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Lake Washington Basin Synthesis of Salmon Research and Monitoring

Investigations Conducted in the Western Lake Washington Basin

Seattle Public Utilities

US Army Corps of Engineers
Seattle Division

Acknowledgements

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Executive Summary

This report summarizes recent research studies and findings on natural and hatchery-origin Chinook, sockeye, and coho salmon and steelhead trout in the western Lake Washington watershed. It includes studies conducted by the Lake Washington Basin Ecosystem Restoration General Investigation Study (LWGI) and identifies management strategies and recommended actions to increase understanding and improve conditions for salmon in the watershed.

The information presented in this report is intended to inform planning for ecosystem improvements and serve as a resource for agencies and jurisdictions involved in salmon management and recovery.

Purpose of the Lake Washington General Investigation Study

The LWGI was undertaken in 1997 by the U.S. Army Corps of Engineers (Corps), at the request of King County and the City of Seattle as local sponsors. The purpose of the study was to identify and implement environmental restoration projects aimed at 1) improving conditions for salmon populations and other wildlife in the basin and 2) using water efficiently at the Locks to ensure adequate fish passage.

The LWGI focuses on protection and restoration of four species of anadromous salmonids in the Lake Washington basin:

1. Chinook salmon, *Oncorhynchus tshawytscha*
2. coho salmon, *O. kisutch*
3. sockeye salmon, *O. nerka*
4. steelhead trout, *O. mykiss*

Lake Washington Watershed and Focus Area

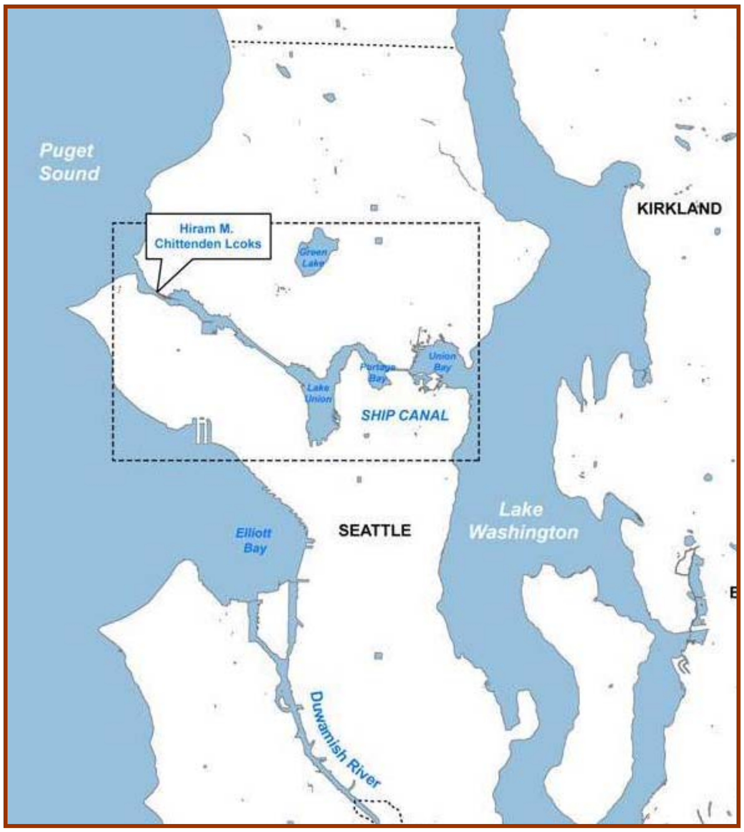
The 692-square-mile Lake Washington watershed is located in western Washington. It includes two major river systems, the Cedar and Sammamish rivers, and three major lakes, Lake Washington, Lake Sammamish, and Lake Union. The watershed drains to central Puget Sound through the city of Seattle. The Lake Washington watershed is home to Chinook, coho, and sockeye salmon, and steelhead, rainbow, cutthroat, and bull trout.

Historically, the Lake Washington watershed drained south into the Black and Duwamish rivers. In 1916 the Corps constructed the Locks and excavated the Ship Canal, connecting the Union Bay area in Lake Washington with Salmon Bay in Puget Sound. These hydrologic changes lowered the lake level 9 feet, dried up lake shoreline wetlands, and disconnected Lake Washington from its historical outlet, the Black River. Salmon populations were forced to find a new route back to their natal streams. Since 1916, shoreline and watershed development has further altered habitat conditions in the Lake Washington system.

Because of the complexity of determining habitat needs within this highly altered system, studies were divided into two phases: the east and west geographic regions. King County served as the local sponsor for the east geographic region (Phase 1) activities, while the City of Seattle sponsored activities for the west geographic region (Phase 2).

The western Lake Washington watershed is the focus area of this report, specifically Lake Washington, the Ship Canal, Lake Union, the Locks, and Shilshole Bay. The Locks represent the most complex passageway for migrating salmon and steelhead. The structure itself contains roughly six different routes fish can move through: the large lock chamber and associated filling culverts, small lock chamber and associated filling culverts, the saltwater drain, the fish ladder, the spillway, and the smolt flumes. The structure also creates physical, biological, and chemical conditions that can affect salmon, such as water temperature and salinity gradients. The Locks are also a key societal component in regulating water levels and providing navigation.

More information about the Lake Washington system, alterations, and the salmon using the basin can be found in Chapter 2 of the report.



Western portion of the Lake Washington watershed, the focus area of this report. The Ship Canal system is outlined

Summary of Research Findings

From freshwater streams to the ocean, salmon occupy many habitats throughout their lives. Salmon respond in several ways to the dynamic structure of the Pacific Northwest ecosystem and the natural and human-induced stresses that influence their survival at all life stages. Management of salmon in the Lake Washington basin is difficult because many factors impact salmon within the area.

Studies completed under Phase 2 of the LWGI include investigation of smolt flume water use efficiency, juvenile Chinook salmon habitat use in Lake Washington, smolt outmigration timing and behavior, and tracking of juvenile Chinook smolts through the Ship Canal, Lake Union, and the Locks. The research gathered in the LWGI and through other studies presents information for improved management of salmon in the Lake Washington basin. Chapter 3 of the report summarizes research findings from the late 1990s to today. Chapter 4 provides conceptual models that illustrate how the research findings relate to what is understood about each species' life history in the Lake Washington system.

The following table summarizes the major research findings presented in this report. The information is grouped into two categories: research findings for juvenile salmon and research findings for adult salmon. For juvenile salmon, the research is grouped by location: Lake Washington Residency, Lake Washington Outmigration, Ship Canal and Lake Union Outmigration, Passage at the Locks, Estuarine transition in Salmon and Shilshole Bays, and Puget Sound Residency. Studies on the return migration of adult Chinook, coho, sockeye salmon, and steelhead are organized according to passage through the study area: Puget Sound Residency, Estuarine Transition, Passage at the Locks, Ship Canal and Lake Union Migration, and Lake Washington.

Management Actions and Further Studies

Studies in the LWGI and by other local groups have identified much about salmon as they move through the Lake Washington basin. Although management actions can be taken with current knowledge, in some cases further research is necessary.

Increasing the survival of juvenile salmon can be achieved through the following actions:

- Improving habitat in Lake Washington and the Ship Canal
- Improving passage through the Locks
- Decreasing water temperature and salinity gradients between Salmon Bay and Shilshole Bay

Increasing the survival of adult salmon may be achieved through the following:

- Increasing pathways for adult salmon between Shilshole Bay and the Ship Canal
- Decreasing water temperatures and salinity gradients between Shilshole Bay and the Ship Canal
- Increasing the area of estuarine conditions around the Locks

More specific recommendations are provided in Chapter 5 of the report.

There are still uncertainties about salmon habitat preferences, behavior, and needs within the Lake Washington basin. Habitat for juvenile salmon in the Ship Canal should be improved and then monitored for effectiveness of various improvement actions. A number of actions at the Locks have improved downstream passage through the Locks. However, further clarity would be helpful on the proportion of outmigrants passing through the various routes available and the survival of fish in each passage route. For adults, little is understood about their behavior downstream of the Locks and how altering Lock passageways to allow for more gradual movement between freshwater and marine systems may benefit conditions for returning salmon.

Major Research Findings for Juvenile and Adult Salmon in the Western Lake Washington Basin (1998-2008)

Location	Findings for Juvenile Salmon	Source
Lake Washington Residency	*Juvenile Chinook, coho, and sockeye occur in Lake Washington. Conditions for juvenile salmon are declining in the lake. More than 70% of the shoreline is developed.*	
Habitat Use & Behavior	• Chinook salmon fry tend to use shallow shoreline area with finer gravel and sand substrates. They use woody debris for cover during the day and tend to avoid armored shorelines. Juveniles avoid overwater structures and are attracted to non-natal tributaries • Chinook fingerlings move into deeper water and avoid overwater structures • Sockeye fry initially inhabit sandy, littoral (shoreline) habitats but move into deep, limnetic (open) waters within a few weeks • Juvenile steelhead and coho may be found in both littoral and limnetic areas. Steelhead in limnetic areas consume zooplankton	Beauchamp 1995 Celedonia et al. 2008a,b Paron and Nelson 2001 Piaskowski and Tabor 2001 Tabor and Piaskowski 2002 Tabor et al. 2004a, 2006
Survival Risks	• More than 70% of the shoreline is developed. This impacts the heavily-used littoral zone and may threaten all salmon species using this area • Juvenile Chinook are opportunistic feeders, with chironomids and zooplankton as top prey items. It does not appear that food availability limits the growth or survival of Chinook or sockeye in Lake Washington • Cutthroat trout are the major predators of juvenile salmon in the lake. Prickly sculpin are important predators from February through June • Population level predation rate estimates vary because predator populations are not known • Predation risks are influenced by spatial overlap between juvenile salmon and potential predators. These overlaps are further influenced by movement patterns (e.g. sockeye diel vertical migration), habitat preferences, water temperatures, and fish size	Beauchamp et al. 2004 Beauchamp et al. 2007 Fayram and Sibley 2000 Koehler 2002 et al. 2006 Nowak et al 2004 Tabor and Piaskowski 2002 Tabor et al 1998, 2004a,b, 2006
Lake Washington Outmigration	*Juvenile salmon migrate through Lake Washington at differing different ages and under different circumstances. Typically juvenile salmon outmigrate from April through early July.*	
Habitat Use & Behavior	• Smolts in the lake tend to follow the lake shoreline while migrating • When they are larger (mid-May) juvenile Chinook move into deeper water. Chinook feed in 6.5 to 13-feet deep water and migrate along the shoreline in similar depths (6.8 to 14.7 ft) • Outmigrating Chinook avoid overwater structures, likely as a result of perceived predation threats • Little is known about the outmigration of coho, sockeye, or steelhead	Fresh 2000 Tabor et al. 2004a, 2006
Survival Risks	• Predators during smolt outmigration are cutthroat trout, rainbow trout, northern pike minnow, and bass • Shoreline development, armoring, and overwater structures may impact outmigrant juvenile salmon	Tabor et al. 2004b Tabor and Piasowski 2002

Location	Findings for Juvenile Salmon	Source
Ship Canal and Lake Union Outmigration	*The Ship Canal was built to connect Lake Washington with Portage Bay, Lake Union, the Locks, and Puget Sound. It resulted in hydrologic changes to the basin and a new migration corridor for salmon. The hydrologic changes have been accompanied by shoreline development. Today, the banks along the Ship Canal are about 96% armored with numerous overwater structures such as docks and piers. Bank armoring, and bulkheads and docks along most of this shoreline severely limit habitat and cover for migrating juvenile salmon. Water temperatures during the summer become particularly high, also influencing migration behavior.*	
Habitat & Behavior	• Sockeye and coho smolts spend the least time in the Ship Canal (less than 1 week), Chinook smolts the most (~1 to 4 weeks) • Average juvenile Chinook smolt migration rates tend to increase as the outmigration season progresses; coho rates are steadier • In PIT-tagging studies, Chinook smolts appear to move along lake shorelines while outmigrating and mix cross-channel in the Ship Canal near the Montlake Cut, Fremont Cut, and Locks forebay • Fine-scale acoustic tracking of individual juvenile Chinook shows various movement patterns, including quickly traveling through the Ship Canal and lingering mid-channel and in littoral areas • Juvenile Chinook use relatively shallow (6 ft) waters in Portage Bay but may inhabit waters as deep as 30 ft in Lake Union • Juvenile Chinook salmon use all of Lake Union, with up to 50% of fish found in the south end of the lake • Juvenile Chinook salmon appear to avoid overwater structures while migrating by moving into deeper water to swim around the piers. Chinook and coho salmon smolts have also been found to residualize (return to the lake for the winter) in the system. Smolts may have a higher probability of residualizing in Lake Washington as the outmigration season progresses and surface water temperatures warm	DeVries et al. 2005 DeVries and Hendrix 2005a Jeanes and Hilget 2002 Johnson et al. 2004c Tabor et al. 2004a
Survival Risks	• Juvenile Chinook often hesitate before entering the Ship Canal at the Montlake Cut. This may be due to lack of shallow water habitat • Elevated water temperatures may also influence juvenile salmon outmigration, especially the later outmigrating Chinook • The large number of overwater structures may substantially influence juvenile Chinook behavior in the Ship Canal and Lake Union • Dominant predators are northern pike minnow, largemouth bass, cutthroat trout, and piscivorous birds. The impact of predation has not been studied	DeVries et al. 2001, 2002, 2003, 2005 DeVries and Hendrix 2005a Tabor et al 2004a,b Celedonia et al. 2008b M. Celedonia unpub data

Location	Findings for Juvenile Salmon	Source
Passage at the Locks	*The Locks present challenges for juvenile salmon passage. Juvenile salmon passage at the Locks has been relatively well-studied.*	
Habitat Use & Behavior	• Chinook smolts upstream of the locks are mostly located near the entrances to the smolt flumes, the large locks, or saltwater drain • Tagged juvenile Coho upstream of the Locks occurred most frequently at the mouth of the spillway flumes and just above the entrance to the large locks • For juvenile salmon, the primary routes through the Locks are the spillway/smolt flumes and large and small locks • Passage at the Locks by young-of-year Chinook and sockeye smolts may be initiated in response to the lunar apogee or quarter moon • Most smolts pass the Locks through the smolt flumes during the day. However, later in the season, most juvenile fish pass through the large lock • The large lock and associated filling culverts are thought to be the second most frequent route for smolts through the Locks. Fish may become entrapped in the filling culverts, which exposes them to descaling and other harm • Water temperature may influence fish location in the water column. This could impact route through the Locks • Fish distribution and route choice do not appear to correlate with flow fields near the Locks • Some Chinook and coho smolts recycle upstream through the large or small lock. No sockeye smolts have been observed to recycle	Biosonics 1997, 2001 DeVries et al. 2004, 2005, 2006 DeVries et al. 2002, 2005 DeVries et al. 2006 Johnson et al. 2001, 2003a, 2004a,b,c WDFW 1996 WDFW unpub data
Survival Risks	• Survival through the Locks is not well understood • Entrainment in the large lock filling culverts is considered the most potentially harmful route through the Locks for juvenile fish. During lockages, the filling culverts have high velocities that can inhibit colitional movement of smolts. The rough, barnacle-encrusted culverts may descale smolts that come into contact with them. Removal of barnacles from the walls of the large lock filling conduit system appears to have significantly reduced heavy descaling of entrained fish • Strobe lights deterred fish from entering the large lock filling culvert	Corps 1999, 2000 Goetz et al. 2001 Johnson et al. 2000, 2001a,b; 2003b; 2004a,b; 2005 Ploskey and Johnson 2001 Ploskey et al. 1998, 2001 Seiler unpub data 1998 Simenstad et al. 2003

Location	Findings for Juvenile Salmon	Source
Estuarine Transition in Salmon and Shilshole Bays	*The artificial estuary below the Locks lacks most of the functions of a natural estuary. Most shoreline in the estuarine transition of Salmon and Shilshole bays is bulkheads, riprap, or naturally steep bluffs. Up to 87% of the eastern shore of nearshore Puget Sound from Shilshole Bay to the King County border is either bulkheaded or rip-rapped.*	
Habitat Use & Behavior	• Smolts may spend little time (less than 1 hour) in the freshwater lens immediately below the Locks • Sockeye smolts spend the least time in the inner bay. Chinook spend the most; coho are intermediate • Acoustically-tagged Chinook smolts on average hold in Shilshole Bay three times as long as coho smolts • Juvenile salmon are a prominent part of the fish population below the Locks from April through October. The diet of juvenile salmon below the Locks is dominated by freshwater zooplankton from above the Locks	Collins et al. 2001 DeVries et al. 2003, 2005 Footen 2000 Johnson et al. 2001, 2004c D. Houck unpub data Seals Price and Schreck 2003 Simenstad et al. 2003 Simenstad and Couch 1999
Survival Risks	• Piscivorous predators of juvenile salmon below the Locks are cutthroat trout, char, and staghorn sculpin • Smolts passing through the Locks are suddenly subject to high salinity, cool waters. This impact on smolts is unknown	DeVries et al. 2005 DeVries and Hendrix 2005a Footen 2001 Johnson 2004b NOAA 2002 Simenstad et al. 2003
Puget Sound Residency	*Studies conducted as part of the LWGI have not examined juvenile residency or migration in Puget Sound. There are concerns about pollutants in the Puget Sound resident fish*	
Habitat Use & Behavior	• Juvenile Chinook and coho may spend up to 2 months rearing in shallow waters of pelagic regions of Puget Sound • These fish consume crab larvae and drift insects	Duffy and Beauchamp 2008
Survival Risks	Survival risks to juvenile Salmon in Puget Sound are not known	
Location	**Findings for Adult Salmon**	**Source**
Estuarine Transition	*The area below the Locks lacks most of the functions of a natural estuary.*	
Habitat Use & Behavior	Largely unknown	
Survival Risks	Pinniped predation on adult salmon and steelhead just downstream of the Locks has been documented in the past. Recent anecdotal information implies this may be occurring in large numbers, despite use of sound in the area to ward off seals and sea lions	NOAA 2002 F. Goetz pers comm

Location	Findings for Adult Salmon	Source
Passage at the Locks	*Adult salmon migrate through the Locks at different times of the year under differing circumstances. Water quality upstream of the Locks presents some survival risks for the fish.*	
Habitat Use & Behavior	• Most adult salmon return through the fish ladder or the large lock chambers. Fewer use the saltwater drain. Not many use the small lock. None use the flumes • Most adult Chinook, coho, and sockeye pass through the fish ladder during the day. Few pass at night • Adult Chinook may hold up to 19 days in the cool water refuge above the Locks. Sockeye and coho do not hold in that area as long. Adults holding at the Locks appear to be choosing their location based on temperatures, DO levels, and water velocity • Adult Chinook arriving at the Locks earlier in the summer tend to hold for longer periods at the Locks than fish that arrive later • Up to 30% of adults appear to recycle at least once through the Locks	DeVries et al. 2003, 2004 DeVries and Hendrix 2005b Goetz et al. 2006 Fresh et al. 1999 Timko et al. 2002 Van Rijn 2001
Survival Risks	• Adult fish may become trapped in the diffuser well that drains saltwater from the forebay through the fish ladder. A screen installed in 2008 upstream of the saltwater drain should prevent this • High water temperatures in the fish ladder may alter route choice for adult Chinook salmon and may be associated with lower returns to Lake Washington • High temperatures and low DO upstream of the Locks may inhibit adult salmon movement away from the cool water refuge	Biosonics 2001 Johnson et al. 2005 Fresh, unpub data Timko et al. 2002
Ship Canal and Lake Union Migration	*Most adult salmon quickly migrate through the Ship Canal and Lake Union. Summer water temperatures in the Ship Canal are high, which may influence migration behavior.*	
Habitat Use & Behavior	• Adult Chinook average 1 day in the Ship Canal, with total time ranging from 4 hours to 7.7 days • Adult sockeye average 4 days in the Ship Canal • Habitat use of adult salmon in this area has not been published	Fresh et al. 1999 Fresh et al. 2000 Fresh unpub data Goetz unpub data Newell and Quinn 2005
Survival Risks	• Enroute mortality has been observed in the Ship Canal in years of high summer temperatures, particularly for adult sockeye. The cause is largely unknown	
Lake Washington		
Habitat Use & Behavior	• Adult Chinook spend 2 to 5 days in Lake Washington before staging near the Cedar or Sammamish rivers. Chinook experience a variety of temperatures while in the lake • Adult sockeye spend an average of 85 days in cool water below the thermocline in Lake Washington	Fresh unpub data Goetz unpub data Newell and Quinn 2005
Survival Risks	• Adult Chinook salmon spend 2 to 5 days in Lake Washington before staging near the Cedar or Sammamish rivers. Chinook experience a variety of temperatures while in the lake	Fresh unpub data Goetz unpub data Newell and Quinn 2005

Location	Findings for Adult Salmon	Source
	• Adult Chinook may experience high temperatures in Lake Washington. Depending on the length of time they spend in high temperatures, it could negatively impact spawning success and gamete health. This has not been studied	

1. Introduction

The *Synthesis of Salmon Research and Monitoring* summarizes recent research findings for the western Lake Washington watershed, focusing on natural and hatchery-origin Chinook, sockeye, and coho salmon and steelhead trout. These findings are taken from many studies, including those conducted under the *Lake Washington Basin Ecosystem Restoration General Investigation study* (LWGI). This report also recommends actions to improve conditions for salmon and identifies future studies needed to increase the understanding of salmon in the Lake Washington basin.

The intent of the report is to summarize LWGI research and guide planning activities for ecosystem improvements. Other agencies, jurisdictions, and organizations involved in salmon recovery within the Lake Washington basin may also find this study useful for their own management decisions

1.1 Organization of this Report

This report is organized into the following chapters:

- **Executive Summary:** This is a summary of the major findings and recommendations in this report.
- **Introduction:** This chapter introduces the report and the LWGI study.
- **Watershed and Focus Area Overview:** This chapter describes the watershed, features of Lake Washington, the Ship Canal, and Locks, and introduces salmon and trout species using the watershed. This section provides context for understanding later sections of the report such as historical watershed changes and fish passageways at the Locks.
- **Summary of Research Findings:** This chapter summarizes salmon research findings from the late 1990s to the present.
- **Salmon Use of the Watershed:** This chapter presents conceptual models of salmon in the western Lake Washington basin. It identifies important survival factors and synthesizes what has been learned from past salmon studies.
- **Focus Area Goals, Objectives and Actions:** Here we recommend high-priority research topics and actions based on the state of science to benefit salmon in the watershed.

1.2 Purpose of Lake Washington General Investigation Study

The LWGI was authorized by Congress under Section 216 (Reauthorization of Existing Project) of the Rivers and Harbors Act of 1970, in connection with the Hiram Chittenden Locks and Lake Washington Ship Canal projects. The purpose of the LWGI is to identify and implement environmental restoration projects for the Lake Washington system aimed at 1) improving conditions for salmon populations, and other wildlife, in the basin and 2) using water efficiently at the Locks.

The following are the primary goals for the LWGI:

- Restoring spawning, rearing, and migration habitat for salmon

- Restoring natural habitat complexity
- Eliminating barriers to fish access and passage
- Restoring stream channel floodplain habitats
- Reducing sedimentation.

The study covers lakes Union, Washington, and Sammamish and their associated rivers, tributaries, and surrounding landscape.

1.2.1 General Investigations with the U.S. Army Corps of Engineers

The LWGI falls within the U.S. Army Corps of Engineers (Corps) General Investigation (GI) study program. That program is a significant avenue through which the Seattle District of the Corps works with local communities, counties, tribes, and other non-federal governments to solve water resource and endangered species problems. Through the GI program, the Corps shares costs with local sponsors to develop workable solutions to water resource problems. General Investigations contain four phases: 1) reconnaissance, 2) feasibility, 3) planning, engineering and design (PED), and 4) construction and monitoring.

Reconnaissance efforts are structured to determine whether interest exists in pursuing a federal water resource project and concludes with a reconnaissance report (905(b) report), a Project Management Plan, and a Feasibility Cost Sharing Agreement. The reconnaissance report identifies water resource problems, opportunities, and potential solutions, and the federal interest in these issues. The Project Management Plan and Feasibility Cost Sharing Agreement define the scope, cost, sponsor funding requirements, and resources needed to complete the feasibility study phase. Upon approval by the Corps Division Office and signing of the cost sharing agreement, feasibility begins with study costs paid 50% by both parties.

The purpose of feasibility is to establish baseline conditions in the project area, identify and evaluate measures and alternative plans, develop a recommendation plan, identify any needed mitigation, develop cost estimates, and prepare a feasibility report. At this stage, the general investigation has identified construction projects, at a 35% design level. The feasibility report, with supporting public review and National Environmental Policy Act (NEPA) documentation, is submitted through Corps Headquarters and the Assistant Secretary of the Army to the federal Office of Management and Budget, and finally to Congress for authorization. With federal authorization and funding allocations, the Corps and local sponsor can proceed into the PED and construction and monitoring phases.

1.2.2 Status of the LWGI

The Corps started the LWGI in 1997, at the request of King County and the City of Seattle as local sponsors. The reconnaissance study examined long-term water efficiency improvements to fish passage at the Locks, fish passage enhancement, and watershed restoration. In July 1998, the Corps produced a reconnaissance report recommending a feasibility study of 1) modifications to the Locks and Ship Canal for salmon, and 2) Lake Washington basin habitat restoration projects. After approval of the reconnaissance report, the Corps signed a cost-sharing agreement with the City of Seattle and King County and began the feasibility phase. Puget Sound Chinook salmon were listed as a threatened species under the Endangered Species Act (ESA) in 1999.

Due to the complexity of determining habitat needs within a highly altered system, the study was divided into two phases: the east and west geographic regions within the Lake Washington basin. Phasing the study facilitated progress on Phase 1 (east) while allowing for further study of Phase 2 (west). King County served as the local sponsor for Phase 1 activities, while Seattle sponsored

Phase 2 activities. The Lake Washington/Cedar /Sammamish watershed (WRIA 8) also helped provide local match dollars through King County Conservation District grants.

Phase 1 of the LWGI emphasizes the *eastern* portion of the Lake Washington basin including portions of Lake Washington, the Cedar and Sammamish rivers, Lake Sammamish, Issaquah Creek and tributaries to each (Figure 1). Although they are not located in the eastern portion of the watershed, improvements to the Salmon Bay estuary were also included in Phase 1. In 2006, King County, in coordination with WRIA 8, chose to discontinue the Phase 1 study and instead pursue funding for Phase 1 projects through other avenues.

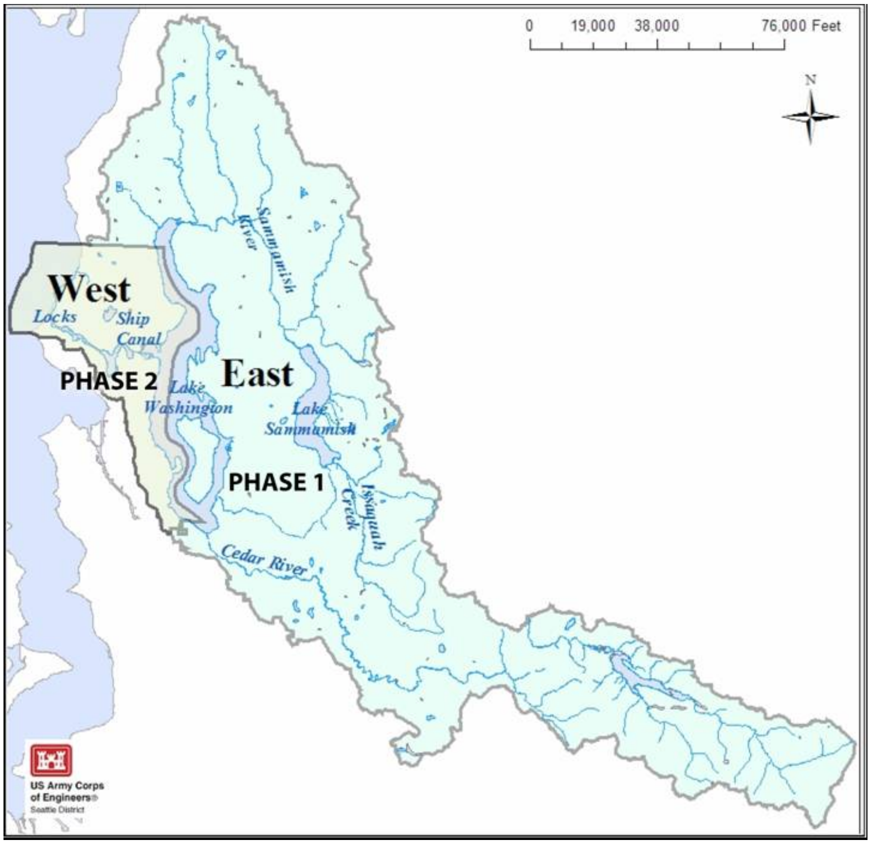


Figure 1
Lake Washington Basin Ecosystem Restoration General Investigation (LWGI) study area

Phase 2 comprises the western portion of the study area, including portions of lakes Washington and Union, the Ship Canal, the Locks and Salmon Bay estuary. Studies completed under Phase 2 of the LWGI include investigation of smolt flume water use efficiency, juvenile Chinook salmon habitat use in Lake Washington, smolt outmigration timing and behavior, and tracking of juvenile Chinook smolts through the Ship Canal, Lake Union, and the Locks. This report is a milestone in the Phase 2 study, which was discontinued in January 2009.

2. Lake Washington Watershed and Focus Area

The western Lake Washington watershed is the focus area of this report. Background on the watershed is important to understanding the conclusions and recommendations provided later in the report. The structure and operation of the Hiram M. Chittenden (or Ballard) Locks, in particular, is a prominent feature in the watershed and has the greatest impact on salmon migration (Figure 2).

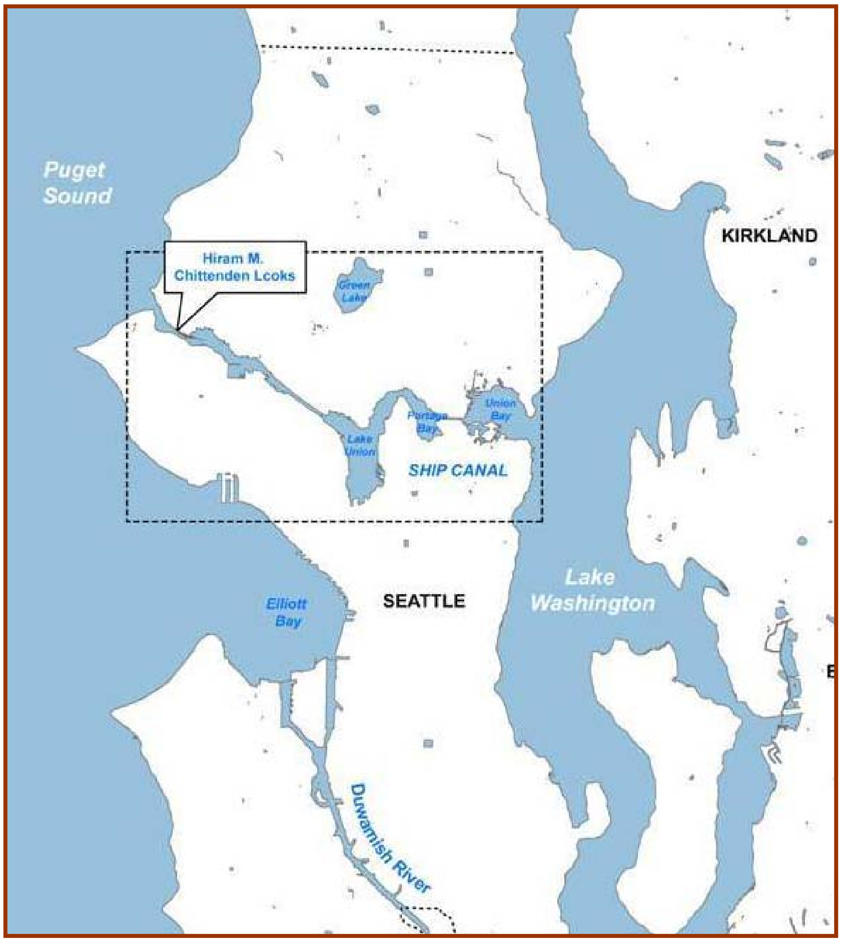


Figure 2
The western portion of the Lake Washington watershed and focus area of this report. The Ship Canal system is outlined

2.1 General Watershed Description

The Lake Washington watershed is located in western Washington and drains to central Puget Sound through the City of Seattle. The 692-square-mile watershed includes two major river systems, the Cedar and Sammamish, and three major lakes, Lake Washington, Lake Sammamish, and Lake Union. The western portion of the watershed includes Lake Washington, the Ship

Canal, Lake Union, the Locks, and Shilshole Bay (Figure 3). With a surface area of 34.6 square miles, Lake Washington is the largest lake in Washington State west of the Cascades. The lake is 18.6 miles long and 1.5 miles wide with an average depth of 108 feet and a maximum depth of 220 feet. The Cedar and Sammamish rivers, and numerous smaller creeks, drain to the lake.

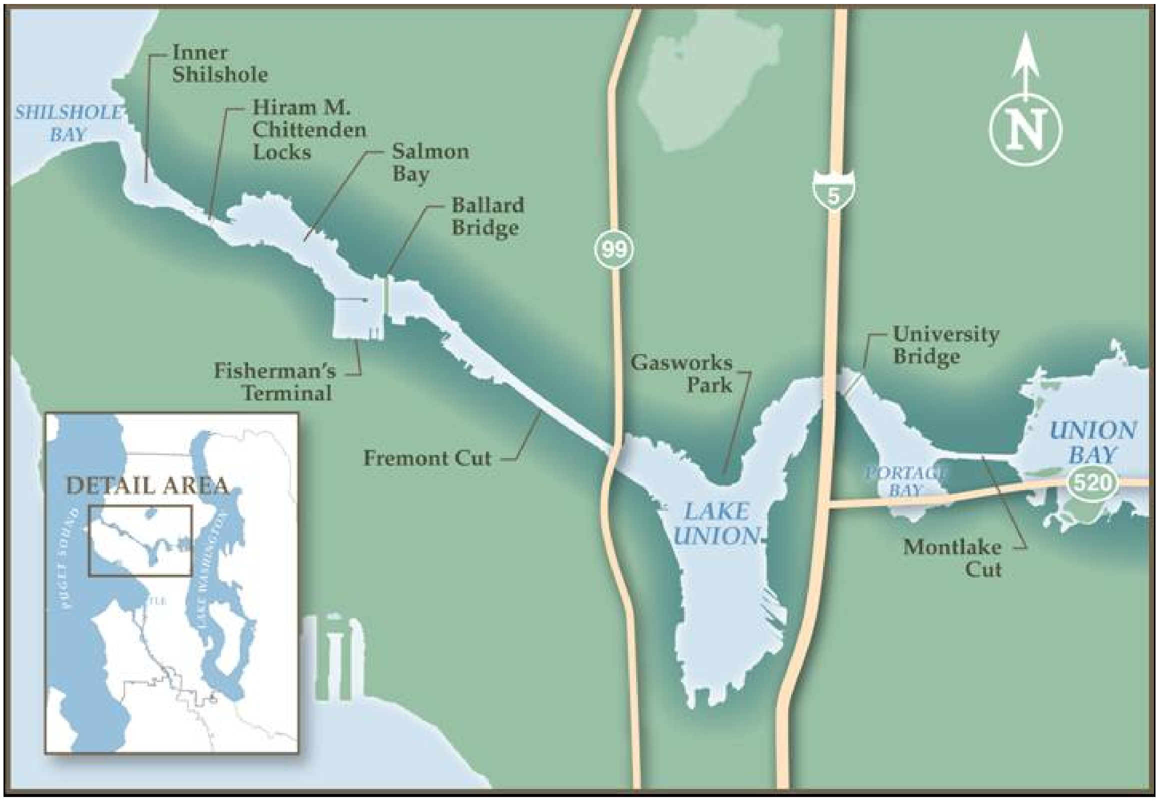


Figure 3
The Ship Canal system, as defined for this report. Ship Canal refers collectively to the Montlake Cut, Portage Bay, Lake Union, the Fremont Cut, and Salmon Bay

Lake Washington undergoes complete mixing from December through March. From June through October the lake is stratified. Monthly water temperature data for Lake Washington west of Mercer Island show maximum water temperatures from 2000 to 2007 peak between 70.7 to 75.2°F (21.5-24°C). Minimum water temperatures range from 42.8 to 46.4°F (6 - 8°C) for the same period (King County 2008).

The Cedar River provides about 50% (663 cubic feet/second [cfs]) of the mean annual flow into Lake Washington. Cedar River flows are affected by the City of Seattle's water storage and diversion activities, which supply water to Seattle and surrounding areas. The City's water operations also provide some flood control during fall and winter peak flows. The Sammamish River contributes about 25% (307 cfs) of the annual mean flow into Lake Washington (Corps 1999).

Lake Washington drains through the Ship Canal to Puget Sound. For this report, *Ship Canal* refers collectively to the Montlake Cut, Portage Bay, Lake Union, the Fremont Cut, and Salmon Bay. The Ship Canal is 8.6 miles long and averages 30 feet deep in the navigational channel. The canal is a narrow, armored channel in the cuts (about 100 ft wide) but widens through Portage

Bay, Lake Union, and Salmon Bay. Lake Union covers just less than 1 square mile and has an average depth of 33 feet.

The Locks regulate water levels in Lake Washington and the Ship Canal between 20 and 22 feet above mean lower low water (MLLW). The Locks can store up to 46,424 acre-feet of water in Lake Washington and the Ship Canal.

2.2 Historical Context

Historically, a ridge separated Union Bay from Lake Union and a small stream drained Lake Union into a tidally-influenced Salmon Bay (Figure 4). The Lake Washington watershed drained south into the Duwamish River.

Figure 4
Lake Union and Salmon Bay circa 1890. A ridge separated Lake Union and Union Bay and a small stream drained Lake Union into tidally-influenced Salmon Bay

However, in 1916, the Ship Canal and Locks became the outlet for Lake Washington when the Corps excavated a navigation channel and constructed the Locks (Figure 5). The hydrologic changes lowered the lake level 9 feet and disconnected Lake Washington from its historical outlet, the Black River. The connection between the Lake Washington system and its historical Duwamish estuary was eliminated. The outlet at Salmon Bay, downstream of the Locks, became the new estuary for the Lake Washington system.

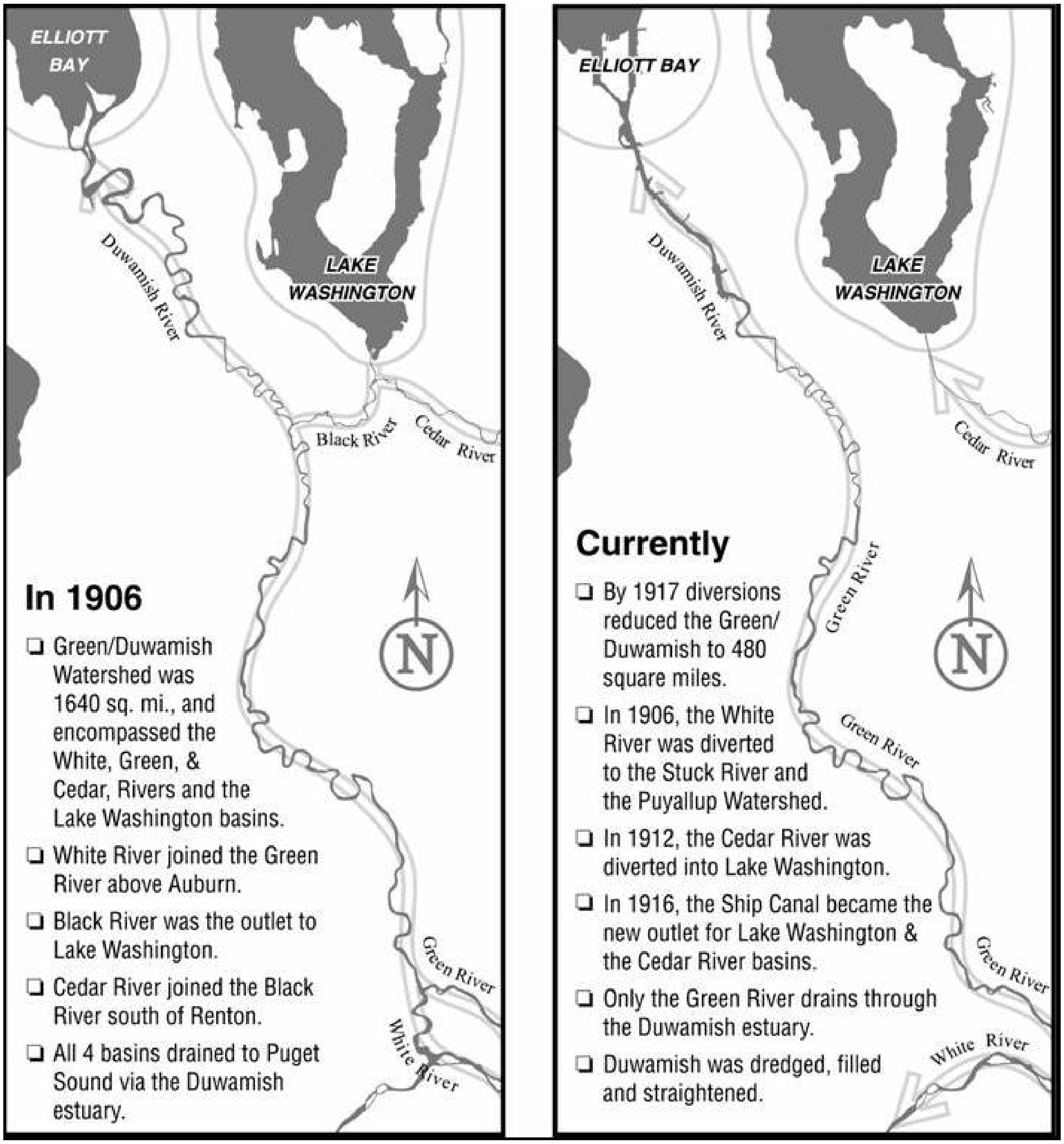


Figure 5
Lake Washington and Duwamish drainage basins before 1900 and after 1916
Source: City of Seattle 2003

2.3 Lake Washington Modifications

The modifications in the Lake Washington drainage system resulted in significant changes to salmon populations. Anadromous (migrating from saltwater to spawn in freshwater) salmon that historically migrated up the Duwamish River then into the Black and Cedar rivers must now spawn in the Green /Duwamish or find the new entrance to the Lake Washington system.

The riparian (bank) and littoral (shallow-water) zones of Lake Washington have changed considerably since pre-settlement times. Lowering Lake Washington exposed 1,334 acres of shallow water habitat, reducing the lake surface area by 7%, and decreasing the shoreline by 10.5 miles (Chrzastowski 1981). The area of freshwater marshes in the lake decreased from an estimated 1,136 acres to 74 acres. The mouths of tributaries entering the lake moved as deltas reformed around the new shoreline and eliminated shallow-sloped alluvial deltas (Warner and Fresh 1998). In contrast, new wetlands and riparian zones have developed along the shore in Union Bay, Portage Bay, Juanita Bay, and Mercer Slough since the Ship Canal was completed (Dillon et al. 2000). Hydrologic changes lowered water levels in Lake Sammamish, and the complex wetland system along the Sammamish River was also lost.

Shoreline vegetation in Lake Washington also changed dramatically. Vegetation was reported as a dense undergrowth of small trees, brush, and Tule grass, but is now primarily landscaped residential properties with bulkheads. Shallow-water habitats are dominated by Eurasian water-milfoil (*Myriophyllum spicatum*), a non-native invasive aquatic plant introduced into the lake in the 1970s. Milfoil replaces native aquatic vegetation and alters substrate in the shallow-water zone (Patmont et al. 1981).

Changes to the Lake Washington basin substantially altered lake water levels. Historically, lake elevations peaked in winter and declined in summer. In 1903, the average lake elevation was about 32 feet. Today, lake elevation peaks at 22 feet in May and reaches its lowest level, 20 feet, in December. Water is regulated at the Locks to keep seasonal fluctuations to within 2 feet annually (Corps 2001). The Corps regulates the lake level based on lake level forecasts and measurement and projected demand for smolt passage flumes, saltwater drain, and lock operations.

Since 1916, Lake Washington has lost much of its natural shoreline habitat. This alteration resulted both from hydrologic modifications within the Lake Washington system and loss of riparian vegetation to installation of bank armoring, and construction of overwater structures associated with the urbanized watershed today. In fact, about 62% of the lake shoreline in Seattle is armored with more than 750 overwater structures (Toft 2001). Less than 25% of the shoreline contains natural vegetation.

2.4 The Ship Canal and Lake Union Modifications

Because it was created as a navigation project to connect Lake Washington with Puget Sound, the Ship Canal is an engineered system. The Montlake and Fremont cuts and the Locks established a slow-moving, freshwater system in an area that was formerly a shallow lake and small stream draining to Puget Sound. The area became a shipping, navigation, and industrial center, with accompanying shoreline development. Today, the banks along the Ship Canal are about 96% armored with numerous overwater structures such as docks and piers (Weitkamp et al. 2000). Invasive species affect the area as well. For example, the Eurasian water-milfoil in Lake Union contributes a large amount of organic material to the lake, which can decrease dissolved oxygen (DO) levels.

The section of the canal closest to the Locks is Salmon Bay. Historically, Salmon Bay was tidally influenced, with water levels varying nearly 20 feet during extreme high and low tides (Corps 2001). At low tides, it was practically dry. The Locks raised and stabilized the water level and converted this section of the canal from an estuary into a freshwater environment.

Within the Ship Canal, there are limited segments of open shoreline east of the Fremont Cut. Undeveloped shorelines include Gas Works Park, a protected cove west of the U.S. Navy pier at the south end of Lake Union, the area south of SR-520 in Union Bay and Portage Bay, and the north side of Union Bay. Vegetation within these areas is limited, with the area south of SR-520 having the highest abundance of natural vegetation, primarily small trees and cattails (*Typha* spp).

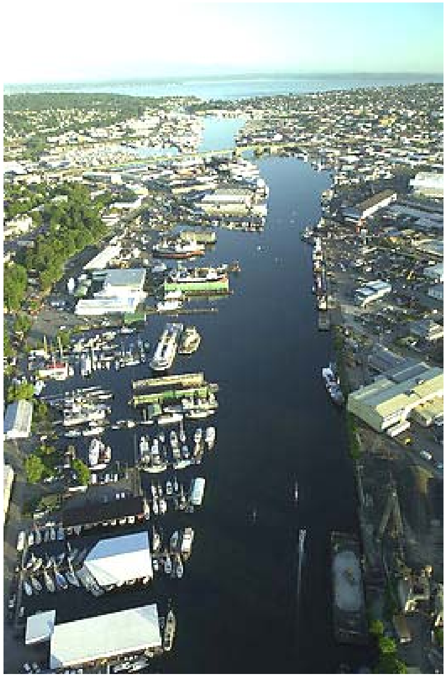


Photo: Aerial view of Ship Canal near Ballard, showing extensive overwater structures and bulkheads. Courtesy: SPU

Photo: Natural marsh area south of SR-520 in the Ship Canal. Courtesy: SPU

2.5 The Locks and Vicinity

The Locks are located at the west end of the Ship Canal and provide passage for vessels between Lake Washington and Puget Sound. A navigation channel continues downstream of the Locks into inner Shilshole Bay. The Locks physically separate the saltwater of Puget Sound and the freshwater of the Ship Canal. Tide levels measured downstream of the Locks in Shilshole Bay fluctuate about 12 feet over each tidal cycle.

The waterway between the Locks and Shilshole Bay is an estuarine area with an abrupt transition between fresh and marine waters for migrating salmon. Historically, this area had shallow water and wetland habitat. Tidal influence extended to the Fremont Cut. The lack of riverine and tidal influences leaves the Ship Canal void of the diversity of habitats and brackish water refugia of unaltered estuaries.

Today, numerous bulkheads and ship-holding areas line this section of the canal and the intertidal habitat has been substantially reduced and degraded. Similar to upstream areas, shorelines are developed for residential and commercial uses and minimal natural vegetation remains.

Estuarine habitats are important during migration of juvenile and adult fish. Estuarine turbidity, which is associated with the mixing process and depositional environment, can provide cover from predators while smolts make the physiological transition to saltwater (Quinn 2005). Characteristics such as vegetated, shallow water areas, woody debris, and deeper aquatic vegetation can also be important to smolts in an estuary. Adult salmon use estuaries to physiologically adjust to fresh water or as holding areas. Adults may hold in estuaries until river flows are appropriate for upstream migration and/or until the fish reach proper maturation for spawning. Fresh- and saltwater gradients with appropriate temperatures and DO levels are important aspects of estuaries for returning adult salmon. The location of the gradients typically varies in response to tides and changes in freshwater input rates. In natural systems, each species and population of salmon uses estuaries in a different manner.

Photo: Aerial view of the Locks

The saltwater area below the Locks lacks most functions of a natural estuary, with a limited freshwater lens occurring during the late spring. In the historic Duwamish Estuary, rerouting the Lake Washington outlet removed over 5,000 acres of intertidal wetlands from the migration route of salmon populations, including Cedar River Chinook. Limited intertidal and shallow, nearshore habitat remains in Salmon and Shilshole bays. Most of the shoreline has been modified by construction of bulkheads and riprap or is bordered by the natural steep bluffs of Magnolia Hill. Up to 87% of the eastern shore of nearshore Puget Sound from Shilshole Bay to the King County boundary is bulkhead or riprap. Below the Locks, smolts pass quickly into the marine waters of Puget Sound, allowing little time for an adaptation to saltwater.

Photo: Typical section of shoreline in Shilshole Bay. Courtesy: Jason Toft UW

The Locks significantly impact the estuarine transition between fresh and saltwater by truncating the brackish mixing zone, which is much larger in typical estuaries. The Locks structure and surrounding development have also reduced estuary habitat for salmon exiting to Puget Sound or returning to Lake Washington.

The estuarine habitat below the Locks is defined primarily by the spatial extent of the freshwater lens and mixing area. Water quality data collected by the Corps and King County indicate the freshwater lens and mixing area with salinities below 20 parts per thousand (ppt) generally extends into the upper 3.3 to 9.8 feet of the water column, downstream to the vicinity of the railroad bridge and beyond depending on tides and outflow.

The estuarine zone extends upstream through the large lock into Salmon Bay. As cool, saline water mixes with freshwater in the Ship Canal a salinity gradient forms. That gradient creates a saltwater wedge upstream of the Locks. Cooler water in the area of saltwater immediately upstream of the Locks may provide more favorable habitat for adult and smolt salt- and freshwater transitions when nearsurface water temperatures increase in spring and summer. As the wedge moves upstream, salinity concentrations decrease and are controlled to 1 ppt at the University Bridge, as required by the Washington State Department of Ecology (Ecology). The extent of this wedge varies spatially and temporally, depending on the tide and amount and timing of flow through the Locks.

2.5.1 Physical Features of the Locks

The Locks consist of the following major physical features (Figures 6 and 7):

- Large lock
- Small lock
- Saltwater drain
- Spillway and smolt flumes
- Fish ladder

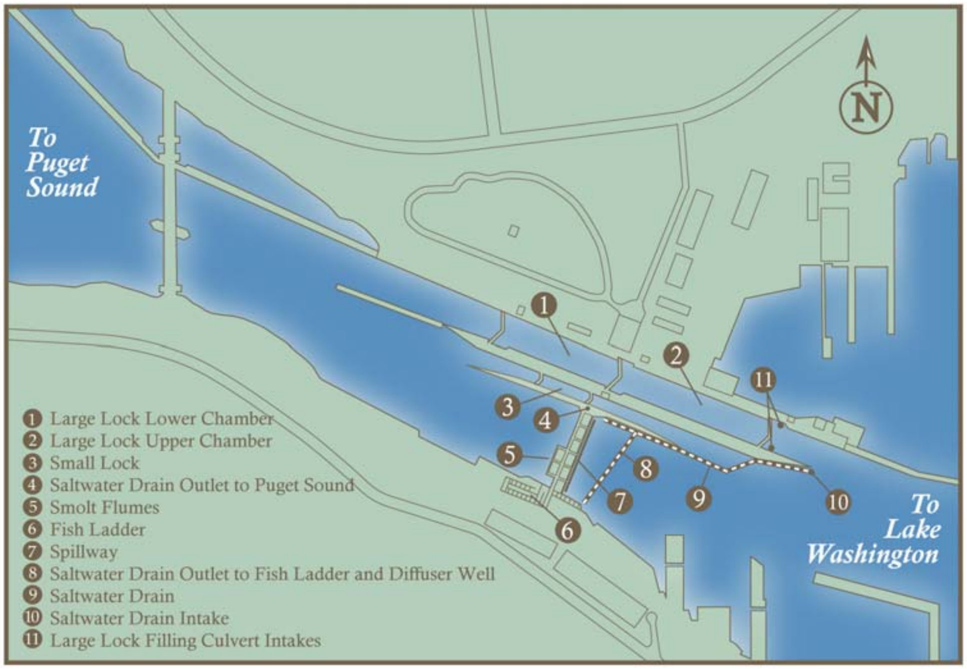


Figure 6
Major physical features of the Locks

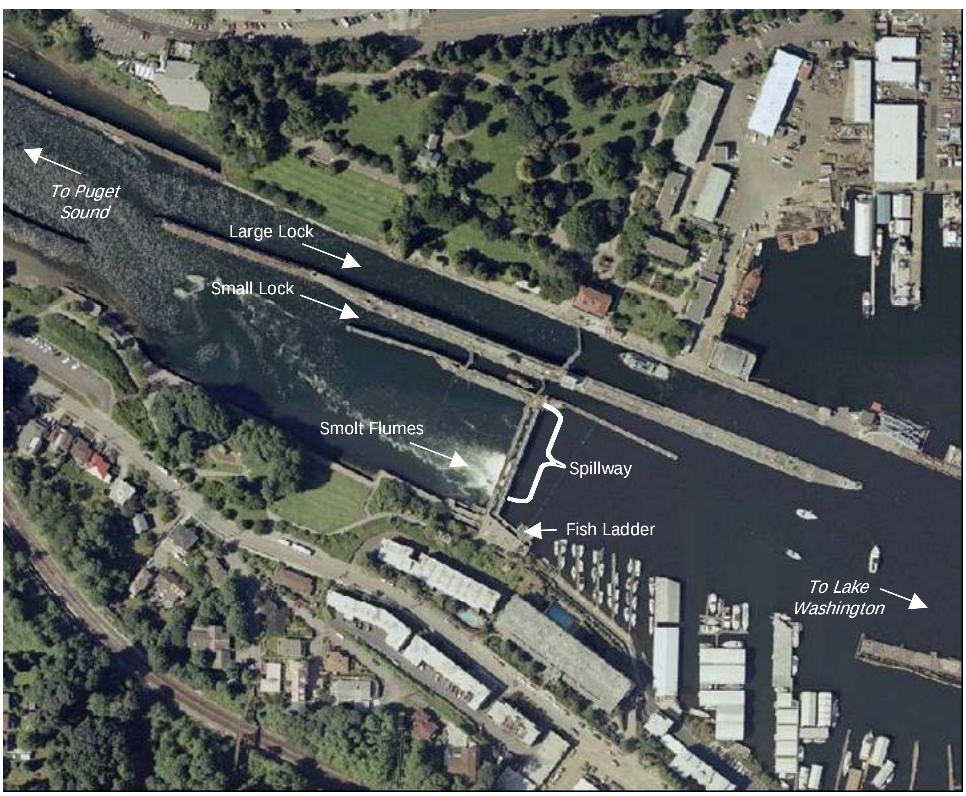


Figure 7
Major physical features of the Locks**.** Large lock chamber upper and lower gates are open and middle gate is closed. Small lock chamber is closed. Smolt flumes are operating

2.5.1.1 Large Lock

The large lock measures 80 feet wide, 825 feet long, and about 50 feet deep. It accommodates large vessels with drafts as deep as 30 feet. A miter gate in the middle of the large lock divides the lock into an upper and lower chamber. This allows lock operators to use only half of the lock at a time if the entire large lock space is not needed. Miter gates are also located at the upstream and downstream ends of the large lock.

Photo: Large lock chamber looking downstream toward the middle miter gate during annual dewatering. Filling ports line the base of the walls

The large lock chamber is filled through two filling culverts that are contained in the walls of the lock chamber (Figure 8). The filling culverts are 14 feet tall and vary between 9 and 16 feet wide. The filling culverts are located underwater and begin just upstream of the upper miter gate. The culverts connect to the chamber through 22 filling ports that are about 4 feet wide by 2 feet tall.

Boats navigate the Ship Canal through *lockages*. When boats pass downstream from the Ship Canal into inner Shilshole Bay, the passage is called a *down lockage*. When boats pass upstream from inner Shilshole Bay to the Ship Canal, it's called an *up lockage*. During a down lockage, boats enter the large lock with the water surface higher than that downstream.

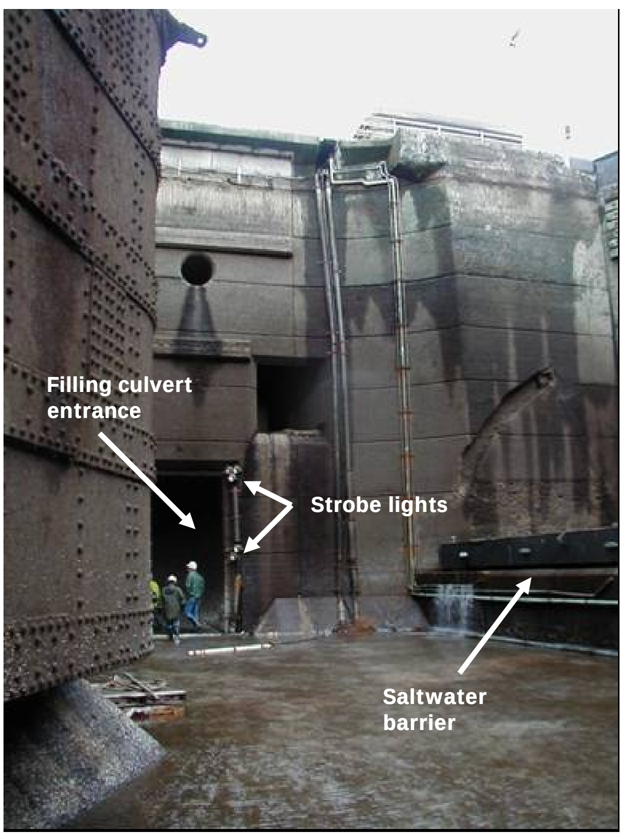


Figure 8
Large lock chamber looking downstream toward the middle miter gate during annual dewatering. The filling culvert entrance is shown in the middle with strobe light. The saltwater barrier is shown far right in down position

The filling culverts are used to drain the water in the large lock until the water surface elevations are equal in the lock and downstream. The lower Stoney gate valves are opened to allow water to discharge downstream. During an up lockage, boats enter the large lock with the water surface lower than that upstream. Water must be added into the lock chamber to elevate the boats. The Stoney gate valves are opened to draw freshwater into the filling culverts. Water is discharged into the lock chamber through the filling ports.

2.5.1.2 Small Lock

The small lock is identical to the large lock, except in size. The lock chamber is 30 feet wide and 150 feet long. It can accommodate vessels with 16-foot-deep drafts. The small lock is not divided into two chambers. It is filled and drained through filling culverts smaller than those for the large lock.

Photo: The small lock chamber at the Locks

2.5.1.3 Saltwater Drain

Saltwater intrudes upstream from Puget Sound into the Ship Canal when the Locks are opened during up lockages. To manage saltwater intrusion in the Ship Canal, the Locks were built with a saltwater drain system to convey the saltwater back downstream below the Locks (Figure 9). The intake for the saltwater drain is a 48-by-4-foot opening at the bottom of the Ship Canal. It is located at the east end of the large lock south wall at a depth between 47 and 51 feet. From the intake, the water flows through a 5-by-6-foot concrete pipe to either of two routes to convey the saltwater back to the Sound. The first route carries saltwater into the fish ladder. This distance is about 900 feet. This water is pumped from a diffuser well through the fish ladder to attract fish to the ladder. The second route through the saltwater drain is a direct outlet to Puget Sound, a distance of about 700 feet.

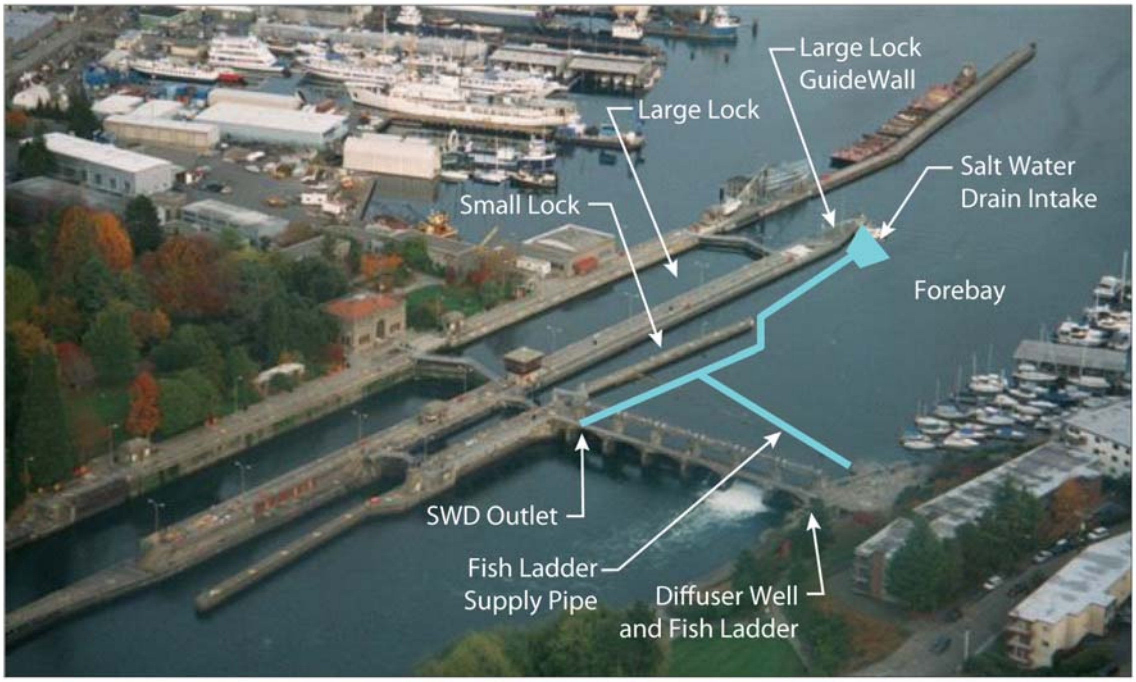


Figure 9
Saltwater drain, showing outlet to Puget Sound and pipe to fish ladder

When water is conveyed to the fish ladder and the outlet to Puget Sound, flow in the saltwater drain can average 300 cfs depending on lake and tidal elevations. Operation of the saltwater drain outlet varies to control saltwater intrusion. Flow to the fish ladder is continuous, with a daily average discharge of about 160 cfs.

In the past, the saltwater drain intake was screened to limit fish movement through this route. The saltwater drain gate was automated so that when it was necessary to control salinity, it would open only at tides less than +6.5 feet. This is intended to prevent fish from jumping upstream through the outlet and getting trapped in the diffuser well. The intake screens were removed after it was discovered they trapped debris and impinged fish on the screen face. Years later, adult fish were discovered trapped and dead in the fish ladder diffuser well. To prevent this, a newly-designed, large screen was placed in front of the intake to prevent adult fish from entering the intake and potentially ending up trapped in the diffuser well in the center of the fish ladder.[1]

2.5.1.4 Spillway and Smolt Flumes

The Locks contain a dam across the southern half of the waterway (see Figure 6). This dam creates a 235-long spillway with six 32-foot-wide bays. Each bay contains a gate that can be opened to spill water. Each bay is capable of passing about 3,000 cfs at maximum discharge.

[1]This screen, installed in 2008, is intended to be a temporary solution. The Corps is developing a more permanent and comprehensive solution to the diffuser well entrapment problem.

Two spillway bays contain smolt passage flumes. These flumes are specially designed slides that increase the safety of juvenile fish passage through the Locks. The flumes are also outfitted with Passive Integrated Transponder (PIT) readers that count tagged fish passing the flumes. Two smolt flumes are located in each bay. The flumes vary in entrance width size from 2 to 6 feet, with smaller flumes spilling less water than larger flumes. When fully opened, all four flumes can discharge about 400 cfs of water.

Photo: Smolt flumes operating below the spillway at the Locks. Inset lower left: White cylinders at ends of flumes are PIT tag readers

The flumes allow water to be used more efficiently at the Locks by regulating spillway discharge at much lower flows than can be attained with the spillway gates alone. The smolt flumes have operated at the Locks since 2000. Before the current flumes were installed, an experimental flume was tested between 1995 and 1998.

2.5.1.5 Fish Ladder

The present fish ladder, located on the south side of the spillway, was completed in 1976 to help returning adult salmon pass upstream. The current ladder is 8 feet wide, with three adjustable weirs at the upstream end, 18 fixed weirs, and two slots at the downstream entrance (Figure 10). Each weir can be thought of as a step in the ladder. To facilitate fish passage, the adjustable weirs are set based on the water depth in the Ship Canal. The slots at the downstream end can also be adjusted to facilitate fish passage at different tidal heights. Six bottom diffusers move water from the saltwater drain into the steps of fish ladder.

Photo: Fish ladder at the Locks

The ladder is designed to operate with about 23 cfs freshwater flow from the Locks forebay and a maximum of 160 cfs flow from the saltwater drain (183 cfs total flow). During low-flow conditions from July through September, the fish ladder uses 50 to 60% (330-350 cfs) of the total water amount passing through the Locks.

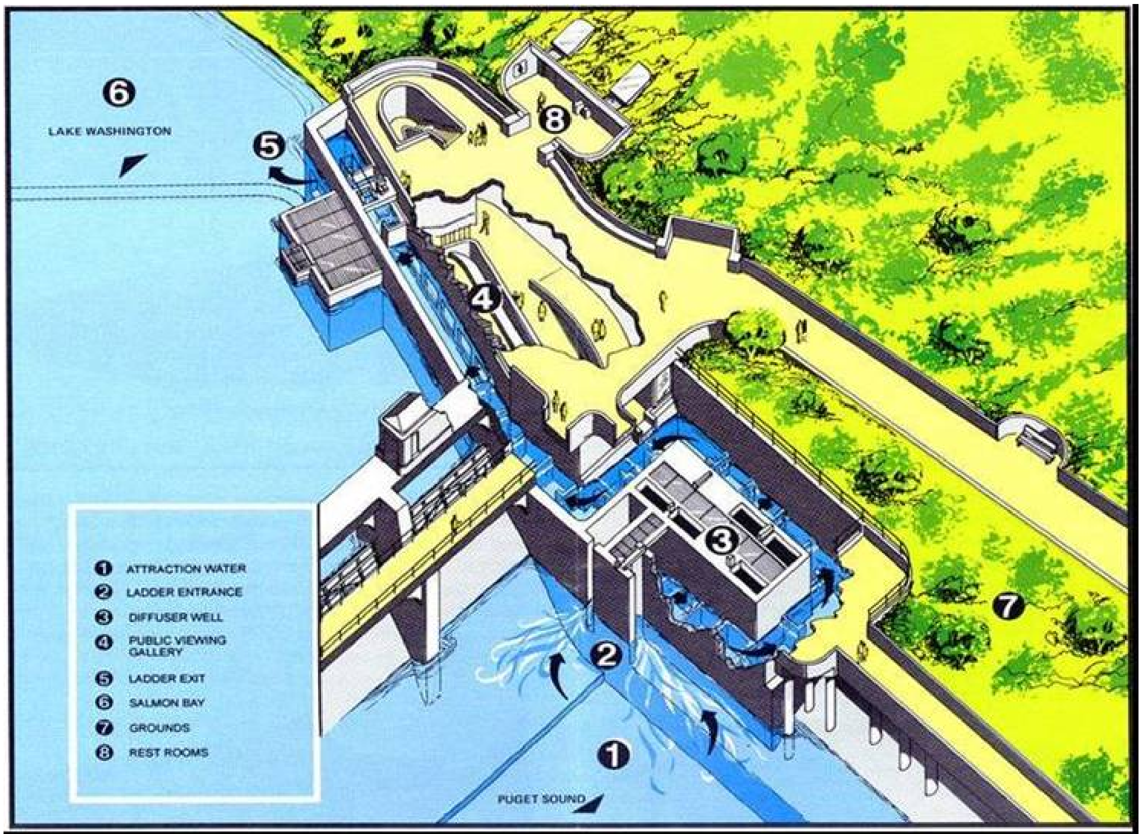


Figure 10
Fixed weirs (steps) within the fish ladder at the Locks

2.5.2 Passage Routes

The Locks contain five major structures that provide passage routes for migrating salmon. These are the large lock, small lock, spillway and smolt flumes, saltwater drain, and fish ladder.

2.5.2.1 Juvenile Passage Routes

Juvenile salmon pass through all five features of the Locks (Figure 11). However, the smolt flumes and Locks are the most used (Johnson et al. 2003b, Johnson et al. 2004a, DeVries and Hendrix 2005a). Juvenile fish may pass through the Locks one or more times. Juveniles may move upstream again after passing through the Locks and may leave the system through a different feature.

For example, a fish initially leaving through the smolt flumes may move back upstream through the small lock and then return downstream through the large lock. Juvenile fish may also be swept into the Locks filling culverts when they are in use. Fish may be damaged or killed while passing through the filling culverts, so the Corps has installed strobe lights to scare fish away from the culvert entrances before fill events start. The Corps also uses slower fill rates to reduce harm to fish swept into the culverts.

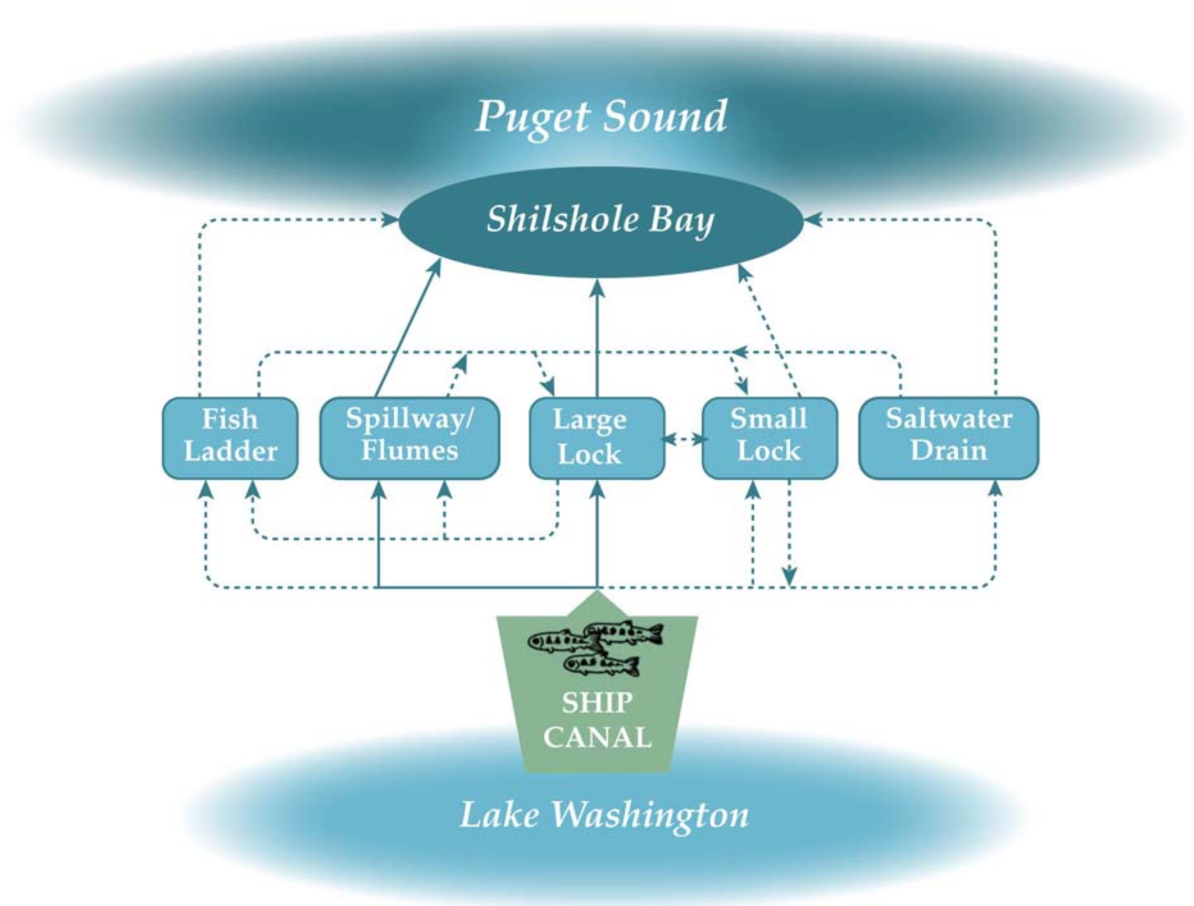


Figure 11
Migration routes of juvenile salmon through the Locks to the Puget Sound. Solid lines represent passage routes most likely used. Dashed lines represent routes of lesser importance

2.5.2.2 Adult Passage Routes

Adult salmon pass through four features of the Locks (Figure 12). However, the large lock and fish ladder are the most used. Adult fish may pass the Locks once, or may recycle through the Locks. Fish that recycle may use multiple pathways.

For example, an adult fish initially entering through the fish ladder may exit through the large lock and move back upstream through the fish ladder again. Alternatively, adult salmon may exit the Locks only once. In the past, adult fish could travel downstream in the saltwater drain and become entrapped in the diffuser well underneath the fish ladder. Today, a large grate keeps adult salmon out of the saltwater drain to prevent this from happening.

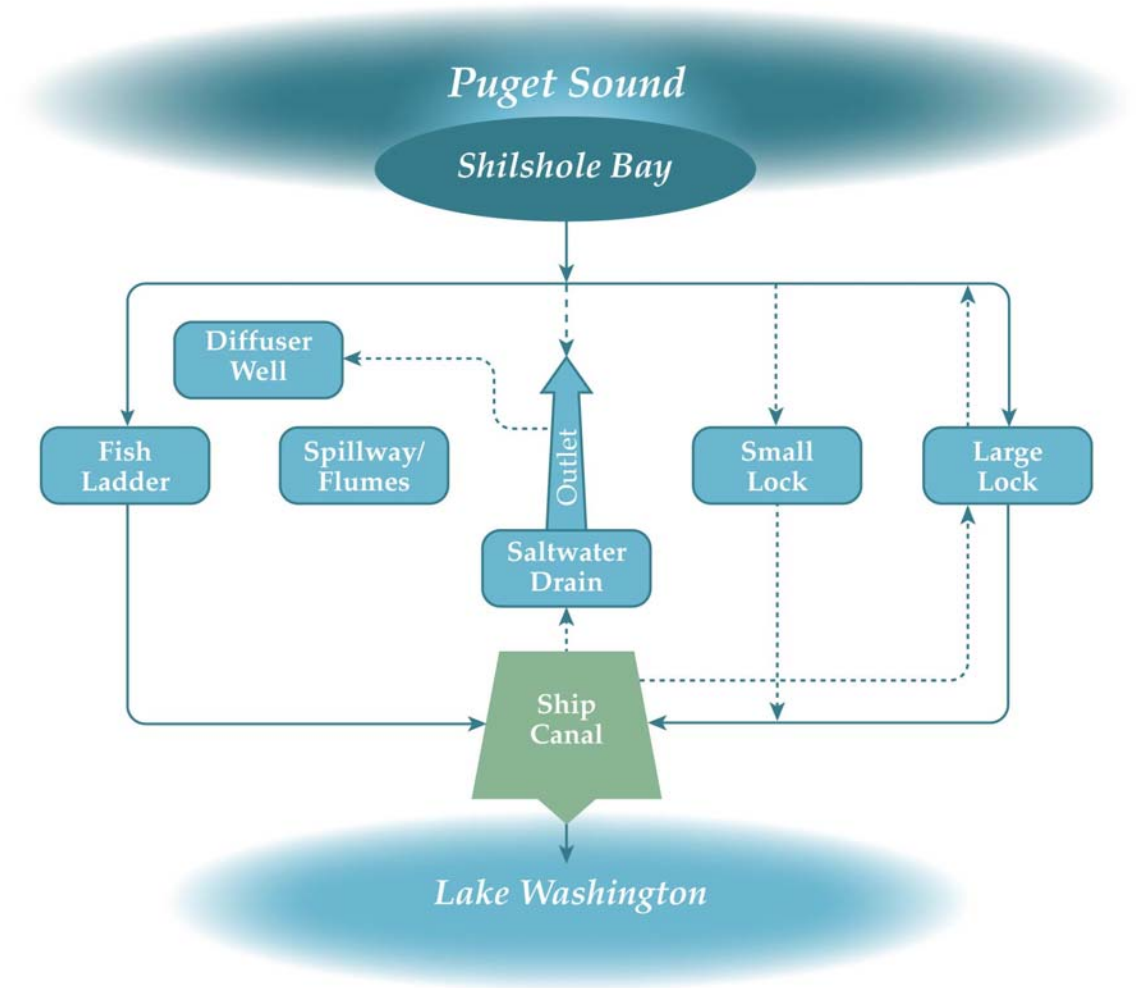


Figure 12
Migration routes of adult salmon through the Locks to Puget Sound. Solid lines are the most likely routes. Dashed lines are less important

2.5.3 Water Management

Water use at the Locks affects water levels in Lake Washington and the Ship Canal. Maintaining water elevations is important because when elevations fall below a set minimum target elevation, there is high potential for damage to the I-90 and SR-520 floating bridges and other facilities, such as supply and waste lines to overwater structures. Maintaining Lake Washington's elevation depends on three factors:

1. The inflow from the Cedar and Sammamish rivers and numerous tributaries to lakes Washington and Sammamish
2. Precipitation and evaporation in Lake Washington and the Ship Canal
3. Water use at the Locks

The Locks are managed to limit saltwater intrusion into the Ship Canal and provide flow for migrating salmon. Navigational responsibilities are also a concern for water management at the Locks.

The low-flow season—July through September—is a critical time for balancing competing water needs. This time period overlaps with juvenile and adult salmon passage at the Locks and the primary recreational boating season. Competing interests at the Locks and the water supply concerns upstream make water conservation at the Locks one of two primary project purposes of the LWGI.

The Corps balances use of water between different parts of the Locks facilities during the low-flow season (Table 1). The Locks, the fish ladder, and the smolt flumes use the most water during low-flow season. Both locks together pass a daily average of 80 to 100 cfs during the summer boating season. This is approximately 25% of the total water passed at the Locks during that time. The discharge of water to the fish ladder and diffuser well through the saltwater drain is 160 cfs per day, or 35 to 50% of the total water passed. The smolt flumes can use up to 25% of the water passed at the Locks during low-flow season. However, smolt passage has diminished by mid-July, so the smolt flumes are generally turned off by that time and no longer pass water. Spill through spillways is not predicted and can vary greatly. The spillways are operated more in years when there is more water within the Lake Washington system and less in drier years. It is a method for maintaining water levels in the system, especially during wet years. Leakage is a minor proportion of the total water passed at the Locks.

Table 1
Daily water use at the Locks May through September in cubic feet per second (cfs)

Facility	Water Use (in cfs / % water budget)	
	May to June	**July to Sept**
Large and Small Locks	100 / 13%-19%	80-100 / 18%-30%
Saltwater Drain discharge to Puget Sound	140 / 18%-27%	70 / 16%-21%
Saltwater Drain discharge to fish ladder diffuser well	160 / 21%-31%	160 / 21%-31%
Spillway	0 / 0%	0 / 0%
Smolt Flumes	100-350 / 13%-67%	0-100 / 0%-30%
Freshwater Flow to the Fish Ladder	23 / 3%-4%	23 / 5%-7%
Total water flow	520 to 770 cfs	330 to 450 cfs

2.5.4 Water Quality Conditions around the Locks

The Locks affect salinity, DO, and temperature levels in the waters upstream and downstream of the facility. Although water is exchanged above and below the Locks, they physically separate Lake Washington and Puget Sound and limit mixing that would occur in a natural estuary. At the Locks, freshwater and saltwater are predominantly exchanged in pulses from lockages. This results in unusual circulation patterns and a very small estuarine zone.

On the upstream side of the Locks, each up lockage in the large and small lock introduces cool, saline, dense water into the freshwater canal. The large lock allows about 25 times more saltwater to enter the Ship Canal during each lockage than does the small lock. Because saltwater is denser than freshwater, saltwater intrusion above the Locks creates brackish water conditions at depth. On the surface, freshwater from the Ship Canal is commonly characterized by high water temperatures and low DO levels in summer. The interface of cool, dense saltwater and warm, less dense freshwater creates a saltwater wedge that extends upstream of the Locks.

In mid-summer, the saltwater wedge just upstream from the Locks is the only stratified, or layered, part of the Ship Canal. Here, at depths of about 23 feet or deeper are the lowest temperatures and highest DO concentrations within the Ship Canal (VanRijn 2001). This area has been termed a *cool water refuge* because it provides better conditions for salmon than anywhere else in the Ship Canal (Figure 13). The cool water refuge is increasingly considered a critical habitat feature for returning adult salmon, which need cooler temperatures and higher DO levels than typical in the Ship Canal in summer. Salmon migrating between salt to freshwater also need areas of varying salinity to adapt to the freshwater environment. During summer, frequent lockages are needed to maintain the cool water refuge.

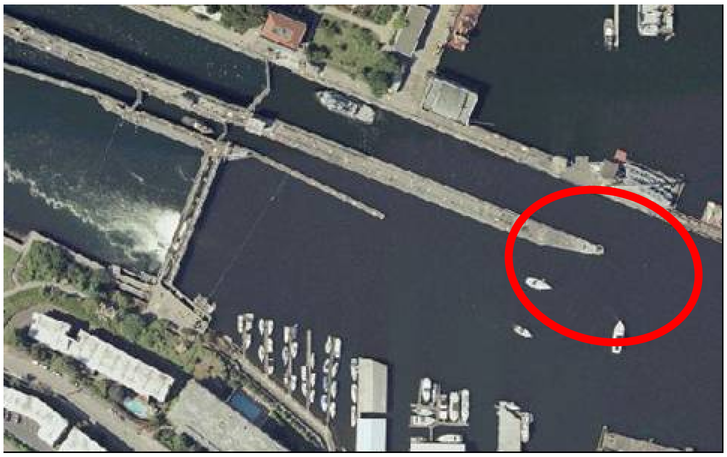


Figure 13
Cool water refuge area formed near intake to the saltwater drain at the Locks

Maintenance of the cool water refuge must be balanced with Ecology water quality standards for salinity in the Ship Canal. To protect the freshwater environment, the Corps must ensure that salinity in the Ship Canal does not exceed 1 ppt at the University Bridge (see Figure 3). Saltwater is considered to be at full salinity at 30 to 40 ppt, reduced salinity at 18 to 30 ppt, and low salinity at less than 18 ppt. Freshwater is < 0.5 ppt. Water is considered brackish between 0.5 to 30 ppt.

Saltwater intrusion into the Ship Canal is primarily an issue during the low-flow season. Given the heavy boat traffic at the Locks in the summer, decrease in river flows to the Lake Washington basin, and decrease in flume flows, saltwater can intrude into Lake Union and up to the Montlake Cut (Corps 1999). The saltwater barrier, saltwater drain, and smolt flume flows are the major methods of limiting saltwater intrusion during the summer. The saltwater barrier can be raised to limit saltwater from migrating up through the large lock chamber. The saltwater drain can drain saltwater from the bottom of the Ship Canal when it is open (see Figure 9). When open, the smolt flumes increase flow in the Ship Canal. This pushes saltwater downstream towards the Locks, where it can be removed via the saltwater drain. In the winter, freshwater flows are generally higher, and, with the saltwater drain open, salinity in the Ship Canal is kept to a minimum.

Flow through the Locks also increases the size of the freshwater lens downstream of the Locks. Freshwater is passed to Shilshole Bay via the spillways, smolt flumes, fish ladder, or in pulses during lockages. This freshwater—which is less dense than saltwater—floats on top of the water column forming a *freshwater lens*. The lens typically extends to a 7-foot depth. The freshwater lens is limited to areas immediately west of the Locks and does not often extend beyond the railroad bridge located in the inner bay (Simenstad et al. 1999). The size and depth of the freshwater lens is influenced by freshwater flowing over the Locks, location of freshwater flow (e.g. locks, spillways), season, and tidal elevation. Salinity immediately below the Locks ranges between 10 and 29 ppt. During summer, lake water levels and available inflow limit both the amount of freshwater flowing over the spillway and the size and depth of the freshwater lens.

2.5.5 Adaptive Management at the Locks

Since the mid-1990s, the Corps has been using fish passage and water-use studies to adaptively manage Locks operations. The intent of adaptive management in this case has been 1) to increase successful passage of salmon smolts and 2) to conserve water use at the Locks. A number of these studies and resulting Lock operational changes are discussed in Chapter 3, Summary of Research Findings.

The Corps has used adaptive management to make the following changes at the Locks:

- Installing smolt flumes in the spillway to improve smolt passage conditions and survival
- Installing strobe lights at the entrance to the large lock filling culverts to reduce entrainment of smolts and subsequent injury and death
- Filling the lock chambers more slowly to reduce smolt entrainment in the filling culverts
- Conducting yearly scraping of the lock filling culverts to remove barnacles that can cause smolt injury and descaling of entrained smolts
- Increasing lockages in warmer months to replenish oxygen levels in the cool water refuge upstream of the Locks for adult salmon
- Increased Lake Washington and Ship Canal fill rate to provide as much water as possible to run up to all smolt flumes and meet water elevation goals by May 31
- Operating the smolt flumes in lieu of the old saltwater drain as long as this flow controls saltwater intrusion into the Ship Canal
- Installation of a large screen over the saltwater drain inlet to prevent adult fish from entering the saltwater drain system
- Operating the saltwater drain outlet to Puget Sound only when tides are less than +6.5 feet to prevent adult fish from jumping up into the saltwater drain system

For juveniles, these changes have improved fish passage. For example, most smolts pass the spillway flumes when at least two flumes are operating (Johnson et al. 2003b, Johnson et al. 2004b, DeVries and Hendrix 2005a)[2]. Based on tests in 2002, strobe lights were shown to reduce the number of juvenile fish trapped in the large lock filling culvert by 75% (Johnson et al. 2005). Slower lock fill rates are decreasing entrainment rates. Barnacle removal is reducing smolt injury by an estimated 75% (WDFW unpub data).

For adults, evaluation of management changes is either preliminary or not directly measurable. The installation of the temporary saltwater drain intake screen in 2008 and ongoing operation of the drain outlet only at high tides have reduced and may have eliminated entrapment of adults in the fish ladder diffuser well. However, the changes are too recent to provide a measure of effectiveness. Other changes have resulted in improved water quality conditions, but the response of adult salmon has not been measured or is uncertain. The increased use of the large lock chamber improves water quality in the cool water refuge where adult Chinook hold for extended periods. Passing water through smolt flumes in July and August creates a larger freshwater lens near the fish ladder.

[2] This varies depending on month and water temperature.

2.6 Lake Washington Basin Salmon

The Lake Washington watershed is home to Chinook, coho, and sockeye salmon, and steelhead, rainbow, cutthroat, and bull trout. Salmon and some trout and char are anadromous fish, which migrate to saltwater to mature and complete their lifecycle by returning to their natal freshwater stream to spawn. After spawning, salmon die. Anadromous trout may pass between the freshwater and marine environments and spawn more than once.

While Lake Washington contains the largest sockeye run in the lower 48 states, the number of Chinook salmon and steelhead trout in the lake has generally declined in the past 20 years (Burgner 1991, Weitkamp et al. 1995, Myers et al. 1998). Sockeye salmon in the lake have been depressed over the last few years, while Chinook numbers have indicated stronger returns. The National Marine Fisheries Service (NMFS) listed Puget Sound Chinook salmon as *Threatened* in March 1999 under the ESA (64 FR-14308). In November of 1999, the U.S. Fish and Wildlife Service (USFWS) listed Puget Sound bull trout as *Threatened* (64 FR 58910). Puget Sound coho salmon are considered a species of concern, with a potential for future listing, and Puget Sound steelhead were listed *Threatened* ESA in May of 2007 (50 CFR Part 223). The LWGI focuses on protection and restoration of four species of salmonids in the Lake Washington basin:

1. Chinook salmon, *Oncorhynchus tshawytscha*
2. coho salmon, *O. kisutch*
3. sockeye salmon, *O. nerka*
4. steelhead trout, *O. mykiss*

2.6.1 Stocks

Lake Washington contains several stocks of salmon and trout (Table 2). *Stocks* are groups of same species fish that differ from other groups in how and when they use habitat. Chinook salmon are broken into two stocks: 1) Cedar River, 2) Sammamish River (Warheit and Bettles 2005). There are two identified coho stocks in the watershed: 1) Cedar River and 2) the Lake Washington and Sammamish tributaries (WDFW 2002). Sockeye in the basin are separated into three stocks: 1) Cedar River, 2) the Lake Washington and Sammamish tributaries, and 3) Lake Washington beach spawning. There is one Lake Washington steelhead stock.

Table 2
Salmon stocks in the Lake Washington basin identified in the Salmonid Stock Inventory (SaSI)

Species	SaSi	Hatchery Influence
Chinook	Cedar River	About 1/3 of returning adults to Cedar River are hatchery fish
	Sammamish River	Composite stock of hatchery and naturally produced fish
Coho	Cedar River	Appears to be minimal hatchery influence from observations at the Landsburg fish ladder. Hatchery releases into the river ended 1970. Some small, educational plantings still occur
Sockeye	Cedar River	Composite stock of hatchery and naturally produced fish. Stock may have originated partially from Baker Lake plantings
	Lake Washington and Sammamish tributaries	Mostly naturally produced fish. Stock may have originated partially from Baker Lake plantings
	Lake Washington Beach Spawning	Natural production originated from Baker Lake plantings
Steelhead		Natural production with past hatchery influence. Records show hatchery plants into Lake Washington basin from 1933 through 2001. Hatchery plants in Cedar ceased after 1993

Source: WDFW 2002

Wild salmon and trout populations in the Lake Washington watershed have long been influenced by hatchery fish stocked in the system. Chinook salmon were introduced from the Green River system (located one watershed to the south and historically connected). The Issaquah Hatchery, located on Issaquah Creek (Lake Sammamish tributary), produces large numbers of Chinook salmon (HSRG 2002). Some of these return to spawn in Lake Washington tributaries, including the Cedar River and Bear Creek. Coho salmon are also produced at the Issaquah Hatchery.

The University of Washington (UW) also operates a hatchery for Chinook and coho salmon in Portage Bay. There is also a sockeye salmon hatchery on the Cedar River (HSRG 2002). Sockeye were not present in Lake Washington in significant numbers before the opening of the Ship Canal and Locks. Their numbers increased substantially following a series of introductions that occurred between the 1930s and 1960s (Shaklee et al. 1996). Kokanee, the freshwater form of sockeye, were likely present in the lake Washington system before the opening of the Ship Canal and Locks. Research suggests kokanee still occur in small numbers in Lake Sammamish.

2.6.2 Life-History Characteristics

Anadromous salmon and trout follow a basic lifecycle that varies with species, environment, and fish size. Adults migrate into a river or creek to spawn. Females deposit eggs in an egg nest called a *redd* and male fish fertilize the eggs. After spawning, the adult salmon die, although some trout may migrate back out to sea and return to spawn again in later years. Eggs incubate in the river or stream for about 4 months before emerging as small fish, called *fry*. Fry may rear in the stream for months or years or head downstream soon after emergence to rear in non-river habitats (Quinn 2005, Volkardt 2006).

Basic lifecycle of anadromous fish

Fry grow into fingerlings in the freshwater environment. When they reach a certain size they undergo physiological changes, become smolts, and migrate to saltwater. Once in the ocean, the fish are considered sub-adults and continue to grow before maturing into adults and returning to the stream where they were born to spawn (Bjornn and Reiser 1991, Quinn 2005).

Lake Washington basin salmon species differ in the timing and areas that they use for spawning, rearing, and migration (Hendry and Quinn 1997, Fresh and Lucchetti 2000). Each species faces various challenges. For Lake Washington salmonids, Chinook salmon have been studied the most extensively.

Table 3 summarizes life-history characteristics of all salmon in the Lake Washington basin. Known life-history traits and concerns for each species are reflected as conceptual models presented in Chapter 4.

Table 3
Life-History characteristics of anadromous salmon in the Lake Washington basin

Characteristic	Species			
	Chinook	**Sockeye**	**Coho**[3]	**Steelhead**[3]
Escapement				
Mean (years)	819 (1994-2007)	133,234 (1994-2007)	871 (1998-2006)	199 (1980-2007)
Lowest	294 in 1997	25,950 in 1999[3]	246 in 2006	8 in 2006-2007 season
Escapement goal	1,500	350,000	15,000	1,600
Spawning				
Duration	Aug-Nov	Oct-Dec	Oct-Feb	Mar-Sept
Peak	Oct	Oct-Nov	Nov-Dec	May
Primary habitat	Mainstem	Mainstem	Tributaries Mainstem	Mainstem, Tributaries
Emergence				
Duration	Jan-June	Jan-Apr	Mar-April	Late May-early Aug
Peak	Feb-Mar	Mar-Apr	Mar	Jul
Freshwater Residence				
Habitat	Lake, littoral; lake limnetic	Lake, limnetic	Tributaries; rivers	Tributaries; rivers; lake, limnetic
Duration (yrs)	<1	0.5-2.3	1.5	2
Dominant type (yrs)	<1	1.3	1.5	2
Outmigration Timing				
Duration	May-Sep	April-June	April-July	Apr-June
Peak	June	May	May	May
Marine Residence (yrs)				
Range	2-5	1-3	0.5-1.5	2-3
Most common	4	2	1.5	2-3

Source: WDFW

[3] Coho and steelhead returns to the system have been lower in recent years than previous years

3. Summary of Research Findings

Many studies have focused on salmon within Lake Washington and along their migration from Lake Washington to Puget Sound. In this section, we summarize the results of recent (primarily late 1990s to the present) research findings for juvenile and adult salmon. A number of these studies were conducted as part of the LWGI. The main sources of data for this report include LWGI-sponsored research conducted by the Corps and SPU, agency reports, and published literature. Available reports and data have been used to the fullest extent possible, and biases and/or drawbacks of research are discussed when necessary. There are several ongoing studies in the area or studies that have not yet been formally published. As more studies are completed on the system, the results will undoubtedly alter some statements in this report.

Most of the following information is grouped by general location primarily for the convenience of summarizing the research. These spatial distinctions are artificial because the fish experience the system as a whole.

3.1 Juveniles

The juvenile research findings are grouped by location:

1. Lake Washington Residency
2. Lake Washington Outmigration
3. Ship Canal and Lake Union Outmigration
4. Passage at the Hiram M. Chittenden Locks (Locks)
5. Estuarine Transition in Salmon and Shilshole Bays
6. Puget Sound Residency

Information is further divided into three categories: timing, habitat and behavior, and survival risks. Then, individual study topics are presented as they have occurred in the literature. The studies are organized by species when appropriate, but for juveniles, multiple species are often included in the same study. In general, there is more information on Chinook and sockeye than on coho or steelhead.

3.1.1 Lake Washington Residency

Chinook, coho, sockeye, and steelhead occur within the Lake Washington basin. With extensive urbanization of the Lake Washington basin, habitat conditions have declined for juvenile salmon and steelhead (see Chapter 2). Cumulatively, these alterations influence juvenile salmon migration movements, rearing behavior, prey availability, and predator behavior and distribution (Warner and Fresh 1998, Kahler et al. 2000, Fresh et al. 2001, Tabor et al. 2004a,b, Koehler et al. 2006, Beauchamp et al. 2004, Mazur and Beauchamp 2006, Overman et al. 2006, Tabor et al. 2007a).

3.1.1.1 Residency Timing

Juvenile salmon species vary in the length of time they reside in Lake Washington and the locations they occupy. Chinook salmon fry enter Lake Washington between January and March, while fingerlings enter from mid-May to early June (Seiler et al. 2004, Volkhardt et al. 2006, Koehler et al. 2006). Juvenile Chinook fry migrants that enter the lake in January appear to be pushed downstream by high winter and early spring flows (Volkhardt et al. 2006). Upon reaching Lake Washington, fry use the lake for 1 to 4 months as rearing habitat before migrating to Puget Sound (DeVries et al. 2005, Seiler et al. 2005). In contrast, fingerling migrants rear in rivers and creeks for 2 to 6 months before moving into the lake (Paron and Nelson 2001, Seiler et al. 2005, Sergeant and Beauchamp 2006, Volkardt et al. 2006). Lake-rearing Chinook fry grow rapidly and attain larger sizes than juvenile Chinook in nearby freshwater systems of Puget Sound (Koehler et al. 2006). While most juvenile Chinook leave the lake for Puget Sound by summer, a very small percentage of the Chinook population appears to stay in Lake Washington for 1 to 2 years (DeVries et al. 2005, D. Beauchamp unpub data).

Sockeye salmon fry enter Lake Washington from the Cedar River between about mid-January and mid-May (Seiler et al. 2005). They enter at a very small size (about 1.2 inches) and spend over 1 year rearing in the lake. In contrast, coho smolts rear in natal streams for over a year before entering the lake between April and June. Juvenile coho are thought to spend little time in the lake and only pass through on their way to Puget Sound. Steelhead smolts enter the lake in May and are thought to outmigrate quickly. However, they have been caught in limnetic areas in May (Beauchamp 1995, unpub data).

3.1.1.2 Habitat Use and Behavior

The habitat use of juvenile salmon in Lake Washington varies based on time of day and their size (i.e. fry versus fingerling) and season. In January and February, Chinook fry tend to congregate close to shore in the southern end of Lake Washington near the mouth of the Cedar River (Tabor et al. 2004a). There is a substantial increase in the number of juvenile Chinook using nearshore areas of south Lake Washington in early March. As the season progresses, Chinook fry disperse further along the lake shoreline and can be found roughly between Seward Park on the western shoreline and May Creek on the eastern shoreline, including the southern end of Mercer Island (Tabor et al. 2006). Larger juvenile Chinook—both those that entered as fry and have grown in the lake and those that enter the lake as fingerlings—tend to move into deeper waters by late spring/early summer.

Chinook use of the lake varies from other salmon and steelhead. Juvenile sockeye spend over 1 year in the lake, and inhabit deep water (or limnetic) areas. Coho salmon are mainly found in littoral zones. Lake Washington habitat use by juvenile steelhead is poorly understood.

Chinook Fry

Chinook salmon behavior in the lake varies by cohort and time of year. One cohort enters the lake from mid-January through March, with a peak in late February. A second group rear in tributary streams for several weeks and migrate to Lake Washington as fingerlings from April through late June, with a peak in mid-May (Seiler et al. 2005). Juvenile Chinook in the lake are consistently larger than those measured in tributaries (Koehler et al. 2006). Chinook generally inhabit the littoral zone as fry or fingerlings when they first enter the lake, but spend some time in deeper, limnetic waters before migrating into the Ship Canal. When the fish use deeper waters, they are larger in size, deep water prey resources are available, and littoral zone temperatures are higher.

Field observations have found that Chinook salmon fry prefer depths generally less than 1.6 feet deep, gentle slopes, and sand-silt substrates (Piaskowski and Tabor 2001, Tabor and Piaskowski 2002, Sergeant and Beauchamp 2006, Tabor et al. 2006). During the day, Chinook fry are commonly observed in aggregations (sometimes with sockeye), actively feeding on chironomid pupae at the water surface and in water depths up to 13 feet deep. At night, Chinook fry are no longer grouped, are inactive, and usually on the bottom in shallow water close to shore (Tabor and Piaskowski 2002, Tabor et al. 2004a).

A variety of surveys from lakes Washington, Sammamish, and Quinault indicate that overhead cover is an important habitat feature for small Chinook salmon in lakes (Paron and Nelson 2001, Tabor et al. 2006). During the day, field studies in Lake Washington have found greater densities of Chinook fry in areas with woody debris and overhead cover (Tabor et al. 2006). However, at night Chinook fry appear to move away from woody debris and into open water areas.

For example, in an area of Gene Coulon Park with woody debris and overhead cover, only 2% of Chinook salmon fry observed were in open shoreline sections during the day, but 46% were in these sections at night. Of the Chinook seen within survey sections with structure, 65% were located in open areas, away from the structure (Tabor et al. 2006). These field results have not been corroborated by Sergeant and Beauchamp (2006), where Chinook showed a weak response to substrate type, overhanging vegetation, and woody debris during laboratory trials. It is hypothesized that Chinook fry use woody debris and overhead vegetation during the day as refuge from predators. When there is less predation risk, the fish then move into openwater areas, away from cover.

Bank armoring (e.g. bulkheads), docks, and piers influence Chinook salmon fry habitat use. Juvenile Chinook are found in much higher numbers along unarmored shorelines than along armored shorelines (Paron and Nelson 2001, Tabor and Piaskowski 2002, Tabor et al. 2006). Natural shorelines tend to offer a wider range of water depths, while armored shorelines truncate the shallow water zone, especially as Lake Washington's water elevations increase in the spring. Armored shorelines often also have limited or no overhanging vegetation and woody debris, which can offer cover for Chinook fry. Shallow water can serve as refuge from predatory fishes because predators cannot forage effectively in very shallow water. Bank armoring eliminates most of this shallow water refuge. Vertical bulkheads can also have localized effects on bottom slope and substrate type by altering wave energy and silt deposition (Sergeant and Beauchamp 2006). Riprap shorelines are also ideal habitat for large prickly sculpin, predators of Chinook. So, riprap may increase predation risk to Chinook (R. Tabor pers comm). While armored shorelines appear to limit habitat for Chinook fry, docks and piers are sometimes used as a substitute for natural overhead cover during the day in February and March (Tabor and Piaskowski 2002).

A number of studies indicate that Chinook salmon fry are attracted to non-natal tributaries in Lake Washington, and use creek mouths or the low reaches of tributaries for rearing (Tabor et al. 2004a). Potentially large numbers of Chinook use these creeks. For example, as many as 632 Chinook fry were observed in the lower 853 feet of Johns Creek. The use of non-natal tributaries is based on distance from the natal river and size of the tributary. Juveniles may avoid larger creeks because of large predatory fish in the area. Creek deltas offer preferred habitat, specifically shallow water, gradual slopes, and sand substrates. Juvenile Chinook use of creek deltas is highest in February and March, and decreases completely by late June.[4] These creek deltas may also provide better foraging opportunities than adjacent lake shorelines. For example, the abundance of Chinook increased during a high flow event at May Creek, a tributary to Lake Washington (Tabor et al. 2006). An increase in prey availability and flow may attract Chinook to lake tributaries during storms.

In cases where Chinook salmon are using habitat in the tributary, use appears related to their ability to access the creek and find refuge and foraging opportunities (Tabor et al. 2004a). Habitat use studies within Johns Creek, a tributary to Lake Washington close to the mouth of the Cedar River, found that Chinook mostly used glides and scour pools (Tabor et al. 2006). Fry density

[4] From data at Johns Creek (R. Tabor pers comm).

was greatest in glides during February and early March, but as the fish grew, their density in the glides dramatically declined. When fish were found in glides during late March and early April, they were almost always under overhanging vegetation. Scour pools were used from February to May, with fish using shallow edges and tailouts in February and progressively moving into deeper areas of the pools by the end of March. Scour pool densities were greatest in April and May.

Larger Juvenile Chinook

As juvenile Chinook salmon grow, their habitat needs change in response to their prey resources, predation risks, and migration needs. During May and June, fry in the lake have reached a larger size and are joined by fingerlings that have been rearing in the Sammamish and Cedar River systems. These larger fish are found in slightly deeper waters along the lake shoreline (Martz et al. 1996, Warner and Fresh 1998). Fine-scale acoustic tracking of juvenile Chinook in May and June have found the fish in waters between 3 to 18 feet deep during the day, primarily over sand and gravel substrates. Very few fish are found in areas with cobble and larger substrates (Tabor et al. 2004a, 2006). At night, fine-scale acoustic tracking studies show that fish move into offshore limnetic areas (Celedonia et al. 2008a,b). These tracking data are corroborated by daytime observations that show that Chinook salmon often feed in water 6.6 to 13.2 feet deep and migrate parallel to the shoreline in similar water depths of 6.8 to 14.8 feet (Tabor et al. 2006).

Juvenile Chinook salmon also tend to avoid overhead cover as they grow. Tabor et al. (2004a) found that juvenile Chinook did not extensively use cover as they increase in size. During May few Chinook used overhead and small woody debris during either daytime or nighttime (Tabor et al. 2006, Celedonia et al. 2008a,b). However, juvenile Chinook may occasionally use small woody debris and overhead vegetation for cover when predators are present (Tabor et al. 2006). Similarly, larger juvenile Chinook also avoid docks and piers and will move into deeper water as they approach overwater structures (Tabor et al. 2004a, 2006, Gayaldo and Nelson 2006). It is likely that larger Chinook are using deeper water and avoiding overhead cover to balance their predation risks from other fish and birds. This hypothesis, while not tested in Lake Washington, is supported by research by Power (1984).

Sockeye Salmon

Sockeye salmon use of Lake Washington varies. When sockeye fry first enter the lake environment, they may inhabit shallow water areas such as river deltas at night (R. Tabor pers comm). Sockeye fry are also commonly found in other parts of the littoral zone (Martz et al. 1996) but the actual amount of time fry are present in this area is not known. Most of the time, sockeye fry travel in schools in limnetic areas. They are generally located below 66 feet (Woodey 1972). Juvenile sockeye in the lake show consistent movement patterns. They ascend to feed at dusk, staying in shallower waters until daybreak and descend to daytime depths after dusk (Eggers 1978). The difference between the deep and shallow waters inhabited by juvenile sockeye can be up to 43 feet. During summer stratification, sockeye are confined to the deeper, cool waters because of high temperatures on Lake Washington’s surface (D. Beauchamp pers comm). During this period, sockeye are unable to access the high densities of zooplankton in the warm waters.

Kokanee are present in the Lake Washington system. While kokanee fry have never been distinguished from sockeye fry in Lake Washington, larger kokanee have been identified in limnetic waters. Kokanee with fork lengths 5.9 to 11.8 inches have been captured in modest but consistent numbers with gill nets, purse seines, and a large midwater trawl during spring and fall hydroacoustic-midwater trawl surveys during 2001 to 2006 (D. Beauchamp unpub data).

Coho Salmon and Steelhead

Not much information is known about the habitat use of coho salmon and steelhead in Lake Washington. Both are thought to enter Lake Washington at a larger size, which would influence their preferred habitats. In Lake Sammamish, however, coho salmon fry (likely hatchery fry released from Issaquah Hatchery) exhibited habitat use patterns similar to those of Chinook fry. Coho were more strongly affiliated with woody debris (Tabor and Piaskowski 2002, R. Tabor pers comm).

3.1.1.3 Survival Risks

Juvenile salmon survival within Lake Washington depends on the ability to find enough food and to avoid predators. There are other aspects of their lake residency that also impact survival, but these two factors have been the best studied.

Food

For Chinook salmon, diet studies illustrate that juveniles are opportunistic feeders. Juvenile Chinook consume a wide variety of prey items and appear to quickly switch to a locally abundant prey source (Tabor et al. 2006). Two major prey resources within Lake Washington are chironomids and the zooplankton *Daphnia*. While *Daphnia* typically do not become abundant in the lake until June, chironomids are abundant in the nearshore areas of Lake Washington most of the year (Koehler 2002). Where juvenile Chinook are close to lake tributary mouths, benthic and terrestrial insects can be more prevalent in their diets. However, the urbanized shoreline of Lake Washington reduces the availability of these prey items (Koehler et al. 2006).

Juvenile sockeye salmon primarily eat zooplankton, with an emphasis on copepods earlier in the spring and a switch to *Daphnia* spp. when that food source becomes more abundant in June (Chigbu and Sibley 1994, Martz et al. 1996, Beauchamp et al. 2004). Earlier in the spring juvenile sockeye also consume chironomids (Beauchamp et al. 2004). These feeding habits correspond with their residence in limnetic areas of the lake. Bioenergetic modeling for sockeye and Chinook salmon indicates that food availability does not limit the growth and survival of either salmon species while inhabiting Lake Washington (Beauchamp et al. 2004, Koehler et al. 2006).

The size of Chinook and sockeye salmon smolts upon outmigration corroborates the modeling results because they are among the largest found within their species range on the West Coast of the United States. (Duffy et al. 2005). Key prey items for Chinook and sockeye during lake residency include copepods, chironomids, and *Daphnia* (Chigbu and Sibley 1994, Martz et al. 1996, Koehler et al. 2006, Beauchamp et al. 2004). Chinook appear to feed to a large extent at the water surface. Visual observations of Tabor et al. (2007) show this. Chinook also consume chironomid pupae, adult chironomids, and terrestrial insects that are associated with the water's surface (Koehler et al. 2006).

In the lake, steelhead and coho salmon at smaller sizes are likely to eat similar prey items to those consumed by Chinook and sockeye. However, as these fish grow larger, they may switch to eating other fish. Coho and steelhead 11.8 inches FL are highly piscivorous on smelt, juvenile perch, and salmon in Lake Washington (McIntyre et al. 2006, Overman et al. in review, D. Beauchamp unpub data).

Predation

A number of salmon predators occur in Lake Washington. These include native cutthroat trout, rainbow trout, prickly sculpin (*Cottus asper*), juvenile coho and northern pike minnow and non-native yellow perch, smallmouth bass (*Micropterus dolomieui*), and largemouth bass (*M.*

salmoides). Piscivorous (fish-eating) birds—western grebes, mergansers, cormorants, and great blue herons—are also a potential predator on juvenile salmon in the Lake Washington basin. Predation rates in Lake Washington reflect the extent to which juvenile salmon and their predators use the same habitat. If predators overlap with juvenile salmon, consumption rates depend on habitat structure, water temperature, and the body size of both predator and prey (Martz et al. 1996, Nowak et al. 2004, Tabor et al. 2004b).

Sampling of 1,875 predatory fish nearshore in southern Lake Washington from February to June 1995 and 1997 showed only 15 juvenile Chinook salmon in the stomachs of cutthroat trout, prickly sculpin, smallmouth bass, and largemouth bass. Most of the predation loss was attributed to prickly sculpin, which had a substantially larger population size than the other predators. Predatory fish were thought to have consumed less than 10% of the juvenile Chinook that entered the lake from the Cedar River (Tabor et al. 2004b). Based on sockeye salmon fry estimates from Bear Creek and the Cedar River and pre-smolt surveys in recent years, sockeye survival in Lake Washington varies between 2% and 7% (Overman et al. 2006). Therefore, lake predation can substantially impact survival rates of Chinook and sockeye in the Lake Washington watershed. However, it should be noted that it is difficult to conduct predation studies on naturally-produced Chinook due to low numbers of these fish.

During diving surveys in 2000 and 2001, smallmouth bass were observed to use shallow depths in May and June (possibly for spawning) and then shift to deeper water in July and August. Smallmouth bass tend to use shoreline areas devoid of vegetation with gravel and cobble and a gradual slope with a drop-off (Pflug and Pauley 1984, K. Fresh unpub data). Acoustic tracking of mallmouth bass indicates they are usually closely associated with one of three habitat types: 1) overwater structures, 2) steep sloping riprap or bulkheads or 3) the offshore edge of aquatic plants (Celedonia et al. 2008b). Smaller-sized smallmouth bass were observed during diving surveys to occur mostly in shallow areas around 3.3 to 13 feet deep and were most closely associated with structure. On the other hand, larger bass were found at greater depths not often associated with structure. Three-quarters (74.4%) of the bass population was observed within a 6.6 feet distance from structural features such as constructed cover, overwater structure, natural structure (boulders, ledges, walls), and structurally complex large woody debris. Most bass used docks and other artificial structures (Celedonia et al. 2008a,b). Distribution shifts to deeper littoral zones in later summer were theorized to reflect milfoil growth (K. Fresh unpub data). Smallmouth bass also seem to be more active at dawn and dusk than during other periods (Celedonia et al. 2008b).

Smallmouth bass overlap with juvenile Chinook salmon in Lake Washington in May and June, when both are in shoreline areas. In an experimental study of predation on juvenile Chinook, Sergeant and Beauchamp (2006) found that the Chinook did not change habitat use in the presence of predators, which could increase predation risks. Predation rates reflect physical conditions. In low water temperatures, where most Chinook are, smallmouth bass do not feed as actively as they do above 68ºF (20ºC) (Wydoski and Whitney 2003). Chinook also avoid overhead cover, docks and piers, and coarser substrates used by bass, reducing spatial overlap (Tabor et. al 2004a; Gayaldo and Nelson 2006, Tabor et al. 2006, Celedonia et al. 2008a,b). Low predation on Chinook by smallmouth bass may also be due to an abundance of alternative prey such as sculpin (R. Tabor pers comm). Additionally, juvenile Chinook move in deeper waters by late May and early June, and low predation may be due to reduced availability of Chinook.

One study assessed the impact of predation by smallmouth bass on sockeye salmon in Lake Washington Fayram and Sibley (2000). Based on ultrasonic tracking, limited spatial and temporal overlap occurred between smallmouth bass and juvenile sockeye. Some overlap occurred in the littoral zone during migration of sockeye fry from the Cedar River into the lake and during smolt outmigration from the lake through the Ship Canal and into Puget Sound. Salmon occurred in smallmouth bass stomachs only during the outmigration period. For smallmouth bass longer than

6 inches, juvenile salmon constituted 28% of their diet in the lake. The salmon in the diet samples for this study were not identified to species, so the impact on individual species such as sockeye or Chinook was not determined.

Largemouth bass are also predators of juvenile salmon. Their predation on Chinook salmon has not been well studied. They are suspected to consume young of the year, outmigrating sockeye salmon in June and July (E. Warner pers comm).

Cutthroat trout have been observed to prey upon juvenile Chinook and sockeye salmon (Nowak et al. 2004, Beauchamp et al. 2007). There are higher predation rates on sockeye by cutthroat trout than by juvenile coho salmon, rainbow trout, prickly sculpin, smallmouth bass, and yellow perch in the littoral zone of southern Lake Washington (Tabor and Chan 1996, 1997, Nowak et al. 2004). Nowak et al. (2004) observed that cutthroat trout ate sockeye juveniles most heavily in winter and spring. Smaller cutthroat in the littoral zone appear to feed on sockeye when the two occur in the same geographical area. Larger cutthroat trout appear to feed on larger sockeye juveniles in the limnetic zone. Cutthroat trout consume Chinook in littoral and limnetic zones, although Chinook appear in cutthroat diets infrequently (Beauchamp et al. 2007). Reduced cutthroat trout predation rates in May and June are observed and may reflect the increased size and improved swimming ability of juvenile Chinook salmon (Tabor et al. 2004b). Estimates vary for the cutthroat population in Lake Washington. Acoustic surveys, models, and catch-per-unit-effort estimates range from 30,000 to 64,000 (Beauchamp et al. 2007). Depending on the actual number of cutthroat in Lake Washington, cutthroat trout may impact the survival of juvenile Chinook and sockeye in the lake.

Both cutthroat trout and pikeminnow also exerted similar to somewhat higher predation mortality rates on smelt and sticklebacks in 2005 and 2006. No predation was detected on the larger coho and steelhead smolts.

The northern pikeminnow has also been suspected of consuming enough juvenile salmon in Lake Washington to impact survival. Pikeminnow are thought to use littoral areas during the winter where they may overlap with juvenile Chinook salmon and limnetic areas during the summer where they overlap with juvenile sockeye salmon (Olney 1975, Brocksmith 1999). However, most tagged pikeminnow in a recent study were tracked in the littoral zone. Hydroacoustic tracking shows that pikeminnow are strongly associated with overwater structures, are most active at night, and are often present where moderate levels of macrophytes exist (Celedonia et al. 2008a). In a recent study, three-spine stickleback were found to be the primary fish prey of northern pikeminnow (Beauchamp et al. 2007). However, annual estimates of northern pikeminnow-caused mortality were 0.2 to 1.4% for sockeye and 0 to 0.1% for Chinook.

Prickly sculpin may be an important predator on salmon because there is a large population in Lake Washington. Sculpin overlap with Chinook salmon in the littoral zone, where higher sculpin densities were noted in cobble areas than in sandy areas (Tabor et al. 1998). However, once Chinook are over 2.9 inches FL they are less vulnerable to prickly sculpin predation (Tabor et al. 2004b). Most Chinook predation loss during surveys from February to June 1995 and 1997 were attributed to prickly sculpin. So far, predation estimates have only included very small sample sizes of prickly sculpin (R. Tabor pers comm). Since juvenile Chinook avoid cobble and larger substrates, their behavior may reduce predation risks from prickly sculpin. Prickly sculpin consume sockeye salmon in littoral and deep, benthic areas of Lake Washington (Tabor et al. 2007b).

There is concern over the role of bird predation during juvenile salmon lake residency. Great blue herons, mergansers, cormorants, and western grebes are common in the south end of the lake during late winter, spring, and early summer. While bird predation occurs, it has not been examined. For wading birds such as herons, the lack of extensive shallow wading areas may limit the impacts of their predation. Diving birds such as grebes and mergansers do not face such limitations. There is little research on the impact of fish-eating birds on salmon in Lake Washington.

Predation in Lake Washington has been affected by increased lighting at night from surrounding urban areas. Artificial light can reflect off of clouds or directly shine into the water. Increased light at night has increased cutthroat trout predation (Mazur and Beauchamp 2006). Additionally, herons and grebes have been observed foraging at night near artificial lighting and may prey on juvenile Chinook salmon, which appear to be attracted to lights (R. Tabor pers comm).

3.1.2 Lake Washington Outmigration

Juvenile salmon migrate through Lake Washington at different ages and under different circumstances. This section summarizes information about their timing, habitat use and behavior, and survival risks during outmigration. Lake conditions influence all of these life-history characteristics.

3.1.2.1 Outmigration Timing and Age

Juvenile salmon migration out of Lake Washington starts in April and continues until June or early July. Juvenile sockeye salmon generally outmigrate at 1 year in age after spending the previous summer and winter rearing in the lake. However, some sockeye outmigrate in their first year of life, without extensive rearing in freshwater. In some years, the young-of-year sockeye outmigrants can be up to 15% of the population (E. Warner pers comm). Coho salmon are also about 1 year of age, having spent their first year primarily rearing in natal streams and rivers. Outmigrating Chinook salmon are the youngest to leave the lake—they outmigrate within the first year of their life. However, young-of-year sockeye and 1-year-old Chinook have also been noted to outmigrate.

3.1.2.2 Habitat Use and Behavior

Chinook salmon outmigrant behavior has been examined in Lake Washington through observation-based studies and limited fine-scale acoustic tracking. Observations of migrating Chinook indicate that these fish aggregate and move along the shoreline during the day, generally in water depths of 6.8 to 14.8 feet (Tabor et al. 2004a, 2006). Groups of Chinook often encounter docks and piers in their migration. Surveys in 2004 and 2005 found that migrating Chinook would move into deeper water upon encountering a dock or pier and would either pass along the end of the pier (if the pier was shorter) or pass underneath longer piers when they had moved into deeper waters. Chinook behavior near piers and their offshore migration at night may both be responses to predation risk, water characteristics such as clarity, temperature, and migration stage (Celedonia et al. 2008a).

Chinook salmon entrance into the Ship Canal is sometimes stalled, especially later in the season. In fact, some fish may not enter the Ship Canal at all. PIT-tagged fish released on the west side of Union Bay showed a declining trend in detections at the Ballard Locks between mid-May and late-June (DeVries et al. 2005). Likewise, observations of acoustic tagged fish tracked from Lake Washington[5] into the Ship Canal decrease in late June (Celedonia et al. 2008a).

Surface observations along the western shore of Lake Washington show both northerly and southerly movements of Chinook salmon schools (Tabor et al. 2006, R. Tabor unpub data). Some cycling behavior occurs, as well, where Chinook move south from the Ship Canal during the night and migrate back towards the Ship Canal during the day (Celedonia et al. 2008b). Southerly

[5] State Route 520 Bridge.

travel represents upstream movement away from the estuary and can be interpreted as an inhibition to enter the Ship Canal at the Montlake Cut. This inhibition may be explained by the lack of habitat provided in the Montlake Cut. Northward migrating smolts are consistently observed in water 19.7 feet deep (Tabor et al. 2006, Celedonia 2008a,b). The Montlake Cut is about 32.8 feet deep, much deeper than what the fish use in the lake. This may prevent fish initially from moving into the Ship Canal.

Outmigration behaviors of sockeye, coho, and steelhead have not been studied in Lake Washington.

3.1.2.3 Survival Risks

Prey and predation of salmon and steelhead leaving Lake Washington have not been specifically studied.

3.1.3 Ship Canal and Lake Union Outmigration

The Ship Canal connects Lake Washington with Portage Bay, Lake Union, the Locks and Puget Sound, serving as the migration corridor for outmigrating juvenile salmon (see Figure 3). This section describes migration timing, habitat use and behavior, and survival risks of outmigrating salmon and steelhead. Ship Canal and Lake Union water temperatures are a prominent feature and concern for salmon migrating through the area.

3.1.3.1 Migration Timing and Rates

From mid-May to late June, coho and sockeye salmon pass from Lake Washington through the Ship Canal and Lake Union. These fish have typically spent a year rearing in the basin. However, a small number of sockeye may leave as young-of-year fish. Some coho may spend multiple years rearing in freshwater (DeVries et. al. 2005). Sockeye and coho pass through the Ship Canal in a matter of days and do not spend much time milling about in the Ship Canal before transitioning to saltwater. Microacoustic-tagged coho were found to spend 1 to 2 days in the Ship Canal (Johnson et al 2004c)

Chinook salmon smolts typically pass through the Ship Canal in May and June as age-0 fish. However, some Chinook leave the basin as 2-year olds. The outmigration timing of juvenile Chinook through the Ship Canal and Locks appears to be later than that in any other stock in the Puget Sound basin.

PIT-tagging studies of juvenile Chinook salmon have found that juveniles may spend 2 to 4 weeks moving through the area (DeVries et al. 2005). Microacoustic tagging studies of juvenile Chinook have found that these fish can exhibit highly variable migration behaviors. Some fish migrate rapidly and others mill along the migration corridor. Studies in 2004 and 2005 found juvenile Chinook averaging about 40 hours to pass from Portage Bay to the Locks (Johnson et al 2004b) (Table 4). More detailed tracking information found that some Chinook smolts spend several days in Portage Bay before moving on to Lake Union (Celedonia et al. 2008b, unpub data). Tagged Chinook smolts spend 4 to 7 days in parts of Lake Union, including the south end. Tagged fish spent 1 to 4 days in north Lake Union near Gasworks Park (R. Tabor and M. Celedonia unpub data). The fish spend more time in Lake Union than in other areas of the Ship Canal. Recent microacoustic tagging research by USFWS will provide more information on juvenile Chinook movement through Lake Union and the Ship Canal.

Table 4
Mean travel time in hours for Chinook and coho salmon between areas of the Ship Canal

Salmon Species	Portage Bay to Fremont Cut	Fremont Cut to Locks	Locks to Shilshole Bay
Chinook	19	21	13
Coho	21	5	11

Source: Johnson et al. 2004b

PIT tagging studies have found that migration rates increase slightly as the season progresses, although fish are also more variable in their travel times as well (Figure 14) (DeVries et al. 2005). Later outmigrants are larger in size, and it has been hypothesized that these larger fish can travel at greater speeds. However, correlations between size and travel speed has not been verified and the effect of fish size on migration rate cannot be isolated from timing influences.

There is limited information about steelhead in the Ship Canal. Fresh and Luchetti (2000) indicate that most steelhead pass through the Ship Canal in May, although the PIT-tagging data indicate some also pass in early June (DeVries et. al. 2005).

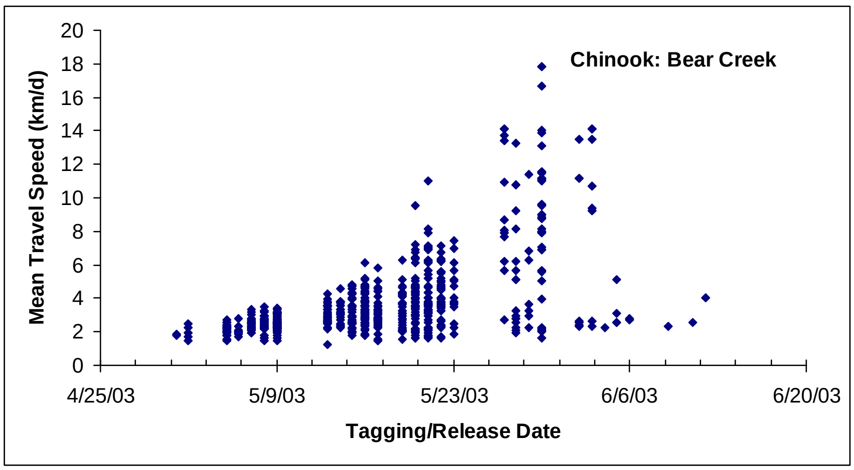


Figure 14
Average travel speed of juvenile PIT-tagged Chinook salmon between Bear Creek and the Locks. Data are plotted by release date
Source: DeVries et al. 2005

3.1.3.2 Habitat Use and Behavior

Habitat use and behavior in the Ship Canal and Lake Union have been studied mainly through PIT tagging and fine-scale acoustic tracking of juvenile Chinook salmon. Less information is known about sockeye and coho salmon. No information is available about steelhead. These studies have provided information on seasonal and diurnal migration timing patterns, shoreline affinity, residualism (fish stay in lake until maturation), and the effects of selected environmental factors such as water temperature in the Ship Canal and lunar phase. Most of the data collected are on coho and Chinook salmon, with fewer data on sockeye.

The USFWS conducted fine-scale acoustic tracking studies at various locations within the Ship Canal, Lake Union, and at the Locks from 2004 to 2008. In 2007 and 2008, tracking was also conducted in Union Bay and Lake Washington. The final results from those studies have not been fully incorporated into this report. Those studies will greatly inform understanding of juvenile Chinook movements within the Ship Canal and Lake Union.

Distribution

Earlier PIT-tagging studies of Chinook salmon smolts indicated that these fish are shoreline oriented as they move through Portage Bay, Lake Union, and Salmon Bay, and mix in the narrower sections including the cuts (DeVries et al. 2005). However, fine-scale acoustic tracking studies conducted more recently have provided more detailed information about fish movements within discrete areas along the migration corridor between Lake Washington and the Locks (Tabor et al. 2006, Celedonia et al. 2008a,b).

Fine-scale acoustic tracking between 2005 and 2007 in the Ship Canal at Portage Bay and north Lake Union showed little evidence of shoreline affinity. Instead, juvenile Chinook salmon smolts were observed fanning out and mixing within Portage Bay and north Lake Union (Celedonia et al. 2008b, unpub data). At Portage Bay, most fish were located at depths greater than 6.6 feet, whereas in north Lake Union most activity occurred at depths greater than 33 feet. Coho and Chinook tracked in the Fremont Cut in 2004 were found most frequently along the middle of the channel, with a slight skew towards the south shore (Johnson et al. 2004b). No day-to-night shifts in depth or location were consistently observed in the Ship Canal (Celedonia et al. 2008b, unpub data).

Chinook salmon smolts appear to briefly reside in Lake Union during their outmigration (1-4 days). Smolts use the entire lake, with 25 to 50% of tagged smolts using the southern part of Lake Union (M. Celedonia unpub data). During this residence, Chinook move around the northern and southern parts of the lake. They have shown up in tracking areas periodically, but not continuously. In Lake Union, Chinook smolts are active during the day, but exhibit variable behavior at night. They appear to avoid overwater structures. The prevalence of overwater structures and lack of shallow water habitat may substantially influence Chinook behavior.

Water Temperature

Water temperatures significantly influence salmon. Smolts may respond to water temperatures through avoidance (around 59°F or 15°C), changes in growth (around 66-68°F or 19-20°C), and smoltification ability (59-61°F or 15-16°C). Temperatures above 66ºF (19ºC) can also led to mortality. These temperatures are reached in the Ship Canal and Lake Union during late spring and early summer (Figure 15). While absolute peak temperature has not significantly increased in this area, the onset and duration of warm water conditions is increasing. A review of Corps temperature data from 1974 to 1998 near Gas Works Park indicates a linear increase of about 2 days per year when water temperature exceeds 68ºF (20ºC). The primary factor influencing water temperature in the Pacific Northwest appears to be air temperature (Wetherbee and Houck 2000).

Water temperatures increase over the outmigration season. Overall water temperatures warm in the Ship Canal in spring and summer reaching 66°F (19°C) around mid-June. Most salmon have passed through the Ship Canal and Locks by this time. However, later Chinook salmon migrants may still be using the area when water temperatures become stressful.

Fish can compensate for warmer temperatures by moving into cool water refugia when it is available. Minor thermal stratification occurs in the Ship Canal until fall, with cooler water near the bottom (Figure 16). For example, smolts appear to be more surface-oriented while water temperatures are below 59ºF (15ºC) and migrate into deeper, cooler waters when temperatures exceed 66ºF (19ºC) (DeVries et al. 2005). Overall, water temperatures and stratification appear to influence smolt distribution (i.e. water depth) and behavior. Fine-scale acoustic tracking stations at the I-5 bridge and at the Locks in 2007 and 2008 should provide more information about the effects of water temperatures on smolt use of differing water depths. The specific effects of climate change on water temperatures and salmon outmigration in the future is unclear. Salmon survival is dependent on the cool water temperatures and the historical climate regime of the Pacific Northwest.

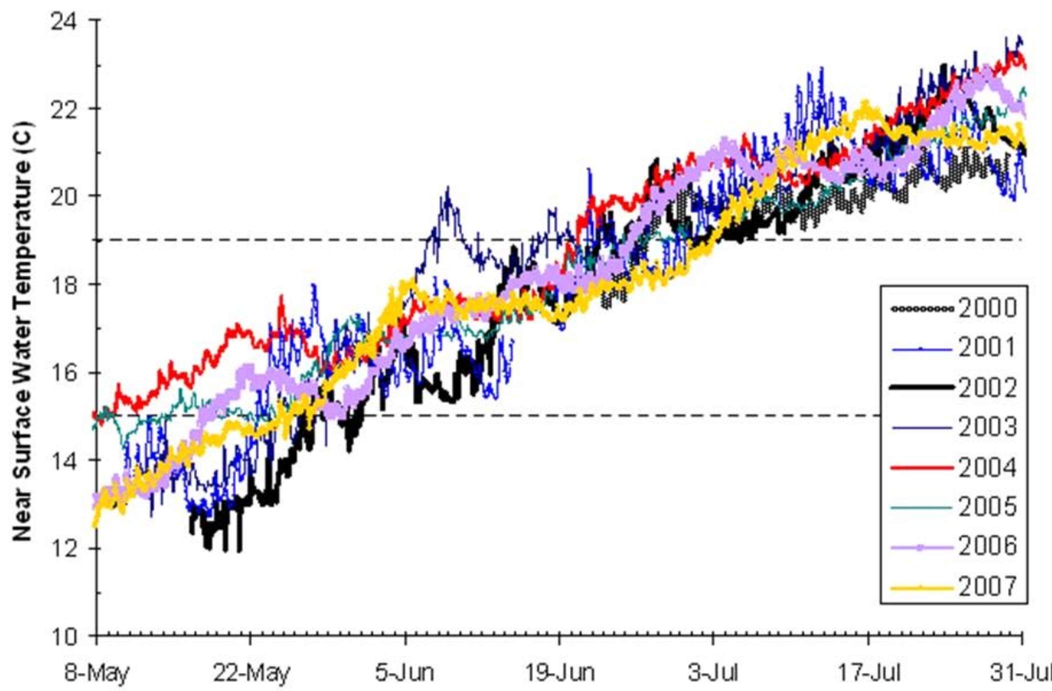


Figure 15
Nearsurface water temperatures (Celsius) in the Lake Washington Ship Canal during smolt outmigration (2001-2005) at Ballard Bridge and Gasworks sites
Source: Corps

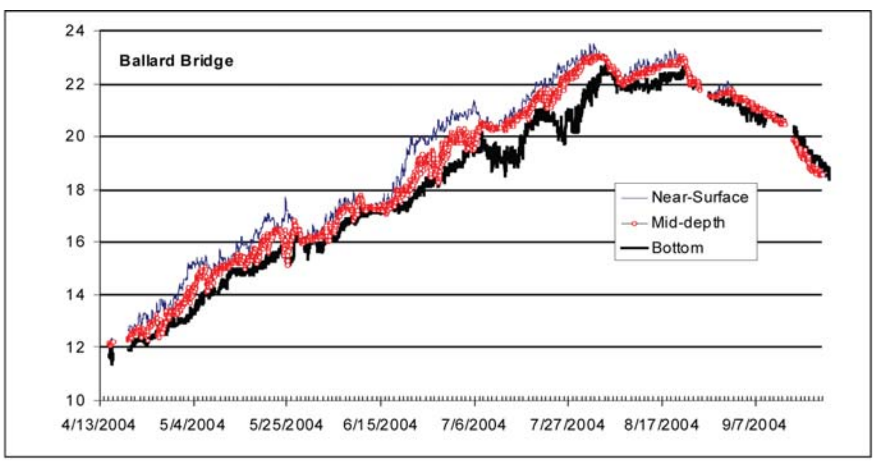


Figure 16
Surface, mid-depth and bottom water temperature (°C) in Ship Canal (spring and summer 2004)
Source: Corps

Residualism

Based on PIT-tagging data, a small number of Chinook, coho, and sockeye salmon migrate out of the Lake Washington system 1 or 2 years later than the bulk of the population (DeVries et al. 2005). Other observations reveal that hatchery steelhead may also residualize (E. Warner pers comm). A few (≤ 0.26%) Chinook, coho, and sockeye smolts were detected passing through the Locks 1 to 2 years after PIT tagging. These fish must have remained in the Lake Washington basin to rear through the winter (DeVries et al. 2005). Some fish may never migrate out to Puget Sound. Because variation in salmon life-history behavior occurs, this delayed outmigration is not surprising. However, there is concern that elevated water temperatures along the migration corridor could be a contributing factor. In addition, anecdotal information suggests residualism of juvenile Chinook may be higher in the Lake Washington basin than commonly found in other river basins (E. Warner pers comm).

One hypothesis for this residualism is that elevated water temperatures in the Ship Canal cause it (DeVries et al. 2005). Elevated water temperatures can also contribute to desmolting (M. Celedonia pers comm). It is thought that this may particularly impact later outmigrants, which face higher water temperatures along their migration route. However, a fish may also overwinter in freshwater water due to lack or a reversal of migration cues related to changes in day length, fish size, or growth rates. Another reason for residualism may be the abundant prey resources available in the lake during the smolt outmigration (R. Tabor pers comm). The lake possibly provides more prey resources for juvenile salmon than a riverine system would. Overall, the benefits or drawbacks of residualism and the link to water temperatures in the Ship Canal remain uncertain.

3.1.3.3 Survival Risks

PIT-tag studies conducted under the LWGI offer information on smolt survival in the system (DeVries et al. 2003, 2005). In these studies, smolts are implanted with PIT tags, usually as they leave their natal rivers. They are detected as they leave the Lake Washington system through the smolt flumes at the Locks. Detection rates at the Locks are roughly associated with survival rates. However, they are not synonymous with survival rates because fish may pass through a route other than the smolt flumes at the Locks. Additionally, the PIT tag readers are not 100% effective at detecting all tags, and a very small percentage is not detected at the Locks.

PIT-tagging results collectively show that detection rates of Chinook smolts from Bear Creek and the Cedar River to the Locks are relatively high (50 to 100%) until about mid-June (Figure 17) (D. Beauchamp pers comm). Detection rates decline to between 0% and 50% in late June or early July (DeVries et al. 2005, DeVries and Hendrix 2005a, D. Beauchamp pers comm). A similar decline in detection rates is also seen for coho smolts (Figure 18). Collectively, these results may indicate decreasing smolt survival during late June and early July.

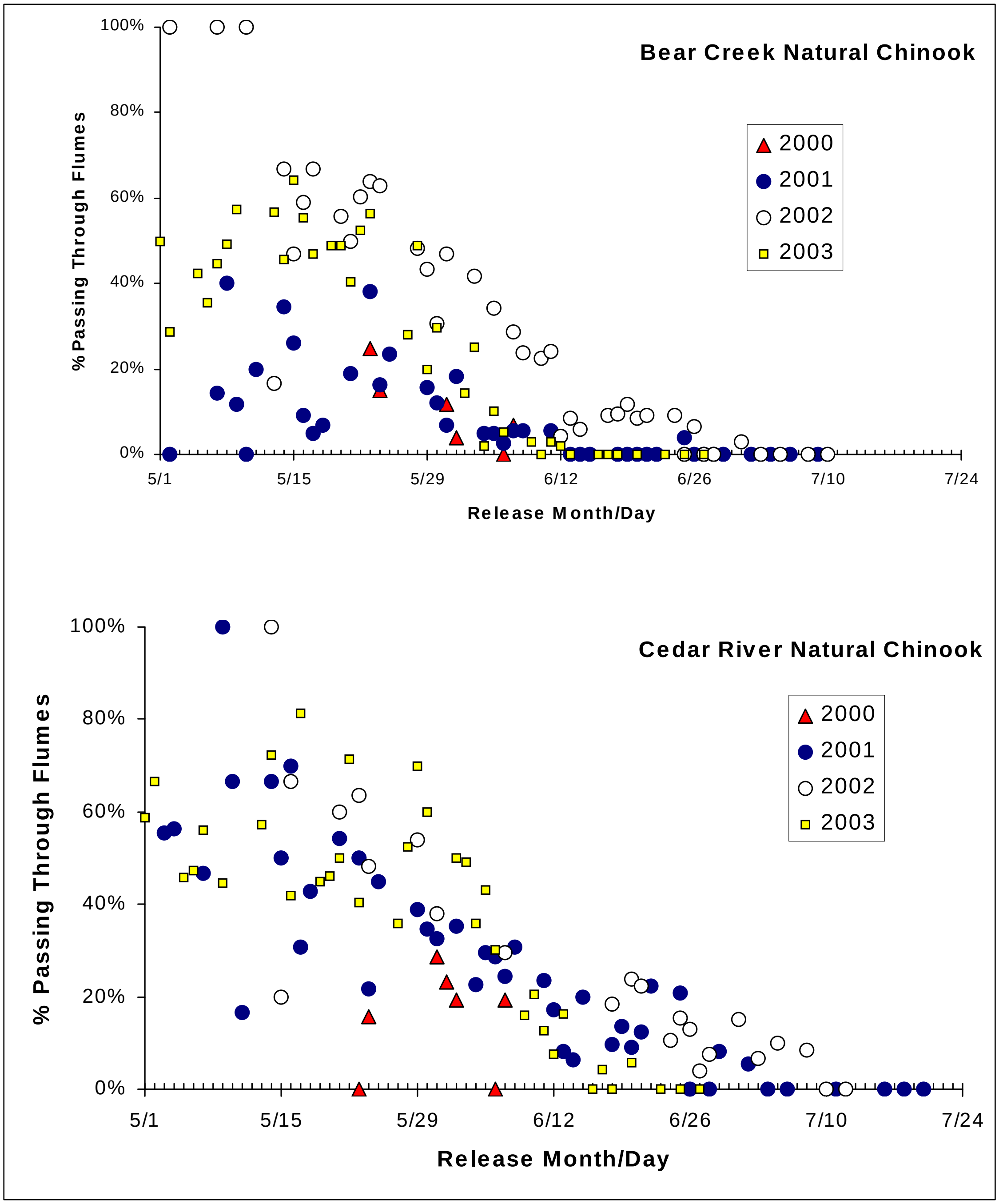
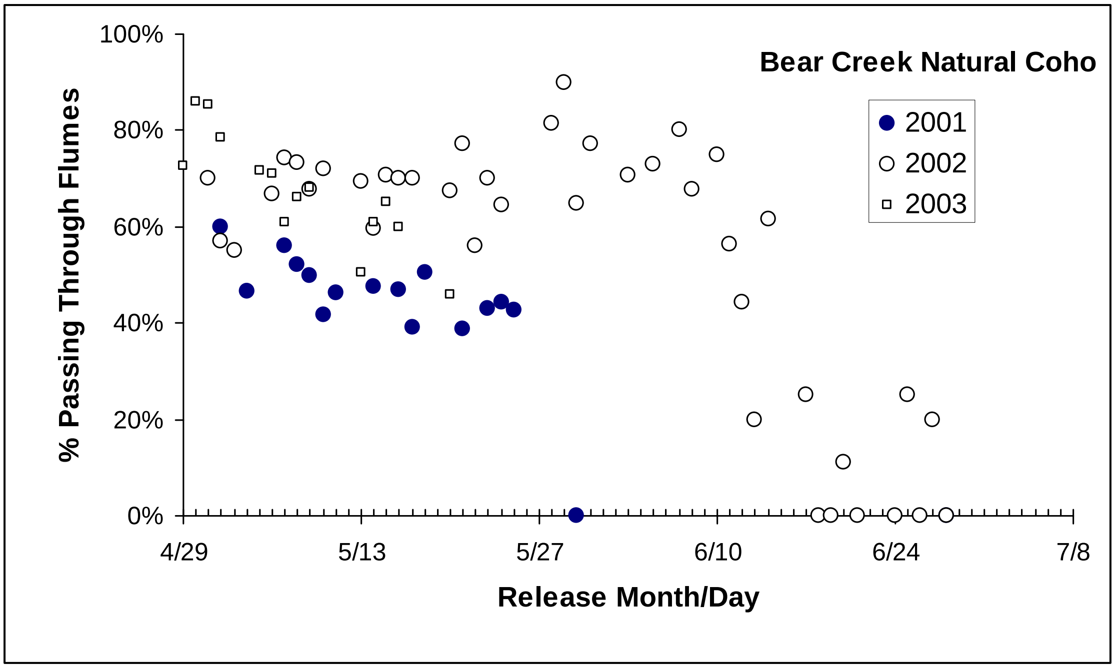


Figure 17
Smolt flume detection rates for naturally-produced, juvenile Chinook salmon by date. Top shows fish released in Bear Creek. Bottom shows fish released in the Cedar River. Numbers were adjusted for detection efficiencies

Source: Corps unpub data



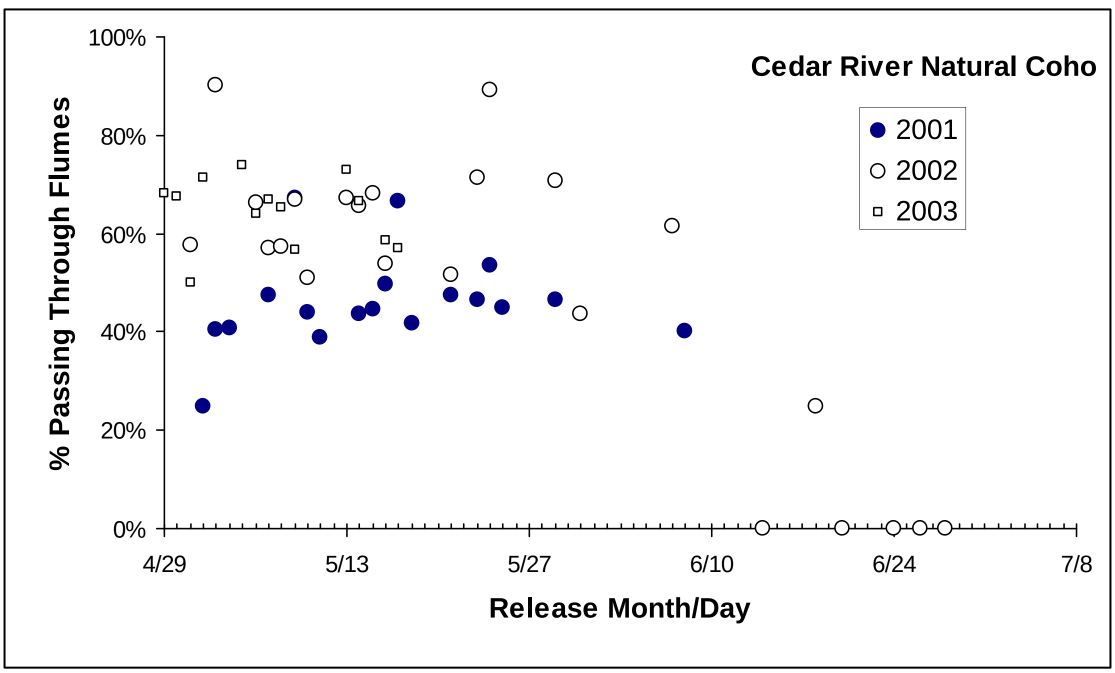


Figure 18
Smolt flume detection rates for naturally-produced, juvenile coho salmon by date. Top shows fish released in Bear Creek. Bottom shows fish released in Cedar River

Source: Corps unpub data

Low detection rates of Chinook salmon late in the outmigration season might be related to 1) increased rates of predation, 2) increased rates of residualism, and 3) increased use of alternative migration pathways at the Locks. All of these explanations are intertwined with effects of water temperature. For the Ship Canal and Lake Union, water temperatures and predation are of primary concern. Chinook smolts and young-of-year sockeye are the most susceptible because they migrate later in the season than age-1 sockeye and coho and at a much smaller size. The limited information on steelhead suggests they are similar to age-1 sockeye and coho outmigrants in timing and size.

Water Temperature

Water temperature may affect juvenile salmon through: 1) acute lethal effects, 2) reduced growth, and 3) changes in smolt readiness (Hicks 2002). This section focuses on Chinook smolts as the most at risk from elevated temperatures. It is reasonable to assume that other salmon species would be affected in similar ways.

Acute Lethal Effects

The lethal temperature for juvenile Chinook salmon is likely higher than that for adult Chinook. The temperature 69°F (21°C) is a migration block to several salmon species (Beschta et al. 1987, ODEQ 1995). Sometimes this temperature is recorded in the Ship Canal in early June (see Figure 15). With thorough acclimation, however, consistent exposure to temperatures of 73 to 75°F (23-24°C) is necessary to produce a real risk of direct mortality to juvenile Chinook (Hicks 2002).

Acute lethal effects have not been studied in the Ship Canal or Lake Union.

Reduced Growth

Growth is dictated by fish metabolism and prey availability. At higher temperatures, fish metabolism increases. When food is more plentiful, fish can grow larger in warmer waters (Hicks 2002). Studies elsewhere have found that juvenile Chinook have optimal growth rates between 58 to 66°F (14-19°C) (Brett et al. 1982, Seymour 1956). In the Ship Canal and Lake Union, it is likely that Chinook smolt growth may be affected at temperatures of 66°F (19°C). The growth effects due to high water temperatures may be tempered somewhat by the following:

- Acclimization to higher temperatures that exist in the surface waters of Lake Washington and in the Ship Canal and Lake Union
- Limited amount of time spent migrating through the Ship Canal
- Availability of sufficient prey

However, this matter has not been studied.

Smoltification

The physiological preparation of juvenile fish for life at sea is commonly referred to as *smoltification*. High water temperatures affect the ability of smolts to transition to, and grow in, saltwater, and hence reduce their fitness and survival. In some salmon species—Chinook and steelhead, for example—delayed migration timing (such as from a thermal barrier) or exposure to water temperatures above 68°F (20ºC) may result in smolts reverting back to freshwater form (Adams et al. 1975, Chapman et al. 1994). This is called *desmolitifcation*. Desmoltification can also be caused by prolonged exposure to slightly elevated temperatures over a period of time. Rapid temperature changes, such as from the Ship Canal to the saltwater downstream of the Locks, may also create substantial stress.

Predation

Predominant predators in the Ship Canal are northern pikeminnow (*Ptychocheilus oregonensis*), small- and largemouth bass, cutthroat trout, and piscivorous birds. Yellow perch and rock bass are potential predators in the Ship Canal. Predation rates in the Ship Canal most likely reflect outmigration timing, run size of each species and water temperature (Tabor et al. 2006). Fish size likely affects predation rates because larger fish have fewer predators. Fish predators are relatively well studied, but little is known about bird predation on salmon smolts in the area.

Predation studies to date suggest that predation in the Ship Canal may be between 1 and 10% (Fayram and Sibley 2000, Tabor et al. 2004b). However, it is hypothesized that predation rates increase during the outmigration season as water temperatures increase, increasing metabolic demands of predators, and the number of smolts decline. Smolt PIT-tag detection rates indicate that survival may decrease as the outmigration season progresses, and predation may play a role (DeVries et al. 2005, DeVries and Hendrix 2005a).

Among the predatory fish, smallmouth bass populations appear to be the largest in number. Northern pikeminnow and largemouth bass populations appear to be smaller and less evenly distributed in Lake Washington and the Ship Canal (K. Fresh unpub data). Preliminary research done by the Muckleshoot Indian Tribe, USFWS, and UW in 1995 and 1997 indicates that smallmouth bass might be an important predator of salmon smolts in the Ship Canal (Tabor et al. 2004b). While yellow perch have been thought to be a potential predator in the Ship Canal, no evidence shows yellow perch play a substantial role in predation on juvenile salmon there. Recently, rock bass have been observed in the Ship Canal. These fish may be another predator of juvenile salmon because rock bass can reach 8.4 inches FL in length (R. Tabor pers comm). Tabor et al. (2004b) noted that catch rates of predators were generally low in Portage Bay. Few piscivorous fish have been found in Salmon Bay and the Fremont Cut (Tabor et al. 2004b).

Smallmouth Bass

Smallmouth bass consume smolts in the Ship Canal between mid-May and July. Tabor et al. (2007a) studied predators in the Ship Canal from the end of April to the end of July in 1999. They and estimated that about 3,400 smallmouth bass were in the area and could consume juvenile salmon. Smallmouth bass were found to be more important predators than largemouth in the Ship Canal. Smallmouth bass 5 inches FL eat salmon, with the greatest consumption rate in June when salmon were about 50% of the bass diet. Tabor et al. estimate that the smallmouth bass predation level on the Chinook smolt population ranges between 0.4 and 3%.

Fine-scale acoustic telemetry of smallmouth bass indicates they are usually closely associated with one of three habitat types: 1) overwater structure, 2) steep sloping riprap or bulkhead, or 3) the offshore edge of aquatic plants (Celedonia et al. 2008b). Another study tracked smallmouth bass released near the mouth of Union Bay and determined that most remained in the littoral zone within that same area (Fayram and Sibley 2000). The researchers estimated that smallmouth bass densities in the Ship Canal were about 34 times higher than in Lake Washington. Tabor et al. (2007a) found that smaller Chinook smolts used habitats more similar to those of smallmouth bass than the habitats used by larger Chinook smolts. This was especially the case during the warmer part of the outmigration season when bass consumption rates were higher. Most smallmouth bass inhabit the Ship Canal from March or April until July or August. During the fall and winter, bass migrate from the Ship Canal into Lake Washington (R. Tabor unpub data).

Largemouth Bass

As with smallmouth bass, largemouth bass consume smolts between mid May and July. Between April and July 1999, Tabor et al. (2007a) estimated there were about 2,500 largemouth bass in the

Ship Canal capable of consuming juvenile salmon. Largemouth bass consumed salmon at a generally low rate and only fish that were 5.8 to 9.8 inches long were observed preying on salmon. Largemouth bass also consumed more coho than Chinook or sockeye salmon. Largemouth bass were noted to be more common in vegetated areas with gentle slopes and fine substrates such as south Portage Bay, Lake Union, and Salmon Bay. Tabor et al. thought smolts tended to be less concentrated in largemouth bass habitat than in smallmouth bass habitat.

Northern Pikeminnow

Northern pikeminnow also consume salmon in the Ship Canal. Tabor et al. (2004b) studied predator diets between April and July 1999. They found that about 45% of the northern pikeminnow diet consisted of salmon. Of those, 45% were Chinook salmon smolts, 40% were coho and 15% were sockeye. Most of the consumed juvenile salmon appeared to be subyearling fish. Tabor et al. could not derive a population estimate for northern pikeminnow. The distributions of northern pikeminnow are not well known. It is possible their habitat use patterns overlap with juvenile salmon more than do those of the two bass species. Because salmon make up a substantial portion of northern pikeminnow diet, this species could be a significant predator if their population size in Ship Canal is large. Pikeminnow appear to be more mobile than bass and congregate at areas with many smolts, particularly at the UW hatchery, along the shoreline of Gasworks Park, and at the Fremont Cut. Based on electrofishing catch rates in 1999 and recent gill netting and beach seining, northern pikeminnow in the Ship Canal are abundant in Portage Bay near the UW hatchery outflow in May and June and in Lake Union and the Fremont Cut in July (R. Tabor unpub data).

3.1.4 Passage at the Hiram M. Chittenden Locks (Locks)

Studies of juvenile salmon passage at the Locks emphasize passage timing and rates, passageways, and fish survival. Upon reaching the Locks, juvenile salmon must get through the Locks structure to reach Puget Sound. The Locks have physical conditions that are important context for understanding how fish move through the Locks area (see Chapter 2).

When juvenile salmon migrate into the Locks area, they are exposed to complex salinity, oxygen, and temperature conditions. Salt- and freshwater mixing is constrained by the Locks. At the same time, there is saltwater at depth upstream in the Ship Canal due to lock operations. This saltwater develops into a saltwater wedge that underlies the freshwater in the canal. The saltwater wedge has traveled as far as the Montlake Cut in the past. However, Ecology regulations require that salinity not exceed 1 ppt at the University Bridge in the Ship Canal. The Corps manages water operations at the Locks to meet that condition. The limited mixing and saltwater intrusion can lead to low levels of DO, particularly when water temperatures are high above the Locks.

3.1.4.1 Passage Timing and Rates

Over the last 10 years, passage timing through the Locks predominantly has been determined by monitoring the number of fish using the flumes and seining for fish in the large lock chamber. The routes provide access to Puget Sound at various water depths (Figure 19). PIT-tag and purse-seining data show peak passage periods for sockeye salmon first in late April/early May, coho salmon in May, and both natural origin and Issaquah hatchery Chinook salmon between late May and mid-June. Peak passage of steelhead smolts occurs generally in May (WDFW 1996, Fresh and Luchetti 2000). Migration timing of smolts has resulted in two general size distributions migrating at different times through the Ship Canal: 1) larger fish passing the Locks first and 2) a mix of large and medium-sized fish passing later in the season (DeVries and Hendrix 2005a). While the smolt outmigration at the Locks has been studied for years and relative timing is understood, counts of outmigrants are still rough estimates.

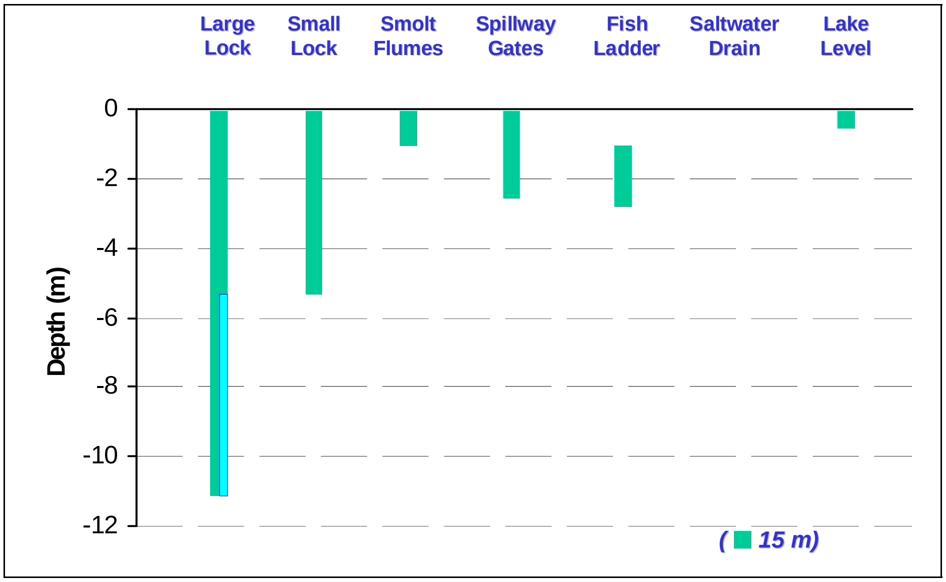


Figure 19
Optional passages for juvenile salmon through the Locks. Fish can only access each pathway at certain depths. Depths are relative to full pool. For the large lock, the saltwater barrier depth is indicated with a lighter blue bar

Source: Corps 1992

Lunar Phase

The moon appears to influence seasonal passage timing. The PIT-tagging studies reveal a strong relation between lunar phase and when each species begins to pass through the Locks. Passage at the Locks appears most substantial within a few days of the date that the moon was at apogee (farthest from the earth). A weaker relationship was observed for the quarter moon phase (DeVries et al. 2004). The relationship was strongest for Chinook salmon smolts and weaker for coho salmon smolts. This phenomenon was consistent across all 4 years between 2000 and 2003. The relationship was not as strong in the 2004 and 2005 data, although both years had similar passage timing distributions. The similarity between the 2004 and 2005 data—which were years with relatively warmer spring temperatures—suggested a possible over-riding influence of water temperature on the lunar effect (DeVries et al. 2006).

Daily Passage Timing

The rate at which smolts pass the Locks fluctuates hourly with most passage occurring during the day. Annually, some years show slight peaks occurring in both morning and afternoon (1997 and 2002). Sometimes only a single peak in passage is apparent (e.g. midday in 2001, late morning in 2003). Passage rates are uniform in some years (1998, 2000, and 2004).

More than 90% of PIT-tagged smolts passed through the flumes during daylight on days the flumes were open 24 hours (BioSonics 2001, DeVries et al. 2005). Sockeye salmon show the strongest daytime passage behavior, with no fish passing at night in 2000 and very few in 2001. Peak passage was mid-morning overall. In general, hourly passage timing distributions did not significantly differ among stocks for a given species in any given year (α=0.05). The daily variation in smolt passage timing may reflect daily vertical migration in the water column. Hydroacoustic data suggest smolts (and other fish) have a greater tendency to move towards the surface during the day and towards the bottom at night (DeVries et al. 2006). Beginning in 2002, the daytime passage trend was used to revise operations to conserve water.

3.1.4.2 Habitat Use and Behavior

The behavior of smolts at the Locks influences their passage through the Locks structure. Smolts may pass through one of five main routes, with each route presenting a different possibility of injury or mortality (see Figure 11). The five routes provide access to Puget Sound over various depths (Figure 20). The routes also differ in their attractiveness to smolts based on velocity, temperatures, salinity, and perhaps other, unknown factors. This section describes studies that have looked at the five passageways through the Locks to see how operational and environmental conditions affect route choice.

For juvenile salmon, the primary routes through the Locks are the spillway/smolt flumes and large and small locks. Spillway passage can occur through six bays, two of which contain smolt flumes, depending on spillway operations. If fish pass through the Locks, they may travel through the lock chambers or become entrained in the lock chamber filling culverts. Outmigrants can also pass the Locks via the adult fish ladder or the saltwater drain. Lock operations and environmental conditions such as water temperature influence both passage route choice and rate.

A pilot fine-scale acoustic tracking study in 2003 found that Chinook salmon smolts upstream of the Locks were mostly located near the entrances to the smolt flumes, and near the entrance to the large locks and the saltwater drain (Johnson et al. 2004b) (Figure 21). Coho salmon at the Locks occurred most frequently at the mouth of the spillway flumes, on the north side of the spillway forebay, and just above the entrance to the large locks. Coho were generally located deeper than Chinook smolts.

A large fraction of smolts pass through the smolt flumes or over the spillway when the spillway gates are open, particularly early in outmigration season before water temperatures increase. Later in the season, studies suggest that most fish pass through the large lock. Preliminary investigations indicate that few fish get through the Locks by passing through the small lock, saltwater drain, or fish ladder. The fine-scale acoustic tracking study of salmon smolts in 2003 found that of the 11 fish successfully tracked at the Locks, only 3 fish used the flumes (Johnson et al. 2004b). However, given the small sample size in the study and the late study period, the data do not support strong conclusions. Tracking studies conducted by the USFWS in 2006 to 2008 should provide additional information about route selection by Chinook smolts, and coho to a lesser extent. The discussion that follows focuses on each potential passage through the Locks.

Smolt Flumes and Spillway Gates

Smolt flume passage rates have been studied using PIT tagging and visually counting smolts in the flumes. These studies show that the estimated number of smolts passing through the flumes is orders of magnitude greater than the estimated number entrained in the large lock filling culverts (Johnson et al. 2003a, 2004a, DeVries and Hendrix 2005a). Smolts appear to primarily use the spillway in large numbers (40-60% of the total passing per day) when water temperatures are less than 66ºF (19ºC). However, there is a consistent decrease in detection rates in the flumes during outmigration season. Detection rates of individual groups released on a given day are generally high in May, but then decline steadily (see Figures 17 and 18). Studies also found that the number of fish using the flumes decreased later in the season (Johnson et al. 2004a, DeVries and Hendrix 2005a). Fewer fish using the flumes appears to reflect the influence of water temperature on passage behavior.

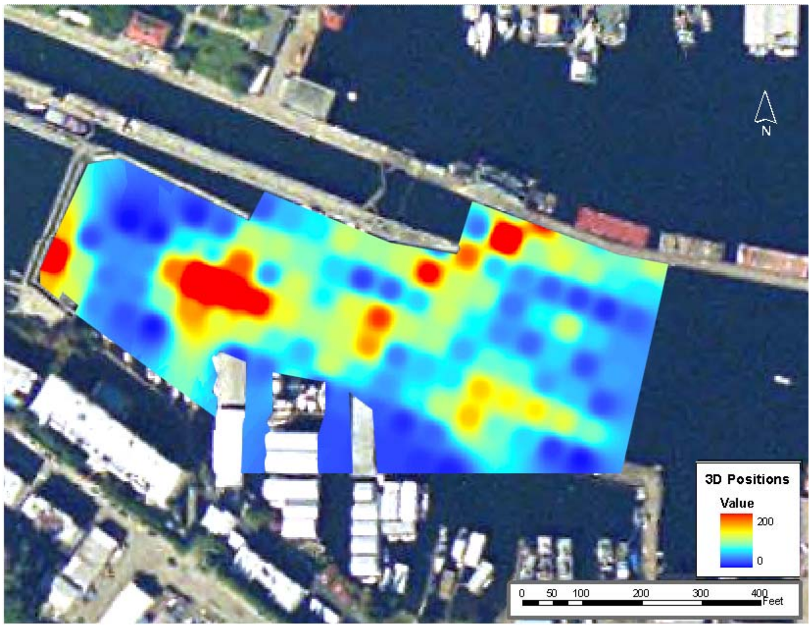


Figure 20
Chinook salmon positions at the Locks. Blue indicates no usage and red indicates highest usage. Colors between show a gradient
Source: Johnson et al. 2004b

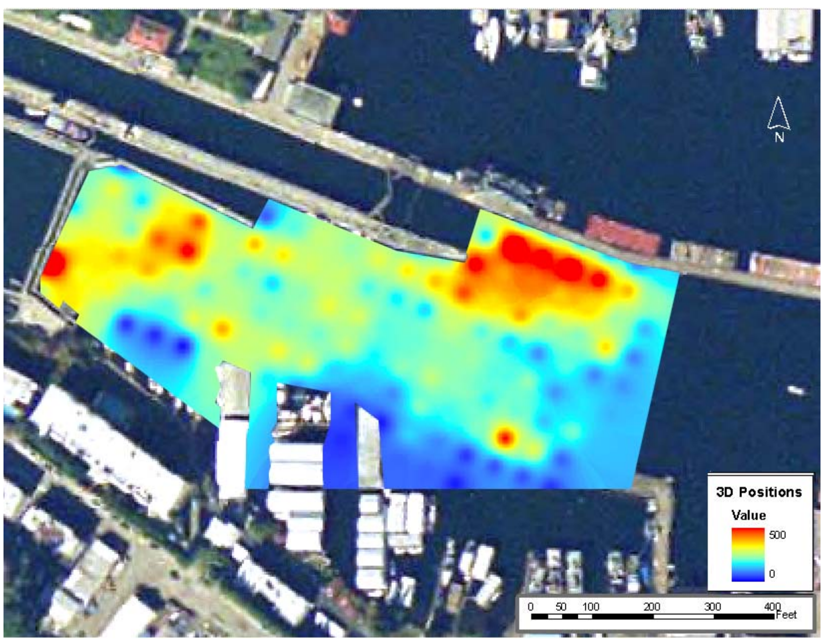


Figure 21
Coho salmon positions at the Locks. Blue indicates no usage and red indicates the highest usage. Colors between show a gradient

Source: Johnson et al. 2004b

Flume passage rates are also affected by flows. There is a relationship between decreasing flume flow rate later in the season (a result of water management) and the decreasing number of fish using the flumes as water temperature increases. At the same time, the number of fish arriving at the Locks decreases because they are nearing the end of the outmigration period. Nonetheless, passage numbers of PIT-tagged Chinook salmon in 2002 and 2004 appeared to increase with total flume flow rate. This was particularly evident in the 1 to 2 weeks after the moon was at apogee in 2004 (DeVries et al. 2005, DeVries and Hendrix 2005a). Among the flumes, passage rates appear to be highest per unit volume of water in the two large flumes. The smaller flumes consistently underperformed the larger flumes with the exception of the year 2003. However, when flows increase above about 200 cfs, there is no longer a large increase in smolt passage. This suggests that operation of one large flume at 130 cfs and a medium flume at 90 cfs makes good use of smolt flumes. This tactic may also save water.

Passage rates in the flumes also increase in response to lock operations. The passage rate of PIT-tagged smolts in the flumes during small lock fills averages twice the rate of the non-fill period (DeVries et al. 2005). However, small lockages do not influence passage rates in the flumes at night. During the night, smolts are in deeper water and do not use the flumes. During the day, lock filling operations influence passage timing in the flumes through changing velocity patterns in the forebay, inducing smolts to move as a response. Increased swimming may increase the probability that outmigrants encounter and pass through the smolt flumes.

Spillway Gates

In addition to the flumes, smolts can pass the Locks over the spillways when the spillway gates are open. Biosonics, Inc. (2001) assessed juvenile fish passage under one of the spillway gates. Fish passage through the spillways was generally higher when passage rates through the flumes were lower, and vice versa. Passage through the spillway gates is thought to be safe for smolts, but this has not been studied. Smolts appear to primarily use the spillway in large numbers (40-60% of daily total) when water temperatures are less than 66°F (19ºC).

Large Lock and Large Lock Filling Culverts

The large lock and associated filling culverts are thought to be the second most frequent route for smolts through the Locks. Historically, passage through the large lock filling culverts significantly increased the risk of substantial injury and mortality to smolts. The Corps has taken actions in recent years to reduce entrainment, injury and mortality. Studies below are focused on fish upstream of the Locks becoming entrained into the filling culverts. It is possible that smolts within the large lock chamber could become trapped in the filling culverts during downstream lockages. However, this matter has not been studied.

Preliminary analyses from microacoustic studies at the Locks show that at the entrance to the large lock outmigrating Chinook salmon smolts are primarily located near the water's surface while surface water temperatures are less than 65ºF (18.5ºC) (M. Celedonia pers comm). This generally occurs in June (Figure 22). When temperatures warm to 67ºF (19.5ºC) and higher, fish distribute throughout the water column. This concentration generally occurs in July. Juvenile Chinook are also more likely to use deeper areas during late afternoon, but come back up to the surface at night.

Several studies have looked at smolt entrainment into the large lock filling culverts. Passage rates through the large lock chamber itself have not been studied. Some studies indicate that entrainment numbers increase with nearsurface water temperature. This finding was partially discovered because researchers seining for fish below the Locks were catching the same number of fish even though smolt detections in the flumes declined (Figure 23) (Simenstad et al. 2003,

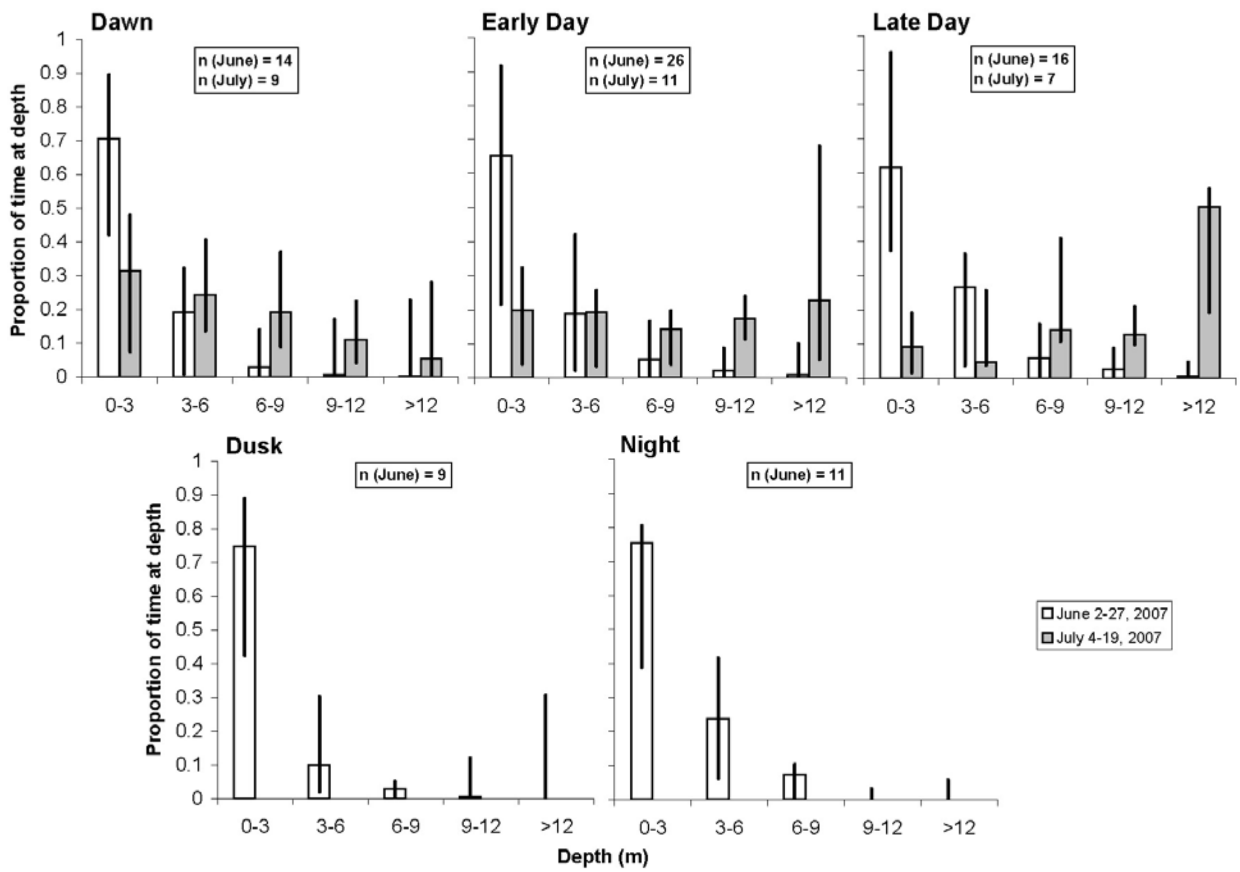


Figure 22
Diel depth distribution of tagged Chinook salmon smolts at the entrance to the large lock, June-July, 2007. Median proportion of time spent at depth is shown and 10th and 90th percentiles are indicated with error bars

Source: M Celedonia and R. Tabor ubpub data

DeVries and Hendrix 2005a). That finding suggests that fish passing the Locks were using a different route than the flumes.

Year 2004 studies show that smolt entrainment in the filling culvert remains extremely low (90% of values <0.05%) until the third week in June when nearsurface water temperatures are nearly 64.4ºF (18ºC) (DeVries and Hendrix 2005a). Earlier arriving, surface-oriented smolts are thought to have a lower risk of entrainment than later arriving smolts. Late migrating smolts are thought to be at a greater risk of entrainment when surface water temperatures increase and smolts seek deeper water. However, this assumption was refuted by the 2004 studies because the fish estimated as entrained by volume of water in the culverts was similar irrespective of water temperature.

Year 2004 studies indicate that the number of smolts entrained in the large lock filling culverts largely reflect large lock fill volume (DeVries and Hendrix 2005a). Of the factors evaluated, the most effective change in Locks operations for reducing entrainment appears to be reducing the total daily volume of fills in the large lock. Large-lock entrainment mortality is estimated at less than 0.01 to 0.1%. Therefore, it appears that changes in culvert filling operations may have little impact on the population.

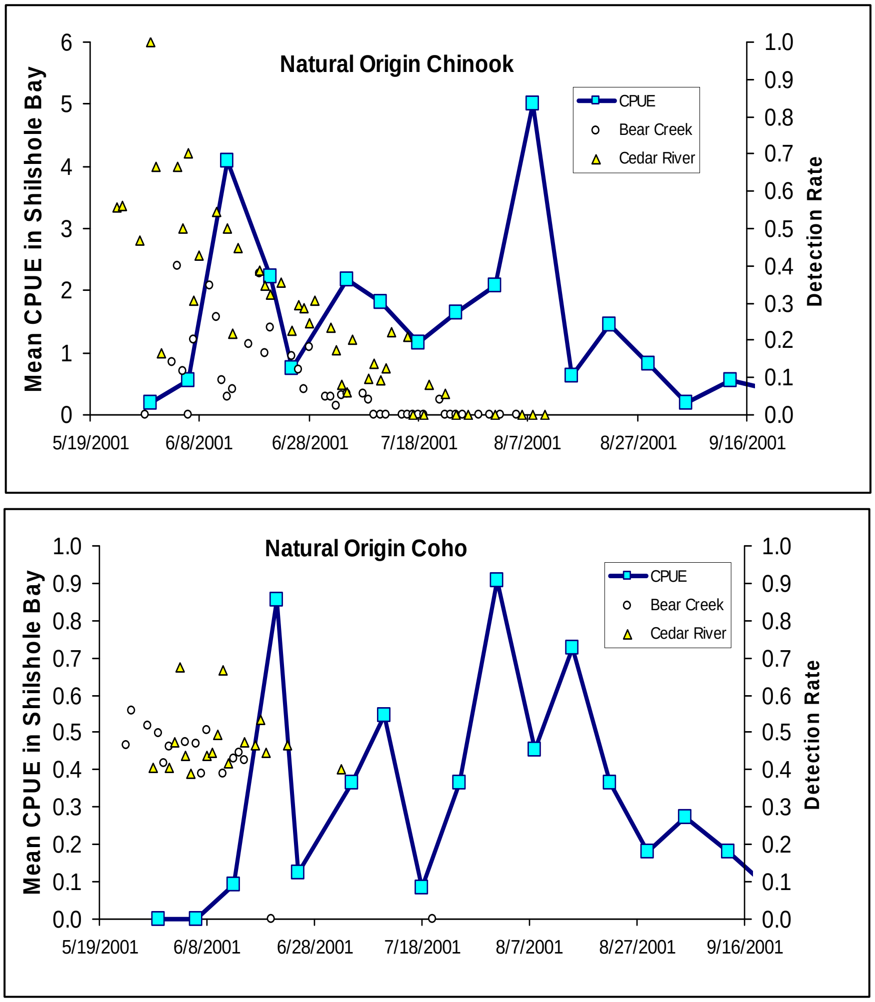


Figure 23
Average catch size (blue line is catch per unit effort or CPUE) of natural origin Chinook and coho salmon smolts below the Locks and PIT-tag detection rates in smolt flumes (symbols) in 2001. Estimated release date for each group plus median travel time for each species: ~27/21 days for Bear Creek/Cedar River Chinook and ~25/27 days for Bear Creek/Cedar River coho

Source: DeVries and Hendrix 2005a

Small Lock and Small Lock Filling Culverts

There have been only exploratory investigations into use of the small lock and the small lock filling culverts. That research used an underwater video camera, which showed little use of the small lock or its filling culverts. However, these investigations did not look at use throughout the outmigration season (C. Ebel pers comm).

Fish Ladder

The fish ladder passes very few migrating juvenile salmon. In 1994, before the first flume installation in 1995, 1% of an estimated 3 to 5 million smolts used the fish ladder (D. Seiler unpub data). PIT-tagging data from 2004 and 2005 indicate a much smaller proportion now uses the fish ladder. All juvenile fish passing through the fish ladder from top to the bottom pools are presumed uninjured.

Saltwater Drain

The number and proportion of juveniles passing through the saltwater drain has not been studied.

Water Temperature and Route Choice

Because temperature influences vertical position of smolts in the water column, water temperature may affect passage routes for smolts at the Locks. Very few smolts have been observed to pass through the flumes after surface temperatures exceed about 66 to 70ºF (19-21ºC) (Figure 24). It is hypothesized that warmer water temperatures cause smolts to migrate at greater depths in the Ship Canal where the water is cooler, and the use of deeper waters causes more smolts to use the small and large locks as passages past the Locks. However, the decline in the numbers of smolts using the flumes later in the outmigration season could also be a reflection of fewer fish passing the Locks as the outmigration season is ending, or could reflect that some of the later migrants may also residualize in Lake Washington. Results from microacoustic tracking studies by the USFWS at the Locks were not available for this report. Those reports will provide more information on water temperature and route choice.

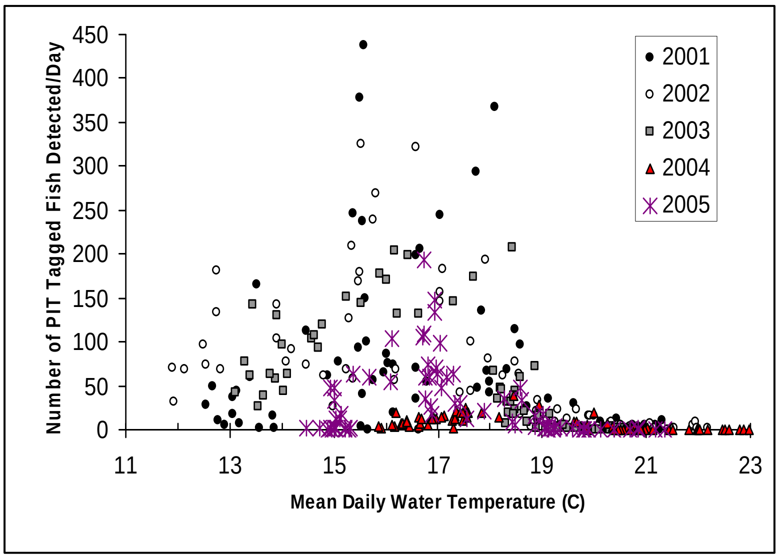


Figure 24
Daily PIT-tag detections at the Locks by average daily nearsurface water temperatures in the Ship Canal during smolt outmigration, 2001-2005

Source: Corps (Temperature data); PIT tag data DeVries et al. 2006

Flow and Route Choice

Variations in water velocities create flow fields, which can affect the migration of salmon smolts. Studies at the Locks have examined how operations of the small and large locks create different flow fields in the Locks forebay. These flows may be manipulated to direct salmon through safer passage routes.

To date, fish distribution has not been found to correlate with flow fields near the Locks. Mobile hydroacoustic surveys have indicated patchy distributions of fish in the area upstream of the entrance to the large locks and inside the large lock chamber. Small-, medium-, and large-sized aggregations of fish were found irregularly throughout the survey area (Biosonics 1997). No discernible pattern was evident in the vertical distribution of these aggregations.

PIT-tag data suggest a correlation between the small lock filling and flume passage rate. Higher numbers of fish appear to pass the smolt flumes during small lock fill. Although PIT-tagging data suggest a correlation, the evidence does not yet establish a cause and effect relationship between small lock filling and increased flume passage. Velocity measurements (Johnson et al. 2001a, 2003b) and steady state (i.e. time averaged) hydrodynamic numerical modeling (University of Iowa unpub data) are underway. Assessments indicate that larger flumes create larger velocity fields in front of their entrances, which may relate to the larger flumes passing more fish (Johnson et al. 2003b). Limited data suggest the passage rate of PIT-tagged smolts in the flumes during small lock fills is, on average, twice the rate when the small lock in not filling (DeVries et al. 2005). However, small lock operations do not appear to influence daily variation in flume passage, suggesting that small lock operations only influence this behavior during the day (DeVries et al. 2006). Hydrodynamic modeling may provide more information about how structural or operational changes in the Locks may influence route choice.

Recycling through the Locks

A small portion of salmon smolts *recycle* through the Locks. Recycling refers to the fish behavior of passing downstream through the Locks once, then passing back upstream before heading back through the structure again. A small number of fish recycle more than once. Upstream passage mostly likely occurs through the large or small locks. Hatchery Chinook salmon smolts released directly into the flumes as part of calibration testing and those from the UW hatchery were found to recycle the most (DeVries et al. 2003, 2005). Weaker recycling behavior was seen in natural origin fish, which generally take less time to pass the Locks. Some natural origin Chinook and coho salmon have also been observed to recycle more than twice in both 2002 and 2003. Sockeye salmon juveniles were never observed to recycle.

Recycling may reflect extended rearing times in the vicinity of the Locks and/or the need for further acclimization to saltwater. In all years, the time between first and second detections shortened as the outmigration season progressed (DeVries et al. 2003, 2005). Recycling times were not found to be correlated with either the group of fish released (which shared a common background and release timing) or the size of the fish when released.

Recycling may simply reflect a fish being in the wrong place at the wrong time and becoming entrained in the large lock chamber. One study of fish distribution below the Locks determined that fish near the entrance to the large lock-filling culvert were distributed in two distinct groups: 1) near the bottom and 2) near the surface (Johnson et al. 2001a). Although species in each group were not determined, the composition may reflect vertical salinity differences with downstream migrant smolts remaining in the upper freshwater layer when the upper large Lock gates are opened, and shiner surfperch (*Cymatogaster aggregata*) residing in the lower layer. Fish in the surface layer below the Locks would be less likely to be entrained in the large lock during gate openings.

The causes for recycling and the effects on salmon smolts are poorly understood. However, given the small number of smolts that exhibit the behavior, it is not likely to strongly influence Lake Washington salmon population survival and fitness.

3.1.4.3 Survival Risks

Survival of smolts passing the Locks is not well understood. Given the large numbers of descaled, injured, and dead fish observed during lock operations in the 1980s and early 1990s, researchers focused on the large lock filling culverts. Studies primarily addressed entrainment of smolts in these culverts through the upstream entrances. Other studies have worked on ways to deter fish from becoming entrained in the filling culverts.

Large Lock Filling System Entrainment

Compared to all other passage routes at the Locks, entrainment in the large lock filling culverts is considered the most potentially harmful route for juvenile fish. It results in the highest direct and indirect mortality. Wounds, lacerations, and descaling during entrainment through the lock filling system reduce the survival of outmigrant salmon and steelhead (WDFW 1996, Goetz et al. 2001). Sharp-edged barnacles cover more than 80% of the filling culvert surface area. When combined with high water velocities, barnacles can lacerate and descale smolts as they pass through the culverts and into the lock chambers. Several 90-degree bends in the filling culverts can entrain smolts and cause them to strike against concrete and barnacles. High water velocities and pressure gradients can also injure fish.

Hydroacoustic studies show that the number of fish entrained in the large lock filling culverts varies each year and by Lock operations (Johnson et al. 2001a, 2004a). Full chamber fill events tend to trap more fish but occur less frequently, while upper chamber-only fill events trap fewer fish but occur more often (Figure 25). In both upper chamber-only and full fill events, the highest entrapment generally occurs during the night. In the full chamber, 2001 and 2002 were exceptions to this, with highest entrainment occurring around 8 am.

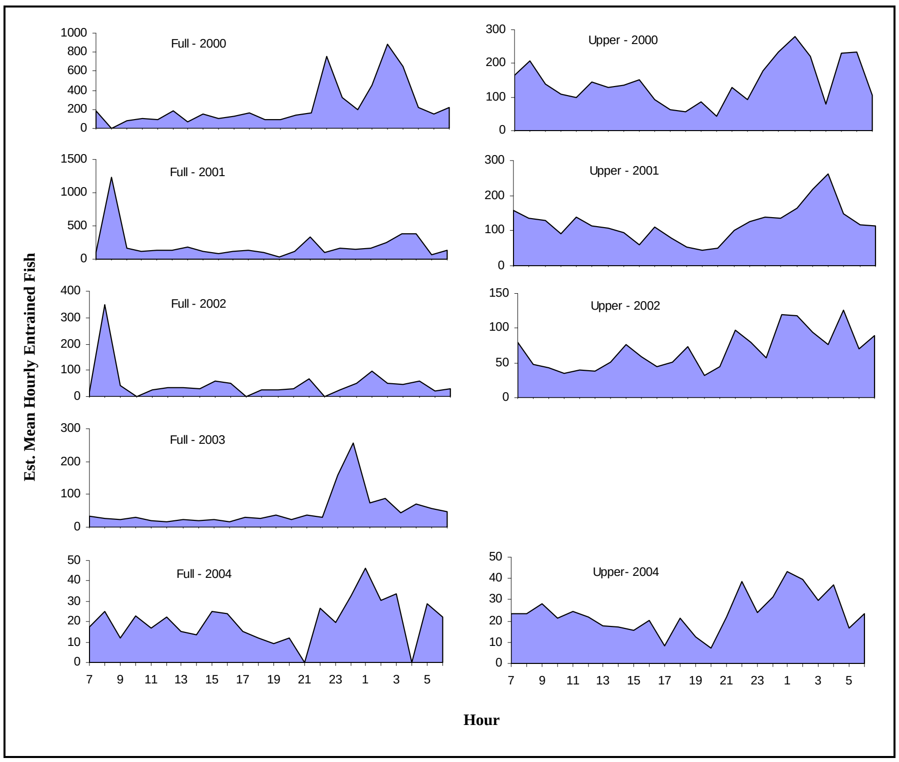


Figure 25
Hourly estimates of the average number of fish entrained in the large lock chamber filling culverts during full chamber (left) and upper chamber (right) fill events in 2000-2004

The depth of entrained fish also varies between day and night (Figure 26). During the day, entrained fish were distributed in greatest proportions at depths centered at the middle of the culvert entrances. Night distributions of trapped fish were deeper and near the floor of the culvert entrances.

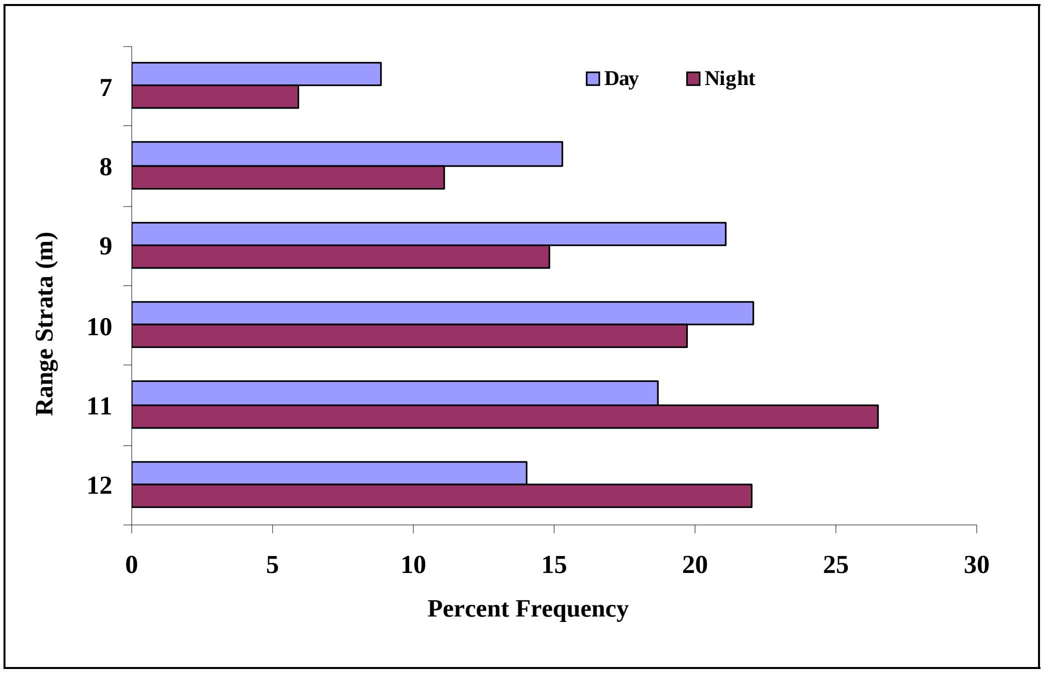


Figure 26
Depth ranges of fish entrained in the large lock filling culverts day and night in 2000-2004

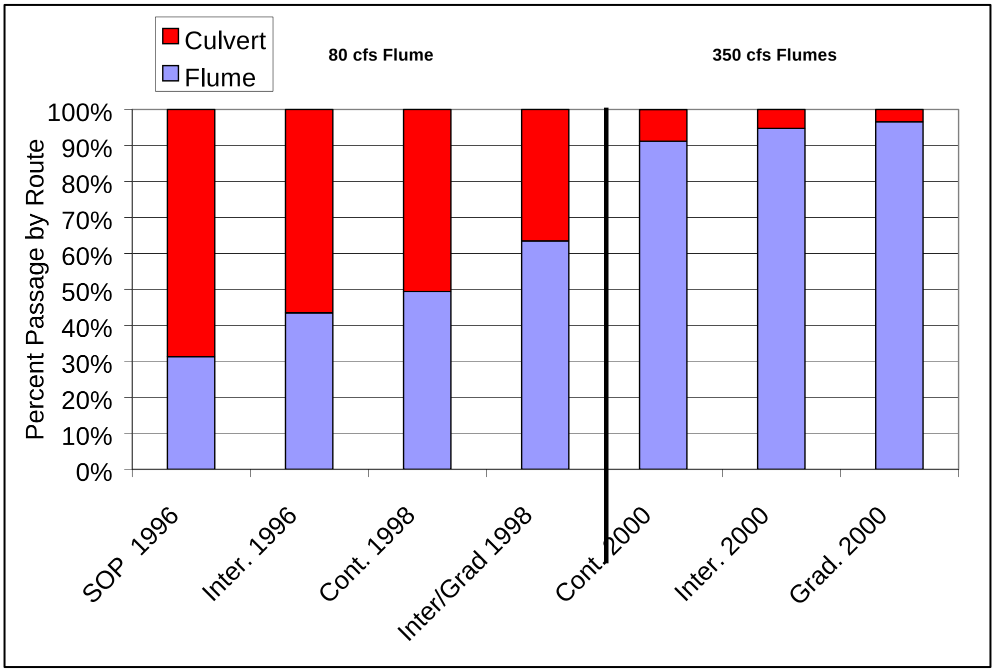
The number of fish entrained may depend on the rate at which the large lock is filled during lockages (Table 5). Slower fill rates are associated with smaller velocities. It is hypothesized that slower fill rates trap and injure fewer fish. Three different fill types were evaluated: *intermediate*, *gradual* and *continuous*. Each type has the following effects on entrapment:

- Intermediate fills reduced entrapment between 35 and 37% from continuous fills
- Graduated fills reduced catch by between 65 and 69% from a continuous fills
- Graduated fills reduced catch by between 45% and 51% from intermediate fills

Table 5
Large lock fill type, speed, time, and rate

Fill Type	Speed	Time (min)	Rate (ft/min)
Graduated	slowest	intermediate	fastest
Intermediate	14 - 16	10 - 12	6 - 8
Continuous	0.9 – 1.6	1.6 – 2.4	2.5 – 3.5

Fill rates impact fish passage (Figure 27). Irrespective of fill type, more fish pass through the flumes at the high flow rate. When fill rates are intermediate or graduated and three flumes are open at a velocity of 350 cfs, the fewest fish are entrained. Entrainment rates in the filling culverts more strongly reflect frequency and volume of large lock fillings as opposed to fill type, particularly later in the outmigration season as nearsurface water temperatures warm and fish inhabit deeper water (DeVries and Hendrix 2005a).



*SOP (standard fill)
Inter (intermediate fill types)
Cont (continuous fill types)
Inter/Grad (intermediate and graduated fill types)
Grad (graduated fill types

Figure 27
Estimated proportion of fish passing through Locks for 1 flume at 80 cfs or 3 flumes at 350 cfs*

Since 1999, all of the filling conduits of the large lock chamber have been cleaned of barnacles annually. Workers use high-pressure washing and scraping to clean the culverts to bare concrete. This practice has led to a 75% reduction in heavy descaling of fish in the large lock chamber. Before barnacle removal (1998), from 10 to 15% (13% on average) of smolts were heavily descaled when entrained and passed through the filling conduits in the upper half of the large lock chamber (Figure 28). After barnacle removal (fall 1999) 1 to 5% (3% on average) of smolts were heavily descaled when entrained (D. Seiler unpub data).

Photo: Annual barnacle removal from the large lock filling culverts

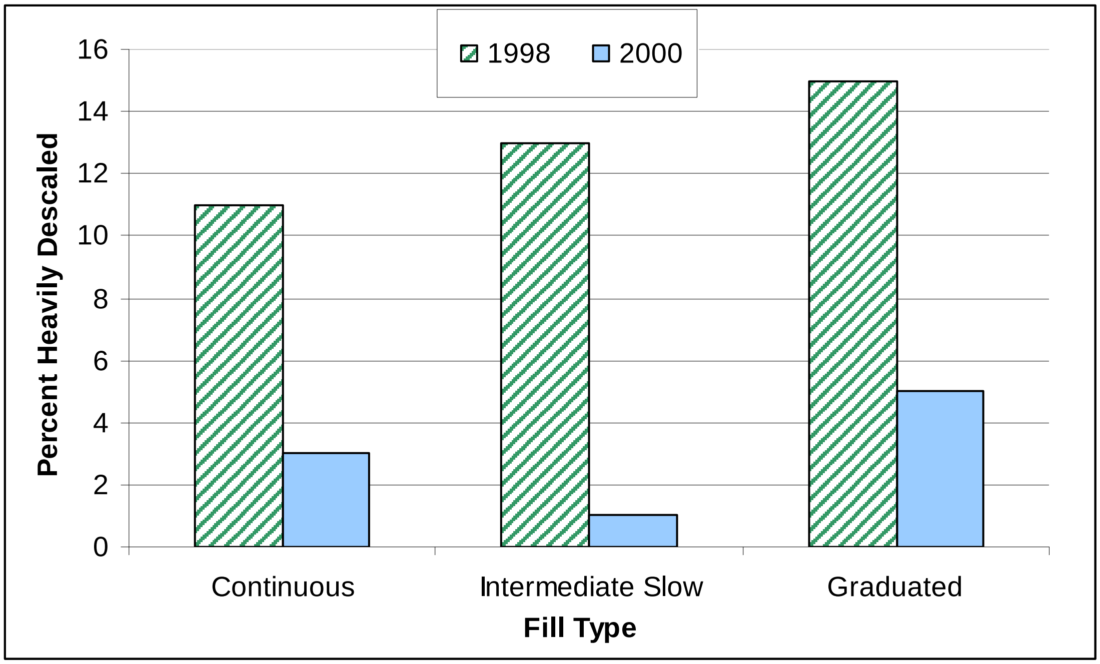


Figure 28
Percent smolts in large lock with heavy (> 10%) descaling before (1998) and after (2000) barnacle removal by three fill types

Source: D. Seiler unpub data

Little is known about entrainment in the small locks filling system. This passage route has not yet been assessed. However, it is likely to be less an issue than the large lock filling culverts because the large lock uses up to 25 times more water than does the small locks. The small locks are also generally free of barnacles.

Reducing Entrainment Rates

Two behavioral avoidance technologies have been evaluated to reduce entrainment in the filling culverts. The first was a low-frequency sound used to elicit avoidance response in juvenile salmon (Knudsen et al. 1992, 1994, 1997; Ploskey et al. 1998; Ploskey and Johnson 2001; Ploskey et al. 2001). The second was strobe lights.

Two low-frequency sound systems for guiding smolts away from the entrance to the large lock were tested. The sound treatment did not affect the density of salmon inside the lock chamber. No significant difference in the density of salmon was observed in the lock chamber between treatments or over time. Similarly, no significant difference was detected between sound treatments at different times of the day.

The use of strobe lights was tested to deter smolts from entering the filling culverts (Puckett and Anderson 1987, McKinley and Patrick 1988, Nemeth and Anderson 1992, Bernier 1995, Johnson et al. 2005). Strobe lights were installed around the perimeter and in front of the upstream north large lock filling culvert entrance in 1998 (Johnson et al. 2000; 2001b) and the upstream south entrance in 2002 (Johnson et al. 2003a; 2005). Split beam hydracoustic monitoring tests during daytime hours in 1998 indicated that most fish moved away from the filling culverts into shallower water when strobe lights were turned on (Figure 29). These findings were statistically significant.

When strobe lights were off, the distribution of fish in front of the culverts was relatively uniform, with slightly greater average densities 26.2 to 32.8 feet from the surface. Fish densities at the culvert depth decreased by 87% when strobe lights were on. Night tests were also conducted, but fish densities were too low at night in front of the filling culvert entrances for a meaningful analysis. Monitoring in 2002 gave similar results, indicating that strobe lights reduced entrainment by approximately 75%.

A study conducted in 2003 evaluated the possibility of habituation by smolts to strobe light operation at night (Johnson et al. 2004c). The estimated numbers of fish entrained when the strobe lights were operating all night long did not significantly differ from the numbers entrained when the strobe lights were operated for only 15 minutes before each fill event. This finding suggests habituation was unlikely to strobe lights during the night.

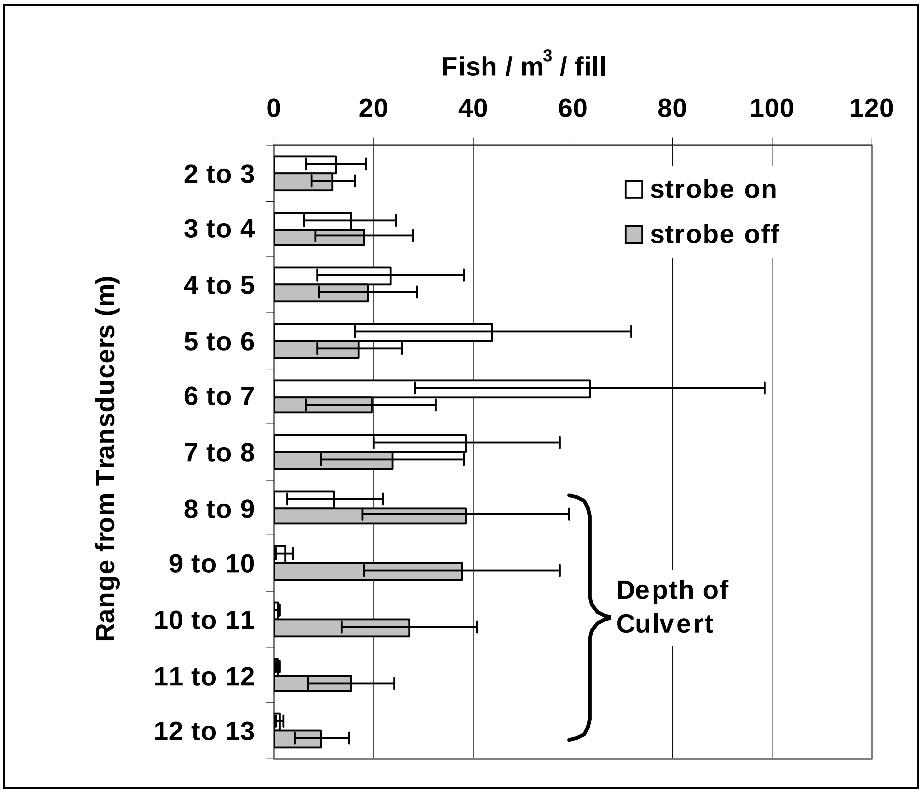


Figure 29
Average density of fish by depth under strobe on (white bars) and strobe off (gray bars) scenarios during daytime fill events at Locks (0800 to 1700 hours) from 9 to 20 May, 1998. Bracketed range strata indicate elevation of culvert entrances in range from transducers. Error bars indicate 95% confidence limits

Source: Johnson et al. 2001b

Predation

No detailed studies have been conducted to quantify predation at the Locks.

3.1.5 Estuarine Transition in Salmon and Shilshole Bays

This section addresses salmon smolt behavior below the Locks and summarizes research on how estuary alterations affect smolt survival. Very little information is available on juvenile salmon in Salmon and Shilshole bays.

3.1.5.1 Timing

PIT-tag and microacoustic tag data suggest that natural origin smolts of all species spend about 12 hours or less in the lower salinity lens below the Locks before transitioning to higher salinity water (Johnson et al. 2004b, DeVries et al. 2005). During beach seining, PIT-tagged Chinook and coho salmon smolts were recaptured below the Locks. Sockeye salmon smolts were not recaptured, indicating that they either spend very little time below the Locks before heading out to larger Puget Sound or that sockeye are not adequately sampled through beach seining. In another study, hatchery Chinook spent up to 3 weeks in Shilshole Bay, while natural fish were there less than 1 week (DeVries et al. 2005). Acoustic studies in 2004 found that tagged Chinook and coho took 13 and 11 hours on average, respectively, to reach the outer Shilshole Bay array after passing the Locks (Johnson et al. 2004b). Based on five Chinook and three coho detected within the Shilshole hydrophone array, residence time for Chinook was more than three times as along as that estimated for coho.

3.1.5.2 Habitat Use and Behavior

A pilot study on marine predators assessed juvenile Chinook salmon habitat use below the Locks (Footen 2000). Footen found that Chinook smolt habitat use was likely density dependent and that at low densities, the greatest numbers of smolts were found over cobble substrate. At higher smolt densities, smolts were found in large numbers over sandy substrates. When spill ceased, the number of fish caught below the Locks decreased dramatically. The lower captures could be a function of the end of the outmigration period, or indicate that, without spill, smolts are delayed above the Locks.

Another study captured juvenile salmon below the Locks in greatest numbers in June, with numbers dropping off in late June and early July (Simenstad et al. 2003). Chum and hatchery Chinook comprised the largest fraction of salmon caught. The chum salmon caught indicated that salmon from other Puget Sound basins move into the area downstream of the Locks because the Lake Washington system does not support any chum populations. Other species and natural origin Chinook stocks were found in much lower numbers, but were present below the Locks throughout the summer. Sockeye salmon were caught in lowest numbers, appearing only sporadically in the catches. Salmon were concentrated at a few locations in the bay early in the outmigration season, but spatial distributions became more even around the bay after June. Hatchery Chinook and natural origin coho smolts were found in higher densities closer to the Locks than further out in Shilshole Bay.

3.1.5.3 Survival Risks

Survival of smolts downstream of the Locks is related to their ability to adapt to higher salinity and cooler water, find food, and avoid predators. Many of the risks are not well-studied.

Abrupt Salinity and Water Temperature Changes

Water quality profile data collected below the Locks between 1999 and 2001 indicate a low-salinity lens less than 20 ppt in concentration located in the upper 3.3 to 9.8 feet of the water surface (C. Simenstad and W. Couch unpub data, D. Houck unpub data). This lens sometimes extends out to the railroad bridge and beyond depending on discharge at the Locks and tide. While there is concern that the rapid transition from freshwater to saltwater may affect smolt survival, this has not been studied downstream of the Locks. PIT-tag data collected in 2001 suggested that a rapid osmotic transition had occurred in many of the juveniles captured in the beach seine samples in the inner bay area, where salinities nearer the surface ranged from 15 to 20 ppt during spring outflow (DeVries et al. 2001). Research elsewhere has shown that juvenile Chinook salmon can make a sudden transition from freshwater to water with salinities as high as

16 to 20 ppt without apparent adverse survival effects (Macdonald et al. 1988, Healey 1991, Clarke and Hirano 1995, Kreeger 1995). However, transitions to higher salinities (>30 ppt) and the possibility of delayed saltwater mortality after an abrupt transition may affect smolts leaving the Lake Washington system (Clarke and Hirano 1995; Macdonald et al. 1988). Furthermore, Chinook smolts in other systems preferably hold at areas of low salinity (M. Celedonia pers comm).

Smolts passing through the flumes also experience an initial decrease in temperature as they enter the mixing zone of the flume outfall. Most studies of temperature change on salmon smolts have involved sudden temperature increases, which likely have a greater adverse effect than sudden temperature decreases (Fagerlund et al. 1995). Sudden temperature decreases may result in elevated stress levels, but whether the effect is significant is unknown. The mixing zone below the flumes contains areas where temperatures are intermediate to temperatures in the Ship Canal and Shilshole Bay, which may aid with acclimization to both salinity and temperatures downstream of the Locks.

There are potential effects on saltwater smolt survival from elevated water temperatures in the Ship Canal (e.g. premature smolting and desmoltification) and from passage route choice through the Locks (DeVries and Hendrix 2005a). These potential impacts are uncertain.

Food

A stomach contents survey of salmon below the Locks was conducted over spring and summer of 2001 (Simenstad et al. 2003). The research determined that the Ship Canal was a major source of juvenile salmon prey in Shilshole Bay. Abundant taxa included freshwater cladocerans, and calanoid and cyclopoid copepods. The sampled stomachs contained a variety of these and other organisms, and did not indicate a food shortage.

Predation

Little is known about predation on juvenile salmon directly downstream of the Locks. Birds and marine mammals have been observed feeding on juvenile fish below the Locks, but the prevalence of this has not been studied.

Marine Mammals

Puget Sound supports a variety of marine mammals, including cetaceans (e.g. orcas, gray whales) and pinnipeds (e.g. California sea lions, harbor seals). Within the Locks area, California sea lions and harbor seals frequent the saltwater side of the facility. Steller sea lions are only rarely sighted. Sea lions and seals feed on a variety of fish species, including salmon. Sea lions have been known to congregate below the Locks periodically to feed on salmon and steelhead.

Fish Predators

One study has assessed piscivore predation of juvenile salmon in marine habitats below the Locks (Footen 2001). The researcher used beach-seining techniques for fish capture and gastric lavage for stomach content analysis. Seven study locations were chosen in both the Inner Bay (from immediately downstream of the Locks to Shilshole Bay) and Outer Bay (Shilshole Bay). These locations were typically sampled from April through September of 2000.

Results indicated that most piscivores were caught in the inner bay, and overall catch rate of predator fish was low. Juvenile Chinook salmon were found in the diets of cutthroat trout, char, and staghorn sculpin in the Inner Bay but were not present in the predators sampled in the Outer Bay. Significant predator prey overlap was limited to the inner bay, with the greatest overlap of predators and juvenile Chinook occurring near the railroad bridge. Interestingly, neither juvenile coho nor sockeye salmon were identified in the diets of any predators sampled. Based on these limited data, predation on juvenile salmon within the inner bay littoral zone appeared to be minimal. Large, piscivorous char and cutthroat trout have been captured in nearshore areas of Puget Sound (Duffy and Beauchamp 2008, unpub data). However, their impact on outmigrating juvenile salmon is not known.

3.1.6 Puget Sound Residency

The studies conducted as part of the LWGI have not examined issues related to salmon residency in and outmigration from Puget Sound. The pelagic region of Puget Sound represents an important summer rearing habitat for Chinook and coho salmon, which generally spend July through September, and maybe longer in this area (D. Beauchamp pers comm). These fish are found at shallow depths in pelagic waters. However, Lake Washington basin Chinook are disproportionately under-represented in annual, pelagic, midwater trawls during July and September in Puget Sound (E. Duffy unpub data). Given outmigration conditions and timing, there are concerns about how Lake Washington basin salmon fare in the marine environment and whether conditions in the basin and at the Locks cause any delayed mortality. A bioenergetics model estimate of cutthroat predation on juvenile Chinook showed only a minor impact on the population (Duffy and Beauchamp 2008).

3.2 Adults

This section summarizes results of recent research findings on return migration of adult Chinook, coho, sockeye salmon and steelhead. The findings are organized according to passage through the study area:

1. Puget Sound Residency
2. Estuarine Transition
3. Passage at the Locks
4. Ship Canal and Lake Union Migration
5. Lake Washington

Information is further grouped into three categories: timing, habitat and behavior, and survival risks. Then, individual study topics are presented. When appropriate, study summaries are organized by species.

3.2.1 Puget Sound Residency

Puget Sound residency varies by species. While adult salmon in the Lake Washington basin are impacted by their time in Puget Sound, this information is outside of the scope of the LWGI. In some cases, very little is known about adult salmon from the Lake Washington basin in Puget Sound. For Chinook and coho salmon, both Puget Sound resident and ocean-rearing populations occur. Puget Sound resident fish grow to adulthood within Puget Sound. Ocean-resident fish spend time in other parts of the Pacific Ocean during adulthood.

Recent results indicate that Puget Sound-resident Chinook salmon have higher levels of persistent organic pollutants than ocean-migrant Chinook as a consequence of their feeding in the Puget Sound food web (O'Neill et al. 2006). Chinook are also the primary prey of the federally-listed, endangered orca, representing up to 90% of the diet of the Southern Pod during some times of the year (Orca Workshop, Seattle, WA, May 2006).

3.2.2 Estuarine Transition

Little is known about adult salmon use of Salmon Bay downstream of the Locks. It appears that adult fish use the areas above and below the Locks as a staging area before freshwater entry. This may be a matter for future study.

3.2.2.1 Timing and Behavior

Adult salmon likely inhabit Shilshole Bay in the summer. There is no characteristic behavior for any species. Adult fish may enter Shilshole Bay and head to the Locks, or leave the bay for other Puget Sound areas before they enter the Locks. Fish may also hold in Shilshole Bay before passing at the Locks, but this behavior has not been documented.

3.2.2.2 Survival Risks

The only known survival risk to adult salmon in Salmon Bay is from pinnipeds downstream of the Locks. Sea lion and seal predation on steelhead in the late 1970s was thought to be detrimental to an already depleted population. In 1985, NMFS, WDFW, the Seattle District of the Corps, and the Muckleshoot and Suquamish Indian Tribes joined in an effort to protect the steelhead run by controlling sea lion predation downstream of the Locks.

Predation reduction efforts included harassment of sea lions using underwater firecrackers, chaser boats, acoustic harassment devices (AHD), acoustic deterrent devices (ADD), taste aversion conditioning, experimental barrier nets and marine mammal relocation. In the mid-1980s, an ADD sound emitter was installed near the Locks. The ADD is a behavioral barrier to sea lions. It emits sounds in a frequency range that excludes most marine mammals from the area (Fox et al. 1996). In 1996, the state was granted a permit to remove *nuisance* animals when sea lions were observed to eat more than 10% of the steelhead counted through the fish ladder in a week. WDFW removed three notorious sea lions by March of 1996. The following year, no young sea lions were observed to replace these older males (Corps 2001a). Although the ADD and removal deterred sea lions, predation greatly decreased in 1993 as steelhead numbers drastically declined.

While no studies have been conducted since pinniped predation on steelhead, coho, and other adult salmon below the Locks has been observed. In September 2005 a Corps employee observed a sea lion feeding on coho salmon it obtained from a Suquamish Tribal gill net set immediately below the entrance of the Ship Canal fish ladder. Harbor seals and California sea lions are major predators of coho.

There is evidence that marine mammals in the area are accustomed to ADD and will enter the ensonified area to feed on salmon. The first occurrence was noted in September 2001, where a marked sea-lion captured a coho in the ensonified area, while sea lions were frequently observed during the coho run (NOAA 2002). More recently, predation occurred during mid-September 2007 near the height of the coho run and tribal fishing. Sea-lions entered the tailrace area and ate an unknown number of coho caught in gillnets in the ensonified area. There was one sea lion observed in the fish ladder during Chinook salmon migration in 2008 (F. Goetz pers comm). These sightings raise the possibility that one or more of these sea lions may already have developed a tolerance to the acoustic devices (NOAA 2002).

3.2.3 Passage at the Locks

This section describes adult fish passage at the Locks and outlines what is known about fish residence in the Locks area. Acoustic- and PIT-tagging efforts have led to many of the results presented in this section.

3.2.3.1 Passage Timing and Rates

Different species of salmon return to Lake Washington at different times. Steelhead begin their upstream migration first, arriving and passing through the Locks between January and May. Of the salmon species, sockeye salmon begin their upstream migration next, migrating through the Locks from late May through October. The main run of sockeye is from early June through August. Sockeye are followed by Chinook salmon, which have a migration that typically runs from mid-July through the end of September, with smaller numbers arriving in June and October. Coho salmon return slightly later, with the run beginning in late August and ending in mid-November. Run timing at the Locks has been documented annually through the following means:

- Observer counts in the fish ladder and large lock chamber
- PIT-tagged fish detected by readers in the fish ladder
- Acoustic telemetry studies of tagged fish

Run Timing

Adult salmon returns are estimated by Muckleshoot Indian Tribe and WDFW fish counts at the Locks. These counts support decisions for harvest seasons by tribal and recreational fishers. Fish are counted in the fish ladder viewing chamber and near surface in the large lock chamber. Counts have been consistently conducted for Chinook, coho, and sockeye salmon since 1995. Through 1994, the standard count period ran from June 12 to July 31. Since 1995, it has been extended to October 2.[6] The Muckleshoot Indian Tribe and WDFW routinely provide count data to agencies that work in the Lake Washington watershed. Steelhead counts have not been conducted at the Locks since those taken during sea-lion predation studies in the late 1980s and early 1990s. Counts at the Locks do not accurately reflect numbers on spawning grounds. There is some proportion of straying from the system after fish are counted at the Locks. There is also enroute mortality to the spawning grounds that impacts the number of fish that reach spawning areas.

In 2004, PIT-tag readers were installed in the fish ladder to monitor returns of adult fish. The antennae and PIT tag readers provide information on adult timing, fish passage route, and recycling. From 2004 to 2007, varying amounts of juvenile fish were PIT-tagged. Therefore, PIT-tag return data on adults can sometimes reflect information from only a few fish.

PIT-tagging is also a method for estimating the contribution of juvenile fish to adult returns. Juvenile salmon in Lake Washington have been PIT-tagged at irregular intervals by stock, location, and year as a means to evaluate migration timing and provide an indicator of potential juvenile survival estimates. Since 2004, PIT-tag readers at the Locks have provided adult return information. Because of the multiple pathways through which fish exit and enter the system, the ability to accurately assess survival rates is challenging.

Adult Chinook salmon were monitored in the Locks and Ship Canal in 2000 using 3-D acoustic telemetry. Acoustic telemetry can show fish location and depth and is very valuable. These studies provide insight on fish movement, travel rates, and use of the Locks. Figure 30 shows migration timing return for Chinook, coho and sockeye salmon through the Locks for 1995 through 2007.

[6]Daily counts for periods beyond July 31 of each year are not included in the data presented in this report.

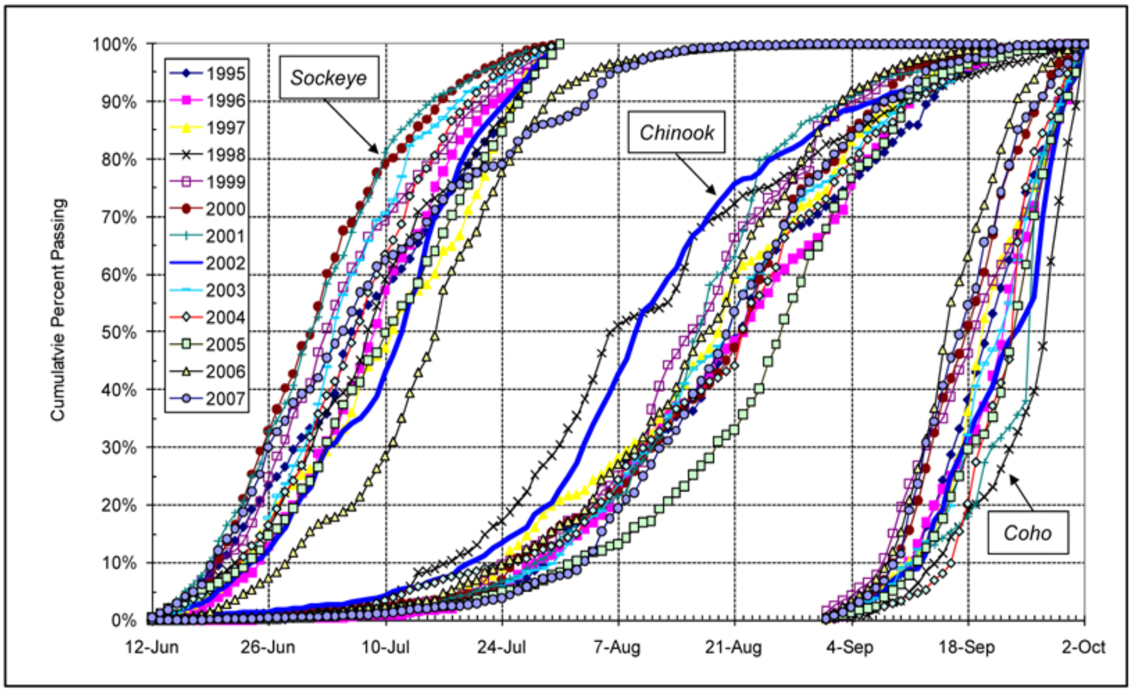


Figure 30
Migration timing (cumulative percent) of Chinook, coho, and sockeye salmon through the Locks 1995–2007. Based on daily passage counts at fish ladder and large lock chamber

Chinook Salmon

The median date Chinook salmon return to the Locks for all years combined is August 16 with the earliest median date August 6 and the latest August 27. PIT-tag monitoring and telemetry studies show that Chinook are observed at the Locks outside the beginning and ends of the counting periods in some years (Fresh et al. 1999; Timko et al. 2002; DeVries 2004; DeVries and Hendrix 2005b; DeVries 2007). For example, in 2004, PIT-tagged Chinook passed the fish ladder between June 22 and October 3. Most Chinook passing through the Locks migrate into Lake Washington. However, variable proportions of the fish have been shown to be strays that leave the Locks for other systems (Fresh et al. 1999, 2000, Goetz 2006).

Coho Salmon

Incomplete fish count data show that the median date of coho salmon timing at the Locks for all years is September 22 with the earliest date September 16 and latest September 28. Counting ends before coho migration ends. PIT-tagged adult coho salmon were detected at the Locks between September 9 and November 1 in 2004. Coho presumably arrive and depart the Locks before and after the counting period.

PIT-tag results show that coho salmon pass through the Locks as late as mid-November (DeVries 2007). In 2007, Issaquah hatchery fish migrated 2 to 3 weeks earlier (August 20-October 16) than Cedar River coho (September 12-November 9).

Sockeye Salmon

The median data of sockeye salmon timing at the Locks for all years is July 7. Sockeye have been observed at the Locks every year on the first and last day of the standard counting period (June

12-July 31). PIT-tag monitoring and telemetry studies show that sockeye are observed at the Locks outside the set counting periods every year. PIT-tag data show adult sockeye passing the fish ladder between June 8 and July 25. In 2007, the latest date of sockeye observations was September 18.

Steelhead

Steelhead migration timing has been described qualitatively in several reports and has included hatchery and wild counts. NMFS (1996) describes hatchery fish as returning from late November to early February, and the wild fish returning late December through May (Muckleshoot Indian Tribe and USFWS 1976). Observers were used to count steelhead passing through the fish ladder in 1986 and 1987. They documented fish migration from mid-November through the end of April (Gearin et al. 1986, 1988). A fish ladder tunnel counter was used in some years after 1989 and 1990 and confirmed the general timing of January to April (Pfeifer 1990, 1991, 1994). One study reported on fish tunnel counts for 1995 as beginning in January and ending in May (Foley 1995). No PIT-tagged adult steelhead have been detected in the fish ladder. Recent adult steelhead returns into the Cedar River are very low, based on redd surveys (Burton 2006).

3.2.3.2 Habitat Use and Behavior

Adult salmon may pass through the fish ladder, large lock, small lock and saltwater drain outlet as they return to Lake Washington. Adult fish may also use these pathways to recycle through the Locks before heading to spawning grounds. The primary passage routes for adult fish into the Lake Washington system are the fish ladder and the large lock. While adults could theoretically use the smolt flumes to move downstream at the Locks, this has not been observed and this pathway is not discussed.

Studies at the Locks have largely focused on Chinook salmon behavior although some results have been reported for sockeye salmon and steelhead. Fish spend varying amounts of time in different areas of the Locks, depending on species and time of entrance.

Fish Ladder

Most salmon species use the fish ladder to pass through the Locks. Estimates for Chinook salmon (1997-2005) show an annual average of 72% of counted fish using the fish ladder. Between 1995 and 2005 an annual average of 85% of coho salmon adults used the fish ladder (Corps unpub data). The proportion of sockeye passing through the fish ladder ranged from 82 to 91% over 3 years.[7] Estimates of steelhead using the fish ladder are not available. For each species, the majority of fish pass through the fish ladder during daylight.

In 1976, the fish ladder was remodeled to attract more fish and to facilitate upstream migration. The ladder was redesigned because the WDFW suggested that upstream migration delay may have reduced annual runs of sockeye and Chinook salmon by as much as 20% (Corps 2001a). The ladder was redesigned to have a saltwater attraction flow from the saltwater drain to increase passage of Chinook and other salmon species through the adder.

Chinook Salmon

On average, 72% of adult Chinook salmon use the fish ladder to return to the Lake Washington system. Annually, this ranges from 53 to 95%. Nearly all Chinook in the ladder migrate during daylight (6 am to 10 pm) with peak migration at 4 pm (Corps 2000). Tide stage affects upstream movement of Chinook. In general, adults migrate through the fish ladder during flood tides. In

[7] 2002, 2007 and 2008.

1999, the rate of Chinook passing through the ladder increased steadily from a 2-foot tide to a maximum 12-foot tide (Figure 31). Fish movement declined at tides over 12 feet. Reduced movement at high tides may be a result of low water velocities at the ladder entrance as it fully flooded by the incoming tide. Some researchers think that fish use the ladder less frequently in years with high water temperatures.

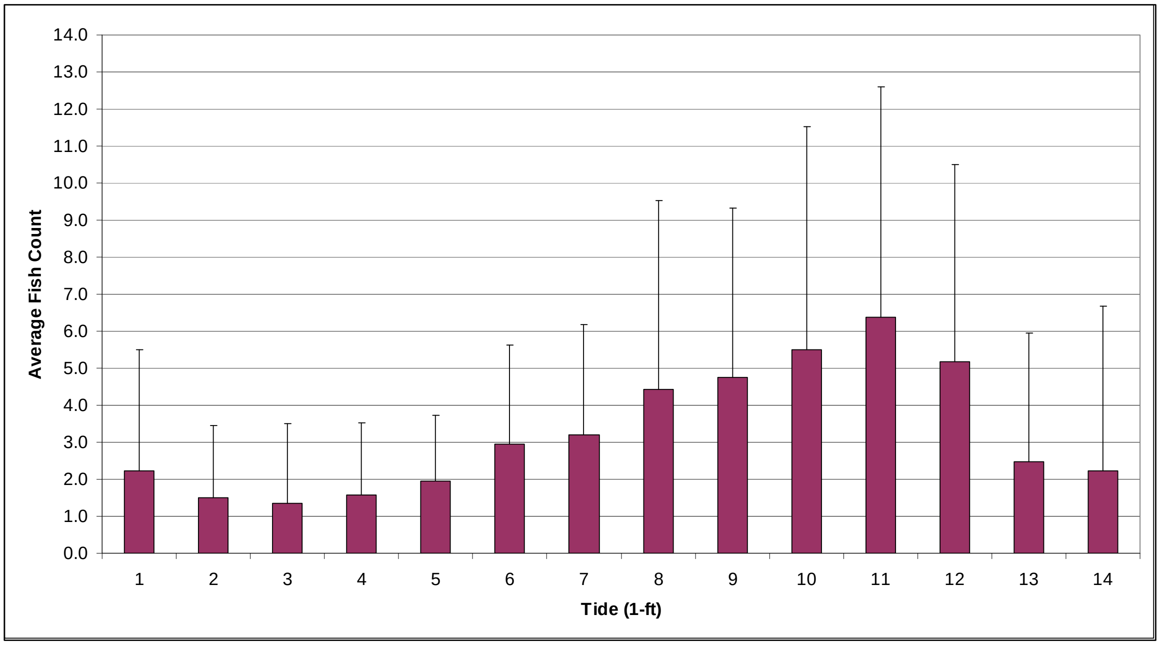


Figure 31
Average Chinook salmon counted in the fish ladder by tidal elevation for August 11 - 31, 1999. Error bars show the standard deviation from the mean

Source: Goetz et al. 2006

Excess water spill over the gates or through a smolt flume has not been found to attract more adult fish to the ladder. The Corps investigated this issue by using observer counts. During periods with flume or gate spill, 17% of the fish used the Locks and 83% used the ladder. During periods without spill, 15% used the Locks and 85% used the fish ladder (Corps 2000). This finding suggests that spill may not change the pathway selection for Chinook salmon. Spill may serve other benefits for adult Chinook, such as drawing fish closer into the Locks, but this has not been investigated. Spill may also increase the area of salt and fresh water mixing below the Locks.

There may be a gender and size bias in the upstream pathways adult Chinook salmon use (E. Warner pers comm). Based on 3 years of acoustic tracking at the Locks, the WDFW and Muckleshoot Indian Tribe believe they have seen more Chinook males and small fish using the fish ladder than females or larger fish. In August of 2000, the Muckleshoot Indian Tribe purse seined the large lock chamber and predominantly captured female Chinook. Perhaps the vertical gates on the fish ladder are either too narrow to pass the largest fish, which are typically females. Or it is possible female Chinook are not using the fish ladder for other reasons. This issue has not been studied. The existing fish ladder entrance is a single vertical slot that is adjusted with tide elevation. At low tides, the opening width can be as narrow as 8 inches, impeding access for larger-bodied Chinook to enter the fish ladder. The Corps is working on replacing the ladder entrance with a horizontal telescoping weir design to facilitate access for all salmon at all tide levels.

Coho Salmon

Between 1995 and 2005 an annual average of 85% of coho salmon adults used the fish ladder. PIT-tag data from 2004 and 2006 reveal 86 to 98% of coho pass through the fish ladder during the day. In 2007, only three PIT-tagged coho passed the Locks. They all passed during the day (DeVries 2004 and 2007).

Sockeye Salmon

In 2004, 19 adult sockeye salmon passed the fish ladder during the day (86%) and three at twilight (12%) (DeVries 2004). No PIT-tagged adult sockeye were detected in 2005, 2006, or 2007. An estimate of sockeye passing the fish ladder or other pathways through the Locks is not available due to low numbers of sockeye tagged after the 2000 brood year.

Steelhead

There are no data on the number of steelhead that use the fish ladder compared to other pathways through the Locks. Tabor et al. (1994, 1995) studied adult steelhead passage through fish ladder. They tagged fish in Shilshole Bay and tracked them through the Locks. Few of the tagged fish traveled through the Locks during the study period. The steelhead that passed through the fish ladder tended to travel through in about an hour. There was no correlation between spill from the gates and steelhead passing through the ladder.

Tabor et al. hypothesized that salinity in the fish ladder influenced attraction of steelhead to the fish ladder. Their tracking conditions were under periods of moderate to low salinity with instantaneous salinity values of less than 3.3 ppt in the entry pool. This finding has been refuted in other studies that show higher salinities potentially inhibit steelhead passage (e.g. Infometrix 1994, Pfeifer 1994). For the Locks, data are inconclusive on this.

Tabor et al. also cited velocity as a factor influencing attraction of steelhead to the fish ladder. Although discharge in the fish ladder is maintained at a constant 183 cfs, water velocities through the entry pool gate vary depending on tidal stage. The two tagged fish entered the ladder during afternoon-evening flood tides. Another study showed a preference by steelhead for early-morning-to-midday flood tides (Infometrix 1994).

Discharge at the spillway was tested at the Locks by Infometrix, Inc. In 1995, the Corps began providing 200 cfs attraction flow through the spillway for steelhead from February 1 to April 1. An analysis failed to show any strong correlation between spill volumes and steelhead counts in the ladder (Infometrix 1994).

Large Lock

The large lock is thought to be the second-most used pathway for adult salmon entering the Lake Washington system even though passage opportunities are sporadic. Unless a lockage is occurring, one or both of the lock gates are closed. Between 1997 and 2008, the average number of summer daytime lockages was 4 to 7 (Muckleshoot Indian Tribe unpub data). When long periods of inactivity occur between lockages, it is possible that salmon may be trapped in the chamber for hours.

It is also possible that adult salmon hold in the large lock chamber because of its unique water quality characteristics. Water temperature and salinity in the large lock chamber vary dramatically based on gate openings, lockages and water depth. If the lower gates are open to saltwater, marine waters dominate in the chamber. If the upper gates are open, freshwater intrudes and nearsurface conditions become more like the Ship Canal. During lockages, the chamber is filled primarily by fresh and brackish water from the locks forebay area. Repeated lockages result in stratification of denser, cooler saltwater below warmer freshwater.

Use of the large lock chamber varies by species. About 28% of Chinook salmon use the large locks with a range of 9 to 47%. Coho salmon average 15% with a range of 9 to 32%. During large sockeye salmon runs, lockmasters have often conducted *fish lockings* when large numbers of adult sockeye hold in the large lock chamber.

Most data on passage through the large lock are for Chinook salmon. Johnson (2005) investigated adult Chinook presence in the large lock entrance using an acoustic camera. Individual fish were observed at the uppermost part of the entrance immediately next to the Ship Canal. No adults were found in lower areas of the entrance by the miter gates and filling culverts.

Acoustic telemetry studies show fish may hold in the Locks for longer than 2 weeks (Goetz et al. 2006). Individual fish may move through the chamber many times. While in the chamber, fish are usually near the bottom, but they infrequently ascend to shallower water (Figure 32). The deep areas of the large lock have cold, saline waters, so fish may be selecting this area as a refuge from warmer waters. It is also possible the water quality within the large lock is appropriate for a fish to make the physiological adjustment to freshwater. The depths most-frequented by adult fish are outside of the depths used by deep draft vessels in the navigation channel. Therefore, these fish are unlikely to be harmed by vessels in the lock.

Small Lock

The small lock is a potential passage route for adult salmon. It is possible that adults may also enter the filling culverts during filling of the lock, but this is not known. Small lock lockages occur frequently during the summer with around 30 lockings per day.

Salmon are infrequently observed in the small lock by Locks workers. A brief investigation of salmon presence in the inlet to the small locks was conducted in September of 2005 (Johnson 2004). An acoustic camera was used to survey the inlet. No salmon were observed in the outer inlet, but within 50 feet of the upper gates a number of salmon were observed milling.

During 2004, the warmest year in the recent past, there was apparently a high mortality rate of sockeye salmon in the Ship Canal and near the Locks (Newell 2005). Anecdotally, during late July and early August lockmasters reported observing 10 to 20 or more dead sockeye salmon locked downstream during small lock lockages.

Saltwater Drain

The saltwater drain inlet is upstream of the Locks. It has two outlets, one to Puget Sound and the other to the fish ladder (see Figure 9). Water entering the drain can reach the fish ladder, and be pumped through the ladder via the diffuser well. Fish primarily travel downstream via the saltwater drain, but adult salmon can potentially enter the drain through the inlet at high enough tides and when the drain is open. Adult salmon can also follow the saltwater drain to the fish ladder and get trapped in the diffuser well. In 2008, the Corps screened the saltwater drain entrance to prevent fish from entering the saltwater drain and getting trapped in the diffuser well.

Pathways

The saltwater drain intake is located 49.5 feet deep at the end of the middle lock wall. It is the deepest passage way through the Locks. Flow in the saltwater drain goes to the fish ladder and diffuser well. Under certain conditions, flow is also allowed out to Shilshole Bay.

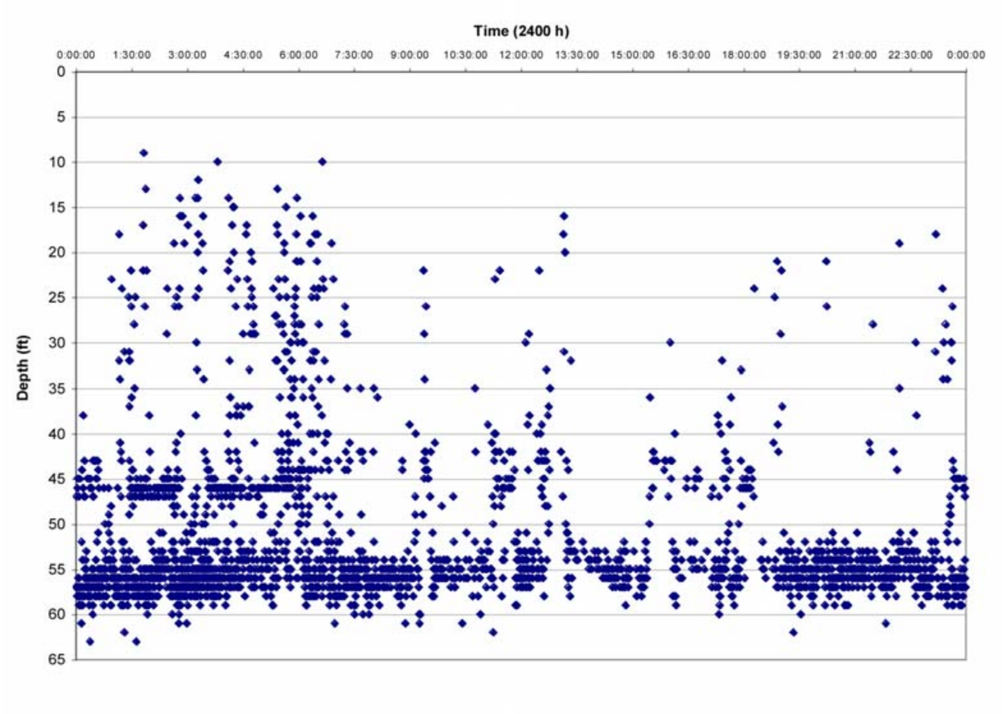


Figure 32
Depth of adult Chinook in the large lock chamber over time in 2005. Each point represents the depth of one fish by time of day over a selected 2-week period

Source: F. Goetz upub data

Before 2008, adult salmon entered the intake of the saltwater drain in the forebay of the Locks. The intake was originally screened in the late 1970s, but accumulation of debris required that the screen be removed. If the drain is open, salmon entering the saltwater drain may swim out because velocities within the pipe are within the swimming ability of most adult salmon (mean=5.6 ft/sec). The velocity in the saltwater drain varies, however. If the outlet to Puget Sound is not open, flow is 160 cfs. If the outlet is open, flow reaches 300 cfs.

The Puget Sound outlet can be manually opened and closed by Locks operators. It is only accessible to adult salmon when open for operation. Salmon that enter the outlet may swim into freshwater above the Locks through the inlet. The fish could also access the pipe to the fish ladder and diffuser well.

From 1980 to 1994, an exclusion screen at the Puget Sound outlet prevented adult salmon from entering the saltwater drain. However, the screen prevented salmon smolts from exiting the drain, and several smolts were found impinged on the screen. So the screen was removed 1994. In 1994, the saltwater drain was monitored by video for the first time. Eleven adult Chinook and 1 sockeye salmon were observed. This led to changes in operation of the saltwater drain in 1998 to minimize attraction of fish to the drain outlet. Fish attraction is reduced by closing the drain during summer tides exceeding 7 feet and by operating the drain primarily at night when fewer adults migrate.

Adult salmon and steelhead have been observed in the diffuser well over the past two decades. These fish must have entered the saltwater drain inlet and swam or were carried by swift currents into the fish ladder and diffuser well where they became trapped. In 2004, 350 Chinook and sockeye salmon were found in the diffuser well. Many of these fish were dead. In 2007, 128 adult

Chinook were found in the diffuser well. Sixty of these fish were dead. As a result, in 2008 the Corps placed a fish exclusion screen over the saltwater drain intake. The screening project is temporary until a more permanent system to prevent salmon entrapment can be designed and funded.

Adult Salmon Use

One study continuously monitored fish use of the saltwater drain intake from April 24 to September 30, 2000, using both underwater video and split-beam hydroacoustics (Biosonics 2001). Adult Chinook salmon were first observed holding at the intake on July 21. In September, an estimated several hundred adults were shown in this area. Video and acoustic data showed adults moving in and out of the saltwater drain intake. Fish are at risk of entrainment if they are carried too far into the structure to resist the rapidly accelerating flow when the outlet to Puget Sound is open. The monitoring for this study showed this effect. Adults were observed in the inlet only during daylight hours with a peak at midday. No estimate of total entrainment was available.

Another study monitored short-term movements of salmon in and around the saltwater drain intake with the outlet to Puget Sound off (160 cfs flow) and with the outlet on (300 cfs flow) (Johnson 2004). When the saltwater drain was off, salmon were observed making random horizontal and vertical movements near the drain intake. Fish were not aligned with any particular flow. When the saltwater drain was turned on, fish aligned with the flow from the drain. This study result shows that fish behavior near the intakes is mainly affected when the saltwater drain is open to the Puget Sound outlet.

Residence

Most fish hold upstream from the Locks for a period before migrating through the Ship Canal and into Lake Washington. The amount of time spent in this area varies by species, date, and water temperatures in the Ship Canal. Chinook are thought to reside at the Locks longer than the other species. Sockeye salmon generally move beyond the Locks quickly. Coho migrating up the fish ladder may reside above the Locks for more than 10 days. Little is known about adult steelhead upstream of the Locks.

Chinook Salmon

Hydroacoustic and temperature tagging studies provide insight into adult Chinook salmon residence at the Locks. Chinook salmon show a wide variety of behaviors at the Locks and use a wide range of thermal habitats (Goetz et al. 2006). Adult Chinook salmon remain in the Locks area for 17 to 19 days, on average (Table 6) (Fresh et al. 1999, 2000; Timko et al. 2002). Most of this time is spent near the saltwater drain intake and the forebay. Residence times vary by when fish pass the Locks. In some years, adult fish migrating earliest in the season stay the longest, while later arrivals stay at the Locks for a shorter period. Fish entering the fish ladder and tagged behaved as follows (Timko et al. 2002):

- Late July: an average of 35 days in the project area
- Early to mid-August: 20 days
- Late August: 15 days
- Early to mid-September: 5 to 10 days

From 1998 to 2000, the longest residence time for any tagged adult fish at the Locks was 52 days. Although one study reported that residence time was not related to fish size or gender (Timko et al. 2002) , another found that females spend more time at the Locks (Fresh et al. 2000).

Table 6
Mean residence and migration times from acoustic telemetry studies at the Locks*

Year	# fish tagged	Residence time at Locks in days standard deviation (SD)		Migration time, Locks to UW hatchery in days (SD)
		Male	Female	Males and Females
1998 – late	52	17.4 (10.4)	19.1 (13.5)	1.1 (0.7)
1999 – early	49	19.7 (13.0)	21.5 (12.8)	0.75 (1.1)
1999 – late	48	12.8 (8.8)	16.5 (11.9)	0.90 (1.3)
2000 – early	56	23.0 (10.6)	17.8 (10.3)	1.3 (0.7)
2000 – late	33	11.5 (7.7)	17.6 (11.1)	1.2 (0.9)

*Early group is from the first 50% of the run. Late group is from the second 50% of the run. In 1998, only late fish were tagged. The distance from the Locks to the UW hatchery is 8.5 miles

Source: K. Fresh unpub data

Adult Chinook salmon hold in three main areas once they pass the Locks:

1. In the cool water refuge in front of the saltwater drain intake
2. Upstream of the small lock
3. Upstream of the large lock (Fresh et al. 1999, 2000; Timko et al. 2002)

Fish may move between these areas or travel upstream from the Locks and return to these areas. Adult Chinook salmon are in the large lock entrance or saltwater drain area 80% of the time. Timko et al. (2002) report that Chinook spend 66% of the time in front of the saltwater drain, 12% in the small lock, 7% in the large lock, and 15% in the fish ladder, Ship Canal, or other places.

Environmental and biological factors such as water quality, lock operations, and other fish may impact adult Chinook salmon residency upstream of the Locks. There are several suggested explanations for variability of residence time. The mean depth of Chinook above the Locks is 23 or 24 feet. The water in this area is brackish, with salinity values of 0.5 to 12 ppt. Temperatures at this depth range from 68.9 to 70.7°F (20.5-22°C) and DO levels here are between 6.7 and 7.5 mg/L during Chinook residence. These conditions are not likely to negatively impact adult salmon. However, further into the Ship Canal water quality decreases. Thus, the relatively good conditions in the area just upstream of the Locks may be most suitable for holding before migration through the poor conditions.

Locks residency may also be influenced by water temperature. Fresh et al. (1999) report that Chinook salmon move from the Locks immediately after nearsurface temperatures drop below 71.6°F (22°C). The percentage of adults leaving the Locks by August 27 was 0% in 1998 and 25% in 1999. There is a strong, positive relationship between total degrees of water temperature above 66.2°F (19°C) and increased residence time at the Locks (Figure 33).

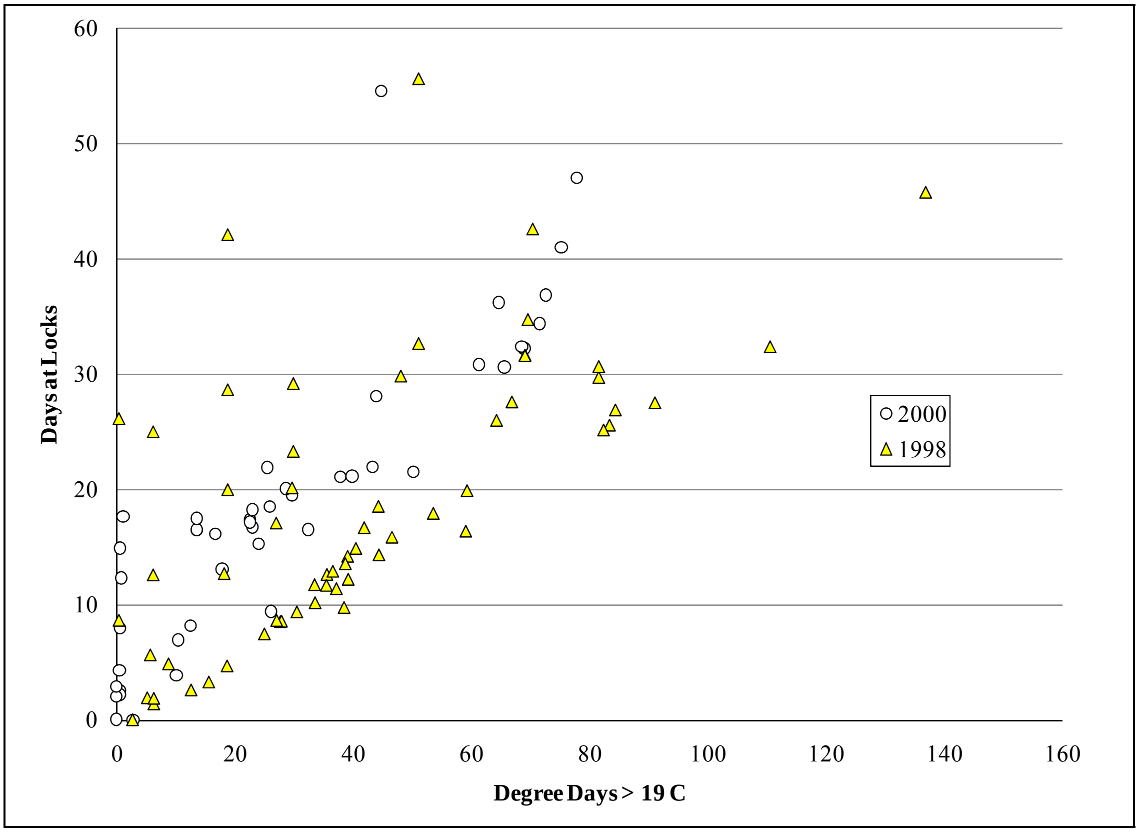


Figure 33
Residence time (°C) for adult Chinook salmon at Locks in days compared to degree days above 66.2°F (19°C) per day

Source: Fresh et al. 1999, Timko et al. 2002

Relationships between residence time and days above 68°F (20°C) and 69.8°F (21°C) were not as strongly associated. It is possible that water temperature in the Ship Canal can be too warm for fish migration, so fish hold in the cool water refuge. Water temperatures in the Ship Canal generally reach temperatures known to stress adult salmon (over 68°F 20C°) near the end of July.

Adult Chinook may also be attracted to the velocity near the saltwater drain. Due to continual intake of brackish water, the drain is also the only area with velocity upstream of the Locks.

Adult residence upstream of the Locks may also be related to number of fish. As the population of adult salmon above the Locks exceeds a certain threshold, fish begin to use the area upstream of the small lock (F. Goetz pers comm). Holding times at the Locks may also be related to readiness for spawning. Fish that enter freshwater later in the season may be more ready to spawn than those that entered a few weeks earlier. Once fish reach a certain maturity, they are ready to spawn and will move up in natural systems (Quinn 2005). Another factor that may impact residence time is physiological readiness for freshwater. Additionally, the duration of spawning for Chinook in the Cedar River is shorter than the duration of passage at the Locks. This may be why Chinook hold for varying periods in the Locks.

In a study that investigated correlations between environmental and biological variables and residence time, most variables did not impact residence at the Locks (Timko et al. 2002). However, the Corps is using an ecological model to investigate further the correlation between environmental and biological variables and fish location.

Fallback

Fish occasionally pass back downstream of the Locks. This behavior is called *fallback*. Fallback is normal behavior for adult salmon searching for their natal streams. Fish that fallback may either recycle through the Locks or are strays that travel to another system. Fallback can result in fish injury or death, migration delays, and biases in fish counts at the Locks.

Rough estimates have been made of fallback for adult Chinook salmon at the Locks. Sockeye fallback is much less than that for Chinook. Little information is available on coho salmon fallback at the Locks. No estimates of fallback for steelhead are available. For all species, the consequences of fallback at the Locks are unknown. The major fallback route at the Locks is presumed to be the large lock.

Telemetry data show that annually 2 to 40% of the acoustic-tagged Chinook salmon adults fell back below the Locks one or more times (K. Fresh unpub data, F. Goetz unpub data). Other estimates for this fall back range from 11 to 13% for PIT-tagged fish (DeVries and Hendrix 2005b) and 10 to 27 % from 1998 to 2000 (Muckleshoot Indian Tribe unpub data).

PIT-tag results suggest 9% of coho salmon adults fall back through the Locks (DeVries 2007). In 2004, 18% of sockeye salmon were detected in the fish ladder more than once.

For adult Chinook salmon, fallback is related to average residence times at the Locks. Acoustic data from 1999 show that fallback fish had a longer residence time at the Locks (23.5 days) than did non-fallback fish (15 days) (Goetz 2006).

Recycling

A portion of adult salmon fallback and re-enter the Locks. This behavior is called *recycling*. PIT-tag and acoustic telemetry studies provide information on recycling for Chinook, coho, and sockeye salmon. Estimates of recycling from PIT-tag and acoustic tracking are likely underestimates because fish may recycle through pathways other than the fish ladder.

Chinook salmon recycling at the Locks varies by year. Between 2005 and 2007, 9 to 18% of tagged fish recycled using the fish ladder (DeVries and Hendrix 2005b, Goetz et al. 2006). In 2005, recycling time varied from 2 and 20 days. In 2006, recycling times ranged from 1 to 8 days, while in 2007 it took up to 25 or 30 days (DeVries 2007). Adult Chinook may recycle from 1 to 4 times (Fresh et al. 2000). Recycling once is most common (DeVries and Hendrix 2005b).

PIT-tag readers in the fish ladder show that low proportions of adult coho and sockeye salmon recycle at the Locks. In 2006, three coho (9%) were detected twice in the fish ladder. In 2004, 18% of the sockeye detected in the fish ladder passed twice. Recycling times for these fish ranged from 1 to 54 days. However, these data are based on low proportions of PIT-tagged juveniles and even lower proportions of returning adults. Sockeye fallback appears to be primarily recycling. Sockeye recycling rates are not constant over the run timing but generally occur towards the end of the run. The highest rates of observed sockeye recycling are 12% per week (E. Warner pers comm). Sockeye recycling is thought to be related to flow over the spillways because rates consistently peak when the combined flow through the slides drops below 100 cfs.

Straying

Some fish that pass through the Locks are strays, or fish that have entered the wrong system in their search for their natal stream. These fish leave again to head for other river systems. Straying was noted for adult Chinook salmon (Fresh et al. 1999, 2000; Goetz et al. 2006) and steelhead (Tabor et al. 1994 and 1995). One study found that around 20% of adult Chinook that passed did not enter Lake Washington (Fresh et al. 1999, 2000). Another study reported that approximately 20% of fish tagged in the large lock chamber and released below the Locks exited from the area and were not detected in the Lake Washington basin (Goetz et al. 2006). Other estimates of strays entering the Locks are lower; from 1998 to 2000 strays accounted for 11 to 14% of tagged Chinook (Muckleshoot Indian Tribe unpub data).

3.2.3.3 Survival Risks

The following section describes how warm waters might impact adult salmon. The overall impact of the Locks on adult salmon survival is still largely unknown. To date, studies have focused on water temperature. Water temperature is hypothesized to play a part in the timing, behavior, and survival of salmon at and beyond the Locks. The timing of freshwater entry of some species (e.g. adult Chinook and sockeye salmon) also coincides with some of the warmest water temperatures of the year. Adult salmon migrating through the Locks or fish ladder during mid-summer experience a temperature change of up to 16ºF (9ºC) as they move from cold, marine water into warm freshwater (Goetz et al. 2006). In other systems, thermal blockages to migration begin at 64.4ºF (18ºC) (MacDonald et al. 2000). Mid-summer water temperatures above the Locks can range up to 73.4°F (23ºC).

Thermal Gradients in the Fish Ladder

At the Locks, as adult Chinook salmon go up the fish ladder they experience an abrupt thermal gradient. They are migrating from marine water temperatures of 53.6 to 60.8°F (12-16ºC) to freshwater temperatures of 68 to 73.4°F (20-23ºC). High water temperatures in the ladder may alter route choice for adult salmon and may be associated with lower returns to Lake Washington. As mean water temperature increases above 68.0° (20ºC) there is a hypothesis that the number of adult Chinook counted at the fish ladder declines. Reduced counts during periods of high temperatures may be attributed to other factors such as ocean survival of fish during warm years and natural pattern of entrance into the system.

Water Quality Upstream of the Locks

Water quality parameters such as temperature and DO may inhibit adult salmon movement away from the cool water refuge. Telemetry studies suggest that salmon opt for cooler temperatures rather than higher DO down to almost 3 mg/L (D. Beauchamp pers comm). Researchers used 2 years of telemetry data to compare water temperatures for 1998 and 2000 (K. Fresh unpub data, Timko et al 2002). They identified 66.2°F (19ºC) as a temperature that most fish move through and 71.6°F (22ºC) as the boundary beyond which fish do not migrate. In general, water temperatures above 66.2°F (19ºC) correlate with fish staying longer at the Locks.

Salinity near the saltwater drain ranges from about 3 to 12 ppt near the bottom (46 ft) to 0 ppt at 17 feet. DO ranges from approximately 5.3 to 7.7 mg/L near the bottom (46 ft) to 6.8 to 8.3 mg/L at 17 feet. Thus, the relatively cold bottom waters were associated with higher salinity and lower DO. Based on estimates of 5.4 to 7.5 mg/l DO at 18 feet and higher levels near the surface, it does not appear that oxygen levels alone would have inhibited adult Chinook salmon migration. However, oxygen concentration at mid-depths may change from year to year and the combined effect of moderately low oxygen at mid-depths and high temperature may contribute to the holding of adult Chinook near the Locks (Corps 2000, 2001a, Timko et al. 2002).

The water temperatures in the Ship Canal in 1998 were the highest recorded in the last two decades with daily average peaks of 74.3°F (23.5ºC) in early August (Figure 34).

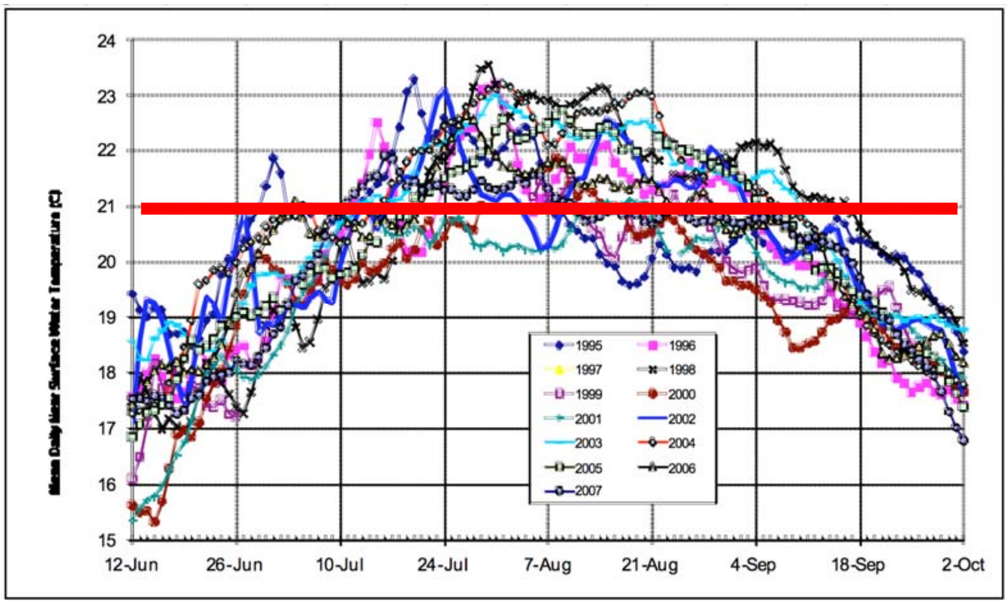


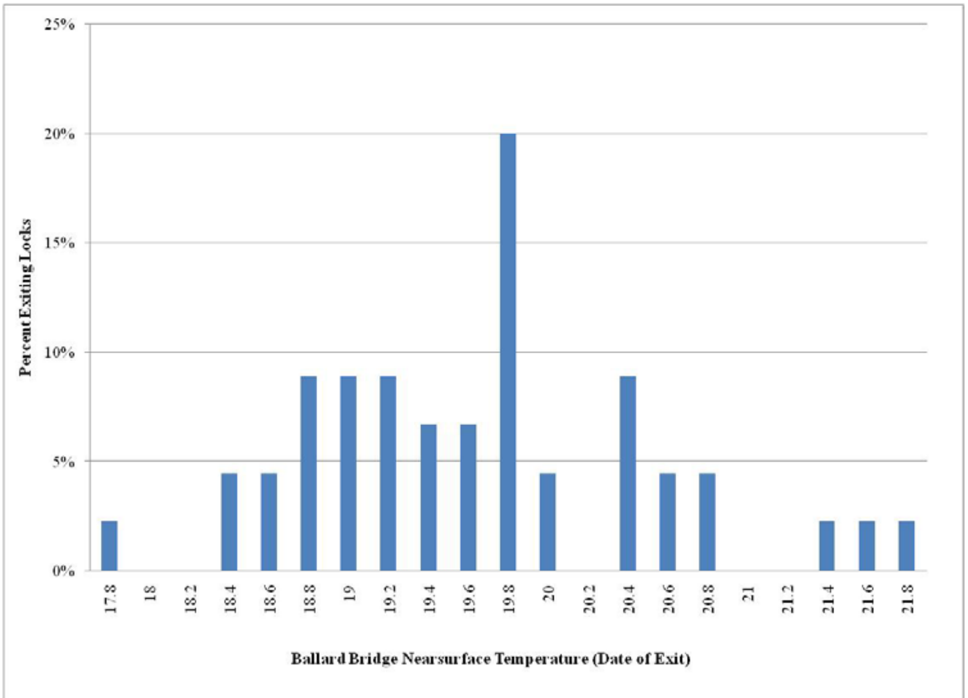
Figure 34
Average, daily nearsurface water temperature (°C) in the Ship Canal during the adult salmon migration 1995-2007. Red line shows estimated temperature tolerance for adults, 70ºF (21ºC)

Time of departure (percent passing at a particular temperature) was compared for 1998 and 2000 to nearsurface stream temperatures at the Ballard Bridge (Figure 35). Adult fish migrated in 2000 through a fairly narrow temperature range, 63.5° to 70.7°F (17.5-21.5ºC), with 80% of the fish passing at temperatures between 66.2° to 68.9°F (19-20.5ºC). This narrow band is interesting given the fairly broad range of temperatures during the adult Chinook salmon migration period (late July through early October). In 1998, adult fish migration was spread over a much broader range of temperatures, between 57.2 to 71.6°F (14-22ºC). This range reflects the broad range of migration departure dates fish selected in 1998, with some migrating late in October. In contrast to 2000, temperatures during the expected primary migration period (August/September) were exceptionally high. Most fish migrated during peak temperatures, with over 50% exiting at temperatures exceeding 69.8°F (21ºC), a temperature typically expected to be a barrier to migration.

The combined effect of the Locks and the stratification of the water column leads to water quality conditions that may adversely affect adult salmon, especially in years of high summer temperature (e.g. 1998). The following initial hypotheses have been developed to address this situation:

- High water temperatures and/or low DO upstream of the Locks are a barrier that adults will not swim through
- Area within 1,000 ft of the Locks is a necessary cool water refuge where adults can safely hold until temperatures drop
- Modifications in lock operations or changes in the structural configuration of the Locks can improve the quality of the cool water refuge

So far, acoustic tracking and lock operation experiments have not provided enough information to change operations. Future modeling work may inform future changes at the Locks.



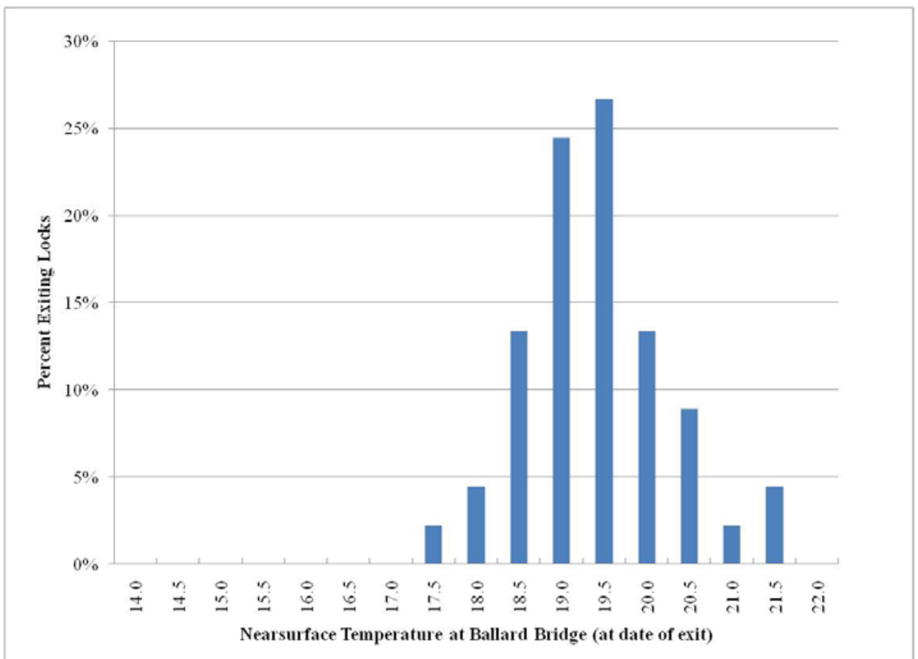


Figure 35
Locks exit times for percent migrating at temperature for acoustic tagged fish in 1998 (top) and 2000 (bottom) relative to Ship Canal nearsurface temperatures (°C) at Ballard Bridge

3.2.4 Ship Canal and Lake Union Migration

Very little is known about adult salmon migration through the Ship Canal and Lake Union. There are some data on Chinook and sockeye salmon from tagging studies (Fresh et al. 1999, 2000; Newell and Quinn 2005). In general, adult salmon do not spend a lot of time in the Ship Canal.

Typically, Chinook pass through the Ship Canal in 2 or fewer days (Fresh et al. 1999, 2000). Sockeye also have a rapid migration through the Ship Canal, averaging only 4 days (Newell and Quinn 2005).

Adult salmon passage through the Ship Canal and Lake Union is thought to be influenced by warm water temperatures in the Ship Canal, among other things. Both sockeye and Chinook salmon may be impacted by these high temperatures. Sockeye tend to spend longer in the Ship Canal, but also keep to a tighter temperature range than Chinook. Chinook enter the Ship Canal later in the season when temperatures are higher, however.

3.2.4.1 Passage Timing and Rates

Each year, adult Chinook salmon pass through the Ship Canal and Lake Union from the end of July through the beginning of September. Adult coho salmon pass through that area from late September through November. Adult sockeye salmon travel through the area roughly from June through the beginning of August (Newell and Quinn 2005). Adult steelhead may pass through the Ship Canal from February through June. Rates for adult Chinook and sockeye are around the order of a number of days. Rates for adult coho and steelhead are unknown.

The total time of adult Chinook salmon migration from the Locks to arrival at tributary spawning grounds can take up to 55 days, but averages less than 30 (Fresh et al. 2000). The total time decreases as the season progresses (Table 7). This timing mimics patterns in Locks residence time, which also decreases as the season progresses and could reflect maturation level of the fish. Once fish leave the Locks, most fish move through the Ship Canal in less than 1 day, varying from 4 hours to 7.7 days. In 1998, the average migration time was 1.9 days with a minimum of 0.15 days to a maximum of 22.85 days (K. Fresh unpub data). Larger Chinook migrate faster through the Ship Canal than do smaller Chinook. Male Chinook migrate faster than females.

Table 7
Average time (number of days) by tag date for Chinook salmon migrating from the Locks to tributary spawning grounds

Tag date	1999	2000	Average
Jul 31	25.0	31.7	28.35
Aug 15	19.5	22.7	21.1
Aug 31	12.8	15.2	12.8
Sep 15	9.8	6.7	8.25

Source: Fresh et al. 1999, 2000

Most sockeye spend only a few days in the Ship Canal before reaching Lake Washington. Fish tagged in 2003 spent an average of 4.05 days in the Ship Canal (Newell and Quinn 2005). It is thought that the sockeye move through the Ship Canal as quickly as possible in order to reach Lake Washington where they can select cooler temperatures by dropping below the lake thermocline.

3.2.4.2 Habitat Use and Behavior

The habitats used by adult salmon migrating through the Ship Canal and Lake Union are unknown. Only one report shows that Chinook salmon are generally found near depths of 20 feet in the Ship Canal (Fresh et al. 1999).

3.2.4.3 Survival Risks

Survival risks in the Ship Canal and Lake Union have not been extensively studied. However, the high water temperatures in the Ship Canal are a concern. High temperatures may cause direct death, prespawning mortality or sublethal effects that impact spawning success. High water temperatures may impact all species, but only temperatures for Chinook and sockeye salmon have recently been studied. Coho salmon and steelhead do not migrate through the Ship Canal and Lake Union during peak summer temperatures. Thus, these species may be less impacted by high water temperatures in these areas.

Water Quality

Summer water temperatures in the Ship Canal and Lake Union consistently exceed values that are physiologically stressful to salmon (> 68ºF or >20ºC) (see Figure 23). The Ship Canal and Lake Union are relatively homogenous in water temperature.

The temperatures fish experience migrating through the Lake Washington basin have been tested by placing archival temperature loggers on adult Chinook and sockeye salmon. These data can provide insight into the types of habitats fish use. Presumably, if a range of temperatures are available, fish will move to the most comfortable temperature or the best temperature for their life-history stage. In Lake Washington, results from monitoring adult Chinook and sockeye salmon suggest that each species uses unique strategies for thermoregulation.

Adult Chinook salmon experience a variety of temperatures when migrating from the Locks to their spawning grounds (Figure 36). In the Ship Canal and into Lake Washington, Chinook may move between temperatures from 48 to 72ºF (9-22ºC). Wild Chinook experience a wider temperature range on a daily and seasonal basis than do hatchery Chinook.

Sockeye salmon exhibit temperature patterns that correspond to rather precise movements throughout the system. During summer 2003, Newell and Quinn (2005) tagged 257 adult sockeye salmon with temperature loggers as the fish ascended the fish ladder between July 16 and 18, which is near the typical peak of migration. Of these, 38 tags were recovered from dead fish on the spawning grounds or from fish caught in tribal fisheries in Lake Washington or Lake Sammamish. These fish spent a short time in relatively high temperatures at the Locks and in the Ship Canal and Lake Union (Figure 37). The range in temperatures that these adult sockeye experienced is smaller than the range that adult Chinook experience in the Ship Canal.

Summer DO levels in Lake Union may also be a problem for adult salmon. DO levels less than 4.25 are critical for salmon. The lake is generally under low-DO conditions from June until October (Figure 38). These low-DO concentrations in the lake may prevent salmon from using the water column below a 33-foot depth. Warmer surface temperatures later in July may generally affect use of the upper portions of the water column. DO levels may even fall below 1 mg/L near the bottom of Lake Union (King County 2008).

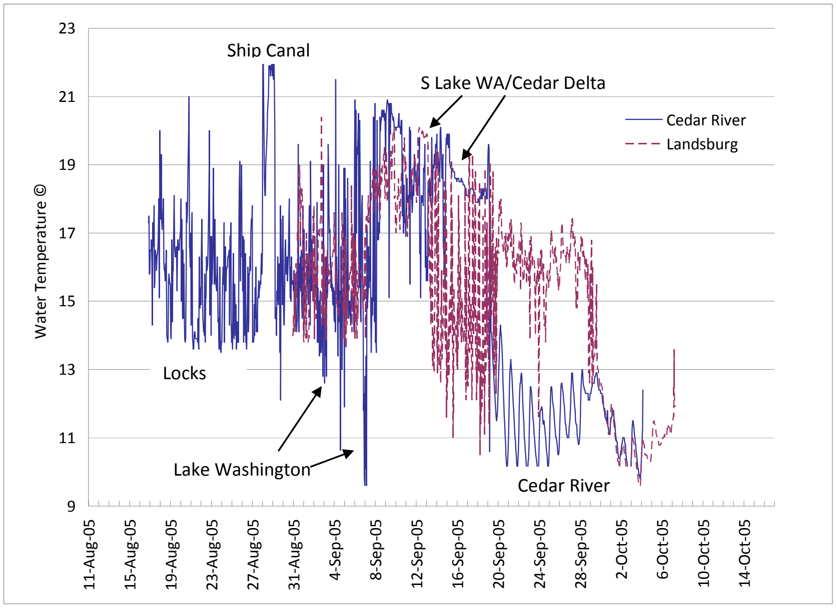


Figure 36
Temperatures (°C) experienced by two adult Chinook salmon tagged in 2005 at the Locks. Solid blue line is a fish that returned to lower Cedar River; dashed red line is a fish that returned to the Landsburg area of the Cedar River

Source: F. Goetz unpub data

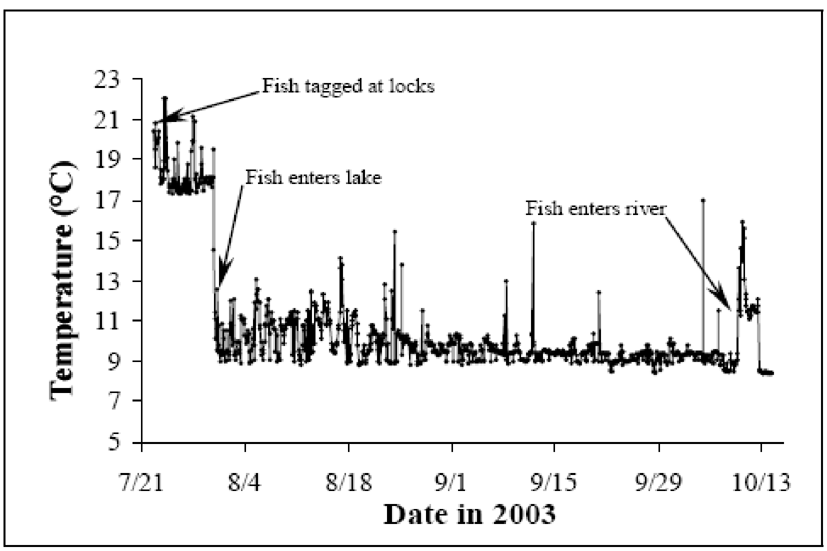


Figure 37
Temperatures (°C) experienced by an adult sockeye salmon in Lake Washington basin

Source: Newell and Quinn 2005

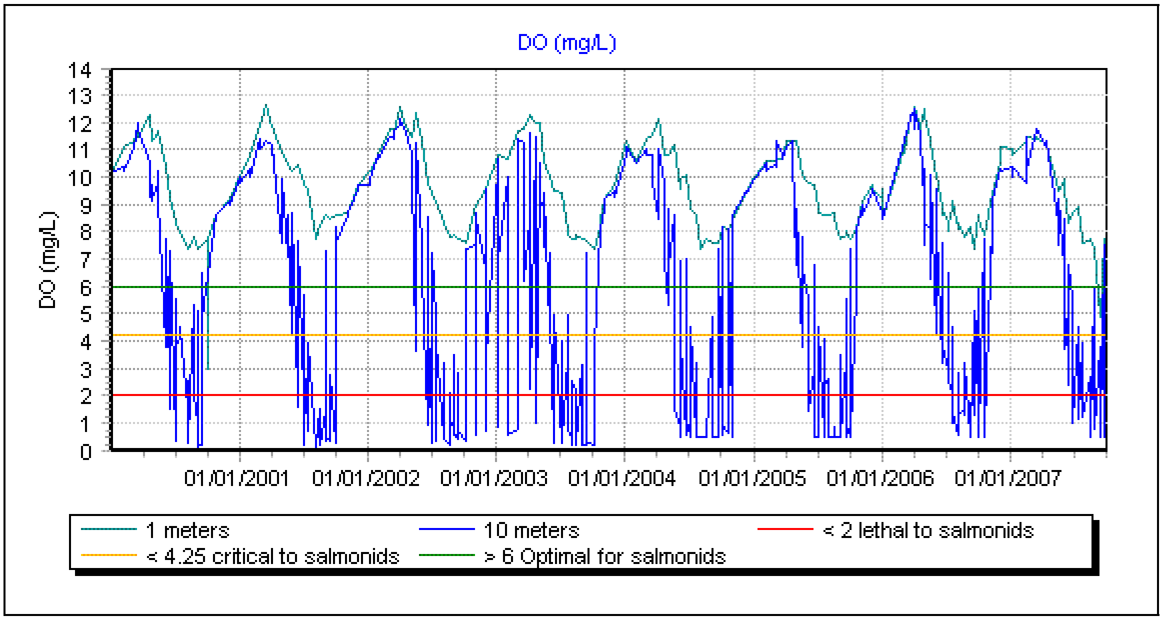


Figure 38
Dissolved oxygen (DO) concentrations at 3 feet (1 m) and 33 feet (10 m) at the Fremont Cut, northwest Lake Union, from 2000 to 2007

Source: King County

Enroute and Pre-Spawning Mortality

Enroute mortality has been observed at the Locks for upstream migrating adult sockeye salmon primarily during years with high summer temperatures. In 1998 and 2004, observers noted dead sockeye salmon near the Locks and in the Ship Canal. In 2004, dozens to hundreds of dead adult sockeye were noted during late July during peak water temperatures. During the record high temperatures in 1998, dead prespawned Chinook were observed in the Ship Canal (enroute) and the Sammamish Slough (pre-spawning) (Fresh et al. 1999). Newell and Quinn (2005) also found a lower proportion of recovered, tagged fish during a higher temperature year than a low temperature year, suggesting higher mortality. This matter deserves further study.

Studies at the Locks have not evaluated the incidence of disease and whether it may contribute to early mortality. However, the close proximity, high water temperatures, and long-duration of holding at the Locks by adult Chinook salmon could be risk factors. Salmon holding in poor quality habitats can become stressed and crowded (Schreck and Li 1991, Matthews and Berg 1997). Under these conditions, outbreaks of diseases such as *Flexibacter columnaris* (Holt et al. 1975, Wakabayashi 1991) and *Ichthyophthirius multifiliis* (Ich) are possible (Bodensteiner et al. 2000). This has not been documented in the Lake Washington basin.

Sublethal Effects

Physiological condition and body energy levels impact spawning. Studies at the Locks have not evaluated the fitness or survival of gametes of adult salmon migrating through high temperatures. It is possible that the high temperatures are impacting spawning success. These effects have not been studied.

3.2.5 Lake Washington

Each adult salmon species spends various times in Lake Washington. Adult Chinook salmon return to fresh water later than do adult sockeye salmon. Adult Chinook are generally more mature than adult sockeye upon entering the Lake Washington basin. Sockeye salmon complete their maturation in the lake. However, Chinook that are destined to spawn in tributaries to Lake Washington spend some time in the lake before swimming upstream to spawn.

During the summer, Lake Washington is stratified. Temperatures in the surface layer vary from 64.4 to 77ºF (18-25ºC). The thermocline lies at 32 to 65 feet. Temperatures in the lower layer of the lake vary from 46.4 to 50ºF (8-10ºC) (Nowak and Quinn 2002).

3.2.5.1 Timing and Rates

Adult Chinook salmon generally enter Lake Washington between August and September. Adult coho salmon enter the lake later in the year, from September through November. Sockeye enter the lake as early as June and stay until October. Steelhead may be in Lake Washington from February through June. Travel rates for fish in the lake are not known. In many cases, adult salmon hold in a small area within the lake before entering the rivers for spawning.

3.2.5.2 Habitat Use and Behavior

Once adult salmon enter Lake Washington, they are neither avoiding predators nor seeking prey, and the temperature is not confounded by interactions between depth and salinity (Quinn et al. 1989). Presumably, adult fish remain in a temperature range that is ideal for maturation or holding (Randall et al. 2002). Sockeye salmon inhabit cooler water in the lake (Newell and Quinn 2005), but Chinook salmon do not (K. Fresh pers comm). Acoustic tracking and temperature tagging studies have provided some insight into adult fish behavior in the lake. Other than that, little is known about the specific habitat use of adult salmon in Lake Washington.

Chinook Salmon

Adult Chinook salmon may enter Lake Washington days before moving into rivers for spawning. The average time spent by adult Chinook in Lake Washington in 1998 was 2.9 days (Fresh et al. 1999). For Sammamish watershed fish, the average was 4.9 days. Some Chinook move into the Sammamish River, where they hold in deep pools for an extended period before moving upstream to spawn (R. Tabor pers comm).

Acoustic and temperature tags on adult Chinook salmon show that these fish inhabit waters of varying depth and temperature. Temperature tag studies show temperatures occupied by fish in the lake range from 48 to 70ºF (9-21ºC) (F. Goetz unpub data). The adult Chinook do not seem to seek out cool waters, but will hold near the mouths of the Cedar and Sammamish rivers in warm, shallow waters.

Sockeye Salmon

Adult sockeye salmon enter Lake Washington well in advance of spawning. They enter freshwater in the summer and spawn in October and November (Newell and Quinn 2005). Adult sockeye spend on average 85 days in Lake Washington. The range is from 57 to 132 days. Most adult sockeye spend their time in Lake Washington below the thermocline where temperatures are cooler. In fact, 92 to 95% of temperature detections in the lake were between 48.2 and 51.8°F (9-11ºC). These temperatures are only found at depths of 59 to 98 feet, so sockeye are spending their time in Lake Washington in very deep waters.

Acoustically tracked sockeye data show that fish move throughout the lake shortly after entering. Within about a month, fish congregated near the mouth of the Cedar River (Newell et al. 2007). This spot is where they held at depth, in cooler waters, until they traveled upstream to spawn.

3.2.5.3 Survival Risks

Survival risks to adult salmon in Lake Washington are unknown.

4. Salmon Use of the Lake Washington Watershed

From freshwater streams to the ocean, salmon occupy many habitats throughout their lives. Salmon respond in several ways to the dynamic structure of the Pacific Northwest ecosystem and the natural and human-induced stresses that influence their survival at all life stages. Management of salmon in the Lake Washington basin is difficult because many factors impact salmon within the area.

The research gathered in the LWGI and through other studies presents valuable information for improved management of salmon in the Lake Washington basin. This section summarizes research findings for each species in the basin. It combines these findings with survival risks and a timeline in the form of a conceptual model for each species. This section also addresses the changing climate of the area and how salmon may be impacted by it. The information presented here is meant to assist management of the species within the basin in coordination with the focus area goals and objectives described in Chapter 5.

4.1 Conceptual Models for Lake Washington Salmon

This section presents a conceptual model for each salmon species covered in this report. Conceptual models are simplified views of known behavior and risks for each species. The models should be used as tools for building a framework for adaptive management and monitoring programs.

The models convey the story of each species by summarizing the current knowledge, including habitats, prey, and life-history concerns during each month the fish live in the Lake Washington basin. Although the models present the best knowledge about each species, they do not show all the variability that can occur within the basin. Instead, the model should be considered a diagram of salmon habitat use and survival risks throughout the year.

4.1.1 Chinook Salmon

Chinook salmon in the Lake Washington watershed are generally considered ocean-type Chinook. They spend less than 1 year rearing in freshwater and some amount of time rearing in estuaries (Wydoski and Whitney 2003, Healey 1991, Myers et al. 1998). Adults spend 3, 4, or 5 years in the ocean before migrating back to the Lake Washington basin to spawn. Both Puget Sound resident and ocean populations occur.

4.1.1.1 Juvenile Chinook Salmon

Juvenile Chinook enter Lake Washington as fry between January and early April (Paron and Nelson 2001, Seiler et al. 2005, Volkardt et al. 2006). A portion of the juvenile population remains in rivers into April and moves into the lake as fingerlings or smolts during May and June (Paron and Nelson 2001, Seiler et al. 2005). See the conceptual model for Chinook salmon in the Lake Washington basin (page 95).

Freshwater

The juvenile Chinook salmon that enter Lake Washington as recently emerged fry use the lake as rearing habitat for 1 to 4 months before migrating to the marine environment. Fry are small and inhabit the shoreline areas from early February to late May (Warner and Fresh 1998, Tabor et al. 2004a). Fry initially prefer sand or gravel substrates in water less than 3 feet deep and seem to avoid overwater structures (Tabor and Piaskowski 2002). They also prefer to use stream deltas and shorelines with overhanging vegetation during the day but move into open areas at night (Tabor et al. 2004a). In late May and June, juvenile Chinook salmon —predominantly large individuals—begin to use deeper areas (Martz et al. 1996, Warner and Fresh 1998). These fish consume epibenthic insects (e.g. chironomids) early in the season and zooplankton later on when they move into deeper areas (Koehler et al. 2006).

The Chinook salmon that rear for a few months in their natal streams and enter the lake later in the spring generally spend just a few weeks in shallow-water areas before moving out into deeper water. Risks to juvenile Chinook in Lake Washington include risk from predators such as cutthroat trout, sculpin, bass and northern pikeminnow. They may also be negatively impacted by the large number of overwater structures, lack of shallow, gently sloping shorelines and high water temperatures in the shallow areas of the lake.

Outmigration

Juvenile Chinook salmon typically migrate out of the Lake Washington basin between late May and early July, with a peak in June (Fresh and Lucchetti 2000). This range incorporates yearly variation in outmigration timing between Cedar and Sammamish river smolts. Hatchery Chinook smolts may be delayed for release until they grow larger, which lengthens the migration period. Generally, differences in migration timing are less than 1 week for hatchery and natural original Chinook smolts (P. DeVries pers comm).

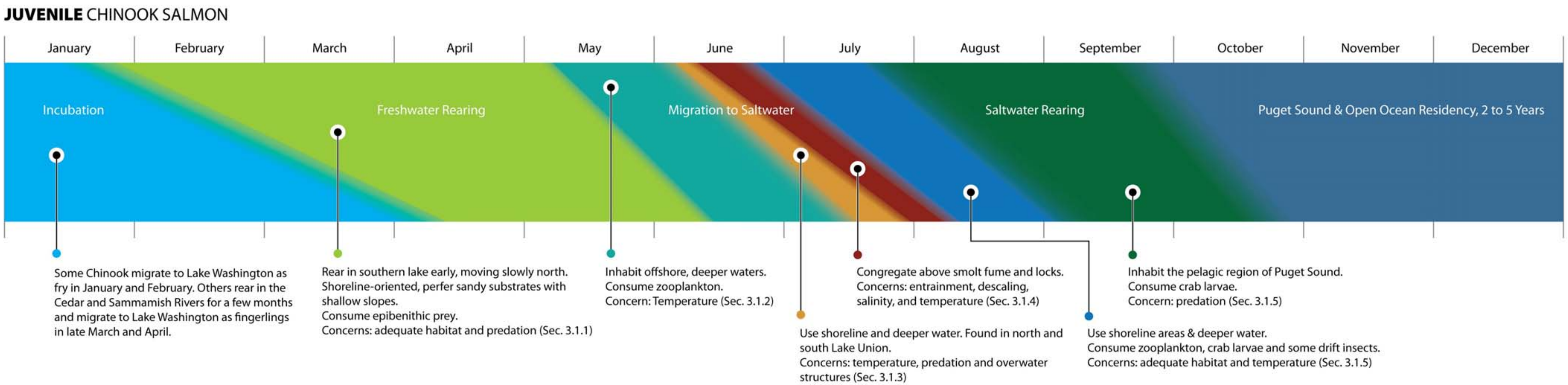
Predators in the Ship Canal and Lake Union may also impact outmigrating Chinook salmon. The many overwater structures in the area increase the likelihood that predators can capture the outmigrating fish. Water quality, particularly temperature, affects outmigrating Chinook. High water temperatures in the Ship Canal and upstream of the Locks push juvenile Chinook into cooler, deeper water. These fish may not exit through the smolt flumes, even if the flumes are operating, and instead seek deeper routes such as the large locks.

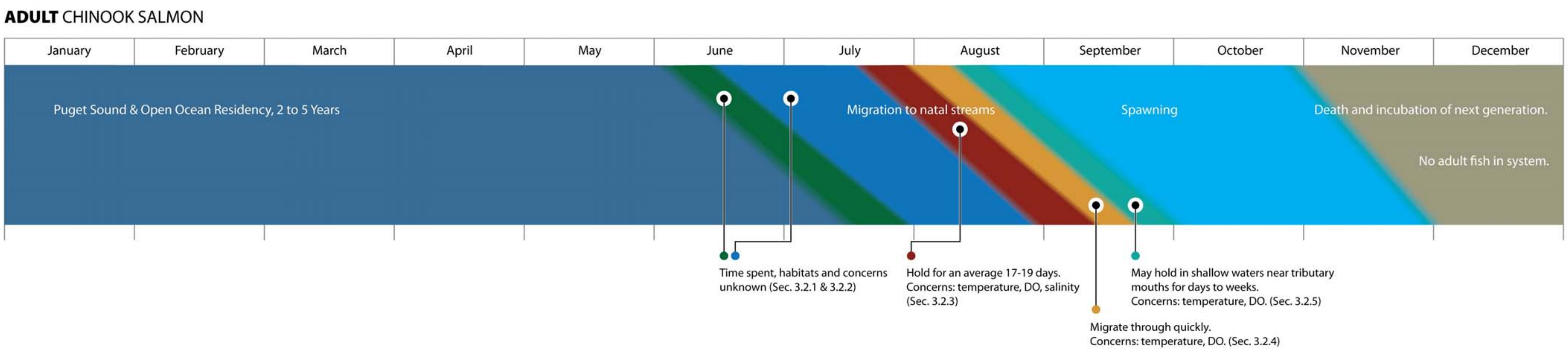
It is unclear how many Chinook are subject to high water temperatures in the Ship Canal and upstream of the Locks. Fish that leave the basin near the end of outmigration season are subject to water use conflicts at the Locks. In dry years, smolt flumes may be turned off during the end of the Chinook smolt outmigration. Chinook must then outmigrate through the saltwater drain, the Locks, or the fish ladder.

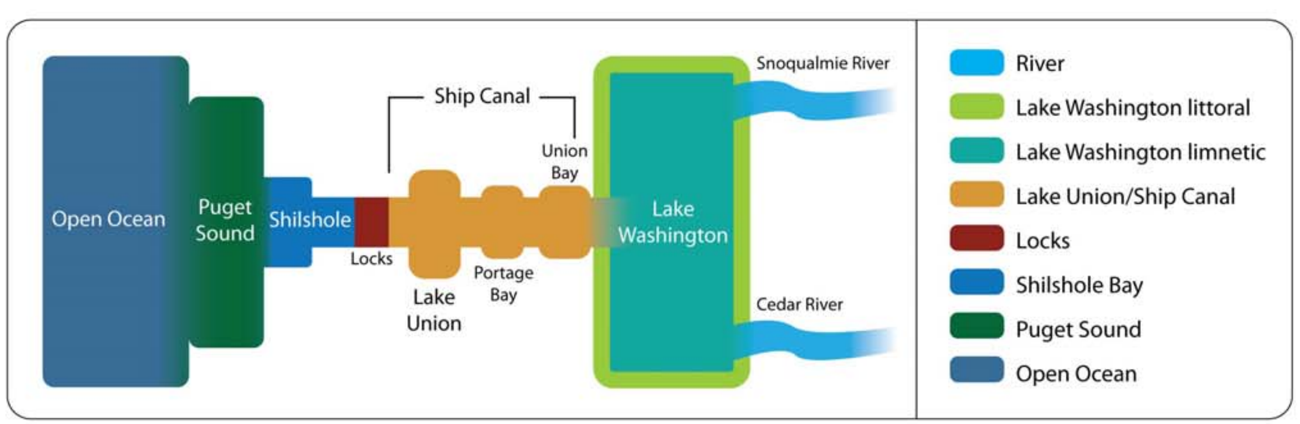
Juvenile Chinook salmon generally hold upstream of the smolt flumes and Locks for days to a couple of weeks. They pass the Locks in June and July. When the fish pass the Locks, they can use several different pathways. Lock filling culverts pose a treat to juvenile Chinook because the fish might become trapped or descaled in the large pipes. Fish are also exposed to high salinities and very cool waters directly after passing through the Locks.

Estuary

The importance of estuarine rearing habitat is well-documented for ocean-type juvenile Chinook salmon (Congleton et al. 1981, Levy and Northcote 1982, Kjelson et al. 1982). The Lake Washington watershed is an engineered system without natural estuarine habitats. Rerouting the Cedar River into Lake Washington prevents newly emerged fry from migrating directly into







Conceptual Model for Chinook Salmon

This figure shows a conceptual model for Chinook Salmon in the Lake Washington Basin. Life-history stage, location and characteristics are shown on the horizontal bars. Life-history stage can be reviewed for adult and juvenile Chinook Salmon by calendar year.

estuarine habitats and thus eliminates at least one key habitat that is typically used by ocean-type Chinook salmon.

After passing through the Locks, Chinook salmon may inhabit inner Shilshole Bay for up to 2 months (Simenstad et al. 1999). There is likely some rearing occurring in this area. Chinook consume zooplankton and some drift insects in this area. Concerns are adequate habitat and temperature and salinity shock from traveling from the warm, freshwaters of the Ship Canal directly into cool, salty waters of Shilshole Bay. The impact of this change on Chinook has not been studied in nearshore areas and Puget Sound.

Chinook salmon may rear in pelagic regions of Puget Sound from July through September. In those regions, they are susceptible to predation by large piscivores.

4.1.1.2 Adult Chinook Salmon

Adult Chinook salmon return to the Lake Washington basin to spawn after 3 to 5 years in marine waters. See the conceptual model for Chinook in the Lake Washington basin (page 97).

Estuary

Adult Chinook salmon migration through estuaries is relatively unknown and acknowledged as a critical data gap for the Lake Washington basin (Fresh et al. 2005). It is hypothesized that adult Chinook undergo their physiological adaptation to freshwater in the estuary downstream of the Locks and/or in the brackish waters above the Locks. However, no studies document the process. It is thought that adult Chinook enter Shilshole Bay as early as June and may remain there for some time before passing through the Locks. Predation by marine mammals is a possible survival risk for adult Chinook downstream of the Locks, but this has not been explicitly documented.

Immigration

Adult Chinook salmon generally pass the Locks through the fish ladder or in the large lock during lockages. Chinook pass through the Locks from mid-June through September, but the peak migration is usually around mid-August. These fish hold above the Locks for 17 to 19 days on average before migrating through the Ship Canal into Lake Washington.

Adult Chinook salmon migration through the Ship Canal occurs very quickly, ranging from 4 hours to 8 days. Little is known about the habitat and behavior of Chinook in the Ship Canal, although depths of 20 feet are reported in one tracking study (Fresh et al. 1999).

High water temperatures and low DO above the Locks in the Ship Canal pose risks to returning Chinook salmon. Studies documenting specific lethal or sublethal effects have not been conducted.

Freshwater

Adult Chinook salmon generally enter Lake Washington between August and September. Travel rates for fish in Lake Washington are unknown. In many cases, adult salmon hold in a small area within the lake before entering the rivers for spawning, encountering a wide range of temperatures while they mature.

4.1.2 Coho Salmon

Coho have not been well-studied in the Lake Washington system. Juvenile coho salmon typically reside in freshwater stream habitats for 15 to 18 months before outmigration. Coho usually spend 1.5 years in marine waters before returning to the Lake Washington system. Both Puget Sound resident and ocean populations occur.

4.1.2.1 Juvenile Coho Salmon

Juvenile coho salmon use a variety of habitats for rearing including lakes, small tributaries, perennially wetted areas, off-channel ponds, sloughs, and swamps (Cedarholm and Scarlett 1981, Hartman and Brown 1987, Swales et al. 1988, Bryant et al. 1996, Pollard et al. 1997). In the Lake Washington basin, juvenile coho rear in their natal streams for up to 1 year before entering Lake Washington. See the conceptual model for coho salmon in the Lake Washington basin (page 99).

Freshwater

In the Lake Washington watershed, coho salmon mostly rear in stream and river habitats. However, small numbers of juvenile coho spend some time rearing in Lake Washington (R. Tabor pers comm). Snorkel surveys in Lake Washington in 2001 revealed that coho fry in the lake were associated with small tributaries. In most years, most natural origin coho smolts from the Cedar River enter Lake Washington in May and June (Volkardt et al. 2006).

Outmigration

Age 1+ coho salmon outmigrate from Lake Washington from late April through late May, with a peak usually in early May (Fresh and Lucchetti 2000). It is thought that coho generally move through the lake and into Shilshole Bay more quickly than Chinook salmon because of their large size upon entry into Lake Washington. However, considerable variation occurs on a yearly basis (Seiler et al. 1981, Blankenship et al. 1983).

Most coho salmon tagged and released in the Ship Canal pass the Locks within 2 weeks. Habitats and behavior during this period are largely unknown. Survival risks for coho during outmigration include potential predators in the Ship Canal, entrainment and descaling at the Locks, and salinity and temperature downstream of the Locks.

Estuary

Outmigrant yearling coho salmon tend to move rapidly through estuarine habitats as compared with other species (Emmett et al. 1991). Downstream of the Locks, little is known about coho salmon, although they are found in Shilshole Bay (Simenstad et al. 1999). It is unknown whether or not these fish are from the Lake Washington system, however. In 2001, a few PIT-tagged coho salmon smolts were recaptured below the Locks. These fish appear to spend less time than Chinook salmon smolts in Shilshole Bay before entering Puget Sound (DeVries et al. 2005). Juvenile coho may spend their first summer, from July through September, rearing in pelagic regions of Puget Sound, where they consume zooplankton and may be subject to predation.

4.1.2.2 Adult Coho Salmon

Adult coho salmon generally return to the Lake Washington basin after 1.5 years in marine waters. See the conceptual model for coho salmon in the Lake Washington basin (page 99).

Estuary

Very little is known about coho salmon in Shilshole Bay. Coho may inhabit the bay from August through October, although this has not been documented. Marine mammal predation on coho is a known survival risk to fish in this area.

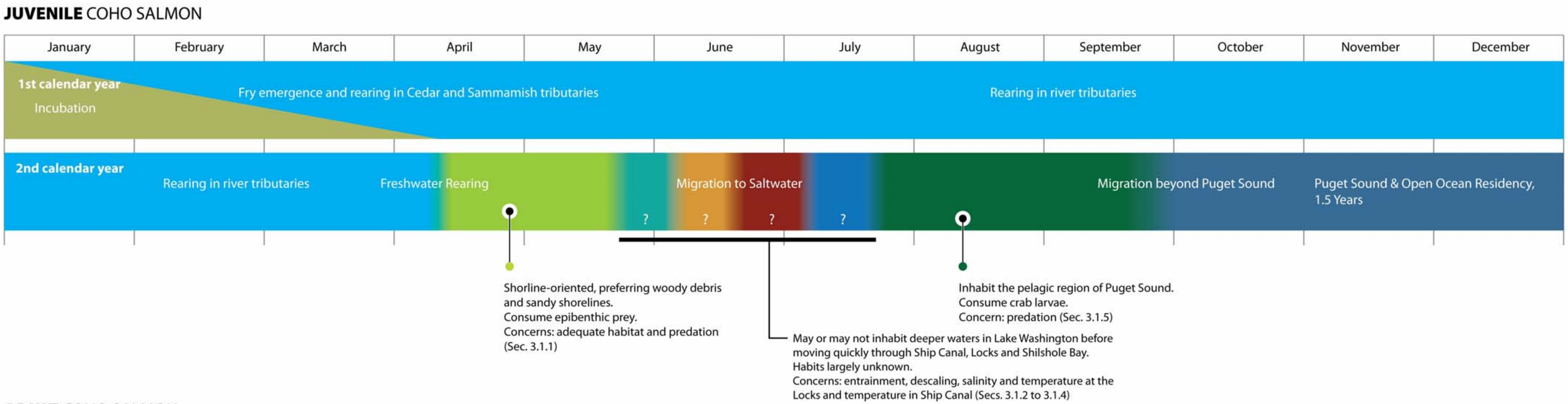
Immigration

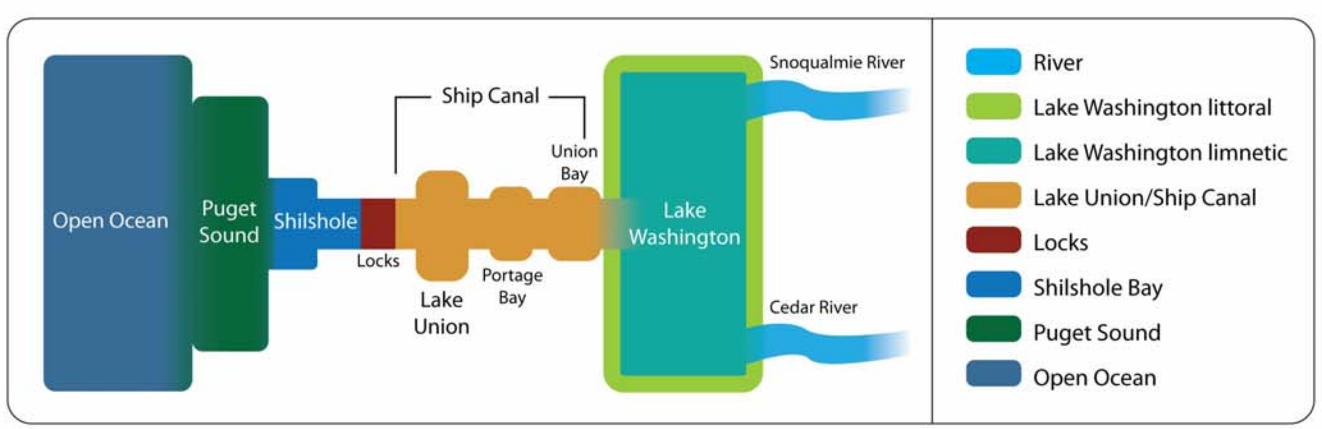
Coho salmon pass through the Locks from the end of August through November. Most adult coho pass the Locks through the fish ladder. The peak return of coho usually occurs in late September.

Little is known about adult coho or steelhead upstream of the Locks. Neither observations nor studies have documented any effects of poor water quality on coho.

Freshwater

Adult coho salmon enter the lake from September through November. Very little is known about habitat, behavior, or survival risks to coho in Lake Washington. It is likely that they hold in the lake near tributary mouths for some time before entering spawning streams after heavy rains in November.





Conceptual Model for Coho Salmon

This figure shows a conceptual model for Coho Salmon in the Lake Washington Basin. Life-history stage, location and characteristics are shown on the horizontal bars. Life-history stage can be reviewed for adult and juvenile Coho Salmon by calendar year.

4.1.3 Sockeye Salmon

Sockeye salmon in the Lake Washington watershed are lake-rearing type. Lake-rearing sockeye typically spend 1 to 3 years in lacustrine (lake) habitats before seaward migration (Burgner 1991). These fish spend a little over 1 year in the Lake Washington watershed before heading to marine waters. Sockeye spend 1, 2, or 3 years in marine waters before returning to the Lake Washington system.

4.1.3.1 Juvenile Sockeye Salmon

Sockeye salmon fry enter Lake Washington from the Cedar River between mid-January and mid-May (Seiler et al. 2005). See the conceptual model for sockeye salmon in the Lake Washington basin (page 101).

Freshwater

Sockeye salmon enter Lake Washington at a very small size (about 1 to 2 in). They generally spend over 1 year rearing in deep water (limnetic) areas of the lake. A few sockeye spend some time in shallow water (littoral areas) or riverine habitats, but limnetic environments are very valuable to juvenile sockeye. Martz (1996) found higher growth rates in juvenile sockeye in limnetic areas than in littoral areas. Sockeye in Lake Washington are known to school more than other species. Beauchamp et al. (1999) reported that both individuals and schools of sockeye salmon located at or below the thermocline during the day in July. Schools disbursed at dusk and were located between 50 and 60 feet throughout the night. Eggers (1978) noted that sockeye salmon move closer to the lake surface when light intensity is low.

Small numbers of sub-yearling sockeye have also been observed at the Locks (Warner 1996). This indicates that a few juvenile sockeye rear in the Lake Washington watershed for less than 1 year.

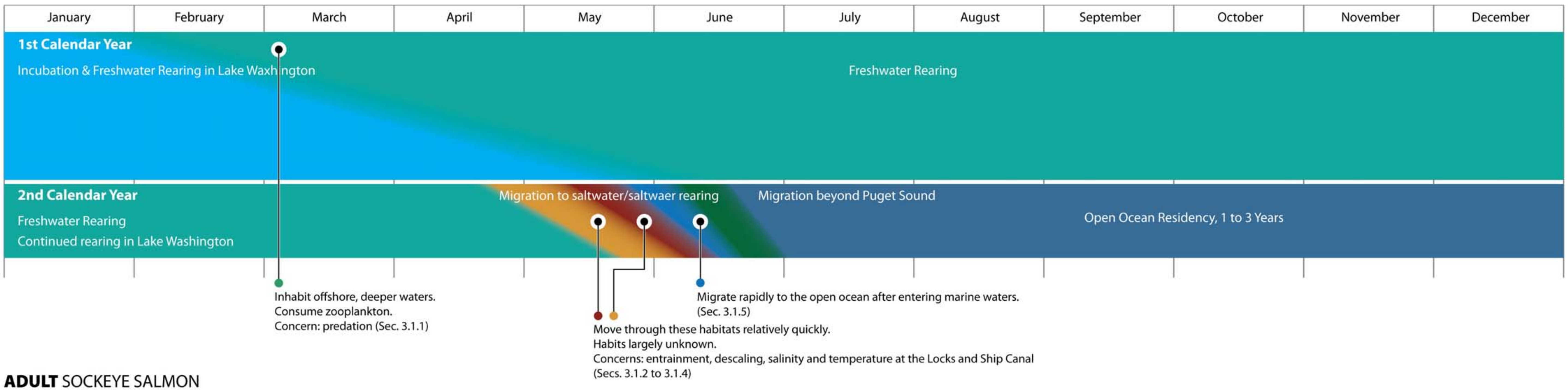
Outmigration

Juvenile sockeye salmon leave the lake from late April through early June with peaks typically occurring in May (Fresh and Lucchetti 2000). Gustafson et al. (1997) report that sockeye outmigration usually occurs at night, but upon entering the Locks, juvenile sockeye become more diurnal in their movements (Corps unpub data). While most sockeye juveniles typically spend at least 1 year in a lake before smolting, a portion of the sockeye population leave as young-of-year fish. Yearling sockeye are observed to pass the Locks first, followed by young-of-year sockeye (DeVries et al. 2003). Scale analyses suggest that the young-of-year outmigrants survive poorly and do not significantly contribute to adult returns.

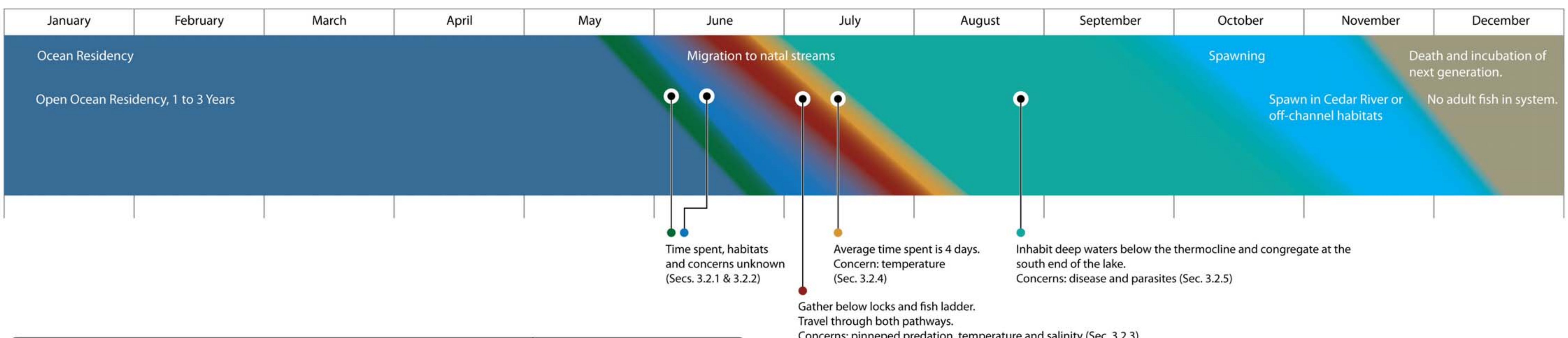
Estuary

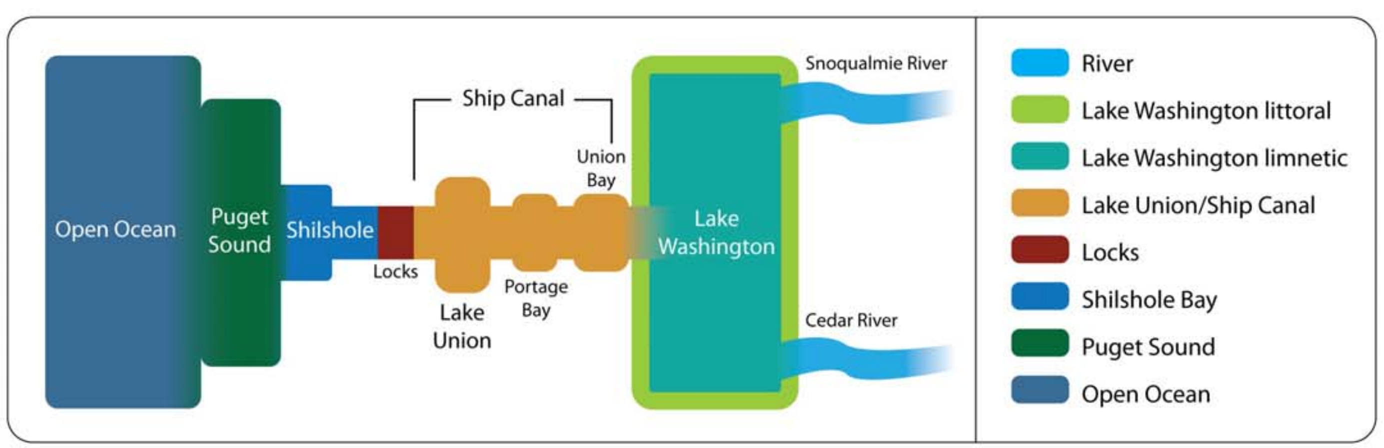
Little is known about sockeye salmon smolts beyond the Locks. Generally, sockeye move quickly through estuaries (Quinn 2005). Sockeye juveniles are rarely caught in offshore regions of Puget Sound, suggesting that sockeye migrate rapidly to the open ocean after entering marine waters (D. Beauchamp unpub data).

JUVENILE SOCKEYE SALMON



ADULT SOCKEYE SALMON





Conceptual Model for Sockeye Salmon

This figure shows a conceptual model for Sockey Salmon in the Lake Washington Basin. Life-history stage, location and characteristics are shown on the horizontal bars. Life-history stage can be reviewed for adult and juvenile Sockey Salmon by calendar year.

4.1.3.2 Adult Sockeye Salmon

Adult sockeye salmon generally return to the Lake Washington basin after 1 to 3 years in marine waters. See the conceptual model for sockeye salmon in the Lake Washington basin (page 101).

Estuary

Very little is known about adult sockeye use of the Shilshole Bay estuary. It is possible that sockeye spend some time here in May and June before migrating upstream through the Locks, but this has not been recorded. Predation by marine mammals may be a survival risk to sockeye in this area.

Immigration

The sockeye salmon immigration generally ranges from June through July. The median date of sockeye salmon passing the Locks is July 7. Most sockeye use the fish ladder. Some sockeye pass the Locks via up lockages. Unlike Chinook salmon, sockeye generally quickly move beyond the Locks.

Sockeye salmon tagged in 2003 spent an average of 4.05 days in the Ship Canal (Newell and Quinn 2005). It is thought that sockeye move through the Ship Canal as quickly as possible in order to reach Lake Washington where they can select cooler temperatures. Water temperatures in the Ship Canal during July and August are generally the highest temperatures of the year. Little is known about the habitat and behavior of salmon while migrating through the Ship Canal.

Enroute mortality has been observed directly and indirectly for upstream migrating adult sockeye salmon primarily during years with high summer temperatures (K. Fresh pers comm). This matter has not been extensively studied, however. This finding underscores the need to link water quality in the Ship Canal with lethal and sublethal effects on adult salmon.

Freshwater

Sockeye enter the lake as early as June and stay until October or November. Sockeye spend an average of 85 days in the lake with a range from 57 to 132 days (Newell and Quinn 2005). While in the lake, sockeye stay in deep, cool waters. Sockeye generally move throughout the lake shortly after entering, but congregate near the mouth of the Cedar and Sammamish rivers after about 1 month in the lake (Newell et al. 2007).

4.1.4 Steelhead/Rainbow Trout

There are few remaining steelhead in the Lake Washington basin. The fish may spend 2 years rearing in freshwater before migrating to marine areas. Steelhead spend 2 to 3 years in the open ocean before returning to the basin.

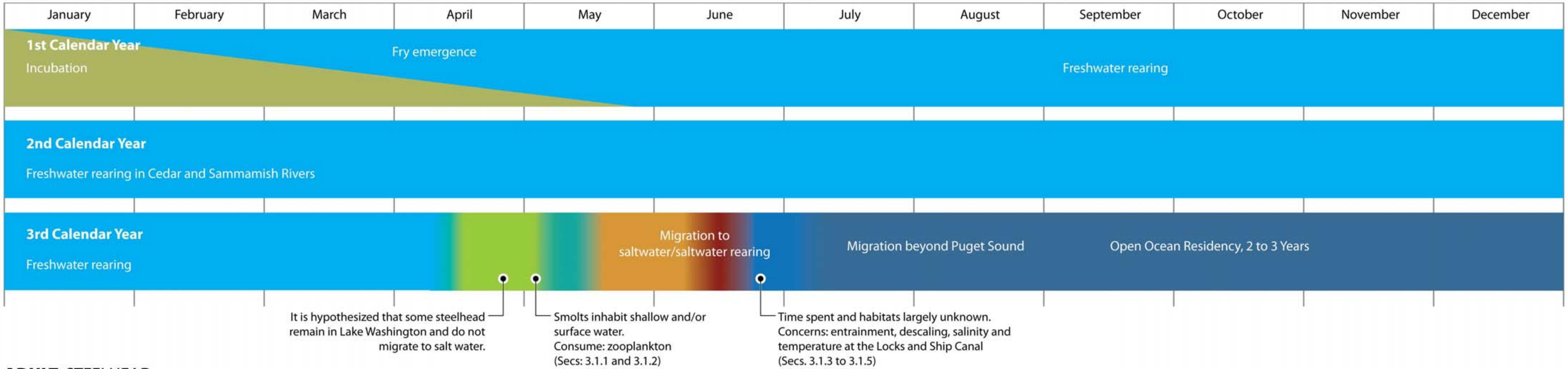
4.1.4.1 Juvenile Steelhead/Rainbow Trout

Juvenile steelhead from the Lake Washington watershed rear in streams for 1 to 2 years before migrating seaward (Fresh and Lucchetti 2000). See the conceptual model for steelhead in the Lake Washington basin (page 103).

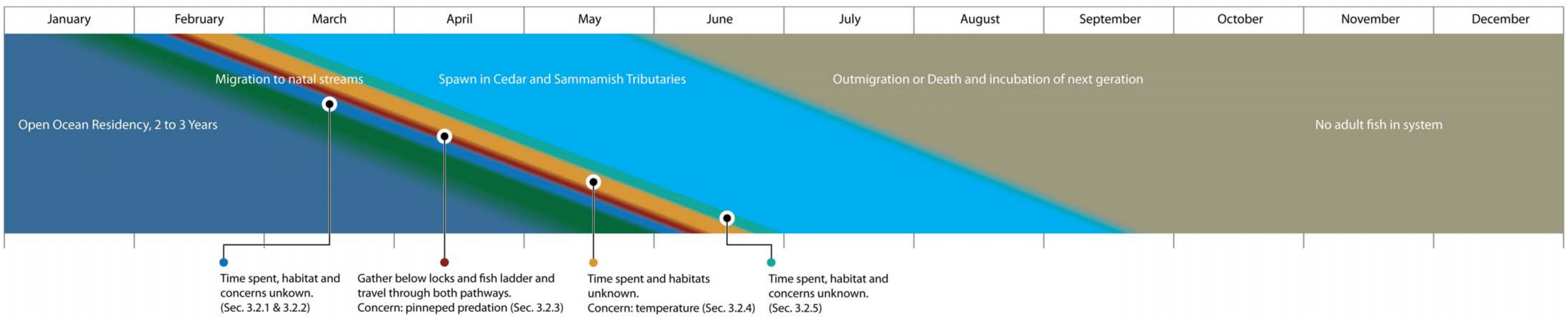
Freshwater

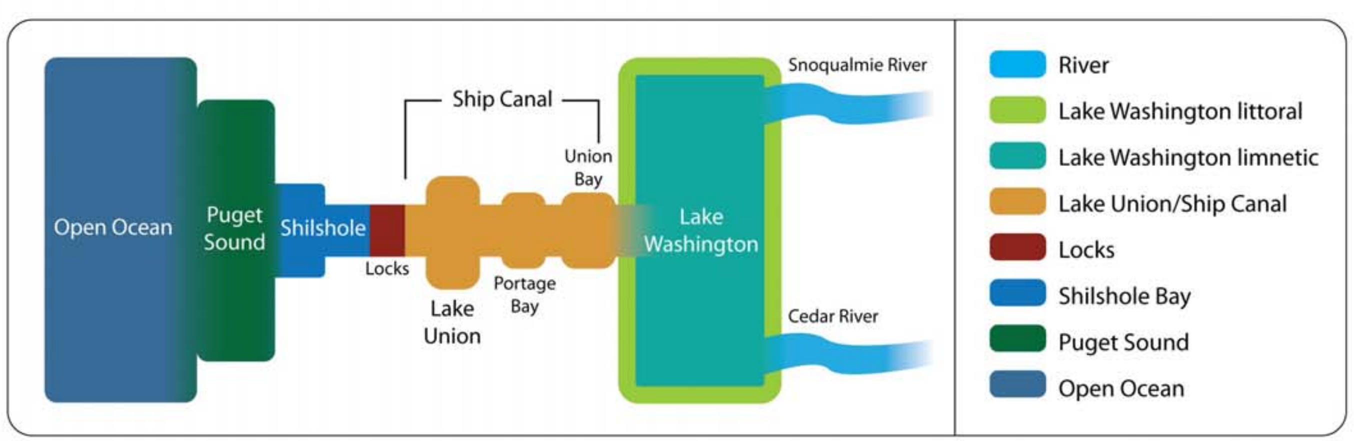
Although this population is known to use Lake Washington, detailed information is not available on their life-history. Steelhead smolts in the 1980s migrated into Lake Washington in April and May and fed heavily on *Daphnia* for about 1 month before migrating to sea (Beauchamp 1995).

JUVENILE STEELHEAD



ADULT STEELHEAD





Conceptual Model for Steelhead

This figure shows a conceptual model for Steelhead in the Lake Washington Basin. Life-history stage, location and characteristics are shown on the horizontal bars. Life-history stage can be reviewed for adult and juvenile Steelhead by calendar year.

Outmigration

Juvenile steelhead outmigration spans April to May and peaks in early May (Fresh and Lucchetti 2000). Little is known about their habits, behaviors, or survival risks while outmigrating.

Estuary

Little is known about the estuarine transition for juvenile steelhead from the Lake Washington watershed.

4.1.4.2 Adult Steelhead/Rainbow Trout

Adult steelhead return to Lake Washington to spawn after 2 to 3 years in marine waters. See the conceptual model for steelhead in the Lake Washington basin (page 103).

Estuary

Little research has been done on steelhead in Shilshole Bay. Sea lion and seal predation on steelhead in the late 1970s was blamed for further depleting an already small population. Since that time, the Corps has tried to limit marine mammal predation on steelhead and other adult salmon downstream of the Locks.

Immigration

Steelhead begin their upstream migration early in the year. They may arrive at and pass through the Locks from January and May. It is likely that most steelhead pass through the fish ladder, but no estimates are available of fish passing the ladder versus through other areas of the Locks. Researchers have not investigated the habitats, behaviors, or survival risks to steelhead while migrating through the Ship Canal. Water quality in the Ship Canal does not pose as great a risk to steelhead as it does to the other salmon because steelhead migrate through in the spring time when waters are still cool and DO is not yet a problem.

Freshwater

Adult steelhead may be in Lake Washington from February through June. No other information exists on adult steelhead in Lake Washington.

4.2 Climate Change: Adapting Conceptual Models

Future environmental conditions in Lake Washington and the Ship Canal will eventually reflect climate change. The primary effects of climate change on salmon in Lake Washington are most likely to result from increasing water temperature. Changes in precipitation are less likely to affect summer water-quality conditions in Lake Washington because of flow regulation and the dominant effect of air temperature on water temperature. This section describes the ways that temperature and precipitation may affect salmon life-history stages that depend on lake residency.

4.2.1 Climate Change and Salmon in the Lake Washington Basin

Anadromous fish evolve and adapt to a naturally variable environment. Francis and Mantua (2003) suggest that natural climate variability itself is not a primary concern to sustainability of salmon stocks. They propose that impacts to salmon are more likely when climate change is superimposed on other human-caused changes in salmon habitats. Battin et al. (2007) suggest that habitat deterioration associated with climate change may make salmon recovery targets harder to attain. The Lake Washington basin is heavily developed and plagued with human-caused changes.

Overall, the warm phase of the Pacific Decadal Oscillation (PDO) has been used as a surrogate to assess potential effects of global warming on salmon (Mote et al. 2003). The warm phase has been generally linked to diminished salmon abundance in the Pacific Northwest. However, the effect in abundance is much weaker for Puget Sound stocks than coastal stocks. The mechanisms for these responses are not well understood.

Predicted changes attributable to climate in the Lake Washington Basin include the following (Mote et al. 2003, Edmunds et al. 2003, Snover et al. 2005, Palmer 2007):

- Increased summer water temperatures
- Increased winter precipitation and peak flows
- Earlier spring runoff

Snover et al. (2005) predict that climate change impacts to Puget Sound salmon will occur through elevated summer water temperatures, increased winter flooding, and decreased summer and fall stream flows. Population modeling in the Snohomish River basin indicates that climate change impacts to salmon productivity in freshwater may be greatest because of peak flows during the incubation period, elevated water temperatures during the late fall pre-spawning period, and minimum flows during the spawning period (Battin et al. 2007). Increased summer water temperatures can affect juvenile and adult salmon, while increased winter precipitation will primarily impact incubation. Earlier spring runoff periods could impact smolt outmigration and returning adults.

Climate change impacts may also indirectly impact salmon in the Lake Washington basin. Changes in life-history timing for key species may cause mismatches between peak food supply and demand by juvenile salmon. Climate change may also impact piscivorous animals and non-native species in the system. These ecological shifts will have ramifications for salmon, but have not been studied.

4.2.1.1 Temperature Increases

Water temperature changes impact the Lake Washington basin in many ways. Water temperatures have already increased in the basin, making it likely that temperatures will continue to rise. For example, from 1964 to 1998 Lake Washington surface water temperatures have warmed by 0.11ºF (0.063 ºC/yr) (Arhonditsis et al. 2004). These changes will adversely affect salmon in the system.

Historically, maximum daily air temperatures in the Pacific Northwest are under 66ºF (18 ºC). However, air temperatures increased 1.4ºF (0.8ºC) during the 20th century (Mote et al. 2003). Air temperatures in the Pacific Northwest are projected to further increase during the 21st century (Mohseni and Stefan 1999). Predicting air temperature increases can be difficult and is generally done with complex modeling. One model predicts air temperature increases of 0.9 to 4.5ºF (0.5-2.5ºC) by the 2020s and 2.7 to 5.8ºF (1.5-3.2ºC) by the 2040s (Mote et al. 2003). Another predicts increases up to 7 or 8ºF (4.0 or 4.5 ºC) in the Pacific Northwest by the 2090s (Edmonds et al. 2003). A third model predicts that warming in the region may average 0.5 to 1.0ºF (0.3-0.6ºC) per decade (Mote et al. 2005). Recent analyses of projected summer air temperature increases on the Cedar River are 3.6 to 8ºF (2-4ºC) by 2075, with maximum daily air temperatures reaching 70ºF (21ºC) (Climate Variables Database).

Water temperature trends generally reflect air temperature trends in the Pacific Northwest. In fact, changes in water temperature are already observable in the Lake Washington basin. Since 1950, a steady increase in shallow waters of the lake has been documented annually (Edmondson et al. 2003) and in September (Quinn et al. 2002). One study calculated an average summer warming rate from 1964 to 1998 of about 0.063 ºC/yr in the upper 33 feet of Lake Washington (Arhonditsis et al. 2004). These changes are associated with an increased duration of the summer stratification period. Currently, stratification begins 16 days earlier and ends 9 days later than it did historically (Winder and Schindler 2004a).

Water temperature data through 2007 imply that the change in stratification could be associated with warming near-surface, spring water temperature trends (Figure 39).[8] Temperature decreases in the fall also appear to occur later (Figure 40). The extended duration of stratification appears to reflect long-term climate warming and variability associated with the PDO and El Niño–southern oscillation (ENSO) (Winder and Schindler 2004a,b).

Figures 44 and 45 show dates when temperatures in Lake Washington exceeded salmon tolerances for various life stages. Analysis of cumulative thermal stress in shallow waters, represented by degree days above 68ºF (20ºC), indicates a general increase in thermal loading of Lake Washington between 1964 and 2006.

Water entering the Ship Canal is drawn through the Montlake Cut, which is about 30 feet deep and draws primarily from Lake Washington's surface waters. Therefore, a water temperature increase similar to that for Lake Washington is expected in the Ship Canal.

Increased air temperatures are also expected to increase evapotranspiration from Lake Washington. This change could result in less water available for fish passage at the Locks.

4.2.1.2 Winter Precipitation Increases

Winter precipitation is expected to increase in the Pacific Northwest. However, winter air temperatures are expected to increase. This will also lead to reduced snowpacks and higher winter flows. The hydrologic effects of reduced snowpack volume could lead to a reduction in stored water to municipalities and for wildlife. Wiley (2004) projects that combined inflows to the primary water sources for SPU will decrease at an average rate of 6% per decade between 2000 and 2040. SPU is preparing for the impacts of climate change by increasing operational flexibility and continuing efforts to reduce demand. However, instream flow necessary for protection of salmon in the Cedar River also depends on water supply from Chester Morse Lake. The latest predicted effects of climate change on water supply should not affect the City's ability to meet the Cedar River instream flow obligations in the foreseeable future.

Increased winter flows could impact the survival of embryos in the basin (Battin et al. 2007). Higher peak winter flows may lead to more scour in areas where fish typically spawn. This will *wash out* embryos that would probably be safe from scour under lower flows. Also, the number of young Chinook salmon entering Lake Washington may be influenced by stream flow. When late winter and early spring stream flows are high in the Cedar River, juvenile Chinook tend to move downstream into Lake Washington. When stream flows are more moderate during this period, a higher proportion of juveniles may rear in the river.

A decreased snowpack in the region will decrease water available for late juvenile salmon outmigrants and returning adults. To assist passage of both groups, operational changes may be needed for the saltwater drain and fish ladder during summer and early fall when adult return.

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[8] These temperatures approximate health and migration threshold criteria reported for juvenile and adult salmon (McCullough 1999; Hicks 2002; Quinn et al. 2002).

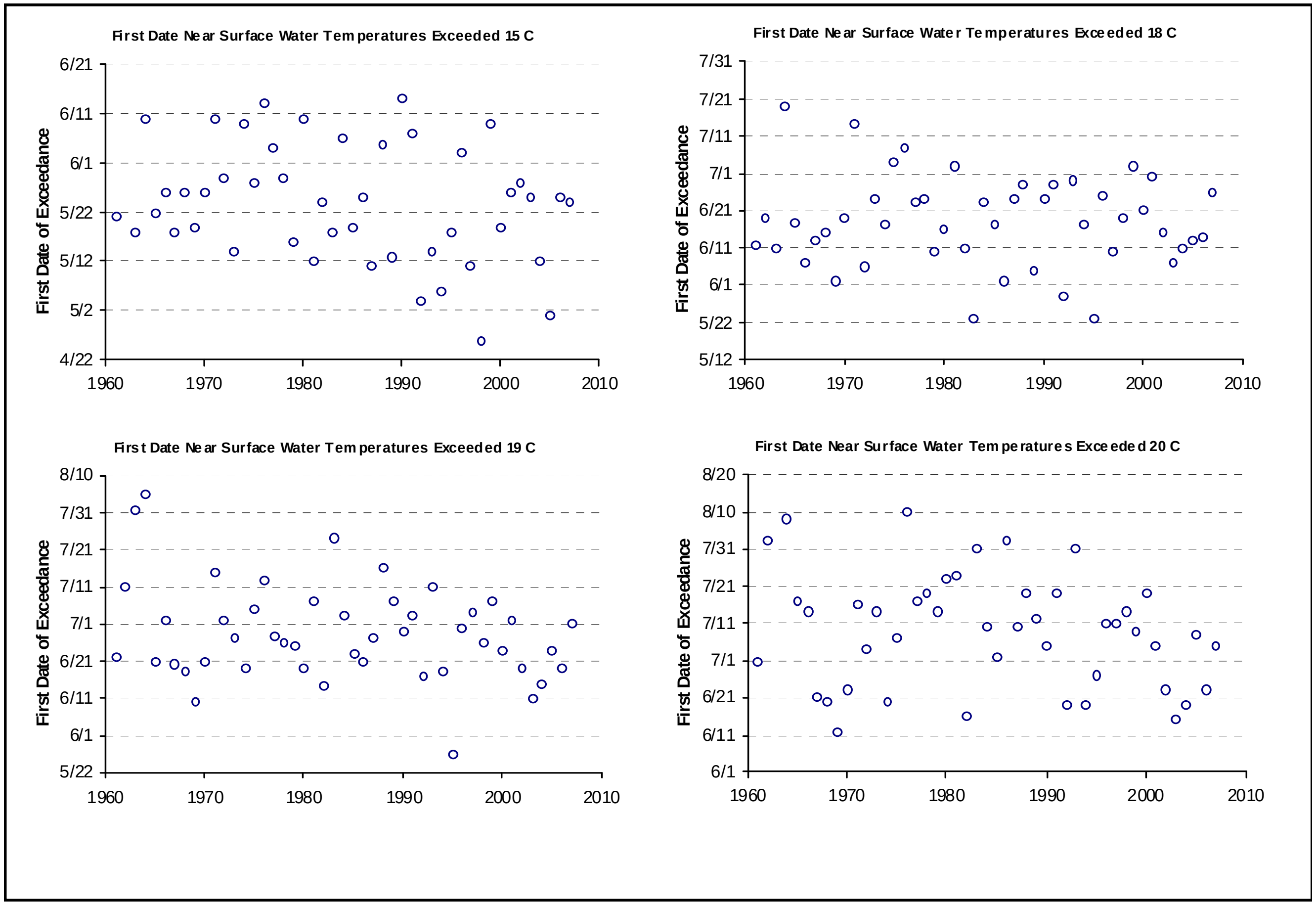

Figure 39
Estimated first date in spring nearsurface water temperatures in Lake Washington 15º, 18º, 19º, and 20ºC near Madison Park (1960-2000)

Source: D.E. Schindler unpub data

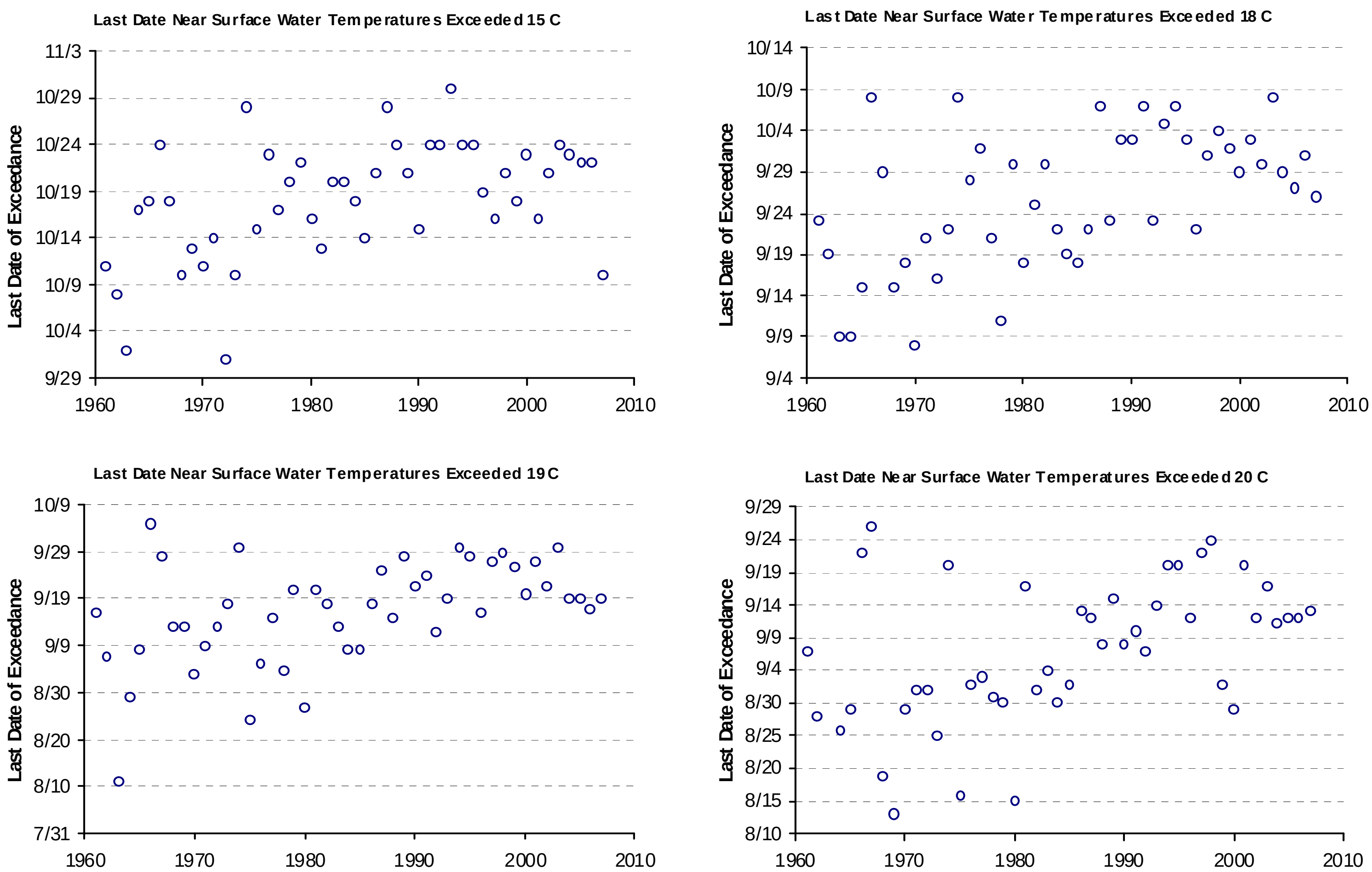

Figure 40
Estimated last date in summer/early fall spring nearsurface water temperatures in Lake Washington equaled or exceeded 15º, 18º, 19º, and 20ºC near Madison Park (1960-2008)
Source: D.E. Schindler unpub data

4.2.1.3 Earlier Spring Runoff

Earlier spring runoff from warming temperatures in the region may impact salmon in the Lake Washington basin. Climate change modeling in 2007 projected that average Cedar River flow in April to June will decline 3% by 2050 and 12% by 2075 compared to historic flow (Palmer 2007). June to August flows are predicted to decline 28% by 2050 and 37% by 2075.

The following are some thoughts on how earlier spring runoff will impact juvenile salmon:

- Earlier spring runoff may encourage juvenile salmon to move out of their natal streams earlier than they would under normal conditions. The fish may run into prey shortages in Lake Washington.
- Earlier spring runoff may also impact water management for salmon at the Locks. More water earlier may mean that the Locks need to spill more water earlier to maintain water levels in the Lake. There may also be less water available during the juvenile outmigration season for smolt flume operation.
- Decreased flows through the fish ladder and decreased lockages to improve water storage during warm summer months may impact adult salmon emigration.

4.2.2 Juvenile Salmon and Regional Climate Change

Changes in lake water temperature are the main climate change that will impact juvenile salmon in the Lake Washington basin. While in Lake Washington, juvenile salmon consume zooplankton very heavily during certain life stages. Zooplankton consume phytoplankton, which depend on sunlight, water temperature, and water clarity for production. The temperature effects of climate change may already be affecting juvenile salmon in the lake by impacting plankton peak-population times and abundance (Winder and Schindler 2004a,b). Advanced timing of stratification is linked to an earlier *spring bloom* of phytoplankton. Currently, juvenile salmon food is not limited in the lake (Beauchamp et al. 2004, Koehler et al. 2006). However, changes in plankton timing and abundance could affect feeding patterns for these fish. Juvenile salmon may respond by changing to alternate food sources

With the warming of Lake Washington and Ship Canal, it is possible that juvenile salmon could become more susceptible to predation. Arhonditsis et al. (2004) hypothesize that earlier annual warming may lead to increased predation of juvenile outmigrant salmon by non-native warm-water species such as smallmouth bass, northern pikeminnow, and lake-dwelling cutthroat trout. Bass get more active and effective at preying on salmon when temperatures approach 68ºF (20ºC). The present balance between outmigration timing, predation efficiency, and water temperature could shift to increased predation-related mortality with water temperature increases.

4.2.3 Adult Salmon and Regional Climate Change

Increases in summer and early fall water temperatures may affect the timing of upstream migration of adult salmon. Effects will vary by species. Adult Chinook and sockeye salmon are the most likely to be impacted by climate change, but coho salmon and steelhead may also be impacted.

Chinook salmon may be the species most sensitive to water temperature increases. Juveniles outmigrate in the late spring, and adults pass through the Ship Canal in August and September. Both of these life-history stages already encounter temperatures higher than published tolerances. Adult Chinook also spend long periods holding above the Locks in the Ship Canal and are found at a variety of temperatures in Lake Washington.

Sockeye adult migration peaks in early July before maximum temperatures in the Ship Canal. Sockeye migrate more quickly through the Ship Canal than do Chinook and immediately seek cold water at depth in Lake Washington. Coho and steelhead are theoretically better off than sockeye or Chinook because they migrate during cooler periods. Coho and steelhead also spend more time in streams, which may be a factor in their survival.

However, increased water temperatures may lead to reduced use of the fish ladder and increased use of the large lock by returning adults. Exploratory analyses suggest that fewer adult Chinook salmon pass upstream through the fish ladder in years when nearsurface Ship Canal temperatures are warmer (DeVries 2007). As temperatures continue to warm, there will be increasing concern about lethal and sublethal effects of temperature in Lake Union and the Ship Canal.

It is not clear if hatchery-origin Chinook salmon adult passage timing will be affected by climate change. Spawning timing for hatchery-origin fish can be manipulated by hatchery selection practices (Quinn et al. 2002). Earlier spawning by hatchery-origin fish contrasts with the warming trends expected with climate change. Perhaps hatchery selection pressures can override selection pressures from temperature increases. However, at some point, emigration of all adult fish could pass a thermal threshold in Lake Union. If so, hatchery-origin fish would be as affected by climate change as would natural origin Chinook.

The biggest risk to sockeye salmon with climate change is adult movement through the Ship Canal and Lake Union. Given that temperatures in Lake Washington are often over 68°F (20 °C) during sockeye emigration, and that the warm period is extending longer into fall, perhaps over the long term, sockeye migration will shift. Earlier migrants would hold longer in Lake Washington than they currently do. Later migrants would coincide with Chinook and coho salmon passage timing at the Locks. The impact of changes in migration timing by sockeye is unknown.

Natural spawning fish might adapt to prolonged warmer fall water temperatures by migrating later than hatchery fish. Adult coho salmon pass the Locks when water temperatures are less stressful. Because water temperatures are generally more favorable in the Ship Canal during peak coho migration, coho adults are the least likely of the four salmon species to be affected by changes in water temperature associated with climate change.

Little is known or hypothesized about adult steelhead and climate change in the Lake Washington basin. Steelhead may not be as affected as the other species because they migrate into the system early in the year.

5. Management Actions and Further Study

Studies in the LWGI and by others have identified much about salmon as they move through the Lake Washington basin. Although some management actions may be taken with current knowledge, in some cases further research is necessary. **The goal for all species is to increase survival and life history diversity and maintain productivity while in Lake Washington, the Ship Canal, and Locks.**

Given what is known about salmon in the Lake Washington system, the following actions are recommended for implementation, continuation, investigation, and consideration. In some cases, actions address the same areas as issues and need to be analyzed together to evaluate their cumulative benefits and impacts.

5.1 Objectives and Actions for Juvenile Salmon

Increasing the survival of juvenile salmon can be achieved through improving habitat in Lake Washington and the Ship Canal, improving passage through the Locks and decreasing water temperature and salinity gradients between Salmon Bay and Shilshole Bay.

5.1.1 Objective: Improve Habitat for Juvenile Salmon in Lake Washington

Concerns in the littoral zone of Lake Washington are wide-ranging. They include shoreline armoring, overwater structures, lighting, and invasive species such as Eurasian water milfoil. Littoral zone habitats and the impact of urbanization are well understood. For this objective, research and actions are primarily related to improving Chinook salmon habitat. Research in Lake Washington should shift to monitoring the outcomes of salmon habitat improvement projects. Such projects should be examined for their benefit to rearing fry and outmigrating smolts and for potential impacts on predators.

Management Actions

- Continue removal and replacement of shoreline armoring and creation of shallow water habitat with overhanging native vegetation. These actions will improve rearing conditions for Chinook fry. Focus these activities in the southern end of Lake Washington.
- Continue to improve habitat around overwater structures by removing structures, reducing their footprint or improving light penetration.
- Implement removal of in-water debris and riprap to reduce available predator habitat. This may be done with by filling riprap with pea gravel. However, that technique should first be tested.
- Prioritize daylighting tributaries and tributary mouths such as Mapes Creek.

Proposed Studies

- Evaluate the effectiveness of habitat restoration efforts on juvenile salmon survival.

- Evaluate different types of piers and their effect on juvenile salmon movements.
- Investigate the influence of predation on juvenile salmon survival and the relative contribution from fish and avian predators. Research shows varying levels of predation on juvenile salmon in Lake Washington. Predator population numbers are still largely unknown, making predation estimates somewhat unreliable.
- Monitor the impact and abundance of introduced fish (smallmouth bass, rock bass, etc.), aquatic plants (i.e. Brazilian elodea seems to expanding) and invertebrates (crayfish, mussels, etc.).
- Study the impact of artificial lighting on juvenile Chinook and their predators (especially birds). The study should include direct reference to bridge lighting and these other predators.
- Investigate the impact of poor water quality on juvenile salmon. Upland uses have a dramatic effect on the survival of salmon. Pollution from stormwater outfalls, combined sewer overflows, boats, and aerial deposition decrease the quality of water in Lake Washington.

5.1.2 Objective: Improve Habitat for Juvenile Salmon in the Ship Canal and Lake Union

Some uncertainty surrounds habitat preferences of juvenile salmon in the Ship Canal and Lake Union. As in Lake Washington, there are opportunities to improve habitat and reduce favorable conditions for predators. Monitoring should be conducted to ensure that these actions improve habitat for juvenile salmon.

Management Actions

- Implement habitat improvement projects to support juvenile salmon survival and boost salmon prey resources while reducing favorable habitat for predators.

Proposed Studies

- Investigate survival and predation rates in the Ship Canal and Lake Union. Studies to date suggest relatively high survival and low predation rates early in the outmigration season. However, these estimates include several sources of error, and studies on late outmigrants have not yet been conducted. Year-to-year variability and tracking study efficiencies contribute to error in predation estimates. The influence of avian predators should also be examined.
- Further investigate the habitat preferences of smolts. Studies to date provide inconclusive results on habitat use of smolts in Lake Union and the Ship Canal. Research by Celedonia and Tabor from 2004 through 2008 will provide information on this.
- Study the effect of water temperature on migration depth and predation pressure in the Ship Canal. High water temperatures may increase predation on juvenile salmon. The potential for reducing water temperatures in the Ship Canal through human modifications (e.g. piping in water from a cool water source) should also be considered. This may be the most important solution to the threat of long-term climate change.
- Evaluate the effectiveness of habitat restoration in Lake Union and the Ship Canal on juvenile salmon survival.

- Consider relaxing the state-set salinity standard for the Ship Canal. The current authorized operation of the Locks includes managing saltwater intrusion to maintain salinity levels below 1% at the University Bridge. Relaxing the Washington State standard could lead to an increased volume of more saline water upstream of the Locks and may improve surface water flow out of the system. More saltwater upstream would increase estuarine habitat availability.
- Study the apparent decline of entrance into the Montlake Cut later in the outmigration season. Investigate temperature, water clarity, predator abundance, predators, fish behavior, and how these factors influence juvenile Chinook behavior.
- Investigate factors that influence Chinook smolt use of Lake Union, and the consequences of this holding. Do the fish hold because they are inhibited (e.g. Fremont Cut is a barrier) or because it provides more rearing habitat? Is there an elevated predation risk associated with holding here? Does holding here impact fitness or survival?
- Investigate the impact of poor water quality on juvenile salmon. Upland uses have a dramatic effect on the survival of salmon. Pollution from stormwater outfalls, combined sewer overflows, boats, and aerial deposition decrease the quality of water in Lake Union and the Ship Canal.

5.1.3 Objective: Improve Passage through the Locks for Juvenile Salmon

Several adaptive management actions implemented since 1995 have improved smolt passage conditions at the Locks. The largest remaining uncertainties at the Locks are the proportion of outmigrants passing through the various routes available and the survival of fish in each passage route.

Management Actions

Actions are grouped by area of the Locks.

Strobe Lights

a. Continue to use strobe lights at the large lock filling culverts to reduce entrainment.
b. Install automated controls to trigger the strobe lights before large lock operation.
c. Investigate installation of more strobe lights on the Locks to move fish away from potentially harmful areas such as filling ports in the large lock.

Saltwater Drain

a. Implement minimal use of the saltwater drain at temperatures above 66°F (18.9°C) to reduce potential entrainment.
b. Investigate deepening and cleaning the sump near the saltwater drain.
c. Consider constructing a new saltwater drain designed to improve the efficiency of removing the intrusive saltwater and to use water more efficiently. The new drain would replace the existing saltwater drain and prevent entrainment of salmon.
d. Consider closing off the saltwater drain intake discharging directly into Puget Sound to use water more efficiently during juvenile fish passage. Salinity control

could be accomplished with discharge through the fish ladder, flumes, and spillways. Open the saltwater drain intake discharging to Puget Sound only when state water quality levels risk being exceeded.

Lock Chambers

a. Continue to use intermediate-to-slow fill rates to further reduce entrainment into the lock filling culverts.
b. Implement replacement of Stoney gate valves to maintain or reduce current slow fill rates.
c. Investigate maximal use of the small lock to reduce entrainment into the large lock filling culverts and to set up flow velocities to attract juveniles to the smolt flumes.
d. Investigate how false lockages at the small lock could attract juveniles to the flumes.
e. Continue standard operating procedures for the large lock operations for avoiding use of the lower large lock chamber alone during upstream lockages.
f. Investigate reducing the number of lockages to conserve water for fish passage through the flumes when temperatures allow.
g. Construct a new saltwater barrier in the large lock to improve the efficiency of the barrier to reduce the use of the saltwater drain. Three alternatives to consider are 1) a fixed height, shorter barrier, 2) a variable height barrier, and 3) a shorter barrier to complement the existing barrier.
h. Consider scheduled and delayed lockages (i.e. wait until lockages are fully filled with boats), and fee-based lockages as ways to reduce lockage demand and provide more water for fish passage. (This is a consideration for adult salmon also.)
i. Consider lowering the target lake elevation to 19.5 feet project datum to increase water availability for smolt passage and saltwater drain operation. The current authorized operation of the Locks includes managing lake elevations to remain between 20 and 22 feet project datum. (This is a consideration for adult salmon also.)

Smolt Flumes Spillway

a. Continue to close smolt flumes or reduce flume flow at night to provide additional water for daytime use and to conserve water for later summer.
b. Continue to use at least two flumes, as conditions allow, for fish passage including one of the two large flumes.
c. Continue to decrease flume operations when surface water temperatures exceed some threshold between 66.2 to 69.8ºF or in mid-July when smolt outmigration is mostly complete.
d. Implement a reduction in flume use 1 or 2 weeks before the late May/early June lunar apogee and increase flume use in the days after the apogee to use water more efficiently, particularly in dry years.
e. Investigate redesigning the smolts flumes and their installation in the spillway to reduce maintenance and installation costs.
f. Investigate the benefits of adding additional flumes to the spillway.
g. Investigate replacing the smallest flumes with a larger flume (90 or 130 cfs) to increase fish passage.

h. Continue adaptive management of smolt flumes and lockages, as defined in the guidelines for smolt flume operation provided to the lock master each spring.
i. Implement strategic use of spill in years of high water availability to improve fish passage. Monitor the results of this action.
j. Consider providing deep passage routes as an alternative to the large lock for juvenile salmon.
k. Consider turbulence induction to attract juveniles towards safe passage routes. This has been proposed for dams by (Coutant 2001). Assuming that the smolt flumes provide overall a safer route than the large lock, turbulence induction might attract migrants to the flumes.

Proposed Studies

- Plot daily emigration curves for each anadromous salmon species. The curves would improve understanding of the proportion of populations subject to survival risks such as predation and high water temperature over the course of the season.
- Count the proportion of juveniles that pass through the small and large lock chambers. It is unclear how juvenile salmon may be affected by lock chamber filling or draining once they are in the lock chambers during a lockage. Fish may be pulled into filling ports and entrained into the filling culverts during a lock draining.
- Assess the survival of smolts passing over the spillway and through the flumes. While these are thought to be a safe passage routes through the Locks, studies have not been conducted.
- Assess use of the saltwater drain and effects of drain operation on smolt distribution. Smolts near the saltwater drain intake may be impacted by operations of the saltwater drain. Smolts have been found in the diffuser well at the end of the saltwater drain, but the potential impact to smolts is unknown. A temporary screen placed at the entrance by the Corps in 2008 may prevent smolts from becoming trapped in the saltwater drain.
- Assess the survival of smolts downstream of the Locks. Downstream, smolts may be affected by temperature, salinity shock, or predation from birds or fish.
- Investigate ways to reduce smolt entrainment rates into the large lock filling culverts when temperatures are greater than 70ºF (20ºC). Filling volume could be manipulated to reduce smolt entrainment rates. This action can be accomplished in two ways: 1) scheduling large lockages to periods around high tide or 2) using the upper lock chamber only.
- Evaluate the hydrodynamics in the Ship Canal when the smolt flumes are turned off for the night

5.1.4 Objective: Decrease Water Temperature and Salinity Gradients between Salmon Bay and the Ship Canal

This is expected to reduce stress during passage and acclimation in this area. Smolts appear to spend little time in the freshwater-saltwater mixing zone downstream of the Locks. However, it is also the area where the least amount is known about fish behavior and needs. Any actions aimed at improving estuary conditions should be monitored to identify the true benefit and improve future actions.

Management Actions

- Continue shoreline and riparian restoration, including overwater structure removal.
- Investigate enlarging connections between Salmon Bay and freshwater tributaries to enlarge the estuary.
- Investigate increasing lockages to decrease temperature and salinity gradients.

Proposed Studies

- Investigate salinity, DO and temperature downstream of the Locks in relation to juvenile salmon movements. Identify areas of potential thermal or saline shock or areas of salt and fresh water mixing.
- Implement monitoring of rehabilitation activities in Salmon Bay.

5.2 Objectives and Actions for Adult Salmon

Increasing the survival of adult salmon may be achieved through the following:

- Increasing pathways for adult salmon between Shilshole Bay and the Ship Canal
- Decreasing water temperatures and salinity gradients between Shilshole Bay and the Ship Canal
- Increasing the area of estuarine conditions around the Locks

5.2.1 Objective: Increase Volitional Pathways between Shilshole Bay and the Ship Canal

There is very little area with salt- and freshwater mixing above or below the Locks. If pathways between Shilshole Bay and the Ship Canal are opened so adults can easily and safely move between fresh- and saltwater or select appropriate conditions, this may improve conditions for fish. In natural systems estuaries are places for adult salmon to acclimate to freshwater, hold during maturation or wait for favorable environmental conditions in the spawning streams.

Management Actions

- Investigate creation of a new, safe upstream/downstream pathway for adult salmon by combining a permanent resolution to entrapment within the diffuser well with modifications to the saltwater drain. This may include decoupling the fish ladder flow from the saltwater drain. Salmon would then have the option to use the saltwater drain to return to Salmon Bay or as an additional upstream pathway.
- Investigate building a separate channel for fish passage around the Locks or removing the dam at the Locks and replacing it with a fish-passable structure. These alternate pathways would be designed to increase areas of salt and fresh water mixing.

Proposed Studies

- Investigate salinity, DO, and temperature down- and upstream of the Locks. Determine what factor drive salmon movement in the Locks.
- Develop a temperature model for the Ship Canal and Lake Union that includes effects of lock operations. Using the model, investigate whether there are ways to lower peak summer temperatures in these areas.
- Investigate increased large lock lockages as an alternate pathway to the fish ladder.

- Investigate adult salmon in lock filling conduits. Determine what conditions are in the conduits and the impacts on fish.

5.2.2 Objective: Decrease Water Temperature and Salinity Gradients between Shilshole Bay and the Ship Canal

This will reduce stress during passage and acclimation in this area. Temperatures in the Ship Canal are often higher than tolerable limits for adult salmon.

Management Actions

- Continue limiting the hours of Locks operation to the peak times of passage, typically between 6 am and 11 pm.
- Continue efficient water use and adaptive water management at the Locks.
- Continue use of the real-time saltwater monitoring system to operate the saltwater drain efficiently.
- Investigate flexibility in water allocation, including options for getting cooler water into the Ship Canal.
- Conduct regular night-time large lock lockages to maintain temperature, DO and salinity upstream of the Locks for adult salmon.
- Consider investigating active cooling of a passage corridor or refuge habitat in the Ship Canal. Use modeling to predict a method for doing this.

Proposed Studies

- Determine what is causing sockeye die-offs in the Ship Canal. The leading hypothesis is that mortality is related to high water temperatures and temperature-related causes. Basic analyses are needed to evaluate the feasibility of reducing near-surface water temperatures by 3°F (1ºC) or more in localized areas of the Ship Canal. If feasible, such a measure could provide a less stressful migration corridor for smolts and adults.
- Investigate cumulative temperature stress on adult salmon through the Locks and Ship Canal. Investigate the effects of high water temperatures for adults on egg survival.

5.2.3 Objective: Increase Area of Estuarine Conditions around Locks to Improve Adult Fish Habitat

This objective is aimed at increasing appropriate areas for acclimation to freshwater above and below the Locks.

Management Actions

- Investigate building a separate channel for fish passage around the Locks or removing the dam at the Locks and replacing it with a fish-passable structure. Each alternate pathway would combine salt- and freshwaters.
- Increase the area of cool, high-DO water upstream of the Locks to allow more space for adults in delay on a trial basis. This could be completed by increasing lockages and better management of the saltwater drain.

- Continue to spill from the smolt flumes to decrease salinity below the Locks, when water is available.

Proposed Studies

- Investigate adult salmon use of Salmon Bay and the area downstream of the Locks.
- Consider lowering the target lake elevation to 19.5 feet to increase water availability for smolt passage and saltwater drain operation. The current authorized operation of the Locks includes managing lake elevations to remain between 20 and 22 feet project datum. Bathymetry should be investigated as part of this study to ensure a net gain and/or improvement of littoral habitat.
- Consider relaxing the state-set salinity standard for the Ship Canal. The current authorized operation of the Locks includes managing saltwater intrusion to maintain salinity levels below 1% at the University Bridge. Relaxing the standard could lead to an increased volume of more saline water upstream of the Locks and may improve surface water flow out of the system.
- Consider estuary habitat enlargement. Increasing estuarine habitat characteristics in Ship Canal would allow more fish movement between fresh- and saltwater environments. This could benefit smolts and adults.
- Consider installing a new locks facility at the Fremont Cut. This would increase estuarine habitat and reduce the length of water with elevated temperatures that salmon must traverse.
- Consider investigating the recreation of the Black River between Lake Washington and Duwamish River. This action could benefit smolts from the Cedar River in particular by providing a shorter route to cooler and more saline water. However, this measure could also potentially confuse returning adults and lead to imprinting of WRIA 8 stock smolts in WRIA 9 waters (and vice versa). This action would significantly impact the hydrology of Lake Washington and Locks.
- Consider creating an area with estuarine characteristics upstream of the Locks. This could be done by creating a sump area upstream of the Locks spillway bays.
- Consider investigating deepening the channel between the Locks and Lake Union. Because Lake Union is deeper than the Fremont Cut, water in the lake is stagnant until it flows through the Ship Canal pick up in the late fall. If the lake and channel to the Locks were the same depth, the lower layer of water might mix enough to remain cool and oxygenated during the summer. Alternatively, more saltwater could be allowed to leak upstream. This would help adult Chinook salmon and sockeye survival through the canal.

5.2.4 Conflicting Actions

There may be some cases where recommended actions conflict with various needs for management at the Locks. For example, if the smolt flumes are operated around the lunar apogee it may benefit Chinook salmon smolts and improve water efficiency. Coho and sockeye salmon do not show the same pattern of travel as Chinook. If flumes are closed outside of the lunar apogee, it may negatively impact early coho and sockeye migrants. Ongoing or new projects should address whether or not future modifications at the Locks will affect the outcome. These conflicts make it paramount that all projects are evaluated for benefits and consequences.

This report updates the WRIA 8 Salmon Habitat Plan and WRIA 8 Reconnaissance Report with current research on salmon in the western Lake Washington system.

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