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IMPACTS OF FERRY TERMINALS ON JUVENILE SALMON MIGRATING ALONG PUGET SOUND SHORELINES PHASE I: SYNTHESIS OF STATE OF KNOWLEDGE

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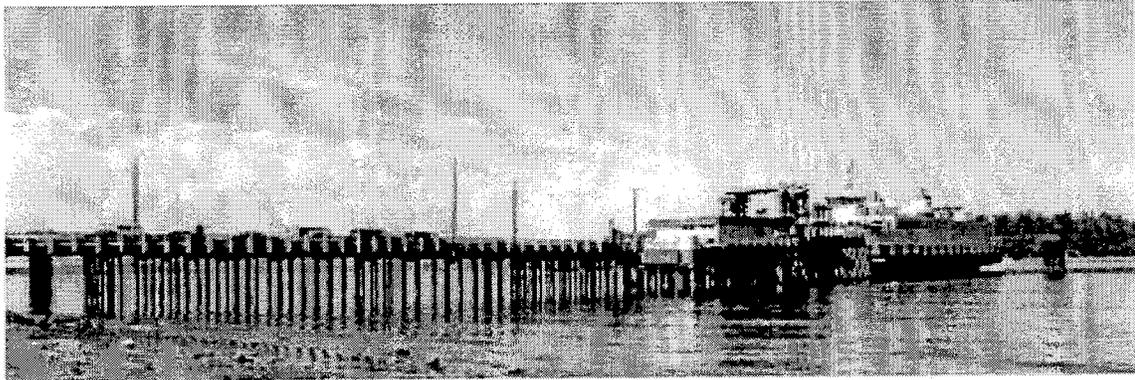


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16. ABSTRACT <p>This project is assessing whether ferry terminals affect juvenile salmon migrating along estuarine and nearshore marine environments and, if so, how design of and modifications to both ferry terminals and operations can mitigate those impacts. This project has three phases. This report summarizes results from Phase I (status of knowledge, initial terminal surveys) and implications for Phase II and III research.</p> <p>We addressed three issues about over-water structures impacts on juvenile salmon: (1) alteration in migratory behavior, (2) reduction in prey production and availability, and (3) increased predation. An assessment of over 60 direct sources of information found evidence that juvenile salmon react to shadows and other artifacts in the shoreline environment created by shoreline structures. While changes in light have been shown to affect salmon migration behavior and thus potentially place them at increased mortality risk, we found no quantitative information on the significance of these behavioral responses to juvenile salmon survival. Juvenile salmon also encounter limited prey resources under shoreline structures when important habitats such as eelgrass (<i>Zostera marina</i>) are disturbed. Modifications to light, temperature, salinity, nutrient levels, and wave action beneath an over-water structure influence the rate of photosynthesis, plant distribution, and survival of specific plant species that directly or indirectly support prey resource composition and production. Despite considerable speculation about increased predation around docks, quantitative evidence for significant increases in predation on salmon associated with docks is lacking.</p> <p>We also conducted short-term underwater diving and video surveys at five ferry terminals (Clinton, Kingston, Port Townsend, Seattle, Vashon) to gather preliminary information on the relationships among variations in over-water structures, fish occurrence and relative abundance, light conditions, biological communities, and potential predators. Juvenile salmon were observed migrating under several structures.</p> <p>Existing information indicates that the effects of shoreline structures on migrating juvenile salmon may vary, depending on the design and orientation of the shoreline structure, extent of alteration of the underwater light field, and presence of artificial light. However, our understanding of the significance of short-term delays in the salmon's migration and cumulative or synergistic effects is insufficient to provide the quantitative relationships that would be necessary as the basis for developing retrofitting or design modifications. Field studies are recommended.</p>			
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Ferry Impact on Salmon



**IMPACTS OF FERRY TERMINALS ON JUVENILE SALMON
MIGRATING ALONG PUGET SOUND SHORLINES
PHASE I: SYNTHESIS OF STATE OF KNOWLEDGE**

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TABLE OF CONTENTS

<i>Section</i>	<i>Page</i>
Executive Summary	xi
1—Introduction to Studies	1
Background.....	5
Assesing the State of Knowledge	9
2—Juvenile Salmon and Their Nearshore Habitat Responses to the Aquatic Light Environment.....	13
Juvenile Salmon and Light Perception.....	13
Underwater Light Environment	20
Light and Salmonid Prey and Predator Recognition.....	21
Artificial Lights and Salmonid Behavior.....	24
Synopsis.....	26
Nearshore Habitat Responses to the Light Environment	27
Light Energy Transmission.....	27
Underwater Light Environments.....	28
Photosynthesis.....	30
Plant Light Absorption Characteristics	32
Other Environmental Factors That Affect Photosynthesis	34
<i>Nutrients</i>	34
<i>Temperature-Salinity</i>	36
Summary.....	38
3—Summary of the Literature Review of Over-Water Structure Effects on Juvenile Salmon Behavior, Habitat, and Potential Predation.....	40
Methods	42
Literature Sources	43
<i>Searching Commercial Databases</i>	43
<i>Mail Requests from Experts</i>	44
Categorizing Information.....	44
<i>Direct Sources</i>	44
<i>Indirect Sources</i>	45
<i>Background Sources</i>	45
Compilation and Assessment of Information and Incorporation into Database	45
Results	45
Migration Behavior	46

Primary and Secondary Production.....	48
Predation	50
Summary Conclusions and Recommendations	54
4—Preliminary Findings of Diving and Light Surveys	58
Methods	58
Diving Surveys.....	62
Light Surveys.....	63
Results	72
Diving Surveys.....	72
Light Surveys	76
Discussion.....	83
Diving Surveys.....	83
Light Surveys	88
Acknowledgments	91
Contributors' Credits	91
References	93
Bibliography.....	103
Appendix A— Synopses of important sources of information on juvenile salmon responses and spectral sensitivity to aquatic light environments	A-1
Appendix B— Assessment of background information on aquatic light environment responses by juvenile salmon.....	B-1
Appendix C— Assessment of background information on spectral sensitivity by juvenile salmon.....	C-1
Appendix D— Synopses of direct sources of information on impacts of overwater structures on migrating juvenile salmon	D-1
Appendix E— Assessment of all information on impacts of overwater structures on estuarine and nearshore marine habitats and fishes.....	E-1
Appendix F— Synopses of information sources on juvenile salmon predation associated with over-water structures.....	F-1

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1	Organization of research phases in UW-BSML studies on ferry terminal impacts on juvenile salmon migrating through Puget Sound nearshore environments 4
2	Potential interactions and points of impact of ferry terminal and operations on the juvenile salmon food web..... 10
3	Conceptual model describing interactions and mechanisms of impact of overwater structures on juvenile salmon and nearshore shallow-water habitats in Puget Sound 12
4	Transverse section through the eye of a juvenile chum salmon (RE=retina) (From Ali and Anctil 1976) 14
5	Retinal cell layers (from Ali and Anctil 1976) 16
6	Transverse Sections of dark-adapted (<i>left</i>) and light-adapted retinas of the Arctic char (<i>Salvelinus alpinus</i>) 17
7	Juvenile salmon behavior patterns related to documented light intensities.... 22
8	Electromagnetic spectrum showing position of visible, UV, and IR wavelengths. (from Withrow & Withrow 1956)..... 29
9	Spectrum of solar energy at the earth's surface (upper dotted curve), and absorption spectra of algal pigments. (from Gantt 1975) 33
10	Effect of temperature on short-term photosynthesis (Fig 2, Bulthuis 1987) .. 36
11	Factors affecting seagrass growth and persistence (from Fig. 1, van Montfrans <i>et al.</i> 1964) 38
12	Conceptual diagram of effects of over-water structure on aquatic light environment impacting primary and secondary production important to juvenile salmon habitat and prey resources 49
13	Route map and terminal locations for the Washington State ferry system..... 59
14	Photos showing our methods for recording measurements of photosynthetically-active radiation (PAR) along the beach at one of the WSDOT ferry terminals, August 1998..... 64
15	Diving and light transects at the Port Townsend ferry terminal, August 1998. 65
16a	Diving and light transects at the Clinton ferry terminal, August 1998 66
16b	Diving and light transects at the Clinton ferry terminal, August 1998 67
17	Diving and light transects at the Kingston ferry terminal, August 1998..... 68
18	Diving and light transects at the Seattle ferry terminal, August 1998 69
19a	Diving and light transects at the Vashon ferry terminal, August 1998 . 70
19b	Diving and light transects at the Vashon ferry terminal, August 1998 71
20	Light attenuation profiles at six WSDOT ferry terminals and one dock (Sequim Bay) collected at mid-day 77
21	PAR in air under the Clinton Terminal. 78
22	PAR in air and at two water depths at Kingston Terminal 79
23	Plot of juvenile salmon behavior versus light level (from Ali 1959)..... 80

24	Relationship between ft-c and PAR and fish behavior. Thresholds based upon Figure 23	81
25	PAR under Seattle Terminal showing only values $2 \mu\text{M}$	82
26	Minimum observed PAR levels under each terminal.....	83

LIST OF TABLES

<i>Table</i>		<i>Page</i>
1	Puget Sound algal pigment and wavelength relationships (from Kozloff 1983).....	34
2	Potential, observed, questionable, and validated predators of juvenile salmon.....	52
3	Decision matrix for prioritizing WSDOT ferry terminals for diving and light surveys.....	60
4	Summary of fish species we observed during our underwater surveys at five ferry terminals in August 1998.....	73
5	Summary of predators on juvenile salmon observed during our underwater surveys at five WSDOT ferry terminals in August 1998.....	75



EXECUTIVE SUMMARY

The University of Washington's School of Fisheries and School of Marine Affairs and Battelle Marine Sciences Laboratory are jointly conducting a comprehensive research project supported by the Washington State Department of Transportation (WSDOT) to determine whether ferry terminals affect migrating juvenile salmon and, if so, how future design and modifications to both ferry terminals and operations can mitigate those impacts.

Shoreline structures such as ferry terminals may affect juvenile salmon (especially ocean-type chinook and chum) directly and indirectly: (1) directly by disrupting their migratory behavior along shallow-water shoreline habitats and (2) indirectly by reducing carrying capacity because of reduced production of under-structure habitats and increased predation by other fish, birds, and marine mammals. Although individual shoreline structures may not impose significant impacts on salmon stocks, the cumulative effect of dense, contiguous shoreline modifications may contribute to the present decline of several Puget Sound salmon stocks and may inhibit the success of future salmon recovery actions.

This project is being conducted in three phases:

- I. assessment of the state of technical knowledge and preliminary characterization of existing light environment and biological communities associated with ferry terminals of different sizes, ages, and construction materials
- II. pilot studies on juvenile salmon response to over-water structures

- III. full-scale implementation of field sampling and experiments on juvenile salmon responses to different ferry terminals and shoreline conditions and their effects on the salmon's prey resources.

This report summarizes our results from Phase I and implications for Phase II and Phase III research.

Our assessment of over 60 direct sources of information found evidence that juvenile salmon react to shadows and other artifacts in the shoreline environment imposed by shoreline structures but revealed no quantitative information on the significance of these behavioral responses to juvenile salmon survival. Docks present sharp underwater light contrasts by casting shade under ambient daylight conditions, and they can also present sharp underwater light contrasts by casting artificial light under ambient nighttime conditions. The studies summarized in this report repeatedly verify that changes in the underwater light environment affect juvenile salmonid physiology and behavior. Laboratory experiments have shown that many behavioral changes (minimum prey capture, first feeding, school dispersion) correspond to a light intensity threshold of 10^{-4} foot candles (f-c), while maximum feeding occurs at light intensities of between 10^{-1} and 1 f-c.

These changes may affect fish migration behavior and place them at increased mortality risk. In a number of studies throughout Puget Sound, juvenile salmon have been observed to alter their behavior upon encountering docks during their nearshore migration. These observations, and those of studies in which salmonids were guided through dangerous structures (i.e., dam turbines, locks) with artificial lighting, imply that

these fish may be exposed to increased risk to mortality as a consequence of the following:

- delays in their migration due to disorientation caused by lighting changes
- loss of schooling refugia due to fish school dispersal under light limitation
- a change in migratory route into deeper waters, without refugia, to avoid the light change.

Juvenile salmon also encounter limited prey resources under shoreline structures when important habitats such as eelgrass (*Zostera marina*) are disturbed. Epibenthic crustaceans are the prey resources of most concern because they are usually associated with nearshore plants (macrophytes, epiphytes, and epilithic microalgae) that are affected by over-water structures.

Light energy drives the plant photosynthetic process—as modified by the synergistic effects of nutrient concentrations, temperature, salinity, and wave action that control the quality and quantity of available light, as well as the plants' physical environment. Modifications to light, temperature, salinity, nutrient levels, and wave action beneath an over-water structure, although relatively localized, influence the rate of photosynthesis, plant distribution, and survival of specific plant species that directly or indirectly (through detritus trapping) support prey resource composition and production. However, the effect of cumulative loss and modification of prey resources by increasing over-water structure coverage has not been examined.

Despite considerable speculation about increased predation around docks, quantitative evidence for significant increases in predation associated with docks is widely lacking. Of 27 species of fish and five birds discussed in the literature as potential

predators, only two fish and one category of birds (cormorants) had been verified as predators on juvenile salmon. Because of the lack of systematic studies of nearshore predation on juvenile salmon, we cannot conclude that many of the other species aren't also potential predators under some circumstances. Perhaps the greatest potential for significant predation would be diving birds that are attracted to lighted piers at night, but no studies have systematically addressed or documented this speculation.

We conducted short-term underwater diving and video surveys at five ferry terminals (Clinton, Kingston, Port Townsend, Seattle, Vashon) to gather preliminary information on the relationship among variations in over-water structures and fish occurrence and relative abundance, light conditions, biological communities, and potential predators. These surveys occurred after the major period of juvenile salmon migration, but juvenile and immature ("blackmouth") chinook were recorded moving back and forth beneath one terminal structure (Kingston) and were also observed beneath another terminal (Vashon). The preliminary results indicate that each terminal differs in terms of its fish community, piling community, substrate, light availability, and degree of physical disturbance from ferry propeller wash. We observed no fish or birds that are confirmed or potential predators on juvenile salmon aggregated under these terminals. These surveys also indicated that (summer) light intensities were above the critical 10^{-4} f-c threshold level required for maintenance of juvenile salmon feeding and schooling, even under the darkest portion of the terminal, at four of the five terminals investigated. However, we cannot conclude that under some conditions (e.g., late winter-spring light, high attenuation) the darker portions of the other four terminals may have bordered on the light level required for maximum feeding.

Existing information indicates that the effects of shoreline structure on migrating juvenile salmon may vary, depending on the design and orientation of the shoreline structure, the extent of alteration of the underwater light field, the presence of artificial light, the significance of short-term delays in the salmon's migration, and cumulative or synergistic effects. Unfortunately, this information is insufficient to provide the quantitative relationships that would be necessary as the basis for developing retrofitting or design modifications. Field studies that document *in situ* behavioral changes in salmon upon their encountering specific dock characteristics and measured light changes are needed to understand and mitigate impacts that increase the risk of juvenile salmon mortality. The studies showed that determining the effects that light-level has on behavior will require both minimum light levels during periods of migration and threshold levels for behavioral responses for the local species and stocks of fish. Light levels are controlled both by ambient factors such as incident solar irradiance, time of day, and attenuation and by characteristics of the over-water structure such as orientation, width, and height above the water. Understanding the relationships among these factors will allow the construction of statistical models for predicting light levels, which can be translated into ferry terminal design parameters to mitigate for potential impacts on migrating juvenile salmon.

1—INTRODUCTION TO STUDIES

Docks and other over-water structures such as ferry terminals pose potential barriers or inhibitors to juvenile salmon migrating along shallow water habitats of Puget Sound during their emigration to the Pacific Ocean. The reason is that many of Puget Sound's salmon populations rely on estuarine and nearshore¹ environments during their early life. This period is associated with the early entry of fry and fingerlings 30-80 mm in length into Puget Sound after no or brief residence in their natal freshwater spawning sites. Accumulating evidence indicates that the estuarine/nearshore period is a critical life history stage during which these "ocean-type" populations meet juvenile energy, growth, and survival requirements (Healey 1991; Salo 1991). Juvenile ocean-type chinook, chum, and pink salmon that migrate early as fry or fingerlings are believed to be particularly vulnerable because they volitionally migrate along the shallow water². Two Puget Sound salmon stocks of concern because of the Endangered Species Act (ESA) (fall chinook, summer chum) are particularly reliant on the estuarine/nearshore period. The mechanisms believed to account for this reliance are

- preference for shallow water habitat as a refuge from predation
- preference for small, non-evasive food organisms that are readily available in shallow water habitats

¹ Nearshore is here defined as the general shoreline environment, from extreme higher high water (EHHW) offshore to the 20-m contour depth (rel. to MLLW).

² Shallow-water habitat refers to that portion of the nearshore estuarine and marine environment habitually occupied by migrating salmon fry (i.e., approximately 30-80 mm long), which includes all the intertidal zone to approximately -2 m (about -6 ft rel. to MLLW). As noted herein, however, salmon fry tend to stay within about 1-m water depths, moving back and forth across the intertidal zone with the changing tide.

- aversion to entering a sharply contrasting light environment to which the juvenile salmon are not adapted or with which they have no experience.

The corollary is that when they encounter certain types of over-water structures, juvenile salmon seeking shallow water are forced into deep water, resulting in higher predation risk and lower feeding capacity. Thus many shoreline structures and modifications, of which ferry terminals are but one type, could potentially affect juvenile salmon behavior and their migratory habitat.

The Washington State Department of Transportation (WSDOT) Washington State Ferries (WSF) is increasingly concerned with the need to mitigate the impacts of its ferry terminals and operations on environmental resources in the estuarine/marine waters of Washington State. Increasing demands for fast, safe, and efficient ferry service will require WSF to expand its ferry terminals. In addition, many ferry terminals are reaching the end of their effective life spans and will require refurbishing and improvements. Consequently, there is an urgent need to gather scientific data that can contribute to impact assessments of ferry terminals and other shoreline structures that potentially affect nearshore resources such as juvenile salmon and the ecological processes that sustain them. WSDOT support of extensive research on the influence of dock shading and other ferry operations on eelgrass (Simenstad *et al.* 1997), an important nearshore habitat for fish and wildlife, exemplifies the scale of the issues and the need for scientifically based solutions to conflicts between conservation of nearshore resources and ferry system design. Because of the increased concern and for Pacific salmon stocks listed under the Endangered Species Act (ESA), WSDOT is specifically interested in resolving issues and finding approaches for mitigating impacts on migrating juvenile salmon.

In response to this need, in early 1998 WSDOT initiated support of a comprehensive research project to evaluate the nearshore effects of its ferry terminals on migrating juvenile salmon. The previous research team (Simenstad *et al.* 1997) of the University of Washington's (UW) School of Fisheries and School of Marine Affairs and the Battelle Marine Sciences Laboratory (BMSL) was reassembled to assess three topics of concern:

- ferry terminals as barriers to estuarine nearshore migration of juvenile salmon
- their effects in reducing estuarine secondary productivity that supports juvenile salmon foraging
- their effects in attracting or concentrating populations of predators on migrating juvenile salmon.

This research program is being conducted in three phases (Figure 1):

- I. assessment of the state of our technical knowledge about the effects of shoreline structures on migrating juvenile salmon and preliminary characterization of existing light environment and biological communities associated with ferry terminals of different sizes, ages, and construction materials
- II. pilot studies on juvenile salmon behavior and response to over-water structures
- III. full-scale implementation of field trials to test the effects of different ferry terminals and ferry activity patterns on migrating juvenile salmon and on the production of their under-structure prey resources.

The objectives of the overall research project are as follows:

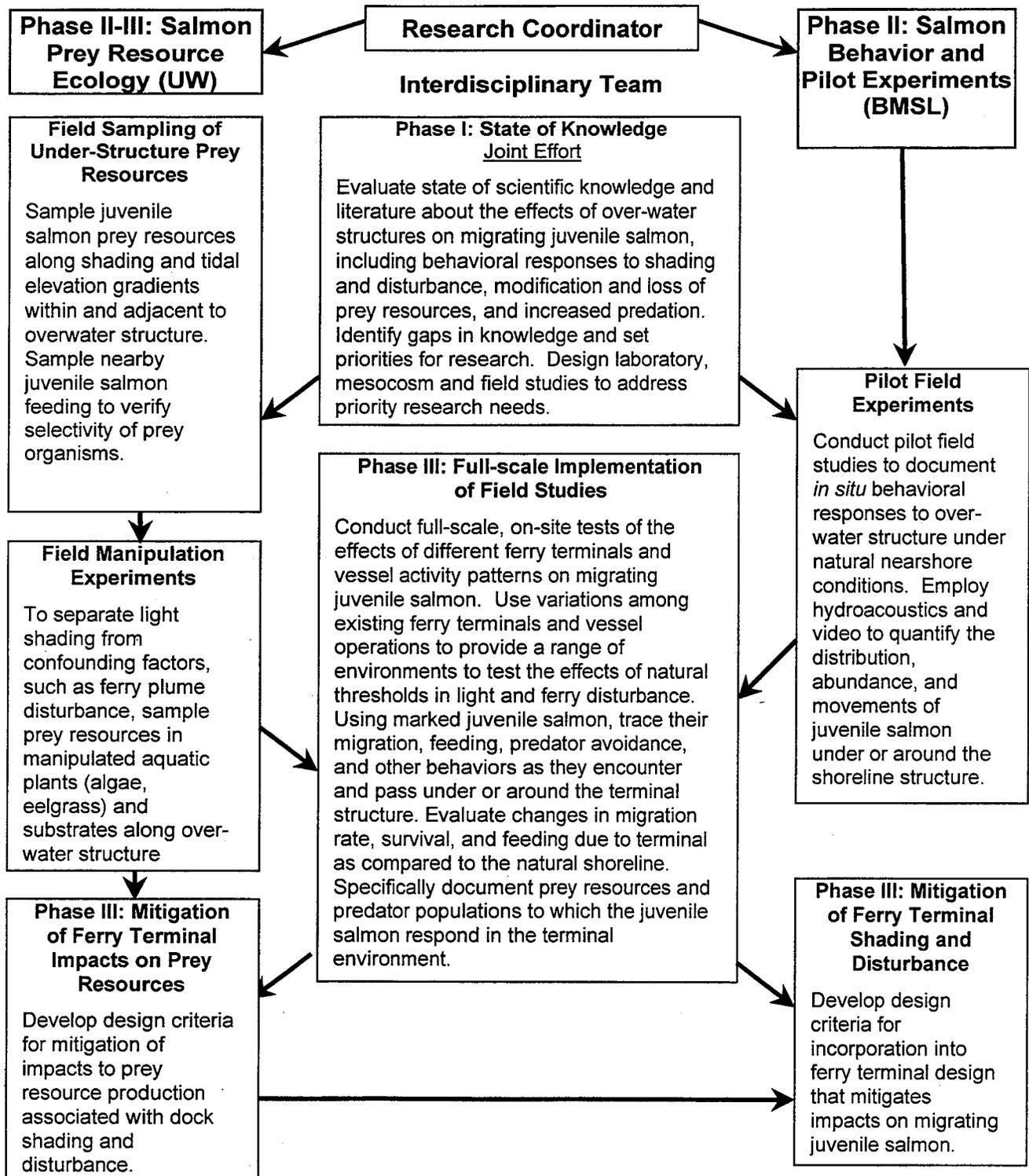


Figure 1. Organization of research phases in UW-BSML studies on ferry terminal impacts on juvenile salmon migrating through Puget Sound nearshore environments.

- identify documented and hypothesized impacts of ferry terminals on juvenile salmon (Phase I)
- synthesize all evidence around the identified mechanisms of impact, analyze the scientific basis for or against impacts, prepare a synopsis of the outstanding gaps in the state of the knowledge, and recommend research to resolve those gaps (Phase I)
- conduct research to identify the mechanisms and magnitude of ferry terminal impacts on migrating juvenile salmon and their requisite nearshore habitats (Phase II-III)
- prepare a final interpretive document that summarizes the synthesis and research results about ferry terminal impacts on juvenile salmon and their nearshore habitat, and provide recommendations for best management practices and mitigation for future ferry terminal construction, retrofitting, and operations (Phase III).

The results of objectives 1 and 2 are reported here.

BACKGROUND

To evaluate the state of knowledge about the potential impacts of WSDOT ferry terminals on migrating juvenile salmon, we examined the scientific and technical literature encompassing the broad scope of how all over-water structures and their associated shoreline development affect intertidal and shallow subtidal organisms and habitats by casting shade, as well as by causing substrate and structural alterations to plant communities and nearshore food webs (Pentilla and Doty 1990; Kenworthy and Haunert 1991; Weitkamp 1991; Burdick and Short 1995; Fresh *et al.* 1995; Parametrix

and Battelle 1996; Thom and Shreffler 1996; Able *et al.* 1998). By altering light, substrate, and wave action, over-water structures can affect primary and secondary production, alter salmonid-predator patterns, and present physical and behavioral barriers to migrating juvenile salmon that rely upon nearshore epibenthic food webs to meet growth and survival requirements (Ratte and Salo 1985; Salo *et al.* 1979; Simenstad 1994).

At the same time, we focused our assessment specifically on salmon species and life history types that are most closely associated with nearshore shallow-water (~1-2 m deep) habitats, such as "ocean-type" chum and chinook fry (e.g., fish 30-60mm FL). The assumption that ocean-type juvenile salmon are reliant on nearshore shallow-water habitats for refuge and unique prey resources has been supported by a variety of studies in Puget Sound and elsewhere across the range of ocean-type salmon in the Northeast Pacific (e.g., Healey 1979, 1982a; Congleton *et al.* 1981; Levy and Northcote 1982; Sibert 1979; Simenstad and Salo 1982; Weitkamp 1982, 1991; Cordell 1986; Hiss *et al.* 1990). For instance, the size and energy requirements of juvenile chum make them particularly dependent upon nearshore habitat for both refuge and prey offered by nearshore vegetation. The chum's specific preference for epibenthic harpacticoid copepods such as *Harpacticus uniremis* and *Tisbe* sp. is believed to be due to the combination of the copepod's small size, motility limitations that enable its capture by juvenile salmonids, and its caloric food value (Wissmar and Simenstad 1988). Shallow-water estuarine and nearshore marine habitats supporting these particular prey taxa, as well as many other preferred prey (Simenstad *et al.* 1991), are supported by light, photosynthesis, substrate stability, and the successive production of plant material, plant

detritus, and associated microbial colonizers serving as the basis of food web pathways leading to juvenile salmon (Sibert 1979; Cordell 1998, pers.comm.). Nearshore bands of eelgrass (*Zostera marina*) have been identified as a particularly important habitat from the standpoint of refuge, habitat of many preferred prey taxa, and a major primary production source of organic matter for the nearshore, detritus-based food web (Simenstad 1994). Any structure that interferes with the availability of light to this ecosystem is likely to decrease the production of critical plant material basic to this copepod-salmonid food web system.

As exemplified by the eelgrass habitat, primary producers serve four general functions in this food web system:

- as a primary source of fixed organic matter contributing to the nearshore detritus pool
- as a substrate for epiphytes and associated animals
- as "microhabitat" of preferred prey such as harpacticoid copepods and gammarid amphipods
- as refugia that offers juvenile salmon shelter from potential predators.

In the Puget Sound, benthic primary production is stimulated in spring by rapidly increasing solar irradiance coupled with the occurrence of extreme low tides during daylight hours (Thom and Albright 1990). It appears that benthic diatom production is stimulated in early spring on mid to high intertidal flats by this increase in irradiance and exposure (Thom *et al.* 1988). Seaweed populations also begin to increase on rocky shores. Eelgrass and associated epiphytes tend to increase their production later in spring

and in early summer as low tides occur during mid-day and as solar irradiance continues to increase toward the summer solstice.

Organic matter sources that support epibenthic prey such as harpacticoid copepods include autotrophic diatoms and bacteria and other microbiota associated with plant detritus (Sibert *et al.* 1977; 1979). Available sunlight, limited turbidity, and wave action directly affect the status of these heterotrophic microbial-meiofauna/small macrofauna food webs. The early spring growth of eelgrass and other higher plant forms increases the areal extent of available substrate (both eelgrass blades and epiphytes) to support abundant prey populations. The successional development of these communities requires the following:

- solar irradiance in quantities that can support photosynthesis (Dennison 1987, Thom 1990, Bulthuis 1994)
- relatively stable substrate
- limited current action that allows the reproduction and survival of plant assemblages, such as eelgrass (Fonesca *et al.* 1983, Thom and Shreffler 1996, Thom *et al.* 1996).

The combined nearshore shallow-water autotrophic sources of eelgrass and its associated epiflora, benthic diatoms, and seaweeds provide great quantities of detrital organic matter to the nearshore system through autumn die-back and atrophy of the emergent growth. Stable isotope studies in Hood Canal indicate that eelgrass and its associated algae are the basis of the food web for outmigrating chum salmon (Simenstad and Wissmar 1985). As a structural habitat, eelgrass also reduces wave and current action, traps sediments and detritus, maintains high dissolved oxygen concentrations through photosynthetic activity,

and by shading at low tide, minimizes fluctuating temperatures that would be induced by direct sunlight.

Thus, migrating juveniles of ocean-type salmon have evolved to take advantage of natural physicochemical and ecological processes that maintain these nearshore shallow-water habitats of Puget Sound. Over-water structures and shoreline development and vessel activity associated with ferry terminals have the potential to alter these natural habitats and processes by suppressing the natural light regimes and increasing disturbance (Figure 2).

ASSESSING THE STATE OF KNOWLEDGE

We implemented Phase I with an informational workshop held on March 3, 1998.

The objectives of this workshop were as follows:

- to introduce resource agencies, tribes, the public, and other stakeholders to the objectives, hypotheses, and scope of the newly initiated research program
- to seek information for incorporation into the synthesis document
- to solicit input before beginning any laboratory or field studies.

One of the primary results of the workshop was the realization that the scope of the literature review would have to include the broad spectrum of over-water structures because information is extremely limited for ferry terminals and comparable structures. Although it was acknowledged that much of the information would not apply to ferry terminals, the benefits of conducting a broader review of over-water structure impacts would outweigh the need to categorize impacts by scale and type of structure.

Subsequently, an intensive survey was conducted of the scientific literature and other technical publications, and input was solicited from experts on estuarine habitats

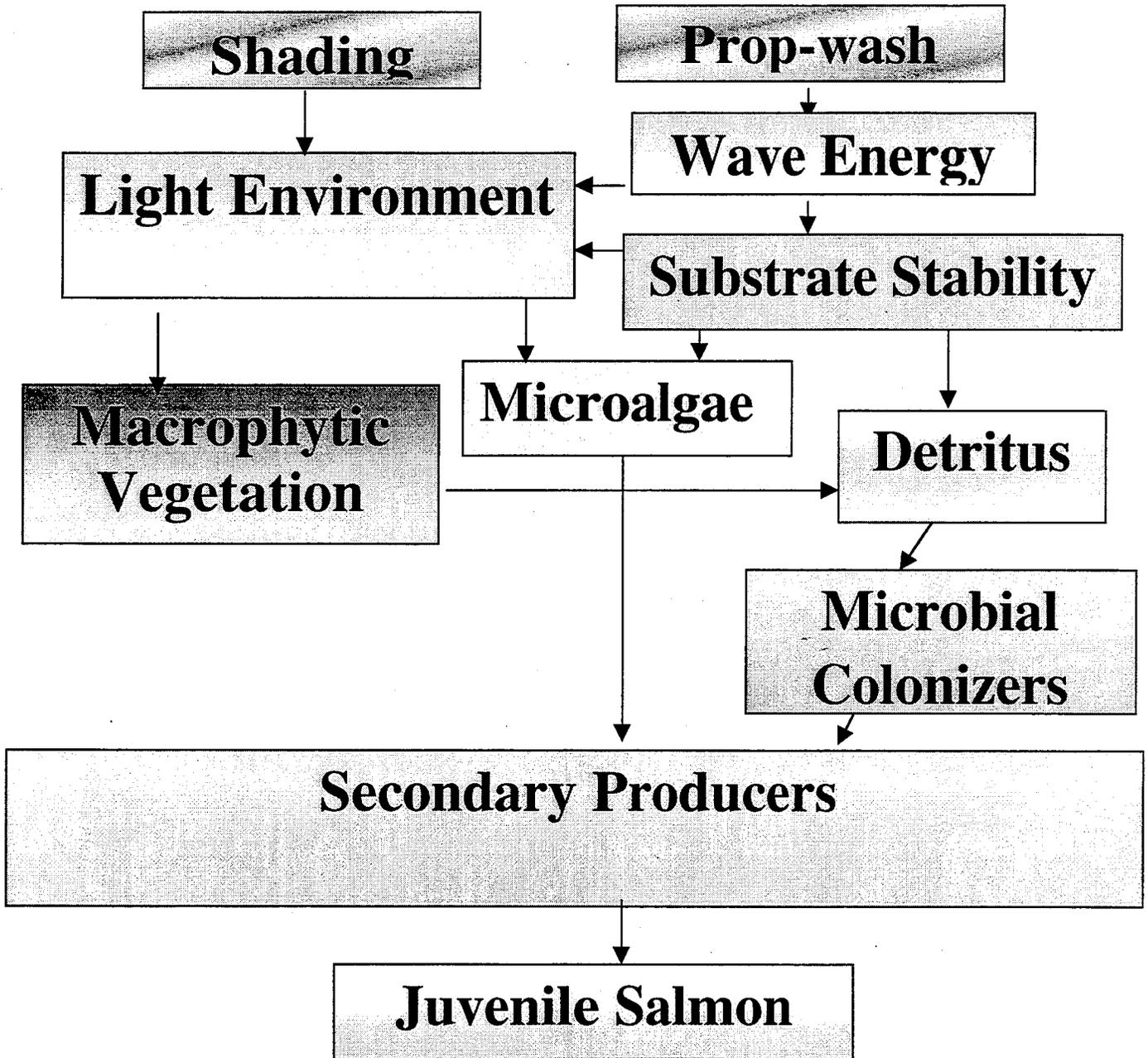


Figure 2. Potential interactions and points of impact of ferry terminal and operations on the juvenile salmon food web.

and salmonid life histories. Over 60 direct sources (explicitly addressing fish, prey, and aquatic habitat responses to over-water structures) were summarized by three topics: migratory behavior, primary-secondary production links to salmon prey resources, and predation on salmon. These were integrated into a simple conceptual model that related both direct and indirect effects (Figure 3). A WorldWideWeb site³ was established to provide the opportunity for review of information as it was gathered and incorporated into the database, and as a mechanism for direct submission of comments, suggestions, and contributions.

In preparation for a second workshop, scientists from BMSL also conducted diving and light surveys at five ferry terminals. The goal of these surveys was to gather preliminary data and underwater video to document the existing light environment and biological communities associated with ferry terminals of different sizes, ages, and construction materials.

A second workshop was held in August 1998 to present the results of the survey and of the team's state of knowledge on the impacts of ferry terminals on migrating juvenile salmon. Three fundamental issues were covered:

- juvenile salmon migratory behavior
- primary-secondary production links to juvenile salmon prey resources
- predation on juvenile salmon.

In coordination with the workshop participants, the UW-BMSL team also developed a research program to address specific gaps in our understanding of identifiable impacts.

³ <http://weber.u.washington.edu/~newwsdot/home.html>

2—JUVENILE SALMON AND THEIR NEARSHORE HABITAT RESPONSES TO THE AQUATIC LIGHT ENVIRONMENT

The following observations have emerged repeatedly in studies of ocean-type juvenile salmon migrating through nearshore shallow-water habitats of Puget Sound:

- Juveniles prefer to migrate along edges of refugia such as eelgrass, dock shadows, turbid zones.
- Schools of juveniles disperse upon encountering docks.
- Juveniles are attracted to under-dock lights at night and to prey resource areas.
- Delays in migration direction occur when juveniles are confronted with conflicts in preferences among alternative light conditions (Prinslow et al 1980, Weitkamp 1982a&b; Ratte and Salo 1985, Dames and Moore 1994, Taylor and Willey 1997, Pentec Environmental 1997).

The following summary provides an overview of the scientific findings on juvenile salmon behavioral responses to changes in the light environment and the physiology behind those responses. Synopses of the more important information sources are attached as Appendix A. Appendix B is a tabular assessment of background information on aquatic light environment responses by juvenile salmon, and Appendix C provides a similar assessment of the information on the spectral sensitivity of juvenile salmon.

JUVENILE SALMON AND LIGHT PERCEPTION

Light has tremendous importance in the life of salmonids. Light is necessary for spatial orientation, prey capture, schooling, predator avoidance, and migration navigation.

For juveniles, light conditions determine the ability to school, signal the presence of potential predators, set a background against which feeding relationships develop, and provide migration orientation.

Light perception is dependent upon the light transmitting qualities of the water coupled with the spectral properties of the retinal visual pigments that function as light receptors. As these visual pigments absorb light, energy is released that electrically activates nerve cells. Changes in light cause electrical impulses to be generated immediately, within several seconds, transmitting immediate signals to the brain. Differences in light absorption capacities of visual pigments are determined by genetics and habitat and differ with the solar spectral compositions specific to the species' habitats (Wald *et al.* 1957, Wald 1960).

As salmonids move from fresh to salt water their retinal pigments change from porphyropsin to rhodopsin dominated (Beatty 1965, Folmar and Dickhoff 1980). These changes alter the visual sensitivity from the red-yellow hues of freshwater streams to the blue color of estuarine and ocean waters. These changes occur during the smoltification process and are believed to be tied to the thyroxine hormone levels that regulate the smolting process. The positions of the smolts' visual cells are responsive to ambient light and not to internal rhythmic diurnal patterns. The retina (Figure 4) is a projection of the brain consisting of various cell types arranged in eight layers and two membranes (Figure 5) (Ali and Anctil 1976).

The external limiting membrane is the point of light quanta reception, with the epilitheal and visual cell layers responding to varying intensities of light reception. The visual cell layer consists of two types of photoreceptors, rods (scotopic) and cones

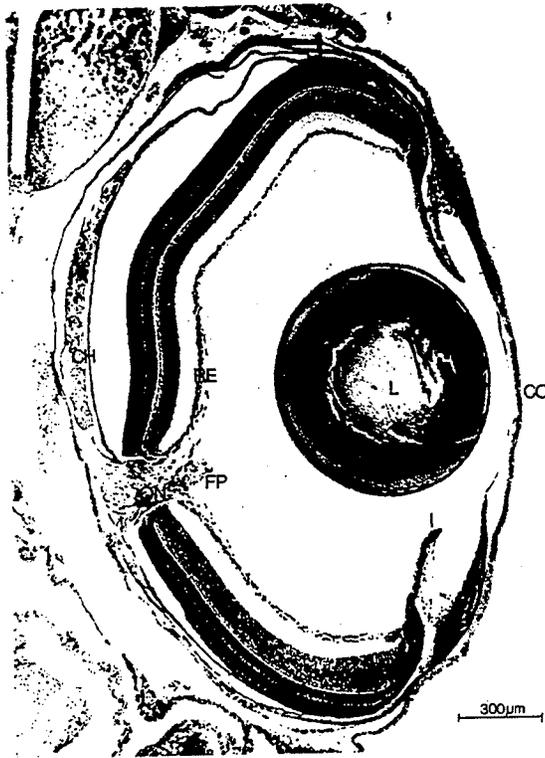


Figure 4. Transverse section through the eye of a juvenile chum salmon (RE=retina)
(From Ali and Anctil 1976)

(photopic). The retinal pigment, cones, and rods have different light thresholds and respond to light and dark with changes in their relative positions. When the light intensity is above the retinal pigment and cone thresholds, the eye assumes the light-adapted state; the cone cells contract to be near the source of light while the rod cells elongate away from the light (Figure 6). When the light intensity falls below threshold values, the cones expand away from the light source while the rods contract toward the light in direct proportion to the logarithm of the light intensity (Ali 1959). When the light drops below the rod threshold, the school disbands and feeding by visual means ceases (Ali 1958). The extent of expansion and elongation is dependent upon ambient conditions (Ali 1971).

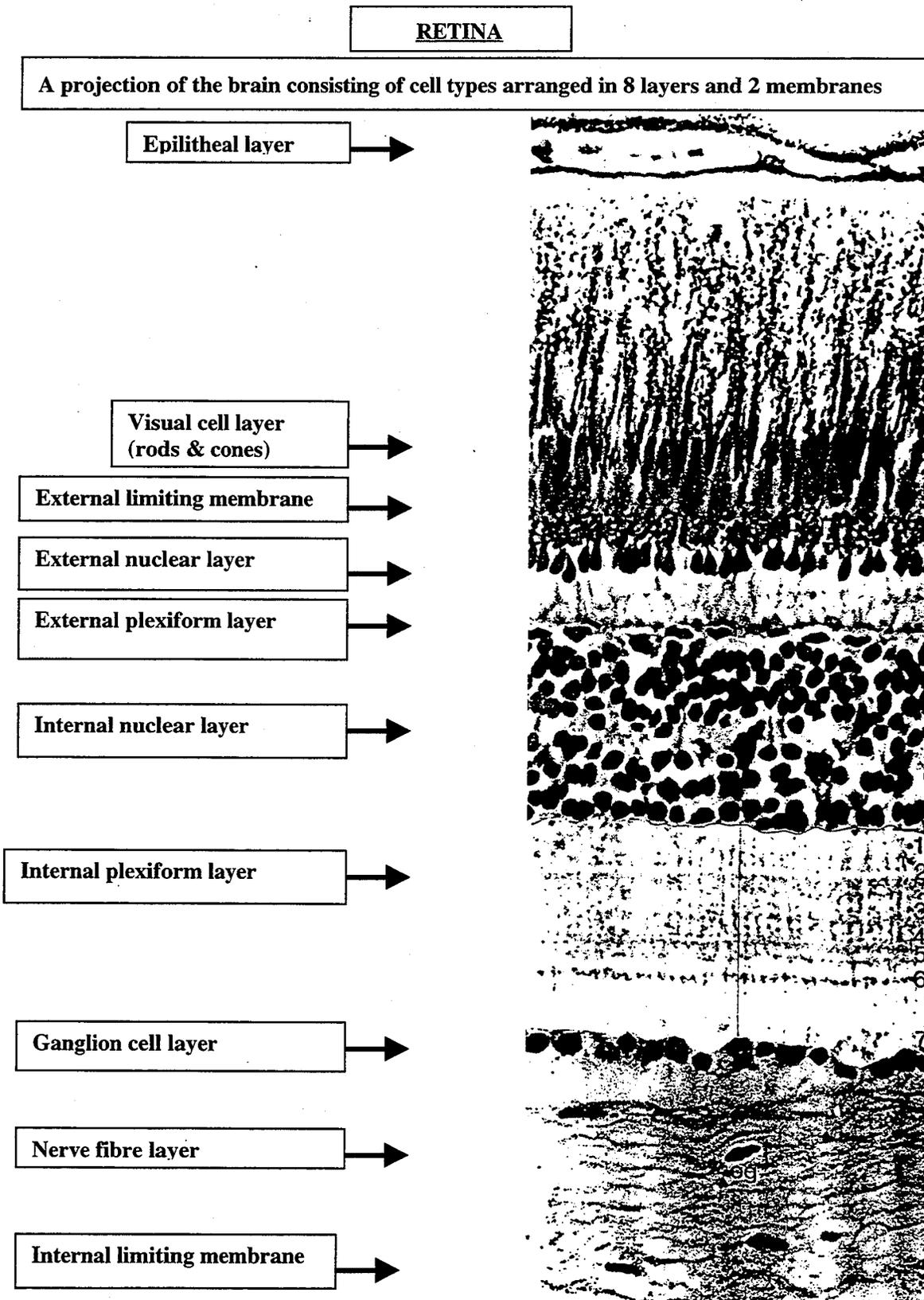


Figure 5. Retinal cell layers (from Ali and Ancia 1976)

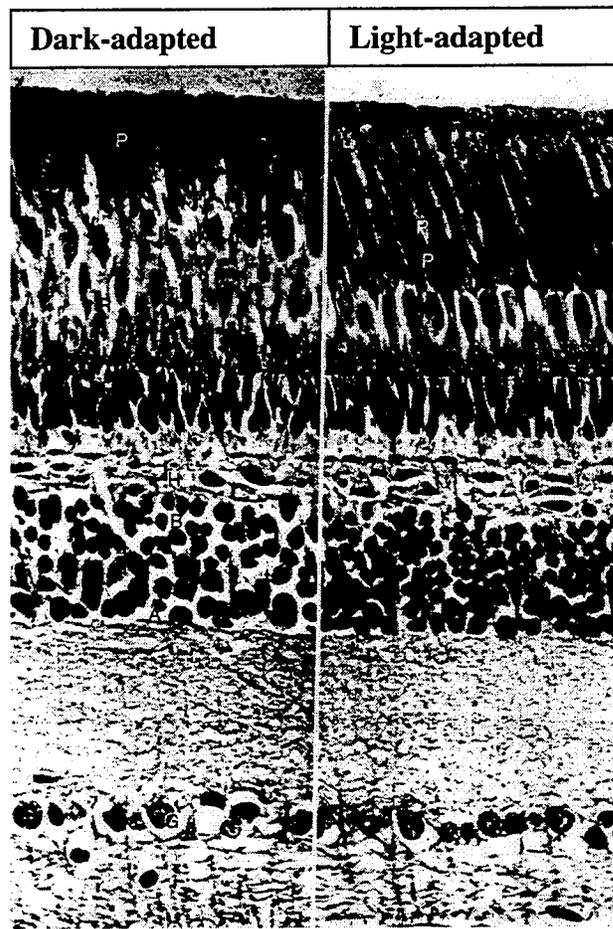


Figure 6. Transverse sections of dark-adapted (*left*) and light-adapted retinas of the Arctic char (*Salvelinus alpinus*)

The time period for such structural changes in response to variations in light intensity varies across species and life stages. The visual pigments of the retinal cells change the retinal spectral sensitivity with quick responses to light intensity and composition variations (Dartnall 1953; Munz and Beatty 1965; Bridges 1967; Allen and Munz 1982). The time required for light-adapted chum and pink fry to fully adapt to dark ranges from 30 to 40 minutes. The time required for dark-adapted fry to adapt to increased light ranges from 20 to 25 minutes (Brett and Ali 1958; Ali 1960; Protasov

1970). During these periods of transition, the chum's visual acuity ranges from periods of blindness to slightly diminished, depending upon the magnitude of light intensity contrasts. As the animals become older, the time required for light adaptation generally shortens. The time necessary to adapt to the dark, on the other hand, tends to increase with age.

The progression of changes from one state to another is influenced by the intensity of the introduced light and the intensity to which the fish has been previously exposed (Ali, 1962, 1975, Fields 1966, Protasov 1970, Puckett and Anderson 1988). Essentially, the contrasts in light levels determine the progression of changes the eye must undergo. Previous levels of light intensity exposure affect the speed of transition. For example, fish previously exposed to higher light intensities become dark-adapted more slowly than those previously exposed to lower light intensities (Ali, 1962). Wavelength is also believed to influence the speed of these reactions. When a fish is exposed to a specific wavelength the retina is believed to adapt to light faster than the retina of another fish exposed to multiple wavelengths (Protasov 1970).

A review of the literature on juvenile salmon behavioral responses to both ambient and artificial light revealed consistent behavioral differences between species and ontogenetic stages. Behavioral responses varied with the basic dispersal patterns of the species. Species that occupy and defend stream territories, such as coho, Atlantic salmon and steelhead, tend to be quiescent at night (Hoar 1951; Northcote 1978; Godin 1982b). Although coho fry occasionally aggregate, they demonstrate no true schooling or milling behavior. On the other hand, species that disperse to nursery lakes (i.e., sockeye) and estuaries—such as chinook, pink and chum—typically school, show nocturnal

activity, and demonstrate negative phototaxis (Hoar 1951; Godin 1982a). In laboratory studies, pink and chum fry darted wildly about when lights were turned on following darkness, whereas coho fry moved briefly or remained quiescent. Upon alarm, pinks scattered wildly in different directions, losing their orderly schooling arrangement, whereas coho, chum and sockeye disappeared beneath the cover of stones. At low light intensities, chum were the first to emerge from cover (Hoar 1958).

Hoar (1951) observed that changes associated with smolt transformation included differences in responses to visual changes. Smolt response to visual disturbance resulted in a longer period of cover than that of fry and a tendency to scatter wildly when light was flashed on them at night. Smolts also showed an increased aggregating tendencies, a lower stimulation threshold, an increased level of general excitability, greater activity during the night, a stronger preference for deeper water, strong cover reaction and reduced activity during the day, and negative rheotaxis (McInerney 1964; Hoar 1976; Folmar and Dickhoff 1981).

Ali (1975) found that unlike some fishes that exhibit diurnal rhythms in their retinal epithelial pigment and visual cells, Pacific salmon do not. Activity rhythms—including feeding cycles, migration patterns, and movement changes—have both endogenous and exogenous components (Nemeth 1989), and species life history patterns determine the predominant behavioral rhythms. The influences of ambient light intensity (Godin 1982), light-dark cycles and transitions (Richardson and McCleave 1974; Bachman *et al.* 1979), and ontogenetic stages (Hoar 1953; Fields and Finger 1954; Byrne 1971) affect the diel activity rhythms in Pacific salmon's behavioral responses to light.

Underwater Light Environment

Salmon are exposed to different light environments throughout their life stages, ranging from clear freshwater streams, through the turbid waters of coastal and estuarine regions, to the blue light spectrum of the open sea. In each of these conditions, the visual pigments adapt to the spectral quality of the ambient light to catch the greatest possible number of quanta (Clarke 1936; Bayliss *et al.* 1936).

In addition to these differences, the non-uniform nature of the distribution of underwater light has important consequences for underwater vision. Not only is the scattered background or sidewelling light 10 to 100 times less bright than downwelling light (Jerlov 1968), but the image-forming light reflected from an underwater object is also scattered by particulate matter in the water, so that the object becomes less visible with increasing distance (Lythgoe 1979). This scattering of light underwater reduces the contrast between an object and its background that would normally be found in air.

Underwater objects are generally perceived because they are slightly brighter or darker than the water background. The task of the eye in such circumstances is not only to catch as many quanta as possible, but also to detect the object by its contrast with the background (Lythgoe 1966, 1968). A nearby object viewed in shallow water along a horizontal sight path reflects a broader band of wavelengths from the surface. This is because the light travels a shorter distance from the surface through the water than the scattered background light.

There is general support for the view that fishes' visual pigments are capable of maximum absorption at wavelengths that are more or less coincidental with the maximum wavelength transmission of the waters in which the fish reside. However, to

discern prey, predators, and companions from a distance requires sensitivity to optical contrast between objects, rather than the incident daylight. Recent studies (Novales-Flamarique 1993, Hawryshyn *et al.* 1988,1990, 1993; Browman *et al* 1993, Bowmaker and Kuntz 1987, Douglas and Hawryshyn 1990, Loew and McFarland 1990) have found spectral sensitivity ranges to be associated with salmonid life stages and prey resources.

Light and Salmonid Prey and Predator Recognition

Studies by Ali (1958, 1959, 1962) revealed threshold light intensities for different behaviors of juvenile salmon (Figure 7). Ali (1958, 1962) found that juvenile chum and pink feeding, minimum prey capture, and schooling are dependent upon specific light intensities of no lower than 10^{-4} ft-c. This light level is nearly equivalent to a clear night with a new moon. Consistently, Ali found that maximum prey capture for chum and pink fry (34-39mm) occurs at 10^0 ft-c, equivalent to the light range of dawn and dusk. When light intensity falls below the cone thresholds of 10^{-1} to 10^0 ft-c the eyes begin to dark-adapt. This can take anywhere from 30 minutes for fry to 50 minutes for smolts (Ali 1958). Evidence suggests that fish migration begins as the light intensity falls below the cone threshold. At this stage, the rate that light intensity decreases in nature is faster than the adaptation rate of the fry retina, leaving the fish in a semi-dark-adapted state and an inability to maintain position in relation to a given reference point. Consequently, it swims with the current or is displaced downstream. Ali found that active feeding stops in the dark, with feeding ceasing at light intensities below the rod threshold. Feeding at intensities between the rod and cone thresholds was found to be proportional to the logarithm of the light intensity (Ali 1958).

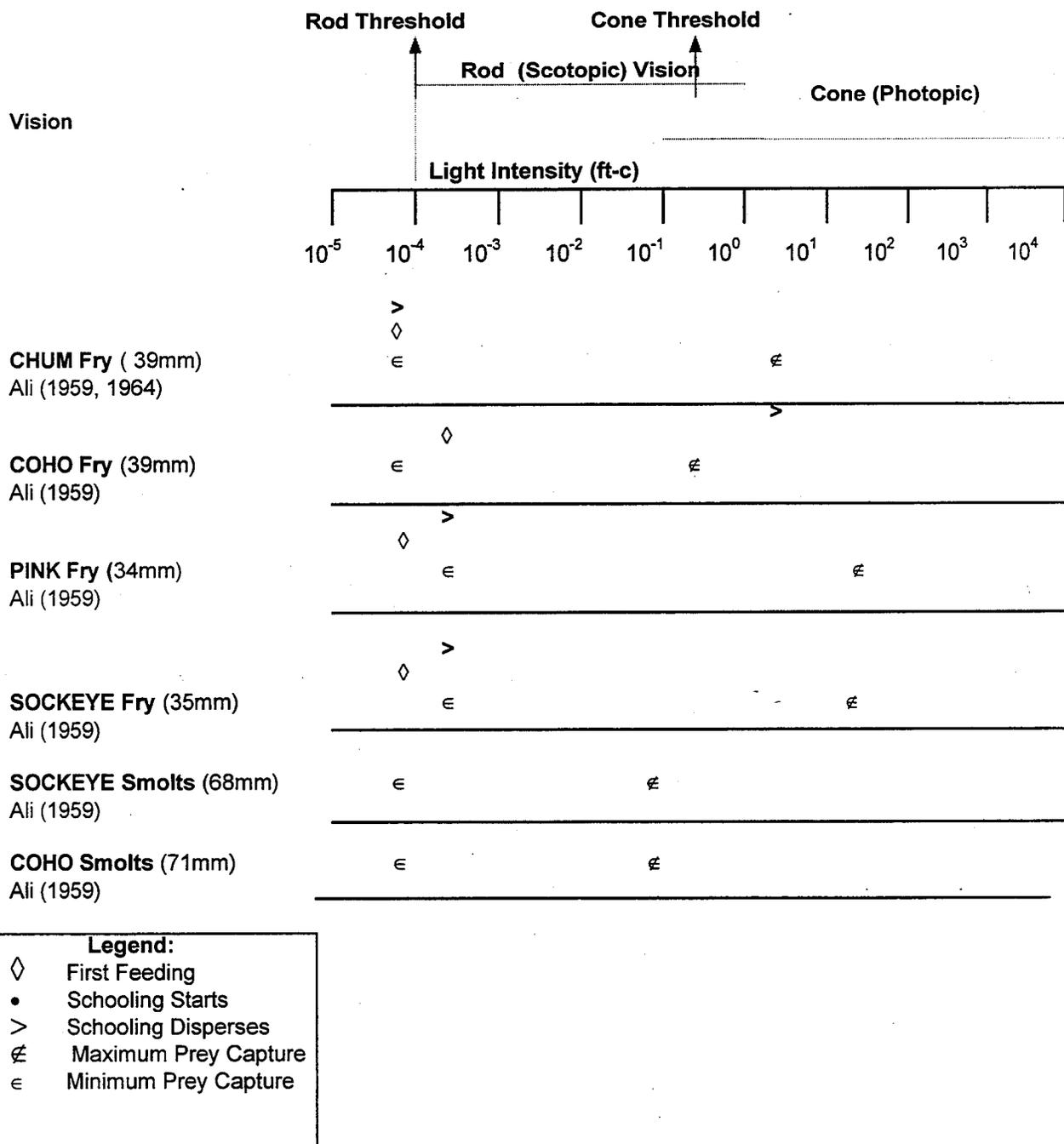


Figure 7. Juvenile salmon behavior patterns related to documented light intensities.

Under rod or scotopic vision in reduced light, visual acuity shifts, and prey search and capture and predator recognition change to the “silhouette method” in which rod sensitivity to light detects the shadow of the prey or predator against the brighter

background. As the light decreases in intensity, the difference between the shadow and background diminishes, making the location of prey or predator increasingly more difficult. When the light intensity falls below the rod threshold, the shadow profile cannot be distinguished from the scatter of background light, resulting in an inability to locate prey and recognize predators. At this point, feeding ceases.

Very small objects, such as zooplankton, are observed most easily in the upper meter of the water column, where they flash on and off at a noticeable rate. This can be attributed to

- the increase of flicker rates in the maximal temporal sensitivity range of humans
- the higher levels of irradiance close to the surface
- the greater modulation contrast of an object that should result from the greater amplitude shifts of flickering light that occur in the upper meter.

Thus, object size and depth beneath the surface determine whether the zooplankton will reflect a fluctuating pattern or merely flash. The line-of-sight significantly affects the visibility of flickering objects. Viewed from below zooplankton merge into the flickering glare of Snell's window. Viewed from the side or from above, they "flash" against a non-flickering background (MacFarland & Munz 1975, Lythgoe 1979; Loew and McFarland 1990).

The eye of the fish contains cone cells that are sensitive to UV light and the polarization of light (Hawryshyn and Harosi 1993; Coughlin and Hawryshyn 1993). Whereas the human eye perceives wavelengths between 400 nm to 700 nm, the salmonid eye perceives and distinguishes wavelengths from the ultraviolet range of 350 nm to the

longer wavelength range of 700 nm. This ability to distinguish UV wavelengths possibly enhances salmonids' ability to see contrasts as well as to read the e-vector of the earth and sun. This is believed to enhance their ability to search and capture tiny zooplankton and to navigate relative to the angle of the sun to the earth (Browman *et al.* 1993; Novales-Flamarique and Hawryshyn 1996).

Artificial Lights and Salmonid Behavior

Key to understanding salmonid behavioral responses to light variations is the recognition that a salmonid's reaction to light stimulus depends upon the ambient light level to which the fish has been exposed before it encounters any changes in the quality or intensity of light caused by an over-water structure. Puckett and Anderson (1987,1988) found that juvenile salmon may be attracted to incandescent light when they encounter a sudden decrease in ambient light intensity. Studies that have examined the use of artificial light to guide salmonids safely through migration barriers, such as hydroelectric dams, have found measurable differences in juvenile responses to both the quantity and quality of the light stimulus. Fish respond quite differently to flickering strobe, mercury, or halogen light sources. The success of using artificial lights to guide fish through structures or to mitigate the impacts of artificial light on the underwater environment requires an understanding of the conditions of illumination and the nature of salmonid light perception.

As an example, consistent with previous studies, Nemeth (1989) found that coho and chinook salmon consistently moved away from flashing strobe lights during both day and night tests. They demonstrated more consistent and intense avoidance of flashing strobe lights than of other light stimuli (mercury vapor, incandescent, and fluorescent)

(Fields and Finger 1954; Patrick *et al.* 1982, 1985; Patrick 1983,; McIninch and Hocutt 1987; Sager *et al.* 1987; Puckett and Anderson 1987). Unlike the normal flickering light caused by wave, cloud, and sun conditions in underwater environments, the discharge of strobe light is abrupt and apparently disturbing to fish (Dera and Gordon 1968; McFarland and Loew 1983). This is hypothesized to be due to the flash rate and duration of the strobe light, rather than to the spectral composition of the light source. The abrupt flashes of a strobe likely produce large contrasts in light intensity over durations too short for salmonids to adapt. The work of Sager *et al.* (1987) with dark-acclimated estuarine fishes and Nemeth (1989) in dark tank conditions consistently demonstrated a greater salmonid avoidance to a strobe light in dark conditions.

Results of tests with mercury lights have differed significantly from strobe light reactions. Wickham (1973) and Pucket and Anderson (1988) found fish to be attracted to mercury lights under certain circumstances. Nemeth (1989) found increased coho and chinook activity with mercury light and a less avoidance in comparison to strobe light conditions. During night tests, Puckett and Anderson (1987) found that steelhead initially avoided mercury light, then swam toward it. The strength of the attraction to a solid, non-flashing light is dependent upon the intensity of the light and the level of light to which the salmonids have previously adapted. On the basis of studies of salmonid attraction to light sources in dark conditions, Puckett and Anderson (1988) describe the attraction to solid light in the following formula:

$$\text{Percent attraction} = A - k\text{Abs}(\log I_p/I_a)$$

where A is a constant expressing the percentage of fish attracted under the best conditions, k is a constant, Abs is the absolute value operator, \log is the logarithm to the

base e , I_s is the intensity of the light that fish encounter, and U_a is the intensity of light to which the fish had been adapted. The maximum attraction occurs when $I_s = I_a$.

Synopsis

Docks can create sharp underwater light contrasts by casting shade under ambient daylight conditions. They can also produce sharp underwater light contrasts by casting light under ambient nighttime conditions. The studies summarized above repeatedly verified the impact of changes in the underwater light environment on juvenile salmonid physiology and behavior. These changes pose a risk of affecting fish migration behavior and placing them at increased mortality risk. The increased risk posed by light changes could result from the following:

- delays in migration caused by disorientation
- loss of schooling in refugia because of fish school dispersal under light limitations
- a change of migratory route into deeper waters, without refugia, to avoid the light change.

These risks are consistent with studies throughout Puget Sound that have documented juvenile salmonid behavioral changes when the fish have encountered docks, as well as studies associated with guiding salmonids through dangerous structures (i.e., dam turbines, locks) with artificial lighting (Prinslow *et al.* 1979; Weitkamp 1982, 1992; Ratte and Salo 1985; Taylor and Willey 1997; Pentec 1997, Fields 1966, Johnson *et al.* 1998). Further field studies documenting *in situ* behavioral changes in fish upon their encountering docks and measured light changes are needed to understand and mitigate identifiable impacts to juvenile behavior that increase the risk of mortality.

NEARSHORE HABITAT RESPONSES TO THE LIGHT ENVIRONMENT

Photosynthetic production of new plant material is the first link in plant and animal food chains. Primary producers such as diatoms and phytoplankton support juvenile salmon, which prey on small copepods feeding on the diatoms and microbial colonizers associated with microalgae and detritus (Cordell 1986, D'Amours 1987). Light provides the essential energy that drives plant photosynthesis. A plant's ability to utilize light energy is defined by the structure and pigments of its chloroplasts, which are the sites of photosynthetic reactions (Lobban 1985).

Light energy transmitted below a threshold amount limits a plant's photosynthetic capacities. Estuarine primary producers such as the diatoms, algae, and macrophytes found in Puget Sound rely upon light transmitted through the water's surface. This makes them very susceptible to the light-limiting impacts of suspended particulates and shade cast by over-water structures (Olson *et al.* 1996, Thom *et al.* 1996, 1997). By altering light, substrates, and wave action, over-water structures can affect primary and secondary production (Pentilla and Doty 1990, Loflin 1993, Thom 1993, Burdick 1995, Thom *et al.* 1995, 1997; Thom and Shreffler 1996, Olson *et al.* 1996, 1997). The following summary overviews the mechanics of light energy transmission and photosynthesis and the environmental factors that synergistically affect primary production in the estuarine waters of Puget Sound.

Light Energy Transmission

Light energy is provided by light quanta, which are indivisible light energy packets consisting of light waves. The energy of a quantum is proportional to both the light wavelength and its frequency. Because atmospheric gases and fine dust scatter

wavelengths, solar radiation reaching the earth's surface varies largely in quality and quantity. The scattering of specific wavelengths varies in proportion to the length of the wavelength. The shorter, higher energy, blue wavelengths scatter more than the longer, red wavelengths. Carbon dioxide absorbs wavelengths longer than 2300 nm. Water vapor attenuates those between 720 and 2300 nm, and the ozone absorbs the 290- to 320-nm wavelengths. On a clear day, wavelengths reaching the earth's surface range from ultraviolet (UV) to near infrared. Figure 8 illustrates the electromagnetic spectrum of solar radiation wavelengths and shows the position of visible light between UV and infrared wavelengths. Radiant energy ranges from long-wave, low-energy quanta of the radio region to short-wave, high-energy cosmic rays. Total irradiance reaching the earth's surface also depends upon the sun's angle to the earth's surface. As the sun shifts from a zenith position toward the horizon relative to the earth's surface, the total irradiance decreases; the maximum energy wavelength then shifts to longer, lower energy wavelengths (Lobban 1985).

Underwater Light Environments

As light reaches the sea surface, its ability to penetrate the surface is further reduced by the processes of reflection and absorption. The percentage of light that is reflected is dependent on the angle of the sun relative to the sea and the roughness of the seas. Reflection from a smooth sea can range from 4 percent at the sun's zenith to 28 percent when the sun is at a 10-degree angle relative to the sea (Holmes 1957). Waves can decrease or increase reflectivity, depending on the angle of the sun relative to the sea (Holmes 1957, Jerlov 1968). Water absorbs light maximally in the infrared wavelength

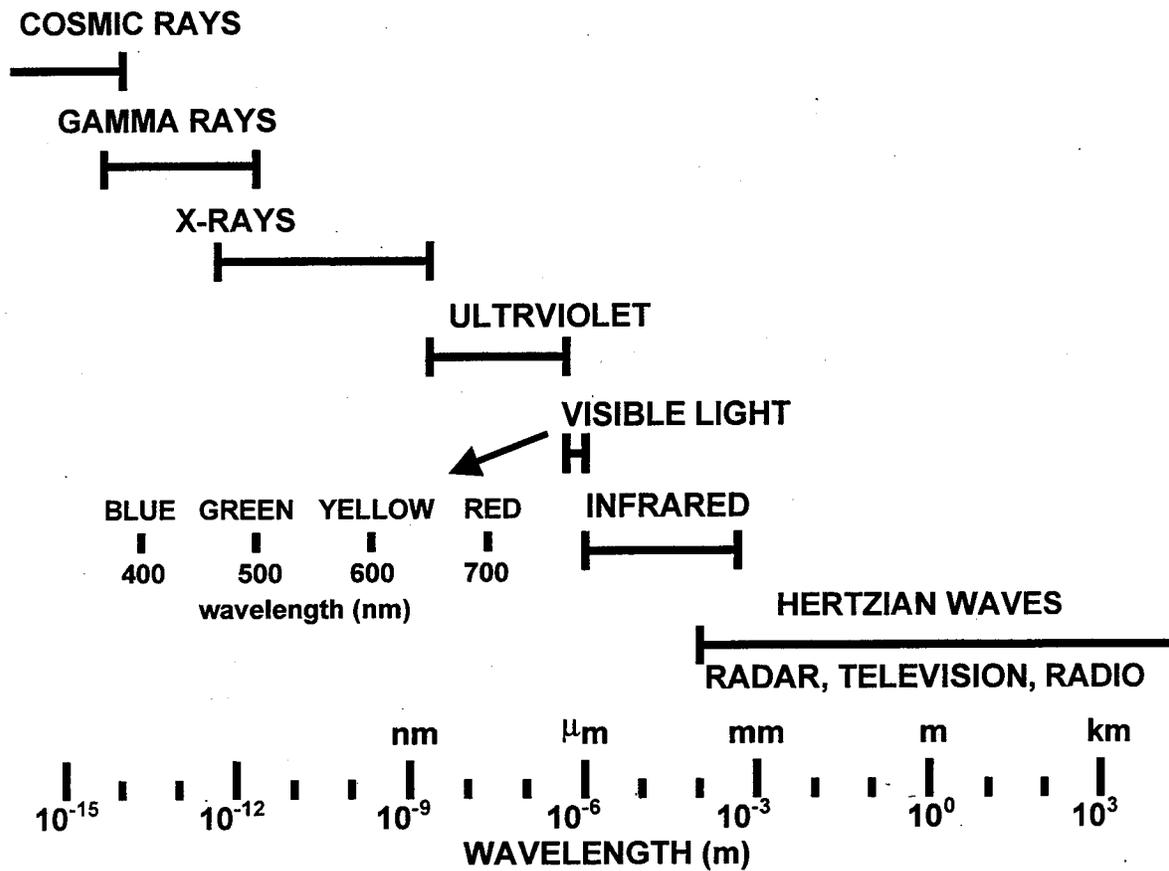


Figure 8. Electromagnetic spectrum showing position of visible, UV, and IR wavelengths. (from Withrow & Withrow 1956)

range above 700 nm. Irradiance at wavelengths of greater than 1300 nm is totally absorbed in the top 10 mm of water (Jerlov 1976).

Marine waters can be divided into two broad categories: green coastal waters and blue oceanic waters (Morel and Smith 1974). The characteristic green color of coastal waters is due to the absorption of shorter wavelengths by plant pigments and dissolved organic substances. With penetration into marine waters, solar energy is altered in both quality and quantity by attenuation, absorption and scattering by plants, and the

dissolution of organic and inorganic particulates in the water. The characteristic green of coastal waters is due to the high quantities of such seston and particulates. Coastal waters often exhibit a 56 percent transmittance of surface irradiance and a maximum light transmittance at 575 nm wavelengths (green). In contrast, the clearest oceanic waters have a maximum transmittance at approximately 475 nm wavelength and surface irradiance as high as 98.2 percent (Jerlov 1976). In estuaries, this zone of light transmission, the photic zone, is characteristically shallow because of the high seston level (Alpine and Cloern 1988). In estuarine waters off southern Vancouver Island, Novales-Flamarique and Hawryshyn (1993) found transmission of UV wavelengths as low as 300 nm at depths of 3 meters but only as low as 400nm wavelength transmission at depths of 12 meters and above.

Photosynthesis

Light is the most important factor affecting plants. The photosynthetic process converts solar energy into photochemical energy through an oxidation-reduction reaction. Basically, in green plant photosynthesis, CO_2 , H_2O , and light energy are the reactants, and O_2 and CH_2O are the products. This process takes place within the plant's chlorophyll containing chloroplast structures (Govindjee and Govindjee 1975). The photochemical process of light trapping increases linearly as irradiance increases until a maximum photosynthetic "saturated" rate is reached for a given plant. At that saturation point, increased irradiance no longer results in increased production. Essentially, growth takes place when enough light energy is received and stored to support

- the initial electron transfers of the reaction process
- the creation of new plant tissue

- the subsequent cellular respiration process that uses O₂ and releases CO₂.

The energy driving this process is provided by light quanta, with the energy quantum being a function of given light wavelengths. Each plant group has characteristic pigments that utilize the energy levels transmitted by a specific wavelength spectrum.

Diatoms, photosynthetic bacteria, phytoplankton, macroalgae, microalgae, and seagrasses require particular light spectrums to support photosynthetic reproduction and growth. The particular light spectrum required by a given plant group corresponds to the particular photosynthetic cellular structure of that plant. Photosynthetically Active Radiation (PAR), used to describe the spectral properties of photosynthetic pigments, is defined as wavelengths between 400 to 700 nm. However, there is evidence that some forms of green algae, such as *Ulva* and some stages of red algae, engage in photosynthetic processes at PAR levels as low as 300 nm.

The minimum light required for persistence of a plant species is defined by the percentage of surface irradiance ($\%I_0 = [I_z * 100] / I_0 = e^{-kz}$) that reaches the lower depth limit of the species (Olson 1996). Using this definition, phytoplankton requires 1 percent of surface irradiance (Strickland 1958); freshwater macrophytes require 10 percent (Sheldon and Boylen 1977), and eelgrass requires a minimum of 10 to 20 percent (Duarte 1991, Dennison *et al.* 1993). Thom and Shreffler (1996) found that eelgrass in Puget Sound is light limited at levels below 300 $\mu\text{Mm}^{-2}\text{s}^{-1}$. The level of irradiance or quantity of light, measured in $\mu\text{Mm}^{-2}\text{s}^{-1}$, required to saturate plant species correlates to the habitat of the plant. Intertidal macroalgae species may require 400-600 $\mu\text{Mm}^{-2}\text{s}^{-1}$, whereas deeper sublittoral macroalgae species may require less than 100 $\mu\text{Mm}^{-2}\text{s}^{-1}$ (Luning 1981).

Plant Light Absorption Characteristics

Absorption and utilization of radiant energy by plant material in the water, such as phytoplankton, diatoms, and other plants, depends on the pigments they contain. Plant pigments such as chlorophylls, carotenoids, and phycobiliproteins provide each plant with light absorbing characteristics particular to that plant group and its environment. Photosynthetic pigments in plants include chlorophyll-*a* plus a variety of other pigments arranged in the plant's reaction center. These pigments are the plant's light harvesting pigments. Each plant group has an array of pigments with characteristic absorption spectrums at given wavelengths. Their rates of photosynthesis depend upon irradiance levels, with each plant group's respective rate of photosynthesis following the curve of absorption spectrum. The light energy absorbed by these pigments is then transferred to reaction centers where the oxidation and reduction reactions occur to convert water and carbon dioxide to carbohydrates and oxygen.

On the basis of differences in pigment and chloroplast structures and the use of the sun's radiant energy, underwater plants can be grouped into seven categories:

- diatoms
- phytoplankton
- green algae
- blue-green algae
- brown algae
- red algae
- higher green plants.

Figure 9 identifies chlorophylls and absorption peaks characteristic to particular algal and diatom groups in Puget sound (Kozloff 1983). The figure graphs the absorption spectra of types of algal pigments. However, it is important to remember that in their respective environments, plants are able to acclimate to a variety of differences in both light quantity and quality.

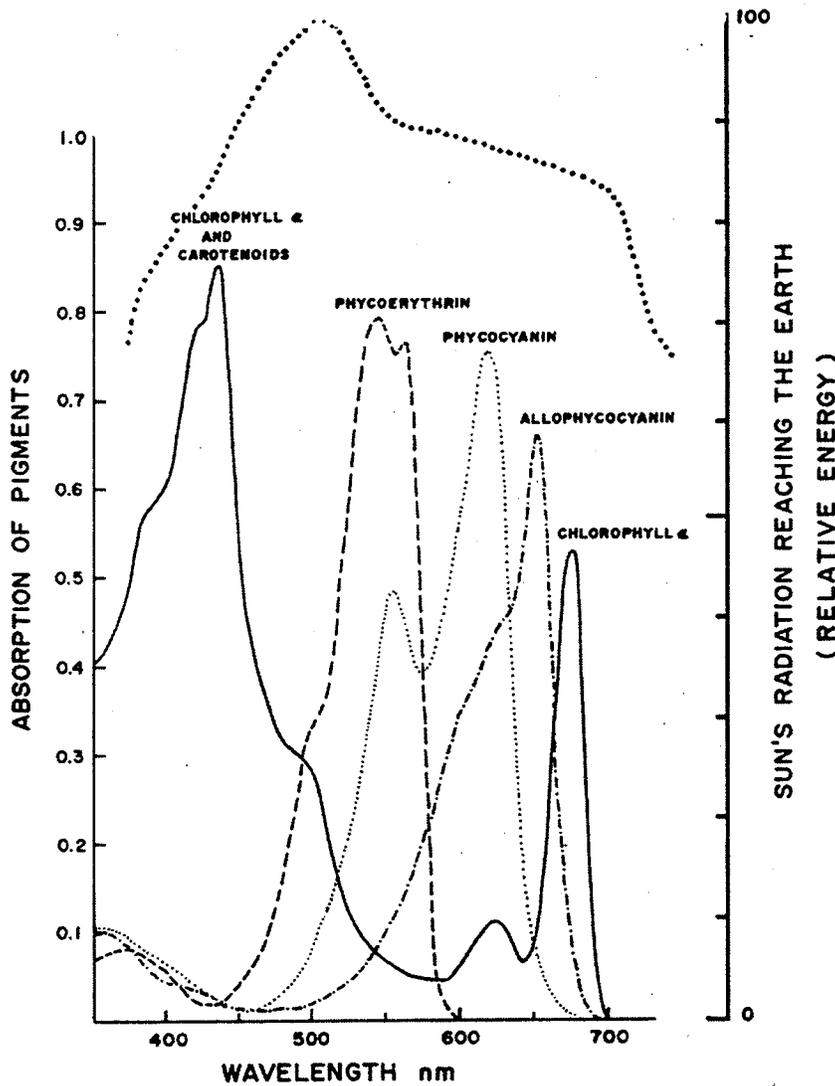


Figure 9. Spectrum of solar energy at the earth's surface (upper dotted curve), and absorption spectra of algal pigments. (from Gantt 1975).

Table 1. Puget Sound algal pigment and wavelength relationships (from Kozloff 1983).

Plant Phylum	Algae common to Puget Sound docks, pilings, <i>Zostera</i> shoots and rocky shorelines	Chief Pigments	Wavelength nm absorption peak
Cyanophyta	Blue-Green Algae (<i>Calothrix</i>)	chlorophyll <i>a</i> , carotenoid (<i>phycoerythrin</i>)	550 435
Chlorophyta	Green Algae (<i>Ulva</i> , <i>Cladophora</i> , <i>Bryopsis</i> , <i>Derbesia</i> , <i>Blidingia</i> , <i>Halicystis</i> <i>Entrophorpha</i> , <i>Kornmannia</i> , <i>Codium</i>)	chlorophylls <i>a,b</i>	435,480
Bacillariophyta	Diatoms (<i>Navicula</i> spp.)	chlorophylls <i>a,c</i> , and carotenoid (<i>fucoxanthin</i>)	435, 650,740
Phaeophyta	Brown Algae and Kelps (<i>Laminaria</i> , <i>Desmarestia</i> , <i>Costaria</i> , <i>Agarum</i> , <i>Vymathere</i> , <i>Egregia</i> , <i>Pterygophora</i> , <i>Alaria</i> , <i>Nereocystis</i> , <i>Sargassum</i> , <i>Cystoseira</i>)	chlorophyll <i>a,c</i> carotenoid (<i>fucoxanthin</i>)	435, 650, 740
Rhodophyta	Red Algae (<i>Antithamnion</i> , <i>Antithamnionella</i> , <i>Hollenbergia</i> , <i>Scagelia</i> , <i>Polysiphonia</i> , <i>Polyneura</i> , <i>Iridaea</i> , <i>Delesseria</i> , <i>Membranoptera</i> , <i>Callophyllis</i> , <i>Smithora</i> , <i>Porphyra</i> , <i>Phyllospadix</i> , <i>Lithothamnium</i> , <i>Corallina</i> , <i>Calliarthron</i> , <i>Bossiella</i> , <i>Constantinea</i> , <i>Gigartina</i> , <i>Iridaea</i> , <i>Odonthalia</i> , <i>Thodmela</i> , <i>Colpomenia</i> , <i>Hymenena</i> , <i>Botryoglossum</i> , <i>Erythrophyllum</i> , <i>Opuntiella</i> , <i>Prionitis</i> , <i>Laurencia</i> , <i>Plocanium</i> , <i>Pterochondria</i> , <i>Microcladia</i> , <i>Callithamnion</i>)	chlorophyll <i>a, d</i> carotenoid (<i>phycoerthrin</i>)	435, 760

Other Environmental Factors That Affect Photosynthesis

Nutrients

Although the duration, intensity, and availability of PAR light is central to determining plant productivity and distribution patterns, plant productivity also depends on many other environmental factors. These include temperature, salinity, wave actions, and nutrient conditions. The rate of plant photosynthesis depends upon numerous factors,

including inorganic carbon and nitrogen supplies, temperature, pH, circadian rhythms, and the age of plant tissue (Lobban 1985).

All primary producers require nitrogen and phosphorous for growth and metabolism (Raymond 1980). These are essential cell building and gene transmitting materials of proteins, nucleic acids, and cells. Plant species differ in what forms of these nutrients they can assimilate and what ratio of these nutrients they need, retain, and excrete. The ratio of carbon to nitrogen and phosphorous (C:N:P), the Redfield Ratio, is an important tool for predicting primary production trends. Atkinson and Smith (1983) found benthic marine macroalgae and seagrasses to be much more depleted in phosphorous (P) than nitrogen (N). The ratio of carbon to nitrogen and phosphorus (C:N:P) for marine plankton is 106C:16N:1P (by atoms). This is considerably lower than the ratio for seaweeds at 550:30:1. A ramification of this difference is that the nutrient amounts required to support macroalgae production is much lower than those required for phytoplankton growth (Lobban 1985). This high C:N:P ratio for seaweeds is thought to be due to their large amount of structural and storage carbon. The average carbohydrate content for phytoplankton is 35 percent, and its average protein content is 50 percent. In contrast, the averages for seaweeds are 80 percent and 15 percent, respectively. Given such differences between plants in nutrient level requirements, coupled with the marked seasonal variations in availability of nutrients, plants vary in their ability to outcompete other plants under particular nutrient limited conditions. For example, if conditions favor phytoplankton or algae growth over higher plants, such as seagrasses, the increasing abundance of epiphytic algae on existing seagrass shoots, as well as in the water column, will attenuate the PAR light before it reaches the seagrasses and higher plants. Puget

Sound waters tend to be nitrogen limited; the N:P ratio of dissolved inorganic nitrogen ($\text{NO}_3 + \text{NO}_2 + \text{NH}_4$) to PO_4 has been repeatedly identified to be 16:1. This indicates that the addition of available nitrogen forms, particularly NO_3 and NH_4 , would likely increase algal growth until another factor, such as phosphorous, light, or oxygen, became limiting.

Temperature-Salinity

Temperature effects on seaweeds are profound because of the effects of temperature on molecular structure and activity (Figure 10). Biochemical reaction rates almost double for each 10°C increase in temperature. Photosynthesis, respiration, and growth, as enzyme reactions, have optimum temperatures. However the effects of temperature are not uniform across all processes. The optimum temperatures vary between and within species. Plants also adapt metabolically to regional temperature changes.

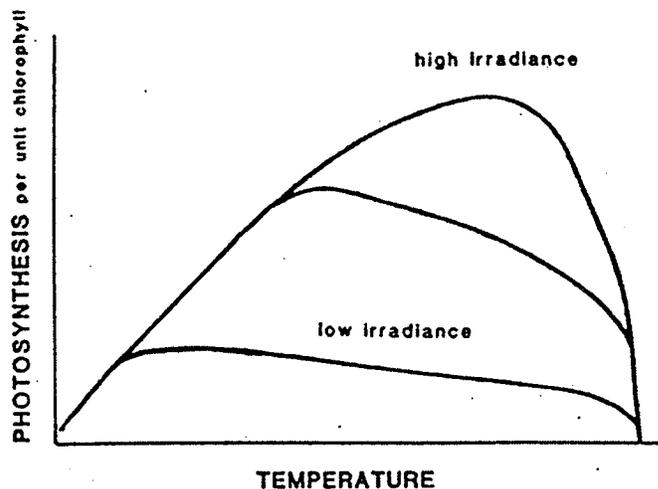


Figure 10. Effect of temperature on short-term photosynthesis (Figure 2, Bulthuis 1987)

Temperature is likely to have an overriding control or synergistic interaction with salinity. Seaweed distribution in estuarine areas, where runoff impacts salinity levels, can be regulated by salinity and temperature interactions. Photosynthesis, respiration, and growth have optimum salinities. Diluted seawater can cause a decline in photosynthesis for some plants. Studies have demonstrated a sharp drop in photosynthetic rate of several marine plants, such as *Ulva*, when they are exposed to distilled freshwater. However, in estuaries fed by spring water, *Ulva* photosynthesis can be greater than in full seawater. It is believed that this is due to important nutrients contained in spring-water runoff into the estuary. Although studies show that red and brown algae do not tend to penetrate into estuaries as far as green seaweeds (Gessner & Schramm 1971, Druehl 1981), photosynthesis of red algae has been found to be greater in spring-fed estuaries than in even full seawater (Hammer 1968, Gessner and Schramm 1971) because of the advantage of nutrient concentrations contained in the spring water.

Variations in these key environmental factors lay the groundwork for biological interactions and competitions that affect growth and reproduction patterns across varying plant species. This includes the relationship between higher plants and epiphytic bacteria, fungi, algae, and sessile animals, as well as predation by herbivores (Lobaan *et al.* 1985). Higher plants, such as seagrasses, require higher levels of radiant energy than the diatoms and epiphytic bacterial forms that utilize their shoots as substrates.

This higher irradiance requirement limits macrophyte and seagrass survival beyond depths with corresponding low irradiance levels. To the degree that epiphytic forms absorb light wavelengths, they limit light to the seagrass plant. Similarly, turbid waters that attenuate shorter wavelength levels and transmit longer, low-energy

wavelengths could transmit the energy required for bacterial and algae growth without transmitting the specific wavelengths that activate eelgrass growth and reproduction. The increase in epiphytic and bacterial growth increases the shoot surface area covered by epiphytes and inhibits the photosynthetic capacity of the seagrass plant (Figure 11). Epiphyte abundance can be reduced by herbivorous epiphyte grazing isopod and amphipod populations. Studies have found that eelgrass biomass declines with decreasing epiphyte grazing populations (Wetzel and Neckles 1986; van Montfrans *et al.* 1984; Williams and Ruckelshaus 1993).

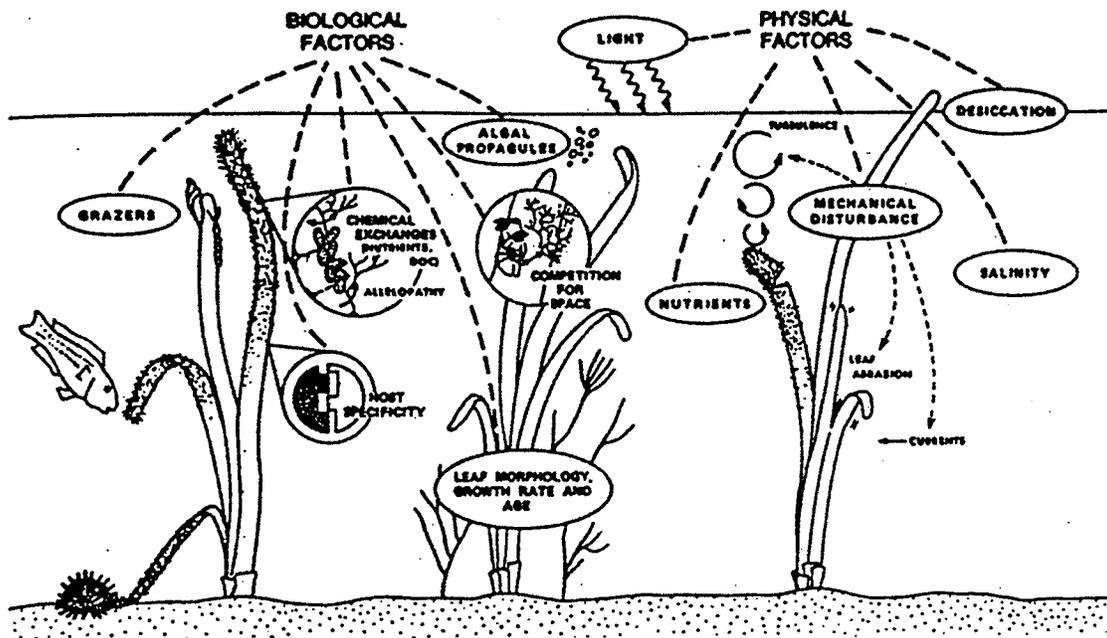


Figure 11. Factors affecting seagrass growth and persistence (from Figure 1, van Montfrans *et al.* 1964)

SUMMARY

Light energy drives the plant photosynthetic process at a variety of wavelengths and energy levels. This process is governed by a variety of plant cellular structures and pigments that absorb and use specific lightwave energies to create new plant material. Nutrients, temperature, salinity, and wave action also play an important part in controlling the quality and quantity of light available. The synergism of these factors controls plant cellular structure and growth processes. Changes in any one environmental factor can change the existing synergistic dynamics and change the biologic assemblages in a given locality. It is the synergistic total created by the particular combination of temperature, salinity, light, nutrient levels, and wave action of a given local environment that ultimately determines the rate of photosynthesis, plant distribution, and survival of specific plant species at any one local site.

3—SUMMARY OF THE LITERATURE REVIEW OF OVER-WATER STRUCTURE EFFECTS ON JUVENILE SALMON BEHAVIOR, HABITAT, AND POTENTIAL PREDATION

The primary objectives in this component of our Phase I investigations were as follows:

- identify existing information sources
- examine the quality of available information
- present the scientific uncertainties and empirically supported evidence that overwater structures can create physical and behavioral barriers to migrating juvenile salmon
- begin the process of making recommendations for research and possible mitigating construction practices.

Our intent was to focus subsequent Phase II-III laboratory and field research on issues about potential ferry terminal impacts that were most apparent and substantiated in the scientific literature, and to distinguish that information from speculation. We did not necessarily expect to find consensus and unambiguous information or interpretations in the literature, but we sought to identify factual bases for variation in observations and findings and to elucidate the conditions that likely produced these differences. The ultimate goal was to identify and prioritize impacts of legitimate concern that could be evaluated empirically by our subsequent research. Thus, both scientific and management uncertainty about the magnitude and mechanisms of impact could be minimized, and mitigation approaches could be identified.

The paradigm under which we operated was as follows:

Over-water structures such as ferry terminals can increase the mortality of juvenile salmon fry migrating through shallow-water habitats along estuarine and nearshore marine shorelines by

- introducing a "behavioral barrier" that deflects or delays migration
- decreasing salmon fry growth and residence time by limiting prey resource production and availability ("carrying capacity") by affecting shallow-water primary and secondary production
- increasing predation by aggregating predators or heightening the predation rates of predators associated with over-water structures.

In surveying the state of the knowledge that addresses this paradigm, we asked the following question: Do modifications to natural shorelines, such as over-water structures, introduce artifacts to the shallow-water migratory corridors of ocean-type juvenile salmon that increase their vulnerability to either proximal mortality factors (i.e., directly associated with the shoreline modification) or subsequent mortality factors (e.g., manifested in the ocean).

The fundamental assumptions behind this issue as we defined it, and which are generally supported by the scientific information on juvenile salmon ecology provided herein, are as follows:

- Shallow-water, nearshore habitats are important sites for the migration of juvenile ocean-type salmon because of the abundance of appropriate prey resources and refuge from predators.

- Evolution has promoted the selection of certain behaviors that optimize the probability of such fish returning to spawn, so that there is a survival cost to altering those behaviors.
- On average, higher growth during salmonids' early estuarine/nearshore marine life stage produces higher survival to return because of reduced mortality of larger fish in the ocean.
- There are no natural analogs to shoreline modifications such as ferry terminals and ferry activity to which salmon would have adapted during the evolution of their early life history patterns.
- Shoreline effects are cumulative but not necessarily linear (i.e., additive) over shoreline "landscapes" such that effects may be influenced by associated habitats.
- It is unrealistic to think that we will be able to evaluate the absolute effect of ferry terminals on total survival because of the complexity of factors that affect salmon survival across all life history stages.

METHODS

We conducted an extensive search of available literature, including but not limited to the following:

- University of Washington libraries' electronic and commercial databases
- previous over-water impact studies specific to Puget Sound
- previous literature surveys that addressed the various components of this project.

Literature Sources

This literature search incorporated analyses of existing data available on both juvenile salmon responses to over-water structures (or comparable effects, such as shading) and basic juvenile salmon ecology, as well as assessment of previous literature searches on this and related topics. To address specifically the question of the impediments to juvenile salmonid migration presented by over-water structures, the review was confined to studies that addressed juvenile salmon migration behavior and associated prey and habitat requirements. More specifically, the review targeted studies that addressed specific juvenile salmonid species and stocks in nearshore habitats of Puget Sound.

Searching Commercial Databases

A preliminary list was compiled from a search of the following databases available on compact disc in the University of Washington library system:

- Aquatic Sciences and Fisheries Abstracts (ASFA)
- Selected Water Resources Abstracts (SWRA)
- National Technical Information Service (NTIS).

The ASFA database includes literature dating back to 1982 covering science, technology, and management of marine and freshwater environments. It includes 5,000 international sources in the form of primary journals, source documents, books, monographic series, conference proceedings, and technical research reports. The Geological Survey, U.S. Department of the Interior, produces the SWRA database that includes pertinent monograph abstracts, journal articles, reports, and publications. The NTIS Government Reports is an index produced by the U.S. Department of Commerce.

This is a central source for public sale of U.S. government-sponsored research, development, and engineering reports.

Mail Requests From Experts

The bibliography compiled from the above databases was posted to the project Web site and followed up by a mail solicitation of comments to targeted salmonid and habitat ecologists considered to be experts in estuarine studies.

Categorizing Information

In an effort to present available data in an easily referenced structure, each information source was categorized by the value of the data as a *direct* source of information on over-water structure impact, as an *indirect* source of information on juvenile salmonid prey and habitat resources, or as a source of *background* information. Studies that directly addressed the impacts of over-water structures on salmonid ecology and habitat components in the Pacific Northwest were assembled in a table format defining study objectives, methods, measured variables, and the targeted ecological components addressed, such as predation, migration, benthic assemblages, and primary production. Summaries of study objectives, methods, and results were also included for each study listed in the table.

Direct Sources

Direct sources are those that directly address and detail impacts of over-water structures on salmonid migration, predation, and available prey resources. These impacts can take the form of shading or other effects that alter juvenile salmon migration patterns, primary and secondary production, habitat substrate, or associated increases in predation exposure.

Indirect Sources

Indirect sources are references that fall into two categories: juvenile salmon migration, and juvenile salmon prey and habitat resources. These references address impacts to juvenile salmonid migration, habitat, and prey resources.

Background Sources

Background sources are studies that describe the basic environmental and behavioral characteristics and requirements of salmonid species, habitat, and prey resources.

Compilation and Assessment of Information and Incorporation into Database

We prepared synopses of all direct information sources. All sources were assessed and compiled into a Microsoft Access™ database, including background information on juvenile salmon ecology and aquatic light environments.

RESULTS

We identified 64 sources that directly addressed the effects of over-water structures or comparable influences on migrating juvenile salmon or their habitat; 19 of these described actual or potential impacts on salmon migration, 32 sources described effects on juvenile salmon prey resources or their estuarine/nearshore marine habitats, and 13 addressed the associated effects of over-water structures on predation on juvenile salmon or influences on potential predators. Synopses of the important direct sources that address the impacts of over-water structures are included as Appendix D. Our assessments of the available literature sources describing the effects of over-water structures on estuarine and nearshore marine shallow-water habitats are included in

Appendix E. Appendix F includes synopses of literature sources about predation on juvenile salmon that is attributable to or associated with over-water structures.

Migration Behavior

Because juvenile ocean-type salmon tend to migrate in shallow-water habitats along estuarine and marine shorelines, over-water structures such as ferry terminals may present physical or behavioral barriers to their normal migration patterns. In addition, alterations to nearshore estuarine habitats, including construction, retrofitting, and maintenance of over-water structures, may reduce salmonid prey and refuge availability. Alterations to this nearshore habitat pose a potential reduction in salmonid prey and refuge availability that carries with it the possibility of diverting small juvenile salmon into deeper water, thereby increasing their exposure to predators. Forcing juvenile salmon into deeper water might further affect salmon survival by decreasing their growth because of limited availability of the appropriate prey resources. The cumulative impact of these migration alterations could be an overall reduction in survival rate as juveniles traverse through Puget Sound.

Evidence for over-water structure effects on juvenile salmon migratory behavior is predominantly observational, with few examples of systematic sampling or experimental approaches (e.g., Ratte and Salo 1985). We found no studies that described empirical evidence supporting or refuting that modification of juvenile salmon behavior in shoreline habitats was reflected in changes in survival. Results were exceedingly variable and appeared to reflect variable conditions (e.g., adjacent shorelines, dock dimensions and material, artificial lighting, etc.) that affected observations.

The responses of juvenile salmon were extremely size-dependent. The smaller the fish, the more their migration appeared to be "behaviorally constrained" to shallow-water habitats, and the more likely they were to avoid entering shaded habitats. Salmon fry tend to use both natural refuge (e.g., vegetation such as eelgrass) and darkness (e.g., shading from docks and floats, turbidity) as refuge but migrate along these edges rather than penetrate them. If prompted by an antipredator fright response, they will seek refuge within vegetated or dark areas. When volitional migratory pathways are blocked by shading or other less-preferred habitat, competing behavioral mandates appear to result in fish confusion and often in delay of active migration.

The scale of shading also introduces an independent factor. The physical design (e.g., dock height and width, construction design and materials, piling number and type, etc.) can influence whether the shadow cast on the nearshore covers a sufficient area and scope of darkness to constitute a barrier. For example, Dames and Moore and Biosonics (1994) found no evidence of stalling or movement offshore of the Manchester Naval Fuel Pier; instead, juvenile salmon appeared to travel between eelgrass habitats on either side of the pier. This implied that the shadow cast was insufficient in intensity or size to deter the salmon fry migration as long as there were sufficient prey resources to bridge the impacted areas.

The response to shading and other effects of over-water structures appear to be extensively dependent upon schooling behavior. Smaller fish are also more likely to remain in schools, rather than migrating as individuals. For instance, juvenile chum salmon 30-60 mm in FL tend to migrate in highly directed schools of hundreds to thousands, whereas chinook are typically found in less dense (~10's) and less directed

schools. Upon encountering shading from over-water structures, juvenile salmon schools have been observed to become "confused" and ultimately to split into different groups, some of which seek alternative pathways and some of which persist in migrating through shallow-water habitats beneath the over-water structure (Pentec Environmental, Inc. 1997; Taylor and Willey 1997).

Attraction to prey concentrations confounds many studies, which found fish feeding in association with over-water structures but did not evaluate feeding success and included habitats (e.g., log booms) that are not necessarily representative of over-water structures such as ferry terminals (Weitkamp 1982). Dock lighting is also observed to induce temporary/localized delays by attracting fish, especially at nighttime. This is perhaps associated with prey attraction and/or visibility of prey.

Primary and Secondary Production

By shading sunlight, over-water structures that decrease light energy below a threshold amount limit photosynthesis of diatoms, benthic algae, eelgrass and associated epiphytes and other autotrophs. These contribute to habitat structure and food webs that support juvenile ocean-type salmon in estuarine and nearshore marine environments (Figure 12; see previous chapter by Nightengale *et al.*). Similar to benthic algae, eelgrass requires a minimum daily-integrated, photosynthetically active radiation (PAR) threshold of $3M\ m^{-2}d^{-1}$ to prevent plant death (Bulthuis 1994; Thom 1993; Olson 1996a; Thom and Shreffler 1996). Factors that limit available light for benthic and eelgrass photosynthesis include light attenuation from particles suspended in the water column and shade cast by over-water structures (Olson *et al.* 1996a, 1997; Thom and Albright 1990; Thom *et al.* 1997a). Studies throughout Puget Sound and the East Coast have demonstrated the

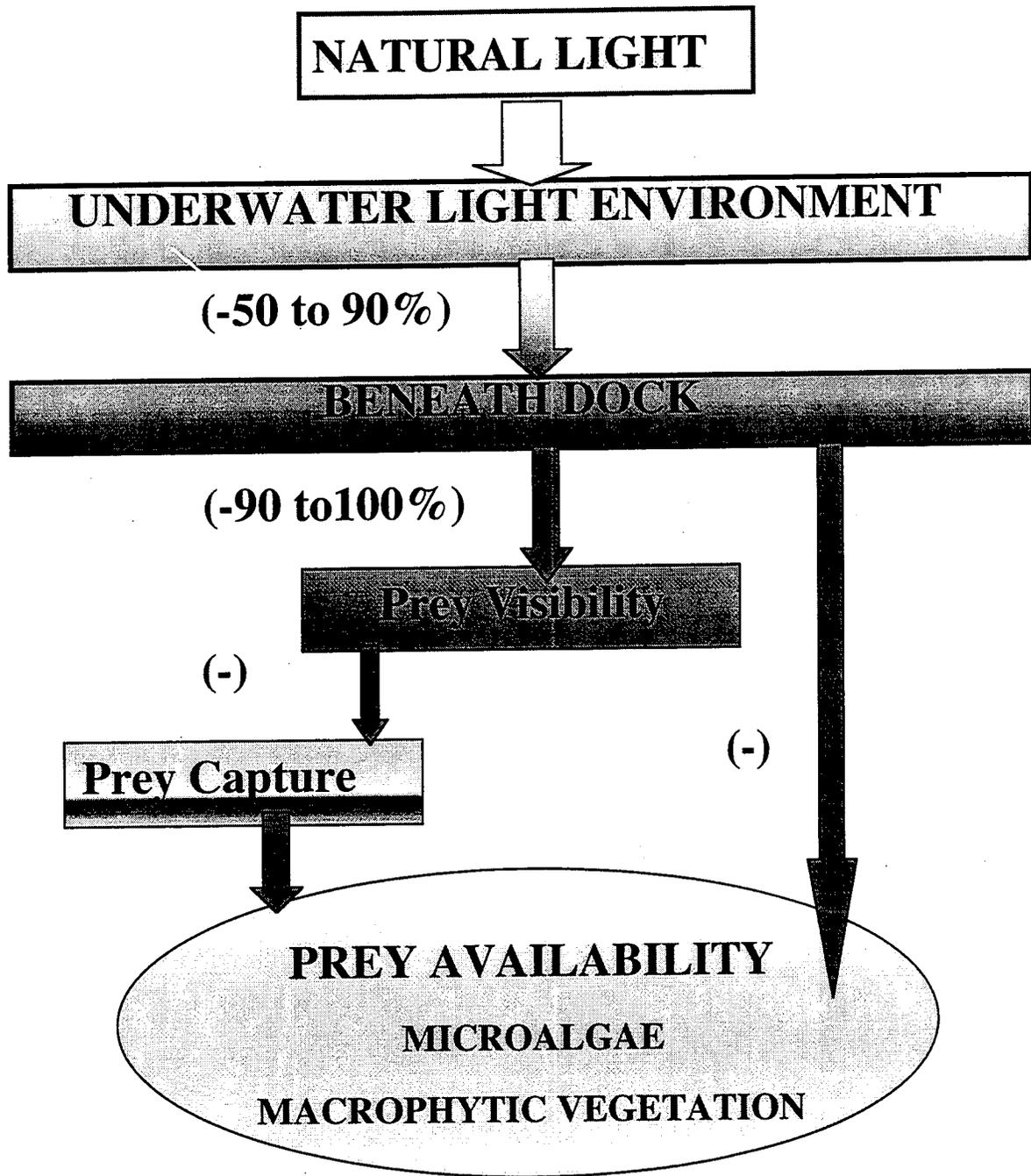


Figure 12. Conceptual diagram of the effects of over-water structures on aquatic light environment affecting primary and secondary production important to juvenile salmon habitat and prey resources.

impacts of dock shading upon eelgrass beds (Pentilla and Doty 1990; Burdick and Short 1995; Loflin 1993; Thom and Shreffler 1996). Ferry terminal impacts to light, eelgrass, benthic communities, and substrates have included decreased benthic vegetation, altered substrates, and altered benthic assemblages due to terminal construction, design, and operations (Thom 1995; Thom *et al.* 1995, 1997a, b & c; Olson *et al.* 1996b; Thom and Shreffler 1996). Shade modeling studies at Clinton Ferry Terminal support the notion that terminal design, specifically dock height, location, width, orientation, construction materials, and dock placement can mitigate these impacts (Olson *et al.* 1996 a & b).

Turbulence studies at Vashon and Anacortes Ferry Terminals have also demonstrated the effects of propeller wash turbulence or current velocity on plants, substrate surfaces, and bathymetry (Thom *et al.* 1996, Thom and Shreffler 1996). Depending on the depth zone and substrate composition relative to the position of the operating ferries (e.g., shallower and finer substrates are more prone to propeller wash disturbance), substrates become scoured and rearranged, eliminating the establishment of epiphytic algae and detrital food webs that provide food for epibenthic prey of juvenile salmon. Similarly, flume studies have demonstrated that beyond a current velocity threshold of 180 cm^{-1} (Thom *et al.* 1996) damage to eelgrass patches will result in continued sediment displacement. This disrupts and interferes with the growth of eelgrass beds, which require stable sediments for the establishment of their seedlings, root, and rhizome systems (Thom *et al.* 1995, 1996).

Predation

Despite considerable speculation about the effects of over-water structures increasing predation on juvenile salmon, evidence supporting this contention is

scientifically uncertain at best. Quantitative assessment of predation around over-water structures is meager. The limited state of knowledge about the relationship between over-water structures and predation is demonstrated by the paucity of existing empirical data. Various lists of "potential" predators have been circulating since the 1970s, but predation has been validated for only a few species in only a few cases (Table 2). In some cases, this list has grown absurdly to include species of fish (e.g., shiner perch, *Cymatogaster aggregata*; English sole, *Pleuronectes vetulus*) that are unreasonable candidates for predators (e.g., their mouth gape is typically too small to handle the smallest of juvenile salmon). In cases that have attempted to verify enhanced predation associated with over-water structures, such as Ratte (1985), predation has actually been shown to be relatively insignificant and limited to one or two species. Although several legitimate (e.g., with highly qualified observers) observations of predation events have been documented, few studies have actually validated the incidence with stomach contents of predators. In addition, the significance of predation to the migrating population has, to our knowledge, never been assessed empirically. No studies have examined the mortality specifically due to predation, much less that attributable to predators specifically associated with over-water structures.

While the present literature suggests that legitimate piscivorous fishes do not appear to aggregate by docks, no studies have addressed whether docks actually concentrate either piscivorous fishes, birds, or marine mammals. A more comprehensive evaluation of predation impacts will require exploration of predator responses to dock structures and dock effects, such as night-time artificial lighting, that might increase the

Table 2. Potential, observed, questionable, and validated predators of juvenile salmon.
 (Normal typeface = potential predators, double underline = validated by stomach contents or unambiguous observation; italicized = questionable.)

Fresh <i>et al.</i> (1978) [validated] ¹	Prinslow <i>et al.</i> (1982) ² [validated]	Ratte and Salo(1985) [validated]	Dames and Moore and Biosonics (1994) [not validated]	Taylor and Willey (1997) [not validated] ³	Pentec Environmental (1997) [not validated]
<ul style="list-style-type: none"> • spiny dogfish • ratfish • coho salmon • chinook salmon • cutthroat trout • rainbow (steelhead) trout • walleye pollock • copper rockfish • quillback rockfish • <u>Pacific staghorn sculpin</u>⁴ • Great sculpin • <i>cabezon</i> • rock sole • starry founder 	<ul style="list-style-type: none"> • spiny dogfish • <u>cutthroat trout</u>⁵ • chinook salmon • coho salmon • Pacific hake • "cottids" 	<ul style="list-style-type: none"> • cutthroat trout • rainbow (steelhead) trout • Dolly Varden • coho salmon • chinook salmon • Pacific cod • walleye pollock • Pacific hake • <i>Pacific tomcod</i> • prickly sculpin • Pacific staghorn sculpin • brown rockfish 	<ul style="list-style-type: none"> • cutthroat trout • rainbow (steelhead) trout • <i>Pacific tomcod</i> • Pacific hake • <i>buffalo sculpin</i> • great sculpin • Pacific staghorn sculpin • <i>shiner perch</i> • <i>striped perch</i> • <i>C-O sole</i> • <i>English sole</i> • rock sole • starry flounder 	<ul style="list-style-type: none"> • western grebe • belted kingfisher • red-breasted merganser • common merganser 	<ul style="list-style-type: none"> • "<u>cormorants</u>"⁶ • "40-cm salmonids"

1 validated by stomach contents analysis on all species in this list of potential predators

2 in Prinslow and Bax (Chap. 2)

3 no stomach contents analysis or otherwise unambiguous determination; observation only

4 stomach contents analysis: n=2, 50% (1/2) frequency; chum fry

5 stomach contents analysis: n=60, 3.3% (2/60) frequency; percent total Index of Relative Importance = 1.1%

6 unambiguous observation

exposure of juvenile salmon to potential predators. Studies have not examined likely predation situations (e.g., a high abundance of juvenile salmon passing under/around docks), and functional responses could account for short-term predation missed by episodic studies.

Over-water structures may act as catalysts of salmonid predation in the following ways:

- They could influence predator response to the relative availability of juvenile salmon:
 - numerical responses, in which predator densities increase relative to increased prey (salmon) availability
 - functional response, involving increased presence of prey in individual predators' diets because of changes in their availability as prey.
- They could increase the vulnerability or exposure of juvenile salmon to potential predators by doing the following:
 - providing habitat for predators next to existing refugia for migratory juvenile salmonids, such as eelgrass beds
 - reducing refugia such as eelgrass
 - focusing/concentrating salmon exposure to predators by diverting juveniles into deeper waters along the offshore edge of docks (i.e., migration route alteration)
 - changing prey detection (e.g., functional response distance) by altering light and turbidity.

SUMMARY CONCLUSIONS AND RECOMMENDATIONS

Fry of ocean-type salmon, and particularly juvenile chinook salmon, appear to prefer to migrate along the edges of refugia such as eelgrass, dark areas, or turbid zones. They will not necessarily penetrate these refugia unless startled (as a flight response) or at night (without lights). Delayed migration of salmonids seems to happen when fish are confronted with conflicts regarding their preferences for eelgrass, dark areas, night lighting, or turbid zones. But differences in behavioral responses of individual fish may be, in part, a function of juvenile salmon school size. The consequences of delayed migration are unknown but are commonly assumed to be detrimental.

Lists of "potential predators" on juvenile salmonids are questionable and have propagated through the literature predominately without validation. No studies have addressed whether docks actually concentrate "potential predators," much less actual predators (fish or birds). Studies to date have not examined likely predation situations (e.g., when a high abundances of juvenile salmon is passing under/around docks, and functional response could account for short-term predation missed by episodic studies).

Predicting the impacts of dramatic changes to an organism's natural environment requires a mechanistic understanding of the organism's behavioral cues and responses, as well as the ecological costs involved in alternative responses. While several scientific studies have consistently documented the impacts of over-water structures on fish fauna (e.g., Burdick and Short 1995; Able *et al.* 1998), the mechanisms of impact to fish production are often complicated and poorly understood. In the case of understanding the potential impact of over-water structures such as ferry terminals, we must be able to predict the outcome of behavioral responses to conflicting behavioral mandates, e.g., with

an empirical model that establishes thresholds and the priority of over-riding factors.

Such predictive capability needs to incorporate at least three factors:

- the strength of the behavioral response, which in the case of juvenile ocean-type salmon we attribute to size and ontogeny
- quantitative relationships among the attributes of over-water structures, their associated activities (e.g., ferry traffic), and the environmental cues to which juvenile salmon are responding
- the mitigating effects of environmental variability.

On the basis of the Phase I analyses, the research team concluded that

- Ocean-type juvenile salmon prefer to migrate in shallow water along the edges of refugia, such as eelgrass, dock shadows, turbid zones.
- Schools of salmon fry and fingerlings disperse upon encountering docks.
- However, they are attracted to under-dock lights at night and to prey resource areas.
- Delays in migration direction occur when juveniles are confronted with conflicts in preferences.
- Few technical data substantiate that shoreline structures aggregate predators, although some conditions (e.g., artificial lighting around docks at night) need to be investigated further.

We acknowledge that we are lacking conclusive evidence of adverse outcomes (e.g., decreased marine mortality) from such conflicts in juvenile salmon behavioral preferences that may be caused by over-water structures. However, the conspicuous behavior of migrating salmon fry implies strong natural selection that we can assume has

been driven by vulnerability to predation. This assumption remains to be tested scientifically.

The workshop participants identified the need for better conceptual models of both fish and aquatic plant responses to light relative to the variability in shoreline structure environments, as well as the need to recognize diel effects on over-water structure impacts on juvenile salmon.

Accordingly, we recommend the following initiatives to generate a more predictive understanding of the impacts of over-water structures and how they may be designed or modified to reduce or eliminate impacts:

- *Need to integrate controlled field and laboratory experiments to gain a predictive understanding of juvenile salmon responses.*

To our knowledge, the behavioral responses to shoreline structures by migrating juvenile salmon have not been examined in laboratory or controlled field experiments. The rigor required to determine whether there is a risk in behavioral changes requires more than anecdotal observational study. Large-scale repeated mark and recapture experiments should be reconsidered to effectively test juvenile responses to ferry terminals under representative conditions.

- *Controlled laboratory experiments should be designed to incorporate both physiological capability and behavioral factors.*

The scope and design of field experiments should match natural field conditions, including lighting and other (e.g., substrate, macrophytes, food availability) environmental conditions. Experiments should assess the strength and predictability of responses relative to both the characteristic of the cue and the

behavioral history of the fish, as well as the interaction of the two. The effects of mitigation approaches, such as reducing shade frequency or intensity (contrast), should also be incorporated into experiments so that appropriate approaches can be incorporated into ferry terminal design and operations.

- *Controlled field experiments should use the natural variability in ferry terminals and settings to explore their effect on responses by migrating juvenile salmon.*

Rigorous mark-recapture, "input-output" type experiments should be conducted to rigorously assess both behavior and consequences (e.g., survival, food consumption) of juvenile salmon that encounter ferry terminals during migration.

Variability in dock structure and ferry operations, environmental setting, and seasonal and artificial lighting effects should all be considered.

- *Effects of artificial lighting need to be incorporated into studies and experiments.*

The effects of artificial lighting from shoreline structures on migrating juvenile salmon, including the attraction of predators, has also not been effectively evaluated. The effects of artificial lighting should be built into the mark and recapture studies and should be designed to study night lighting.

- *Individuals and schools of salmon should be tracked in real time to assess short-term variability in juvenile salmon responses.*

Advanced technology (microtags, hydroacoustics, remote/diver video) should be used to capture individual/school behavior of salmon, especially relative to full-scale terminal "experiments" such as changes in artificial light presence/absence or intensity.

4—PRELIMINARY FINDINGS OF DIVING AND LIGHT SURVEYS

In preparation for the second workshop in August 1998, BMSL scientists conducted diving and light surveys at five ferry terminals. The objective was to gather preliminary data and underwater video to document the existing light environment and biological communities associated with ferry terminals of different sizes, ages, and construction materials. Below are summarized the findings of the diving and light surveys that were presented at the workshop.

METHODS

Diving and light surveys were conducted from August 10 to 14, 1998, at five ferry terminals: Port Townsend, Clinton, Kingston, Seattle, and Vashon. These five terminals were selected to span the geographic range of locations serviced by WSDOT ferries (Figure 13). We developed a decision matrix for selecting candidate terminals for our underwater diving and light surveys from among the twenty WSDOT ferry terminals (Table 3). Our decision criteria included WSDOT's expansion and retrofit priorities, proximity to chum and chinook stocks being considered for listing under the Endangered Species Act (ESA), terminal design (length, width, height, piling material), presence or absence of eelgrass, and shoreline development near the terminals. We excluded the terminals in the San Juan Islands from consideration because WSDOT has no immediate expansion or retrofit plans at these terminals and because there no potential ESA stocks have been identified for this region. Our rationale for selecting the five terminals are summarized below:

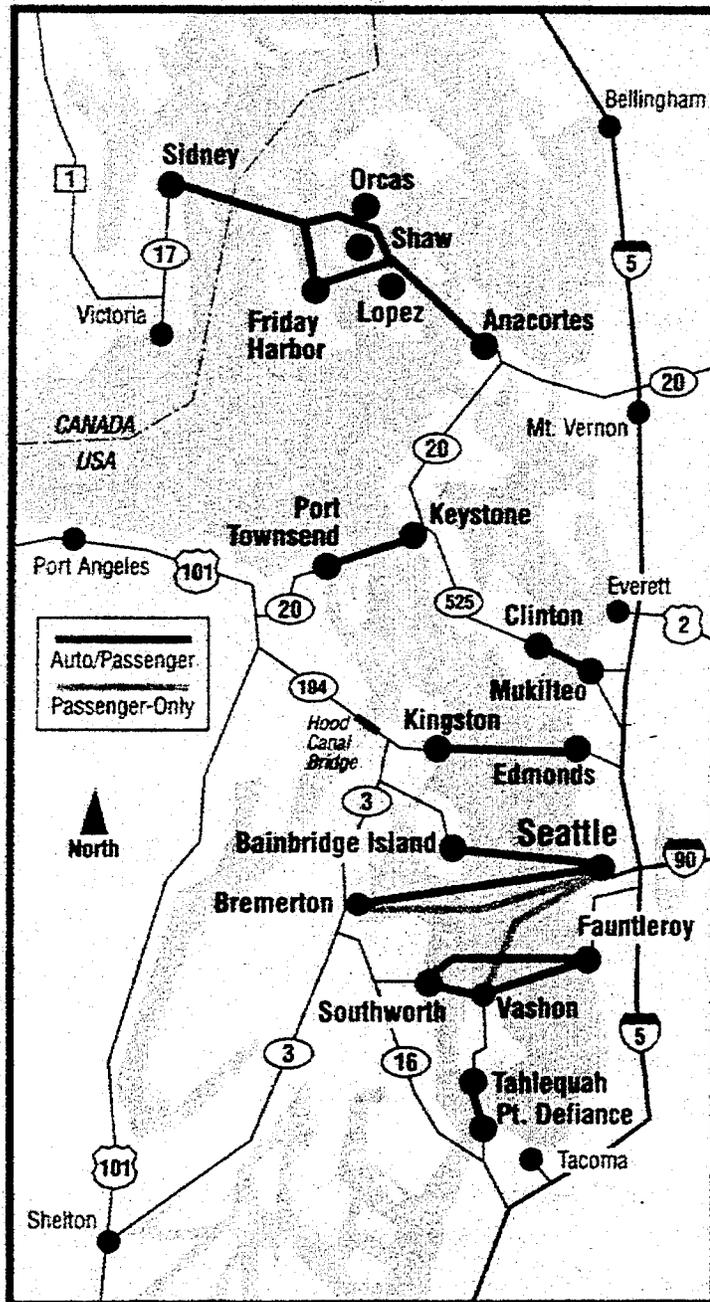


Figure 13. Route map and terminal locations for the Washington State ferry system

Table 3. Decision matrix for prioritizing WSDOT ferry terminals for diving and light surveys.

Terminals	WSDOTs Expansion/ Retrofit Priority	Proximity to ESA species (a)	Length (m)	Width (m)		Height Above 0 MLLW	Piling Material	Eelgrass Present?	Shoreline Development (b)
Point Defiance		Puyallup spring chinook (C)					timber?	?	?
Tahlequah		Puyallup spring chinook (C)					timber?	?	?
Vashon			250main 300pass	35 18.5 base	4.6		timber	yes	low
Southworth	x		163	15.7	5.3		timber	yes	low
Fauntleroy							timber	yes	low
Bremerton			90	14/8/22/160			concrete	no	heavy
Seattle	x		190	> 200	5.3		timber & concrete	no	heavy
Bainbridge	x						timber	?	moderate
Edmonds		Lake Washington chinook (unk)					timber	yes	moderate
Kingston	x	Lake Washington chinook (unk)	105	9.5 slip 1 17.3 slip 2	5.2		concrete	yes	moderate
Mukilteo		Snohomish fall & summer chinook (D)					timber	yes	moderate
Clinton	x	Snohomish fall & summer chinook (D)	130	31.5	4.2		timber	yes	moderate
Port Townsend		Hood Canal summer chum (C)		44.7	3.9		concrete	yes	moderate
Keystone		Hood Canal summer chum (C)					timber	no	moderate
Anacortes		Skagit chinook stocks (D)					timber	yes	low
Lopez									
Friday Harbor									
Shaw									
Orcas									
Sidney, BC									

(a) stock status codes: unk = unknown; D = depressed; C=critical

(b) development codes: heavy =both shorelines adjacent to terminal developed; moderate = 1 shoreline developed; low=neither shoreline developed

- Port Townsend terminal
 - potential ESA issues with Hood Canal summer chum salmon
 - concrete-pile construction
 - moderate shoreline development adjacent to the terminal.
- Clinton terminal
 - expansion priority for WSDOT
 - wealth of existing studies and data to draw upon (Simenstad *et al.* 1997)
 - potential ESA issues with Snohomish River fall and summer chinook
 - timber-pile construction.
- Kingston terminal
 - WSDOT retrofit priority
 - concrete-pile construction
 - potential ESA issues with Lake Washington chinook.
- Seattle terminal
 - heavy shoreline development adjacent to terminal
 - combination of concrete- and timber-pile construction
 - busiest of the 20 terminals
 - one of the longest and widest terminals.
- Vashon terminal
 - low shoreline development
 - timber-pile construction
 - one of the least busy terminals.

In addition, all of these terminals have eelgrass nearby, with the exception of the Seattle terminal.

Diving Surveys

The objective of the diving surveys was to characterize the environment underneath the five selected terminals. We performed these characterizations using two methods: underwater video and diver observations. At each terminal, we recorded underwater video along two transects. We filmed along one transect underneath the middle of each terminal or floating dock from offshore to the beach. Then, we filmed along a second transect perpendicular to the main axis of the over-water structure. The perpendicular transect at each terminal was the same transect used for the diver-assisted underwater light profiles (described below in the methods for the light surveys). Divers used a Sony™ Hi-8mm video camera in a waterproof housing equipped with strobe lights.

The primary focus of our underwater surveys was to film and record observations of the fish community, especially potential predators of juvenile salmon. Along these transects, divers also recorded observations of the following:

- the piling community
- substrate
- qualitative estimates of light availability
- presence/absence of eelgrass or macroalgae
- physical disturbances of ferry operations (e.g., scouring, debris piles).

Light Surveys

We collected light data with a LI-COR LI-1000 data logger that had a LI-COR LI-193SA spherical quantum sensor to measure photosynthetically active radiation (PAR). We recorded measurements by hand, once the readings displayed on the LED display screen of the data logger had stopped fluctuating. We used three methods for surveying the light environment around and underneath the five terminals.

The first method was to position the PAR sensor near the offshore end of each dock. We then conducted vertical light profiles in the water column at this position to determine the amount of light attenuation at each dock. For these profiles, we positioned the light sensor and recorded light readings just above the surface of the water and every 0.5 m down through the water column until the light was below $50 \mu\text{Ms}^{-1}\text{m}^{-2}$ or the sensor was on the sea floor. In addition, we took measurements when a ferry was docking or departing to get an estimate of the amount of light reduction caused by the propeller wash.

For the second method, a diver team swam the PAR sensor along a transect perpendicular to, and underneath, each dock. The divers started the transect 10 m out from the dock and continued under the dock to 10 m on the opposite side. We recorded light readings at the 10-m point, at the edge of the dock, approximately every 5 m under the dock, the opposite edge, and 10 m on the opposite side. At each collection point, we positioned the light sensor and took light readings just above the surface, just below the surface, at the mid-point of the water column, and on the bottom.

The third method was to walk the PAR sensor underneath a dock, along a transect perpendicular to the dock at the upper tidal elevation of the beach. We only used this

third method at low tide, when enough head clearance was available to safely walk upright underneath a terminal. We did walking transects at Clinton and Vashon (see photos, Figure 14).

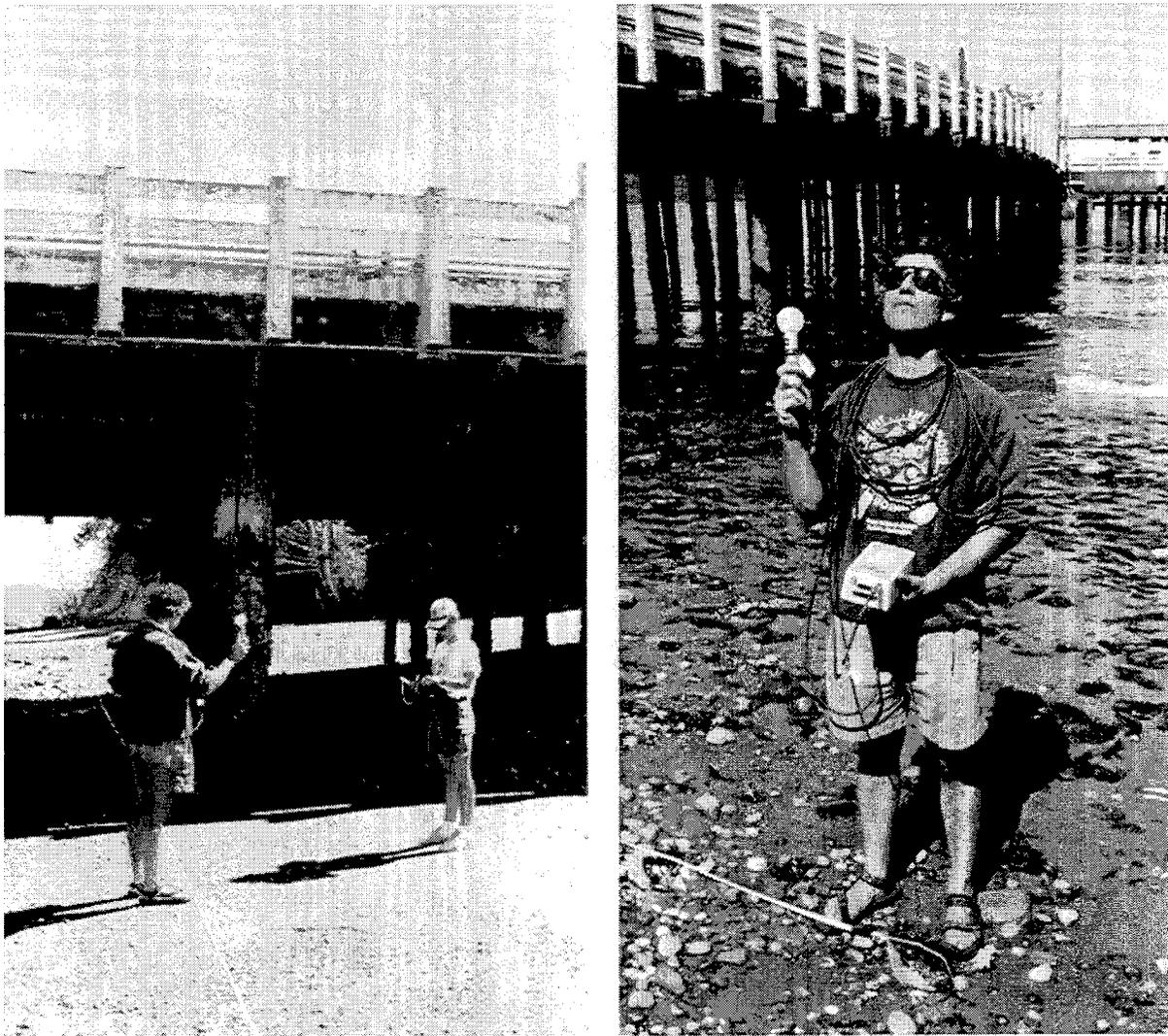


Figure 14. Photos showing our methods for recording measurements of photosynthetically active radiation (PAR) along the beach at one of the WSDOT ferry terminals, August 1998.

The exact locations of our diving and light transects are indicated in the figures of each terminal: Port Townsend (Figure 15), Clinton (Figure 16 a and b), Kingston (Figure 17), Seattle (Figure 18), and Vashon (Figure 19 a and b).

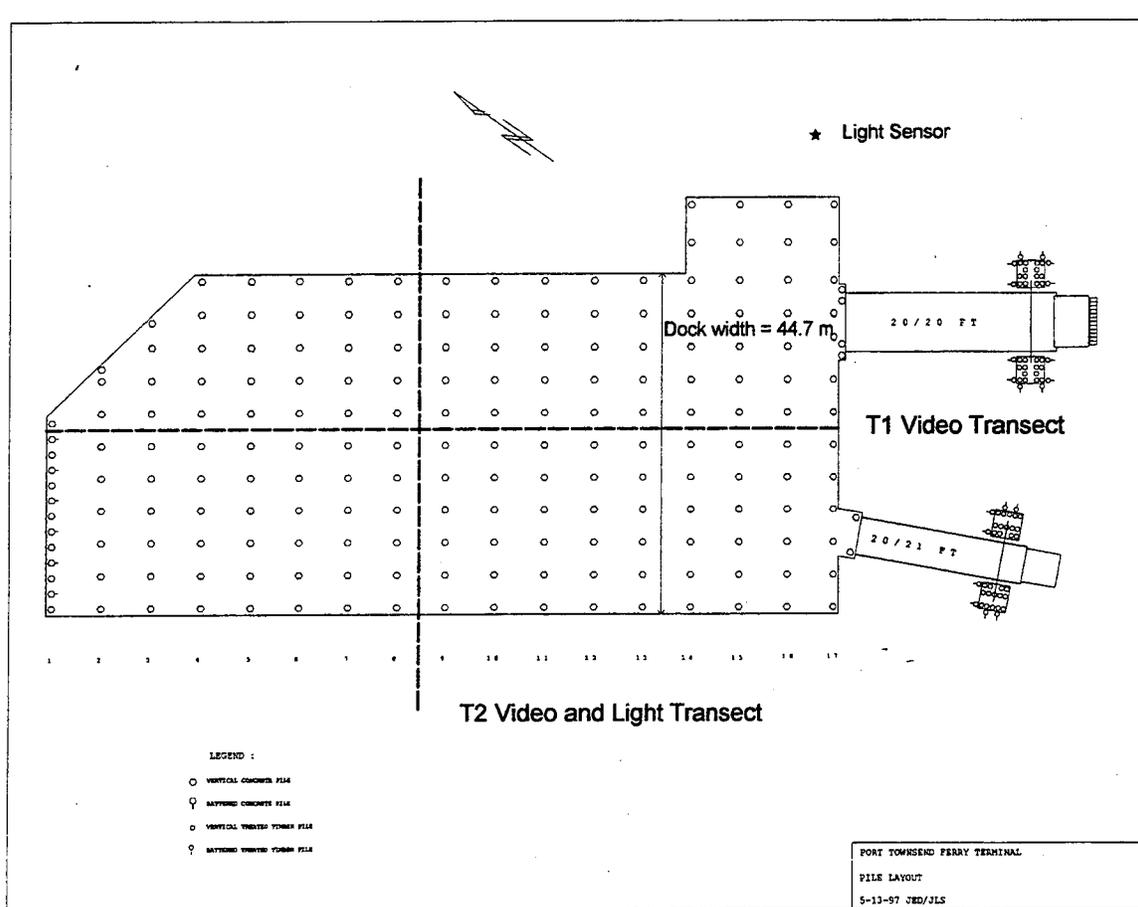
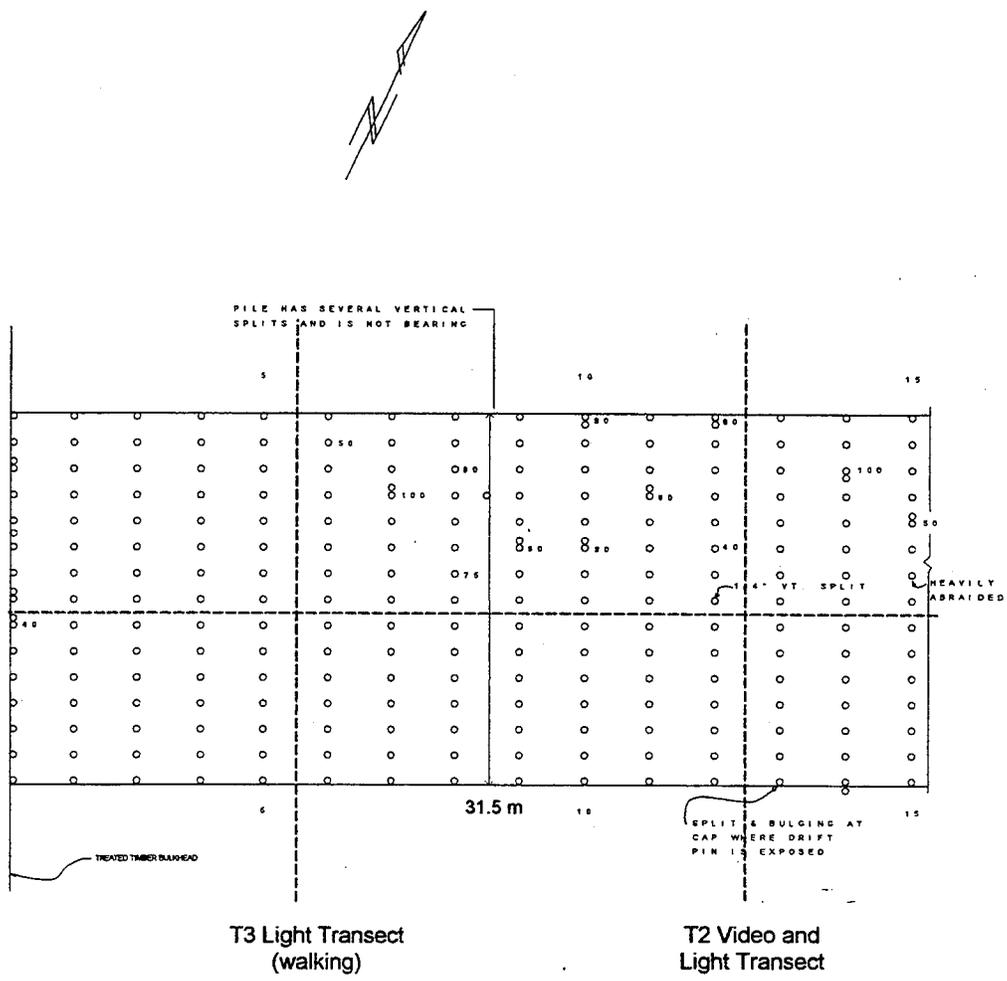


Figure 15. Diving and light transects at the Port Townsend ferry terminal, August 1998.



- LEGEND:
- VERTICAL TREATED TIMBER PILE
 - ◐ DAMAGED TREATED TIMBER PILE
 - ⊖ DAMAGED TIMBER PILE PER 1980 DIVING REPORT

CLINTON FERRY TERMINAL
 PILE LAYOUT
 3-5-87 JED/XLS 1 of 2

Figure 16a. Diving and light transects at the Clinton ferry terminal, August 1998 (1 of 2).

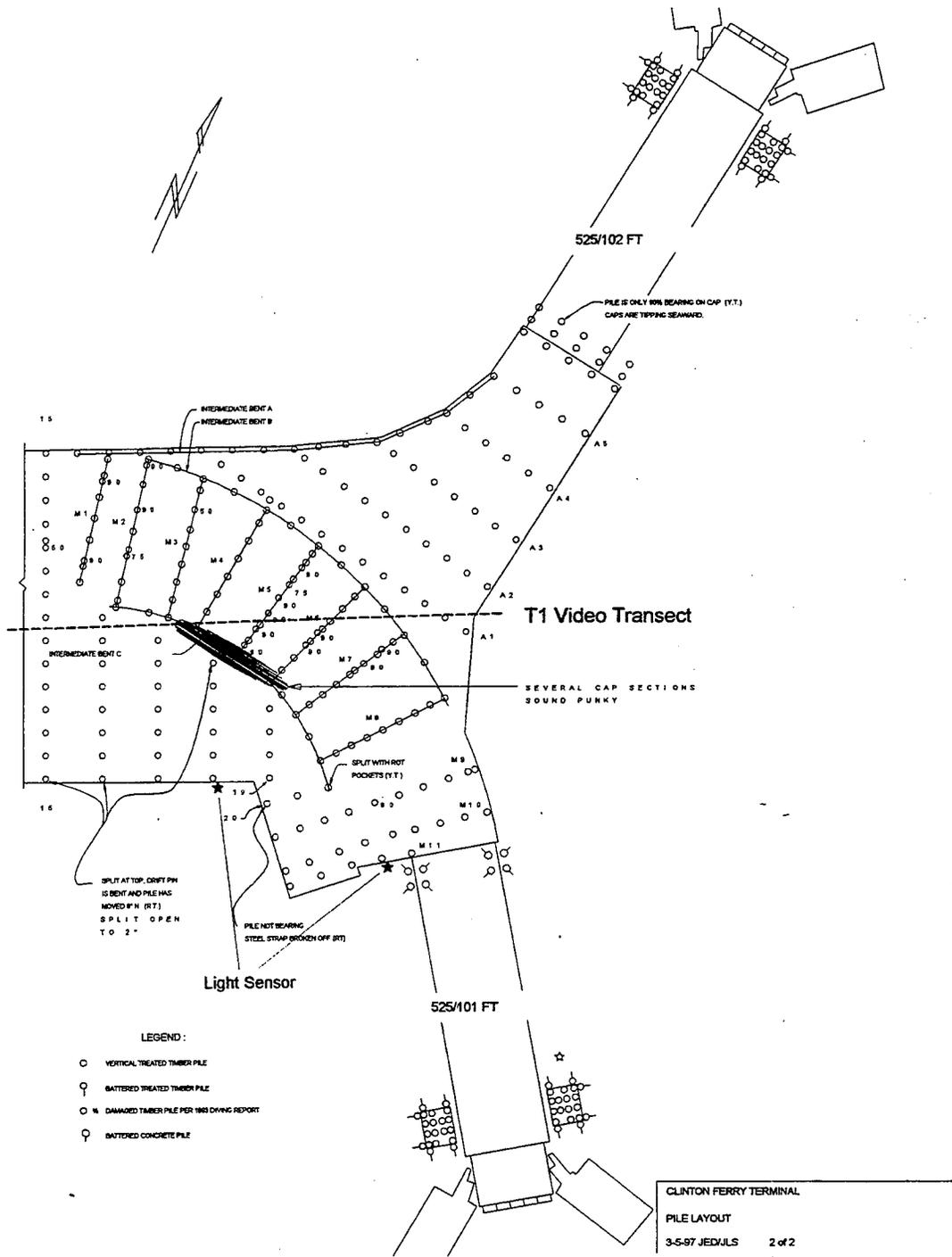


Figure 16b. Diving and light transects at the Clinton ferry terminal, August 1998 (2 of 2).

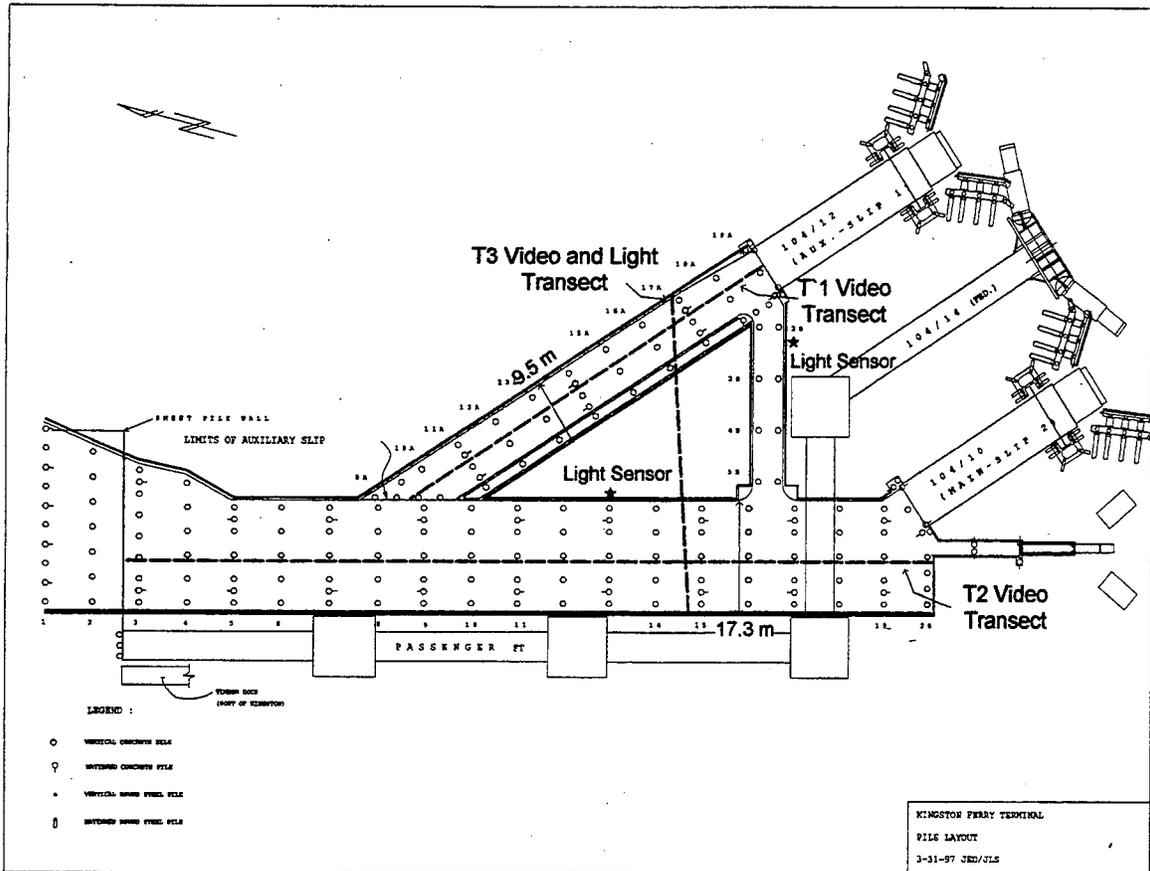


Figure 17. Diving and light transects at the Kingston ferry terminal, August 1998.

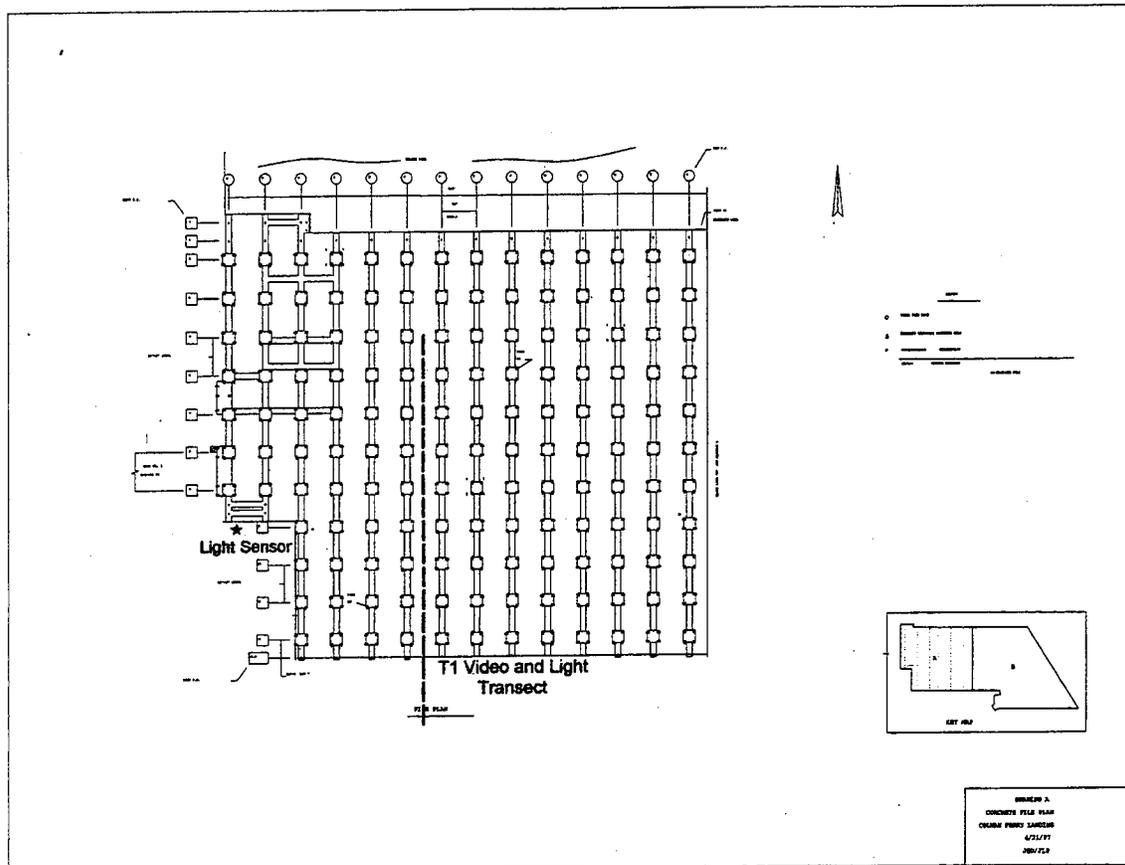


Figure 18. Diving and light transects at the Seattle ferry terminal, August 1998.

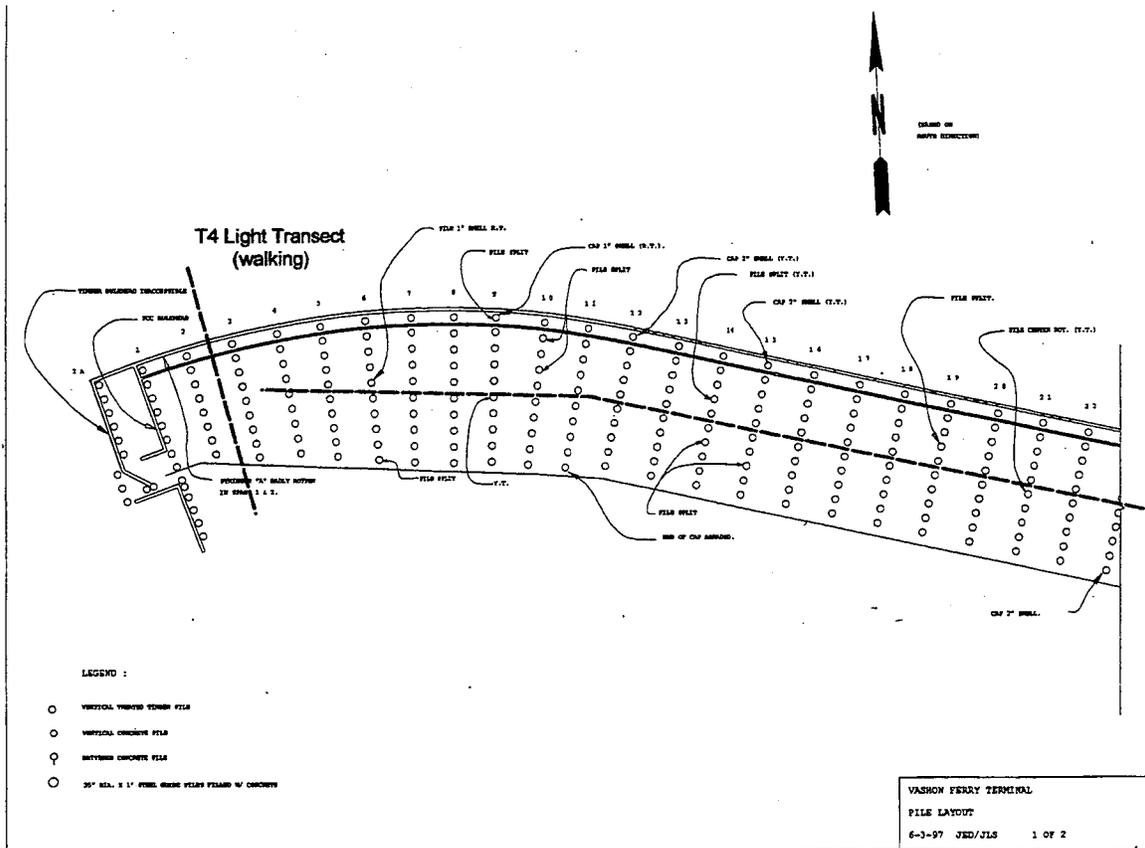


Figure 19a. Diving and light transects at the Vashon ferry terminal, August 1998 (1 of 2).

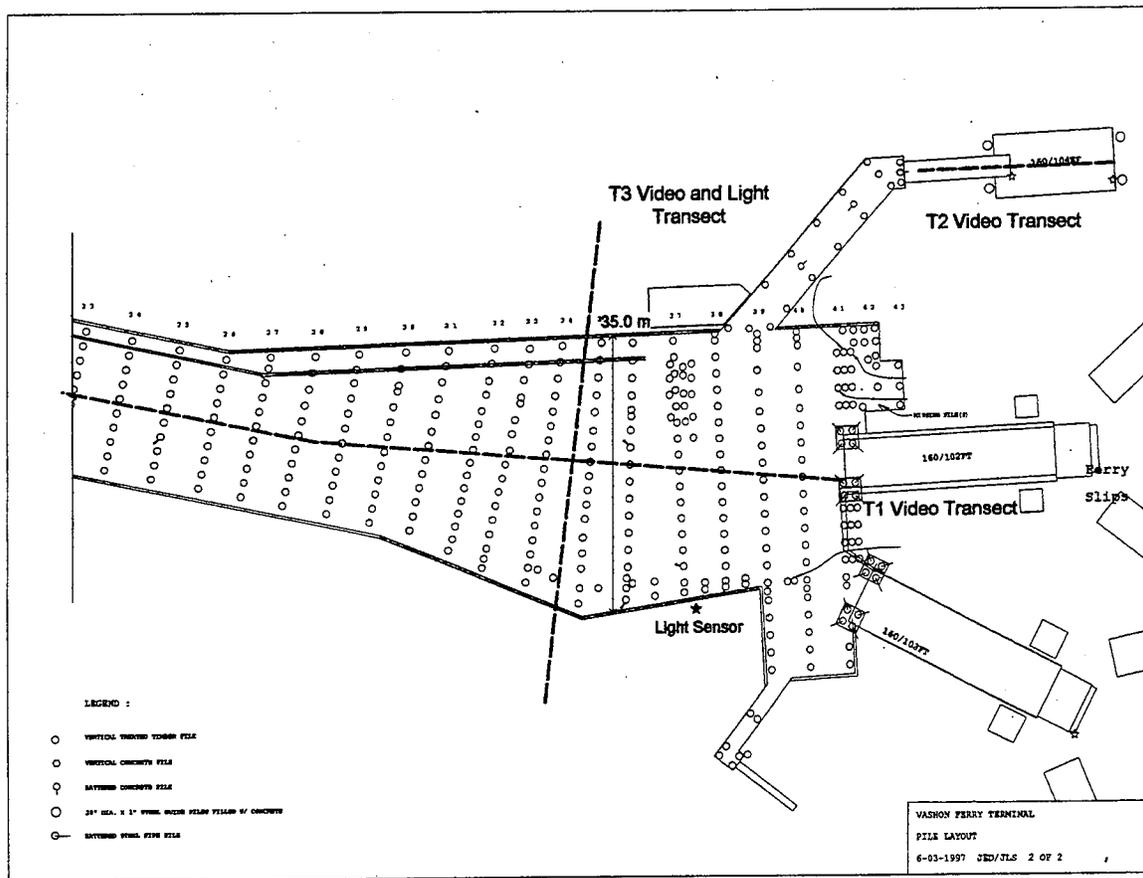


Figure 19b. Diving and light transects at the Vashon ferry terminal, August 1998 (2 of 2).

RESULTS

Diving Surveys

We recorded nearly four hours of underwater video at the five terminals. At the August 25, 1998, workshop, we presented a condensed, 15-minute highlights film. This film was carefully edited to show

- the differences in the piling communities, substrate, and light availability among the five terminals
- juvenile salmon behavior underneath the Kingston terminal
- potential predators of juvenile salmon observed at the five terminals.

The species of fish we observed during our underwater surveys are summarized for each terminal in Table 4. We grouped these species into different categories:

- common and abundant species found under three or more of the five terminals and represented by 20 or more individuals
- common and moderately abundant species found under two of the five terminals and represented by 10 to 19 individuals
- common but not abundant species found under two of the five terminals and represented by 5 to 10 individuals
- uncommon and not abundant species found under only one of the five terminals and represented by <5 individuals
- uncommon but abundant species found under only one of the five terminals and represented by >20 individuals.

Table 4. Summary of fish species we observed during our underwater surveys at five ferry terminals in August 1998.

FISH SPECIES OBSERVED UNDER FERRY TERMINALS	FERRY TERMINAL				
	P.T.	Clinton	Kingston	Seattle	Vashon
Common & Abundant					
shiner perch	x	x	x		x
pile perch		x	x		x
sanddab (Pacific & speckled)		x	x		x
unidentified flatfish (juv.)	x	x	x		
unidentified sculpins	x	x	x	x	x
English sole	x	x			x
saddleback gunnel		x	x		x
Common & Moderately Abundant					
striped perch		x			x
copper rockfish		x			x
Chinook salmon (smolts)			x		x
ratfish				x	x
Common but Not abundant					
buffalo sculpin	x				x
kelp greenling (juv)	x	x			
snake prickleback		x			x
Uncommon & Not Abundant					
chinook salmon (blackmouth)			x		
Pacific staghorn sculpin					x
great sculpin					x
cabezon					x
grunt sculpin	x				
C-O sole		x			
six or seven-gill shark?				x	
Uncommon but Abundant					
tubesnout					x
Species Totals	8	12	7	3	16

The most common and abundant species we observed at all the terminals, with the exception of Colman Dock at Seattle, was shiner perch (*Cymatogaster aggregata*). Shiner perch were ubiquitous in all environments we surveyed, regardless of the

presence/absence of eelgrass, substrate type, or light availability (e.g., under terminal vs. not under terminal). Other common and abundant species that we observed under at least three of the five terminals included pile perch (*Damalichthys vacca*), sanddabs (*Citharichthys* spp.), unidentified flatfish (Bothidae and Pleuronectidae), unidentified sculpins (Cottidae), English sole (*Pleuronectes vetulus*), and saddleback gunnels (*Pholis ornata*). We also observed several species that were common but only moderately abundant. These species included striped perch (*Embiotoca lateralis*), copper rockfish (*Sebastes caurinus*), chinook salmon smolts (*Oncorhynchus tshawytscha*), and ratfish (*Hydrolagus colliei*).

We reorganized the fish species listed in Table 4 according to their likelihood of being predators on juvenile salmon. In Table 5, we list "confirmed predators," "potential predators," "questionable predators," and "not predators" that we observed during our August 1998 diving surveys. Confirmed predators are species that have been documented in the literature with juvenile salmon in their gut contents. Potential predators are species that have been videotaped, photographed, or otherwise reported (based on unambiguous observations) to prey on juvenile salmon. Questionable predators are species that have been suggested to prey on juvenile salmon on the basis of anecdotal reports but no stomach analyses or unambiguous observations. Not predators are species that have never been documented, observed, or suggested to prey on juvenile salmon. Of the fish species we observed at all five terminals, only the Pacific staghorn sculpin (*Leptocottus armatus*) is a confirmed predator of juvenile salmon. We observed two staghorn sculpins at the Vashon terminal. Potential predators that we observed

include chinook salmon (smolts), chinook salmon (blackmouth), copper rockfish, great sculpin (*Myoxocephalus polyacanthocephalus*), and ratfish.

Table 5. Summary of predators on juvenile salmon observed during our underwater surveys at five WSDOT ferry terminals in August 1998.

PREDATORS ON JUVENILE SALMON	FERRY TERMINAL				
	P.T.	Clinton	Kingston	Seattle	Vashon
Confirmed Predators					
Pacific staghorn sculpin					2
Potential Predators					
chinook salmon (smolts)			5		2
chinook salmon (blackmouth)			6		
copper rockfish		1			5
great sculpin					1
ratfish				2	10
Questionable Predators					
cabezon					1
shiner perch	>100	>100	>100		>100
striped perch		~10			~10
C-O sole		1			
English sole	<5	<5			<5
buffalo sculpin	1				1
Not Predators					
sanddabs (Pacific/speckled)	x	x	x		x
unidentified flatfish (juv.)	x	x	x		
unidentified sculpins	x	x	x	x	x
grunt sculpin	x				
kelp greenling (juv.)	x	x			
pile perch		x	x		x
saddleback gunnel		x	x		x
tubesnout					x
snake prickleback		x			x
six or seven-gill shark?				x	

Light Surveys

Vertical light profiles at six WSDOT ferry terminals and the Battelle Marine Sciences Laboratory dock in Sequim Bay showed a typical pattern of light attenuation with depth (Figure 20). Divers noted very clear water at the Vashon Terminal site, which was verified by the light profile data. For example, at a depth of -3m, photosynthetically active radiation (PAR) was greatest at Vashon Terminal and least at the MSL dock in Sequim Bay. Attenuation is greatest in water that has either higher plankton biomass and/or suspended particulate matter. Attenuation must be considered when the effects of light reaching under the terminals are interpreted. That is, a site that has greater average attenuation will have less light available under the terminal than a site that has less average attenuation.

The typical effects of a terminal on PAR are illustrated in the horizontal light profile data from Clinton Terminal (Figure 21). PAR decreased dramatically moving from outside the terminal to under the terminal deck. PAR did penetrate further under the terminal on the south side, and there was a shading effect on the north side of the terminal. Hence, along with attenuation, the orientation of the terminal is another important determinant of light available under the terminal.

The combined effect of a terminal deck and attenuation on PAR is illustrated with data from Kingston Terminal (Figure 22). Of note in this figure is that even the fishing pier (approximately 4m wide) reduced light, although not as greatly as the other wider terminals. In general, light at a -3.0-m depth was less than that at a -1.5-m depth. However, the southwest edge of the south terminal had greater light at the deepest depth. Divers noted that the angle of the sun at the time of the survey caused shading in the

upper part of the water column but not near the bottom. This indicates that sun angle, along with attenuation and dock orientation, is another factor that affects light regimes under terminals.

LIGHT PROFILES (10-13 Aug. 1998)

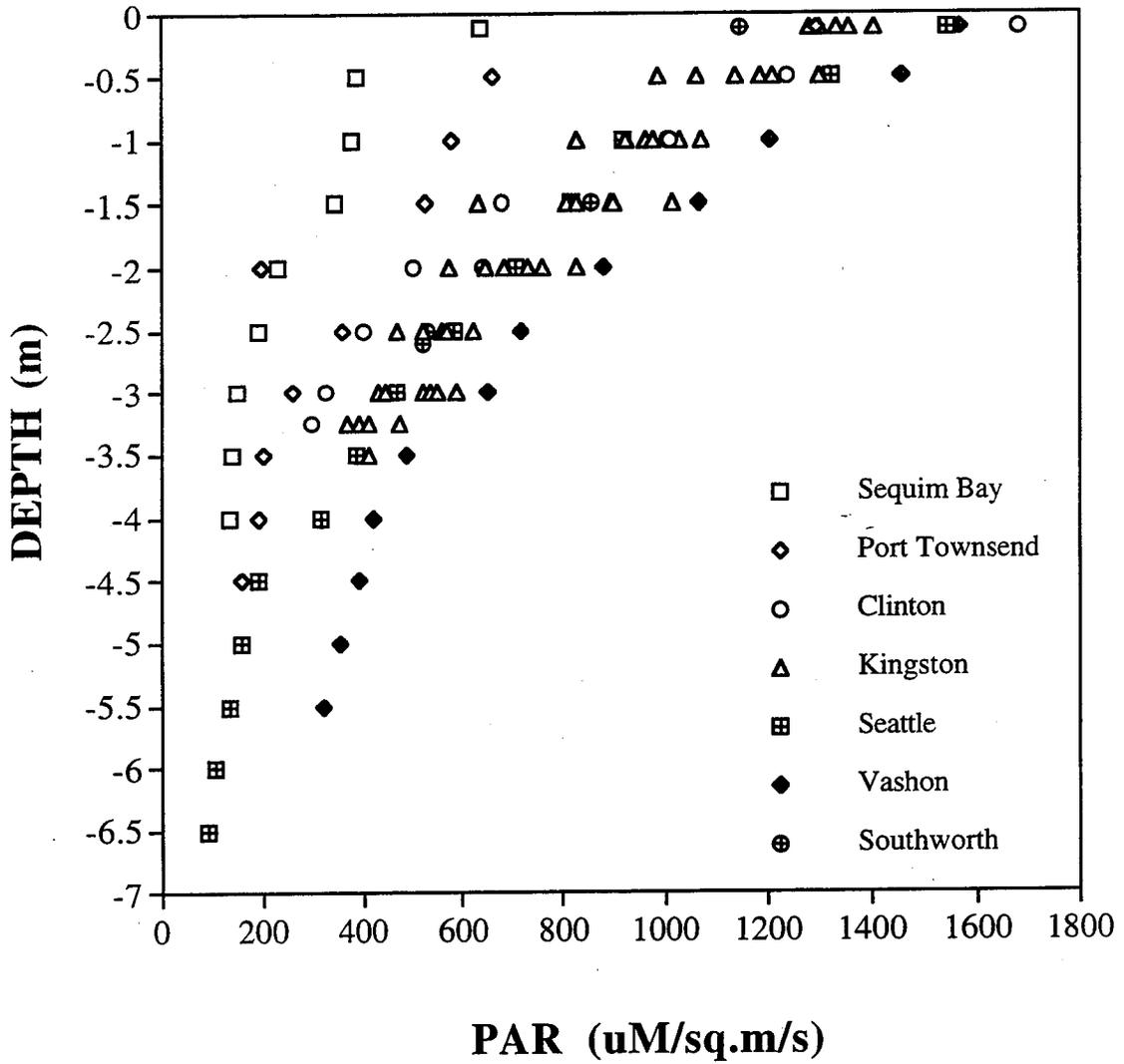


Figure 20. Light attenuation profiles at six WSDOT ferry terminals and one dock (Sequim Bay) collected at mid-day.

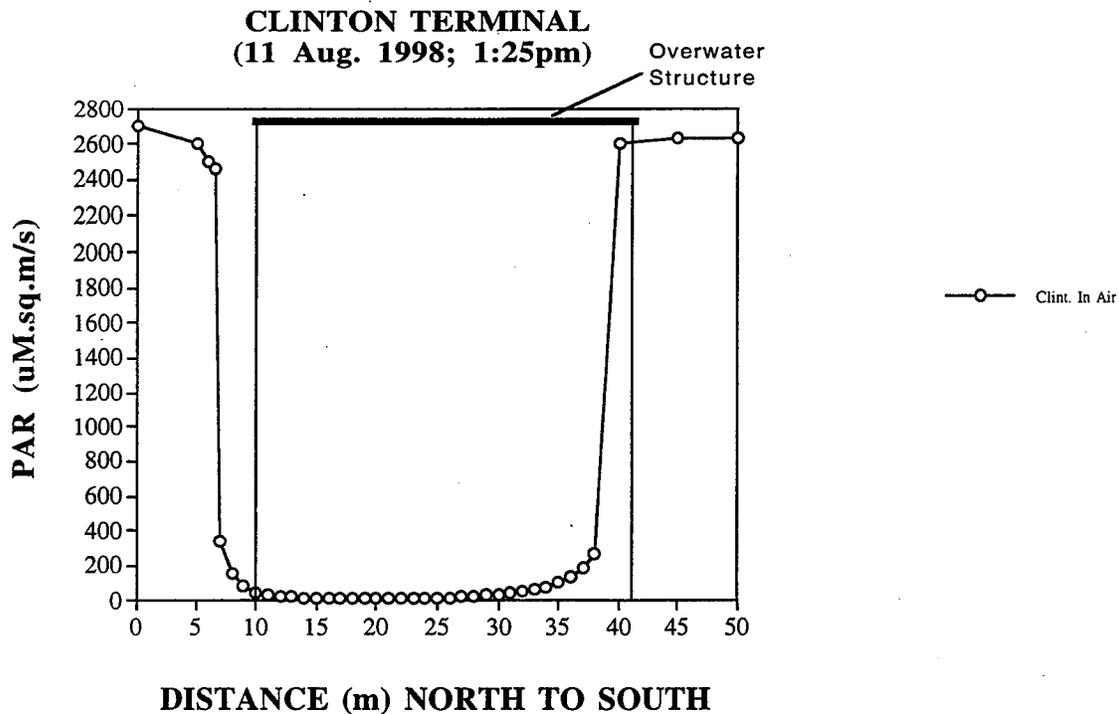


Figure 21. PAR in air under the Clinton Terminal.

To relate the light measurements we took to levels associated with fish behavior, we used the data from Ali (1959) shown in Figure 23. The light data are given in foot candles (ft-c) as opposed to PAR. These data provide threshold levels for juvenile salmon in the laboratory that we expect are related to juvenile salmon behavior patterns at ferry terminals. For example, Ali found that school dispersal occurs at or below 10^{-4} ft-c. The threshold for maximum feeding activity is between 10^{-1} and 1 ft-c. Using conversion factors between ft-c and PAR provided by LI-COR, we related the PAR measurements we took at the terminals to Ali's threshold levels shown in Figure 23 (Figure 24). Figure 24 shows that above approximately 0.5 PAR, alterations in juvenile salmon behavior were not observed.

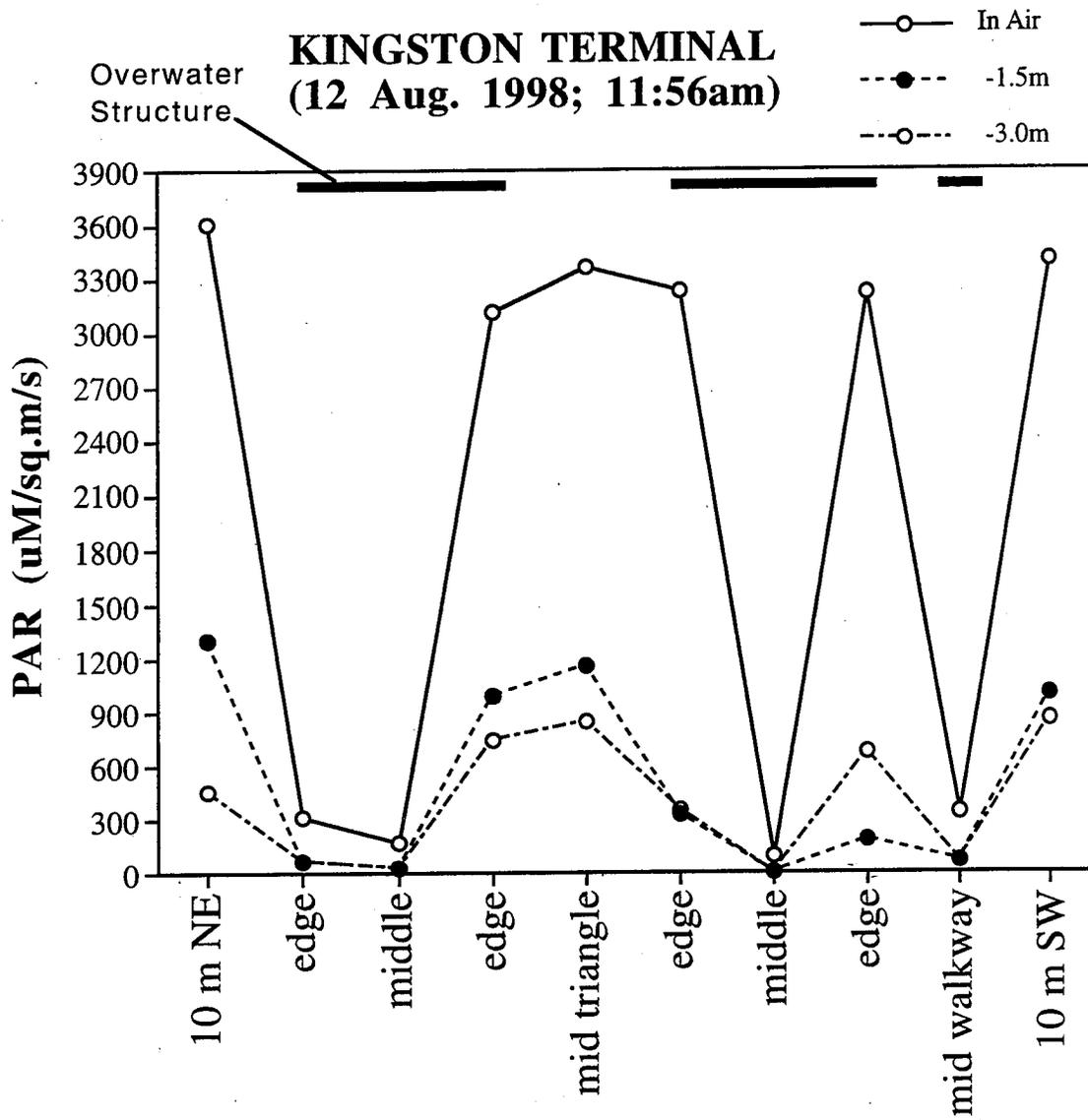


Figure 22. PAR in air and at two water depths at the Kingston Terminal.

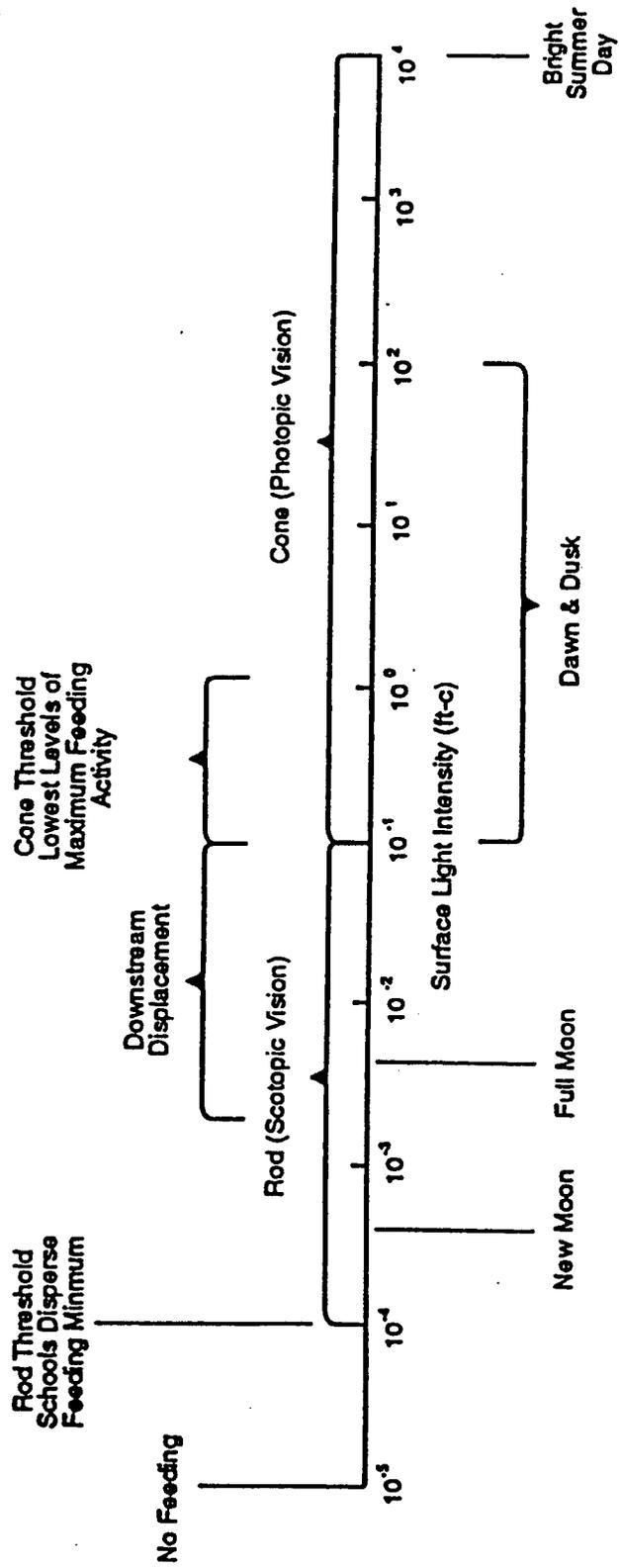


Figure 23. Plot of juvenile salmon behavior versus light level (from Ali 1959).

RELATIONSHIP BETWEEN FOOT CANDLES AND PAR

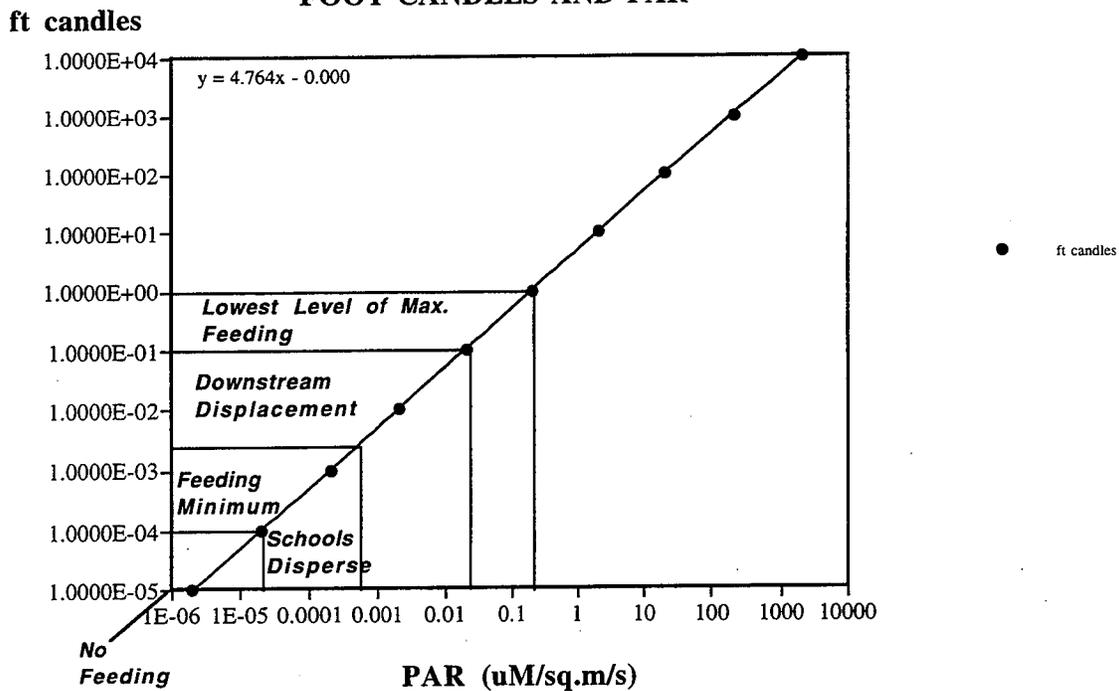


Figure 24. Relationship between ft-c and PAR and fish behavior. Thresholds are based on Figure 23.

We examined the minimum light level recorded during our surveys at the terminals. In Figure 25 we present a plot of light measured at the Seattle Terminal, which emphasizes the minimum PAR values (i.e., 2 μM). What this plot shows is that, between the third and fifth piling in from the outer edge of the terminal, PAR falls to 1 μM and below. Further underneath the terminal PAR is at 0.5 μM or below. Hence, according to the data in Figure 24, juvenile salmon underneath the Seattle terminal would be dispersed and unable to feed.

SEATTLE TERMINAL (12 Aug., 1998; 4:40pm)

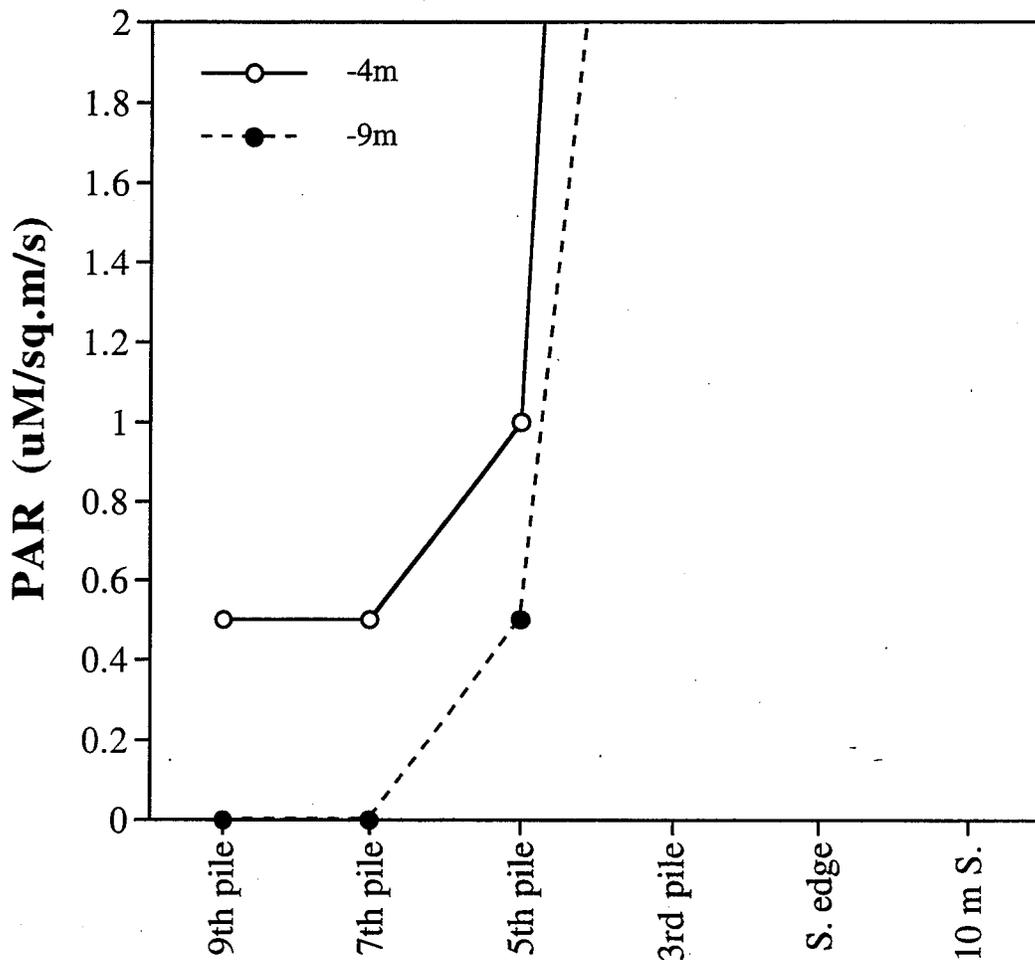


Figure 25. PAR under Seattle Terminal showing only values $> 2 \mu\text{M}$.

On the dates we made measurements, light levels at all the other terminals were $>0.5 \mu\text{M}$ and would not be expected to affect juvenile salmon behavior (Figure 26). Of importance is the fact that most light measurements were made in summer with clear skies, between about 11 am and 4 pm, which represents a period of near maximum incident solar irradiance. In addition, divers indicated that water clarity was high relative

to other times of the year. Hence, during other seasons, weather conditions, and times of day, light would predictably be lower under the terminals.

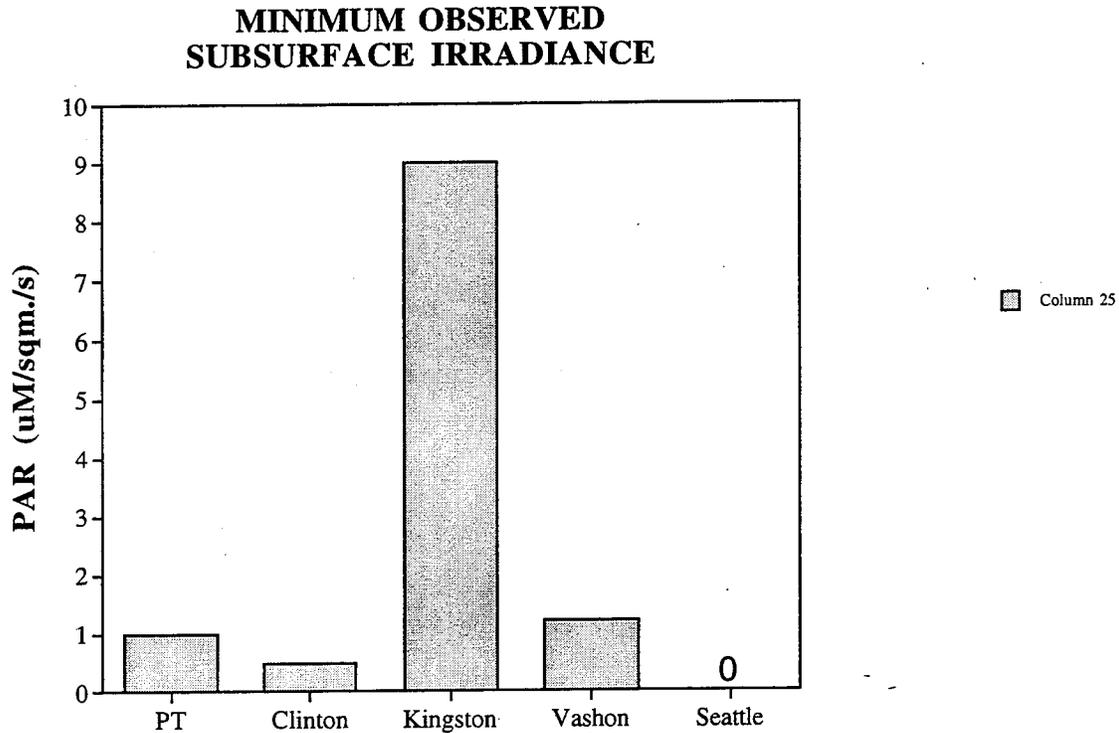


Figure 26. Minimum observed PAR levels under each terminal.

DISCUSSION

Diving Surveys

Preliminary results of the diving surveys indicate that each terminal differs in terms of its fish community, piling community, substrate, light availability, and degree of physical disturbance from ferry propeller wash.

At the five surveyed terminals, embiotocids (e.g., shiner perch, pile perch) were the most common and abundant species. We observed few predators that are confirmed

or potential predators on juvenile salmon. We acknowledge, however, that our observations only spanned one day at each terminal and that these observations were recorded after most juvenile salmon had already migrated to sea. The suite of piscivorous predators on juvenile salmon may change seasonally when there are more salmon available to feed upon. Future studies will more rigorously address the role of predation under and around ferry terminals. These studies may include avian and marine mammal predators, as well as fish predators, on juvenile salmon and will be timed to coincide with the out-migration of juvenile salmon.

We were successful in obtaining video footage that shows juvenile chinook salmon freely swimming back and forth underneath the Kingston ferry terminal. In addition, we recorded a group of 12- to 24-inch blackmouth that appeared to be resting (i.e., holding in one place and not actively swimming) under the Kingston terminal. When disturbed by the divers, the blackmouth briefly darted away and returned to the same place within minutes, showing a preference for the under-terminal environment, as opposed to the adjacent habitat with no over-water structure. The Kingston terminal did not appear to be either a physical or behavioral barrier for the chinook smolts or blackmouth. The Kingston ferry terminal is supported principally by concrete pilings; wider spacing and increased light penetration and reflection associated with the concrete pilings may have contributed to this apparently acceptable environment for these fish. Chinook smolts were also observed, but not filmed, at the Vashon terminal. Future diving surveys will be conducted during the period from April through June, when migratory juvenile salmon are most common around the terminals.

All five of the ferry terminals we surveyed support a diversity of organisms on and around the pilings under the docks. Pilings and docks provide favorable environments for many kinds of seaweeds and invertebrates, especially after pioneering organisms have colonized them. Kozloff (1983) devotes an entire chapter of *Seashore Life of the Northern Pacific Coast* to floating docks and pilings. As noted by Kozloff (1983), the most obvious elements in the complex embroidery of attached organisms on pilings are certain seaweeds, sponges, hydroids, sea anemones, tube-dwelling polychaetes, barnacles, mussels, and ascidians.

At Port Townsend, virtually all of the concrete pilings were scraped clean, and barnacle shell hash was mounded at the base of each piling. Sea stars, primarily *Pisaster* spp. and *Pycnopodia helianthodes*, crabs (*Cancer* spp. and *Pugettia* spp.), and embiotocids seem to be the major predators feeding on the barnacles and creating these shell mounds. Shrimp (*Pandalus* spp.) were more common and abundant on the pilings at Port Townsend than at any of the other four terminals. In contrast, at Clinton the bottom was littered with mussel shells and to a lesser extent barnacle shell hash, horse clam shells, wood debris, and drift algae (primarily *Ulva* spp.). The numbers of sea stars, Dungeness crabs (*Cancer magister*), and red rock crabs (*Cancer productus*) at the Clinton terminal were the highest we have observed around any over-water structure in Puget Sound. We counted 28 *Pycnopodia* on one timber piling, with little open space among the interlocked arms of the sea stars. The numbers of horse clams (*Tresus* spp.) and small sculpins and flatfish at Clinton also far exceeded those of the other four terminals. The ready availability of food under the Clinton terminal attracts a number of invertebrates and fish. We have previously reported this "reef effect" in reports on our

research related to opportunities at the Clinton terminal to mitigate impacts to eelgrass from proposed terminal expansion (Simenstad *et al.* 1997).

The under-terminal environment at the Kingston terminal was most comparable to the Port Townsend terminal. The concrete pilings at Kingston were also scraped clean. Small Dungeness crabs were moderately abundant at the base of the pilings. Red rock crabs were abundant both at the base of the pilings and on the pilings. The substrate was a mixture of sand, cobble, and barnacle shell hash. Sea pens (*Ptilosarcus gurneyi*) were very common on the sandy bottom at both Kingston and Port Townsend. Divers observed sparse eelgrass underneath the Kingston terminal.

In comparison to the other four terminals, the under-terminal environment at Seattle was nearly devoid of life, with the exception of the pilings at the edge of the terminal that supported a variety of macroalgae, anemones, sponges, and polychaete worms. The pilings underneath the terminal had a few shrimp and polychaete worms and not much other life of note. The substrate under the Seattle dock was a silty-mud, which was easily resuspended. One of the divers reported a large (>5 feet long) shark that was most likely a six-gill shark (*Hexanchus griseus*).

In contrast, the Vashon terminal supported a diversity of invertebrates and fish. Divers reported that horse clams, moon snails, flatfish, sculpins, and schools of shiner and pile perch were common. The pilings in deeper water were lined with anemones (*Metridium senile*), as well as large barnacles (*Balanus nubilus*), hydroids, and tubeworms. The bottom was primarily fine sand with some shell hash and wood debris. Among all the over-water structures we surveyed, the floating passenger-only dock at Vashon supported the greatest diversity and abundance of species. The underside of the

floating dock was a solid wall of tubeworms, hydroids, sponges, ascidians, anemones, and kelp (mostly *Laminaria saccharina*). The substrate was littered with shells and wood debris, as well as anemones and tubeworms that had fallen or been dislodged from the floating dock. We observed very large schools of shiner perch and tubesnouts (*Aulorhynchus flavidus*), in addition to eight adult copper rockfish and three juveniles, ten ratfish, pile perch, gunnels, and sanddabs.

In general, the divers observed that the terminals with concrete piles (Port Townsend and Kingston) appeared to allow more light to penetrate underneath than the terminals with timber piles. This greater light penetration seems to be a function of the reduced number of pilings (i.e., fewer pilings are required with concrete than with timber construction) and the greater reflectivity of concrete relative to wood. The Seattle terminal was by far the darkest of the five terminals and had the greatest number of pilings. Five pilings in from the southern edge of the Seattle terminal it was so dark that divers were unable to read their gauges. One diver reported being unable to see his own hands held against the lens of his face mask. According to the divers, the brightest underdock environment was Vashon. We attribute this primarily to the unusually high water clarity, with in-water, horizontal visibility in excess of 30 feet. A diver positioned on the bottom on one edge of the Vashon terminal could count the pilings all the way through to the other side of the terminal, a distance of approximately 35 feet. Given the divers' qualitative observations, light availability underneath a terminal appears to be a function of the pile spacing; cloud cover; in-water visibility; and the width, length, height above the water, and orientation of the over-water structure.

Of the five terminals we surveyed, the propeller wash effects were most pronounced at the Clinton terminal. We saw evidence at Clinton of “pits” of bare substrate near the eastern docking slip, which appeared to be continuously scoured. The pits were rimmed by piles of woody debris and shell hash. We expect these physical disturbances to disappear after the new terminal is constructed. The new docking slip will be further offshore and oriented at an angle that more closely parallels the shoreline. Both of these actions are being implemented by WSDOT to avoid nearshore impacts to eelgrass and the benthic community.

Light Surveys

The light surveys provided some initial indications of how ferry terminals affect light regimes, and, by inference from early studies on light and fish behavior, how light levels under the terminals may affect juvenile salmon migration and feeding. In four of the five terminals investigated, light was above threshold levels even under the darkest portion of the terminal. However, light measurements were taken under high light conditions in summer. We would expect lower light conditions that potentially could affect fish behavior during autumn, winter, and early spring, as well as at night.

The studies showed that determining light-level effects on behavior requires two fundamental pieces of information:

- minimum light levels during periods of migration
- threshold levels for behavioral responses for the local species and stocks of fish.

Factors that control light levels include incident solar irradiance; attenuation; dock orientation, width, and height above the water; and time of day. Understanding the

relationship among these factors will allow statistical models to be constructed to predict light levels. These models should be verified with field investigations. Light attenuation varies on a daily or weekly time scale but can be roughly predicted from secchi depth and light attenuation measurements available for the sites. Developing the relationship between light and behavior will require experimental and fieldwork planned for the future. The strongest data sets will be field verification and calibration studies in which fish behavior is monitored along with light levels at study sites.

The results of the MSL preliminary diving and light surveys will be used to refine the UW-MSL-WSDOT team's research design for full-scale studies that are intended *to experimentally establish light level and dock characteristic thresholds that alter the behavior of migrating juvenile salmon and reduce the abundance and availability of their food organisms*. This research is scheduled to begin in summer 1999.



ACKNOWLEDGMENTS

Support for this research was provided by Washington State Department of Transportation. We especially wish to thank Jim Schafer and Rick Brater for their continued interest in and encouragement of this research and for enabling us to be involved in resolving complex environmental issues that affect WSDOT.

We also appreciate the cooperation of the following WSDOT terminal agents, who assisted in making our diving efforts safe and productive without compromising scheduled ferry sailings: Bill Ewing, Rock Henderson, Jim Olson, Doug Schlieff, and Steve Long.

CONTRIBUTORS' CREDITS

1—Introduction

Charles A. Simenstad, Jeffery R. Cordell, Barbara J. Nightengale, Ronald M. Thom, David K. Shreffler

2— Juvenile Salmon and their Nearshore Habitat Responses to Aquatic Light Environment

Barbara J. Nightengale, Charles A. Simenstad

3—Summary of Literature Review of Over-Water Structure Effects on Juvenile Salmon Behavior, Habitat, and Potential Predation

Charles A. Simenstad, Barbara J. Nightengale, David K. Shreffler

4—Preliminary Findings of Diving and Light Surveys

David K. Shreffler, William M. Gardiner

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APPENDIX A

Synopses of important sources of information on juvenile salmon responses and spectral sensitivity to aquatic light environments

Ali, M.A. 1959. The ocular structure, retinomotor and photo behavioral responses of juvenile pacific salmon. Canadian Journal of Zoology, 37:965-996.

Species: Pacific salmon

Study objectives: Detailed comparative histophysiological examination of the eye to expand the understanding of mechanisms of salmon downstream migration.

Study Methods: Controlled lab experiments using fish troughs with varying light intensities ranging from 1.5 to 2.5 ft-c and water temperatures from 7 to 13 C. Schooling patterns, feeding rates, and other behavioral responses to light were observed. Retinal photomechanical responses to light intensities were sampled with removal of fish lenses to study the neurological arrangement of the retina.

Light Adaptation Results: The eye of the Pacific salmon is not capable of photomechanical changes in diameter due to light. Species differences were noted among Pacific salmon species in rates of light adaptation with pronounced differences between stages of development (i.e. embryos, alevins, fry).

Retinal Response: Embryos - no "dark adapted" embryos of any of the four species showed retinomotor response to exposure to light. Alevins-microscopical examination showed a slight response to light exposure showing a slight expansion of pigment layer and contraction of cone layer with light exposure with the most noticeable changes in coho alevins. Emerged Fry- response to exposure to light is immediate with no measurable latent period prior to expansion or contraction. In the chum fry, a significantly smaller difference between fully expanded and fully contracted epithelial pigment was noted. Late Fry coho and chum light adapt in 10 minutes while sockeye light adapt in 15 minutes and pinks in 20 minutes. Smolt light response is immediate with coho showing a slower movement for the first 5 minutes. Smolt pigment light adapts in 20 minutes and cones in 15 minutes.

Schooling Rates: sockeye, pink and chum form schools in about 15 minutes after illumination. Coho takes 5 minutes longer. The coho schooled less readily with only 86% in the school while other species had 96--98% in schools. The light-adapted late sockeye, pink and chum fry form schools of 98% of the fish in 10 minutes, while the coho takes 20 minutes. Sockeye and coho smolts failed to form schools upon exposure to light with only occasionally two or three fish swimming together for short durations.

Feeding Rates: In every case, maximum prey capture occurs when cones are light-adapted. The coho and chum capture 96-98% of *Daphnia* offered 10 minutes after illumination with coho taking 20 minutes. Sockeye and coho smolts showed maximum feeding 15 minutes after illumination.

Dark Adaptation Results: Embryos showed no cone or pigment movement with exposure to darkness of a "light adapted" embryo. Pigment thickness and cone changes occurred for all species within 15 minutes of exposure to darkness. Emerged fry showed a latent period before contraction in dark. Pinks having the shortest (5 minutes) and chum the longest (15 minutes). The pink's pigment remains half-contracted for 25 minutes after dark exposure. The sockeye late fry pigment is maximally contracted after 45 minutes while the pink takes only 30 minutes. Similarly, the sockeye late fry cones take 40 minutes to contract while other species take only 35 minutes. Sockeye smolts pigment contraction is 5 minutes shorter than coho. But both species take equal time to fully contract. The cones of sockeye and coho have no latent period before expansion but sockeye cones take 50 minutes to light-adapt while coho takes 40 minutes.

Light Intensity Results: Feeding rates were maximum when cones were light-adapted. Tendency to school appears to increase with light. In the case of alevins, no differences were observed in retinal pigment and cone reactions to light intensities between those kept in darkness and those kept in light for 3 days prior to the experiment. Sockeye pigment fully expanded until intensity below 10 ft-c with full contracted at intensities below 10-2 ft-c. chum pigment had a lower threshold for commencement of contraction (10-1 ft-c) with full contraction at 10-2 ft-c. or lower. Full contraction of sockeye cones at 10-1 ft-c with chum at 10-3 ft-c. Late fry of all species, except sockeye, stayed fully expanded until light fell below 100 ft-c. with sockeye contracting at 101 ft-c. When vision changes from photopic to scotopic (light intensity below cone threshold), the animals stay in the bottom third of tank capture prey by detecting their movements and silhouettes. No feeding occurs at 10-5 ft-c or lower. Diurnal rhythm is only apparent in constant dark. When diurnal rhythm is present, upon exposure to constant dark or light, the rhythm disappears.

Conclusions: Alevin retinal development and increased capability of light response culminates in a photopositive fry with marked photomechanical changes to light. Previous studies have documented that as the light intensity decreases at dusk, with exception of coho, fry rise to the surface and either swim or are carried by the current downstream. The difference between species may be due to coho's lower cone threshold enabling them to see at darker light intensities.

It is suggested that these fish commence migration as light intensity begins to decrease beyond a threshold with a state of partial night blindness occurring during the 35 to 40 minute adaptation period. The slow rate of dark adaptation coupled with a rapid

decrease in light intensity triggers mass migration for a brief period with the mechanisms triggering migration being light intensity. Light barriers can decrease vision acuity while the eye goes through its light adaptation period presenting a potentially important period of vulnerability

1. Ocular structure and retinal responses correlate to schooling, feeding and migratory behavior.
2. *Oncorhynchus* eye is typical vertebrate and teleost eye with a retinal arrangement shared with primates.
3. Ability of the eye to undergo photomechanical changes increases with age.
4. With age, a general trend of shortened light adaptation time is noted. However, dark adaptation time tends to increase with age. Dark adaptation, in general, takes a longer time.
5. For all species studied, a latent period before pigment contraction begins does occur with noted differences between species.
6. Maximum prey capture correlates with complete light adaptation and cone thresholds.
7. Sockeye show lower cone thresholds with age, coho show no differences among stages, and chum fry have a higher threshold than alevins.
8. Under constant light or constant dark, there is no diurnal rhythm in the positions of the pigment and cone layers of the Pacific salmon.
9. This research suggests that downstream migration of juvenile Pacific salmon occur as a result of their eyes being in a semi-dark-adapted state for a short period at dusk. This is due to a rapid decrease in incident light intensity and a relatively slower rate of dark adaptation. Consequently the fish lose their reference points and swim with the current and/or are displaced downstream.

Ali, M.A.. 1964. Diurnal rhythm in the rates of oxygen consumption, locomotor and feeding activity of yearling Atlantic Salmon (*Salmo Salar*) under various light conditions. Proceedings of the Indian Academy of Science. 60:249-263.

Species: Atlantic Salmon

Study Objectives: Study of rhythms in the rates of oxygen consumption, locomotor and feeding activity in relation to light as an exogenous factor.

Study Methods: Controlled lab experiments using fluorescent lights, tanks, oxygen consumption measuring apparatus, and a feeding activity recorder under five different experimental light conditions: natural light conditions, continuous light, continuous dark, 12 hours light : 12 hours dark, and 6 hours light: 6 hours dark over five day periods.

Variables Measured: Oxygen consumption rate, locomotor activity, and feeding activity patterns under the five light conditions. Oxygen consumption measured Feb 5-10, Dec 19-24, and Dec 12-17. Locomotor activity measured April 11-16, April 19-24, April 3-5, Mar 19-24; and Oct 2 - 7. Feeding activity measured April 11-16, April 19-24, April 3-8, March 19-24, and Sep 9-14.

Results: Light and oxygen consumption: under natural control light conditions, a diurnal rhythm of oxygen consumption appears with a higher consumption rate at 8 and 14 hours and a minimum rate at midnight; continuous light upsets the normal oxygen consumption rhythm; in continuous dark, a rhythm appears with maximum consumption at 14 hours and a minimum around midnight suggesting a "physiological memory"; in 12hrs dark:12hrs light conditions, oxygen consumption was up during the light period and down during the dark; and in 6hrs dark:6hrs light conditions rate of oxygen consumption displayed a period of adaptation during which correlations of oxygen consumption to light and dark were apparent only at the end of the experimental period. **Light and locomotor activity:** under natural control light conditions, there was greater activity during the day than during the night with peak activity occurring during the morning; under continuous light, the diurnal rhythm is temporarily suppressed for a couple of days with the normal diurnal pattern showing in the first two days and last day; continuous dark disrupted the normal rhythms throughout the experimental period; light 12 hrs:dark 12hrs changes the inherent diurnal rhythm with activity not corresponding to light-dark periods; and light 6 hrs:dark 6 hrs produced a correlation between activity and light-dark at the beginning and end of the experimental period with no pattern showing in the mid period. **Light and feeding activity:** under natural control conditions, feeding was greater during the morning than at night. In continuous light, no rhythm was apparent; in continuous dark, a rhythm persisted; in light 12 hrs: dark 12 hrs no relationship between light-dark periods was evident; and in light 6 hrs: dark 6 hrs a relationship with light-dark was evident at the start and end of the experimental but interrupted during the mid period.

The correlations of light-dark with oxygen consumption, locomotor activity and feeding observed during the 6-hr experiments suggest a complex interplay of endogenous factors, metabolism, light, activity and feeding.

Under control conditions, rates of oxygen consumption, activity and feeding show a rhythm with, in general, higher activity during the day than during the night. The influence of light as an exogenous factor is not clear. This experiment suggests that light plays only a very small role in the production of this rhythm.

Comments: The short duration of these experiments, the lack of simultaneous study of activity, feeding and oxygen consumption, and the use of odiferous food places limits on the conclusions to be drawn from this study.

McFarland, W.N., and E.R. Lowe. 1983. Wave produced changes in underwater light and their relations to vision. Environmental Biology of Fish 8. 173-184.

Study Objective: Exploring the relationships between the spatial and temporal characteristics of vision and light changes to wave-induced light changes in aquatic environments.

Methods: Review of light and vision concepts as they might relate to aquatic habitat characteristics.

Summary and Conclusions: 1) spatial and temporal frequency responses of animals with image-forming eyes are qualitatively similar to humans; 2) contrast sensitivity is maximal at intermediate levels of detail; 3) the spatio-temporal frequencies at which contrast sensitivity is maximal vary in different species and, probably, represent adaptations to detect objects relevant to each species life-style suggesting that the evolution of image-forming vision in invertebrates and vertebrates was influenced by the same selective force; 4) flicker rates from surface waves acting as lenses focusing sunlight beneath the surface match the frequency responses of animals with image forming eyes suggesting that invertebrates and vertebrates visual systems evolved to function in the time-frame set by wave-induced flicker in shallow seas; 5) dorsal patterns and bars on many fish probably relate to wave induced fluctuating frequency patterns.

Comments: Underwater, patterns of light and dark cast by flickering light cause small objects to merge into the flickering glare of the surface when viewed from below. These same objects when viewed from above or the side against a non-flickering background, such as a shallow bottom, tend to flash into view. This vision component could be part of why young zooplankton-feeding salmon select epibenthic zooplankton in shallow water.

Brett, J.R., and C. Groot. 1963. Some aspect of olfactory and visual responses in Pacific salmon. Journal of the Fisheries Research Board of Canada. 20(2):287-303

Region: North America **Species:** Pacific salmon

Study Objectives: Review past and current research on olfactory and visual responses in Pacific salmon.

Summary and Conclusions: Olfactory: Pacific salmon demonstrate an innate ability to perceive highly dilute odors and react selectively. **Vision:** vision plays a dominant role in salmon activities including the registering of environmental features and celestial orientation. The presence of a diurnally timed rhythmic sense is indicated. Studies on coho demonstrated that feeding interference began at .01 ft-c light intensity. A progressive drop occurred beneath that level proportional to the logarithm of the light intensity. A feeding rate of one-half the maximum occurred at .0001 ft-c with extinction at .00001 ft-c. No feeding was possible in complete darkness, despite fish bumping into prey. Light intensity of 9000 ft-c had no effect on feeding rate displaying the highly adaptive nature of the salmon eye. Extensive studies of sockeye Babine Lake have demonstrated sockeye capacity of orientation by celestial cues.

Hoar, W.S. Keenleyside, and R.G. Goodall. 1957. Reactions of juvenile Pacific Salmon to light. Journal of the Fisheries Research Board of Canada.14:815-830.

Region: PNW **Species:** chum, coho, pink, sockeye salmon fry

Study Objectives: A comparative study of photo-responses of four species of *Oncorhynchus* to evaluate the role of light in governing juvenile salmon fresh-water behavior.

Study Methods: Controlled laboratory experiments. Light preferences were measured by fish being placed in aquariums divided into light and dark halves under varying light levels. For comparative purposes, two species were always observed at the same time.

The effect of high light intensity combined with water current and turbulence was measured using rheotaxis tubs at varying light levels.

Results: Light preferences: highest statistically significant values were those responses stimulated by abrupt changes in light. In general the young salmon did not hide in the darkened area or remain constantly in the illuminated area, but were continuously passing to and fro both areas. The maximum values were: 84.5% chum fry in light at 80 ft-c. and 74.5% sockeye smolts in the dark under 150 ft-c. At such low light intensities, chum and pink fry were observed to be uniformly photopositive. Coho were less consistent in their response but at light intensities of 10 ft-c and 45 ft-c were observed in the light in significantly greater numbers while at higher intensities became indifferent to light with equal distribution across areas. Coho smolt displayed a marked and uniform negative response. Juvenile sockeye were found to have negative phototaxis with smaller fry avoiding the light more markedly than the larger and older fry. The sockeye smolt displayed the most strongly marked negative response of any group suddenly exposed to 150 ft-c. **Light Intensities and water turbulence:** At higher light intensities ranging to 1000 ft-c chum and sockeye fry and sockeye smolt retreat under strong light and emerge at low light intensity while pink and coho fry and coho smolt responded in reverse. The smolt groups were less consistent than the fry in these responses. Water turbulence produced little or no effect on fish distribution with small differences due to drifting. Drifting occurred less when rocks were present. Without rocks drifting was more frequent with pinks swimming with the current. Coho and chum fry emerged in larger numbers when stones were present. **Movement in a vertical light gradient:** in tanks divided into three areas, top 30 cm, middle 60 cm and bottom 30 cm exposed to six different intensities ranging from 5 - 1000 ft-c wild pink fry clearly moved out of the upper areas with increased light intensity. In contrast, pink hatchery-reared fry demonstrated no such reaction to changes in light intensities with a preference for areas nearer to the middle of the tank despite changes in light-intensities. Chum hatchery-reared fry responses were very similar to wild stock with no marked response to changing light intensity. Coho fry and smolts showed no response to gradients in light intensities with fry staying closer to the surface than smolts. Coho smolt seemed inactive at intensities below 5 ft-c with activity becoming apparent at 10 ft-c and rapid movement up and down through different levels at 50 ft-c. intensities. Sockeye smolts were indifferent to these light gradients. In the 180 cm water column, however their activity was extreme with individuals displaying "escape behavior" reportedly not related to light gradients. With the addition of stones, sockeye fry remained under the stones at all light intensities. Older sockeye fry showed a change from strong photonegative response toward a photopositive response.

Conclusions: Schools of chum and pink salmon fry show a marked preference for light while sockeye fry retreat to darker areas. Coho fry are indifferent to light of moderately high intensities but become inactive at very low intensities. Recently emerged pink fry rise rapidly to the surface as the light intensity falls and retreat to deeper waters with increased illumination. Chum fry do not seem to have this behavior pattern. This may be related to the intensity of the schooling behavior and alarm reactions of the two species. Recently emerged sockeye retreat from bright light and take shelter under stones. Older sockeye fry rise into shallower water and brighter light but at no time show the strong light preference of chum and pink fry. The smolt stage of sockeye and coho is associated with an increased sensitivity to light and a retreat to darker and deeper areas.

Brett, J.R., and D. MacKinnon. 1953. Preliminary experiments using lights and bubbles to deflect migrating young spring salmon. Journal of the Fisheries Research Board of Canada. 10:548-559.

Region: Canada **Species:** Spring-run chum, coho, pink, rainbow and steelhead trout

Study Objectives: Exploring mechanisms to alter the downstream migratory path of young salmon for safe passage around destructive barriers (i.e. turbines).

Study Methods: Juvenile salmon catch in one of two hoop nets set in each half of a concrete and brick-lined power-intake canal was used to indicate if a bubble curtain deployed at a 40 degree angle in a 3 ft/sec velocity current could successfully deflect the migratory path of juvenile spring salmon.

Results: Under natural conditions, no significant differences existed in the respective catches. Juveniles. A significant difference was obtained, however, when a narrow beam of light was directed into the water in front of one net. Increased deflection occurred on rainy or overcast nights with maximum deflection occurring with flashing light. The average success of deflection with spring migrants can be expressed as two fish deflected for every three fish approaching the net. Cut-throat trout fry and hatchery-reared trout fingerlings were not deflected under these conditions.

Fields, Paul E. 1966. Final report on migrant salmon light guiding studies (Contract No. D.A.-45-108 CIVENG-63-29) at Columbia River Dams. University of Washington. College of Fisheries. Report for the Fisheries Engineering Research Program. U.S. Army Engineer Division, North Pacific Corps of Engineers, Portland, Oregon.

Region: PNW **Species:** Pacific salmon

Study Objectives: Summarize field studies, 1953 to the present, investigating the types of stimuli that can be used in the design of methods to control downstream movements of migrant salmon and steelhead trout.

Results on Light Effects: Under conditions of dark-adapted fish, McNary Dam Oregon Intake experiment results under a range of light intensities from 50 W, 200W, 300W to 500W lamps showed a significant reduction of migrants caught on the lighted side, as compared to the darker side, under the two 300W reflector flood lamps. Under multiple 50W lights, there was little difference between smolts and fry caught in light or dark sides. While under the same conditions, use of a 200W light resulted in significantly more smolts and fry caught on the dark side. When experimental findings were in contradiction, other variables were analyzed. Contradictions occurred between some 300W lamp experiments and it was determined that the contradictions reflected the influence of velocity. It was found that when the velocity exceeded the adaptation time of the retina, light repulsion was displayed, while if the velocity did not exceed the rate of retinal adaptation, light repulsion was not demonstrated. Likewise, in experiments with trash racks and lights, it was found that if migrants floated down toward the trash rack in the shadow of the crossbar, its eyes would not become light-adapted altering the results. Under light-adapted conditions (migrants previously light-adapted by the powerhouse mercury vapor deck lights) of the McNary Dam Powerhouse Trash Sluiceway, experiments using a range of light intensities from Dark, 200W, 350W to 700W light caught more fish under any of the three lighted conditions than the Dark condition. Two trap baskets were placed under each of the above three illumination conditions, one basket (*lighted*) closer to the light and one basket (*darker*) further from the light source while for the Dark condition, baskets were set one north and one south of the turbine. The level of illumination did not affect the proportion of the total catch that entered the *lighted* basket versus the *darker* basket of any trap set; the *darker* of each of the set of two baskets caught from 3 to 5 times as many migrants as the average of the two baskets in a completely dark bay; the greatest light intensity attracted the most migrants; and there was no significant difference in the size of the catch in the two baskets (north and south) of the dark trap (without lights).

An experiment comparing the effects of a 200W clear bulb, a No. 2 photoflood light and a 500W mercury vapor lamp favored the No. 2 photoflood with significantly more fish caught under the No. 2. A reduced catch with the mercury vapor 500W bulb was believed to be due to the wave length difference of the mercury lamp. Comparing 5 light conditions of Dark, 200W, 800W, 850W and 1200W, showed the largest distribution with the 1200W light. Responses to combined light intensities also suggested that the pattern of light was important with the angle of some spotlights providing a greater distance for retinal adaptation to increased light intensity. An optimum was the combination of a 200W light with a 150W reflector light turned along the water surface to provide a lighted pathway. Under the conditions of a study on the diversion of downstream migrants from the McNary Dam turbines into the trash sluiceway and emergency gate slots, most migrants were caught by a 200W lamp than a 1000W lamp. It was suggested that the swift water velocity caused the repulsion reaction to the 1000W light. In this study, there was a significant difference between species: in the dark slots, more chinooks were caught than sockeye or chinooks with equal numbers of chinooks and sockeye; while at the 200W area, the same comparisons held but at higher levels; and in the 1000W level, there was significantly more steelhead than sockeyes with the other species comparisons still holding but not as high. Comparisons within species revealed that significantly more chinooks were caught in the lighted (200W and 1000W) slots than dark.

Migration Delay Results: In a study directed towards eliminating migration delay at the counting board (a lighted area through which fish pass at the top of the fish ladder), the use of direct versus indirect light was tested. The total number of passes was larger and rejections smaller under the direct light. It is felt that this is explained by the wide illumination light-adapting the fish and thus facilitating their passage over the counting board. In an attempt to increase the number of adults crossing the lighted counting board by adapting them to bright light before they attempt to cross, the counting board was constantly illuminated under 200W clear glass bulbs (4-6 bulbs). The highly significant increase in passes clearly indicated that adult salmon can be induced to pass over the lighted counting board by preadapting to light.

Comments: This represents only a small sampling of the light studies reviewed in this document.

APPENDIX B

Assessment of background information on aquatic light environment responses by
juvenile salmon

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark-Adapted Fish Responses
Ali, M.A. 1959	Identify photo-mechanical & behavioral responses to light.	co.ch,sk,pk hatchery fish	late fry 34-39mm	Lab: artificial light reflector flood lamps (3000 - 7000 Angstroms wavelengths)	10^{-5} to 10^2 ft-c	Following light adaptation, reduced light intensities (ft-c) of 10^{-5} to 10^{-2} (sk,pk); 10^{-5} to 10^{-3} (co); 10^{-5} to 10^{-1} (ch) ft-c cause retinal pigment to contract taking 45 min (sk); 40 min (ch); 35 min (co); 25 min (pk).	Dark adapted pigment expands to light: 10 min (sk); 20 min (co, ch, pk). Cone contraction to light: 10 min (co, ch); 5 min (sk); 25 min (pk). Schooling resumed in 10 - 15 min (pk, ch, sk); 20 min (co). Feeding resumed in 10 min (co, ch); 10+min (sk, pk).
						Simultaneously, at 10^{-5} to 10^{-2} (sk); 10^{-5} to 10^{-3} (co); 10^{-5} to 10^{-1} (pk, ch) cones expand. Cone adaptation to dark take 40 min for (sk) and 35 min for (co, ch, pk). At some point in this adaptation period, fish may experience a period of blindness	At ft-c of 10^{-1} (sk, pk); 10^{-2} (co); 10^0 (ch) pigment starts to expand w/mex exp. at 10^1 (sk); 10^0 (co, ch, pk) At 10^{-1} (sk, co); 10^0 (pk, ch) cones contract in response to light.
		sk, co	smolts 68-71mm			Transition from light adaptation (expanded pigment and contracted cones) takes 50 min (40 min for pigment contraction and 50 min for cone expansion) Schools disperse at light intensities below 10^{-4} ft-c which is the threshold for rod or scotopic vision.	The transition from dark-adaptation with its contracted pigment and expanded cones requires 20 min (20 min for pigment to expand and 15 min for cones to contract) with slight variation among species. Feeding resumes 15 min upon exposure to light.
Ali, M.A. 1974	Review of photo-mechanical and behavior findings.	co, ch, sk, pk brown trout	fry, smolt alevin	Review of previous experimental finding	10^{-5} to 9×10^2 ft-c	Previous studies on brown trout have found that 520 nm light wavelengths stimulate pigment expansion (mex. absorption spectrum of scotopic pigments). Light intensity levels control dark adapt times w/ higher light intensity increasing dark adapt times.	Following dark adaptation, exposure to 900 ft-c required 55 min for cones and 35 min for pigments to adapt in Brook Trout.
						Following light adaptation, exposure to 900 ft-c required 70 min cone and pigment adaptation. After 1 ft-c exposure, pigment adaptation required 45 min & cone adaptation required 25 min. Light adapted (co) smolt cones are slower dark adapting than fry cones.	(co, sk) have lower cone thresholds prior to scotopic (night) vision transition providing longer feeding periods prior to night migration and increased predator avoidance.

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark Adapted Fish Responses
Ali 1974 (contd.)						Different wavelengths bring on different retinal responses (rod reactions to green wavelengths are slower). Scotopic to photopic transition occurs when light energy is too great for rods to absorb. Dark to light adaptation is faster than light to dark.	
Azuma & Iwata 1994	Understand vision role in schooling through analysis of nearest neighbor distances under various light intensities.	co	1+ year 137mm	Fresh water lab experiment. Artificial light: w/four 500W incandescent electric lamps. Fish held in tanks using blind and sighted fish.	0 to 4000 lux	Sighted Fish: largest nearest neighbor distance (NND) in 0 light with subsequent decreases in NND under higher illumination intensities. 4 and 40 lux were lowest NND with small increase at 400 and 4000 lux.	Blinded Fish: NND did not reflect changes in light intensity and remained at 0 lux level independent of light intensity.
Brett & Alderdice 1958	Assessment of the ability to feed at varying light levels.	co		Freshwater lab w/experimental tank and artificial lighting w/ Mazda bulbs of 15-150W and 1000W flood	0 to 10 ⁴ ft-c	Light intensity of 10 ⁻² ft-c was first light related interference w/feeding with feeding rates progressively dropping by 50% at 10 ⁻⁴ ft-c and extinction of feeding at 10 ⁻⁵ ft-c.	
Brett & McKinnon 1953	Experiment testing bubbles or light beams in deflecting salmon around dangerous barriers.	co, ch, pk, sthd, cutth.	fy: co, ch, pk, sthd 60mm, cutt 33mm	Freshwater, dam canal experiment w/combination of tubing and artificial light creating deflecting wall of bubbles. Light source: three sealed beam headlights, continuous and flashing.	3.5 ft-c at water surface (bubbles, flashing or continuous light or bubbles w/flash or continuous light.		Light deflected migratory course. Largest deflector was beam of flashing light.

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark-Adapted Fish Responses
Congleton & Wagner 1988	Determine variation in plasma cortisol levels between day and night after a stressful flume passage	ck, sthd	smalls:ck 120-160mm; sthd 160-240mm	Variety of covered and uncovered experimental flumes and receiving tanks. Freshwater. Incidental ambient light.	<1 to 3600 lux (dark=1-4lux, part dark=400-900lux at water surface, undarkened=3600lux)	Plasma cortisol concentrations followed a diel cycle in chinook held at 1-4 lux and 3600 lux. Cortisol concentrations significantly lower at night than by day. Following handling, cortisol dropped faster by night than day.	
Fields 1966	Summarize field studies, 1953 to 1966 investigating types of stimuli to control downstream movements of migrant salmon and steelhead.	ck,sk,pk,sh	fry	Freshwater experiments around dam structures using artificial lights of 71/2W, 25W, 200W clear glass bulbs or 200W,150W, 200W and/or 300W reflector flood lights, #2 photofloods, and 500W mercury vapor lights.	Described in terms of numbers light wattages of power source ranging from dark to 1200W.	Guidance by light-effective if migrants previously adapted to light. Effect of velocity and light intensity resulted in repulsion from light if velocity exceeded eye adaptation or attracted to light if velocity consistent with eye adaptation rates.	Bright light exposure without light adaptation resulted in stopping typical downstream nighttime migration until daytime and fish swimming away from light source. Earlier spring migrants most readily light repulsed. Later migrants less light repulsed.
Hanson 1984		ck	fry		10 ³ to 10 ⁻⁴ ft-c and ambient light levels.	Juveniles were able to detect and respond to low velocity water currents independent of light intensity suggesting that nocturnal seaward migration is not necessarily the result of a loss of the ability to detect and respond to water currents at night.	

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark-Adapted Fish Responses
Hanson & Li 1983	Determine behavioral response of juvenile salmon to vertical trash racks under varying light intensities.	ck	fry 45mm	Freshwater flume lab experiment using artificial lights: eight 75W incandescent light bulbs to light water surface.	10^{-4} to 14 ft-c	Trash rack transit times not significantly different between the two light levels of 10^{-2} and 14 ft-c rather trash rack bar spacing was the more important variable due to predation at the trash rack due to changes in orientation to pass through the rack.	
Eisler 1957	Increase understanding of effects of light spectrum on salmonid eggs and fingerlings.	ck	fingerlings 52-76mm hatchery fish	Freshwater lab experiment using fluorescent lighting 3350-6000 Angstroms w/each tube controlled to eliminate UV rays.	0.02, 88, 116 and 157 ft-c	Growth of light-reared fingerlings over 40% longer and 56% heavier than dark reared fingerlings. Also faster growth periods under light rearing. When field included substantial blue light fish exhibit a clear orientation response to the polarized light field.	Migration begins at dusk. Decrease in activity and response levels at dark.
Hoar, Keenleyside Goodall 1957	Evaluate the role of light in governing juvenile freshwater behavior.	ch, pk, sk, co	fry	Freshwater lab experiments using aquarium with controlled illumination w/75W reflector lamps and 500W photoflood lamps..	Series 1: Dark adapt with light intensity change from 10^{-1} to 50 ft-c. Light adapt with change from 150 to 10 ft-c.	Distribution Changes with light adaptation: (wild ch, pk) increased movement into light (sk, co, hatchery ch) decrease or small increase into light. Distribution changes: (wild ch, pk) photonegative; (hatchery ch) less so; (sk) photonegative, less so at 100+mm length; co less consistent with larger numbers in lower intensities and retreat at higher intensities.	Upon sudden illumination to 500 ft-c: Fry: (ch) 56% in 500 ft-c; (co) 39% in 500 ft-c; (sk) 42-48% in 500 ft-c light. Smolt: (co) 12% in 500 ft-c. Recently emerged (sk) retreat from bright light and take shelter under stones. Older (sk) fry rise into shallower water and bright light but do not show strong light preference of the (ch) and (pk) fry. (Sk) and (co) smolt show increased sensitivity to light and retreat to darker and deeper areas.
						Vertical distribution with light increases: (wild pk) near surface retreat lower, (wild pk) near bottom move higher, (hatchery pk) near bottom move higher, (hatchery ch) slight changes; (wild and hatchery ch) in mid water column show little change with light. Co showed no response to gradients in light intensities. Fry closer to the surface than smolts.	

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark-Adapted Fish Responses
Johnson, Goetz, Ploskey 1998 (in progress)	Evaluate use of strobe lights for vertical smolt redistribution in front of Seattle lock chamber	Juveniles	smolts	Outdoor on-sight experiments using 600W strobe lights w/300 flashes per min and hydroacoustic monitoring.		With strobe lights on fish moved up in water column w/greatest density at 5-6m and decreased by 87-96% at 8-13 m with greatest decreases at 12-13m depth.	
McDonald 1960	Understand downstream migration behavior of salmon fry.	sk.co,pk.ch	fry	Trapnets and controlled field experiments using in freshwater river system using two gasoline lanterns averaging 3 ft-c at water surface.	10 ⁻² and 3 ft-c.	Chum fry were caught during daylight during a period of water rise. Surface distance sockeye were observed to migrate upstream in day. Pk and sk migration occurred at times during day.	Migration typically at night when light intensity dropped to 10 ⁻² ft-c. Light intensity of 3 ft-c stopped migration. Migration precisely regulated by light and its intensity. Begin movement downstream at dark and terminate at approaching daylight.
Mork & Gulbrandsen 1994	Establish activity level of All. Salmon, sea trout and charr exposed to light-dark cycles	charr, sea & rainbow trout All. salmon	fry 100-150mm	Freshwater lab tank experiments using periods of light 20h light:4h darkness.	0.6 lux, 150 lux and <0.1 lux (6 lux=twilight, 150lux = light and <0.1 lux =dark.	All. Salm: Light to dark->50% activity increase near bottom; 33% decrease near surface. Sea trout: light to dark-> 20% bottom activity increase; 200% surface activity increase. Rainbows: 100% bottom activity increase; 50% surface activity increase	All. Salm: Dark to light->240% activity increase near bottom; 80% activity decrease near surface. Sea trout: 25% activity increase near bottom; 50% decrease near surface. Rainbows: 50% increase near bottom; 83% decrease in surface activity.

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark-Adapted Fish Responses
Nemeth 1989	Investigate the behavioral responses of juvenile salmon to lights commonly used to guide fish.	ck,co	juvenile 74-115mm (smolt transition period)	Freshwater lab experiment using tanks and artificial lighting; Hydro Model L2 mercury vapor 1000W underwater light and EG&G Model SS-122 underwater strobe light. Tests under 4 conditions: normal day, normal night and reversed day, reversed light.	Strobe = 5uE/m2/s w/ 300 p/min flash rate. Mercury = 140uE/m2/s Light intensity varied w/distance from light.	Swam away from light source. Co were sensitive to flashing lights. Co hid under strobe. Mercury light did not stun either species but sometimes startled them with both species swimming away in a few minutes.	Both species scattered wildly or were stunned when strobes turned on. Ck re-oriented and moved away from light sooner. Almost all fish swam away from light after a few minutes. Co swam under the strobe to hide. Ck showed a greater avoidance of strobe and less avoidance to mercury light. 10% coho attracted to mercury with attraction decreasing w/increased exposure. 90% of coho avoided strobe and a significant decrease in avoidance to mercury.
				Ambient light, four incandescent flood lamps		5% coho attracted to mercury. 90% of coho avoided strobe and mercury light. Co hid under strobe housing during ambient day/light and with lights on with occasional emergence as a milling group or a tight ball. Light adapted Co during the night milled or balled w and w/o strobe but during mercury tests, tight ball often startling. After 60 min test light exposure, Co showed greater avoidance than Ck. Co showed greater avoidance than Ck to strobe light under all conditions.	Co under normal night light passively milled. Strobe caused fish to seek cover under housing. Mercury caused activity of cruising in long groups throughout tank. Dark adapted Co during the day milled around.

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark-Adapted Fish Responses
Nemeth & Anderson 1992	Determine if differences in ambient lighting alter initial and subsequent behavior in response to strobe and mercury light.	co.ck hatchery fish	smolts 74-115mm	Outdoor, freshwater, reaway tests w/natural and artificial light. 1000W Hydromodel L2 underwater mercury vapor light at EG & G model SS-1322 w/ 300 flash/min underwater strobe	> 1,000 uE/m ² /s (full sunlight) to 5 uE/m ² /s (dark).	Changes in response to strobe and mercury exposure were in first 10 min w/continued exposure having no effect. Coho adapted to 5 uE/m ² /s at night hid upon exposure to mercury light. Ck showed little activity during daylight exposure to mercury light.	Coho adapted to normal night conditions hid upon exposure to strobe and swam actively about upon exposure to mercury light. Coho adapted to dark during the day, failed to seek cover and increased swimming.
						Coho remained at greater distance from lights than chinook. Both species avoided strobe and full intensity mercury light. Coho had a strong cover-seeking reaction in bright daylight.	Chinook showed little activity during adaptation to light but increased swimming when exposed to mercury light. Initially moved toward mercury light when first turned on but retreated with increasing intensity.
							Abrupt introduction to strobe usually startled both species and stunned a few fish, especially under dark conditions. After initial exposure, coho and chinook moved to the darkest areas (<0.05 ft-c).
Pinhorn & Andrews (1963)	Understand the effect of light intensity on All. Salmon maturation.	All. salmon	fly 24-60mm	Freshwater lab experiments using tanks and artificial lights w/ fish conditioned to artificial fluorescent light in durations of 16h light, 8h dark were put through a series of 10, 30 and 60 second exposures to 0.1, 0.2, 2, 20 and 200 ft-c.	10 ⁻¹ to 200 ft-c.	Greater % of fish in light at 10 sec. exposures, reduced % in longer exposures. % of fish in light at 20 ft-c = % in 200 ft-c. Tendency to move into dark with high intensities. Magnitude of reaction increased with higher intensities. At highest intensity (200 ft-c) fish darted into dark compartment. Light exposed fish were very active, reacting to stimuli more readily at all light intensities. Except at the lowest intensities, negative response to flashing and continuous light.	At 10 ⁻¹ ft-c, % of fish in light significantly greater than in dark for 30-sec exposure. At 0.2 ft-c and above, % significantly less in light than dark. Light seeking tendency displayed in successive exposures, most significant differences between 0.1 and 0.2 ft-c. Dark adapted fish were very quiet on the bottom except at high light intensities. Except at the lowest intensities, negative response to flashing and continuous light.

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark Adapted Fish Responses
Prinslow, Whitmus, Dawson, Bax, Snyder, Salo 1979	Assess the effects of wharf lighting at the Bangor Naval Base on outmigrating juvenile salmon in Hood Canal.	Ch	fry 28mm	Marine waters, field experiments. Controlled intervals of artificial lighting using 35W, 150W and 110 VAC incandescent spotlights coupled with sampling to test for attraction of fish (salmon or predators) to different lights and wavelengths.	2-13 lux	No large scale aggregation of salmon observed.No difference observed in predators present with lights on or off.	
				Mode II: 1500W quartz lamps and white light Mode III: 250-500, and street lamp, 400W and 1000W metal halide lamps amber light and white light	2-13, and 200 lux 2-66 lux and 400 lux	Attracted and delayed chum (1-2 days). Attracted and delayed chum (1-2 days).	

Salmonid Light Responses

References	Study Objectives	Species	Life Stage	Experimental Conditions	Light Intensity	Light-Adapted Fish Responses	Dark-Adapted Fish Responses
Puckett and Anderson (1988)	Test if salmon species are repelled by strobe light and attracted to mercury lights in still-water lab setting.	co, ck, sh All. salm	juvenile 51-101 mm	Freshwater, enclosed outdoor raceway for 30 and 60 min intervals w/dark and light adapted fish using Hydro-Products Model L2 mercury vapor underwater light 1000W EG&G Model SS-122 underwater strobe lights.	Ranged from 0.05 to 11 umoles/s/m ² varying with distance from light source.	Strobe: Ck-avoid; Co-hide; sh-avoid; All-no test. Mercury Light: Ck-inconsistent; Co-hide; sthd-inconsistent. All-no test.	Dark-Adapted Fish Responses: Strobe: Ck-avoid; Co-hide; sthd-avoid; All-avoid. Mercury Light: Ck-oscillate; Co-oscillate; sh-attract; All.-inconsistent. All species avoid strobe light. Only Sthd tested at night displayed attraction to mercury lights.
Wallace, Kolbeinshavn, Aasjord 1988	Study the effects of hatchery lighting conditions on the growth of charr and All. salmon.	charr, All. Salmon	fry, fingerling to 1.43 grams	Freshwater lab experiments using lined tanks w/artificial illumination w/no external sources of illumination. Tanks were held in darkness w/exception of tanks 40 cm from water surface continuously illuminating at 700, 200, 50 or 10 lux.	700, 200, 50, 10 lux	Salmon: highest growth rate at 700 lux; 2nd highest at 200 lux; 3rd highest at 0 lux and least growth at 10 lux. Charr: Highest growth rate at 50 lux; 2nd highest at 10 lux; and 3rd highest at 200 lux. Highest mortality at 700 lux.	



APPENDIX C

Assessment of background information on spectral sensitivity by juvenile salmon

Salmonid Light Reception

Reference	Study Objective	Species	Life Stage	Experimental Conditions	Findings
Bowmaker and Kunz 1987	Investigating the age related differences in the presence of UV sensitive cones.	brown trout hatchery fish	sub-yearlings yearlings, and 2-year olds	Lab experiments using microspectrophotometry(msp) carried out under dim red light (>750nm) w/Liebman msp computer controlled to step from 750 to 370nm in 2nm steps.	Two year old fish did not possess the UV cone cells of yearling trout. The corner cells providing UV sensitivity are lost with growth suggesting that subyearlings emerging from the gravel feeding on invertebrate drift rely on UV light for prey detection through scatter and absorption of UV. It is thought that some zooplankton:1) contain lipid droplets that absorb UV silhouetting them against a bright background, and 2) some may use UV reflection to attract mates or repel enemies.
Browman, Novales-Flamarique, Hawryshyn 1994	Testing the hypothesis that UV contributes to prey search in small juvenile rainbow trout.	rainbow	38mm	Lab experiment using 250W quartz tungsten halogen bulb w/450 LP filter for UV absence test for full spectrum illumination testing 350-800nm. Shadow video photography to record foraging and prey search behavior.	Absorption of UV radiation by fish retina plays a direct role in improving their prey search and detection due to their UV photoreceptors picking up contrasts in prey's ability to absorb or scatter UV photons and background UV light environment.
Coughlin and Hawryshyn 1993	Investigate the spectral sensitivity of units in the torus semicircularis of small juvenile trout.	rainbow :	juvenile small= 98-118mm large= 162-193mm	Lab experiments using fluorescent bulbs w/av. intensity of 33.54 mW cm ⁻² and surgical procedure was used to determine brain spectral sensitivity curves. Thresholds were detected at given wavelength-intensity combinations for 21 wavelengths.	Spectral sensitivity profiles of both luminance and color coded units of small vs large rainbow trouts were compiled from threshold responses at given wavelength-intensity combinations. Results: TS (a midbrain region that integrates inputs from several sensory systems) UV inputs present in 19 of 20 cone visual units of small trout and only in 9 of 19 units in large trout.

Salmonid Light Reception

Reference	Study Objective	Species	Life Stage	Experimental Conditions	Findings
Coughlin et al. 1993 (contd.)					While large trout had a higher proportion of TS luminance-sensitive units, relative to color-coded units, than small fish. Luminance units comprised only 1 of 20 visual units observed in small fish, but totaled 7 of 19 units in large fish. All TS units in small fish have UV and/or S inputs, several units with no shorter wavelengths than M were observed in large fish. Two changes corresponding to growth were identified as: 1) rise in proportion of luminance-sensitive units relative to color-coded units dramatically increases with growth, and 2) spectral sensitivity changes in UV range.
Hawryshyn, Arnold, Chaisson and Martin 1988	Describe the developmental changes in UV sensitivity.	rainbow hatchery fish	small=<320g large=>60g	Lab experiment using ocular transmission technology after exposing fish to 50% delamped double tube fluorescent lighting alternating between 12 hr dark and 12 hr light and mean irradiance of 18.3X10 ⁻⁶ W cm ⁻²	TS units were previously recognized as serving the function of observation and detection of sudden and/or small changes in the visual scenery. These results suggest that TS units play a greater role in wavelength discrimination. UV Spectral sensitivity range by age: 1) 14g fish=360-430nm; 2) 44g fish=389-430nm; 3) 90g fish=430nm. Spectral shifts in sensitivity were only observed in the UV mechanism. The cones important to UV sensitivity are controlled by thyroid hormones.

Salmonid Light Reception

Reference	Study Objective	Species	Life Stage	Experimental Conditions	Findings
Hawryshyn, Arnold Bowering, Cole 1990	Determine trout E-vector discrimination, origin of polarization sensitivity and plane-polarized light influence on orientation.	rainbow	juveniles 30g and 50-60g weight	Lab experiments using tanks and 250W Tungsten Halogen Prado Projector w/UV Polarizer to study the orientation mechanisms of rainbow trout.	Trout discriminated e-vectors in orientation to certain polarized light fields. With UV radiation eliminated, they lost their ability to discriminate e-vector and orient. Older trout appear to lose this capacity. When the fields included substantial blue light, fish exhibited a clear orientation response to the polarized light field. Sensitivity shifts increasingly towards the longer wavelengths with growth. After smoltification, the shift in diet towards larger prey may lessen the need for a UV cone mechanism in larger trout.
Hawryshyn and Harosi 1993	Identify and spectrally characterize the underlying visual pigments in the photoreceptors of rainbow trout.	rainbow hatchery fish	juvenile 5-40g	Lab experiment using microspectrophotometry using single-beam, wavelength-scanning instruments that simultaneously record average and polarized transmitted fluxes as a function of wavelength.	Five spectrally distinct visual pigments found in each retina associated with four cone types and a fifth in rods: mean wavelength of peak absorbance: Rods = 521 nm, UV cones = 366 nm; blue-absorbing = 434 nm; green-absorbing = 527 nm; red-absorbing = 574 nm.
Novales-Flamarique and Hawryshyn 1993	Measure UV light levels in coastal waters of Vancouver Island under different atmospheric conditions, DOM and chlorophyll concentrations.		all migrating stages	Measured transmission of natural UV light on both east and west coasts of south Vancouver Island during sunny and cloudy conditions.	Minimum UV light levels required to stimulate salmonid UV cone receptors were found at 20 m and 15 m in clear or cloudy conditions dependent upon chl a concentrations. Study developed spectral irradiance profiles at six depths in each cove. Lower UV light levels corresponded with higher chl a concentrations. Navigation using polarized light for sunlight directionality appeared possible even under cloudy conditions.

Salmonid Light Reception

Reference	Study Objective	Species	Life Stage	Experimental Conditions	Findings
Novales-Flamarique and Hawryshyn 1996	Document retinal layer and cone growth during early growth and measure the spectral and polarized light sensitivities prior to and after smoltification.	sockeye	embryo, alevins, parr, smolt hatchery fish	Lab experiments using electrophysiological recording technology and light stimulation from a 300W xenon light source (Oriol), and (2) background channels using 250W tungsten-halogen sources (EJH Spectro).	Embryos possess all five photoreceptor types in alevin or parr (UV, short, middle and long wavelength cones and a rod) with all retinal layers. Smolt sensitivity peaks: UV=380nm, short wavelength=425nm, middle=520nm and long=635 nm.
					Additional rods, cone diameter increases and density decreases occur with development. UV sensitivity diminishes with UV light introduced in background illumination. Under scotopic conditions, the rod driven spectral sensitivity curve peaked at 540 nm. Calculations on minimum angles of separation permit calculation of the maximum distance at which a young fry at 30 mm FL could locate a prey item of 1.2mm in length. This calculates to be a maximum distance of 78 mm. It is possible that the previous UV sensitive cones transform into rod cones. This loss of UV sensitivity parallels the shift in behavioral ecology from UV absorbing zooplankton to larger invertebrates and small fish.
Parkyn and Hawryshyn 1993	Characterize polarization sensitivity in rainbow trout.	non-anadromous wild rainbow	smolt (8-10 grams)	Lab experiments measuring ganglion cell responses from axons in the optic nerve. 250W tungsten halogen (EJH Spectro) using interference filters (Corion) w/ Uniblitz controlled 750 ms light shutter from a 150W xenon lamp (Oriol).	Under scotopic conditions, no sensitivity to e-vector was apparent. Under photopic conditions, parr exhibited e-vector sensitivity. UV stimulus (380 nm) on white background evoked a 3-peaked (90 and 180 degree) response to e-vector orientations. Medium and Long wavelength cones showed maximum sensitivity only to 90 degree plane, and short wavelength cones showed no polarization sensitivity. Removal of the UV portion of the spectrum impairs the ability of the fish to orient.

APPENDIX D

Synopses of direct sources of information on impacts of overwater structures on
migrating juvenile salmon

Bravender, B.A., S.S. Anderson and J. VanTine. Juvenile salmon survey. 1996. Discovery Harbor Marina and surrounding nearshore area, Campbell River B.C. Pacific Biological Station. Nanaimo B.C. Document #SSCFS97131023E.

REGION: Canada **SPECIES:** ck,ch,pk

STUDY OBJECTIVES: Assess distribution and abundance of juvenile salmon within and outside Discovery Harbor Marina on Discovery Passage in B.C.

METHODS: Purse and beach seines within marina, outside marina and in estuary. Mark and recapture.

RESULTS: Salmon were predominately found at shallow ends of breakwater near thick zooplankton areas. 100 seines were undertaken with 47 inside marina, 44 outside marina and 9 in estuary. Catches: pinks 23,088 with 22,267 of these outside the marina; chums 7,869 with 6,190 outside the marina; chinook (mkd)10,030 with only 444 inside marina; chinook (unmkd) 12,899 with 5,949 of these inside the marina. Rockfish and perch schooled in deeper areas while salmon were found mainly in shallow areas.

Burdick, D.M. and F.T. Short. 1995 The Effects of Boat Docks on Eelgrass Beds in Massachusetts Coastal Waters. Waquoit Bay National Estuarine Research Reserve. 30 pp.

Study Objectives: Determine: 1) the direct physical effects of docks to eelgrass in Waquoit Bay and Nantucket Harbor, including displacement and reduction of light availability, and 2) assess the overall area lost by docks.

Methods: Measurement, identification and comparison of extent and type of eelgrass beds, past and present, using aerial photography. Measurement and analysis of dock areas and characteristics over a variety of dock types and uses. Light data measured by spherical quantum sensor.

Light: Developed descriptive equation models for predicting eelgrass bed quality based upon dock height and dock axis bearing and upon % light under dock and dock width. Basically, north-south docks require less height to mitigate light impacts than east-west docks and reduced % light can be mitigated by a combination of dock width and dock height.

Findings: Height of the dock over the marine bottom was the most important variable for predicting the relative light reaching the eelgrass and for predicting eelgrass bed quality under the docks. With increased dock height, the intensity of shading from a dock diminishes because sunlight has a greater distance to diffuse and refract around the dock surface before it reaches the eelgrass canopy. Docks oriented north-south admit more light providing better support for eelgrass, due to its angle with the arc of the sun and the consequent decreased shadow period.

The strongest observed impact adjacent to docks was disturbance to bottom sediments from boat propellers. In general, their findings support narrow docks, greater than 3m over the marine bottom with a north-south orientation to mitigate light reduction, extended to the edge of the navigable channel to reduce prop damage to pose the least impacts to eelgrass beds.

Cardwell, R.D., S.J. Olsen, M.I. Carr, and E.W. Sanborn. 1980. Biotic, water quality and hydrologic characteristics of Skyline Marina in 1978. Washington Department of Fisheries, Technical Report 54.

Region: PNW **Species:** co, ck, ch, pk, herring

Study Objectives: Document impacts on zooplankton, fish, prey, water quality. Appraise pollutant accumulation in shellfish and sediments. Assess relationship of impacts to flushing and marina design.

Methods: Purse seine, mark and release, plankton nets, spectroscopy and polarography oyster analysis. Spectrophotometry analysis for chlorophyll and plant carotenoid concentration. Sediment analysis included AAS, combustion, extraction and reflux. Study compared water quality, fish, and fish prey abundance and distribution of marina waters with outer bay. Measured variables included water temperatures, salinity, pH, dissolved oxygen levels, chlorophyll and ammonia concentrations and nitrite-nitrate and ortho-phosphate levels.

Results: Majority of coho, chinook and herring were caught in marina where primary prey existed. Majority of chum and pink caught in bay where their primary prey existed. Chum appeared to have a median residence of 1 week or less. Prey resource appeared to determine distribution of species.

Coho, chinook prey were teleost larvae, brachyura and were predominately in the marina. Pink and chum prey primary prey were calanoid copepods predominately in bay. Predation judged to be low due to lack of fish and bird predators present during peak salmonid migration periods.

Oysters in marina were high in copper and zinc concentrations. Perhaps due to leaching from boat bottom paints.

Conclusions: Marina water significantly warmer and more oxygenated than the bay. Among the lowest water exchanges in Puget Sound. Surface zooplankton were less dense and rich in marina than in bay with several holoplanktonic species absent in marina. Water quality expected to change considerably between neap and spring tide cycles.

Fresh, K.L., B. Williams, D. Pentilla. 1995. Overwater Structures and Impacts on Eelgrass in Puget Sound, Washington. Puget Sound Research '95 Proceedings.

STUDY OBJECTIVES: Impact Assessment. Determine if small single-family residence docks cause a decline in eelgrass densities under and adjacent to piers and assess if the use of gratings mitigate the impacts.

METHODS: Empirical: eelgrass density was measured under and adjacent to a selection of seven "single-family" dock sites in Puget Sound from Roche Harbor to South Hood Canal. Baseline measurements and one year of post-project monitoring were also taken for five sites to assess effectiveness of mitigating impacts with grating.

OBSERVED DENSITY DECLINES: Six out of the seven sites selected to measure declines without mitigating construction methods demonstrated measurable declines and/or absence of eelgrass growing under the docks. The one site that did not show measurable impact appeared to have a mitigating aspect to its structure as the dock moved up and down and side to side with tidal fluctuations.

Four of the five structures evaluated for alternative mitigating construction methods demonstrated eelgrass densities decline when compared to undisturbed reference areas. At the fifth structure site, eelgrass density increased but increased substantially less than it increased in the reference area.

COMMENTS: Preliminary results support the hypothesis that shading is the major cause of eelgrass density loss. This is demonstrated by significant reductions in density under docks and diminished reductions under docks with grating used to mitigate shading impacts. Structure length, height over the bottom, design, orientation, and local environmental conditions (i.e. current patterns) may also play a role in the nature and extent of impact.

Loflin, R.K. 199. The Effects of Docks on Seagrass Beds in the Charlotte Harbor Estuary. A report to the city of Sanibel, Florida. unpublished report.

Study Objectives: Determine the condition of seagrasses in the vicinity of existing docks with that of adjacent natural grassbeds.

Methods: Twenty-seven docks over grassbeds were studied at Sanibel Island. These sites were selected based on the presence of extensive shallow grass flats. Seagrass shoot density and percent were measured and correlated to placement relative to the dock (i.e. under dock, adjacent to dock and prop-dredged area).

Findings: Multiple regression analysis was completed using total area of seagrass shadow for total dock area. Only total area was significantly correlated with shadow area. No significant correlation was found between dock width or height and seagrass loss. Dock orientation did not significantly affect the total area of seagrass shadow. Considering Sanibel Island with 87 platted single family lots and 24 multi-family buildings, if these lots/buildings each had one associated dock, an estimated 1.43 ha (3.54 acres) of seagrass would be impacted (not including prop-dredging effects). Areas where seagrass was removed by prop scarring were associated boat lifts. Variation in epiphytic algal loading on grass blades appeared to be related to dock orientation, with less algae growth on the more shaded side of the dock.

The authors concluded that the proliferation of docks in SW Florida over shallow grass flats appears to have important adverse effects on marine seagrasses contributing substantially to seagrass losses.

Comment: Other studies have demonstrated a significant correlation with dock height, width and seagrass loss. It is unclear why this study differs from those findings. Perhaps the difference lies in a difference in turbidity between different study areas.

Olson, A.M., S.D. Visconty and C.M. Sweeney. 1997. Modeling the shade cast by overwater structures. University of Washington. School of Marine Affairs. SMA Working Paper-97-1.

Region: PNW **Species:** Eelgrass

Study Objectives: Mitigation Planning. Designing a tool to quantitatively define the impacts of shade on eelgrass and specifically address how overwater structures effect the underwater light environment and how the light environment effects eelgrass health and abundance.

Study Method: Developed **computer shade modeling** by constructing a three-dimensional model, to predict the light environment at the Clinton ferry terminal, using computer-assisted design software, dock dimensions, bathymetry, piling configurations, latitude, longitude, date and time. The resulting image represents a snapshot of the shade cast on the benthos at a specific location, date and time. Shadows were rendered for December 21, June 21, and March 21 at half-hour intervals between 10 am and 2 pm and produced a map representing the daily light budget.

Using In situ light meters to gather data on submarine light environment at the Clinton terminal and test the ability of the shade model to predict the light environment. Used HOBO light intensity data loggers at four benthic stations of varying shade magnitudes which were monitored for two week periods in March and April 1996. The light intensity data was converted to photosynthetically active radiation (PAR). In an attempt to relate in situ light levels to eelgrass requirements, measures of daily integrated irradiance (DII) and irradiance exceeding saturating (Isat) were calculated to predict light levels that sustain eelgrass productivity at each of the four stations.

Conclusions: Assuming that eelgrass has a minimum DII for plant growth, it appears that there is enough light for eelgrass to survive during the test period for all but the 100% shaded station. In attempt to compensate for a possible over-estimation of irradiance with DII a measure of the number of hours exceeding saturated irradiance was used using two hypothetical values: 1) a winter-adapted value and 2) a summer-adapted value. Using winter-adapted plant saturating irradiance, it appears that there is enough light to sustain eelgrass at the unshaded station but not enough at the 100% shaded station and during April, light at the 37.2% and 62.5% shaded stations appeared to be sufficient. Assuming plants adapted to summer conditions, it is likely that there is not enough light to support eelgrass growth and reproduction at any of the stations in either month.

The combination of untested measurement technologies and the paucity of data on Pacific Northwest eelgrass makes it difficult to evaluate with any scientific certainty whether a given level of in situ irradiance is sufficient for eelgrass growth. This research gap will need to be filled in order to answer the original research questions.

Parametrix Inc. and Battelle Marine Sciences Laboratory. 1996. Anacortes Ferry Terminal eelgrass, macroalgae, and macrofauna habitat survey report. Report for Sverdrup Civil, Inc. and WSDOT. 12 pp.

REGION: PNW **SPECIES:** eelgrass, macroalgae, macrofauna

STUDY OBJECTIVES: Mitigation/Impact Assessment. Conduct an eelgrass, macroalgae, macrofauna survey at the existing terminal and evaluate the physical and biological features of potential mitigation areas.

METHODS: **Empirical:** eelgrass dive survey, quadrat. Information gathered included substrate type, percent cover of macroalgae, number of eelgrass shoots, eelgrass density and kelp count. **Observational:** presence/absence and abundance of macroinvertebrate and vertebrate species.

EELGRASS RESULTS: In general, the greatest densities occurred 20 and 50 m from shore. The inner eelgrass boundary is found at about 15 to 20 m from shore where depths exceed -3m. Maximum eelgrass densities occur between -.3 and -1.2 m MLLW. The maximum depth at which appreciable densities of eelgrass were recorded was about -3 m MLLW. Densities west of terminal exceeded densities east. Eelgrass directly under the dock is nearly non-existent. Overwater walkway showed few indications of effects on eelgrass presumably due to the height (6 to 11 m above MLLW) and width (3.75 m) Main and auxiliary docks had no eelgrass presumably due to dock height (5 m above MLLW).

RESULTS-WEST SIDE: Substrate of boulder, cobble and gravel between +1.8 and +0.3 m MLLW. Below MLLW the substrates consist of coarse sand, sand and shell debris. From about -2.4 MLLW outward, this area has a 33 percent slope. Dominant macroalgae species included ulva and fucus distichus. Kelp was observed below MLLW. Eelgrass was observed in highest densities at -0.3 to -1.2 m MLLW with moderate to dense epiphyte growth including brown diatoms and red algae. Benthic macrofauna included barnacles, limpets juvenile sculpin, red rock crab, and Dungeness crab.

RESULTS UNDER FACILITY: Cobble and gravel substrates in upper intertidal area to sand, fine sand, and shell debris below MLLW. No macroalgae was observed except for a small patch of ulva. Kelp was observed attached to a piling with low densities of eelgrass at -0.3 and -1.2 m MLLW. Macrofauna included Dungeness crab, sculpins, anemones, red rock crab, starfish, kelp greenling, gaper claims, nudibranchs and a helmet crab.

RESULTS-EAST SIDE: Cobble and gravel substrate with sand matrix above MLLW and fine sand and silt below MLLW. Dominant macroalgae were fucus disticus and ulva. Low to moderate eelgrass between -0.3 and -2.1 m MLLW with heavy epiphytic growth. Macrofauna similar to rest of study area.

CONCLUSIONS: Areas east and west of existing facility offer potential mitigation sites to allow for natural eelgrass colonization with changes made to accommodate to the impact of propeller backwash. The major eelgrass impacts are associated with initial dock construction, shading and propeller wash including the creation of a clay bench under the facility resulting from ferry backwash eroding sand and silt substrates. Backwash has changed the intertidal slope at -2.4 MLLW. Significant areas are available for eelgrass restoration adjacent to the terminal and with modifications of the terminal design.

Pentilla, D. and D. Doty. 1990. Progress Report. Results of 1989 Eelgrass Shading Studies in Puget Sound. Washington Department of Fisheries, Marine Fish Habitat Investigations Division.

REGION: PNW **Species:** eelgrass

STUDY OBJECTIVES: Mitigation/Impact Assessment. Determine effects of direct shading on marine vegetation community, in particular beds of eelgrass.

METHODS: Empirical: quadrat, diver eelgrass surveys. Three Puget Sound study sites with littoral zone structures were selected on the basis of the presence of homogenous eelgrass, homogenous bottom topography and bottom topography unaffected by the construction or long term presence of the structure itself. The sites were surveyed for assessment of plant stature and counts per area during July-September 1989. A qualitatively different fourth site was also sampled at an intertidal eelgrass bed near an "oyster rack" culture structure.

FINDINGS: All fixed dock structures reduced eelgrass density to zero even when visual light attenuation did not approach full darkness with little or no evidence of impacts on the stature of the surviving plants. The oyster rack site also significantly reduced eelgrass density from 244.5 plants per m² to 10.6 plants per m² directly beneath racks. In contrast, the floating dock site with the chained-anchor moorage system that allowed a swing with wind and tidal currents showed no negative impacts on the density of the eelgrass in the structure's vicinity. This may be due to the flexible nature and movement of the dock and the resulting lack of shading cast continuously over any given bottom area.

CONCLUSIONS: The authors concluded that construction of partially shading types of structures, floating or on pilings, can be expected to largely eliminate the existing macroflora with little chance for replacement plant growth on new introduced solid structures. Algae species also appear to be impacted by shading structures. Other impacts they would expect over time include: altered sediment distribution and topography along piling lines, tidal drainage streams created by topographic changes, and substrates in the immediate vicinity of piling structures to be enriched with calcareous debris from barnacles and mollusks inhabiting the structures hard surfaces.

They suggest future studies of designs and orientations of fixed structures that might mitigate habitat damage. They recommend: 1) no fixed floating structures of any kind over herring spawning grounds vegetation, 2) fixed elevated structures over littoral zones should be designed to eliminate shade impacts, 3) elimination of net loss vegetation and structural shading, including moored vessel shadow, should be considered by WDF policy, mitigation techniques, and case-by-case design consideration, 4) seasonal fixed structure should not be permitted over littoral zone vegetation beds in excess of 6 continuous weeks, and 5) further field studies should be undertaken on dock designs that can reduce or eliminate shading.

Shreffler, D.K. 1993. Fisheries surveys for the proposed commercial boat marina in Neah Bay, Washington, January-June 1993. Battelle/Marine Sciences Laboratory, Sequim, Washington. Report prepared for the Makah Tribe, Neah Bay, Washington. Contract # 19823.

REGION: PNW **SPECIES:** ch, ck, sculpin, sole flounder, smelt, flatfish, rockfish, greenling, lingcod, sand lance.

STUDY OBJECTIVES: salmon surveys to determine the relative abundance and distribution and run timing of species using the bay during spring seaward migration. Baitfish surveys to determine if sand lance or surf smelt spawn on site beach. Zooplankton surveys to determine presence or absence of sand lance and surf smelt larvae in water column at proposed site.

METHODS: Sediments screen for fish eggs. Plankton tows for zooplankton. Juvenile salmon surveys used beach and purse seines.

FINDINGS: Peak chum fry caught on March 13, 1993 and no capture after May 6, 1993. Previously pink and chinook were caught in low numbers in 1984 and none in 1993.

CONCLUSIONS: Proposed marina should have no direct impact on spawning of herring, sand lance or surf smelt. Impacts to juvenile salmon are more difficult to predict but juvenile salmon were not abundant in the bay during seaward migration.

Simenstad, C.A., R.M. Thom, K.A. Kuzis, J.R. Cordell and D.K. Shreffler. 1988. Nearshore community studies of Neah Bay, Washington. Report to U.S. Army Corps of Engineers. University of Washington. Wetland Ecosystem Team. Fisheries Research Institute. FRI-UW- 8811. 114pp.

Region: PNW **Species:** Macrophyte, fish, benthic macroinvertebrate epibenthos, pelagic zooplankton assemblages.

Study Objectives: Impact assessment in response to proposed projects to develop intertidal and subtidal areas for log shipping and commercial fishing boat moorage. In the context of the proposed projects, evaluate the functions and relative importance of nearshore macrophyte habitats: 1) compare fish and invertebrate assemblage structure and standing stock between macrophyte and non-macrophyte habitats, 2) evaluate the function of these macrophyte habitats, 3) document seasonal variation in structure, production and function of macrophyte habitats, 4) evaluate functional contributions of macrophyte communities to adjacent, non-macrophyte habitats, and 5) hypothesize and estimate consequences to nearshore communities of macrophyte habitat loss and/or degradation in habitat quality. Study is organized around five basic components: 1) fish and motile macroinvertebrate assemblages, 2) epibenthos and pelagic zooplankton assemblages, 3) benthic infaunal macroinvertebrates, 4) macrophyte assemblages, and 5) ecological interactions.

Study Methods: Beach seine, purse seine, Otter Trawl, benthic grab sampling, epibenthos pump sampling, infaunal bivalve suction pump sampling, underwater transect surveys, quadrats, oxygen flux measurements for net seaweed primary productivity estimates for four sites: Baadah Point, Evans Mole, Crown Z, and Turning Basin.

Fish and Motile Macroinvertebrates Results: Baadah Point showed 40 fish species, twice the number of species observed at other sites, with increased diversity in numerical composition and no one species predominating. While, at Evans Mole Pacific staghorn sculpins dominated at 44%, and at Crown Z. shiner perch dominated for 73% of the standing crop of fishes. Four species of juvenile Pacific salmon occurred: chum, coho, chinook and pink. Chums were collected at all sites in May and July 1986 and March 1987. Coho and pink were captured in July and were abundant at the Baadah Point end of the Bay. Chinook occurred at all sites in September.

Epibenthos Results: harpacticoid copepods were the predominant organisms at all sites except near the Crown Z. dock, comprising 55% of the numerical composition at Baadah Point at 0.0. m and 83% at Baadah Point subtidal Z. marina. In contrast the Crown Z. dock was not dominated by any single taxa. Rather, dominance was shared by unidentified invertebrate eggs.

Pelagic Zooplankton Results: 1) harpacticoid copepods were prominent at Baadah Pint and at the head of the bay, but not at Crown Z. dock and Evans Mole, 2) calanoid copepods were abundant at head of the bay and Evans Mole, 3) barnacle were numerous at Crown Z dock and Evans Mole, and 4) crab zoeae occurred in moderate numbers at all sites except the head of the bay.

Benthic Taxa Results: Gammarid amphipods, polychaete annelids, and bivalves were prominent. Polychaetes and bivalves were the most prominent taxa in biomass. Eleven taxa of infaunal bivalves were identified. Macroinvertebrate infauna densities were similar across sites.

Habitat Utilization Results: herring, smelt, sand lance and salmonids appeared extensively as juveniles but showed no site specificity. Dungeness crabs appeared to move around within the Bay with highest densities at Evans Mole and Crown Z in July and September. Juvenile, sub adult, and adult shrimp at various depths and sites across the bay. Densities of shrimp species were highest near the mouth of the bay.

Factors Affecting Epibenthos and Pelagic Zooplankton Structure and Standing Stock: Epibenthic/epiphytic harpacticoid copepods predominated at Baadah Point and Head of Bay. While more planktonic, barnacles, calanoid copepods and crab zoeae predominated at Evans Mole and Crown Z. sites. Epibenthic harpacticoids were particularly high in September in Z. marina beds at head of the bay while low abundances were found on the Z. marina at Baadah Point which receives higher wave energy.

Trophic Relationships Between Fish and Zooplankton: Macrophytic habitats, such as Z. marina, represent direct and indirect sources of fish prey resources due to the unique associations between seagrasses, seaweeds, kelp and prey organisms (i.e. harpacticoid copepods and amphipods). Harpacticoids occur in the diets of many juvenile fish and are characteristic of seagrass and other habitats with epiphytic diatoms and microalgal growth. Indirectly, eelgrass and other macrophytes support epibenthos and other detritivores by the production of detritus.

Macrophyte Assemblages and Net Primary Productivity: Baadah Point represents a rocky outcrop with a species-rich, abundant and productive seaweed-dominated habitat. Crown Z. and at the Head of the Bay had few species and generally less abundant algal flora with the exception of the dense stand of eelgrass immediately south of the Head of the Bay. Substrata differences, exposure to currents, and present and historical levels of disturbance may explain differences among sites. Baadah

Point at head of bay receives nutrient rich inputs. Due to the geomorphic structure of Baadah Point benthic scouring does not tend to occur and the community is relatively undisturbed by sediment movement. This could explain the stable seaweed community developing at this site. Due to cliffs and small freshwater stream at Head of the Bay, sediments are fine and cover much of the bottom with no rocky outcrops. Therefore, shifting sediments play a greater role in regulating assemblage structure. Crown Z. site biologically impoverished state is anomalous due to increased turbidity, lower tidal exchange, log bashing, log storage and debris.

Conclusions: Deepening the channel would not likely change the Bay's primary production potential as increased residence time would likely increase phytoplankton and zooplankton production. However, secondary benthic production would probably shift qualitatively to less diverse, polychaete-dominated assemblages characteristics of deeper, finer sediment habitats and potentially decrease production of specific taxa between the turning basin and other habitats. Decreased current velocities at the entrance and eastern region of the Bay would increase deposition of fine sediment and detritus east of the turning basin and extend the deposit-feeding assemblages.

However, loss and disruption of habitat by dredging and filling for the marina could significantly decrease diversity and production of macrophyte, demersal fish, motile macroinvertebrate, epibenthos and benthos diversity, and production with the magnitude dependent upon the site chosen.

Short-term Effects of Dredging and Filling: Release toxicants from benthic sediments, increase turbidity during dredging and modify natural environmental characteristics such as sound and light which impact behaviors in pelagic fish. Fish would avoid an of abnormally high sound and turbidity. Therefore, if the dredging operations were to occur between March and October, the result could be the exclusion of pelagic fishes from planktonic food resources. Dredging at the mouth of the bay could effectively close off the bay to any immigration during the periods of operation.

Taylor, W.S., W.S. Willey. 1997. Port of Seattle Fish Migration Study. Pier 64/65 short-stay moorage facility: Qualitative fish and avian predator observations. Draft report to the Port of Seattle prepared for Beak Consultants Inc. May 1997.

Region: PNW **Species:** juvenile chum, chinook, and coho salmon

Study Objectives: Impact assessment. Monitoring the effects of Pier 64/65 moorage development upon juvenile salmonid migration behavior and rates in Elliott Bay, during the summer of 1996 to determine if juveniles successfully negotiated and migrated past the facility through a fish opening and whether avian predators were concentrating within the facility as a result of its construction.

Study Methods: Dockside and underwater observations during peak outmigration period. Observations took place at two-week intervals over a period of four months to cover temporal differences throughout the outmigration period. These observations were made twice daily for a total of seven days, totaling 14 underwater and 14 dockside observations over the four month period. These observations were qualitative and not quantitative.

Fish Results: Chum, chinook and coho migrate through the Pier 64/65 facility. Their observed migration pattern was the typical Green/Duwamish River migration from south to north. Occasionally fish were observed migrating north to south or making no net migration progress. This lack of progress could have been due to disorientation/confusion from moorage facility structures. Only chinook and coho juveniles were observed passing through the fish openings. However, chum were present around the fish passage. Peak outmigration was observed in May with a subsequent decline in numbers throughout the summer. This pattern is assumed to reflect the chum outmigration period. **Chum** were the most actively migrating fish found in schools between 25 and 300-500 ranging in size from 50 to 80mm. These schools were always oriented 2-15 feet from the shoreline or other moorage facility structure and tended to be oriented to the surface down to 10-foot depth. Conversely, **chinook** and coho were frequently alone. Chinook were first observed in late May, increasing in observed numbers to a peak in late June, and declining to 0 in late July. Chinook schools were between 10 and 50 fish with sizes ranging from 150 to 250mm. The chinooks showed a slower migration rate with frequently no net migration at all. Chinooks were usually found at a depth of between 5 to 20 feet with little time spent near the surface.

Avian Predator Results: Unusual congregations of avian predators were not observed. There was no indication that avians were feeding at a greater rate around or within the facility. The surveys observed no predatory avians near the fish opening. Bird species observed were typical for the Elliott Bay shoreline. Species included Western grebes, belted kingfishers, gulls and mergansers. A total of 24 birds were observed during the study period. Predatory birds were not observed during the height of the salmon outmigration (May-June). Rather avians were observed diving and catching fish within the facility during April. Gulls were never observed feeding fish. They were observed feeding on starfish and crabs. The most prevalent predatory bird species observed in June and July was the belted kingfisher. Two kingfishers were observed flying back and forth between the harbor master's office and the seawall. They were not seen catching or eating fish, but they were apparently building nests and roosting.

Conclusions: Fish migrated successfully through the facility in a south-north pattern typical for the Puget Sound area. Fish migrated through the fish passage opening. They tended to use the shoreline and edges of facility structures and/or shade cast by structures. Avian predators did not appear to be unusually concentrated within or around the facility. Considerable fish predation was not observed. Avian fish predation were not observed during the peak of outmigration. Avians observed were typical for Elliott Bay.

Thom, R.M., A.B. Borde, P.J. Farley, M.C. Horn and A. Ogston. Battelle Marine Sciences Laboratory. 1996. Passenger-only ferry propeller wash study: threshold velocity determinations and field study, Vashon Terminal. Report to WSDOT. PNWD-2376/UC- 000. 15+pp.

REGION: PNW **SPECIES:** Eelgrass

STUDY OBJECTIVES: Impact assessment. Determine critical current velocities that damage eelgrass and compare experimental flume data with a field verification study at the Vashon Passenger-only Ferry Terminal documenting current velocities, suspended sediment concentrations and PAR.

METHODS: Empirical: controlled flume experiment at Battelle Laboratory to assess currents that damage eelgrass leaves and rhizomes. The successive treatments were not independent rendering cumulative eelgrass with each treatment. **Empirical: on-site field investigation** of actual bottom current speeds were measured at various prop speeds and at various distances from the ferry, covering the predicted region of bottom impact over various speeds. Instruments used included velocimeter, backscatter sensor and PAR data logger, digital compass and tilt sensor.

VELOCITY IMPACTS: Bottom currents were increased from 2 to 30 cm per second by prop speeds of 550 rpm and 750 rpm at 32 m from the boat. While bottom currents increased at 750 rpm and slightly for 1000 rpm at 57 m from the boat. At the nearest station, only prop speed of 550 rpm increased bottom currents. Prop wash reached the bottom nearer the ferry at slower prop speeds. Conversely, at higher prop speeds, the wash contacted bottom further behind the boat. The prop's spiraling effect and bottom impact resulted in high variability in currents along the horizontal axis. This turbulence is likely to stir up bottom sediments and disrupt eelgrass and other benthic organisms. Temporal variability was great between prop speeds and prop-induced current speeds across varying distances from the boat.

LIGHT IMPACTS: PAR decreased with increasing prop speed: 30% at 550 rpm, 50% at 750 rpm and 70% at 1000 rpm. The greatest impacts were at the sites closest to the boat. The reduction in transparency was due to increased suspended matter and bubbles which increased with increased prop wash. The reflective nature of the prop bubbles resulted in some higher PAR values with at 550 rpm than at 0 rpm. It is also possible that suspended matter settles out of the water column prior to the dissipation of the bubble plume. The findings suggest that the shading from the ship's hull may be more important than prop wash in reducing light.

SUSPENDED MATTER IMPACTS: At 41 m from the boat, a slight increase in bottom current speeds resulted in a slight increase in suspended matter. The pass-over runs did not affect suspended matter. The depth of the water (6.7m) prevented the wash plume from affecting the bottom sediments.

THRESHOLD VELOCITIES (flume studies): Current speeds on the order of 50-80 cm per second potentially erode eelgrass patches with speeds over 180 cm per second severely damaging patch edge. Cumulatively, the erosive events remove sediments from the root rhizome system and expose below ground plant parts to degradative processes. The eelgrass mat did not completely erode at the greatest velocities tested, suggesting a significant capacity to remain in place despite erosive prop wash forces. Repeated erosion and changes to sediments around the plants can result in plant death or meadow migration. Eelgrass depends upon biogeochemical processes in the sediments to maintain its growth. Sediments also protect the plants from drying and animal foraging.

Conclusions: Current speeds over 180 cm per second could severely damage the edge of an eelgrass patch. However, eelgrass patches in Puget Sound can survive tidal currents velocities as great as 200 cm per second. The displacement of sediments brought on by increased currents threatens the integrity of the plant. Effects varied with both distance and prop speed with lower prop speeds increasing bottom currents close to the vessel and higher prop speeds increasing currents away from the vessel. The net effect of high turbulence may be important in loosening sediment particles and eroding eelgrass. A mean of the 30 greatest velocities measured may be more indicative of the erosive stresses of ecological significance. These maximum and mean velocities should be factors when designing ferry terminal setback. At 57 m from the boat, it is likely that the prop wash has little effect on the existing eelgrass. The strongest correlation was between propeller speed and PAR. This indicates that increased prop speed increases suspended matter and bubbles that lower bottom light levels. Increased prop speed increases the light reduction impact which is manifested at increasing distances from the boat.

Weitkamp, D.E. and T.H. Schadt. 1982. 1980 Juvenile salmonid study, Port of Seattle, Washington. Unpublished report by Parametrix, Inc. to Port of Seattle, Seattle, Washington. 43 pp + appendices.

Region: PNW **Species:** chinook, coho, pinks, chum juvenile salmon

Study Objective: Describe the behavior of juvenile salmonids migrating or rearing along the shorelines of the lower Duwamish Waterway and Elliott Bay comparing juvenile salmonid behavior in semi-natural shorelines to their behavior in highly modified shorelines. This behavior was to be described by the timing and duration of their presence. The area covered included the mouth of the Duwamish Waterway up to RM 5.1.

Study Methods: Beach seine of semi-natural shorelines with 6 substrate types: mud with scattered debris, muddy sand w/ mud and debris at lower intertidal level, entirely mud, faintly sloping mud with rip rap at higher tide level, predominantly sandy gravel w/ scattered large rocks, and compact sand at higher intertidal level with mud and scattered debris at lower intertidal levels and purse seines at concrete and wood pile sites.

Chinook Results: Mid-May- peak juvenile chinook outmigration The juvenile chinook were captured most frequently at muddy sand w/ mud and debris at lower intertidal level habitat site. Throughout the month of May their mean size of 71-74mm remained constant reflecting either a low rate of growth or a steady movement of similarly sized fish moving through the area. A comparison of beach seine to purse seine catches indicated that :1) juvenile chinook utilize the shallow shoreline habitat more than the deep water habitat, 2) larger fish inhabit water having greater depth during the outmigration. Chinook caught in Elliott Bay were 10-15mm larger than those in Duwamish waterway. No discernible difference in temporal and size distribution between juvenile chinook at locations along Elliott Bay. Large number of chinook caught May 5th and 6th possibly due to release of 3 million on April 21st.

Chum Results: April chum size constant at 39-40 mm. May-August: steady increase from 40 to 81. Source for chum predominately wild. During peak residency in Elliott Bay-av chum size 41- 46mm. Twice as many chum caught at gently sloping mud w/rip rap habitat than sandy gravel and compact sand habitat.

Pink Results: No pinks in waterway only in Elliott Bay. Probably migrated from a source other than Duwamish waterway. Their size range 40-47mm during last week of April to first week of May.

Coho Results: Collected in low numbers in May but absent by the first of June. The coho catch numbers showed no evidence of waterway residency but rather a concentrated migration through the waterway to Puget Sound.

Feeding Behavior Results: Stomach content analysis using IRI to rank prey importance ran from March 27th to July 1st 1980. Waterway diets were high in Diptera while Puget Sound diets were high in calanoid and harpacticoid copepods. Beach seine chum showed diptera and harpacticoid predominance. While purse seines showed almost entirely to be calanoida. Comparing samples by size and diet: 30-39mm--> Harpacticoid 58.5, Diptera 39.9; 40-49mm-> Harpacticoida 68.2 and Diptera 18.9 and Gammaridae 2.2. 50 and above no harpacticoida and increasingly more calanoida with sizes of 80-89. Purse seines for chum: high calanoida values and no harpacticoida. Pinks' diets were very similar to chums without diptera which was correlated to prey within the waterway. Chinook Results: Diets comprised of calanoids brachyura and diptera with no harpacticoida indicating substantial feeding on pelagic as opposed to epibenthic feedings. Note: the size of chinooks were 71-118mm The diet difference is probably due to size difference and the ability to handle the mobility and body morphology of the brachyura.

Chum (30-49mm) - harpacticoids and dipterans; larger chums (50-79mm) - calanoid copepods (pelagic)

Weitkamp, D.E. 1982. Juvenile chum and chinook salmon behavior at Terminal 91, Seattle, Washington. Report by Parametrix Inc. to Port of Seattle, Washington 21 pp.

REGION: PNW **SPECIES:** salmon

STUDY OBJECTIVES: Mitigation/Impact Assessment. Determine how shoreline oriented juvenile salmonids behave in the immediate vicinity of existing piers. Study site: Port of Seattle's Piers 90 and 91.

METHODS: Observational: visual observations by two boat observers, followed by SCUBA observations along selected pier apron portions where juvenile salmon were observed were compared to beach seine results. **Empirical:** beach seine sampling from two intertidal shoreline sites, without piers, east and west of the Pier 90/91 complex. The study period was coordinated with an expected optimum outmigration period at this location between May 11th and May 28th.

OBSERVED FEEDING: In summary, the surveys observed juvenile salmon distribution to be predominately on the west side of the piers and in the west open, sun-exposed sites in the Pier 90 apron. The study results do not distinguish between the sizes of juveniles observed, limiting its size differential to less than 75mm in length. This overlooks a key size differential in juvenile salmon feeding and prey resources. Fish were reportedly feeding in schools of 20 to several hundred in the water column from biota scraping off from boom logs tied to apron piles and from around outside rows of pier apron piles.

OBSERVED LIGHT REACTIONS: The juveniles were reluctant to pass beneath the pier apron into darkened areas. There was a very marked, significant and consistent difference between the numbers of juveniles observed on the east side of the piers compared to the west side and the juveniles observed in the west sun-exposed opening compared to the east opening. The study makes note of this but does not discuss the possible meaning indicated in these differences which are likely to be related to differences in the amount of sunlight consistently received providing increased food resources and visibility to feeding juveniles.

OBSERVED FISH SIZES: As the study does not distinguish between sizes any smaller than 75mm, it overlooks an important difference in available feeding resources. Without this information, and given the knowledge that smaller juveniles ranging 45mm and less tend to feed from smaller prey resources available in greater abundances in specific nearshore habitats, the conclusion that juveniles did not quickly pass by the docks in search of more appropriate prey sites is not supported. Although habitat at their beach seine sites is described as very desirable for juvenile salmon, actual prey resources available within those habitat are not identified. Without information on specific prey resource availability, habitat desirability to specific sizes of juvenile salmonids is largely left unknown.

BEACH SEINE FISH SIZES: The beach seine catches sizes ranged 40-86 mm.

COMMENTS: The conclusion that juveniles do feed in habitat along the pier aprons is supported by the existence of feeding juveniles along pier aprons. However, as the floating log booms appear to be a major source of prey, this conclusion is limited in its ability to be applied more generally to piers without log booms attached.

Weitkamp, D.E., and Williams, G.T., Epibenthic Zooplankton Production and Fish Distribution at Selected Pier Apron and Adjacent Non-apron Sites in Commencement Bay, Washington . Report to the Port of Tacoma. March 1991. 32+ pp.

REGION: PNW **SPECIES:** salmon

STUDY OBJECTIVES: 1) Assess the quality of foraging habitat for juvenile salmon in pier apron areas versus non-apron areas of similar substrate type in Sitcom and Blair waterways. The major goal being to assess differences in productivity between apron and non-apron habitats and adjacent areas with otherwise similar conditions by measuring epibenthic abundances, and 2) determine if juvenile salmon and other fish species use the apron habitats.

METHODS: Empirical: epibenthos sampling taken before, during and after peak juvenile salmon outmigrations between March 24th and June 9th, from six stations at two tidal levels, by epibenthos suction pumps. Thirty replicates were taken at each station each day with ten from each tidal level.

RESULTS: Out of 91 identified taxa, ten major epibenthic prey taxa were identified with the most abundant being harpacticoids, Tisbe, and *Harpacticus uniremus*. Non-apron sites had the highest average prey and epibenthos abundances with the -2 ft tide levels having more prey and total epibenthos than the +2 ft tide levels.

In the Blair Waterway, most apron stations differed significantly in abundance from non-apron stations. Two stations averaged 45-46% more prey production in non-apron paired stations, one pair showed that the aproned station produced more epibenthic prey than the non-apron, one pair was equal. Differences were due to different substrates, slopes, and seasonal differences in epibenthic life cycles. Although the analysis of epibenthos abundance and community structure differences between apron and non-apron stations was complicated by differing slopes and substrates, in general, non-apron stations had significantly higher total epibenthos and prey epibenthos than their paired apron stations. In Sitcom abundance ratios of apron to non-apron were .86:1 for total epibenthos and about .84:1 for prey taxa. In sitcom, the ratio averaged about 1:1 at +2 tide and .68:1 at the -2 ft tide level. In Blair, 5 of the 6 comparisons had ratios ranging from .02:1 to .69:1 for apron to non-apron samples. The stations with the highest epibenthos and prey abundances were substrates with considerable gravel and sand with a slope of 10:1 and no rip rap.

For small juvenile chum and pink salmon, the harpacticoid copepods, *Harpacticus uniremus* group and Tisbe spp. are probably the most important prey zooplankters (Simenstad et al. 1988, Parametrix, 1991.) The community niche of Harpacticus and Tisbe differ somewhat. Tisbe are found where there is abundant detrital vegetation, whether that detritus is under an apron or not. Harpacticus seems to be primarily epiphytic on growing algae and eelgrass (Simenstad et al. 1988; D'Amours 1987). Therefore, Harpacticus is unlikely to be found under pier aprons, because they prefer substrate that cannot grow in low-light conditions. It was concluded that it was more important to influence substrate type and slope than the presence or absence of aprons as epibenthos are more abundant in apron habitats, if they are provided with a beach that has a gentle slope with a small particle-sized substrate.

COMMENT: The conclusion that substrate slope and size is more important than apron or non-apron does not hold true for the Harpacticus Copepod which is the most important prey zooplankton for juvenile chum and pink salmon.

APPENDIX E

Assessment of all information on impacts of overwater structures on estuarine and nearshore marine habitats and fishes

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Burdick, Short The Effects of Boat docks on Eelgrass beds in Massachusetts Coastal Waters 1995	EG	Impact Assessment 1) determine effect of docks to eelgrass. 2) assess overall area lost by docks.	Dock height, width, axis bearing, density & extent of eelgrass bed, percent available light	Variety: fixed & floating (20 dock structures in estuary)	Eelgrass				Dock height, width and orientation impact EG quality & light availability	Dock features impacting light availability and EG quality correlates to light available for PP. Sediments disturbed and scoured by prop scouring	Dock height is #1 variable for predicting light availability to EG and EG quality. Strong sediment disturbance by props. Recommend: narrow docks (over 3m above bottom, north- south orientation, dock placement

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Cardwell, Olsen, Carr and Sanborn. 1980. Biotic Water Quality and Hydrologic Characteristics of Skyline Marina in 1978.	co, ck, herring	Impact Assessment. Empirical. Document impacts on zooplankton, fish, food habits, water quality. Appraise pollutant accumulation in shellfish and sediments. Assess relationship of impacts to flushing and marina design.	Marina fish and zooplankton prey abundances and distribution compared to bay. Measured waters for temperature, pH, D.O., chlorophyll, ammonia, nitrite-nitrate and orthophosphate. Presence of copper and zinc in sediments and shellfish.	Marina	Sand, gravel silt and clay bottoms. depth mainly <20 ft below mean lower low water. Oyster, salmon and herring habitat.	Majority of co, ck herring were caught in marina where primary prey existed. Majority of chum and pink caught in bay where primary prey existed. Chum appeared to have a median residence time of 1 wk or less.	Feeding appeared to determine distribution of species.	Predation judged low due to lack of fish and bird predators present during peak salmonid migration period.		Oysters in marina were high in copper and zinc concentrations. Perhaps due to leaching from boat bottom paints.	Marina water significantly warmer and more oxygenated than the bay. Among lowest water exchanges in Puget Sound. Surface zooplankton were less dense and rich in marine than bay with several holoplanktonic species absent.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Dames & Moore and Biosonics. Salmon Migration Study Manchester Naval Fuel Pier, Manchester WA 1994.	ch	Impact Assessment Observe & empirical. observe beach & purse seine and soundings. 1) Determine impact of pier on juvenile salmon migratory patterns and predation risks.	1) number of salmon 2) species, size and length 3) position of location and observed fish	Fuel Pier	EG/Sand	Migration dependent upon preferred prey resource availability. Most catches and observations were nearshore.	Movement believed to be dependent upon prey resources in eelgrass beds.	No determination of pier causing increased or decreased levels of predation.	No observed shade avoidance		The physical design and consequent limited shadow casting capacity of this pier diminishes its impact on prey habitat and limits the ability to generalize its effects to piers with substantially increased shadow casting attributes.
Fresh, Williams, Pentilla Overwater Structures and Impacts on Eelgrass in Puget Sound. 1995	EG	Impact Assessment Empirical- quadrats 1) determine if small single-family docks cause a decline in EG density under and adjacent to piers. 2) assess mitigating construction techniques.	EG density, dock length, width, and orientation.	Single Family Docks	EG				Shade significantly reduces EG density	Reduced PP from light limitations dependent upon site factors, dock design and dock usage. Changes in community structure and substrate due to dock and piling structures	Findings support the hypothesis that shading is the major reason for decreased eelgrass density around docks. Docks significantly reduce EG density unless mitigating construction techniques are used. Size of shading impact dependent on dock characteristics.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Heiser and Finn, 1970. Observations of Juvenile Chum and Pink Salmon in Marina and Bulkheaded Areas	ch, pk	Observational fish; empirical water quality	Number of juvenile salmonids and predators observed in and around marina areas. Water depth, temp, salinity, DO, turbidity, and pH.	Marinas	Docks, bulkheads and breakwaters	Pink and chum concentrated inside marinas. Juvenile chum and pinks (35-45mm) reluctant to leave shoreline areas to venture along bulkheads or breakwaters. Sizes 50-70mm moved offshore and into deeper waters in response to large pier.		Unable to derive actual predation rates. Concluded that visual observations of predation indicated discouraged due to human presence.			Water quality measurements were empirical. But fish observation was cursory observation. Predation conclusion based on very little evidence.
Loflin, The Effects of Docks on Seagrass Beds in the Charlotte Harbor Estuary, 1993.	Seagrasses	Impact Assessment. Empirical. plant count /surveys. Determine condition of seagrass near docks.	Seagrass density	27 private single boat docks, most with terminal platforms & lifts	Seagrass				Seagrass reduced by dock shadow	Epiphytic algal loading on seagrass blades reduced by dock shadow. Lift area sediments scoured and seagrasses removed by prop action	Study concludes that docks contribute substantially to seagrass loss. Total dock area was significantly correlated only to shadow area. In contrast to other studies, dock orientation did not correlate significantly to seagrass shadow.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Olson, Visconti and Sweeney. Modeling the shade cast by overwater structures. SMA working Paper 97-1	EG	Mitigation. Designing a tool to quantitatively define shade impacts of overwater structures on eelgrass.	Shadows cast per to dock dimensions, bathymetry, piling configs., latitude, longitude and time of day.	Ferry Terminals	EG				Assuming a minimum DII and/or a winter adaptation for eelgrass. This makes it difficult to assess how overwater structure shade impacts eelgrass.	There is an information gap on the in situ irradiance requirements of PNW eelgrass. This makes it difficult to assess how overwater structure shade impacts eelgrass.	
Pentec Environmental Inc. Movement of Juvenile Salmon through Industrialized Everett Harbor. 1997	ch	Impact Assessment. 1) Determine juvenile salmon migration around piers. Do they migrate outside piers into deeper waters to avoid piers? Do they turn and head back significantly delaying their migration?	Observation 1) number of fish observed. 2) observed species, observed school size, 3) observed migration direction, 4) observed distance from shore	Industrial piers	2h: 1v slope riprap & cobble/ gravel	Fish encountering piers milled around w/ no net gain for 5-2 hrs. Greatest number of schools and largest schools observed at shorelines. Fewest schools seen at piers. Schools were smaller at piers. Most pierside observations at shoreline end of piers	Feeding observed along shores not piers.	Observed predators: cormorant and larger salmonid	Dark areas used for refuge.	Feeding observed in open beaches.	Study concluded the net effect of juvenile salmon encountering overwater structures was impossible to assess with available data. Upon encountering piers, fish split up and moved around piers. Interferences on under pier behavior were not empirically substantiated.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Penilla, Doty Results of 1989 Eelgrass Shading Studies in Puget Sound. 1990.	EG	Impact Assessment Observation Determine effects of direct shading on EG and other marine vegetation.	EG densities, EG plant height and width, EG bed area, tidal elevation, dock height, width, length, distance from pier.	Vary: fixed, floating, refinery, private moorage and oyster racks)	Eelgrass				Fixed docks can reduce EG densities to zero depending on dock features.	Net loss in vegetation with shading. EG and macroflora eliminated and, algae species impacted with little chance of replacement growth. Community structures altered by pilings through changes in topography, tidal drainage and calcareous debris from crustaceans occupying pilings and surface.	Study concluded that overwater structures shading littoral zones can be expected to largely eliminate existing macroflora with little chance for replacement plant growth. Dock designs can mitigate some impacts.
Prinslow, Whitmus, Dewan, Bax Snyder and Salo, 1979. Effects of wharf lighting on outmigrating salmon.	Ch, pk	Assess the effects of wharf lighting at the U.S. Naval Submarine Base Banor on outmigrating salmon in Hood Canal.	Fish abundance, distribution, survival and residence time through mark and recapture and hydro-acoustic monitoring, stomach content analysis. Light response measured under 2-13 lux and 200-400 lux.	Naval Submar. Base	Deep bay purse seining and tow net. Nearshore wharf habitat impacted by artificial lighting.	Light intensities of 200-400 lux appeared to attract and delay chum for 1-2 days while lower intensities (2-13 lux) did not. They may have also remained in area due to food availability. Too few tests to conclude delay cause.	Prey availability appeared to possibly delay salmon migration. Too few tests to conclude.	Insignificant predation detected (i.e. <4%) of predators caught contained salmonid remains. Few implicated predators were observed as present.	Artificial lighting possibly delayed migration at high intensities (200-400 lux). Lower intensities appeared to result in no large scale aggregation.		

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Ratte, Salo, Under-Pier Ecology of Juvenile Pacific Salmon (Oncorhynchus spp.) in Commencement Bay, Washington. 1985.	ch, ck, co	Impact Assessment. Empirical-net traps, lab. exper. and trammel nets. Assess ecology of juvenile salmon under piers. Particularly behavior in relation to light availability and ship berthing.	Juvenile salmon species identified and counted. Salmonid predators counted, measured (length & width) and stomach analysis. Measured photoresponse time in laboratory lighting experiments	Industrial ship berths	Dredged and filled industrial waterway	Fish seemed to prefer dark, nearshore environment when lights were off. Some fish headed to outer pier edge when lights were on. Chum appeared impartial to either nearshore or offshore under-pier habitat. Fewer chum caught with ships present.		Predators appeared to be less abundant in shaded habitat. "Potential" predator stomach analysis showed no prey item to be juvenile salmonid.	Light chamber experiments: pinks preferred dark side over lighted side for 50% of trials w/ random fish distribution between light and dark sides.		Results based on a very low numbers of fish, including predators, caught. Environment under these piers is very dark, if not entirely dark with ships berthed.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Shreffler, 1993. Fisheries surveys for the proposed commercial boat marina in Neah Bay, Washington January-June 1993.	chick sculpin, sole, flounder, smelt, fetfish, rockfish, greenling, g., lingcod, sand lance	Impact Assessment. Empirical. Salmon surveys: determine the relative abundance distribution and run timing of species using the bay during spring seaward migration. Baitfish surveys = determine if sand lance or surf smelt spawn on beach of site. Zooplankton = quantify fish	Fish and fish larvae abundance and distribution.	Proposed Marina	Nursery or rearing area for herring, surf smelt and sand lance.	Peak chum fry caught on March 13, 1993 and no capture after May 6, 1993. Previously pink were caught in low numbers in 1984 and none in 1993.					Proposed marina should have no direct impact on spawning of herring, sand lance, or surf smelt. Impacts to juvenile salmon are more difficult to predict. But juvenile salmon were not abundant in the bay during seaward migration.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Simenstad, Thorn, Kuzis, Cordell and Shreffler Nearshore Community Studies of Neah Bay, WA, 1988.	Benthic, epi-benthic, pelagic, macrophyte, fish, macro-inverts.	Impact Assessment. Empirical - epibenthos, quadrats, stomach content, beach & purse seine, trawl, grab samples. Evaluate the functions, contributions, variations and degradation consequences of macrophyte habitats.	Abundance density, standing stock, distribution, composition, and size of fish, epibenthos, macroinvertebrate and pelagic zooplankton, and IRI of fish prey. Macrophyte assemblage structure, stock and percent cover. NIPP	Fishing and log shipping.	EG, water column, silty sand, clear sand, rocks, laminaries, ulva, thick silt wood chips and detritus.	Migrating juvenile salmon use bay's prey resources. Dredging activities expected to alter fish migration during dredging hours.	Supports diverse fish assemblages including juvenile salmon.			Dredging and breakwater construction would substitute intertidal and shallow subtidal areas for deeper water communities. NPP patterns would shift with secondary benthic production shifting to a less diverse, polychaete-dominated assemblage. Macrophyte habitat, rocky outcrop with species-rich, abundant productive seaweed habitat, cobble field w/algal dominated assemblages and	Loss and disruption of habitat by dredging and filling could significantly decrease diversity and production of macrophyte, demersal fish, mollie macroinvertebrate, epibenthos and benthos diversity and production.
Taylor and Willey Port of Seattle Fish Migration Studies: Pier 64/65 Short-Stay Moorage Facility. Qualitative Fish and Avian Predator Observations. 1997.	ch	Impact assessment. Monitoring effect of moorage facility on migrating juveniles. Determine if they successfully negotiate and migrate past the facility and if avian predators are concentrating in the facility.	Observed and estimated fish abundance, school size, fish size, bird abundances and notes on fish activity.	Small short-stay public marina	Rocky, cobble	Juv. Salmon appeared to migrate through facility in a south-north pattern through the fish passage opening using shorelines and edges of dock structures.		No unusual congregation of avian predators. Observed. Grebes & mergansers seen catching fish in April. Observed avian predators were grebes, mergansers, kingfishers and gulls.			Fish migrated through the facility using the shoreline and edges of facility structures. No unusual congregation of avian predators observed within or around the facility. Considerable fish predation was not observed. No avian predation at peak migration.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Thom, Borde, Farley, Horn, Ogston Passenger-only Ferry Propeller Wash Study: Threshold Velocity Determinations and Field Study, Vashon Terminal, 1996.	EG	Impact Assessment: Empirical Lab. exper. & field research. Determine critical current velocities that damage EG.	Bottom current velocities, prop rpm, suspended sediment concentrations, PAR (photosynthetically active radiation), distance from boat experimental flume currents, shoot count, sediment changes	Ferry Terminal	EG				PAR decreased with increased prop speed. Greatest shade impacts closest to boat. Findings suggest that shedding from ship's hull may be more important than prop wash in reducing light.	Light limitations, erosive sediment changes, and scouring from prop backwash and hull shading can eliminate EG beds. Benthic plant communities are impacted by changes in light, sediments and currents. Indirectly, disturbed benthic plant communities impact benthic fauna.	Prop speed impacts available light and causes sediment erosion. Current speeds of 50-80 cm/s erodes EG and speeds over 180 cm/s can seriously damage EG. Repeated erosion and changes to sediments around plants can result in plant death or meadow migration.
Thom, Simenstad, Cordell, Solo Fisheries Mitigation Plan for Expansion of Mooreage at Blaine Marina, Blaine, WA, 1988.	ch, ck, co	Mitigation Assessment: Empirical. Determine existing prey habitat and evaluate potential mitigation alternatives available to counter impacts of proposed elimination of high intertidal mudflats habitat for the expansion of Blaine Marina.	EG, epibenthos, salmon, fish and crab densities, Fish species richness, Vegetation standing stock.	Marina	EG, Mudflats (w/wo slope), Salt marsh.		Salmon densities reflected epibenthic & plant densities.	High fish densities with high vegetation cover		Chlorophyll a values measured & compared across 3 habitat types. Epibenthos and fish densities reflecting changes in chlorophyll a measures and vegetation increases. Comparative analysis of assemblages across 3-4 habitat types: epibenthos densities change with changes in vegetation	Removal of 14 acres of high intertidal mudflats mitigated on a habitat value translates into 3 acres of eelgrass habitat based on expected increases in prey abundance, food web support, duration of prey, foraging and refuge availability.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Thom, Simenstad, Cordell and Salo. Fish and their epibenthic Prey in a Marina and Adjacent Mudflats and Eelgrass Meadow in a Small Estuarine Bay. 1989	EG, epibenthos fish, salmon, crab	Impact assessment. Determine the relative importance of marsh, protected mudflats, exposed mudflats, and EG habitats to fisheries resources in the bay.	Densities and abundance of epibenthos (salmon prey), fish and crab. Fish species richness, Chlorophyll a concentration. EG biomass and standing stock. Salinity and water temperature.	Marina	EG, mudflats w/wo slope, and salt marsh	Maximum density of juve. salmon immediately followed prey density peak juv. Salmon using the harbor were transient rather than resident.	Salmon density followed prey (nauplioid copepod) density trends.			Changes in vegetation, primary salmon prey energy source and refuge, reflected light & heat availability with increased energy benthic algal microflora & chlorophyll a and epibenthos and salmon flux. Epibenthos densities mirrored chlorophyll a and vegetation densities.	Fish assemblages in EG habitat consistently contained increased species richness over the mudflats. Mudflats received sun energy earlier in season with less wind producing increasing algal production and standing stock. Salmon densities MF:EG=1:8.
Weitkamp, Shact. 1980 Juvenile Salmonid Study, Seattle, WA. 1982.	ck, ch pk co	Empirical. Beach seine, purse seine, stomach analysis. 1) Describe the behavior of migrating juvenile salmon in the lower Duwamish Waterway and Elliott Bay 2) Compare juv. Salmon behavior in semi-natural versus highly modified	Fish size, species, length	Industrial	Mud/debris mud/sand, mud/slope mud/ripraps andyrock co impact sand	ck-juveniles use shoreline-May peak. ch-mud/riprap-May-Aug Pinks - PS only-late April-early May	30-49mm fish fed on nearshore epibenthos 50-89mm fish fed more on pelagic zooplankton 80+ mm fish diet was all pelagic.				Chinook - mid May peak at constant size (71-74mm) reflecting low growth or steady movement CK used shallow shoreline. April Chum (39-40mm) with steady increase to 81 mm. Peaks in early April and May. Coho in May only. Pinks 40-47mm in late April-early May.

Overwater Structure Studies

Reference	Spp.	Study Objective	Variables Measured	Dock Types	Habitat	Migration	Feeding	Predation	Light	Prey Resources	Comments
Weikamp, Williams Epibenthic Zooplankton Production and Fish Distribution at Selected Pier Apron and Adjacent Non-apron Sites in Commencement Bay, WA, 1991.	ch,ck sculpin, sole, flounder, smelt, fluffish, rockfish, greenling, g., lingcod, sand lance	Impact Assessment: Empirical. epibenthos pump sampling. 1) Assess productivity differences between apron and non-apron sites. 2) Determine if juvenile salmon use apron habitats.	Abundance and identity of epibenthic prey taxa.	Industrial Pier (Port of Tacoma)	Sand /gravel & rock riprap			no predators observed	reduced light availability reduced prey abundance	Although non-apron sites had significantly higher total epibenthos than apron sites, it was concluded that substrate type and slope were the major influencing factors. Primary salmonid prey, harpacticoid, prefers light-dependent algae-eelgrass substrate. General species diversity was low w/ apron vs non-apron diversity differing slightly	Study concludes that it was more important to influence substrate type and slope than apron presence/absence. Determining factor is the presence/absence of a gentle slope with a small particle-sized substrate.
Weikamp Juvenile Chum and Chinook salmon Behavior at Terminal 91, Seattle, WA 1982.	ch,ck	Impact Assessment: Empirical & Observational. Determine how shoreline oriented juvenile salmonids behave near Port of Seattle Piers 90 and 901.	Fish count species, length	Industrial (Port of Seattle)	Muddy sand/gravel rock riprap	Inconclusive. Juveniles reluctant to pass under piers except under areas open to light.	Feeding on west side of piers & near log booms				The study's conclusion that juveniles fed along pier aprons should be qualified by the fact that pier-side floating log booms provided a major source of prey. The actual prey resource and size of observed juveniles is not specified.

APPENDIX F

Synopses of information sources on juvenile salmon predation associated with overwater structures

Overwater Structures and Juvenile Salmonid Predator Patterns

Studies Exploring Salmonid Predation

Dames & Moore Inc. and Biosonics, 1994 Salmon migration study Manchester naval fuel pier, Manchester, Washington. March-June 1993. Report to U.S. Navy

This study attempts to assess the impact of the Manchester fuel pier upon the outmigration of juvenile chum, specifically addressing whether outmigrating salmonids ignored the pier, altered or delayed their course of migration, or encountered predation due to the pier. Their methods included observational and inferential data from combined hydroacoustic soundings, visual observations, and seining. From the data, it was inferred that the pier's shadow did not appear to alter migratory patterns. Migratory behavior was believed to be dependent upon preferred prey resource availability in eelgrass beds on both sides of the docks. No significant stalling or movement offshore was apparent. No direct evidence of increased predation was present. Although 13 predators were identified in the area, there was no determination of increased or decreased levels of predation in relation to the pier. It is important to note that the physical design (i.e. pier height and width, number and types of pilings) and consequent shadow casting capacity of this pier diminishes its impact on nearshore prey habitat.

Taylor, W.S. and W.S. Willey. 1997. Port of Seattle fish migration study. Pier 64/65 short-stay moorage facility: qualitative fish and avian predator observations. Prepared for Beak Consultants, Inc. Draft report to the Port of Seattle.

This study attempts to assess the effects of Pier 64/65 moorage development on the ability of outmigrating juvenile salmonid to successfully negotiate and migrate past the facility through a fish opening. It also sought to determine if avian predators were concentrating within the facility as a result of its construction. Study methods consisted of dockside and underwater observations twice daily for a total of seven days (14 observations) at two-week intervals over a four-month period.

Unusual congregations of avian predators were not observed. There was no indication that avian predators were feeding at a greater rate around or within the facility. The surveys observed no predatory avians near the fish opening. Bird species observed were typical for the Elliott Bay shoreline. Species observed included: western grebe, belted kingfishers, gulls, and mergansers. A total of 24 birds were observed during the study period. Predatory birds were not observed during the height of the salmon outmigration (May-June). Rather, avians were observed diving and catching fish within the facility during April. Gulls were never observed feeding on fish rather they fed on starfish and crabs. The most prevalent predatory bird species observed in June and July was the belted Kingfisher. Two kingfishers were observed flying back and forth between the harbor master's office and the seawall. They were not seen catching or eating fish, but they were apparently building nests and roosting.

It was concluded that fish migrated successfully through the facility in a south-north pattern typical for the Puget Sound area. Fish migrated through the fish passage opening and tended to use the shoreline and edges of facility structures and/or shade cast by structures. Avian predators did not appear to be unusually concentrated within or around the facility. Considerable fish predation was not observed. Avian fish predation was not observed during the peak of outmigration and the avians observed were typical for Elliott Bay.

Pentec Environmental, Inc. 1997. Movement of juvenile salmon through industrialized Everett Harbor. Report to Port of Everett.

This study attempts to assess juvenile salmonid migration around Port of Everett finger piers in Everett Harbor. It sought to determine if salmonids migrate under piers, go outside of piers into deeper waters, or

turn and head back, thereby delaying their migration upon encountering a pier. Their methods were observational from piers and shorelines consisting of 3 gradual slope riprap or cobble gravel shorelines, 3 vertical bulkhead shorelines, 9 pier sites at Piers 1 and 3 northeast of Berth 1. Sampling occurred between 4/9-5/6/97. The greatest number and sizes of schools were observed at shorelines. The second largest were at bulkhead sites. The fewest and smaller schools were at pier sites, with the highest percentage of pierside observations being at the shoreline end of the piers. Feeding was only observed at shoreline sites. Observations included two predator reactions at the base of Pier 1. These incidents consisted of a cormorant catching a fish with the remaining fish diving and swimming under a barge ramp, and a large 40 cm salmonid passing by and the school of juveniles closing ranks and darting towards shore in response.

Upon encountering pier bases and the ends of piers, the fish milled around moving north then south with little net gain in movement for long periods of time. The study inferred from the lack of schools observed at pier sites, the variation in school sizes, and the observed splitting up of schools upon encountering piers that salmonids, upon encountering piers, split up with some moving out around the pier and others moving under the pier. The study concluded that the net effect of piers was impossible to assess with available data. It was inferred that their lack of pierside observations suggest that fish perhaps move faster under and around piers.

Prinslow, T.E., C.J. Whitmus, J.J. Dawson, N.J. Bax, B.P. Snyder, and E.O. Salo. 1980. Effects of wharf lighting on outmigrating juvenile salmon. University of Washington. Fisheries Research Institute. Report to the U.S. Navy. FRI-UW-8007.

This study attempts to assess the effects of wharf lighting at U.S. Naval Submarine Base-Bangor on outmigrating juvenile salmon in Hood Canal, specifically addressing: 1) the effects of security lights on the distribution and abundance of outmigrating juvenile chum and their potential predators in the wharf area; 2) the predation rate on juvenile chum by means of stomach analysis of potential predators; 3) the relative attraction of juvenile chum and potential predators to different wavelengths and intensities of light; 4) the survival of chum smolts during migration out of Hood Canal, and 5) the residence time of chum at the wharf. Study methods consisted of net sampling, observations, and hydroacoustic monitoring in areas adjacent to the wharf.

The brighter intensity lights appeared to attract and delay chum from their normal migration timing. It was speculated that the chum were attracted by the lights and upon finding prey at the lighted site, delayed at the site. Predation rate (measured by purse seine, beach seine and townet catches of pelagic piscivorous predators and their gut contents) was insignificant with lights on or off (bottom-dwelling piscivores - rockfish, ling cod, cabezon were not sampled). Predation was considered insignificant as <4% of predators caught contained salmonid remains and very few known salmonid predators were present. Therefore, it was concluded that the attraction and delay did not appear to harm the salmon.

Prinslow, T.E. and N.J. Bax. 1980. Predation at the Explosives Handling Wharf: analysis of purse seine, beach seine, and townet sampling for chum and predators.

Study attempts to assess impacts of wharf lighting on chum predation. Study methods comprised of purse and beach seines, townets, hydroacoustics, and visual observations. Predators were considered to be any fish above 15 cm caught by seine or townet. This included chinook, coho, cutthroat, dogfish, hake and sculpin. The security lights at the Explosives Wharf attracted juvenile chum and potential predators leading to higher densities of both fish at the "lit" wharf.

Security lighting at EHW had a localized temporary effect of attracting outmigrating chum. Predation on chum by piscivores was insignificant. Piscivores included adult salmon, trout, hake, sculpin, and dogfish.

Ratte, L.D. and E.O. Salo. 1985. Under-pier ecology of juvenile Pacific salmon (*Oncorhynchus* spp.) in Commencement Bay, Washington.

This study attempts to assess the effects of light reduction under piers on the habitat of juvenile salmon including the role of shading in predation on juvenile salmonids. Although structures can provide refuge for prey and predator alike, most juvenile salmon predators use vision to feed, and, therefore, the reduction in light could hinder their efforts to locate prey. Abundance of potential salmonid predators (based on catches) were low. Predators were less abundant in the shaded habitat. Stomach analysis of potential predators did not have a single prey item identifiable as juvenile salmonids. Predation on juvenile salmonids by predatory fish species was not intense at sample sites.

Heiser, D.W. and E.L. Finn, Jr. 1970. Observations of juvenile chum and pink salmon in marina and bulkheaded areas. Washington Dept. of Fisheries. Supplemental Progress Report. Puget Sound Stream Studies.

Juvenile chum and pink salmon were observed during their estuarine rearing in and around Puget Sound marinas. Very small juveniles (35-45mm) were reluctant to leave shoreline areas such as bulkheads and breakwaters. Larger fish (50-70mm) were willing to move away from the shorelines. Inside marinas, the fish tended to disperse along all shorelines and docks.

Gregory, R.S. 1993. Effect of turbidity on the predator avoidance behavior of juvenile chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences. Volume 50, number 21, pp. 241-246.

This study explores questions concerning the effects of turbidity on predator avoidance behavior in turbid water: 1) whether turbidity affects the response of juvenile chinook to the presence of a predator, and 2) whether turbidity affects the post exposure duration of this response. These questions were explored in controlled laboratory experiments using models of a glaucous-winged gull and a dogfish as two general salmonid predators. Study results supported the notion that salmonids perceived turbid conditions as "cover" from predators which suggests that turbid conditions may reduce predation on juvenile salmon.

Simenstad, C.A., K.L. Fresh, and E.O. Salo. 1982. The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon: an unappreciated function. Estuarine Comparisons.

This synopsis itemizes estuaries used by Pacific salmon and reports that evidence of significant predation in Washington's estuarine and nearshore marine habitats is lacking. However, it is possible that mortality rates due to predators is significant. Marine birds and mammals may represent significant sources of predation mortality. While juvenile salmon are common prey for the rhinoceros auklets at Protection Island, Pacific salmon show low incidences in the stomach contents of Pacific harbor seals and orca, who appear to prefer subadults and adults. The synopsis does report that impacts to primary production due to turbidity from suspended sediment loads can reduce the effective euphotic zone, thereby limiting prey availability. Such prey limitations carry the potential of reducing juvenile growth and changing residence times causing fish to forage over wider areas or leave the estuary prematurely in search of sufficient densities of prey. In this manner, the estuary's carrying capacity for juvenile salmon is reduced.

