Duwamish Estuary

The following write-up relies heavily on the *Case Study of Elliott Bay and the Duwamish River Estuary* by John Houghton, Pentac Environmental, in the *State of the Nearshore Ecosystem: Eastern Shore of Central Puget Sound, Including Vashon and Maury Islands (WRIAs 8 and 9).* January 2001 (Review Draft) for the WRIA 8 and 9 Nearshore Technical Committee.

Overview

The Duwamish River estuary is located at the lowermost extent of the Green/Duwamish River system (WRIA 9), a 93 mile long river system that originates in the Cascade Mountains near Stampede Pass and flows generally west and northwest toward the city of Seattle. Currently, the Green/Duwamish River basin drains 483 square miles (Weitkamp *et al.* 2000). Tidal influences are observed upstream to about the mouth of the Black River in the city of Tukwila. These last 11 miles of the system are a brackish estuarine environment called the Duwamish estuary. The Duwamish is considered "vital to salmon as a transition area for adaptation of migrants to salinity changes." (Williams *et al.* 1975). The last 4.6 miles of the estuary are located within the city of Seattle.

The last 5.3 miles of the Duwamish are dredged for navigation and contain deep water habitats where none previously existed (Warner and Fritz, 1995). This lower area has been developed for water dependent commerce and heavy industry. The Port of Seattle operates a series of terminal facilities at the mouth of the river.

The tides in the Duwamish River estuary have marked inequalities in the successive high- or low-water stages. The datum plane (0 point) for tide height in the Duwamish River estuary is mean lower low water at a tide reference station about 1 mile northeast of the estuary mouth. According to the Army Corps of Engineers, the mean tide stage is 6.5 ft above MLLW, and maximum and minimum estimated stages are 15.00 ft ± 0.5 ft above MLLW and 4.5 ft ± 0.5 ft below MLLW, respectively (KCDNR, 2001).

Circulation of water within a stratified estuary comprises a net upstream movement of water within a lowermost salt-water wedge and a net downstream movement of fresher water in the layer overriding the wedge (Pritchard 1955). The saline wedge water, which has its source in Elliott Bay, oscillates upstream and downstream with the tide. During periods of low fresh-water inflow and high tide stage the salt-water wedge has extended as far upstream as the Foster Bridge, 10.2 mi above the mouth. At fresh-water inflow greater than 1,000 cfs the salt-water wedge does not extend upstream beyond the East Marginal Way Bridge (RM 7.8) regardless of the tide height (Stoner 1967).

The Duwamish River transports fine material in a freshwater plume emptying into Elliott Bay. Sediments return from Elliott Bay to the Duwamish as a near-bottom sediment load contained in the salt-water wedge (GeoSea Consulting 1994).

Eight species of anadromous salmonids have been noted in the Duwamish Estuary. Chinook, coho, chum and steelhead are common; pink, sockeye, sea-run cutthroat trout and bull trout are rare. Chinook salmon returning to the Green River have been a mixture of natural and hatchery Chinook salmon since approximately 1904, when the first hatchery fish returned to the Green River Hatchery on Soos Creek. The naturally spawning component of the Green River Chinook run contains a mixture of wild and hatchery Chinook. Approximately 3-12 million Chinook salmon have been released into the Green River each year since 1953.

There has been no means to differentiate hatchery Chinook from natural Chinook salmon in the past. Draft run-re-construction information for the years 1989 – 1997 inclusive indicates approximately 56 percent (range: 25 to 83 percent) of the natural escapement in the mainstem Green River are from hatchery reared and released fish (Cropp, pers. comm. 1999 reported in Kerwin *et al.* 2000). It is not possible to determine to what extent the remaining approximate 40 percent of the mainstem Green River escapement has its ancestry from hatchery origin fish that have spawned for one or more generations in the wild.

In the spring of 2000, 100% of the hatchery Chinook were marked with an adipose fin clip which will make it possible to identify hatchery fish in the future. (Weitkamp *et al.* 2000).

Survival of Green River hatchery Chinook salmon (coded wire tag (CWT)-based estimates) was compared to survival estimates of Chinook in several other watersheds in Puget Sound (Nisqually, Sammamish, Snohomish, Skagit, Hood Canal) using CWT releases and recoveries. The time period of analysis encompassed brood years 1972-1993, but annual estimates were not available for all stocks in all years. No statistical difference in survival was found between systems. However, survival of Green River fall Chinook salmon (avg. 0.76%) tended to be somewhat higher than that of Nisqually (0.45%), Hood Canal (0.51%), Snohomish (0.45%), and Skagit (0.23%), but similar to Chinook released from the Issaquah hatchery (0.87%)(Weitkamp *et al.* 2000).

From 1968 to 1998 the estimated run of fall Chinook salmon in the Green/Duwamish River ranged from 12,750 in 1982 to 40,508 in 1989 and averaged 20,900 fish. Run size tended to be higher during recent years (1983 to 1998) compared to earlier years (1968 to 1982), indicating that the downward trend common to other Puget Sound stocks is not evident in the Green/Duwamish basin (WDFW unpublished data reported in KCDNR, 2000).

According to the Washington Department of Fish and Wildlife (WDFW and WWTIT 1994), the status of the Green/Duwamish stock is healthy based on recent escapement levels. The average escapement for the past 20 years is 6,153, with the minimum escapement of 1,804 occurring in 1982 and the maximum escapement of 11,512 occurring in 1989. The escapement goal set for this stock by WDFW is 5,800 (WDFW and WWTIT 1994). Escapement goals have been reached in 12 of the last 30 years and in 7 of the last 10 years (1988 to 1997) (KCDNR, 2001). WDFW reports that Chinook salmon released from the Green River hatchery display a higher marine survival rate than any other hatchery stock in Puget Sound (T. Cropp, personal communication reported in KCDNR, 2001).

Historical Modifications

Physical Changes

Extensive water regime and channel modifications have resulted in existing habitat conditions that were not historically present in the Green/Duwamish River system (Blomberg *et al.* 1988). Prior to the 1910's, the Duwamish River drained a much larger watershed including all flows from the present Green River watershed (WRIA 9), the Lake Washington drainage basin (WRIA 8), and the White River (now part of WRIA 10). Both natural and man-made modifications during the early 1900's reduced the drainage basin to its present size and configuration. Flows from the White River were diverted to the Puyallup River by a flood in 1906, and later man-made structures made this diversion permanent. Flows from Lake Washington were diverted west to Lake Union and Salmon Bay after the construction of the Ballard Locks and Lake Washington Ship Canal in 1916. At this same time the Cedar River was diverted from the Black River into Lake Washington, so that the Green no longer received those flows.

Currently the Green/Duwamish River drains about one quarter of its original extent (Warner and Fritz 1995). The mean annual flow for the Duwamish River was estimated at 2,500 to 9,000 cfs prior to the diversion (Fuerstenberg, *et al.* 1996). By 1996 the mean annual flow of the Duwamish River was estimated to be approximately 1,700 cfs (U.S. Army Corps of Engineers (ACOE), 1997), a total reduction between 32 percent and 81 percent.

By 1913, the city of Tacoma completed a water diversion dam on the Green River, with a maximum withdrawal of 113 cfs. In 1962, the Howard Hansen Dam (HHD) was built by the ACOE in the Eagle Gorge of the upper Green River for flood control and low flow augmentation. The dam limits flows to a maximum of 12,000 cfs,

A more natural Duwamish beach.

further reducing hydrologic channel forming (KCDNR, 2001).

Most of the major landscape forming events effecting the estuary occurred in the early 1900's. During this time, a substantial quantity of filling and dredging occurred to construct Harbor Island, the East and West Waterways, and the Duwamish shipping channel upstream to the Turning Basin. Dredging has resulted in the replacement of 9.3 miles of estuarine channel habitat with the 5.3 miles of deep channel habitat that exists today (Blomberg *et al.* 1988). Filling to increase the developable land base has resulted in a reduction of between 96 percent and 99 percent of the intertidal mudflats and estuarine wetlands historically present in the Duwamish estuary (KCDNR, 2001).

Kellogg Island was formed by extensive fill placements, but includes remnants of two historical channels and has a densely vegetated riparian zone and intertidal wetlands. These represent a majority of the remaining intertidal wetlands in the Duwamish Estuary (Simenstad *et al.* 1991).

Shoreline armoring in remaining areas has reduced the functionality of most of the rest of the intertidal habitat. Upper and middle intertidal habitat in the estuary has been eliminated by the construction of bulkheads and piers. Upstream of the Turning Basin, there has been less modification by shoreline armoring and the construction of piers and bulkheads and higher quality middle and lower intertidal areas are still found, but extensive diking has reduced the quantity of upper intertidal habitats (Weitkamp *et al.* 2000).

Where shorelines are not intensively developed, substantial middle and upper tidal flat habitat remain or have been recreated (Weitkamp *et al.* 2000). Since estuarine prey production is most abundant at about +2 to –2 ft. MLLW (mean lower low water), this habitat is important to young salmon (Weitkamp *et al.* 2000). Also, young Chinook commonly feed within about 0.3 – 1 m of the water surface. Given the tidal fluctuations in the estuary, substrate at these middle and lower intertidal elevations provide the estuarine shoreline habitat and water depths most frequently used by juvenile Chinook salmon (Weitkamp *et al.* 2000).

Some places still have mud flats at low tide. Other places have steep rip-rap with no mud flats.

Recent habitat management policies and restoration projects, as well implementation of requirements for mitigation for any new losses of habitat, have begun to address the degraded conditions along the Duwamish River (Kerwin *et al.* 2000). The Kellogg Island area has recently been the focus of efforts to recreate estuarine wetlands and restore intertidal habitat (Weitkamp *et al.* 2000). Other restoration efforts have included a 1.6-acre estuarine wetland restoration project at the Turning Basin, Hamm Creek and Seaboard restorations under the Elliott Bay Duwamish River Panel (natural resource trustees administering a settlement agreement for natural resources damages with Seattle and King County) and various shoreline improvement projects associated with improvements at the Port of Seattle facilities. Although small by historical standards, these actions have served to improve habitat conditions in the estuary.

Tides, Salinity and Sediment Deposition

Regular dredging operations (every 2-3 years) in the Duwamish Waterway have deepened the main active channel for navigation purposes. A report issued by ACOE (U.S. ACOE, 1997 p.36) implied that due to dredging practices, the tide migrates farther upstream than it had prior to channelization and dredging. This assumption appears to be valid when considering the combined effects of deepening the channel, reducing the watershed area by 70 percent, and reducing the freshwater discharge by 70 percent (U.S.ACOE 1997). Reducing the mean annual flow from 2500 cfs (conservatively) to 1700 cfs compromises the stream flow's ability to resist upstream migration of the tide for longer periods of time than occurred historically. Dredging the channel lowers the elevation of the channel bottom thereby making it more accessible to a wider range of tides (KCDNR, 2001). Therefore it is likely that the point of greatest aggregation for saltwater acclimation for Chinook has moved upstream from earlier times.

Tidal activity is reported to dominate sediment deposition in the Duwamish Waterway (GeoSea Consulting 1994) and as a result it may also control the kinds of sediment that are deposited. If tidal activity is occurring farther upstream than it previously had, then it could have changed the composition of the streambed (KCDNR, 2001).

Sediment sampling performed by GeoSea Consulting (1994) suggests that sand in the Duwamish River is becoming increasingly rare, and its removal (from dredging activities) may result in favoring the deposition of mud (silts and clays). What remains inconclusive in the study completed by GeoSea Consulting (1994) is how mud deposition is distributed as the result of riverine processes versus tidal activity (KCDNR, 2001).

Sediment Contamination and Water Quality

The urbanization of the lower Green River and industrialization of the Duwamish Estuary has had significant impacts on sediment and water quality. Most industrial discharges which historically occurred have been eliminated, but the resultant contamination remains in the sediments of the Duwamish.

Pursuant to the Clean Water Act, the Duwamish River and Elliott Bay are on the state's 303(d) list. Initial characterizations indicate state water quality and sediment standards are exceeded for more than 30 toxic compounds and 8 metals. The sediment standards serve as a basis for identifying areas that will require further study using biological screening methods.

Earlier, portions of Harbor Island and surrounding waters were designated as a Superfund site by the Environmental Protection Agency (EPA) pursuant to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Remedial investigations of upland soils and marine sediments and cleanup activities within this site have been ongoing for over ten years. In addition, the Port of Seattle has been working since the early 1990's with the Department of Ecology, EPA, and the Army Corps of Engineers to coordinate other regulatory reviews in implementing the Southwest Harbor Cleanup and Redevelopment Project. In 2002, the portion of the Duwamish from the south tip of Harbor Island to the Turning Basin was named to the Superfund list. Seattle, King County, the Port of Seattle and the Boeing Company are conducting studies to support necessary clean up actions.

Water quality in the Duwamish River and Elliott Bay is potentially adversely affected by discharges from public and private stormwater drains, combined sewer outfalls (CSOs) and industrial discharges and sediment contamination. The largest current discharges of stormwater occur at the major combined sewer outfalls (Weitkamp *et al.* 2000). King County (King County 1999) recently conducted a water quality assessment of CSO impacts in the Duwamish River and Elliott Bay. This assessment identified minimal risks to aquatic life from chemicals in the water column, no risks to juvenile salmon from direct exposure to chemicals in the water, and no risks to salmon smolt from consuming amphipods in the Duwamish Estuary. Evaluation of specific toxic levels of contaminants in salmon prey (*Corophium* sp. and *Eogammarus confervicolus*) did not demonstrate any risk to the growth of young salmon. These estimates of risk did not change when the contributions of CSOs were mathematically removed from the system using a sophisticated fate and transport model (King County 1999).

Both temperature and low dissolved oxygen (DO) have been noted as problems in the upper part of the Duwamish. There has been a trend towards increasing surface water temperatures in most tributaries in the urban and urbanizing areas of the region over the past 20 years, probably attributable to urbanization and development, including increased runoff from impervious surfaces and loss of riparian vegetation (Kerwin *et al.* 2000). Water temperature can be exceptionally warm (22-25 degrees C) in the lower river during the late summer period. A 1994 study reported that dissolved oxygen levels are somewhat higher than previously reported, presumably because the effluent from the Renton wastewater treatment plant was diverted from the Duwamish in the 1980s (Warner and Fritz 1995).

Exotic Plants and Animals

There is limited information regarding the effect or impact of exotic plant and animal species on habitats or Chinook salmon in the Duwamish estuary. However, a study of Puget Sound marine species conducted in 1998 found 39 non-native species in samples collected in Puget Sound.

Eleven non-native species found in the survey were new observations for Puget Sound. (KCDNR, 2001) Phragmites is known to invade and overtake native vegetation in some sites.

Overwater Structures

From the Turning Basin (RM 5.3) to the mouth of the Duwamish River, overwater structures occupy about 12,150 linear feet, or 2.3 miles, on both banks of the river. This represents about 15 percent of the lower estuarine shoreline. Overwater structures in the upper Duwamish Estuary between RM 11 and RM 5.3 are limited to road and railway bridges (KCDNR, 2001).

Chinook Utilization of the Duwamish Estuary

The Duwamish estuary provides habitat for:

- ❏ Adult migration
- ❏ Juvenile migration and rearing
- ❏ Transition zone for both adults and juveniles

Adults

The Green/Duwamish River system historically supported both spring run and summer/fall run Chinook salmon. Presently, only summer/fall run Chinook are thought to exist as a self-sustaining population, although spring Chinook are occasionally found in the system. Green/Duwamish River fall Chinook salmon migrate through the Duwamish Estuary from late June through mid-November, peaking between late September and late October (Grette and Salo 1986).

Three stocks of Chinook are present in the basin—a hatchery stock that is descended from a wild run; the Green/Duwamish stock, which spawns throughout the basin; and the Newaukum Creek stock, which spawns in this middle tributary of the Green River. The Green/Duwamish and Newaukum Creek stocks are considered "natural stocks," defined as naturally spawning fish that are descended from both wild and hatchery fish (WDFW and WWTIT 1994).

Chinook salmon in the Green/Duwamish River system are a mix of hatchery-reared fish, naturally producing fish of hatchery origin, and wild Chinook. Hatchery strays are thought to have had a large influence on wild Chinook stocks in the river. Hatchery-based fisheries management of Green/Duwamish River Chinook historically resulted in both artificially high counts of natural production, resulting from straying hatchery fish, and the establishment of harvests limits that did not allow adequate wild stock escapement (Myers *et al.* 1998). In addition, hatchery management practices are thought to have led to earlier run-timing of returning adult Chinook in recent decades (Weitkamp *et al.* 2000).

Chinook spawning occurs primarily in the Green River between river mile (RM) 24 and RM 61. Spawning also occurs in larger tributaries including Soos Creek, Newaukum Creek, and Burns Creek (Grette and Salo, 1986). All these streams join the river upstream of the estuary. No Chinook spawning is known to occur in the estuary or in smaller streams flowing into the estuary (Weitkamp *et al.* 2000).

Adult Chinook salmon hold in the lower river (Duwamish to Kent area) until approximately mid-September, depending on temperature and flow (T. Cropp, Green River salmon biologist, WDFW, pers. comm. reported in Weitkamp *et al.* 2000). Low oxygen levels in the lower river and estuary (e.g., near 14th Ave. bridge) also may inhibit upstream migration (Miller and Stauffer 1967, Salo 1969). More recent studies suggest that the problems of low DO may be somewhat alleviated by changes in the outfall from the Renton Sewage Treatment Plant. (Warner and Fritz 1995).

Juveniles

Wild Chinook salmon produced in the Green/Duwamish River system are classified as "ocean type" fish because they typically spend little time rearing in freshwater after emerging from spawning gravels. Juveniles are found to be abundant in the main stem of the Green River mid-February through April.

Although juvenile Chinook salmon are present in the Duwamish Estuary over an 8-month period, catch data show an abrupt increase in smolts in mid-May followed by an equally abrupt decrease. This indicates that most of the fish represented in the pulse of abundance were not in the estuary for more than 2 weeks (Warner and Fritz 1995). Mark-and-recapture studies conducted by Weitkamp and Schadt (1982) showed similar results with most Chinook remaining in the waterway for about two weeks. The longest individual residence was 24 days. Mark-and-recapture studies conducted by Bostick (1955) indicated that all Chinook spent at least 1 week in the estuary, half spent 2 weeks, and two recaptured fish spent 6 weeks in the Duwamish Estuary (KCDNR, 2001).

Peak abundance in the Duwamish estuary occurs in May and June (Meyer *et al.* 1980; Salo, 1969). Warner and Fritz (1995) reported that peak use of Chinook salmon in the Duwamish estuary occurred shortly following known releases of hatchery-reared fish from the State's Soos Creek hatchery and the Muckleshoot Indian Tribe's hatchery on Keta Creek. Given the high degree of hatchery production in the basin, these timing estimates are thought to be largely influenced by hatchery releases and little data is known specific to wild Chinook juveniles in the basin (Weitkamp *et al.* 2000).

Estimated downstream survival of marked Chinook salmon in 1967 (1,500 cfs) was 51-68% (Salo 1969). Survival of marked hatchery Chinook decreased significantly with lower flow (Wetherall 1971), presumably because downstream migrants are more vulnerable to predators during low flows.

Habitat Requirements

The estuary provides critical habitat elements necessary for the survival of juvenile Chinook salmon and also provides transition and holding habitat for adult salmon waiting to ascend the river to spawning grounds.

Transition to Saltwater

One important function of an estuary is to provide habitat for the transitional changes the juveniles must make as they enter saltwater. The distribution of juveniles in the estuary may be related both to the salinity gradient and the availability of food.

The distribution of juvenile Chinook salmon in the Duwamish Estuary may be associated with the limited amount of natural habitat remaining in the waterway. Warner and Fritz (1995) found the greatest catch over shallow, sloping, soft mud beaches, and these sites produced double the catch ratios of sites with sand, gravel, or cobble substrates. Additionally, this study collected numerous benthic crustaceans and small shrimp at mud habitats, suggesting a higher productivity in comparison to sites with other substrates. This study also found the highest densities of juvenile Chinook salmon in the upper estuary at RM 7.5. This area is a relatively large natural shoreline with intertidal flats and emergent vegetation (Tanner 1991). Modest densities were observed at the Turning Basin (RM 5.2), just downstream of RM 7.5 (Warner and Fritz 1995). These areas are also natural shorelines characterized by intertidal mudflats with some marsh vegetation.

Steady decreases in juvenile Chinook densities were observed downstream of the Turning Basin, with the exception of the most-downstream station at Kellogg Island (RM 1.6). At this station, densities increased to near those found at the Turning Basin (Warner and Fritz 1995). Meyer *et al.* 1981 found that juvenile Chinook salmon were associated with both nearshore and offshore areas, but tended to move inshore at night and tended to move offshore with increasing size. (KCDNR, 2001).

Food

Chinook juveniles appear to be opportunistic feeders in estuaries (Healey 1991). Cordell *et al.* (1997) found that juvenile Chinook fed on taxa that occurred in lower intertidal sediments or in the water column of the Duwamish Estuary. Prey includes gammarid amphapods, copepods, insects, larval fish, mysids, and cumaceans (Parametrix, 1990). In examining diel differences, Meyer *et al.* (1981) found that gammerid amphipods, particularly *Corophium salmonis*, were consumed more at night than during the day and chironomid flies were consumed more during the day.

It is thought that shallow, intertidal habitats with gradual slopes and smaller substrates (cobble to mud) are important food production areas for juvenile Chinook. Shoreline development is a primary cause of the loss of upper intertidal habitats; however, approximately 63 percent of the estuary, even those areas adjacent to highly developed shorelines contain available middle and lower intertidal habitats. However, loss of upper intertidal habitats may reduce the survival of that portion of juveniles that tend to remain in the estuary for prolonged periods. There is no current evidence to indicate whether the rearing capacity of the estuary is limiting (Weitkamp *et al.* 2000).

Estuarine salt marshes and associated wetlands are thought to contribute significantly to the food production and availability for juvenile Chinook. These habitats are valuable both as the basis for primary production and as sources of prey items such as invertebrates and larval fish (KCDNR, 2001). Although there has been a loss of between 95 and 99 percent of estuarine habitat in the lower Duwamish basin, there is no evidence of inadequate food supplies for existing populations (Weitkamp *et al.* 2000). Individual Chinook spend relatively limited time in the estuary. Although limited time is spent in the estuary, Chinook salmon grow significantly during estuarine residency (Shepard, 1981; Salo 1969). Salo (1969) found that Chinook captured in early June in the estuary averaged 76 mm in length while Chinook captured in early July averaged 90 mm. In a study of coded wire tagged Chinook fry, Warner and Fritz (1995) found that hatchery Chinook increased their body weight an average of 70 percent during the period between release and recapture in the estuary. This same study found that juvenile Chinook spent on average only 25 days rearing in the mainstem of the river before entering the estuary (range 8 to 61 days).

It should be noted; however, that hatchery management practices may account for some of the differences between wild and hatchery fish (Weitkamp *et al.* 2000). Hatchery Chinook released in the system have historically been reared to larger sizes prior to release as compared to their wild counterparts. Up until recently, there has been no way to distinguish between large hatchery reared fish entering the estuary and wild or naturally produced Chinook juveniles that have spent weeks rearing in the natural environments (Weitkamp *et al.* 2000).

Predator Avoidance

Most of the fish predators, such as smallmouth and largemouth bass, that are found in freshwater systems such as Lake Washington are not present in the Duwamish estuary. Predators on juvenile Chinook in the Duwamish Estuary are thought to include river lamprey, juvenile coho salmon, and avian species including great blue heron, western grebe, merganser, cormorant, pigeon guillemont, and kingfisher. River lamprey may be a significant predator on juvenile Chinook with 7% of juveniles observed showing lamprey marks (Salo, 1969). Specific studies of river lamprey predation on juvenile Chinook have not been conducted in the Duwamish estuary, but Beamish and Neville (1995) estimated that lamprey were killing 25% - 65% of the young Chinook and coho migrating out of the Fraser River.

Although the estuary contains many overwater structures and piers, fish predators are rarely present under these piers (Weitkamp and Farley, 1976; Weitkamp and Katz, 1976; Weitkamp, 1982; Ratte, 1985; Williams and Weitkamp, 1991). There is presently insufficient information to determine what effect other predators may have on Chinook juvenile survival in the estuary (Weitkamp *et al.* 2000).

Water Quality

While sediment contamination and occasional water quality deficiencies are commonplace in the estuary, it is less clear what effects, if any, these have on juvenile salmon survival. King County found that there were no acute risks to juvenile salmon from contamination in the water column during their recent CSO study (KCDNR, 1999). This conclusion was largely attributed to low residence times for water column pollutants and the relatively short time juvenile Chinook spend in the estuary. Both factors tend to reduce Chinook exposure to potentially harmful contaminants.

It is thought that historic contaminants in the sediments of the Duwamish estuary have little potential to have a direct impact on juvenile salmon (Weitkamp *et al.* 2000); however, some investigators have indicated that many of the contaminants common in the sediments of the Duwamish estuary may have a long-term chronic effect on Chinook (McCain, *et al.* 1990; Varanasi *et al.* 1993; Stein *et al.* 1995; Arkoosh *et al.* 1998). Additional investigation is necessary to better understand the potential long term effects of water and sediment contamination on Chinook survival. In addition, the rate and role of natural attenuation is not well understood in the estuary. Given recent reductions in contaminant inputs, it is not clear whether, or to what degree, natural burial and attenuation is reducing contaminant concentrations over time (KCDNR 2001).

While the effect of impaired water quality on juvenile survival appears limited, the combination of low summer flows, low dissolved oxygen levels, and high temperatures have been shown to delay adult migration and increase the time adult Chinook spend holding in the estuary and lower river (Miller and Stauffer 1967; Salo 1969; Weitkamp *et al.* 2000). The water quality conditions leading to delays of adult migration are thought to be most significant above the South Park Bridge, beyond the Seattle city limits, where water quality is influenced more by inflows from the upper basin and is less benefited by mixing of water from Puget Sound (Weitkamp *et al.* 2000). It should be noted that the diversion of discharges from the Renton wastewater treatment plant in the 1980's and operational changes in Howard Hansen Dam to provide higher summer flows implemented in the mid 1990's may be improving water quality conditions in the estuary (Weitkamp *et al.* 2000).

Habitat Access

There are no other known barriers to adult Chinook migration through the estuary except as discussed above related to water quality.

Docks and other overwater structures pose potential barriers or inhibitors to juvenile salmon migrating along shallow-water habitats of Puget Sound during their emigration to the Pacific Ocean. Juvenile ocean-type Chinook and chum salmon, the two most abundant juveniles in the Duwamish Estuary, are believed to be particularly vulnerable because they migrate along the nearshore in shallow water (Weitkamp 1982; Tanner 1991; Simenstad *et al.* 1991; Simenstad *et al.* 1982.). The modification of salmonids migrating behavior in response to overwater structures may also increase their susceptibility to predation (Simenstad *et al.* 1982).

However, many authors have found that juvenile outmigration through the Duwamish estuary is not affected by these structures (Weitkamp *et al.* 2000). Weitkamp and Farley (1976) observed juvenile salmon along open shorelines and under piers in the lower Duwamish. They noted that more Chinook are seen along shorelines than under piers, but that coho showed little reluctance to enter areas covered by piers and over deeper water (KCDNR 2001). Further investigation may help clarify if behavioral responses to overwater structures actually impede juvenile salmon migration in the Duwamish.

Landscape and Habitat Forming Processes

The Duwamish River and estuary provide several important habitat and physiological functions to juvenile Chinook migrating out of the Green River drainage into Puget Sound. The Duwamish is used as a rearing area by juvenile Chinook salmon, although the length of residency by this species within this area is not well understood. Side channels, sloughs, and other off-channel habitats provided the most important habitat areas to juvenile Chinook salmon on a historical basis. The preferred habitat type for juvenile Chinook salmon in larger rivers such as the Duwamish are shallow habitats along the margins of the river bank, and off channel habitat areas. Channel margin and off channel habitats provide refuge areas from river currents which may be high during the spring outmigration period of Chinook, from tidal currents present within the lower sections of the river, and from predators. The margin and off channel habitat areas are also important foraging areas for juvenile Chinook.

Off-channel habitats in lower river areas including estuaries and deltas are formed by complex interactions of several key processes (Figure 6). Sediment derived from the upper watershed is transported by moderate to high river flows into the lower river, where it is deposited under natural conditions to form a broad floodplain. The river channel in these low gradient depositional areas is highly sinuous, and meanders on a lateral basis over time to form off-channel habitats such as oxbows and side channels. In the delta and estuary areas of rivers, a finely

This recreated off-channel habitat provides shallow water refuge at high tide.

outbranching network of channels called "distributaries" is typically formed by the interaction of river currents and tidal processes. These habitats are scarce under current conditions as a result of extensive channelization and dredging of the Duwamish River channel, and industrial development along the Duwamish shoreline.

Almost all of the off-channel habitats that were historically present in the lower Duwamish River and estuary were destroyed during the late 1800s and early 1900s when the lower Duwamish River was channelized (straightened and deepened) to create a navigation channel, and when natural channel meanders, sloughs, and side channels were filled for industrial and residential development. Dikes and levees which have been constructed along sections of the Duwamish for flood protection further hinder the formation of off-channel habitat areas by restricting the active floodplain to a narrow corridor along the mainstem river channel. Tide gates intended to prevent saltwater intrusion into urban areas also prevent the tidal currents from forming and maintaining blind sloughs and other off-channel habitat areas. Extensive armoring (e.g., riprap) and bulkheading along the banks of the Duwamish now inhibit the lateral migration of the river, preventing the formation side-channels, oxbows, and sloughs.

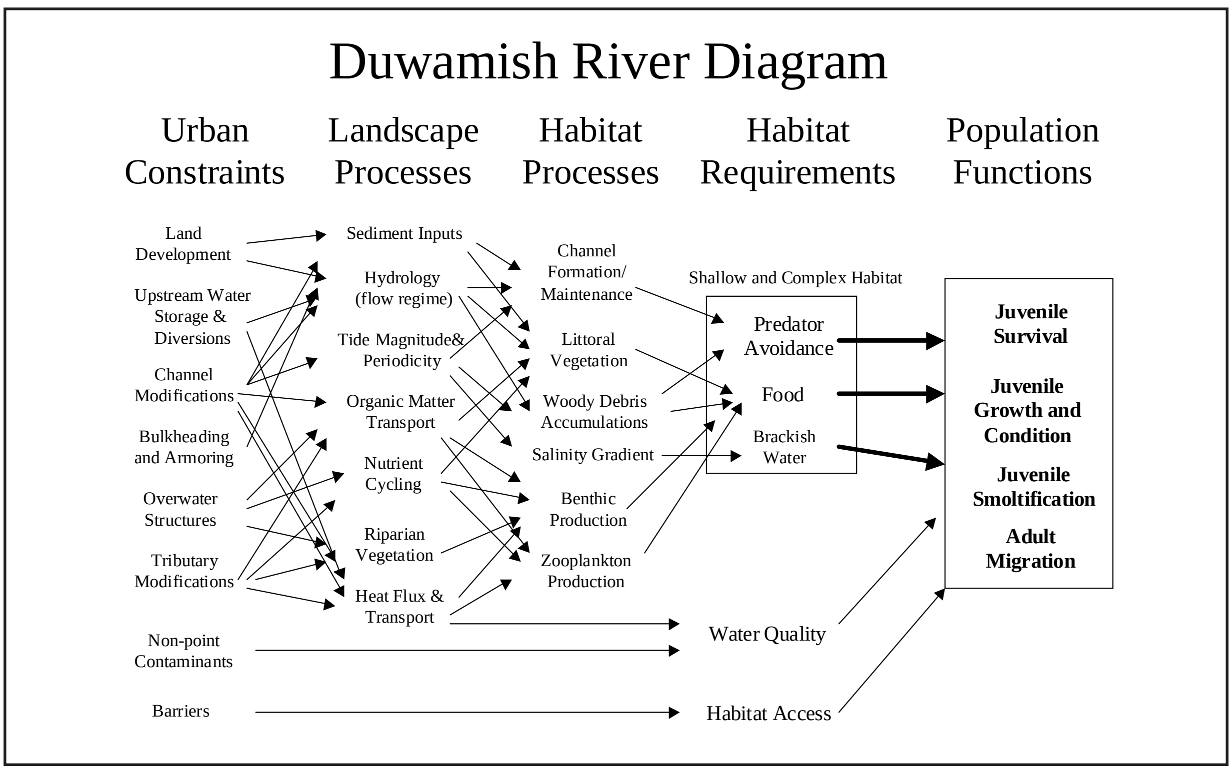

Figure 6. Hierarchical relationship between urban constraints, landscape processes, and Chinook habitat requirements in the Duwamish River system.

Preliminary Focus Areas

Based on the analysis above, the following table summarizes our understanding of the most significant factors for juvenile Chinook survival and fitness in nearshore areas.

Population Function	Habitat Function	Habitat characteristic/ condition	Habitat forming processes	Constraints
Juvenile rearing and outmigration	Predator Avoidance	Shallow water (1m or less depth from -2ft to +6ft tide) Small substrates (mud to small cobbles) Off-channel habitats (including side channels, sloughs, and distributary channels) Hydraulic continuity through off-channel areas	Sediment sources (upper watershed, bank erosion) Flow regime (high flows transport sediments; off-channel habitat formation) Tidal magnitude and pattern (off-channel habitat formation) Woody debris transport and deposition	Bank armoring and bulkheading Dike and levees Channel modifications including dredging Filling of side-channel areas Overwater structures Loss of riparian vegetation
	Food Availability	Diverse substrates (esp. macrophytes, woody debris, gravels, and cobbles) along banks and within off-channel habitats	Organic matter transport from upper watershed Salinity change (high food densities within mixing zone and salt wedge) Aquatic macrophyte and algae growth Riparian vegetation growth	Upstream dams Channelization (impacts greatest within freshwater - saltwater mixing zone) Bank armoring and bulkheading Reduction in side-channel habitats Tributary diversions Loss of riparian vegetation
	Water Quality	Clean and cold water	Flow Regime (low flows increase potential for warmer water, reduced dissolved oxygen) Heat transport from upper watershed Organic matter transport and deposition (biological oxygen demand)	CSOs Reduction in freshwater inflows Water quality conditions have substantially improved within last two decades Impacts of contaminants uncertain. Sediment contaminant impacts under debate
	Access	No barriers in mainstem river and estuary Access to off-channel areas for rearing and habitat refugia	Flow regime of tributaries Hydraulic connectivity of side channels	Access to some off-channel habitat areas and tributaries blocked by flood gates and culverts
Juvenile transition to saltwater	Brackish Water	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel	Hydrology Tide magnitude and timing	Land development (including filling) Upstream dams Channelization
Adult upmigration	Access	No barriers in mainstem river and estuary	Flow Regime	Upstream migration may be hindered by warm water during low flow periods

Among these factors, the protection and restoration of estuarine wetlands and complex off-channel habitat and upper and middle intertidal habitats emerge as key areas of focus.

Habitat Improvement Projects in the Duwamish Estuary

Habitat improvement projects should focus on improving those habitat qualities that the science indicates will likely provide the greatest benefit for fish. Habitat restoration projects will be monitored whenever possible. Monitoring will track those critical variables that will help the City to assess effectiveness in meeting project objectives. The City will seek to design and monitor habitat restoration projects that create benefits for multiple species where this practical and where doing so does not undermine the main objectives of the project. The following table notes projects which have already been completed and projects which might be considered, noting the benefits for fish which each project may create. (Many existing projects in the Duwamish have been done with Port of Seattle participation.)

Project Name Project Cost or estimate Status of Project	Project Description	Habitat Requirement Predator Avoidance	 Food Availability	 Brackish Water
1st Ave South Bridge Potential	Property negotiations are now going on to close out the 1st Ave. South Bridge project. Shoreline at the northwest side of the bridge will be converted to an intertidal slough similar to Seaboard. This area is adjacent to the outlet for the SR-509 wetlands.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel
2nd Ave S. Street end Potential	This street end has good middle to lower intertidal habitat. Regrading of the bank will increase the middle and upper intertidal areas.	Restoration of upper and middle intertidal habitats		
Ball Foster Glass Bank Improvement Completed	This non-water dependent business fully uses its parcel with a truck driveway abutting the river. When they repaired their bank armoring, they used smaller rock, and cleaned up rubbish from the intertidal area. Though there is nothing visible that looks like a restoration project, this work was likely beneficial to juvenile salmonids	Improved bank conditions		
Boeing Public Access Bank Revegetation Completed Potential	Boeing did a partial bank set back and some revegetation to create a public access site on the bank of one of their buildings. The site needs some stewardship and additional restoration will increase the value of the area for salmonid habitat. Some work may be possible in conjunction with sediment remediation expected just up-river from this site. In addition, if the disincentives of the Shoreline Management Act were removed, there is ample area to dramatically increase the middle and upper intertidal habitat.	Restoration of upper and middle intertidal habitats.	Intertidal vegetation Bank revegetation	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel

Cecil B. Moses Park Intertidal Habitat Completed	Also known as North Wind's Weir, this site belongs to King County and has been restored to an intertidal slough through the Elliott Bay Restoration Panel. This site is directly across the river from Site # 1(see later in this table). Together these sites are anchor sites for salmonids at the end of the saltwater wedge. During beach seining done by the Muckleshoots about 5 years ago, this part of the river seemed to be a major aggregation site for salmonid juveniles.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel
City Light Pump Station Potential	The street end at 8th Ave. S. will supply some options for restoration in the future. Just north of this site, on the riverbank, is the old City Light pump station which drew water for the Georgetown Steam Plant. The site will be developed as an intertidal marsh or slough. Public amenities will be included so that the site will be a good public access site as well—adjacent to the existing Gateway North public access site.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel
City Light South Potential	There is potential to restore the shoreline at this site just downriver from the Kenco Marine site and within an important transition area for juvenile salmon.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	
Coastal America Turning Basin Intertidal Habitat Completed	This Port of Seattle property was restored with assistance from a Coastal America grant. Restoration included removal of fill, regrading of the bank line, replanting of intertidal vegetation, and removal of a derelict ferry boat.	Restoration of upper and middle intertidal habitats		Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel
Diagonal Duwamish Potential	There is a small cove at the outfall that may be a base for additional habitat work when the proposed sediment remediation is done under the auspices of the Elliott Bay Panel.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	
Gateway North Bank Revegetation Completed	This small public access area off 8th Ave. S. and E. Marginal Way has been developed and kept up by community members. The bank revegetation contributes detritus and insects to the river's food web. It is adjacent to the City Light Pump Station site and could be included in restoration done in the future to increase intertidal habitat.		Bank revegetation	

Gateway South Bank Revegetation Completed	This small public access area off 8th Ave. S. and Riverside Dr. S. has been developed and kept up by community members. The bank revegetation contributes detritus and insects to the river's food web.		Bank revegetation	
Glacier N.W. Bay Potential	One of Glacier NW 's facilities sits in this remnant of a meander. The bay is a good intertidal mudflat. Glacier is considering doing some bank revegetation to increase the insects available to aquatic life that use the bay. Glacier NW uses this site to unload Portland cement. It has a cement dock built at the edge of the dredged waterway, so it does not cover the shallow waters of the mudflats. The dock has widely spaced piers and is relatively narrow, so light can get under it. This is a good design for fish as it has less overwater coverage than older wooden docks. The operation of transferring the cement to the silos is done through a closed system.		Intertidal vegetation Bank revegetation	
GSA Coastal America Site Intertidal Habitat Completed	The U.S. General Services Administration hosted a Coastal America project that took out a part of the parking lot at the south end of the riverbank and pulled back part of an old dock. The area was planted but otherwise left to develop into an intertidal mudflat. There is significant erosion happening because of boat wakes and it may be necessary to do some armoring of the bank edge in the near future.	Restoration of estuarine upper and middle intertidal habitats Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel
Hamm Creek Intertidal Habitat Completed	This site, belonging to Seattle City Light, is a restoration done by King County under the Elliott Bay Restoration Panel. Hamm Creek, previously in a pipe, now flows into the new intertidal slough.	Restoration of upper and middle intertidal habitats		Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel
Herring's House Park Intertidal Habitat $5,000,000 Completed	The old Seaboard Lumber mill site has been transformed into an intertidal marsh of nearly two acres, along with an extensively planted upland buffer with native trees and shrubs.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel

Kellogg Island Intertidal Habitat Completed	This island (a remnant of the original mudflats) has been the repository for dredging spoils. Some restoration has been done on the north end of the island, removing some of the spoils to reduce the elevations to intertidal mudflats. The island hosts herons, osprey, otters, and other estuarine wildlife. At low tides the west channel drains and is impassable even by kayak.		Intertidal vegetation Bank revegetation	
Kelp Beds East Waterway Completed	The Port built some mounds in the channel and established kelp beds to increase aquatic habitat.		Aquatic vegetation	
Kenco Marine Bank Improvement & Revegetation Underway	This site was purchased under the auspices of the Elliott Bay Restoration Panel and is owned by the Muckleshoot Indian Tribe. They have drawn up a restoration plan and expect to do significant work at the site this year Work will be similar to the POS Turning Basin site, regrading the bank and removing fill and dock and pier structures.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Transition
LaFarge T-108 Potential	This Port property is adjacent to the Port's existing T-108 restoration and public access site. The Port has indicated they will likely create an intertidal slough at this property as part of the mitigation for disposal of East Waterway dredge spoils.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel
POS Turning Basin Intertidal Habitat Completed	Restoration of middle and upper intertidal habitat by removing fill, regrading the bank line and replanting intertidal vegetation.	Restoration of estuarine upper and middle intertidal habitats		Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel

Puget Creek Estuary Completed	The south end of T-107 is where Puget Creek would have emptied to the Duwamish if it were still in its natural channel. Instead, it enters the Duwamish through a pipe somewhat downstream. The Army Corps of Engineers created this intertidal area in 1999. If Puget Creek is ever daylighted, it will provide a source of freshwater to this off-channel area. Daylighting the Creek is problematic: 1) the geometry of getting the creek under the road and railroad and over the Renton Effluent Transfer pipe while landing on the beach at the right height is challenging. 2) The creek has a high pH likely related to running through remnants of old cement kiln dust deposited upstream. The latter problem reduces the value of the creek for sustaining meaningful habitat for salmonids though the water quality issues are reduced once the creek mixes with Duwamish water.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel
SeaKing Industrial Park Potential	This site, in unincorporated King County, has some good stormwater detention ponds. The owner has indicated an interest in looking at potential shoreline restoration designs.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	
Site # 1 Intertidal Habitat $1.85 million Underway	Curtis Tanner identified this site for restoration during the concept study done for the Elliott Bay Restoration Panel. In the March 2000 Salmon Recovery Funding Board grant round, WRIA 9, (the Green/Duwamish watershed planning group), was awarded $500,000 toward acquisition of the parcel. The site has been acquired. The real-estate equity will serve as the required match for the Army Corps of Engineers to create an intertidal slough under the Ecosystem Restoration Study, a General Investigation Study done by the Corps in conjunction with the Green /Duwamish Forum in the late 1990s. Seattle contributed $100,000 to this important regional project.	Restoration of upper and middle intertidal habitats		Complex off-channel habitat areas (e.g., sloughs, distributaries) that are connected to main channel

South Park Duwamish Revival Bank Improvements Underway	Charlie Cunniff, of ECOSS, has helped create interest in bank restoration among riverfront property owners in this largely residential area. A project concept has been developed. This area of unincorporated King County, known as the Sliver on the River, is currently on septic, creating a potential water quality issue. However there is a possiblity of doing some bank work that will increase middle and upper intertidal habitat and also revegetate the bank.	Restoration of upper and middle intertidal habitats	Bank revegetation	
Spokane Street Bridge Bank Improvements $350,000 Underway	Metro, the Port of Seattle, and SDOT are landscaping the site on the northwest shoreline under the bridge. SPU conducted a feasibility analysis for regrading the shoreline to increase middle and upper intertidal habitat. The site is behind a wing wall and may be adequately protected from erosion from boat wake to avoid heavy armoring.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	
SR 509 Wetlands Completed	During the construction of SR-509 WSDOT created a stormwater detention pond and a wetland. The wetland drains through a tidal slough to the Duwamish River.	Restoration of estuarine upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	
T-104 Intertidal Bench Completed	The Port created an intertidal bench on the shoreline in the East Waterway.	Restoration of upper and middle intertidal habitats		
T-105 Coastal America Site Completed	This Port of Seattle Public Access site includes a long channel perpendicular to the river, which hosts chum and Chinook juveniles at high tide in the spring/summer. It is a good example of shoehorning habitat into an industrial area.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	Intertidal vegetation Bank revegetation
T-105 shoreline Potential	Just up river from T-105 public access is river frontage, owned by the Port, that is currently mudflats and many old wood pilings. The Port intends to do a restoration project on this shoreline in the future, thus increasing the contiguous rearing areas for fish.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation	

T-108 Intertidal Habitat Completed	The Port developed a public access site at this street end and also pulled back a small intertidal slough to the north of the public access. This site is adjacent to the LaFarge site—a potential restoration site.	Restoration of upper and middle intertidal habitats	Intertidal vegetation Bank revegetation

Addressing Uncertainties

Biological indicators

The Duwamish estuary may be less of a limitation to Chinook salmon in WRIA 9 than is initially indicated by the enormous loss of pre-settlement intertidal habitat and estuarine wetlands. However, due to long standing and intensive hatchery plants in the basin, the specific needs and limiting factors for wild Chinook are poorly understood. In the longer term, a significant body of research is needed to address how, and to what extent, hatcheries and habitat loss have affected wild Chinook in the Green/Duwamish River basin. Pit tagging studies and fin-clipping all hatchery Chinook released in the basin will assist in this regard.

Key research and assessment issues include:

1. The identification of specific habitat needs related to wild Chinook through the entire Green/Duwamish River, including the estuary.
2. Quantification of mortality of wild Chinook at each life stage.
3. The role of predation on juvenile Chinook in the estuary.
4. Impact of contaminated sediments on juvenile Chinook survival.
5. Habitat preference in nearshore areas of wild versus hatchery juvenile Chinook.
6. The characterization and distribution of various life-history strategies for wild Chinook in the basin.
7. The effect of overwater structures on juvenile salmonid mortality in the estuary.

Literature Cited

Arkoosh, M. R., E. Casillas, P. Huffman, E. Clemons, J. Evered, J. E. Stein, and U. Varanasi. 1998. Increased susceptibility of juvenile Chinook salmon from a contaminated estuary to *Vibrio anguillarum*. Transactions of the American Fisheries Society 127:360-374.

Beamish, R.J., and C.M. Neville. 1995. Pacific salmon and Pacific herring mortalities in the Fraser River plume caused by river lamprey (Lampetra ayresi). Canadian Journal of Fisheries and Aquatic Sciences. 52: 644-650.

Blomberg, G., C. Simenstad, and P. Hickey. 1988. Changes in Duwamish River estuary habitat over the past 125 years. Pages 437-454 In: Proceedings of the First Annual Meeting on Puget Sound Research. Volume II. Puget Sound Water Quality Authority, Seattle, Washington.

Cordell, J. R., L. M. Tear, C. A. Simenstad, and W. G. Hood. 1996. Duwamish River Coastal America restoration and reference sites: results from 1995 monitoring studies. University of Washington, School of Fisheries, Fisheries Resource Institute, FRI-UW-96-12, Seattle.

Cordell, J. R., L. M. Tear, K. Jensen, and V. Luiting. 1997. Duwamish River Coastal America restoration and reference sites: Results from 1996 monitoring studies. University of Washington, School of Fisheries, Fisheries Resource Institute, FRI-UW-97-09, Seattle.

Cordell, J. R., L. M. Tear, K. Jensen, and H. H. Higgins. 1998. Duwamish River coastal America restoration and reference sites: results from 1997 monitoring studies. University of Washington, Fisheries Research Institute, Seattle.

Fuerstenburg, R. R., K. Nelson, and R. Blomquist. 1996. Ecological conditions and limitations to salmonid diversity in the Green River, Washington, USA. King County Surface Water Management, Bellevue, Washington.

GeoSea Consulting. 1994. Sediment transport in Elliott Bay and the Duwamish River, Seattle: implications to estuarine management. Prepared for Washington State Department of Ecology, Toxics Cleanup Group, Olympia.

Grette, G.B. and E. O. Salo. 1986. The status of anadromous fishes of the Green/Duwamish River system. Final report to the US Army Corps of Engineers, Seattle, Washington. 213 p.

Heg, R. 1952. Duwamish River Chinook studies. Washington Department of Fisheries Progress Report. July-November 1952.

Kerwin, John, and Tom S. Nelson. December 2000. "Habitat Limiting Factors and Reconnaissance Assessment Report, Green/ Duwamish and Central Puget Sound Watersheds (WRIA 9 and Vashon Island)." Washington Conservation Commission and the King County Department of Natural Resources.

King County. 1999. Combined Sewer Overflow Water Quality Assessment for the Duwamish River and Elliott Bay. Prepared by Parametrix, Inc. and King County Department of Natural Resources. Seattle, WA.

King County Department of Natural Resources (KCDNR). 2001. State of the Nearshore Ecosystem: Eastern Shore of Central Puget Sound, Including Vashon and Maury Islands (WRIAs 8 and 0). Prepared by Battelle Marine Sciences Laboratory Sequim, Washington, Pentec Environ-mental Seattle, Washington, Striplin Environmental Associates Seattle, Washington, Shapiro Associates, Inc. Seattle, Washington. Prepared for King County Department of Natural Resources Seattle, Washington. January 2001 (Review Draft). 292 p.

McCain, M., D. Fuller, L. Decker, and K. Overton. 1990. Stream habitat classification and inventory procedures for Northern California. Fish Habitat Relationships Currents, Number 1, U.S. Department of Agriculture, Forest Service, Pacific Southwest Region.

Meyer, J. A., T. A. Pearce, and S. B. Patlan. 1980. Distribution and food habits of juvenile salmonids in the Duwamish Estuary, Washington, 1980. U.S. Fish and Wildlife Service, Fisheries Assistance Office, unpublished report, Olympia, Washington.

Miller, D. M. and G. D. Stauffer. 1967. Study of the migration and spawning distribution of the runs of Chinook and coho in the Green-Duwamish River system in the fall of 1965. Fisheries Res. Institute Circ. no 67-4. University of Washington Seattle, Washington.

Myers, J. M., R. G. Kope, G. J. Bryant, D. Teel, L. J. Lierheimer, T. C. Wainwright, W. S. Grand, F. W. Waknitz, K. Neely, S. T. Lindley, and R. S. Waples. 1998. Status review of Chinook salmon from Washington, Idaho, Oregon, and California. NOAA Technical Memorandum NMFS-NWFSC-35. National Oceanic and Atmospheric Administration.

Parametrix, Inc. 1990. Terminal 107 (Kellogg Island) biological assessment. Port of Seattle-1998. Unpublished report to Port of Seattle Engineering Department, Seattle, Washington. 57 p.

Pritchard, H. B. 1955. Estuarine circulation patterns: American Society of Civil Engineers Proceedings, Vol 81, Separate 717, 11 p.

Ratte, L.D. 1985. Under-pier ecology of juvenile Pacific salmon (Oncorhynchus spp.) in Commencement Bay, Washington. Thesis, University of Washington, Seattle, Washington. 182 p.

Salo, E. O. 1969. Estuarine ecology research project. Final Report: June 1965 to September 1968. Prepared for the Fisheries Research Institute, College of Fisheries. University of Washington. Seattle, Washington.

Shepard, M. F. 1981. Status and review of the knowledge pertaining to the estuarine habitat requirements and life history of chum and Chinook salmon juveniles in Puget Sound. Final Report. Washington Cooperative Fisheries Research Unit, College of Fisheries. University of Washington. Seattle, Washington.

Simenstad, C. A., and E. A. Salo. 1982. Foraging success as a determinant of estuarine and nearshore carrying capacity of juvenile chum salmon (*Oncorhynchus keta*) in Hood Canal, Washington. Pages 21-37 In: B.R. Melteff and R.A. Neve (eds.). Proc. North Pac. Aquaculture Symposium, August 18-27, 1980. Anchorage, Alaska, and Newport, Oregon.

Simenstad, C. A., C. D. Tanner, R. M. Thom, and L. L. Conquest. 1991. Puget Sound Estuary Program: estuarine habitat assessment protocol. EPA 910/9-91-037. Prepared for U.S. Environmental Protection Agency, Region 10, Seattle, Washington.

Stein, J. E., T. Hom, T. K. Collier, D. W. Brown, and U. Varanasi. 1995. Contaminant exposure and biochemical effects in outmigrant juvenile Chinook salmon from urban and nonurban estuaries of Puget Sound, Washington. Environmental Toxicology and Chemistry 14:1019-1029.

Stoner, J.D. 1967. Prediction of salt-water intrusion in the Duwamish River estuary, King County, Washington.

Stoner, J. D. 1972. Determination of mass balance and entrainment in the stratified Duwamish River Estuary, King County, Washington. U.S. Geological Survey Water-Supply Paper 1873-F, Washington, U.S. Government Printing Office.

Tanner, C. D. 1991. Potential intertidal habitat restoration sites in the Duwamish River estuary. Prepared for the Port of Seattle Engineering Department and U.S. Environmental Protection Agency, EPA 910/9-91-050, Seattle, Washington.

U.S. Army Corps of Engineers. 1997. Green/Duwamish River Basin general investigation ecosystem restoration study, reconnaissance phase. Prepared by ACOE, Seattle, Washington.

Varanasi, U., E. Casillas, M. R. Arkoosh, T. Hom, D. A. Misitano, D. W. Brown, S-L. Chan, T. K. Collier, B. B. McCain, and J. E. Stein. 1993. Contaminant exposure and associated biological effects in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) from urban and nonurban estuaries of Puget Sound. NOAA Technical Memorandum NMFS NWFSC 8.

Warner, E.J., and R.L. Fritz. 1995. The Distribution and Growth of Green River Chinook Salmon (*Oncorhynchus tshawytscha*) and Chum Salmon (*Oncorhynchus keta*) Outmigrants in the Duwamish Estuary as a Function of Water Quality and Substrate. Muckleshoot Indian Tribe Fisheries Department. Auburn, Washington.

Washington Department of Fish and Wildlife and Western Washington Treaty Indian Tribes. 1994. 1992 Washington State salmon and steelhead stock inventory (SASSI). Appendix 1, Puget Sound stocks, north Puget Sound volume. WDFW and WWTIT, Olympia.

Weitkamp, D. E. 1982. Juvenile chum and Chinook salmon behavior at Terminal 91, Seattle, Washington. Prepared for Port of Seattle. Parametrix, Inc.

Weitkamp, D. E. and M. Katz. 1976. Biological survey and assessment of impacts of alternative redevelopments. In: Southwest Harbor Environmental Studies. Planning and Research Department, Port of Seattle, Washington. 79 p.

Weitkamp, D. E., and T. H. Schadt. 1982. 1980 juvenile salmonid study. Prepared for the Port of Seattle, Document No. 82-0415-012F, by Parametrix, Inc., Bellevue, Washington.

Weitkamp, D., and P. Farley. 1976. Juvenile salmonid observations, 1976 Port of Seattle. Report by Parametrix, Inc. Pages M-1 to M-15 In: Final EIS proposed Terminal 37 expansion project. Port of Seattle, Washington.

Weitkamp, D., G. Ruggerone, L. Sacha, J. Howell, and B. Bachen. 2000. Factors Affecting Chinook Populations, Background Report. Prepared by Parametrix Inc., Natural Resources Consultants, and Cedar River Associates for the City of Seattle, June 2000.224 p.

Wetherall, J.A. 1971. Estimation of survival rates for Chinook salmon during their downstream migration in the Green River, Washington. Ph.D. Dissertation University of Washington. 170 p.

Williams, G. T. and D. E. Weitkamp. 1991. Epibenthic zooplankton production and fish distribution at selected pier apron and adjacent non-apron sites in Commencement Bay, Washington. Report by Parametrix, Inc. to the Port of Tacoma. Tacoma, Washington.

Williams, R.W., R.M. Laramie, and J.J. James. 1975. A Catalog of Washington Streams and Salmon Utilization: Volume 1, Puget Sound Region. Washington State Department of Fisheries. Olympia, Washington.