Habitat area and fish density in delta estuaries

Based on growth rates (Table 1), it appears that density-dependent growth may not be an important factor in these Puget Sound estuaries, which is supported by Levings et al. (1986), who did not observe density-dependent growth rates in a small estuary (0.5 km^2, 1.4 fish·m^{-2}) and by Healey (1980) for the Nanaimo estuary. No correlation was observed for estuary size and Chinook SAR, which was also the case for juvenile Chinook from coastal estuaries (Magnusson and Hilborn 2003). Area is not as important as the density of fish rearing in the estuary, and the present study found no relationship between this factor and Chinook survival. Density-dependent mortality, growth, and emigration is thought to occur in some Pacific Northwest estuaries (Reimers 1973; Greene and Beechie 2004). Reimers (1973) found that ocean-type Chinook exhibited reduced growth during the peak migration, which was hypothesized to be related to the high density of conspecifics. The focus for those growth studies was a very small (0.08 km^2) and shallow (mostly <1 m) area in lower Sixes estuary in Oregon. Fish density (≈2 fish·m^{-2}) was based only on Chinook and is a minimum estimate based on a monthly census that does not account for fish entering or leaving the lower estuary. This density is comparable to those of contaminated estuaries in this study with the highest fish densities for both species.

Predation

Predation is another factor that may influence interestuary differences in Chinook SARs. Very few studies have quantified predator–prey interactions in Pacific Northwest estuaries; however, the available data indicate that this interaction is not important. One study quantified predation on juvenile salmon in Puget Sound by cutthroat trout and determined that the number consumed were minor compared with the total number of outmigrating fish (Duffy and Beauchamp 2008). Another study examined the impact of bird predation, specifically mergansers, on juvenile salmonid mortality. For juvenile Chinook (6 g) the mortality was less than 1.3% in Big Qualicum Creek on Vancouver Island, British Columbia, Canada (Wood 1987). Based on the high abundance of outmigrating juvenile salmon from hatcheries and the relatively low abundance of some predators, predation is likely not an important factor in local Puget Sound estuaries. This is supported by Simenstad et al. (1982) and Macdonald et al. (1988), who also noted low rates of predation and suggested that estuaries may be a sanctuary from predators. Predation can be significant depending on the species, life stage, and estuary (Wood 1987) in addition to increased predation rates in the marine environment (Brodeur et al. 2003). Predation was not examined for the freshwater portion of the migration to the estuary. Distance to the estuary (Table 1) was considered a surrogate for potential source of mortality, assuming that all such systems in Puget Sound contain similar types and densities of predators. There was no correlation between Chinook SAR and distance to the estuary. Once in open water, size-selective predation is an important factor for juvenile Chinook and may account for a high percentage of the early marine-phase mortality (Beauchamp and Duffy 2011).

Spatial distribution within marine waters

All available data indicate that Chinook in open water comingle and are not likely to exhibit differential survival as a function of their natal hatchery location. The total number of subyearling Chinook released into Puget Sound from hatcheries has been relatively consistent, ranging from 45 to 55 million per year since the early 1970s (Ruggerone and Goetz 2004). For the first several months after leaving the estuary, juvenile Chinook from many of the hatcheries in this study appear to mix within Puget Sound. One study (Brennan et al. 2004) sampled juvenile Chinook from May through December in 2001 and 2002 and found that fish exhibited a variety of movement patterns. For this period, it appears that fish from hatcheries all over Puget Sound comingle, and in many cases appear to move south after leaving their local estuary. This was noted for fish from the Soos Creek, Samish, Wallace River, and Lummi sea ponds. This was confirmed by Rice et al. (2011), who observed substantial movement and mixing of juvenile fish from hatcheries all over Puget Sound, with the most co-occurrences in mid- to northern Puget Sound. Fresh et al. (2006) also noted high percentages of juvenile Chinook from the Nisqually, Soos Creek, Wallace, and Grovers, in addition to the local fish from Gorst Creek in outer Sinclair Inlet in June and July 2001 and 2002.

A high percentage of ocean-type Chinook appear to spend their entire life in coastal British Columbia and the Salish Sea, which includes Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca as based on CWT recovery (Healey 1991; Weitkamp 2010). As noted by Weitkamp (2010), salmon released from a common freshwater area (e.g., Puget Sound watershed) have a similar marine distribution. The marine distribution for coho is similar to that for Chinook as a function of their freshwater release location (Weitkamp 2010). Fishery catch records indicate that most adult fall and summer run Chinook (85%–90%) were captured in Puget Sound, the Strait of Georgia, or southern Vancouver Island (Quinn et al. 2005; Weitkamp 2010), indicating that they likely experienced relatively similar ocean conditions.

Other factors

Chinook from all hatcheries in this analysis are considered part of the Puget Sound evolutionarily significant unit for this species. All juvenile Chinook released from these hatcheries come from stocks originating within Puget Sound, and many of the hatchery programs were founded with, or utilized fish from, the Green River stock, resulting in a similar genetic background for many of the hatchery fish released into this evolutionarily significant unit (Myers et al. 1998).

No information was found regarding potential hatchery problems. This study included many comparisons of Chinook and coho from the same hatchery, which allowed some insight. As shown in the Results, there was no correlation for the 107 cases where Chinook and coho SAR values co-occurred by release year and hatchery. A noteworthy example is the Wallace River hatchery, where the SAR values for coho were the highest for all groups, but were among the lowest for Chinook (Tables 3 and 4).

This analysis does not explicitly consider the El Niño – Southern Oscillation and Pacific Decadal Oscillation cycles or other oceanic conditions such as upwelling and salinity that are considered relevant for salmonid survival. Even though these cycles are known to have a significant impact on juvenile growth and survival (Brodeur et al. 2003), the focus of this study is on annual comparisons among hatcheries and therefore incorporates such impacts, because all fish for a given release year experience similar oceanic conditions. Of course, these cycles may magnify the effects. For example, fish from contaminated estuaries may be at a greater disadvantage when prey abundance is impacted by an adverse El Niño – Southern Oscillation cycle.

Potential effects due to contamination

A number of contaminants in these estuaries are known to affect growth, reproduction, immune function, physiological homeostasis, and the behavior of salmon, which may explain the reduced survival observed for Chinook. Even though growth appears to be relatively unaffected for fish captured within contaminated estuaries, growth impairment would likely be delayed for several weeks until they had accumulated toxic levels and exited to open water. Another possibility is that some of the contaminants can lead to increased susceptibility to pathogens, also leading to delayed mortality. Altered behavior is another important consideration that would certainly impact the ability of juvenile fish to catch prey and avoid predation, especially outside the estuary.