A Review of Some of the Effects of Reduced Dissolved Oxygen on the Fish and Invertebrate Resources of Ward Cove, Alaska

for

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March 6, 2003

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Acknowledgments

This review could not have been completed in the short time that it was needed without the outstanding literature research support from Ikuyo Fredrickson and Olga Shargorodska of ASRC Aerospace Corp., contractors for the EPA Region 10 library. I also appreciate the assistance of four Region 10 colleagues: Lorraine Edmond and Michael Watson for their review comments on the preliminary draft, Peter Leinenbach for the spatial analysis used to develop the dissolved oxygen contours for Figure 2, and Jennifer Wu for assistance throughout this project.

Dave Sturdevant, of the Alaska Department of Environmental Conservation, and Susan Walker, Linda Shaw, Lawrence Peltz, and Robert Stone of the Alaska Regional Office of the National Marine Fisheries Service reviewed the July 17, 2002 draft and provided many helpful suggestions.

Executive Summary

This review was conducted to provide a better understanding of the likelihood of adverse effects of depressed dissolved oxygen on aquatic resources in Ward Cove, a small embayment adjacent to Tongass Narrows near Ketchikan, Alaska. Water quality monitoring from 1998 to 2002 found that dissolved oxygen levels less than 4 mg/l commonly occurred in Ward Cove during the summer and early fall. During this time, hypoxic conditions (dissolved oxygen <2 mg/l) occurred occasionally at and near the bottom and less frequently in midwater areas. Field and laboratory studies for species similar to those inhabiting Ward Cove indicate that sublethal and lethal effects begin at dissolved oxygen levels of approximately 4 mg/l and 2 mg/l, respectively.

Aquatic resources at risk in Ward Cove include the subadult or adult stages of eight anadromous salmonids, approximately 75 non-salmonid estuarine and marine fish species, and a benthic invertebrate fauna. Adult salmonids will usually avoid hypoxic conditions, except when staging to enter freshwater during their annual spawning migrations. Salmonids encountering prolonged hypoxic conditions in Ward Cove may sustain sublethal effects like reduced reproductive success. More severe hypoxic exposures in combination with low flows and high water temperatures in Ward Creek may result in adult mortality. Juvenile salmonids out-migrating from Ward Creek appear to move through the cove prior to the onset of depressed dissolved oxygen conditions.

Non-salmonid estuarine and marine fish are considerably less sensitive than salmonids to depressed oxygen levels and can also avoid hypoxic conditions. However, some species and life stages of fish with low mobility residing in Ward Cove can be adversely affected by depressed oxygen. Non-mobile benthic invertebrates are similarly affected. Lethal exposures are believed to have occurred for some of these organisms as hypoxic conditions persisted for at least 14 days during 1998 and 1999. Sublethal stress more commonly occurred as dissolved oxygen levels less than 4 mg/l persisted within the cove from early August to mid to late September during 1998, 1999, and 2002.

1.0 Introduction

Ward Cove, a small estuary adjacent to Tongass Narrows, is located approximately 5 miles north of Ketchikan, Alaska. Ketchikan Pulp Company (KPC), formerly located on the north shore of the cove, discharged pulp mill effluent to the cove from 1954 until March 1997. During approximately 43 years of handling logs and discharging wastes, much of the bottom of the cove was covered by pulp residues, sunken logs, and other wood wastes (Exponent 1999). A fish processing plant, located on the south shore, has been discharging fish wastes to the cove since 1912 (Sturdevant 2002). In recent years, it usually operates only during a salmon season that begins in July and continues through mid-September.

Water circulation is restricted within the cove. A counter-clockwise circulation brings Tongass Narrow water into the cove along the south shore. Modeling indicates that the average residence time for water in the cove is 15 days (Rodriguez 2002). Site specific information on dissolved oxygen (DO) in Ward Cove was obtained during water quality surveys conducted from November 1995 to October 2002 (U.S. EPA 2003). This monitoring found that the water column is strongly stratified during the summer resulting in poor mixing of bottom water across the well defined thermocline. Ward Creek, which enters the head of the cove, drains a 14-square mile basin and has a mean annual stream flow that varies from 28.3 to 173 cfs (USGS 2002)

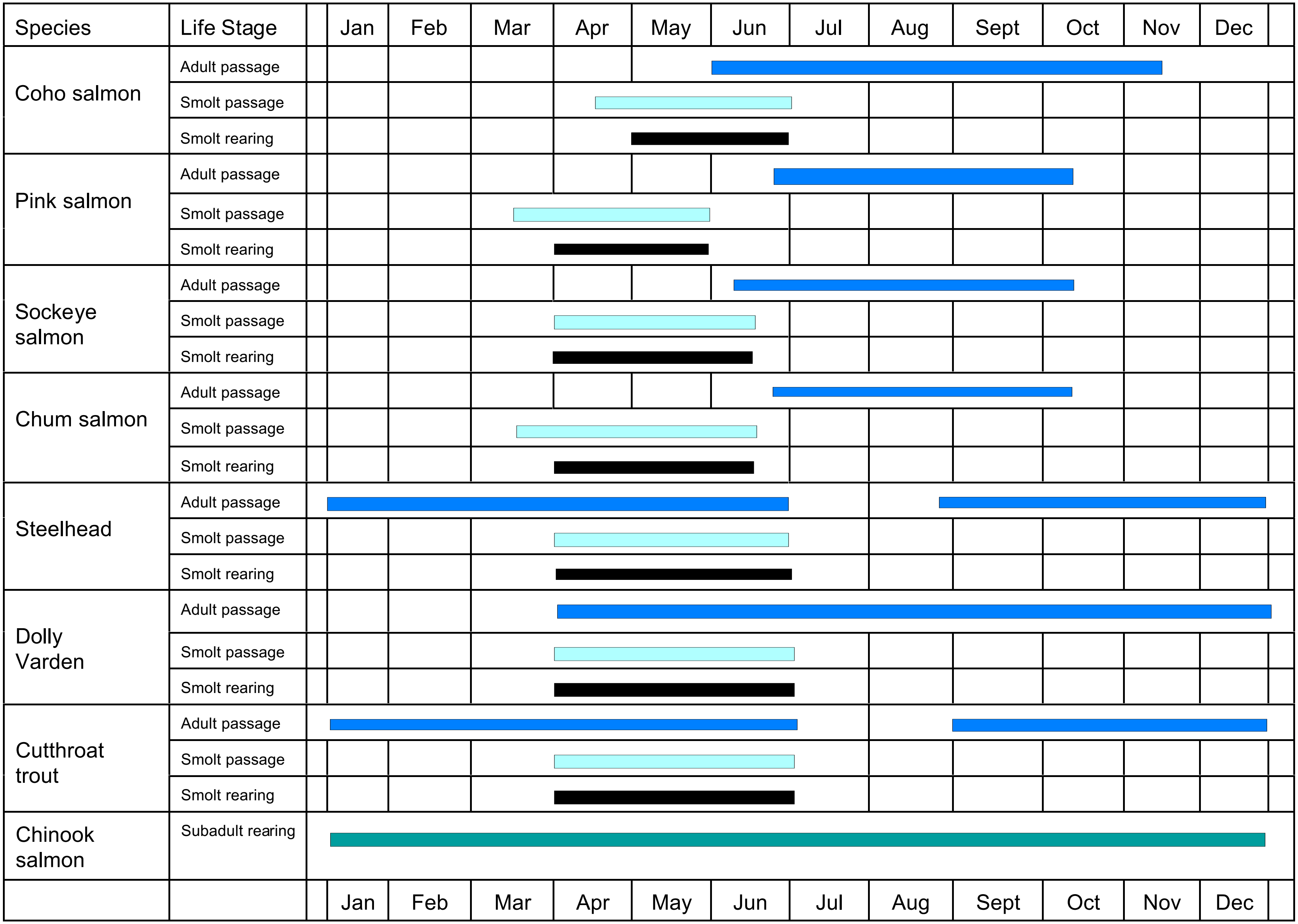
Starting in the late 1950s, reduced DO concentrations and periodic fish kills occurred in Ward Cove (Kruse and Viteri 1988). Jones & Stokes Associates (1989) estimated that about 95% of the BOD (biochemical oxygen demand) loading came from KPC's discharges. Water quality improved with the cessation of these discharges in March 1997; however, subsequent surveys measured DO concentrations <4 mg/l within Ward Cove during the summer from 1997 to 2002 (U.S. EPA 2003). The Alaska water quality standard for minimum DO in Ward Cove is 5.0 mg/l.

For reference, a normal oxygen level (normoxia) for the surface waters of Ward Cove is approximately 8 mg/l at a salinity of 30 ppt and temperature of 10°C. Under natural conditions and vertical stratification, DO levels in deeper waters can vary considerably and be reduced significantly below 8 mg/l by respiration and the decay of organic materials. The results of a limited survey in Ward Cove from October 1951 through September 1952 (prior to KPC), however, found that DO concentrations from the surface down to 30 m in depth did not fall below 7 ppm (Alaska Water Pollution Control Board 1952).

Eight anadromous salmonid species occur in Ward Cove (Figure 1). All are native to Ward Creek except for chinook salmon, which originate from other nearby tributaries (Alaska Department of Fish and Game 1990, Hoffman 2002). In conducting baseline studies in preparation of a plan to modify KPC's effluent discharge system, ENSR (1994) listed 41 fish species potentially occurring in the vicinity of Ward Cove. According to Clemens and Wilbey (1961), Scott and Crossman (1973), Gotshall (1981), Lamb and Edgell (1986), and Kramer et al. (1995), at least 75 non-salmonid fish species may occur within Ward Cove or in the vicinity of the cove in Tongass Narrows. These species are listed in Appendix 1.

Depressed DO, including hypoxia, has a marked effect on many metabolic and behavioral processes in fish. For example feeding, swimming, and migration are restricted by hypoxia (Davis 1975). As a result, fish distribution is affected, growth is reduced, and condition declines making the organism more susceptible to disease and predation. Community-level effects may also occur as fish and benthic invertebrate populations are reduced and change as a result of exposure to hypoxic conditions. In this review, waters with <2 mg/l DO are considered hypoxic.

Figure 1. Periodicity chart for anadromous salmonids in Ward Cove, Alaska (ADF&G 1990, Hoffman 2002).



The purpose of this review is to provide a better understanding of the likelihood of adverse effects on aquatic resources in Ward Cove caused by depressed DO. As site specific information is not available on the effects of depressed DO within Ward Cove, a literature review of studies from other marine and estuarine areas provides the basis for this evaluation. An extensive but not exhaustive literature review was conducted for this assessment. Potential effects will be assessed using site specific water quality information gauged against species-specific information obtained from the literature review.

2.0 Literature Review

2.1 Effects of Low Dissolved Oxygen on Fish Growth

Dissolved oxygen is a limiting factor for fish metabolism and determines growth and activity levels (Brett 1979), and is one of the most important abiotic factors affecting juvenile estuarine fish (Taylor and Miller 2001). Depressed DO may limit fish growth as noted below for salmonid and non-salmonid estuarine and marine fish.

2.1.1 Salmonid Fish

In a review of over 30 laboratory tests on salmonids, JRB Associates (1984) found that the relative sensitivity of each species to dissolved oxygen depletion was influenced by fish size, test duration, temperature, and diet. Overall, growth rate tests on salmon and trout fed unrestricted rations had median growth reductions of 25, 14, and 7% for fish held at 4, 5, and 6 mg/l. However, salmon tended to be more sensitive to reduced DO. The growth rate reductions for juvenile chinook salmon (*Oncorhynchus tshawytscha*) were reduced by 47, 29, and 16%, respectively, at DO concentrations of 3, 4, and 5 mg/l (mean temperature of tests was 15 °C). Similarly, the growth of coho salmon (*O. kisutch*) and sockeye salmon (*O. nerka*) was reduced 37, 21, and 11% and 33, 22, and 12%, respectively, over the same range of DO concentrations (mean temperatures of these tests were 18 and 15 °C, respectively). The water temperature of growth tests is important since growth reductions may be affected less at lower temperatures. For example, Warren et al. (1973) found that the growth rate of coho salmon was about 35% less at 22 °C than at 9 °C at 4 mg/l DO.

2.1.2 Non-Salmonid Estuarine and Marine Fish

In developing national water quality criteria, Chapman (1986) reviewed field and laboratory data for the adult stage of non-salmonid freshwater fish and concluded that the production of these fish was impaired slightly at DO concentrations of 5 mg/l, moderately at 4 mg/l, and severely at 3.5 mg/l. Since the studies reviewed were for freshwater fish, they may not be entirely applicable for the estuarine and marine species that occur in the vicinity of Ward Cove. Some information, however, is available for marine and anadromous fish species.

According to Clemens and Wilbey (1961) and Kramer et al. (1995), at least 12 species of flounder and sole occur in shallow waters in Southeast Alaska and may be found in the vicinity of Ward Cove (Appendix 1). Growth studies are not available for these fish, but they are for five related benthic fish species: the winter flounder (*Pseudopleuronectes americanus*), southern flounder (*Paralichthys lethostigma*), and summer flounder (*P. dentatus*) from the east coast of North America; and the plaice (*Pleuronectes platessa*) and dab (*Limanda limanda*) from Northern Europe.

Bejda et al. (1992) measured growth in winter flounder exposed to DO concentrations of 6.7 mg/l, 2.2 mg/l, and to a diurnal fluctuation ranging from 2.5 to 6.4 mg/l. Growth rates of fish exposed to the higher level were over twice those of fish tested at the lower level, and were significantly higher than the fish exposed to the diurnal fluctuation. In a similar laboratory study, Taylor and Miller (2001) observed that the growth of juvenile southern flounder was significantly reduced at 2.8 mg/l and at exposures ranging from 2.8 to 6.2 mg/l, but not at 4.7 mg/l. Poucher and Coiro (1999) and U.S. EPA (2000) observed that the growth of newly metamorphosed summer flounder was reduced at DO concentrations ranging from 1.8 to 4.49 mg/l in 10 to 14-day studies. In 20-day laboratory studies at 15°C, Petersen and Pihl (1995) found that growth in plaice and dab was reduced by 25 to 30% when DO saturation decreased from 80 to 60%.

Growth studies related to DO concentrations are also not available for the three cod species likely to be present in these waters. In a laboratory study on a closely related species, the Atlantic cod (*Gadus morhua*), Chabot and Dutil (1999) found that hypoxia decreased food consumption and negatively influenced growth, which was measured as fish length, mass, and condition factor. Fish length was significantly reduced at DO levels <56% saturation, and mass and condition factors were significantly reduced at DO levels <65% saturation. The authors believed the negative growth effects on cod in the wild due to hypoxia may be even greater than their results showed. In their laboratory experiment, food was available *ad libitum* and without exertion by the fish. In the wild, cod would almost certainly incur greater metabolic costs capturing food, avoiding predators, and during migrations.

In another study with Atlantic cod, Saunders (1963) found that reducing ambient oxygen from about 10 to 3 mg/l lowers the rate of oxygen consumption slightly, but the respiratory volume (the volume of water pumped over the gills per unit time) was markedly increased. This suggests there is an added stress because the increased metabolic cost of irrigating the gills is not met by increased rate of oxygen consumption. As a result, growth is affected.

Ward Cove is within the range of two North American sturgeons (Scott and Crossman 1973). Of these, growth information is only available for the white sturgeon. Juvenile white sturgeon fed *ad libitum* rations and tested at 15, 20 and 25 °C had significantly reduced growth when DO concentrations were reduced from approximately 7.7 to 5.3 mg/l (Cech et al. 1984). In another laboratory growth study, Secor and Gunderson (1998) observed that the growth of the juvenile stage of a related species, the Atlantic sturgeon (*Acipenser oxyrhyncus*), was 2.9 times less at 3 mg/l than at 7 mg/l.

2.2 Effects of Low Dissolved Oxygen on Fish Diseases

Except for laboratory and hatchery exposures, little information is available on stress-induced fish diseases caused by exposure to hypoxic conditions. However, diseases that are endemic in some Northeast Pacific fish species such as VHSV (viral hemorrhagic septicemia virus), a disease affecting fish kidneys and livers, may be brought on by other stressors such as crowding or contaminant exposure (Hershberger et al. 1999, Carls et al. 1998).

2.2.1 Salmonid Fish

In reviewing stress-induced fish diseases in hatcheries, Wedemeyer (1970) and Wedemeyer and Wood (1974) found that facultative fish pathogens continuously present in most waters cause diseases to occur when fish immune systems weaken. The authors listed furunculosis (*Aeromonas salmonicida*), aeromonad and pseudomonad hemorrhagic septicemia, and vibriosis (*Vibrio anguillarum*) as diseases for which low dissolved oxygen is one of several environmental factors predisposing fish to epizootics. Wedemeyer and Wood (1974) also determined that optimum fish health usually occurred at dissolved oxygen concentrations of 6.9 mg/l or higher. Water temperatures >16 °C are another important factor predisposing fish to diseases (Ordal and Rucker 1944, Fryer and Pilcher 1974, Servizi and Jensen 1977); however, the virulence of bacterial kidney disease in juvenile coho salmon and steelhead may not be related to water temperature (Fryer et al. 1976) and the virulence of *Flavobacterium psychrophilum* infection in coho may be highest at low temperatures (Ordal and Pacha 1963).

2.2.2 Non-Salmonid Estuarine and Marine Fish

There are many endemic diseases in the marine environment. Vibriosis and the protist *Ichthyophonus* sp. are important diseases affecting cod, herring, and flatfish (Millemann 1969). According to Meyers and Winton (1995), VHSV is enzootic in the Northeastern Pacific among Pacific herring (*C. pallasi*) and Pacific cod (*G. macrocephalus*) stocks. Further, viral erythrocytic necrosis, a disease that affects fish blood and livers, has been associated with epizootics and high mortality in Pacific herring in Southeast Alaska, including in Ward Cove (Meyers et al. 1986). Unfortunately, water quality analyses at the time of this fish kill in Ward Cove did not substantiate the cause of death (B. Hoffman, Alaska Department of Environmental Conservation, personal communication cited by Meyers et al. 1986).

Research reviewed by Austin (1999) indicates that some fish diseases result from generally adverse water quality including organic enrichment and oxygen depletion.

2.3 Lethal Effects of Hypoxia

Hypoxia has caused acute mortality to fish and benthic organisms in marine areas all over the world, and sensitive species have been periodically or permanently removed from many areas (Diaz and Rosenberg 1995). Rosenberg (1980) found that a notable deterioration of the benthic community began rather abruptly at 2 mg/l of DO. Diaz (2001) noted a variance in the point at which various aquatic species suffocate, but effects generally starts to appear when DO drops below 2 mg/l.

2.3.1 Salmonid Fish

Based on a literature review completed by Hicks (2000), salmonid mortality would not be expected when minimum oxygen concentrations are at 3.5 to 4.0 mg/l, even at water temperatures as high as 20 °C. He found that mortality generally increases at concentrations below 3.0 mg/l, with mortality becoming consistently high at oxygen levels at or below 2.5 to 2.0 mg/l depending on water temperature. Hicks noted, however, that most of the studies that he reviewed were conducted in a laboratory where fish were free of the stresses and biological interactions found in a field environment. To compensate for these additional stresses, he recommends that daily minimum oxygen concentrations be maintained above 4.0 to 4.5 mg/l to prevent any reasonable chance of direct mortality to juvenile or adult salmonids.

2.3.2 Non-Salmonid Estuarine and Marine Fish

Available information indicates estuarine and marine fish are considerably less sensitive than salmonids to depressed DO. Burggren and Randall (1978) provide an example of this in their study of the white sturgeon, which may live in marine, estuarine, or freshwater areas. They observed that juvenile white sturgeon survived extreme hypoxic exposures (5 to 10% of normoxic levels) for 25 to 35 minutes and lacked any compensatory increases in ventilation and oxygen consumption after return to normoxic conditions. They concluded the sturgeon appears to reduce total energy expenditures during periods of reduced oxygen availability. Similarly, Croaker and Cech (1997) found that juvenile white sturgeon decreased overall energy expenditures during hypoxia via reductions in spontaneous swimming activity. They believed this behavior may increase the survival of white sturgeon trapped in hypoxic areas.

In another example of non-salmonids being less sensitive to hypoxia, Kim et al. (1995) found that the juvenile stage of four Western Pacific fish species could withstand hypoxic conditions in laboratory experiments. Of these, the rockfish, *Sebastes schlegeli*, and the olive flounder, *Paralichthys olivaceus*, are most closely related to the fish species inhabiting Southeast Alaska. The acute lethal DO levels for the rockfish and flounder were 0.79 and 0.66 mg/l, respectively.

U.S. EPA (2000) used the results of 10 years of research conducted mainly in the laboratory, but supported in part by field observations, to develop salt water criteria for DO in coastal and estuarine areas from Cape Cod, MA to Cape Hatteras, NC. These recommendations for DO criteria are meant to apply within 3 miles from shore in the defined area, and likely would need to be modified if used as water quality criteria in any other coastal region of the United States. The basic research supporting this effort provides useful information on how hypoxia affects juvenile and adult salt water animals. Survival to hypoxia by 12 invertebrate and 11 fish species (almost all data are for juveniles) native to the east coast was determined using accepted guidelines (Stephan et al. 1985). For exposures ranging from 24 to 96 hours, LC50s (lethal concentrations for one half of the test animal population) for the fish ranged from 0.90 mg/l for the windowpane flounder (*Scopthalmus aquosus*) to 1.63 mg/l for the pipe fish (*Syngnathus fuscus*). In addition to these fish, four other fish species tested are closely related to West Coast species. They are (with LC50 levels): fourspine stickleback (*Apeltes quadracus*) - 0.91 mg/l, Atlantic menhaden (*Brevoortia tyrannus*) - 1.12 mg/l, summer flounder (*Paralichthys dentatus*) - 1.32 mg/l, and the winter flounder (*Pleuronectes americanus*) - 1.38 mg/l.

In another laboratory study, Hoff (1967) found that the lethal DO levels for three Atlantic Ocean fish species varied with water temperature. Of those tested, only the winter flounder (*P. americanus*) is closely related to Southeast Alaska fish species. Hoff determined that the lethal DO levels for the winter flounder ranged from 1.03 to 0.66 mg/l at water temperatures ranging from 25 to 12 °C. In comparison, Plante et al. (1998) found that survival to hypoxia by Atlantic cod (*G. morhua*) from the Gulf of St. Lawrence was not measurably affected in LC50 tests at 6 and 2 °C. These authors noted that no cod survived 10% saturation, only a few survived 16% saturation, and no mortality occurred at 34 and 40% DO saturation during their 96-hr tests.

2.3.3 Benthic Invertebrates

Even though some benthic invertebrate species can tolerate hypoxia, the benthic communities may be significantly affected by periodic hypoxia. In Chesapeake Bay, Dauer (1993) observed that macrobenthic communities in areas exposed to low DO (<2 ppm) events during the summer were characterized by lower values for community biomass, number or individuals, and species richness. These areas also had lower numbers of infauna living deeper than 5 cm in the sediment, lower equilibrium species (long-lived species found in undisturbed or unstressed habitats), and a greater dominance of opportunistic species in comparison to reference areas. In a review of benthic faunal reactions to oxygen deficiency in ten fjords and estuaries in Northern Europe, Rosenberg (1980) found that the number of species, abundance, and biomass declined abruptly at approximately 2 mg/l DO. He also found that some species, mainly molluscs, survived periodic DO depletion, but that most species did not tolerate hypoxia for extended periods of time. Similar results were obtained by Nilsson and Rosenberg (1994), who found that the structure of the benthic community changed during hypoxia. These authors observed that the number of species was significantly reduced at DO levels of about 1.0 mg/l DO, compared to normoxia (>8.0 mg/l), and that two polychaete species were able to tolerate hypoxia better than clams, echinoderms, sea cucumbers, and snails.

In comparison to the above studies, Diaz et al. (1992) found that the macrobenthic community structure (diversity, species richness and evenness) was not affected by mild hypoxia (levels near 2 ppm DO) for a few days in a study in the York River, just off the Chesapeake Bay. The benthos was dominated, however, by four polychaete species that are common to the area. During hypoxic events, many different infaunal species were seen lying on the sediment surface where they were more susceptible to predators. Pihl et al. (1992) documented the opportunistic exploitation by predators on benthic prey sublethally affected during hypoxic events.

In the development of saltwater criteria (U.S. EPA 2000), LC50 tests showed that invertebrate species may survive periodic hypoxia. Of the 12 invertebrates tested, eight species are more closely related to the invertebrate fauna in Southeast Alaska. The LC50s for these species ranged from 0.43 mg/l (for the Atlantic surfclam, *Spisula solidissima*) to 1.27 mg/l (for the mysid, *Americamysis bahia*). The balance of the eight invertebrates were represented by one amphipod species, two species of crab, and three species of shrimp. Similar results were found in a laboratory study conducted by Rosenberg et al. (1991), who observed that eight infaunal species from the Northeast Atlantic continental shelf tolerated hypoxic conditions for several days to weeks. The authors found, however, that exposures of 32 to 43 days at DO levels of about 1.4 mg/l caused high mortalities to four bivalve and two echinoderm species.

With an emphasis on Canadian species, Davis (1975) reviewed the minimum DO requirements of aquatic life, including aquatic invertebrates. He found these requirements to be species-specific and that tolerance to hypoxia tended to be correlated with habitat. With the information available in 1975, Davis found it difficult to determine safe levels of DO for aquatic invertebrate communities. Subsequent research on hypoxia in British Columbian waters provides further information on the minimum DO levels required by invertebrates. Levings (1980) found that infauna and sedentary epifauna in 24 km^2 of Howe Sound were killed when DO levels decreased below 0.5 mg/l. In studying hypoxic conditions in Saanich Inlet, Jamieson and Pikitch (1988) believed the minimum lethal tolerance limit for the spot prawn (*Pandulus platyceros)* was approximately 1 ml/l dissolved oxygen, but munid decapods (*Munida quadrispina*) were unaffected at that DO level, and pink shrimp (*P. jordani*) moved to avoid the zone with <1ml/l dissolved oxygen. Burd and Brinkhurst (1984, 1985) observed that large adult *M. quadrispina* were consistently found at DO levels as low as 0.1 to 0.15 ml/l in Saanich Inlet where their population density was greatest. [Conversion of dissolved oxygen from ml/l to mg/l is dependant on pressure, salinity, and temperature. In a marine environment, 2 ml/l is roughly equal to 2.8 mg/l (Wu 2002)].

With regard to important commercial shrimp species, Renaud (1986) suggested that hypoxia in bottom waters off Louisiana affected the abundance and distribution of brown shrimp (*Penaeus aztecus*) and white shrimp (*P. setiferus*). Brown shrimp avoided DO concentrations $\leq$ 2 ppm, while white shrimp avoided concentrations $\leq$1.5 ppm. The minimum critical holding level for unfed (i.e., starved) spot prawn in a laboratory study was found to be 3.5 to 4.0 mg/l DO (at salinity of 30 ppt and 5 °C). Below this level, metabolism declined directly with lowering oxygen concentration until asphyxial levels were reached (Whyte and Carswell 1982).

3.0 Discussion

The purpose of this review is to provide a better understanding of the potential adverse effects of depressed dissolved oxygen on aquatic resources in Ward Cove. From the above literature review, two bench mark levels are apparent below which adverse effects occur *if* dissolved oxygen is depressed on a wide scale (i.e., in space and time) in a water body and aquatic resources are present. These levels are 2 and 4 mg/l. As DO falls below 2 mg/l, aquatic species begin to suffer acute mortality and adverse community level effects occur. At DO levels between 2 and 4 mg/l, chronic effects like reduced growth or increased susceptibility to disease impair fish health, particularly if other stressors are present.

Because KPC discharged high BOD wastes to Ward Cove until March 1997, only the results of DO monitoring in Ward Cove after 1997 will be gauged against information obtained from this literature review. DO conditions prior to 1998 may not represent conditions that occur today as KPC has permanently stopped all operations. The post-1997 monitoring data (Appendix B) show that DO <2 mg/l occurred more frequently in waters near the bottom in the central part of Ward Cove, and less frequently in the upper water column. As DO concentrations typically decrease with increasing water depth, hypoxic conditions will more likely occur near the bottom. In considering cove-wide monitoring, hypoxic conditions appear to have persisted in bottom waters in the central part of Ward Cove for at least two to four weeks (see stations 44, 45, and 46 in Table B1 in Appendix B) during August 1998 and from August to September 1999. The station locations are shown in Appendix C.

Figure 2 shows dissolved oxygen levels at water depths ranging from 20 to 29 m in the cove on five days when monitoring occurred from June to October 1999. During this time, hypoxia occurs only in one small cell within the cove in this depth range. This depth range was selected as it is a good representation of the spatial and temporal variability of DO conditions that occur in or near midwater areas each summer.

During the monitoring period from 1998 to 2002, DO levels between 2 and 4 mg/l were commonly observed in Ward Cove. As shown in Appendix B, these conditions began at water depths greater than approximately 20 m in mid to late July and continued until early October. During this time, DO levels between 2 and 4 mg/l may also occur in water as shallow as 15 m.

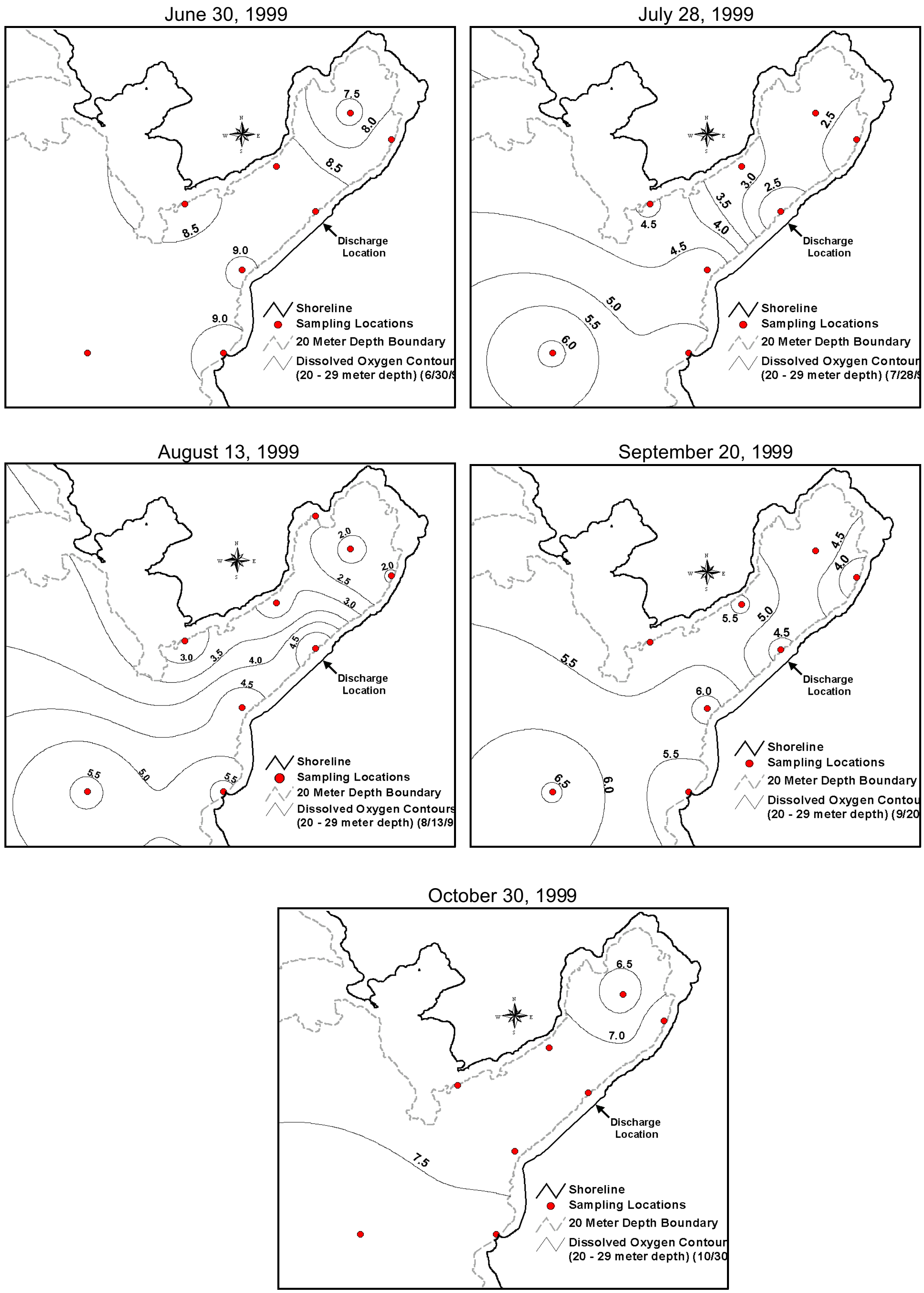
The adult stage of seven salmonid species (Figure 1), the adult or juvenile stage of approximately 75 non-salmonid estuarine and marine fish species (Appendix 1), and benthic and pelagic invertebrates are present during the time depressed DO conditions occurred in Ward Cove and adjacent waters. Further, year-round resident subadult chinook salmon, known to rear and feed in Tongass Narrows and adjacent embayments (Hoffman 2002), may also be exposed to these conditions.

3.1 Effects on Salmonids

Depressed dissolved oxygen conditions are unlikely to significantly affect the growth of juvenile or adult salmonids migrating through or feeding in or near Ward Cove. Some minor indirect effects, however, may occur as a result of hypoxia-induced changes to food chain organisms inhabiting the cove and adjacent waters.

The growth cycles of the adult stage of all seven anadromous salmon and trout species native to Ward Creek should be completed prior to their arrival in the cove from the ocean. Some feeding by adult cutthroat trout and Dolly Varden may occur in or near the cove as they hold in preparation for entering Ward Creek. The growth of subadult chinook salmon, a fish species not native to Ward Creek, is also not likely affected by exposures to these conditions. Whitmore et al. (1960) observed that juvenile chinook salmon can sense and avoid hypoxic

Figure 2. Dissolved oxygen concentrations (mg/l) in the depth range 20 to 29 m in Ward Cove from June to November 1999.



waters. Juvenile salmonids from Ward Creek temporarily rearing in Ward Cove are also unlikely to be affected directly by depressed DO since they are believed to move through the cove from April to mid June each year, which is prior to the onset of these conditions (Figure 1).

Returning adult salmonids may be present in the cove when the lowest dissolved oxygen and highest water temperatures occur in late summer and early fall. Adult salmonids will usually avoid hypoxic conditions, except when staging to enter freshwater during the latter part of their annual spawning migrations. Severe depressed DO levels at this time in combination with low flows and high water temperatures in Ward Creek can result in adult mortality. Fish kills have not been observed recently in the cove, likely because the depressed DO conditions have not extended into a greater portion of the water column in combination with low flows in Ward Creek.

In a review, Hicks (2000) noted that mortality to salmonids generally increased at dissolved oxygen concentrations below 3 mg/l, with mortality becoming consistently high at oxygen levels at or below 2.5 mg/l. However, at lower water temperatures they may be able to survive mean concentrations as low as 2.2 to 2 mg/l. A large part of the middle of Ward Cove was at or below these levels for at least two to four weeks during August 1998 and from August to September 1999. These levels occurred at or near the bottom, however, presenting less of a risk of mortality to returning adult salmon and trout.

Salmonids encountering prolonged hypoxic conditions in Ward Cove may sustain sublethal effects like reduced reproductive success, which may be an important consideration. If gravid adult salmonids are delayed from reaching their spawning grounds due to depressed oxygen conditions in combination with other stressors like increased water temperature, fecundity may be impaired. Reduced recruitment may adversely affect some of the smaller anadromous fish populations entering Ward Creek. The approximate size of these runs are: pink salmon - 1,000's, early coho salmon - 1000's, late coho salmon - 100's, chum salmon - 100's, sockeye salmon - 100's, dolly varden - 1000's, Spring steelhead - 100's, Fall steelhead - 100's, cutthroat trout - 100's (Hoffman 2002).

3.2 Effects on Other Estuarine and Marine Organisms

In comparison to salmonids, the potential for depressed DO conditions to adversely affect the growth of other estuarine and marine fish species in Ward Cove is much higher because these fish are present year-round, may be present in the more sensitive juvenile stage, and are more commonly found in deeper water where hypoxic conditions are more prone to occur. It is not possible to quantify growth loss by estuarine and marine fish species with the information that is available. Field and laboratory studies, however, show that growth is affected by the depressed DO conditions similar to those observed in Ward Cove. For example, Bejda et al. (1992) measured reduced growth in winter flounder exposed for 10 to 11 weeks to DO concentrations of 2.3 mg/l or to a fluctuating DO concentration ranging from 2.5 to 6.5 mg/l.

Non-salmonid estuarine and marine fish are less sensitive to depressed oxygen levels than salmonids. Most of the studies cited in section 2.3.2 for the lethal effects of hypoxia were laboratory exposures with juvenile fish. For exposures of 1 to 4 days, lethal DO concentrations for these fish ranged from approximately 1.6 to 0.9 mg/l (U.S. EPA 2000). In Ward Cove, DO concentrations in or near this range occurred during August 1998 and August and September 1999, and these conditions usually occurred at or near the bottom. These conditions were more widespread in August 1998 (6 of the 9 stations in Ward Cove) than in August and September 1999 (4 of the 9 stations). During the five-year observation period, hypoxic conditions were observed only in 1998, 1999, and 2002, when they ranged from 1.99 to 0.64

mg/l. Further, DO levels below 1 mg/l were observed only on two occasions during this time (0.64 mg/l on 8/6/98 at 14.8 m at station 43, and 0.76 mg/l on 9/20/99 at 40 m at station 44).

Depressed DO conditions likely have the greatest effect on benthic invertebrate fauna, particularly those that are not mobile, have weak swimming abilities, or live within the sediment. In literature reviews, Rosenberg (1980) and Wu (2002) found that prolonged hypoxia may cause major deterioration of the benthic community structure. A field study in Byford Estuary on the coast of Sweden found that benthic invertebrates can tolerate exposures to DO concentrations of <1 mg/l for a few days without any significant effect, but long term exposures to DO concentrations of 1 to 2 mg/l caused a 20 species reduction in the benthos (Rosenberg 1977). This mortality or the migration of mobile species from hypoxic areas can result in a significant change in the benthic community structure. Information is not available showing similar reductions in Ward Cove, but the spatial and temporal distribution of DO concentrations <2 mg/l indicate that these adverse effects may occur seasonally within the cove.

Some invertebrates can easily withstand or appear to prefer hypoxic conditions (Rosenberg 1980, Burd and Brinkhurst 1984, Diaz et al. 1992), but these organism are believed to be the exception rather than the rule.

Lastly, the distribution and abundance of aquatic species may be adversely affected as many fish and invertebrate species detect and successfully avoid hypoxic conditions. During hypoxic events in the lower York River off the Chesapeake Bay in 1989, spot (*Leiotomus xanthurus*), hogchocker (*Trinectes maculatus*), Atlantic croaker (*Micropogonias undulatus*), mantis shrimp (*Squilla empusa*), and blue crab (*Callinectes sapidus*) were observed migrating from deeper to shallower water (Pihl et al. 1991, Diaz et al. 1992). Similarly, juvenile spot, Atlantic croaker, pinfish (*Lagodon rhompoides*), Atlantic menhaden (*Brevoortia tyrannus*), southern flounder (*P. lethostigma*), red hake (*Urophycis chuss*), and brown shrimp (*P. aztecus*) could detect and move away from hypoxic water in laboratory exposures (Deubler and Posner 1963, Bejda et al. 1987, Wannamaker and Rice 2000). Due to small size and weak swimming ability, however, it is difficult for juvenile fish to avoid hypoxic conditions (Breitburg 1992). Further, when juvenile fish do avoid hypoxia they typically move up in the water column where they may become more susceptible to predation (Bejda et al. 1987).

3.3 Fish Diseases

Environmental stress, including hypoxia, may weaken fish immune systems resulting in increased susceptibility to disease (Wedemeyer et al. 1976). Mellergaard and Nielsen (1995) believed that the stress of oxygen deficiency, especially at sublethal levels, triggered an outbreak of two viral diseases, lymphocystis and epidermal papilloma, in dab (*L. limanda*) in Northern Europe. Determining the importance of hypoxia as a stressor in Ward Cove is not possible given the lack of information on fish diseases in and near the cove and on all stresses potentially affecting fish in this area. Contaminated bottom sediments in the cove may also be an important stressor for fish and benthic life. The virulence of several endemic diseases, however, is increased by exposure to reduced dissolved oxygen levels (Wedemeyer et al. 1976).

Given that the incidence of disease in wild fish is rare in Southeast Alaska (Meyers 2002) and that widespread and persistent hypoxia does not occur, hypoxia-induced disease is likely less of a problem than other factors affecting fish species in Ward Cove.

4.0 Limitations of this Review

It is important to point out several limitations with this assessment: (1) there may be juvenile salmonids from streams other than Ward Creek moving through Ward Cove during the time when deteriorated water quality occurs, (2) those days or areas within Ward Cove when DO was lowest may not have been surveyed, (3) the DO values in Figure 2 are estimations, and lack of observations in Tongass Narrows weakens the confidence in the DO levels shown for that area, (4) the biochemical and physiological responses of affected aquatic life were not addressed, and (5) the synergistic or additive effect of organic pollution with hypoxia was not addressed.

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Appendix A - Native fish species potentially occurring in or near Ward Cove, AK

Pacific lamprey	*Lampetra tridentata* [1]
River lamprey	*L. ayresi* [1]
Spotted ratfish	*Hydrolagus colliei* [2, 3]
Spiny dogfish	*Squalus acanthias* [2, 3]
Salmon shark	*Lamna ditropis* [2]
Basking shark	*Cetorhinus maximus* [2]
Longnose skate	*Raja rhina* [2, 4]
Big skate	*R. binoculata* [2, 3]
White sturgeon	*Acipenser transmontanus* [1]
Green sturgeon	*A. medirostris* [1]
Capelin	*Mallotus villosus* [4]
Pacific herring	*Clupea pallasi* [2, 4]
Surf smelt	*Hypomesus pretiosus* [2, 4]
Eulachon	*Thaleichthys pacificus* [2, 4]
Pink salmon	*Oncorhynchus gorbuscha*
Chum salmon	*O. keta* [1]
Coho salmon	O. kisutch [1]
Sockeye salmon	*O. nerka* [1]
Chinook salmon	*O. tshawytscha* [1]
Cutthroat trout	*O. clarki* [1]
Steelhead	*O. mykiss* [1]
Dolly Varden	*Salvelinus malma* [1]
Pacific cod	*Gadus macrocephalus* [2, 4]
Pacific tomcod	*Microgadus proximus* [2, 4]
Walleye pollock	*Theragra chalcogramma* [2, 4]
Sablefish	*Anoplopoma fimbria* [2, 4]
Plainfin midshipman	*Porichthys notatus* [2, 4]
Threespine stickleback	*Gasterosteus aculeatus* [1, 2, 4]
Northern clingfish	*Gobiesox maeandricus* [4]
Bay pipefish	*Syngnathus leptorhynchus* [2, 4]
Brown rockfish	*Sebastes auriculatus* [2, 4, 5]
Quillback rockfish	*S. maliger* [2, 4, 5]
China rockfish	*S. nebulosus* [2, 4, 5]
Copper rockfish	*S. caurinus* [2, 4, 5]
Black rockfish	*S. melanops* [2, 4, 5]
Blue rockfish	*S. mystinus* [2, 4, 5]
Dusky rockfish	*S. ciliatus* [2, 4, 5]
Bocaccio (juv.)	*S. paucispinis* [2, 4, 5]
Silvergray rockfish	*S. brevispinis* [2, 4, 5]
Greenstripe rockfish	*S. elongatus* [2, 4, 5]
Canary rockfish	*S. pinniger* [2, 4, 5]
Tiger rockfish	*S. nigrocinctus* [2, 4, 5]
Rougheye rockfish	*S. aleutianus* [2, 4, 5]
Yellowtail rockfish	*S. flavidus* [2, 4, 5]
Pacific Ocean perch	*S. alutus* [2, 4, 5]
Puget Sound rockfish	*S. emphaeus* [2, 4, 5]

Widow rockfish	*S. entomelas* [2, 4, 5]
Kelp greenling	*Hexagrammos decagrammus* [2, 4]
Whitespotted greenling	*H. stelleri* [2, 4]
Rock greenling	*H. lagocephalus* [2, 4]
Ling cod	*Ophiodon elongatus* [2, 4]
Painted greenling	*Oxylebius pictus* [2, 4]
Cabezon	*Scorpaenichthys marmoratus* [2, 4]
Red Irish lord	*Hemilepidotus hemilepidotus* [2, 4]
Brown Irish lord	*H. spinosus* [2, 4]
Smoothhead sculpin	*Artedius lateralis* [2, 4]
Buffalo sculpin	*Enophrys bison* [2, 4]
Pacific staghorn sculpin	*Leptocottus armatus* [2, 4]
Pile perch	*Rhacochilus vacca* [2, 4]
Striped seaperch	*Embiotoca lateralis* [2, 4]
Pacific sand lance	*Ammodytes hexapterus* [2, 4]
Pacific halibut	*Hippoglossus stenolepis* [2, 4]
Starry flounder	*Platichthys stellatus* [2, 4]
Flathead sole	*Hippoglossoides elassodon* [2, 4]
C-O sole	*Pleuronichthys coenosus* [2, 4]
Curlfin sole	*P. decurrens* [2, 4]
Butter sole	*Pleuronectes isolepis* [2, 4]
Rock sole (juv.)	*P. bilineatus* [2, 4]
English sole (juv.)	*P. vetulus* [2, 4]
Dover sole	*Microstomus pacificus* [2, 4]
Slender sole	*Eopsetta exilis* [2, 4]
Rex sole	*Errex zachirus* [2, 4]
Sand sole	*Psettichthys melanostictus* [2, 4]
Pacific sanddab	*Citharichthys sordius* [2, 4]
Wolf eel	*Anarrhichthys ocellatus* [2]

Note: This list may not include all fish species that could possibly occur in Ward Cove and the waters of nearby Tongass Narrows or those that are only present during part of their life cycle. Further some of the above listed species may occur only rarely in this area.

Appendix A References:

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Appendix B - Location and date of occurrence of dissolved oxygen levels <4 mg/l in and near Ward Cove, Alaska

Table B1. Water depths with dissolved oxygen levels ≤2 mg/l and >2 but <4 mg/l at stations in and near Ward Cove, 1998 to 2002. Notes: A dash (-) indicates that DOs were ≥4 mg/l. Underlined water depths are the deepest DO measurement at the station and are usually representative of the layer of water on the bottom. The maximum water depth at a station varies apparently due to poor station positioning, drifting, and differences in tidal elevation during the time that monitoring occurred. See Appendix C for station locations.

Date	DO mg/l	Station										
		41	42	43	44	45	46	47	48	49	50	51
7-11-98	≤2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	-	-	35 - 41.6	-	-	-	-	-
7-23-98	≤2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	-	-	-	-	-	-	-	-
8-6-98	≤2	11.8	-	14.8 - 17.5	15 - 20	-	14.9	-	-	-	-	-
	>2 - <4	-	-	-	20.1 - 25	14	20 - 20.1	-	15	-	-	-
8-20-98	≤2	-	-	-	20 - 22.2	-	25 & 50	25	20.1	-	-	-
	>2 - <4	-	-	17.8	-	-	20 - 25 30 - 45.1 50.1 - 51.2	19.9 25.2 - 30.1	-	-	-	-
9-3-98	≤2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	25 - 28.4	21.9	25.1 35 - 38	-	-	-	-	-
9-17-98	≤2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	25 - 31.4	-	35 - 39.6 44.9 - 45.1	-	-	-	-	-
10-1-98	≤2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	29.9 - 34.7	-	29.6 - 43	28.6	-	-	-	-

Table B1 - (Continued 2 of 3)

Date	DO mg/l	Station										
		41	42	43	44	45	46	47	48	49	50	51
7-28-99	≤ 2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	25 - 27.9	23.1	25 40 - 42.4	20	-	-	-	-
8-13-99	≤ 2	-	-	-	24	25.1 - 32.9	-	-	-	-	-	-
	>2 - <4	-	-	20.1 - 21.2	20	20.2	25 35 - 42.7	30.1 39.9 - 49.8	20 - 25.7	-	-	-
8-31-99	≤ 2	-	-	-	-	34.9	-	-	-	-	-	-
	>2 - <4	-	-	-	-	-	30 - 35 45	35 - 40.1	-	-	-	-
9-20-99	≤ 2	-	-	-	-	34.2	40 - 41.3	40.1	-	-	-	-
	>2 - <4	-	-	-	30 - 31.3	25	35	34.9 & 43.4	-	40 - 50.4	-	-
9-30-99	≤ 2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	30 - 34.2	29.9 - 30.5	30 - 38.1	44	-	-	-	-
8-4-00	≤ 2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	29.9	19	-	-	-	-	15.8	-
9-5-00	≤ 2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	-	-	35 - 37.4	-	-	-	-	-

Table B1 - (Continued 3 of 3)

Date	DO mg/l	Station										
		41	42	43	44	45	46	47	48	49	50	51
7-30-01	≤ 2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	19.9	-	20	-	-	-	-	-
8-11-01	≤ 2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	-	-	-	-	25.1 - 26.7	-	-	-
8-2-02	≤ 2	-	-	-	-	-	-	-	20	-	-	-
	>2 - <4	-	-	-	15 - 30	-	29.9 - 32.6	19.7 & 30	-	-	-	-
8-14-02	≤ 2	-	-	-	20	-	-	-	-	-	-	-
	>2 - <4	-	-	-	25 - 30	-	20 - 33.9	14.9 - 19.7	-	-	-	-
9-13-02	≤ 2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	-	-	40	-	-	-	-	-
10-11-02	≤ 2	-	-	-	-	-	-	-	-	-	-	-
	>2 - <4	-	-	-	-	-	30 - 31.2	-	-	-	-	-

Appendix C - Water quality monitoring stations in and near Ward Cove, Alaska

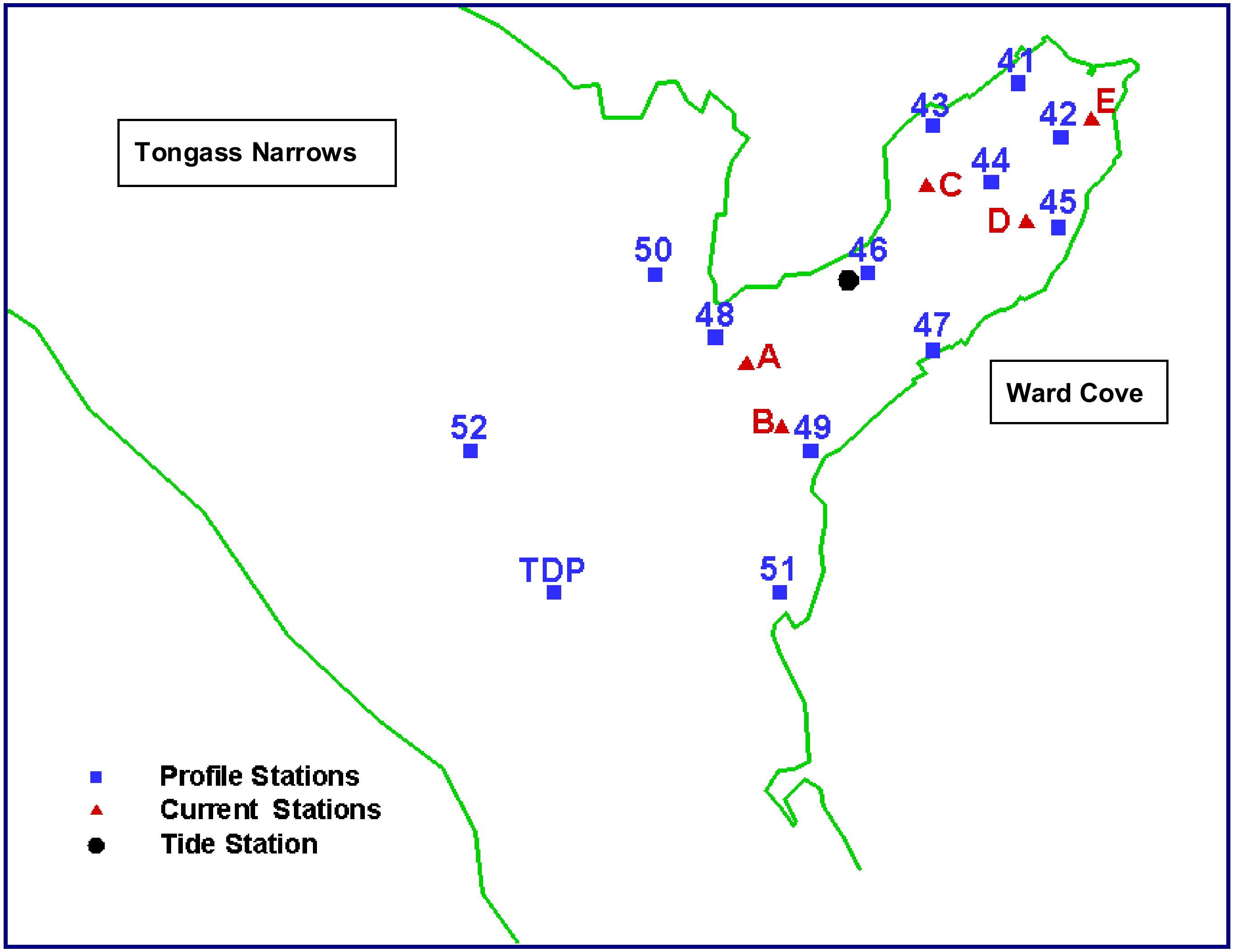

Figure C1. Location of monitoring stations in Ward Cove and Tongass Narrows.