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Comments on the Sensitivity of Salmonids to Reduced Levels of Dissolved Oxygen and to Pulp Mill Pollution in Neroutsos Inlet, British Columbia

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May 1989

Canadian Technical Report of
Fisheries and Aquatic Sciences
No. 1695

Fisheries and Oceans   Pêches et Océans

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Canadian Technical Report of Fisheries and Aquatic Sciences

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COMMENTS ON THE SENSITIVITY OF SALMONIDS TO REDUCED LEVELS OF DISSOLVED OXYGEN AND TO PULP MILL POLLUTION IN NEROUTSOS INLET, BRITISH COLUMBIA

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Cat. No. Fs 97-6/1695 ISSN 0706-6457

Correct citation for this publication:

Birtwell, I. K. 1989. Comments on the sensitivity of salmonids to reduced levels of dissolved oxygen and to pulp mill pollution in Neroutsos Inlet, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1695: 27 p.

PREFACE

These comments provide an overview of some current information and knowledge on the dissolved oxygen requirements of fish, in particular salmonids, in B.C. coastal and estuarine environments. This review was prompted by the documentation of persistent and significantly deteriorated water quality (e.g. hypoxic conditions) in Neroutsos Inlet, the continuing concern over the ability of adult salmon to successfully migrate and spawn in their natal streams which enter at the head of the inlet, and the possible negative effects on rearing and migratory juvenile salmon, and other aquatic organisms that reside in the area.

It is recognized that effluent from the Port Alice pulp mill has resulted in the deterioration of aquatic conditions in Neroutsos Inlet. The ability of the waters to accommodate the wastes, without undue change, has been exceeded. That is, the assimilative capacity has been exceeded, producing a zone of reduced water quality and thereby disrupting the integrity of the inlet, and hence its ecology. The extent of this effect is, however, dependent upon many factors such as the nature of the wastes, manner of their discharge and prevailing climatic conditions.

In the late 1970's documented "environmental improvement" occurred in Neroutsos Inlet associated with a modification of waste treatment practices at the pulp mill. Due to these efforts the extent of the zone of deteriorated water quality was reduced. However, in recent years there has been a regression in water quality to a level that the Department of Fisheries and Oceans considers unacceptable for the perpetuation of healthy fishery resources.

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The capacity of the 20-km-long Neroutsos Inlet to assimilate effluent from the Port Alice pulp mill has been exceeded over many years and this has produced a sub-optimal environment for many aquatic organisms. Severely depressed dissolved oxygen levels persisted in summer and early autumn 1985 during the initial stages of adult salmon migrations. These deteriorated water quality conditions were considered to hinder or block the first-run fish from entering their natal streams at the head of the inlet.

This report reviews some current information on the effects of hypoxic conditions on salmonids and focusses upon the conditions necessary to ensure their successful migrations and the well-being of aquatic organisms in Neroutsos Inlet. Emphasis is placed upon dissolved oxygen levels which permit fish to function normally in contrast to levels which may be tolerated for brief periods.

Key words: salmon, dissolved oxygen, pulp mill pollution, hypoxia

RÉSUMÉ

Birtwell, I. K. 1989. Comments on the sensitivity of salmonids to reduced levels of dissolved oxygen, and to pulp mill pollution in Neroutsos Inlet, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1695: 27 p.

La capacité du bras Neroutsos d'une longueur de 20 km d'assimiler les effluents de l'usine de pâtes de Port Alice a été dépassée pendant de nombreuses années; cette situation a eu pour effet de produire un environment sub-optimal pour de numbreux organismes aquatiques. Des concentrations d'oxygène dissous très faibles ont persisté durant l'été et le début de l'automne 1985, durant les stades initiaux des migrations de saumons adultes. On pense que cette détérioration de la qualité de l'eau empêche les saumons de la première remonte de pénétrer dans leur cours d'eau natal à l'extrémité amont du bras, ou du moins les gène.

Le présent rapport examine certaines informations actuelles sur les effets de l'hypoxie sur les salmonidés et décrit les conditions nécessaires à leur migration et au bien-être des organismes aquatiques dans le bras Neroutsos. L'accent est mis sur les concentrations d'oxygène dissous qui permettent aux poissons de fonctionner normalement, par opposition aux concentrations qui peuvent être tolérées pendant de courtes périodes de temps.

Mots-clés: saumon, oxygène dissous, pollution par les usines de pâtes, hypoxie

INTRODUCTION

GENERAL ASPECTS

The Port Alice pulp mill has a daily production of about 430 air dried tonnes of dissolving and paper grade bleached sulphite pulp. It is currently operated by Western Pulp Ltd. Partnership and is situated towards the head, and on the eastern shore, of Neroutsos Inlet, a 20km-long arm of Quatsino Sound, Vancouver Island (Figure 1). Effluent from this sulphite mill is discharged at a rate of 125×10^3 $m^3 \cdot d^{-1}$ into Neroutsos Inlet and this has resulted in deteriorated water quality over many years (e.g. Waldichuk 1958; Waldichuk et al. 1968; Davis et al. 1978; Tollefson 1982). Due to the oxygen demand of the effluent the waters of Neroutsos Inlet generally have reduced dissolved oxygen levels, and the most severe hypoxic conditions occur in summer and early autumn. An associated relatively high effluent toxicity has also affected water quality, and habitat degradation has occurred along a substantial portion of the inlet. The federal government's Departments of Fisheries and Oceans (DFO) and Environment (DOE) have had concern over this situation for many years and as a result of negotiations between governments and industry, improvements were made in the pulp mill's waste treatment practices in the 1970's. A number of investigations were undertaken to record the anticipated changes in aquatic conditions and the responses of organisms in Neroutsos Inlet. The results of these studies were summarized by Tollefson (1982) who reported a number of "improvements", including an overall increase of about 2 $mg \cdot L^{-1}$ dissolved oxygen in inlet waters. But, despite the general "improvements", waters proximal to the pulp mill remained acutely toxic to juvenile salmonids (McGreer et al. 1982; McGreer and Vigers 1983) and underutilized by them (Poulin and Oguss 1982). Furthermore, avoidance reactions by juvenile salmon were quantified up to 10 km from the pulp mill on an ebb tide (McGreer and Vigers 1983). Thus, although significant improvements in water quality had occurred, and aquatic organisms had responded to these beneficial changes areas of the inlet remained which were sub-optimal for, or lethal to, juvenile salmon.

RECENT INVESTIGATIONS

Despite the installation of a clarifier and an effluent diffuser in 1985 there has been a general decrease in dissolved oxygen levels in Neroutsos Inlet. The Departments of Fisheries and Oceans and Environment investigated the situation in 1985 and using in-situ bioassay experiments with juvenile salmon confirmed the existence of lethal conditions in surface waters of the inlet (G.M. Kruzynski, DFO, personal communication); extremely low dissolved oxygen levels were recorded in many locations in September 1985 (Fisheries and Oceans and Environment Canada, unpublished data). Kruzynski observed caged juvenile chinook salmon to be in respiratory distress in waters containing 4.9 $mg \cdot L^{-1}$ dissolved oxygen, whereas the fish died in <2 h at 1.9 $mg \cdot L^{-1}$ dissolved oxygen. Recognizing that these conditions were not conducive to maintaining the health of returning adult salmon, a capture program on adult migrants entering Neroutsos Inlet was initiated by DFO (unpublished information). It was concluded that most, if not all, of the early part of the run of chum salmon were prevented from reaching streams at the head of the inlet (J. Morrison, DFO, personal communication).

During fishing with gill nets (0-8 m depth) the majority of salmon were captured when average (0-8 m) dissolved oxygen levels were above 4 $mg \cdot L^{-1}$. Salmon entering the inlet in September moved to a 'holding area' seaward, and on the opposite shore from the Port Alice pulp mill. Here their condition changed rapidly, and over 3 days (September 19-22, 1985) the percentage of fish which were extremely dark coloured (indicative of advanced maturation) increased from 18.2 to 100%. At the end of this period many fish had eggs or milt running freely from them. These fish were considered to be too far advanced in maturity to spawn successfully had they been able to reach the creeks at the head of the inlet. In addition D.F. Alderdice (DFO, personal communication) suggested that the viability of salmon eggs would be adversely affected due to 'stress' imposed on adult females by the prevailing aquatic conditions. Subsequent fishing did not yield such dark coloured fish in the 'holding area', but there was a very small (20-50) influx of salmon into Cayeghle Creek at the head of Neroutsos Inlet, and the presence of more dark coloured fish down the inlet (possibly due to a redistribution of fish seaward of the 'holding area'). At this time dead herring were observed close to the pulp mill. Three days later more fish entered the 'holding area'. They were 50-80% dark coloured, and on September 29 an estimated 80-120 fish entered Cayeghle Creek. Very few fish ($<50 \cdot d^{-1}$) entered the creek until October 11 when about 1000 fish were observed. These salmon were 'bright coloured', as expected of freshly-run fish. They entered the creek during increasing dissolved oxygen levels in inlet water following strong winds and heavy rainfall. Figure 2 depicts the changes in dissolved oxygen which occurred towards the head of Neroutsos Inlet from September to October 1985 during the initial stages of the adult salmon migration. Even when a significant number of fish gained access to Cayeghle and Colonial Creeks on October 11, dissolved oxygen concentrations were at levels which posed a risk of severe to moderate harm (Davis 1975a,b). But within one week much less stressful hypoxic conditions existed and surface water values ranged between 6.4 and 8.6 $mg \cdot L^{-1}$ within 10 km of the head of the inlet: an area, which two weeks earlier contained waters with <3 $mg \cdot L^{-1}$ dissolved oxygen, a highly stressful if not lethal situation for salmon (Figure 2; Department of Environment, Pacific Region, unpublished information).

DISSOLVED OXYGEN REQUIREMENTS FOR SALMON MIGRATION

In order to ensure the migratory success of adult and juvenile migratory salmon and to protect other fishery resources, DFO and DOE stipulated that Western Pulp Ltd. Partnership should operate the Port Alice pulp mill to ensure that dissolved oxygen levels were at an average of at least 5 $mg \cdot L^{-1}$ in the surface 10 m of the Neroutsos Inlet water column. Notwithstanding the exacerbating effects of pulp mill effluent on salmon, it was recognized that the 5 $mg \cdot L^{-1}$ dissolved oxygen level was a compromise solely for the purposes of promoting the successful migration of adult salmon, and was not a level that conferred a high level of safety upon resident or transient fish communities.

OBJECTIVES

The following comments are intended to address the suitability of the stipulated 5 $mg \cdot L^{-1}$ dissolved oxygen level, and to comment briefly upon some effects of reduced levels of dissolved oxygen on fish. The latter topic has received considerable attention, primarily for the establishment of criteria to protect aquatic organisms (e.g. Doudoroff and Shumway 1967; Davis 1975a, b, EPA 1986). There remains, however, a need to document the combined effects of hypoxic conditions and contaminants on fishery resources, especially in relation to coastal and estuarine organisms.

GENERAL CONSIDERATIONS

Fish typically abstract oxygen from the water in which they live, just as we abstract it from air. The gills are the site at which this abstraction process occurs (together with other processes) and the oxygen is transported to the tissues in the blood. In order that fish may function normally in their natural environment it is essential that dissolved oxygen levels are adequate to ensure the blood remains fully saturated.

The amount of oxygen dissolved in water depends upon a number of variables, such as temperature, salinity, barometric pressure. Water equilibrated with air is said to be fully (i.e. 100%) saturated. For example, at 15°C, in fresh water exposed to air (an atmosphere containing 20.9% oxygen under a pressure of 760 mm Hg) 10.15 parts of oxygen would be present in a million parts of water, approximately expressed as 10.15 $mg \cdot L^{-1}$ (milligrams per litre). Similarly at a temperature of 15°C and a salinity of 28‰, saturated water would contain 8.6 $mg \cdot L^{-1}$ dissolved oxygen (further examples and tables are provided by Davis 1975a, b).

EFFECTS OF HYPOXIC WATERS ON FISH

A reduction in the external dissolved oxygen level which results in the blood becoming less than 100% saturated will, in turn, affect tissue oxygen levels. Accordingly a variety of normal activities may be compromised due to the reduced availability of oxygen, but in addition the fish will attempt to compensate for the deficiency through modification in behaviour, activity, increased respiration etc. Each of the compensatory activities will be at some cost to the fish, most typically through increased energy expenditure. While fish at moderate oxygen levels may reduce physical activity and concentrate on respiration, energy expenditure could decrease initially with the "cost" of respiration accelerating as severity of hypoxia increases (J.C. Davis, Department of Fisheries and Oceans, personal communication). Accordingly there would be reduction in energy available for general metabolic processes. The level at which the blood of salmonids ceases to become fully saturated is approximately 120 mm Hg: that is, about 76% of the saturation level (D. Randall, Department of Zoology, University of British Columbia, personal communication). This level is dependent upon a number of factors such as temperature and pH. At this level measurable physiological responses occur, but the response of fish to reduced levels of dissolved oxygen varies among species, life history stage, etc. Numerous documents have described the responses of fish to changes in dissolved oxygen, for example, behaviour (Bishai 1962, Kramer 1987) growth (Brett and Blackburn 1981) swimming (Dahlberg et al. 1968) respiration (Warren et al. 1973) fecundity (Brungs 1971) disease resistance (Meyer 1970; Wedemeyer 1974) and feeding (Warren et al. 1973). Much of the pertinent work has been summarized by (Doudoroff and Shumway 1967; Davis 1975a, b; EPA 1986) and this report derives much information from these reviews.

The ability of fish to survive hypoxic conditions depends not only upon the species, its health, life cycle stage and prevailing environmental conditions but also upon the extent of exposure, level and constancy of dissolved oxygen. At concentrations of dissolved oxygen less than 3 $mg \cdot L^{-1}$ lethal effects on salmon will occur. Chapman (1940) examining the effects of a decreased supply of oxygen on sockeye and chinook salmon found that below 3 $mg \cdot L^{-1}$ some fish died. Doudoroff and Shumway (1970) document the lethal effects of low dissolved oxygen levels on many species of fish.

TOXICANTS AND HYPOXIC CONDITIONS

A number of effects have been documented in the literature describing both the lethal and sublethal effects of dissolved oxygen on fish. Compounding the effects of hypoxia on fish is the presence of contaminants. Alderdice and Brett (1957) and Hicks and De Witt (1971) recorded more rapid mortality in young sockeye and coho salmon when they were subjected to pulp mill wastes at reduced levels of dissolved oxygen. McGreer and Vigers (1983) determined that dissolved oxygen was a significant variable explaining fish avoidance in Neroutsos Inlet due to the effluent from the Port Alice pulp mill. These authors reported the findings of Marier (1973) who concluded that a reduction in dissolved oxygen from 6.5 to 4.0 $mg \cdot L^{-1}$ increased the toxicity of kraft mill effluent up to three fold (the test species was not identified, however). The ability of fish to tolerate hypoxic conditions is significantly reduced in the presence of these contaminants. Sprague (1985) reviewed some of the literature on this inadequately researched topic and reported that, in general, a reduction in dissolved oxygen from 100% to 80% of air saturation will cause increased mortality of fish exposed to contaminants. The work of Tuurala and Sovio (1982) provides additional information in relation to the effects of dehydroabietic acid (DHA), a toxic constituent in pulp mill effluents, on rainbow trout gills. The net effect of a sublethal concentration of DHA (1.6 $mg \cdot L^{-1}$) was to cause morphological changes in the gills thereby impairing oxygen uptake, an effect which would be of importance in hypoxic waters where respiratory activities would be increased even in the absence of contaminants.

While the synergistic effects of pulp mill effluent and hypoxic conditions on fish are of concern, it is also important to remember that the effects of pulp mill effluent alone can have serious consequences for aquatic organisms. Recently reported research from Sweden exemplifies this concern. Andersson et al. (1988) reported profound effects of bleached kraft mill effluents on several fundamental biochemical and physiological functions in perch (Perca fluviatilis) inhabiting coastal waters near pulp mills. For example, effects on white blood cell patterns indicate a suppressed immune defence, and alterations in the red blood cell status and the ion balance suggest an impaired gill function. Such disturbances were most apparent within 4.5 km of the pulp mill outfalls, but many physiological effects could be detected up to 10 km away.

DISSOLVED OXYGEN CRITERIA

A number of individuals and organizations have developed dissolved oxygen criteria for the protection of aquatic organisms. Davis (1975 a,b) summarizes some of these, and the most recent is that provided by EPA (1986).The greatest value of the criteria lies in their application in "pristine" waters and less so for polluted environments where contaminants may compound the effects due to dissolved oxygen levels alone. While the originators of the criteria recognize the problems of application, inadequate information prevents their full utility in polluted environments. It is most likely that the levels of dissolved oxygen required to protect aquatic organisms in polluted habitats are substantially greater than those required in the absence of contaminants (this assumes that the fish can accommodate exposure to the contaminant.)

Davis (1975 a,b) provides dissolved oxygen criteria, with particular reference to the Canadian environment. Based on a review of the literature Davis considered three levels of protection:

"Level A - This level represents more or less ideal conditions (i.e. little or no foreseeable harm) and permits little depression of oxygen from full saturation. It represents a level that assures a high degree of safeguard for many important stocks in prime areas". (Davis (1975a).

"Level B - At this level, some degree of risk (i.e. possibility of moderate harm) to a portion of a fish population exists if the oxygen minimum period is prolonged beyond a few hours". Davis (1975a). "This level represents the oxygen value where the average member of a species in a fish community starts to exhibit symptoms of oxygen distress". Davis (1975b).

"Level C - At this level, a large portion of a given fish population or fish community may be affected by low oxygen. This deleterious effect may be severe (i.e. possibility of severe harm), especially if the oxygen minimum is prolonged beyond a very few hours". Davis (1975a).

> "This level should be applied only if fish populations in an area are judged hardy or of marginal significance, or of marginal economic importance and as such are dispensible (i.e. in the socio-economic sense)". Davis (1975b).

For anadromous salmonids (such as salmon) in seawater (a situation that would pertain in Neroutsos Inlet), Davis (1975b) considers the following levels of protection:

Protection Level	Dissolved Oxygen Concentration PO_2	Dissolved Oxygen Concentration ($mg \cdot L^{-1}$)	Percentage Saturation 0 to 25°C
A	160	9.0	100
B	125	6.5	79-94
C	90	4.0	57-58

Thus, for the full protection of salmon in salt water, fully saturated dissolved oxygen levels should be maintained.

EPA (1986) recommend dissolved oxygen concentration criteria and consider that for salmonid waters the "no production impairment" level for embryo and larval stages should be 11 $mg \cdot L^{-1}$ and the acute mortality limits (the minimum level considered not to risk direct mortality) is 6 $mg \cdot L^{-1}$. For older salmonid life stages the respective levels are 8 and 3 $mg \cdot L^{-1}$ dissolved oxygen. The criteria do not represent assured no-effect levels, and EPA (1986) reiterate that "the presence of chemicals, pathogens, and temperature at slightly stressful levels aggravate or enhance the effects of what might otherwise be acceptable, but borderline, dissolved oxygen concentrations".

In support of the criteria which EPA (1986) recommend, are numerous references for studies on the effects of dissolved oxygen on cold- and warm-water fish. For the Salmonidae the reports are grouped under the headings of: physiology, lethality, growth, behaviour, swimming and early life stages. While it would be a duplication of effort to produce the same information in this report, brief comment will be made with respect to salmonids and the effects of reduced dissolved oxygen levels in relation to Neroutsos Inlet and the maintenance of healthy populations of fish.

SPECIFIC CONSIDERATIONS

In order to survive in the natural environment, fish must be able to function normally. For example, they must be able to seek food, avoid predators, resist currents, reproduce successfully. Therefore, there is little logic in accepting dissolved oxygen levels as suitable criteria which are at, or close to, lethal levels for fish. If a fish's ability, for example, to escape predation is impaired due to the effect of reduced dissolved oxygen levels in its natural environment, its survival is jeopardized. Criteria for dissolved oxygen which recognize such effects, and their significance, must be applied for the maintenance of healthy aquatic organisms and their habitat (e.g. Davis

1975a, b). Before the onset of death due to dissolved oxygen reduction, higher, but still reduced, levels may cause numerous harmful effects, such as severely limiting energy expenditure for migration or maximum feeding, eliciting avoidance reactions, affecting growth rates (refer to Davis 1975a, b; EPA 1986).

BEHAVIOUR

Adult and juvenile salmon transit Neroutsos Inlet and both are, typically, found in surface waters. Studies which have investigated the behaviour of juvenile Pacific salmon have revealed a strong surface water orientation during seaward migration and estuarine rearing phases (Birtwell 1977; Birtwell and Harbo 1980; Beak Consultants Ltd. 1981; Birtwell and Kruzynski 1987; Macdonald et al. 1987; Birtwell and Kruzynski 1989). Adult Atlantic salmon have been recorded close to the water surface for protracted periods of time (months) in estuaries, seemingly associated with the depth of the halocline (Brawn 1982). Furthermore, Westerberg (1984) and Döving et al. (1985) conclude that the fine-scale hydrographic features (e.g. thermal microstructure) may provide a necessary reference system for successful orientation by salmon in nearshore coastal regions.

The above comments are of importance in relation to the discharge of waste waters (and their associated effects) into surface waters. In that effluent from the Port Alice pulp mill enters surface waters, albeit initially via a diffuser, the potential exists for a conflict due to the requirement of salmon and other organisms for appropriate water quality.

Vertical distribution and survival of salmon in relation to pollutants

We have examined the behaviour and survival of caged juvenile salmon in waters receiving pulp mill effluent (Birtwell 1977; Birtwell and Harbo 1980; Birtwell and Kruzynski 1989). At Port Alberni, caged juvenile chinook salmon held at 6.5 m depth died within 24 hours. The cause of death was considered to be related to fluctuating environmental conditions, especially reduced dissolved oxygen levels (average values of 4.0 ± 1.6 mg$\cdot$L^{-1}). Survival of fish caged at 0.5 m depth was much greater, and although pulp mill effluent was present, dissolved oxygen concentrations ranged between 6.1 and 11.0 mg$\cdot$L^{-1} with an average value of 9.3 ± 0.9 mg$\cdot$L^{-1}. The results of experiments on the behaviour of juvenile salmon support the inference that the dissolved oxygen levels (and possibly other environmental factors) at depth were unsuitable for these fish. Juvenile chinook salmon, given the choice of locations in the water column, avoided the deeper waters which contained the reduced levels of dissolved oxygen (less than about 40% of saturated values). It was concluded from statistical analyses of the data relating the presence of juvenile chinook salmon to water characteristics, that dissolved oxygen was the most significant variable relating to the fish distribution. The results of stepwise multiple regression analysis yielded the equation: Log (fish number +1) = 2.48 + 1.95 Log (dissolved oxygen), $n = 70$, $R^2 = 0.69$ (Birtwell and Kruzynski 1989).

Further evidence regarding the avoidance of waters with reduced dissolved oxygen levels in Alberni Inlet comes from the results of gill net catches on immature and returning adult salmon. Five times more salmonids were captured in the surface (0.0 to 2.5 m depth) zone, despite the presence of pulp mill effluent, than in the deeper (2.5 to 5.0 m) waters which were fished. Dissolved oxygen in the surface zone ranged between 6.2 and 9.1 $mg \cdot L^{-1}$ (65 to 95% saturation) and 2.8 to 9.1 $mg \cdot L^{-1}$ (25 to 95% saturation) in the deeper zone. The only occasion when coho and chinook salmon were captured in the 2.5 - 5.0 m zone was when the level of dissolved oxygen rose to about 6.7 $mg \cdot L^{-1}$, approximately 70% of air saturation (Birtwell et al. 1983).

Using the same cage apparatus that we used to examine the behaviour of salmon, stickleback, and herring in their natural environment, McGreer and Vigers (1983) examined the behaviour of fish in Neroutsos Inlet. Dissolved oxygen and pH were shown to be the most significant water quality variables in explaining the shift in vertical distribution of test fish in Neroutsos Inlet in 1979, and in 1980 they were color, salinity and dissolved oxygen. The avoidance of the uppermost parts of the water column by chum salmon, was used to define a zone of influence which extended 10 km down the inlet from the pulp mill (Figure 3). "The predictions of fish movement based on avoidance tests were consistent with the data from juvenile (chum salmon) out-migrant studies carried out at Neroutsos Inlet in 1978 and 1979, which showed that migrating juveniles avoided the mill outfall and much of the eastern shoreline down inlet from the mill" (McGreer and Vigers 1983). In addition, significant mortalities occurred in their behaviour experiments up to 2 km from the mill discharge. This was unexpected in view of the opportunity presented to the fish to move deeper and thereby avoid the more highly toxic waters close to the surface. We too have recorded the death of some fish in similar behaviour experiments in waters receiving pulp mill effluent wherein we gave them the opportunity to move vertically in the water column (Birtwell and Harbo 1980; Birtwell and Kruzynski 1989). Using dye-tagged juvenile coho salmon we were able to determine that the mortalities were not a function of initial placement position within the experimental cages. Recent research on the behaviour of chinook salmon in relation to hypoxic conditions within a simulated estuarine water column also reveals that these salmon will move into waters which are of sub-optimal quality (Birtwell and Kruzynski 1987; Birtwell and Kruzysnki 1989).

Both fish capture and laboratory studies support to our contention that the behaviour of juvenile salmon to occupy surface waters may override some potentially adaptive avoidance reactions (i.e. a vertical distribution shift); the fish enter water layers containing toxic concentrations of pulp mill effluent and thereby may jeopardize their survival. Alternatively, discrimination of potentially less harmful waters may be impaired due to the lack of suitable gradients and sensory cues (Höglund 1961). Another factor may be the attraction of the test fish to the effluent and its constituents, for it has been demonstrated that attraction to lethal levels of contaminants occurs, for example, with rainbow trout and chlorine (Hadjinicolaou and Laroche 1988). Consequently, it may be significant that aquatic conditions which the juvenile salmon may choose or prefer could inadvertently jeopardize their survival. In this context, the paucity or absence of juvenile salmon close to the Port Alice pulp mill at the time of studies by Davis et al. (1978), McGreer and Vigers (1983) and Poulin and Oguss (1982), may not be solely due to avoidance of the region but also to mortality of fish, that had encountered, and chosen to remain in, this degraded habitat.

Thus there is evidence that juvenile salmon in particular have a strong surface water orientation, that this may be disrupted by pulp mill effluents and hypoxic conditions, and that despite the presence of sub-optimal conditions, the innate behaviour of these fish may override reactions which favour their survival. Accordingly the use of fish presence as indicative of appropriate water quality in the vicinity of effluent discharges is fraught with problems, for presence per se is, at the very best, only a coarse indicator of environmental health.

Laboratory studies on the effects of hypoxic conditions

Avoidance of hypoxic conditions by juvenile chinook salmon has been the focus of our recent research (Birtwell and Kruzynski 1987; Birtwell and Kruzynski 1989). Under simulated estuarine conditions, we examined the response of underyearling coho and chinook salmon to reductions in dissolved oxygen in fresh water, overlying salt water: a highly stratified situation typical of many coastal fjord-type estuaries (for example, that at the head of Neroutsos Inlet). Underyearling chinook salmon avoided levels of dissolved oxygen which were typically less than 7-8 $mg \cdot L^{-1}$ (Birtwell and Kruzynski 1989): levels much higher than those which have been reported to be lethal to salmon (Tsai 1975) and also induce avoidance reactions (e.g. Bishai 1962) but similar to the 8.3 ppm response threshold for brook trout (Dandy 1970). We have found that the fish will make excursions into the waters of reduced oxygen content but rapidly (generally in seconds) return to waters of higher oxygen content (close to saturation). We have recorded such excursions during feeding activity, and in the absence of food (unpublished data).

It seems that juvenile chinook salmon in hypoxic conditions, do not respond in the same manner as many other species, that is, they do not go to the water surface (Gee et al. 1978) and employ aquatic surface respiration Kramer (1987); a behavioural trait that enhances the survival of certain species of fish under hypoxic conditions and in the presence of contaminants (Kulakkattolickal and Kramer 1987).

Salmon migration

The successful migration of adult salmon and juveniles in Neroutsos Inlet, particularly to and from the major creeks, Colonial and Cayeghle, at the inlet head, is of concern due to the often adverse water quality conditions. Figure 4 depicts the zones of hypoxic waters in the inlet in 1987, at the time of juvenile salmon migrations.

Adult fish have occurred in Neroutsos Inlet in early September, despite the presence of low dissolved oxygen levels. Adult salmon have successfully migrated to the major creeks but this has generally occurred when aquatic conditions were improving (e.g. October) with the onset of rain and gales. It seems that the motivation of such fish is high, and that they had the ability to migrate through waters deemed to the sub-optimal. It is possible that 'migration corridors', wherein dissolved oxygen values were 'tolerable', permitted such migrations to occur. In previous years (in the absence of diffuser operation and acetate pulp production, but under 'normal' operating output and 'usual' climatic conditions), it is possible that such migration corridors could have existed, possibly along the western shoreline and biased towards the discharge of fresh water from Colonial and Cayeghle Creeks, and even behind Ketchen Island. However, measurements of dissolved oxygen behind Ketchen Island (e.g. about 2.3 to 0.8 $mg \cdot L^{-1}$, surface to 4 m depth Sept. 6, 1985; M. Pomeroy, Environment Canada, personal communication) would imply that no such migration corridor existed in this area on that occasion. In due course, with the advent of rainfall and gales in October, there was a greater freshwater input to the head of Neroutsos Inlet and an elevation in dissolved oxygen which was coincident with the influx of salmon to their spawning streams, as reported earlier.

Assuming a typical adult salmon migration speed of about 0.5 $m \cdot s^{-1}$ (Rosberg and Greer 1985), about 11 hours would be required to travel the 20 km length of Neroutsos Inlet and substantially less time from the mid-inlet 'holding area' found during gill net fishing in September 1985 (DFO unpublished information) - under optimal unpolluted conditions. The lowest levels of dissolved oxygen which have occurred in recent years in the inlet in summer and early autumn, would not be conducive to this migration occurring. Levels of dissolved oxygen of less than 2 $mg \cdot L^{-1}$ would, even without pulp mill effluent, be at the threshold of tolerance for salmon (Alderdice and Brett 1957) and some would be expected to die at levels around 3.0 $mg \cdot L^{-1}$ (Chapman 1940). Davis et al. (1978) examined the ability of underyearling chum salmon to abstract oxygen from surface (2 m) and deeper (20 m) waters of Neroutsos Inlet 16-19 d after the pulp mill had stopped operating. Dissolved oxygen levels in surface waters were close to full saturation, a marked contrast to the situation which existed under operating conditions. In residual oxygen bioassays, juvenile salmon died at dissolved oxygen levels <3 $mg \cdot L^{-1}$, even in the relative absence of pulp mill effluent (Davis et al. 1978). Furthermore conditions lethal to juvenile salmon were revealed during in-situ bioassays undertaken when the pulp mill was operating during the summer period (Davis et al. 1978; DFO unpublished information).

Beamish (1978) in his review on the 'swimming capacity' of fish reports the work of Kutty and Saunders (1973) with Atlantic salmon (23.4 cm) which sustained speeds of 50 and 75 $cm \cdot s^{-1}$ (2.1 and 3.0 $lengths \cdot s^{-1}$) for several hours until ambient oxygen was reduced to 4.0 and 4.8 $mg \cdot L^{-1}$. The swimming speed of coho salmon was shown to decline at dissolved oxygen concentrations below saturation (Dahlberg et al. 1968). However, the significance of the effect of reductions in dissolved oxygen on swimming performance is directly related to the requirement for, for example, survival, growth, and reproduction. There is a high metabolic (energy) cost upon acute physical stress and delayed mortality can occur as a result of exhausting exercise (Wood et al. 1983). Barton and Schreck (1987) reported that acute physical stress adversely affected juvenile steelhead trout by reducing, by about 25%, the energy available for other activities within the scope of activity of the fish. Bleached kraft mill effluent at concentrations close to that of the 96 h LC50 value also resulted in a reduction (72%) in the swimming capacity of coho salmon (Howard 1975). Hence we could assume that the swimming speed of salmon exposed to both dilutions of pulp mill effluent and hypoxic conditions would be decreased.

In recognition of the reported dissolved oxygen conditions in

Neroutsos Inlet it is highly probable that there frequently exists, in late summer and early autumn, a barrier to the migration of adult salmon.

The ability of motivated migrating salmon to overcome 'obstacles' is well known, but it is also known that adequate dissolved oxygen levels must be maintained for the success of such movements. Alabaster (1972) cites a study on coho salmon which continued to swim at their usual rate ($0.56\ m \cdot s^{-1}$) for an hour at dissolved oxygen levels of 5 to 6.6 $mg \cdot L^{-1}$ and for a further hour at 4.5 to 5.0 $mg \cdot L^{-1}$. However, other fish exposed for the second hour to dissolved oxygen concentrations of 4 to 4.5 $mg \cdot L^{-1}$ became fatigued. With dissolved oxygen levels in Neroutsos Inlet generally under 4.5 $mg \cdot L^{-1}$ in late summer and early autumn and with the predicted migration time of about 11 hours along the total length of the Inlet, (under optimal conditions), it is apparent that migrating salmon may become fatigued (assuming similar conditions pertain to those cited by Alabaster), move at a slower speed, or possibly cease migration. Alabaster also reports the results of an 11 year study on the migration of adult chinook salmon, through a fish pass, which was apparently inhibited by dissolved oxygen values below 4 to 5 $mg \cdot L^{-1}$ - but in two exceptional years, a few fish passed when it was as low as 3 $mg \cdot L^{-1}$ (Sams and Conover 1969). Unfortunately, the duration of exposure to these reduced oxygen levels, water flows, temperatures, etc. were not reported, for they are required in order to interpret the results.

Hallock et al. (1970) tagged migrating adult chinook salmon. In three successive years they concluded that dissolved oxygen concentrations seemed to be the factor that controlled the movement of the salmon. Dissolved oxygen levels about 4.2 $mg \cdot L^{-1}$ were present when the salmon migrated past a certain location in the Sacramento-San Jaoquin delta. In all three years migration occurred when dissolved oxygen levels were above 5 $mg \cdot L^{-1}$ (the dissolved oxygen depletion problem was primarily due to the discharge of fruit and vegetable canning wastes). Hallock et al. (1970) concluded that less than 4.5 $mg \cdot L^{-1}$ dissolved oxygen should be regarded as a block to the migration of adult chinook salmon in the system studied. Alabaster (1988) evaluated data on the migration of chinook salmon up the Willamette River. He deduced that the dissolved oxygen level at which the majority of fish were migrating, and beneath which they were not, was 3.5 $mg \cdot L^{-1}$. A comparison of Hallock's (1970) results with those of Alabaster's (1988) was reported by Alabaster (1989). He concluded that dissolved oxygen was the most influencial variable associated with the migration of chinook salmon and that the rate of change of dissolved oxygen and temperature during the migration period may explain differences in the results between river systems.

Studies by Alabaster and Gough (1986) indicated that the successful passage of salmon through the River Thames estuary was achieved when the median dissolved oxygen level was 3.5-5.9 $mg \cdot L^{-1}$ and the 5-percentile level 1.6-2.6 $mg \cdot L^{-1}$. The fish were considered to have migrated through a 15 km reach where the dissolved oxygen levels were always $<4.7\ mg \cdot L^{-1}$. However, the exact nature of the migration route, depth, specific microhabitat occupancy, precise level of dissolved oxygen experienced and duration of exposure, etc., are unknown (Alabaster and Gough 1986). Hypoxic waters in the well-mixed River Thames estuary are moved landward and seaward by flood and ebb tides respectively (Birtwell 1972), and the tidal excursion is about 14 km (Arthur 1972). If one assumes that migrating adult salmon, as other organisms, invade the estuary on the flooding tide and in waters of relatively higher dissolved oxygen levels (Arthur 1972; Huddart and Arthur 1971a; 1971b) and continue to move upstream or maintain position through the ensuing ebb tide (refer to Priede et al. 1988, Stasko 1975), their exposure to hypoxic conditions could be much briefer than that which may be deduced from an analysis of the extent of reduced dissolved oxygen levels at specific locations in the estuary. We may conclude from this work that salmon migrating through the estuary would have encountered hypoxic conditions, but the exact level which they experienced is unknown. We cannot conclude, therefore, that the dissolved oxygen levels recorded in the estuary during the period when fish were captured upstream, were suitable for the salmon to function "normally". It is somewhat misleading, at least to me, that Alabaster and Gough (1986) consider their data "an opportunity to define the dissolved oxygen requirements of adult fish ascending the estuary to reach fresh water". The work of Priede et al. (1988) provides some very relevant information. They used adult salmon equipped with acoustic oxygen sensing transmitters to track their movements in the organically polluted estuary of the River Ribble. While fish moved with the tides within the turbulent and well-mixed estuary they experienced cyclical changes in dissolved oxygen. Fish movement was inhibited below 40% of the air saturation value and there was evidence of avoidance below 55%. Based upon this unique research which recorded the actual values of dissolved oxygen experienced by the migrating salmon, Priede et al. (1988) conclude that dissolved oxygen values >60% of air saturation are preferred for the migration of salmon. In waters of 25‰ salinity at 15°C this would equate to about 5.2 $mg \cdot L^{-1}$, and in fresh water 6.0 $mg \cdot L^{-1}$, values much lower than those reported by Hugman et al. (1984) for estuaries which support regular salmonid fisheries. Even if precise dissolved oxygen levels to which the fish were exposed, and the duration, were known, one must always differentiate between the lower levels which may be tolerated versus the higher values which are required for 'normal' metabolic and behavioural functions.

METABOLISM

Numerous physiological studies indicate that under reduced levels of dissolved oxygen the blood's decreased loading capacity limits the amount of oxygen transported to tissues, thereby restricting the ability of fish to maximize metabolic performance.

The growth of salmonids is susceptible to the effects of low dissolved oxygen, and specific attention is devoted to this topic by EPA (1986). The attainment of a suitable size during the transition to a saltwater phase in the life cycle of salmon is considered to be an advantage regarding survival and smolting. Reductions in the growth rate of salmonids were recorded at levels as high as 7 $mg \cdot L^{-1}$ (EPA 1986). Reduced feeding activity may be related to the recorded reduction in growth rates.

In that reduced levels of dissolved oxygen frequently occur in Neroutsos Inlet at the time when the upstream migration of adult salmon begins, it is likely that effects on spawning could occur. Such effects would probably be in relation to the energy expended in travelling through polluted hypoxic waters. Based upon the comments presented above it is possible that some energy which would otherwise be devoted to the production of gametes and for spawning activities may have been used during migration. It is presumed that these fish would not be feeding, therefore they would rely upon finite internal energy reserves. I am not aware of any studies on the effects of reduced levels of dissolved oxygen on reproduction of salmonids. EPA (1986) report that the number of eggs produced per female fathead minnow was reduced at 2 $mg \cdot L^{-1}$ dissolved oxygen, but not at higher concentrations, and that no spawning occurred at 1 $mg \cdot L^{-1}$ dissolved oxygen (levels which would be lethal to juvenile Pacific salmon).

GENERAL CONCLUDING REMARKS

Information in the literature indicates that hypoxic conditions affect salmon in a variety of ways. Effects are manifest at different levels, but it is apparent that even at relatively high levels (7-8 $mg \cdot L^{-1}$) quantifiable responses can be measured. In that much of the information has been gained from laboratory studies in which the fish did not have to compete for survival, oxygen requirements may well have been underestimated. In addition, the combined effects of toxicants may produce more severe effects than those caused by hypoxic conditions alone.

DISSOLVED OXYGEN CRITERIA

Alabaster (1972) provides, as others have done (see Davis 1975a, b; EPA 1986) tentative criteria for maintaining 'the normal attributes of the life cycle of fish' - under otherwise favourable environmental conditions (that is, without the presence of toxic effluents such as pulp mill wastes). For the upstream migration of salmon, Alabaster recommends a minimum dissolved oxygen value of 5 $mg \cdot L^{-1}$. He, like others, stresses caution in the use of such a criterion and recognizes that local seasonal and natural variations in dissolved oxygen should be taken into account. Other authors have stressed that oxygen minima must not fall below 4 to 6 $mg \cdot L^{-1}$ in coastal and estuarine environments (see Davis 1975a). Such criteria are based upon knowledge of the effects of dissolved oxygen reduction on a variety of fish. If salmon are of sole interest, these minimum values should be raised substantially (Alabaster 1972; Davis 1975b); a position that seems easy to endorse based upon the foregoing information, and information regarding fisheries in English Rivers and estuaries. Hugman et al. (1984) deduced that minimum dissolved oxygen concentrations exceeded 7 $mg \cdot L^{-1}$ and 10 $mg \cdot L^{-1}$ for 95% and 50% of the time respectively, in estuaries supporting regular salmonid fisheries. In the River Trent, Alabaster (1972) reported that "trout fisheries" occurred when the 50 percentile and 5 percentile of the annual distribution of dissolved oxygen were about 9 and 5 $mg \cdot L^{-1}$ respectively. It is possible that trout (e.g. brook trout) may have a greater sensitivity to low ambient oxygen than Atlantic salmon as mentioned by Dandy (1970).

NEROUTSOS INLET

It is imperative that dissolved oxygen levels are elevated in Neroutsos Inlet for the benefit of resident and transient aquatic organisms. It is most unlikely that a successful migration of salmon to Colonial and Cayeghle Creeks will occur when dissolved oxygen levels are severely reduced. Levels should be maintained close to saturation for full protection, and the position adopted by the Department of Fisheries and Oceans for an average concentration of 5 $mg \cdot L^{-1}$ in the surface 10 m should encompass values both higher and lower in these waters. But, if this were not so, there can be no assurance that salmon, delayed by adverse water quality conditions, will spawn elsewhere, and if they did, that egg and fry survival would be equal to that in their natal streams. Neither is there reason to believe that the returning adult salmon can be delayed indefinitely, without harm, while on their spawning migration. The consequences of an impoverished or no migration (and thereafter spawning) of adult salmon to Colonial and Cayeghle Creeks would most probably affect future salmon production in the area.

If severe dissolved oxygen depression (as recorded in summer and early autumn over the last 3 years in particular) is extensive and persistent in Neroutsos Inlet over winter and during the juvenile salmon spring migration period, the conditions would be stressful, if not lethal, to these fish. This, coupled with the effect of pulp mill effluent, would probably jeopardize fry survival.

Irrespective of dissolved oxygen levels returning to what have now become "accepted", yet depressed levels in Neroutsos Inlet (i.e. those recorded in the late 1970's), it is obvious that this area is adversely impacted by the discharge of effluent from the Port Alice pulp mill to the extent that the aquatic habitat is impaired and, therefore, is a sub-standard aquatic environment for salmonids. In recognition of the foregoing comments it is apparent that one cannot rely solely upon the presence of fish, or the successful migration of adult salmon through regions of deteriorated water quality, to indicate the suitability of conditions necessary to maintain healthy populations of fish and other aquatic organisms in Neroutsos Inlet.

ACKNOWLEDGMENTS

The cooperation of M. Pomeroy, A. Colodey, L. Adamache (DOE), J. Morrison, and R. Russell (DFO) in providing information is appreciated. B. Gordon drafted the figures while Mrs. D. Price typed the text which was reviewed by M.D. Nassichuk and Dr. J.C. Davis.

REFERENCES

Alabaster, J.S. 1972. Oxygen in estuaries: requirements for fisheries. pp. 15-33. In: Water Pollution Research Technical Paper No. 13, McCorquodale Printers Limited, London.

Alabaster, J.S. 1989. The dissolved oxygen and temperature requirements of king salmon, Oncorhynchus tshawytscha, in the San Joaquin Delta, California. J. Fish. Biol. 34: 331-332.

Alabaster, J.S. and P.J. Gough. 1986. The dissolved oxygen requirements for Altantic salmon, Salmo salar L., in the Thames Estuary. J. Fish. Biol. 29: 613-621.

Alderdice, D.F. and J.R. Brett. 1957. Some effects of kraft mill effluent on young Pacific salmon. J. Fish. Res. Board Can. 14(5): 783-795.

Andersson, T. and L. Farlin, J. Hardig and A. Larsson. 1988. Biochemical and physiological disturbances in fish inhabiting coastal waters polluted with bleached kraft mill effluents. Mar. Environ. Res. 24: 233-236.

Arthur, D.R. 1972. Katabolic and resource pollution in estuaries. pp. 65-83. In: Proceedings of the 8th Annual Symposium, Eugenics Society, P.R. Cox and J. Peel (eds.). Academic Press, New York.

Barton, B.A. and C.D. Schreck. 1987. Metabolic cost of acute physical stress in juvenile steelhead. Trans. Am. Fish. Soc. 116: 257-263.

Beak Consultants Ltd. 1981. Environmental impact statement of proposed improvements to the Fraser River shipping channel. Publ. Works. Can. Vancouver, B.C. 635 p.

Beamish, F.W.H. 1978. Swimming capacity. pp. 101-187 In: Fish physiology, Vol. 7. D.J. Randall (ed.). Acad. Press, New York.

Birtwell, I.K. 1972. Ecophysiological aspects of tubificids in the Thames estuary. Ph.D. Thesis. Univ. of London. 504 p.

Birtwell, I.K. 1977. A field technique for studying the avoidance of fish to pollutants. In: Proc. 3rd Aquatic Toxicity Workshop, Halifax, N.S. Nov. 2-3, 1976. Environmental Protection Service Tech. Rep. EPS-S-AR-77-1: 69-86.

Birtwell, I.K., J.C. Davis, M. Hobbs, M.D. Nassichuk, M. Waldichuk and J.A. Servizi. 1981. Brief presented to the British Columbia Pollution Control Board Inquiry pertaining to the Annacis Island sewage treatment plant and municipal waste discharges into the lower Fraser River. Can. Ind. Rep. Fish. Aquat.Sci. 126: 40 p.

Birtwell, I.K., G.L. Greer, M.D. Nassichuk and I.H. Rogers. 1983. Studies on the impact of municipal sewage discharged into an intertidal area within the Fraser River estuary, British Columbia. Can. Tech. Rep. Fish Aquat. Sci. 1170: 55 p.

Birtwell, I.K. and R.M. Harbo. 1980. Pulp mill impact studies at Port Alberni and Port Mellon, B.C. Trans. Tech. Sect. Can. Pulp Pap. Assoc. 81(12): 85-88.

Birtwell, I.K. and G.M. Kruzynski. 1987. Laboratory apparatus for studying the behaviour of organisms in vertically stratified waters. Can. J. Fish. Aquat. Sci. 44(7): 1343-1350.

Birtwell, I.K. and G.M. Kruzynski. 1989. In situ and laboratory studies on the behaviour and survival of Pacific salmon (genus Oncorhynchus). In: Environmental Bioassay Techniques and their Application. M. Munawar, G. Dixon, C.I. Mayfield, T. Reynoldson and M.H. Sadar, (eds.). Hydrobiologia (in press). Kluwer Academic Publishers, The Netherlands.

Birtwell, I.K., S. Nelles and R.M. Harbo. 1983. A brief investigation of fish in the surface waters of the Somass River estuary, Port Alberni, British Columbia. Can. Man. Rep. Fish. Aquat. Sci. 1744: 31 p.

Bishai, H.M. 1962. Reactions of larval and young salmonids to water of low oxygen concentrations. J. Cons. Int. Explor. Mer. 27: 167-180.

Brawn, V.M. 1982. Behaviour of Atlantic Salmon (Salmo salar) during suspended migration in an estuary, Sheet Harbour, Nova Scotia, observed visually by ultrasonic tracking. Can. J. Fish. Aquat. Sci. 39: 248-256.

Brett, J.R. and J.M. Blackburn. 1981. Oxygen requirements for growth of young coho salmon (Oncorhynchus kisutch) and sockeye (O. nerka) salmon at 15°C. Can J. Fish. Aquat. Sci. 38: 399-404.

Brungs, W.A. 1971. Chronic effects of of dissolved oxygen concentrations on fathead minnow (Pimephales promelas). J. Fish. Res. Board Can. 28: 1119-1123.

Chapman, W.M. 1940. Effects of a decreased oxygen supply on sockeye and chinook salmon. Trans. Amer. Fish. Soc. 69: 197-204.

Dahlberg, M.L. D.L. Shumway and P. Doudoroff. 1968. Influence of dissolved oxygen and carbon dioxide on swimming performance of large mouth bass and coho salmon. J. Fish. Res. Board Can. 25: 49-70.

Dandy, J.W.T. 1970. Activity response to oxygen in the brook trout Salvelinus fontinalis (Mitchill). Can. J. Zool. 48: 1067-1072.

Davis, J.C. 1975a. Waterborne dissolved oxygen requirements and criteria with particular emphasis on the Canadian environment. National Research Council of Canada, Associate Committee on Scientific Criteria for Environmental Quality, Report No. 13, NRCC 14100: 111 p.

Davis, J.C. 1975b. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Board Can. 32: 2295-2332.

Davis, J.C., I.G. Shand, G. Christie and G. Kosakoski. 1978. Biological and oceanographic observations in the Neroutsos Inlet area with emphasis on the effect of sulfite pulp mill waste on Pacific salmon. 1973-1979. Fish. Mar. Serv. MS Rep. 1447. 88 p.

Doudoroff, P. and D.L. Shumway. 1970. Dissolved oxygen requirements of freshwater fishes. Food Agriculture Organization of the United Nations. FAO Tech. Pap. 86. Rome, Italy. 291 p.

Döving, K.B., H. Westerberg and P.B. Johnson. 1985. Role of olfaction in the behavioural and neuronal responses of Atlantic salmon, Salmo salar, to hydrographic stratification. Can. J. Fish. Aquat. Sci. 42: 1658-1667.

Environmental Protection Agency. 1986. Quality criteria for water, U.S. EPA 440/5-86-001, Washington, D.C. 35 p.

Gee, J.H., R.F. Tallman and H.J. Smart. 1978, Reactions of some great plains fishes to progressive hypoxia. Can. J. Zool. 56: 1962-1966.

Hadjinicolaou, J. and G. LaRoche. 1988. Behavioral responses to low levels of toxic substances in rainbow trout (Salmo gairdneri, Rich), pp. 327-340. In: Aquatic Toxicology and Hazard Assessment: 10th Volume, ASTM STP 971, W.J. Adams, G.A. Chapman, and W.G. Landis, (eds.), American Society for Testing and Materials, Philadelphia,

Hallock, R.J., R.F. Elwell and D.H. Fry, Jr. 1970. Migrations of adult king salmon (Oncorhynchus tshawytscha) in the San Joaquin delta as demonstrated by the use of sonic tags. Calif. Dept. Fish. Bull. 151: 1-92.

Hicks, D.B. and J.W. De Witt. 1971. Effects of dissolved oxygen on kraft pulp mill effluent toxicity. Water Research. 5: 693-701.

Höglund, L.B. 1961. The reactions of fish in concentration gradients. Rep. Inst. Freshwater Res. Drottningholm. 43: 1-147.

Howard, T.E. 1975. Swimming performance of juvenile coho salmon (Oncorhynchus kisutch) exposed to bleached kraft pulp mill effluent. J. Fish. Res. Board Can. 32: 789-793.

Huddart, R. and D.F. Arthur. 1971a. Shrimps in relation to oxygen depletion and its ecological significance in a polluted estuary. Environ. Pollut. 2: 13-35.

Huddart, R. and D.F. Arthur. 1971b. Shrimps and whitebait in the polluted Thames estuary. Int. J. environ. Studies, 2: 21-34.

Hugman, S.J., A.R. O'Donnell and G. Mance. 1984. A survey of estuarine oxygen concentrations in relation to the passage of migratory salmonids. Wat. Res. Centre Rep. 745-M.

Kramer, D.L. 1987. Dissolved oxygen and fish behaviour. Environmental Biology of Fishes. Vol. 18(2): 81-92.

Kulakkattolickal and D.L. Kramer. 1987. Effect of surface access and oxygen concentration on the toxicity of Croton tiglium (Euphorbiaceae) seed extract to Brachydanio rerio (Cyprinidae). Can. J. Fish. Aquat. Sci. 44: 1358-1361.

Kutty, M.N. and R.L. Saunders. 1973. Swimming performance of young Atlantic salmon (Salmo salar) as affected by reduced ambient oxygen concentration. J. Fish. Res. Board Can. 30: 223-227.

Levings, C.D. 1980. Demersal and benthic communities in Howe Sound basin and their responses to dissolved oxygen deficiency. Can. Tech. Rep. Fish. Aquat. Sci. 951: 27 p.

Macdonald, J.S., I.K. Birtwell and G.M. Kruzynski. 1987. Food and habitat utilization by juvenile salmonids in the Campbell River estuary. Can. J. Fish. Aquat. Sci. 44: 1233-1246.

Marier, J.R. 1973. The effects of pulp and paper wastes on aquatic life with particular attention to fish and bioassay procedures for assessment of harmful effects. Environmental Secretariat Publication No. BY 73-3, National Research Council of Canada - Division of Biological Sciences, Ottawa, Ont. Canada.

McGreer, E.R., D.R. Munday, and G.A. Vigers. 1982. Acute toxicity and fish avoidance behaviour studies in Neroutsos Inlet - 1980. Vol 6 of Environmental Improvement at Neroutsos Inlet, B.C. Western Forest Products Ltd., Vancouver, B.C. 25 p.

McGreer, E.R. and G.A. Vigers. 1983. Development and validation of an in-situ fish preference-avoidance technique for environmental monitoring of pulp mill effluents. pp. 519-529. In: Aquatic Toxicology and Hazard Assessment: Sixth Symposium, ASTM STP 802. W.E. Bishop, R.D. Cardwell and B.C. Heidolph, (eds.), American Society for Testing and Materials, Philadelphia. 519-529.

Meyer, F.P. 1970. Seasonal fluctuations in the incidence of disease on fish farms. pp. 21-29. In: A symposium on Diseases of Fish and Shellfishes. Spec. Publ. No. 5. Amer. Fish. Soc., Washington, D.C.

Poulin, V.A. and E. Oguss. 1982. Migration characteristics of juvenile chum salmon in Neroutsos Inlet with particular emphasis on the effects of sulphite mill effluent on migratory behaviour, 1980. Vol. 4 of Environmental Improvement at Neroutsos Inlet, B.C. Western Forest Products Ltd., Vancouver, B.C. 45 p.

Priede, I.G., J.F. de L.G. Solbe, J.E. Nott, K.T. O'Grady and D. Cragg-Hine. 1988. Behaviour of adult Atlantic salmon, Salmo salar L., in the estuary of the River Ribble in relation to variations in dissolved oxygen and tidal flow. J. Fish., Biol. 33: 133-139.

Rosberg, G.E. and G.L. Greer. 1985. Migration role and behaviour of adult sockeye and chum salmon through trained and untrained sections of the lower Fraser River. Can. Tech. Rep. Fish. Aquat. Sci. 1349: 25 p.

Sams, R.E. and K.R. Conover. 1969. Water quality and the migration of fall salmon in the lower Willamette River. Final Report. Fish Commission of Oregon. 58 p.

Sprague, J.B. 1985. Factors that modify toxicity. pp. 124-163. In: Fundamentals of aquatic toxicology. G.M. Rand and S.R. Petrocelli. (eds.). Hemisphere Publ. Corp. Washington, 666 p.

Stasko, A.B. 1975. Progress of migrating Atlantic salmon (Salmo salar) along an estuary, observed by ultrasonic tracking. J. Fish. Biol. 7: 329-338.

Tollefson, R. 1982. Environmental improvement at Neroutsos Inlet, B.C. Western Forest Products Limited, Vancouver, British Columbia. 84 p.

Tsai, C.D. 1975. Effects of sewage treatment plant effluents on fish: a review of literature. Chesapeake Research Consortium, Incorporated publication No. 36, UM CEES-75-100-I.E.L. 229 p.

Tuurala, H. and A. Soivio. 1982. Structural and circulatory changes in the secondary lamellae of Salmo gairdneri gills after sublethal exposures to dehydroabietic acid and zinc. Aquat. Toxicol. 2: 21-29.

Waldichuk, M. 1958. Some oceanographic characteristics of a polluted inlet in British Columbia. J. Mar. Res. 17: 536-551.

Waldichuk, M., J.R. Markert and J.H. Meikle. 1968. Physical and chemical oceanographic data from the west coast of Vancouver Island and the northern British Columbia coast, 1957-1967. Vol. 1, Nootka Sound - Muchalat Inlet and Quatsino Sound - Neroutsos Inlet. Fish. Res. Board Can. MS Rep. 990: 161 p.

Warren, C.E., P. Doudoroff and D.L. Shumway. 1973. Development of dissolved oxygen requirements for fish. Off. Res. Monit., U.S. Environ. Prot. Agency, Wash. D.C. Rep. EPA-R3-73-019. 121 p.

Wedemeyer, G.A. 1974. Stress as a predisposing factor in fish diseases. U.S. Dept. Interior, Fish & Wildlife Service leaflet. FDL-38. 8 p.

Westerberg, H. 1984. The orientation of fish and the vertical stratification at fine and microstructure scales. pp. 179-204 In: Mechanisms of migration in fishes. Plenum Publishing Corp., New York, New York.J.D. Cleave, W.H. Neill, J.J. Dodson and G.P. Arnold (eds.).

Wood, C.M., J.D. Turner and M.S. Graham. 1983. Why do fish fie after severe exercise? J. Fish. Biol. 22: 189-201.

Figure 1. Neroutsos Inlet, British Columbia, and the location of the Port Alice pulp mill.

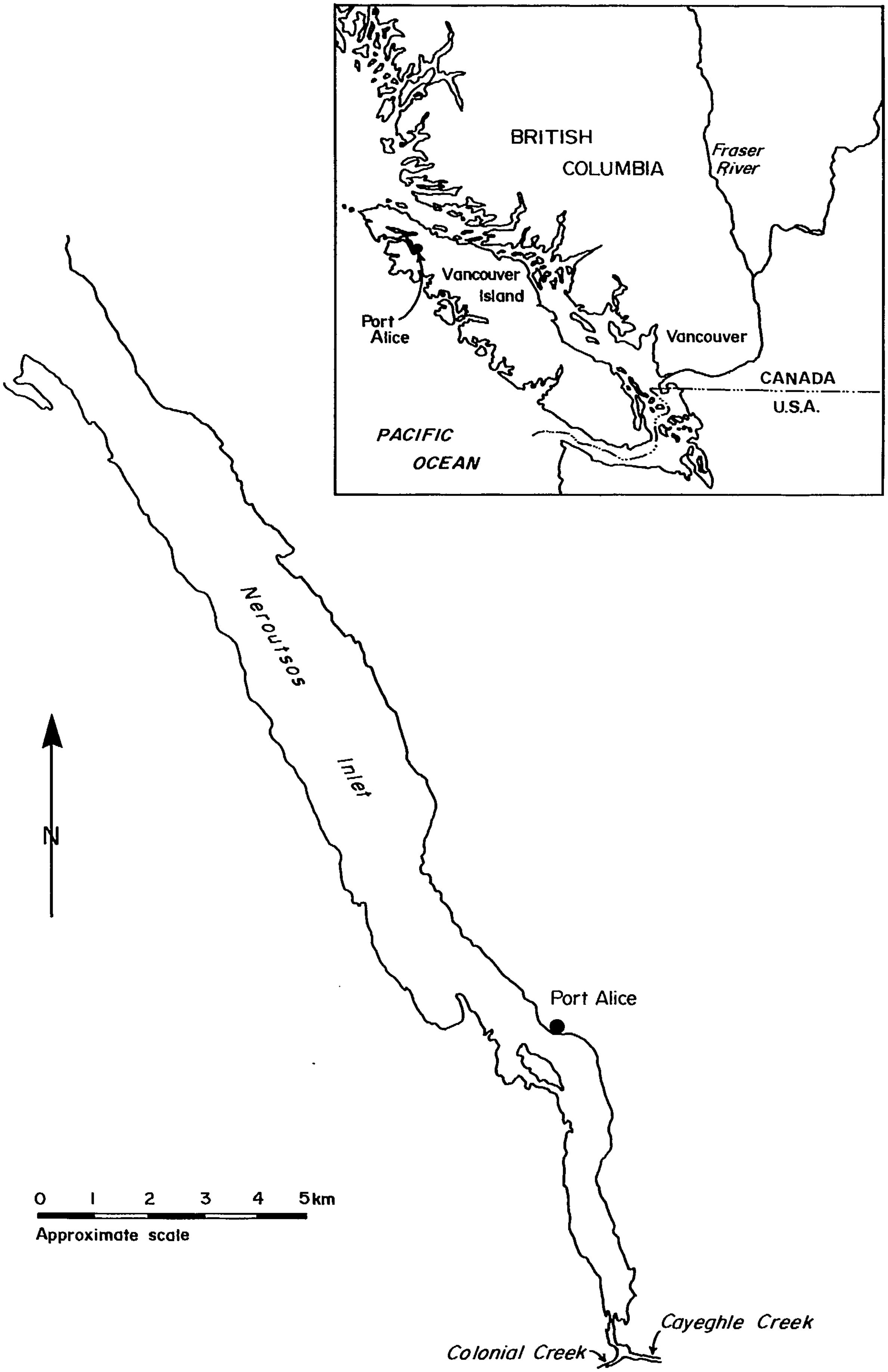

BRITISH
COLUMBIA
Fraser
River
Vancouver
Island
Port
Alice
Vancouver
CANADA
U.S.A.
PACIFIC
OCEAN
Neroutsos
Inlet
N
0 1 2 3 4 5km
Approximate scale
Port Alice
Cayeghle Creek
Colonial Creek

Figure 2. Zones of hypoxic surface waters (<20 m depth) in Neroutsos Inlet when adult salmon were returning to spawn in September and October 1985. Data are courtesy of the Department of Environment, Pacific Region. Approximate boundaries of hypoxic waters are based upon criteria for the protection of salmonids (Davis 1975a, b; EPA 1986).

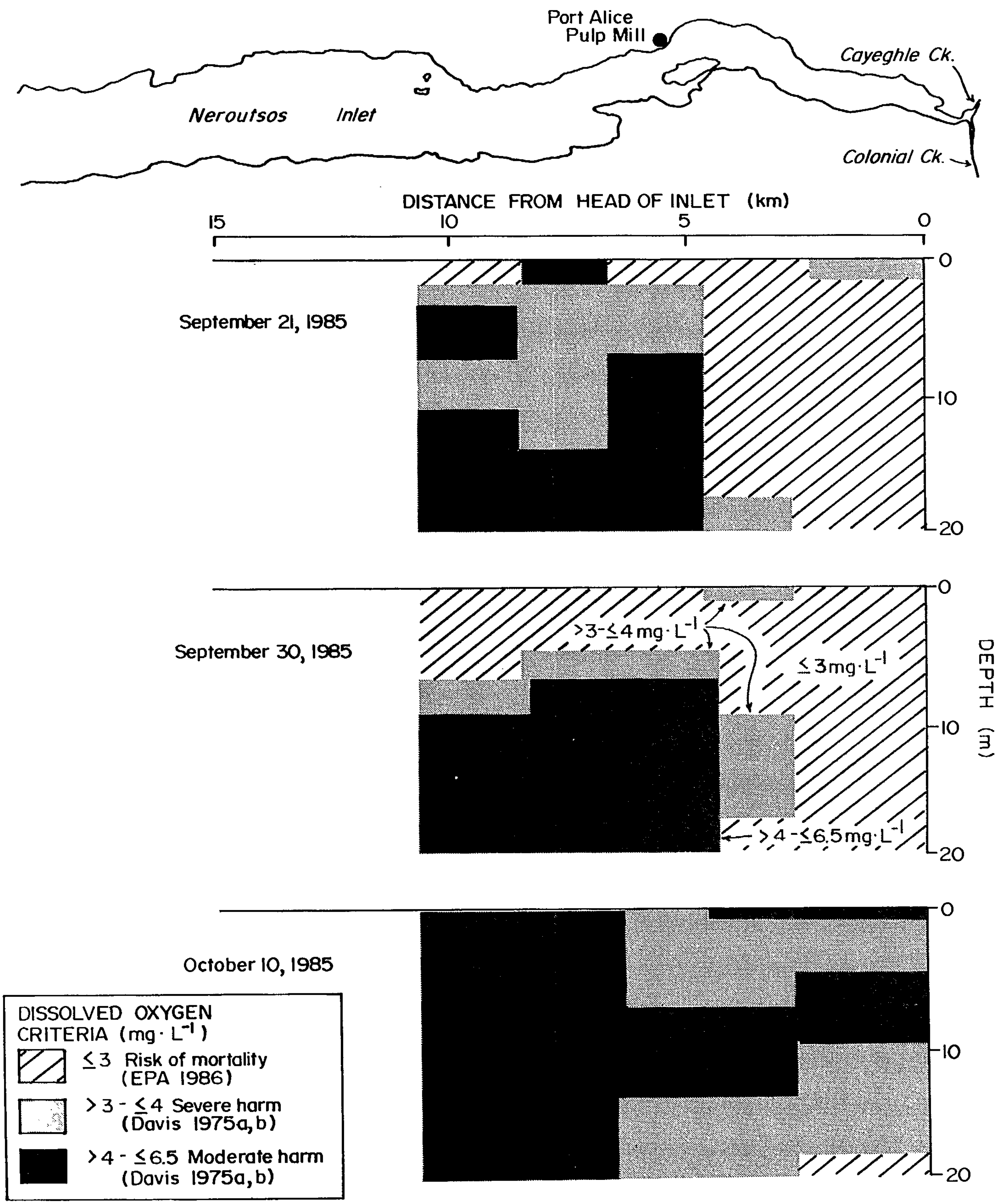

Port Alice
Pulp Mill
Cayeghle Ck.
Neroutsos
Inlet
Colonial Ck.
DISTANCE FROM HEAD OF INLET (km)
15
10
5
0
September 21, 1985
September 30, 1985
October 10, 1985
>3-≤4 mg·L-1
≤3 mg·L-1
>4-≤6.5 mg·L-1
DEPTH (m)
0
10
20
DISSOLVED OXYGEN
CRITERIA (mg·L-1)
≤3 Risk of mortality
(EPA 1986)
>3-≤4 Severe harm
(Davis 1975a,b)
>4-≤6.5 Moderate harm
(Davis 1975a,b)

Figure 3. The surface water avoidance of juvenile chum salmon in response to the discharge of pulp mill effluent into surface waters of Neroutsos Inlet (after McGreer and Vigers 1983). Histograms represent the percentage distribution of fish within 6 compartments of the experimental apparatus (after Birtwell 1977).

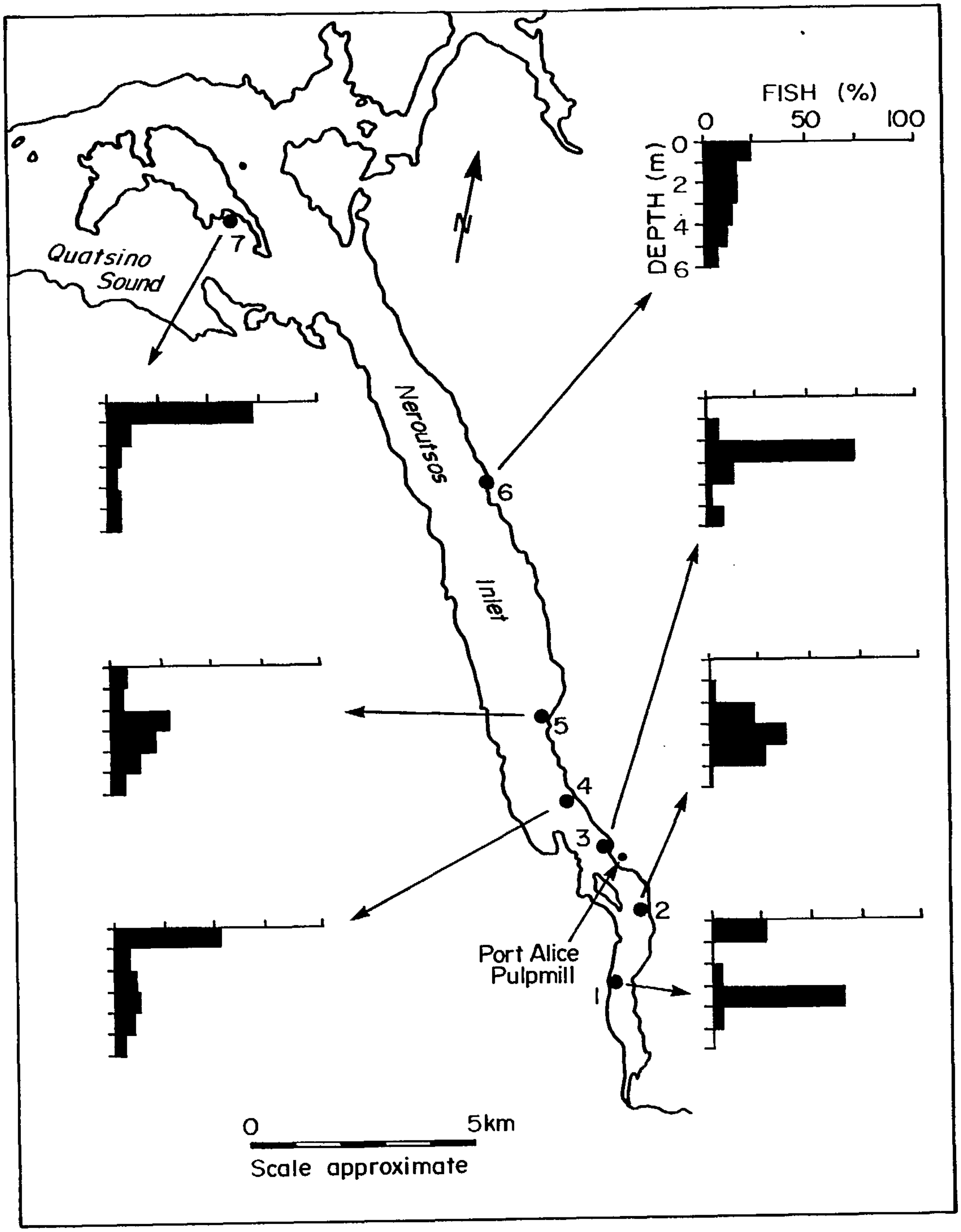
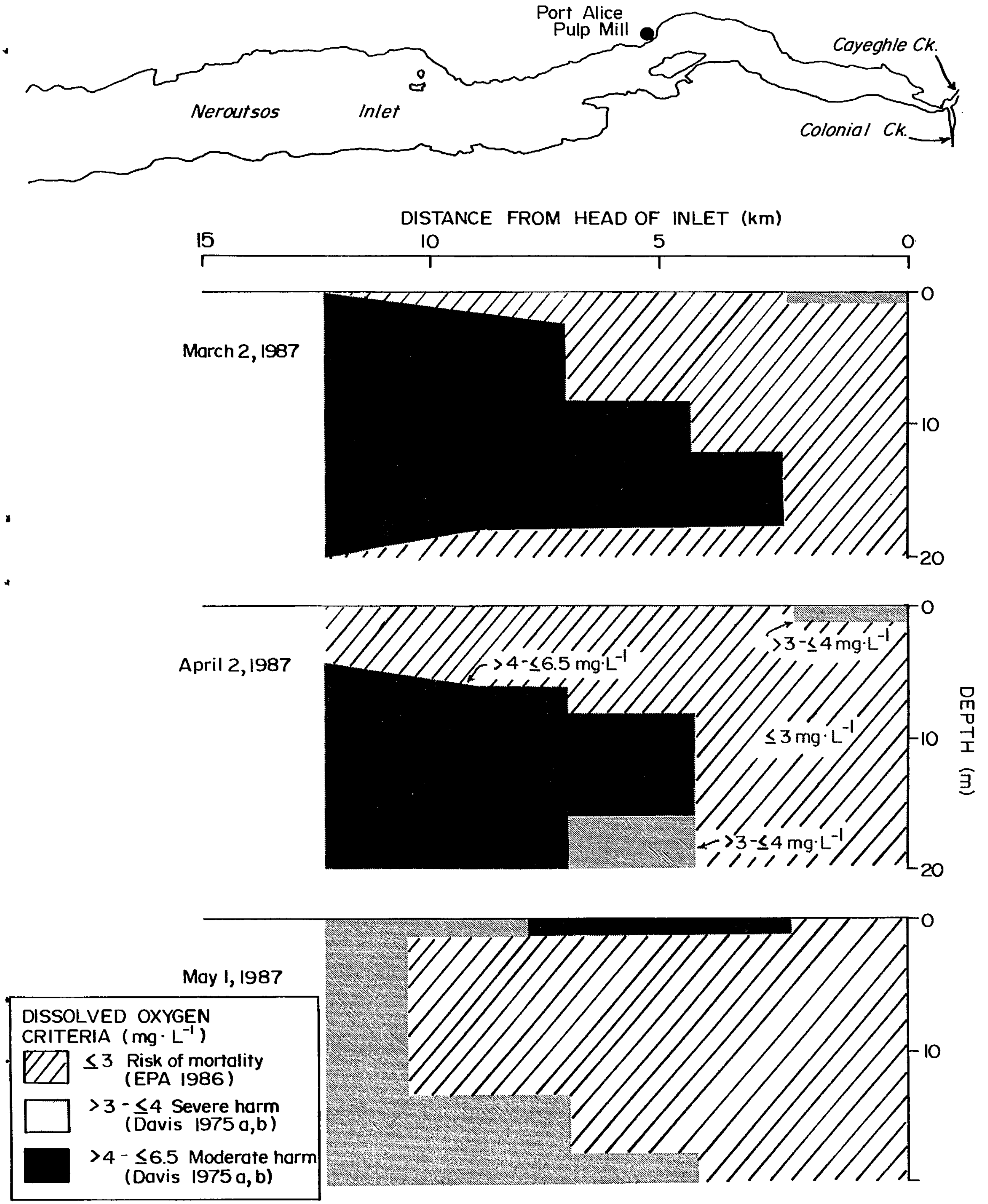

FISH (%)
0
50
100
DEPTH (m)
0
2
4
6
Quatsino Sound
Neroutsos
Inlet
N
7
6
5
4
3
2
1
Port Alice Pulpmill
0
5km
Scale approximate

Figure 4. Zones of hypoxic surface waters (<20 m depth) in Neroutsos Inlet during the period of juvenile chum salmon seaward migration in 1987. Data are courtesy of the Department of Environment, Pacific Region. Approximate boundaries of hypoxic waters are based on criteria for the protection of salmonids (Davis 1975a, b; EPA 1986).


Port Alice
Pulp Mill
Cayeghle Ck.
Neroutsos
Inlet
Colonial Ck.
DISTANCE FROM HEAD OF INLET (km)
15
10
5
0
March 2, 1987
April 2, 1987
>4-≤6.5 mg·L⁻¹
>3-≤4 mg·L⁻¹
≤3 mg·L⁻¹
>3-≤4 mg·L⁻¹
May 1, 1987
DEPTH (m)
0
10
20
DISSOLVED OXYGEN
CRITERIA (mg·L⁻¹)
≤3 Risk of mortality
(EPA 1986)
>3 - ≤4 Severe harm
(Davis 1975 a,b)
>4 - ≤6.5 Moderate harm
(Davis 1975 a,b)

DUE DATE

13/08/90			