based on Bryant et al. (2004).

To further refine carrying capacity estimates, physical thresholds in the HAB sub-model can be used to identify channel reaches suitable for coho salmon spawning and rearing and exclude all other reaches. Life-stage-specific thresholds that can be applied include minimum and maximum substrate size, channel width, and channel depth as predicted by the GEO sub-model. The HAB

sub-model calculates reach-specific carrying capacities for all reaches not excluded. In the Staney Creek model, only channel width values were used to restrict upstream and downstream distribution of spawning and summer and winter rearing. Channel depth and $D_{50}$ thresholds were not utilized in the model. For Current Conditions, the channel width threshold was set to allow summer rearing to occur throughout most of the mainstem of Staney Creek (between 1.75 m and 13.25 m low flow width), but spawning and winter rearing were restricted to the mainstem above the South Fork confluence and tributaries (between 2 m and 21.7 m winter base flow width).

### Barriers

In addition to applying channel width thresholds to restrict fish distribution and habitat utilization in the HAB sub-model, reaches of the stream network upstream of a barrier waterfall on the East Fork, approximately 1.1 km (0.7 mi) from the confluence with the mainstem of Staney Creek, were excluded from all model scenarios. Similarly, reaches upstream of six culverts designated as barriers to fish migration ("red pipes") on Class I stream were excluded from the channel network for the Current Conditions, Forest Restoration, and Degraded Forest scenarios (described in more detail in Section 6.3.1.3 of the report).

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# Appendix C

# Model Parameters Used for Future Scenarios

The following tables document specific parameter values used to simulate alternative future scenarios with Staney Creek Watershed.

**Table C-1.** Habitat type fraction for each channel gradient category used to parameterize the RIPPLE HAB sub-model for Degraded Forest (D), Current Conditions (C), and Restored Forest (R) scenarios.

| Channel gradient | Pool (D/C[a]/R) | Riffle (D/C[a]/R) | Glide (D/C[a]/R) |
|---|---|---|---|
| 0–2% | 0.376[b]/0.470[a]/0.571[c] | 0.482[e]/0.410[a]/0.331[e] | 0.142[e]/0.120[a]/0.097[e] |
| 2–6% | 0.281[b]/0.351[a]/0.568[c] | 0.665[e]/0.600[a]/0.400[e] | 0.054[e]/0.049[a]/0.033[e] |
| 6–16% | 0.179[b]/0.224[a]/0.280[d] | 0.821[f]/0.776[a]/0.720[f] | 0/0/0[g] |

[a] Refer to Table B-2 for source and rationale for Current Conditions values.
[b] Assumed 20% decrease in pool fraction compared with Current Conditions.
[c] Median of pool fraction values measured in old growth forested watersheds (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright)
[d] Median of pool fraction from unharvested watersheds in HC process group (USDA Forest Service habitat survey data provided by E. Tucker).
[e] Relative fraction of riffle and glide (USDA Forest Service habitat survey data provided by E. Tucker) multiplied by *1 - pool fraction* to estimate riffle and glide fraction.
[f] Assumed riffle fraction = *1 – pool fraction*.
[g] Assumed no glides in 6–16% gradients.

**Table C-2.** Fry density and usable fraction values for each habitat type and channel gradient combination used to parameterize the RIPPLE HAB-sub model for Degraded Forest, Current Conditions, and Restored Forest scenarios.

| Channel gradient | Pool | | | Riffle | | | Glide | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Scenario** | **Density (fish/m$^2$)** | **Usable fraction** | **Scenario** | **Density (fish/m$^2$)** | **Usable fraction** | **Scenario** | **Density (fish/m$^2$)** | **Usable fraction** |
| 0–2% | Degraded | 0.088[a,b] | 1 | Degraded | 0.017[a,b] | 1 | Degraded | 0.003[a,b] | 1 |
| | Current | 0.211[c] | | Current | 0.041[c] | | Current | 0.007[c] | |
| | Restored | 0.348[e,b] | | Restored | 0.069[e,b] | | Restored | 0.011[e,b] | |
| 2–6 | Degraded | 0.087[b,d] | 1 | Degraded | 0.017[b,d] | 1 | Degraded | 0.003[b,d] | 1 |
| | Current | 0.220[c] | | Current | 0.043[c] | | Current | 0.007[c] | |
| | Restored | 0.373[f,b] | | Restored | 0.073[f,b] | | Restored | 0.012[f,b] | |
| 6–16% | Degraded | 0.004[g] | 1 | Degraded | 0.001[g] | 1 | Degraded | 0.0001[g] | 1 |
| | Current | 0.011[c] | | Current | 0.002[c] | | Current | 0.0003[c] | |
| | Restored | 0.019[g] | | Restored | 0.004[g] | | Restored | 0.0010[g] | |
| >16%[h] | Degraded | 0 | 0 | Degraded | 0 | 0 | Degraded | 0 | 0 |
| | Current | | | Current | | | Current | | |
| | Restored | | | Restored | | | Restored | | |

[a] 25th percentile of fry density values from the FP process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright).
[b] Median density proportioned by habitat type based on Bryant et al. (1998).
[c] Refer to Table B-2 for source and rationale for Current Conditions values.
[d] 25th percentile of fry density values from the MM process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright).
[e] 75th percentile of fry density values from the FP process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright).
[f] 75th percentile of fry density values from the MM process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright).
[g] Assumes fry density in 6–16% gradients is 5% of that in 2–6% gradients, based on Bryant et al. (2004, Figure 3).
[h] Assumes coho salmon do not rear in gradients above 16%, based on Bryan et al. (2004).

**Table C-3.** Parr density and usable fraction values for each habitat type and channel gradient combination used to parameterize the RIPPLE HAB sub-model for Degraded Forest, Current Conditions, and Restored Forest scenarios.

| Channel gradient | Pool | | | Riffle | | | Glide | | |
|---|---|---|---|---|---|---|---|---|---|
| | Scenario | Density (fish/m$^2$) | Usable fraction | Scenario | Density (fish/m$^2$) | Usable fraction | Scenario | Density (fish/m$^2$) | Usable fraction |
| 0–2% | Degraded | 0.0417[a,b] | 1 | Degraded | 0.0082[a,b] | 1 | Degraded | 0.0014[a,b] | 1 |
| | Current | 0.0671[c] | | Current | 0.0132[c] | | Current | 0.0022[c] | |
| | Restored | 0.1082[e,b] | | Restored | 0.0213[e,b] | | Restored | 0.0035[e,b] | |
| 2–6 | Degraded | 0.0369[b,d] | 1 | Degraded | 0.0073[b,d] | 1 | Degraded | 0.0012[b,d] | 1 |
| | Current | 0.0580[c] | | Current | 0.0114[c] | | Current | 0.0019[c] | |
| | Restored | 0.0949 | | Restored | 0.0187 | | Restored | 0.0031 | |
| 6–16% | Degraded | 0.0037[g] | 1 | Degraded | 0.0007[g] | 1 | Degraded | 0.0001[g] | 1 |
| | Current | 0.0058[c] | | Current | 0.0011[c] | | Current | 0.0002[c] | |
| | Restored | 0.0095[g] | | Restored | 0.0019[g] | | Restored | 0.0003[g] | |
| >16%[h] | Degraded | 0 | 0 | Degraded | 0 | 0 | Degraded | 0 | 0 |
| | Current | | | Current | | | Current | | |
| | Restored | | | Restored | | | Restored | | |

[a] 25th percentile of parr density values from the FP process group (USDA Forest Service 2003–2005 coho monitoring data provided by B. Wright).
[b] Median density proportioned by habitat type based on Bryant et al. (1998).
[c] Refer to Table B-2 for source and rationale for Current Conditions values.
[d] 25th percentile of parr density values from the MM process group (USDA Forest Service 2003-2005 coho monitoring data provided by B. Wright).
[e] 75th percentile of parr density values from the FP process group (USDA Forest Service 2003-2005 coho monitoring data provided by B. Wright).
[f] 75th percentile of parr density values from the MM process group (USDA Forest Service 2003-2005 coho monitoring data provided by B. Wright).
[g] Assumes parr density in 6–16% gradients is 10% of that in 2–6% gradients, based on Bryant et al. (2004, Figure 3).
[h] Assumes coho salmon do not rear in gradients above 16%, based on Bryan et al. (2004).

**Table C-4.** Values used in the POP sub-model for Degraded Forest and Restored Forest scenarios for parameters that differed from Current Conditions. All other parameters were identical to Current Conditions (refer to Table 6-3).

| Parameter | Degraded Forest | Current Conditions[a] | Restored Forest[b] |
|---|---|---|---|
| Summer background survival | 0.68 | 0.86 | 0.93 |
| Winter background survival | 0.68 | 0.86 | 0.93 |
| Embryo background survival | 0.10 | 0.253 | 0.50 |
| Smolt background survival | 0.90 | 0.95 | 0.98 |

[a] POP values identical to Current Conditions were used in Restored Passage scenario.
[b] POP values identical to Restored Forest were used in Restored Forest and Passage.

# Appendix D

# POP Model Figures

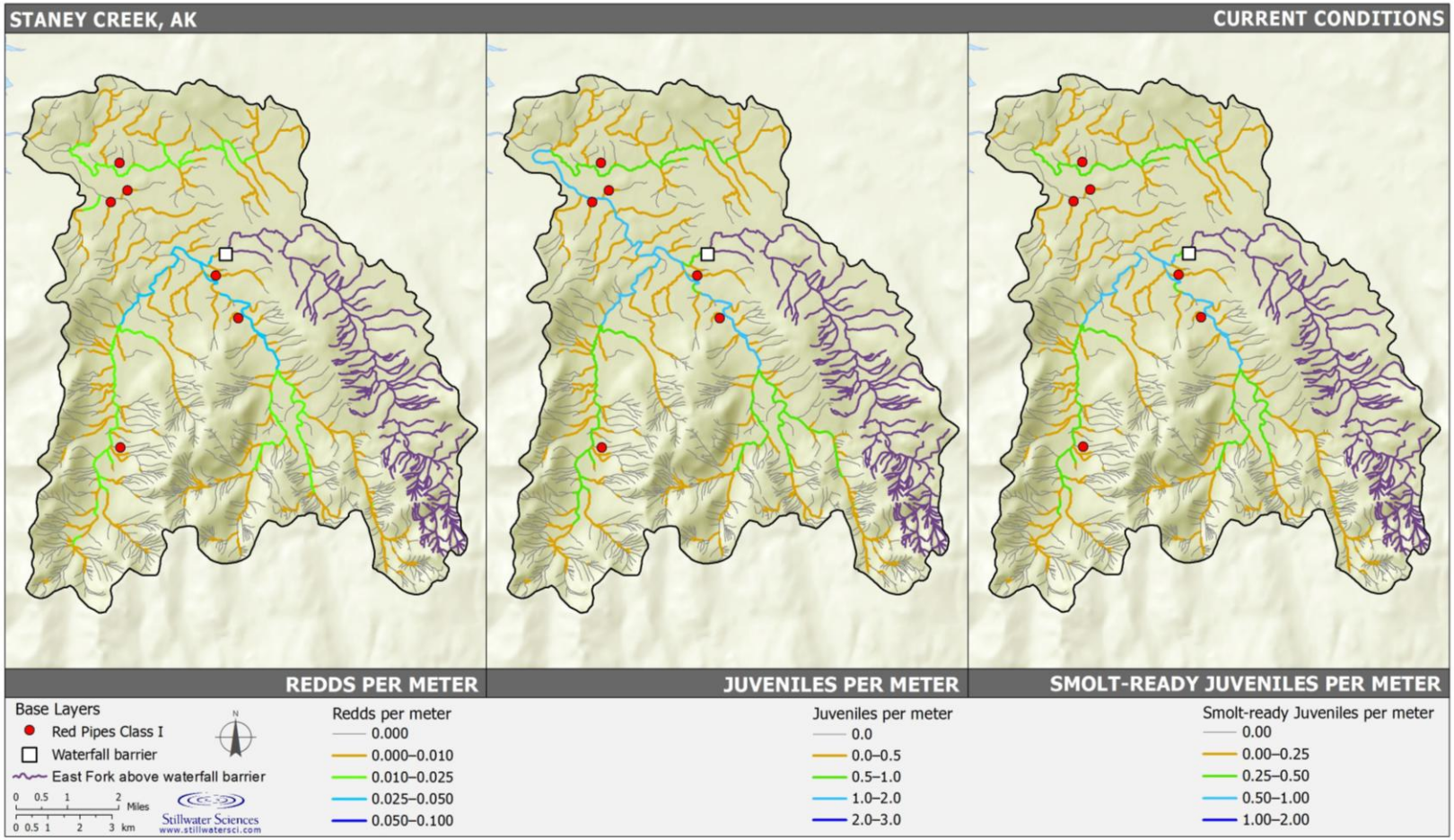


**Figure D-1.** POP sub-model output map showing predicted distribution and number of coho salmon redds, age-0 juveniles, and smolt-ready juveniles produced per meter in the Staney Creek watershed under Current Conditions. Channels upstream of Class I barriers do not contribute to coho production.

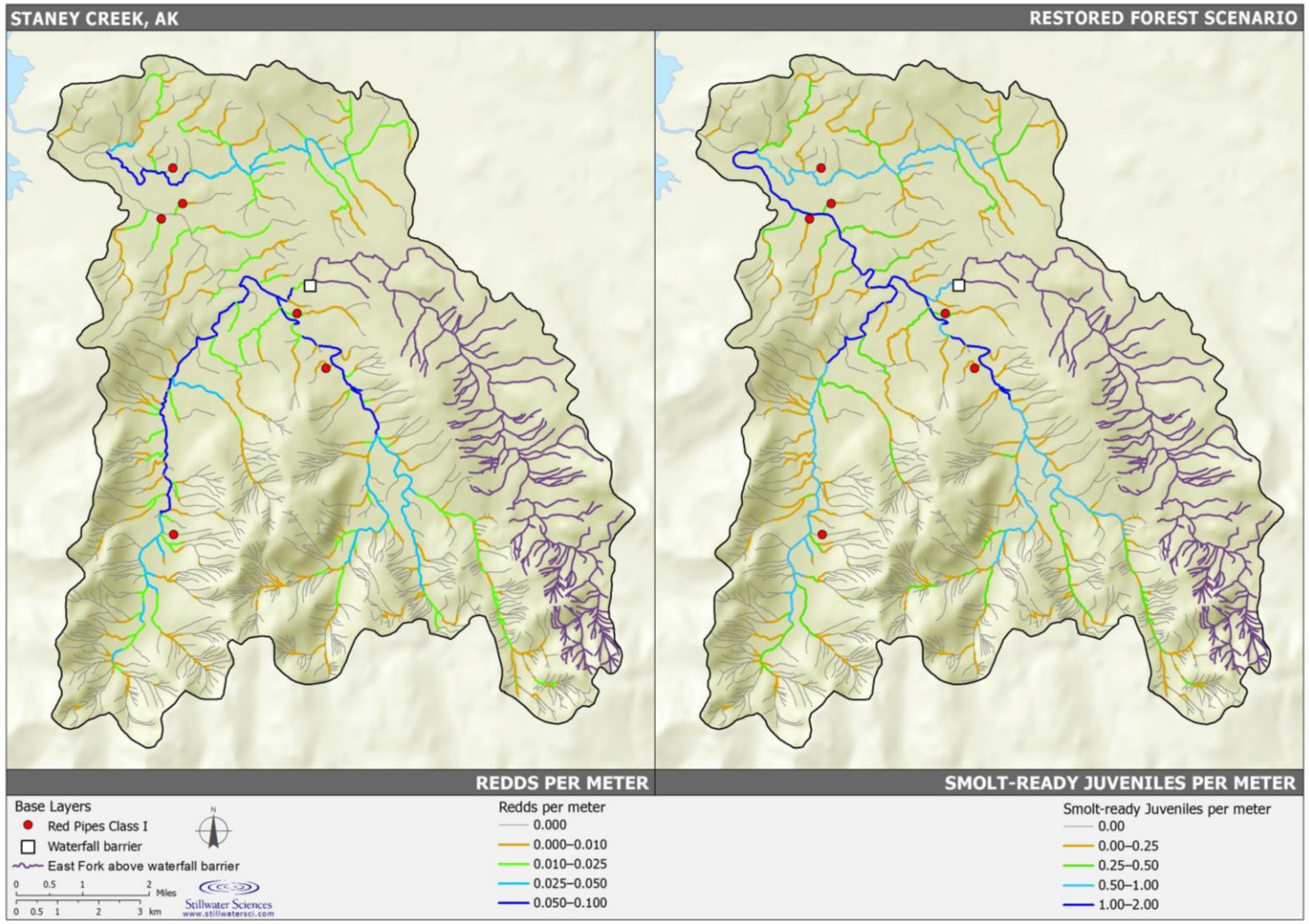


**Figure D-2.** POP sub-model output map showing predicted distribution and number of coho salmon redds and smolt-ready juveniles per meter in the Staney Creek watershed under the Restored Forest scenario.

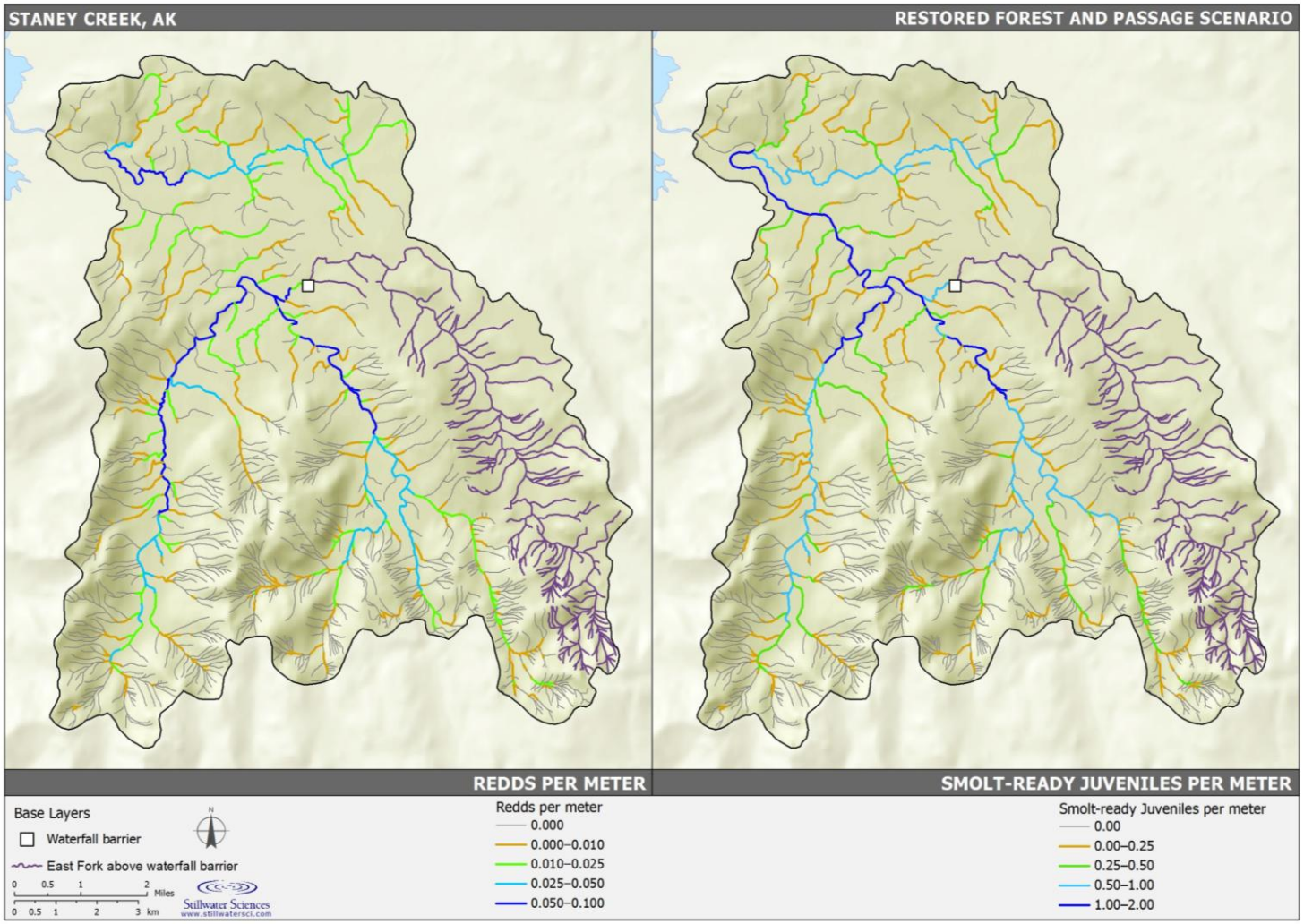


**Figure D-3.** POP sub-model output map showing predicted distribution and number of coho salmon redds and smolt-ready juveniles per meter in the Staney Creek watershed under the Restored Forest and Passage scenario.

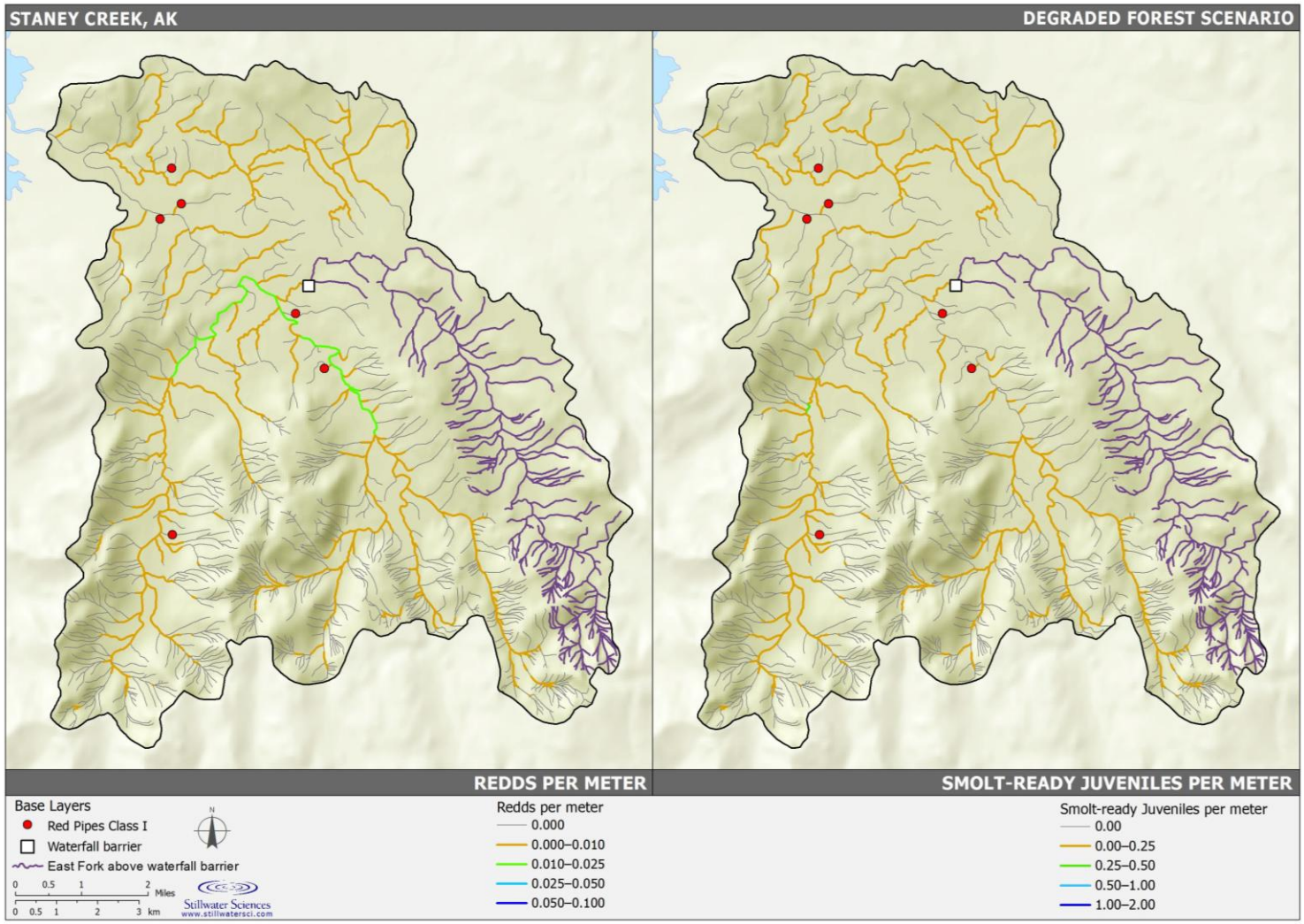


**Figure D-4.** POP sub-model output map showing predicted distribution and number of coho salmon redds and smolt-ready juveniles per meter in the Staney Creek watershed under the Degraded Forest scenario.