Canadian Technical Report of
Fisheries and Aquatic Sciences 2340

2001

THERMAL INPUTS INTO PORT MOODY ARM, BURRARD INLET, BC,AND EFFECTS ON SALMON: A SUMMARY REPORT

by

I.K. Birtwell, A.E. Brotherston[1], R.P. Fink[2], D.B. Fissel[3],
J.D. Greenbank[4], L.I. Heithaus, J.S. Korstrom, and A.E. Taylor[3]

Fisheries and Oceans Canada
Science Branch,
Marine Environment and Habitat Science Division,
Freshwater Habitat Section,
West Vancouver Laboratory,
4160 Marine Drive,
West Vancouver, BC
V7V 1N6

[1] BC Hydro, Burrard Generating Station, Site 7, Box 1, R.R. # 1, Port Moody, BC, V3H 3C8
[2] Global Fisheries Consultants Limited, 13069 Marine Drive, White Rock, BC, V4A 1E5
[3] ASL Environmental Sciences Inc., 1986 Mills Road, Sidney, BC, V8L 5Y3
[4] F. Berry and Associates Ltd., 564 Windermere Street, Vancouver, BC, V5K 4J2

Cat. No. Fs 97-6/2340E ISSN 0706-6457

Correct citation for this publication:

Birtwell, I.K., A.E. Brotherston, R.P. Fink, D.B. Fissel, J.D. Greenbank, L.I. Heithaus, J.S. Korstrom, and A.E. Taylor. 2001. Thermal inputs into Port Moody Arm, Burrard Inlet, BC, and effects on salmon: a summary report. Can. Tech. Rep. Fish. Aquat. Sci. 2340: 56 p.

PREFACE

This report summarizes the results of field and laboratory studies on the effect of heated seawater on chum salmon (*Oncorhynchus keta*), and the heat budget of Port Moody Arm, Burrard Inlet, BC.

The studies were initiated in response to potential increases in the thermal discharge from British Columbia Hydro and Power Authority's (BC Hydro) Burrard Generating Station, into the marine waters of Port Moody Arm. This gas-fired steam-electric station operates under a permit from the provincial government, and utilizes a once-through seawater cooling system. The permit allows for the daily discharge of up to 1.7 million m^3 of cooling waters (≤ 27 °C), drawn from, and discharged to, Port Moody Arm.

An environmental impact study to assess any effects due to the thermal discharge was a requirement of an amendment to the provincial permit. A study plan was submitted by BC Hydro to federal and provincial regulatory authorities in 1996, and it was approved in 1997.

Studies were undertaken over the following 3 years and they investigated the effects of the thermal effluent on the growth of juvenile chum salmon, the heat budget of Port Moody Arm, the potential effects of the effluent on migrating and rearing salmon, behavior and survival, and on planktonic organisms. This report summarizes the results of the studies on salmon and the heat budget for Port Moody Arm.

Primary funding for these studies was provided by BC Hydro.

TABLE OF CONTENTS

ABSTRACT

Birtwell, I.K., A.E. Brotherston, R.P. Fink, D.B. Fissel, J.D. Greenbank, L.I. Heithaus, J.S. Korstrom, and A.E. Taylor. 2001. Thermal inputs into Port Moody Arm, Burrard Inlet, BC, and effects on salmon: a summary report. Can. Tech. Rep. Fish. Aquat. Sci. 2340: 56 p.

PORT MOODY ARM, THERMAL INPUT AND CONCERN FOR SALMON

Port Moody Arm, is situated at the eastern end of Burrard Inlet, BC. The arm is 6.5 km long with a mean width of 0.9 km and a mean depth at low tide of 8.8 m. The central portions of the arm have water depths of 10 m, and in its comparatively narrow entrance they exceed 20 m. The arm also includes over 1 km^2 of natural mud flats which dry at low tide. Five small streams comprise the main freshwater input into the arm (Mossom, Noons, Sutterbrook, and Schoolhouse South and North Creeks).

The main sources of heat to the arm are from solar input and the daily discharge of up to 1.7 billion liters of cooling water at a temperature of ≤ 27 °C from BC Hydro's Burrard Generating Station (BGS) which is situated on its north shore. The volume and temperature of the thermal discharge is variable and related to the operation of the BGS and the production of electricity; the facility may operate intermittently.

Chum salmon (*Oncorhynchus keta*) is the most prevalent of the species of Pacific salmon in the arm. There was concern for their health because the temperature of the BGS cooling water that they may encounter in the surface waters of Port Moody Arm exceeded the laboratory-derived upper lethal limit of 23.8 °C for juvenile chum salmon. The potential also existed for supersaturated levels of dissolved gases [an elevation in total gas pressure (TGP)] to be produced during the heating of the cooling water within the BGS, in addition to that produced naturally. Elevations in TGP can lead to gas bubble trauma (GBT) in fish and thereby affect their health and performance. A number of related studies were undertaken to address these concerns.

HEAT BUDGET FOR PORT MOODY ARM

To determine whether the heat added to Port Moody Arm would produce temperatures that would be harmful to chum salmon the major components of the heat budget of the arm were calculated and the principal sources and sinks of heat in this body of water were identified.

During summer, monthly mean water temperatures at a depth of 2 m at eastern stations are about 2 °C - 3 °C higher than those at the western entrance to the arm. Summer maximum monthly temperatures at these stations and depth are up to 5 °C - 6 °C higher. These observations reflect the mixing with the adjacent Burrard Inlet and Indian Arm to the west. The summer water temperature gradient to the east and towards the head of the arm may be ascribed largely to the distance and lessening exchange with Burrard Inlet, and the effects of the >1 km^2 mudflats. The role of the mudflats in Port Moody Arm is considerable and heat from the atmosphere is accumulated on the flats while they are exposed in summer, and then it is assimilated by the seawater twice daily during tidal immersion.

Calculations of the heat transported into and out of the arm by currents and tides in October 1998, revealed that the dominant loss of heat during that period was through currents and tidal action in the upper 6 m of the water column, amounting in this layer alone to about twice the quantity of heat added to the arm by the cooling water discharged by BGS. There was a sizeable offsetting net heat gain by the arm during that period through currents and tides at mid-depths between 6 m and 10 m, and to a lesser extent below 10 m to the seabed.

The cumulative result of the October 1998 calculation over the entire water column indicated a large overall loss of heat from Port Moody Arm to Burrard Inlet by tidal action.

More than 80% of the BGS thermal discharge to Port Moody Arm in October 1998 left the arm due to currents and tidal exchanges with Burrard Inlet proper, while the remainder was lost to the atmosphere. The magnitude of the heat discharged to Burrard Inlet in the summer months may be greater than that calculated for October 1998, but overall, observational evidence indicates that water temperatures in Port Moody Arm are well regulated by natural processes. In the summer, the arm starts losing heat through natural processes in late July to early August, regardless of BGS cooling water discharge levels. There is also a lack of basin-wide response to the BGS cooling water discharge and heat did not appear to be sequestered within the water body for longer than a tidal cycle.

An increase in mean summer water temperatures throughout the arm of 1 °C to 2 °C may be attributed to the normal operation of the BGS, and only in the upper approximately 5 m of water (the effect of "*El Nino*" in 1997-1998 was a temperature elevation of about 2 °C in Port Moody Arm). In a "near-field" zone within 100 m of the BGS cooling water discharge, monthly mean temperatures were a few tenths of a degree higher than elsewhere in the arm but only in the upper few meters. Water temperatures in this "near-field" were up to 3 °C higher than the BGS intake cooling water temperatures during the non-summer months, and less than 1 °C during July and August. All stations throughout Port Moody Arm exhibited a daily variability of about 3 °C in summer that arose from natural atmospheric heating.

CHUM SALMON IN PORT MOODY ARM

The number and the timing of adult salmon entering the main tributaries to Port Moody Arm were determined through surveys undertaken during the fall of 1998 and 1999 on Mossom, Noons, Sutterbrook, and Schoolhouse North and South Creeks. The springtime downstream migration of juvenile salmonids was also examined in Mossom Creek in 1999 and 2000.

Chum salmon was the dominant salmon species in all of the systems. Coho (*Oncorhynchus kisutch*), and chinook salmon (*Oncorhynchus tshawytscha*) were also observed. Total chum salmon adult escapement estimates for Mossom Creek were 1803 and 658 for 1998 and 1999, respectively. The adults of this species were first noted in Mossom Creek on October 5 and 6 in 1998 and 1999 respectively. The peak of the migration occurred between October 16 and November 9, and the last fish were observed in early December.

A negative impact on migrating adult salmon due to exposure to the thermal discharge from the BGS was considered to be unlikely, based on an analysis of water temperature data collected during September and October 1998. The preferred migration water temperature range for adult chum salmon in fresh water has been stated to be between 8.3 °C and 15.6 °C. We have no knowledge of the preferred migration water temperature in marine waters.

A total of 13,252 and >18,000 downstream migrating chum salmon fry were captured and released in Mossom Creek in 1999 and in 2000, respectively. The downstream-migration period was from early March to early May in both years. A total of 331, and 875 coho salmon fry were captured in 1999 and 2000, respectively; the majority was caught in March and April. Low numbers of coho smolts, cutthroat trout (*Oncorhynchus clarki clarki*) parr and sculpin species were also captured.

In 1997, a total of 528,000 juvenile salmon were released from hatcheries into the waters of Port Moody Arm and Indian Arm, in Burrard Inlet. These releases comprised 66,000 coho salmon, 184,000 chinook salmon and 278,000 chum salmon.

It was deduced that juvenile chum salmon would likely be present in Port Moody Arm from March to July.

EFFECTS OF TEMPERATURE, TGP, AND BGS COOLING WATER ON CHUM SALMON

The consequences to juvenile chum salmon of exposure to the diluted cooling waters from the BGS, in addition to natural seasonal heating of these waters, were examined through physiological and behavioral experiments conducted in the laboratory and in Port Moody Arm.

Growth of chum salmon in dilutions of BGS cooling water

In 1997, three consecutive experiments, each of 20 to 28 days in duration (an exposure duration that approached maximum residence times for these fish in near shore coastal waters), examined the survival and growth of groups of 30-50 juvenile chum salmon which were exposed to 0% (control), 6%, 12%, 25% and 50% of BGS cooling water (CW) mixed with seawater drawn from 3-m depth in Port Moody Arm, at a site removed from the influence of the CW discharge. The experiments were performed between June and September in an indoor test facility located at the BGS. The fish survived and grew in all cooling water treatments. A reduced growth rate occurred at CW concentrations ≥ 25%. Although water pH, dissolved oxygen, total gas pressure, salinity, and temperature were potentially influential variables on fish growth, it was determined that differences in fish growth among treatments could be explained by temperature variation. Total Gas Pressure (TGP) and temperature were highly correlated with each other and with fish growth, and, accordingly, any effects on growth due to TGP could not be isolated from those attributable to temperature.

In 1998 four consecutive experiments, each of 16 to 20 days in duration were conducted between May and August. Groups of 30-50 fish were exposed to 0% (control), 6%, 12%, 25%,

35%, and 50% CW mixed with seawater pumped continuously from 5-m depth in Port Moody Arm. In addition, fish were also studied in 50% CW at low total gas pressure (100% TGP), and in shallow water pumped continuously from 1-m depth within Port Moody Arm (outside the influence of the CW discharge). The latter two treatments enabled a separation of the effects of dissolved gas supersaturation within the BGS effluent from those of elevated temperature, and an assessment of seasonal changes in the shallow surface water on juvenile chum salmon during the late spring and summer, when water temperatures within Port Moody Arm peak naturally. Additional treatments (65% and 75% CW) were incorporated into the fourth experiment, which was conducted in August, to examine fish survival and growth at temperatures proximal to the upper lethal limit for juvenile chum salmon in fresh water (23.8 °C).

The first three experiments conducted in May through July 1998 (at the time of year when juvenile salmon are expected to reside in Port Moody Arm), identified a positive relationship between fish growth rates and their exposure to BGS cooling water at concentrations as high as 50%. Fish survival and growth was also examined in August. In 65% CW (22.6 °C) and 75% CW (23.4 °C) at temperatures proximal to the upper lethal limit for juvenile chum salmon in fresh water (23.8 °C), mortality was 13.3% and 100%, respectively in 5 days. In August exposure to lower (≤ 35%) CW concentrations did not affect fish growth significantly, but at 50% and 65% CW growth rates tended to be retarded (reducing TGP in the 50% CW treatment to eliminate dissolved gas supersaturation did not prevent the retardation of growth).

Overall mortality of juvenile chum salmon among the 0% - 50% CW treatments was less than 1% and it was 2.9% in the 50% CW at low TGP treatment. However, mortality averaged 9.1% in the tanks containing shallow water that was pumped from Port Moody Arm, rising to 28% and 30% mortality in these two shallow-water treatments during seasonal algal blooms.

The low but increasing incidences and severity of external signs of ill health revealed that the condition of fish deteriorated during the course of the first three experiments (fish were not examined in the fourth experiment), typically in response to increasing concentrations of CW. These signs (cataracts, split corneas, scale loss, petechial hemorrhages in the lateral line, and frayed fins, as well as signs of GBT such as exopthalmia, bubbles in the eyes, lateral lines and unpaired fins) increased from the first to third experiment when almost all fish (n = 7-20 fish examined per treatment) showed evidence of deteriorating health. The only treatment, in which a statistically significant increase in the signs of GBT occurred, relative to control fish, was during the first experiment, for the two groups of fish held in shallow water pumped from Port Moody Arm.

Based upon the 1997 and 1998 studies it was concluded that the discharge of CW from the BGS could increase the growth rate of juvenile chum salmon in Port Moody Arm early in the year through an elevation of temperature to levels more favorable for growth (assuming that food was not limiting), relative to individuals in adjacent waters at lower ambient temperatures. Reduced growth rates of juvenile chum salmon were only recorded in experiments that used ≥ 50% concentrations of cooling water and at temperatures that would be expected to occur in summer and after the predicted main residency period of juveniles in Port Moody Arm.

Furthermore, these effects would probably be limited to a very small area of the arm (BGS cooling water in excess of 50% would extend over <300m^2).

It was also concluded that the effects of the BGS discharge of CW would have an insignificant negative impact on the growth of juvenile chum salmon populations that utilize Port Moody Arm.

Behavioral responses to temperature change and to food

To determine whether juvenile chum salmon would utilize waters subject to thermal change due to the BGS discharge their behavioral responses were studied in the laboratory between May and August 1997. The activity and school location of chum salmon were examined in isothermal (10 °C) and thermally stratified (24 °C/10 °C) seawater (with and without food). The experimental conditions were chosen to mimic changes that could occur during the commencement of thermal discharge from the BGS.

In the absence of food, the juvenile salmon occupied the waters proximal to the water surface and only moved from this preferred location as temperatures increased. The responses of the test population of fish were used to define attraction (12.2 °C), preference (13.7 °C to 17.9 °C), and avoidance (20.2 °C) levels. Ninety percent of the fish avoided a temperature of ≥ 22.9 °C. Exposure of the chum salmon to seawater at a temperature of 25 °C, with and without elevated total gas pressure (109%), resulted in median mortality times of 150 and 157 min, respectively. Despite these findings, the chum salmon rapidly and briefly entered potentially lethal temperature waters (25 °C and 30 °C) to feed. The obviously protective and adaptive avoidance responses to these temperatures were temporarily overridden by the presence of food and the motivation to feed.

Effects of the BGS cooling water on the vertical distribution of juvenile chum salmon in Port Moody Arm

To determine if the thermal discharge modified the innate surface water orientation and vertical distribution of chum salmon in Port Moody Arm, "preference/avoidance" cages were deployed at 4 sites in the spring and summer 1997. The apparatus permitted a population of fish, held within its' 6 x 0.5 x 0.5 m confines, to move voluntarily within 6 m of the water surface. After 24 h the location of the fish was determined by simultaneously closing gates which divided the apparatus into 1 x 0.5 x 0.5 m compartments. Overall, fewer fish were present in the uppermost surface waters proximal (70 m) to the thermal discharge, but on comparing all data there was no statistically significant difference in the vertical distribution of chum salmon among the experimental sites that were up to 1200 m from the thermal discharge.

The maximum recorded temperatures (July) approximated 22.5, 23.5, 23.3, and 24.0 °C for the reference location and sites 70 m, 250 m, and 1200 m from the discharge location, respectively.

Throughout the study period at depths shallower than 4.5 m, TGP was elevated above 100%, and differed little among sites. Highest values occurred in July, and the maximum (125.2%) was recorded 1200 m from the CW discharge. However, at this time, mean values typically lay between 105% and 115% at all sites.

Under the conditions that existed in Port Moody Arm during June to August 1997, it was concluded that the thermal discharge from the BGS did not affect the vertical distribution of juvenile chum salmon in a statistically significant manner. The chum salmon tended to occupy their preferred surface water habitats in which temperatures occasionally exceeded optimal values that had been determined under laboratory conditions.

Consequences to juvenile chum salmon of exposure to sublethal temperature and TGP

The behavioral studies in the field revealed that juvenile chum salmon would utilize waters in which the temperature and TGP levels were potentially harmful with prolonged residency. The exact residence time of juvenile chum salmon during their early sea life has been determined to be days to weeks. Thus the potential exists for these fish to encounter effluent from the BGS while in Port Moody Arm. The potential consequences of this exposure were assessed in laboratory experiments (May through August 1998). Juvenile chum salmon were given a sublethal exposure to a combination of elevated temperature and dissolved gas supersaturation and their subsequent susceptibility to predation from marine piscivorous fish was assessed. Significant differences in the prevalence and severity of signs of GBT for each of the treated groups were found in the eyes, lateral line, caudal fin, and gills of fish versus the controls.

These experiments revealed an overall enhanced vulnerability of juvenile chum salmon to predation following exposure to the warm seawater and dissolved gas supersaturation. This increased susceptibility to predation was most likely associated with a performance deficit due to the effects of gas bubbles reducing the sensory capabilities and blood circulation of the fish. It was speculated that this increased vulnerability to predation could have occurred because of the debilitating effects of elevated temperature and TGP on swim performance and an associated reduced ability to recover from fatigue brought on by predator attacks and the need for repetitive escape responses.

Statistical analysis revealed the significantly enhanced vulnerability to the combined sublethal stressors of warm (20.7 °C) seawater and elevations in TGP of 120% for 24 h (22.8% increase with copper and quillback rockfish; 9.8% increase with Pacific staghorn sculpin and kelp greenling predators), or 130% TGP for 12 h (10.7% increase with kelp greenling and Pacific staghorn sculpin predators) relative to controls.

Exposure of the chum salmon to warm (20.7 °C) seawater and 115% TGP for 48 h did not result in a significant increase in susceptibility to predation relative to control fish (6.5% increase with rockfish; 0.3% increase with kelp greenling and Pacific staghorn sculpin predators).

RISK OF HARM TO JUVENILE SALMON UPON EXPOSURE TO BGS COOLING WATER

The numbers of juvenile chum salmon typically decline in near shore coastal areas during the late spring and early summer. At this time, surface water temperatures and dissolved gases in Port Moody Arm tend to increase to levels that, in combination, could lead to an increased vulnerability of juvenile chum salmon to predation [especially so with prolonged (>48 h) residence], reduced growth rates and condition.

The innate tendency of these juvenile salmon to reside for days to weeks in the uppermost surface waters during their early marine life potentially increases the risk of exposure to elevated temperatures and TGP in the surface waters of Port Moody Arm. However, the rapid removal of >80% of the heat entering the arm through tidal action and currents limits the elevation of temperature above seasonal ambient levels. Accordingly, temperatures (and TGP) rarely attain levels that would be harmful to chum salmon during the time of year that they reside in Port Moody Arm.

We deduce that the risks to the wellbeing of chum salmon due to the indiscriminate effect of exposure of the chum salmon population to dilutions of the BGS effluent, and specifically the combination of elevated temperature and TGP, would be minimal. Such risks would be restricted to a few individuals of the population that may remain in Port Moody Arm in the late spring and early summer before their natural migration to the Pacific Ocean. Accordingly, it is concluded that the current discharge of cooling water from BC Hydro's Burrard Generating Station will not adversely affect chum salmon populations that utilize Port Moody Arm.

Key words: *Oncorhynchus keta*, seawater, heat budget, temperature, growth, behavior, distribution, thermal preference, avoidance, feeding, predation, migration.

RÉSUMÉ

Birtwell, I.K., A.E. Brotherston, R.P. Fink, D.B. Fissel, J.D. Greenbank, L.I. Heithaus, J.S. Korstrom, and A.E. Taylor. 2001. Thermal inputs into Port Moody Arm, Burrard Inlet, BC, and effects on salmon: a summary report. Can. Tech. Rep. Fish. Aquat. Sci. 2340: 56 p.

BRAS PORT MOODY: APPORT THERMIQUE ET EFFETS SUR LES SAUMONS

Le bras Port Moody, situé à l'extrémité est de l'inlet Burrard (Colombie-Britannique), a une longueur de 6.5 km, une largeur moyenne de 0.9 km et une profondeur moyenne de 8.8 m à marée basse. La profondeur est de 10 m dans la partie centrale du bras et de plus de 20 m dans son entrée qui est relativement étroite. Le bras comporte des slikkes (vasières naturelles), sur une superficie dépassant 1 km^2, qui sont exposées à marée basse. L'eau douce arrivant dans le bras provient essentiellement de cinq petites rivières: Mossom Creek, Noons Creek, Sutterbrook Creek, Schoolhouse South Creek et North Creek.

Le bras est principalement rechauffé par le rayonnement solaire et par la décharge quotidienne des eaux de refroidissement de la centrale thermique Burrard de BC Hydro, située sur sa rive nord. Le volume et la température de l'eau rejetée, jusqu'à 1.7million m^3 d'eau par jour à une température ≤ 27 °C, varient avec le niveau de fonctionnement de la centrale, l'installation pouvant fonctionner de façon intermittente.

Le saumon kéta (*Oncorhynchus keta*) est l'espèce la plus abondante parmi les saumons du Pacifique qui fréquentent le bras. On s'est récemment inquiétait de leur sort car ils peuvent rencontrer dans le bras Port Moody des eaux de surface réchauffées par les effluents que la centrale thermique Burrard rejette à une température qui dépasse la limite létale (déterminée en laboratoire) de 23.8 °C pour les jeunes de cette espèce. On s'est également demandé si des gaz n'étaient pas dissous à des niveaux sursaturés, entraînant une valeur élevée de la pression des gaz totaux (PGT), lors du réchauffement des eaux de refroidissement à l'intérieur de la centrale, gaz qui viendraient ainsi s'ajouter à ceux naturellement présents dans l'eau. L'élévation de la PGT peut entraîner une embolie gazeuse chez les poissons et donc affecter leur santé et leurs performances. Des études connexes ont été réalisées pour éclaircir ces questions.

BILAN THERMIQUE DU BRAS PORT MOODY

Afin de déterminer si les calories déversées dans le bras Port Moody engendrent un réchauffement de l'eau susceptible d'être néfaste aux saumons kétas, nous avons calculé les principales composantes du bilan thermique du bras, notamment les plus importantes sources de chaleur et les plus importants vecteurs de perte thermique pour l'ensemble de la masse d'eau.

Au cours de l'été, les moyennes mensuelles de la température de l'eau relevées à 2 m de fond dans les stations de l'est sont environ 2° à 3 °C plus élevées que celles enregistrées dans l'entrée ouest du bras. Les moyennes mensuelles maximums de la température enregistrées l'été aux mêmes endroits sont de 5° à 6 °C plus élevées que les valeurs précédentes. Ces observations mettent en évidence un mélange des eaux du bras avec celles de l'inlet Burrard et du fjord Indian

Arm à l'ouest. Le gradient thermique constaté en été à l'est et vers l'entrée du bras est sans doute largement dû à la distance, à la diminution des échanges avec les eaux de l'inlet Burrard et à l'effet des slikkes (vasières) dont la superficie totale dépasse 1 km^2. Les slikkes jouent un rôle très important dans le bilan thermique du bras puisqu'au cours de l'été, la chaleur de l'atmosphère est transférée à la vase découverte à marée basse, puis à l'eau de mer lorsque la marée recouvre les bancs vaseux.

Les calculs effectués pour le mois d'octobre 1998 montrent que la majorité des calories étaient évacuées par l'intermédiaire des courants et des marées dans la couche de 6 mètres immédiatement sous la surface, et que la quantité de chaleur exportée dans cette couche était environ deux fois plus grande que celle ajoutée au bras par le déversement des eaux de refroidissement de la centrale thermique Burrard. On a cependant également constaté qu'au cours de cette même période, les courants et les marées engendraient un bilan calorifique positif du bras (gain de chaleur) entre 6m et 10m, et dans une moindre mesure entre 10m et le fond.

Globalement, les calculs effectués pour le mois d'octobre 1998 sur l'ensemble de la colonne d'eau indiquent qu'il existe un important transfert de calories du bras Port Moody vers l'inlet Burrard sous l'effet de la marée.

Plus de 80% des calories déversées par la centrale thermique en octobre 1998 ont été emportées par les courants de marée dans l'inlet Burrard, tandis que le reste de ces calories ont été absorbées par l'atmosphère. La quantité de calories déversée pendant l'été dans l'inlet Burrard dépasse peut-être celle calculée pour le mois d'octobre 1998 mais dans l'ensemble, les mesures indiquent que la température de l'eau dans le bras Port Moody est bien régulée par des processus naturels. En été, entre fin juillet et début août, le bras commence à perdre des calories par l'intermédiaire de ces processus naturels, quelle que soit la quantité d'eaux de refroidissement déversées par la centrale thermique Burrard. On a par ailleurs observé que le bassin dans son ensemble ne réagissait pas aux déversements de la centrale et que les calories apportées par ces déversements ne semblaient pas demeurer dans la masse d'eau plus longtemps qu'un cycle de marée.

La hausse de la température due au déversement et observé lors d'un fonctionnement normal de la centrale thermique Burrard ne peut dépasser 1° ou 2 °C, et ce phénomène ne concerne que la couche supérieure dont l'épaisseur est d'environ 5m (l'effet *El Niño*, en 1997-1998, a engendré à lui seul une augmentation de température de l'eau du bras Port Moody d'environ 2 °C). Dans la zone située dans un rayon de 100 m autour du déversoir des eaux de refroidissement de la centrale Burrard, les moyennes mensuelles de la température de l'eau dépassaient de quelques dixièmes de degrés la température de l'eau dans d'autres zones du bras mais cette différence n'a été observée que dans la couche de quelques mètres immédiatement sous la surface. Au cours des mois non estivaux, les températures de l'eau mesurées toutes les demi-heures près du déversoir de la centrale pouvaient dépasser de 3 °C la température des eaux de refroidissement puisées par la centrale mais cette différence n'était que de 1 °C en juillet et en août. Toutes les stations de mesure situées dans le bras Port Moody ont enregistré une variabilité quotidienne de la température de l'eau de l'ordre de 3 °C en été, variabilité due au réchauffement naturel de l'eau par l'atmosphère.

SAUMONS AUMONS KÉTAS DANS LE BRAS PORT MOODY

Des recensements ont été réalisés dans les principaux cours d'eau qui se jettent dans le bras Port Moody (les rivières Mossom Creek, Noons Creek, Sutterbrook Creek, Schoolhouse North Creek et South Creek) au cours des automnes de 1998 et de 1999 pour déterminer le nombre et la date d'arrivée des saumons adultes dans ces cours d'eau. La descente de printemps des jeunes saumoneaux (smolts) a par ailleurs été étudiée sur la rivière Mossom Creek en 1999 et en 2000.

Les saumons kétas (*Oncorhynchus keta*) représentaient l'espèce dominante dans tous les cours d'eau. Des saumons cohos (*O. kisutch*) et deux saumons quinnats (*O. tshawytscha*) ont également été observés. L'échappée totale pour les saumons kétas dans la rivière Mossom Creek a été estimée à 1803 poissons en 1998 et à 658 poissons en 1999. Les premiers saumons kétas adultes ont été remarqués dans la rivière Mossom Creek le 5 octobre en 1998 et le 6 octobre en 1999. Le maximum du flux migratoire s'étendait entre le 16 octobre et le 9 novembre et le dernier poisson a été observé au début du mois de décembre pour les deux années.

L'analyse des températures de l'eau enregistrées au cours des mois de septembre et d'octobre 1998 montre qu'il est improbable que le déversement d'eau réchauffée par la centrale thermique Burrard ait un impact négatif sur la migration des saumons dans le bras. La gamme de températures préférée par le saumon kéta adulte lorsqu'il migre en eau douce se situe entre 8.3 °C et 15.6 °C.

Un total de 13252 saumons kétas ont été capturés et remis à l'eau en 1999, plus de 18000 en 2000. Au cours de ces deux années, la descente des smolts a commencé début mars et était pratiquement terminée début mai. Un total de 331 smolts ont été capturés en 1999, 875 en 2000. La majorité de ces poissons furent capturés en mars et en avril. Un petit nombre de saumoneaux cohos (*Oncorhynchus kisutch*) et de truites fardées ainsi que diverses espèces de chabots ont également été capturés dans le piège.

En 1997, un total de 528000 saumoneaux élevés en écloserie ont été relâchés dans les eaux du bras Port Moody, dans le fjord Indian Arm et dans l'inlet Burrard. Ce lâcher comprenait 66000 saumons cohos, 184000 saumons quinnats et 278000 saumons kétas.

Il a été conclu que les jeunes saumons kétas sont probablement présents dans le bras Port Moody entre mars et juillet.

EFFETS DE LA TEMPÉRATURE, DE LA PRESSION DES GAZ TOTAUX ET DES EAUX DE REFROIDISSEMENT REJETÉES PAR LA CENTRALE THERMIQUE BURRARD SUR LES SAUMONS KÉTAS

Des expériences physiologiques et comportementales en laboratoire et dans le bras Port Moody ont permis d'étudier les effets de l'exposition des jeunes saumons kétas aux eaux de refroidissement réchauffées et diluées de la centrale thermique Burrard, déversements qui viennent accentuer l'effet du réchauffement saisonnier des eaux du bras.

Croissance des saumons kétas dans des bassins contenant des eaux de refroidissement réchauffées de la centrale thermique Burrard

En 1997, trois expériences, chacune durant entre 20 et 28 jours (durée proche du temps de résidence maximum de ces poissons dans les eaux du littoral situées proches de la côte), ont permis d'examiner le taux de survie et la croissance de jeunes saumons kétas évoluant dans un mélange contenant des eaux de refroidissement de la centrale thermique Burrard concentrées à 0%, 6%, 12%, 25% et 50% dans de l'eau de mer prélevée à 3 m de profondeur dans le bras Port Moody, à un endroit éloigné du lieu de déversement des eaux de refroidissement de la centrale. Les expériences ont été effectuées entre juin et septembre dans des installations couvertes, à l'intérieur de la centrale. Les poissons ont survécu et ont grandi dans tous les mélanges utilisés. La croissance était néanmoins réduite pour les concentrations ≥ 25%. Bien que le pH, la teneur en oxygène dissous, la pression des gaz totaux (PGT), la salinité et la température de l'eau représentaient autant de facteurs pouvant influencer la croissance des poissons, il a été établi que les différences entre les taux de croissance pouvaient être expliquées par les seules variations de température. La PGT et la température étaient fortement corrélées et affectaient toutes les deux la croissance des poissons. Il a donc été impossible d'isoler les effets dus à la PGT de ceux dus à la température.

Quatre expériences (durant entre 16 et 20 jours) ont été réalisées au cours du printemps et de l'été de 1998. Des groupes de 30 à 50 poissons ont été exposés à des mélanges contenant 0% (témoin), 6%, 12%, 25%, 35% et 50% d'eaux de refroidissement diluées dans de l'eau de mer pompée en continue à 5 m de profondeur. Les poissons ont également été étudiés alors qu'ils évoluaient dans un mélange à 50% d'eaux de refroidissement avec une faible PGT et en eau peu profonde pompée en continue à 1 m de fond dans le bras Port Moody (loin de l'influence du déversoir de la centrale). Ces deux dernières expériences ont permis d'une part de séparer les effets de la sursaturation en gaz (PGT élevée) de ceux de la température et d'autre part d'évaluer l'effet des changements saisonniers dans les eaux de surface sur les jeunes saumons kétas entre la la fin du printemps et la fin de l'été, période au cours de laquelle la température des eaux du bras Port Moody atteint son maximum annuel.

Les trois expériences réalisées entre mai et juillet 1998 (période de l'année où les jeunes saumoneaux résident dans le bras Port Moody) ont permis de mettre en évidence une corrélation positive entre le taux de croissance des poissons et la concentration en eaux de refroidissement réchauffées de la centrale Burrard jusqu'à des concentrations de 50%. En août, l'exposition à des concentrations moindres (≤ 35%) n'a eu aucun effet notable sur la croissance des poissons mais la croissance avait tendance à être retardée pour des concentrations de 50% et de 65% (la réduction de la PGT, c'est à dire l'élimination de la sursaturation des gaz dissous, dans les expériences utilisant une concentration en eaux de refroidissement de 50% n'a pas empêché le retard de croissance).

La mortalité des jeunes saumons kétas est restée inférieure à 1% dans les six mélanges, mais a atteint une moyenne de 9.1% pour les saumons évoluant dans l'eau peu profonde pompée dans le bras Port Moody. Elle était de 2.9% pour une concentration en eaux de refroidissement de 50%.

La mortalité a par contre atteint 28% et 30% pour une des expériences en eau peu profonde pendant une période de fleur d'eau.

La survie et la croissance des poissons ont également été examinées en août. Sur une période de cinq jours, la mortalité était respectivement de 13.3% et de 100% lorsque la concentration en eaux de refroidissement était de 65% (à 22.6 °C) et de 75% (à 23.4 °C), les températures atteintes étant proches de la limite létale pour les jeunes saumons kétas en eau douce (23.8 °C).

La détérioration de la condition des poissons s'est accompagné d'une incidence croissante de signes extérieurs de mauvaise santé de plus en plus sévères au cours des expériences, habituellement en réponse à l'augmentation de la concentration en eaux de refroidissement. Ces signes (cataractes, fissures de la cornée, perte d'écailles, hémorragies ponctuelles sur la ligne latérale et nageoires abîmées, ainsi que des symptômes typiques d'une embolie gazeuse tels que l'exophtalmie, des bulles dans les yeux et sur la ligne latérale ainsi que des nageoires abîmées) ont augmenté entre la première et la troisième étude au cours de laquelle la santé de presque tous les poissons s'est détériorée de façon évidente. Seules les conditions expérimentales appliquées à deux groupes de poissons évoluant dans de l'eau peu profonde du bras Port Moody au cours de la première expérience se sont accompagnées d'une augmentation statistiquement significative de l'incidence des symptômes typique de l'embolie gazeuse par rapport aux témoins.

Compte tenu des résultats obtenus au cours des études de 1997 et de 1998, il a été conclu qu'en début d'année, le déversement des eaux de refroidissement réchauffées provenant de la centrale thermique Burrard pouvait contribuer à augmenter le taux de croissance des jeunes saumons kétas dans le bras Port Moody en élevant la température jusqu'à un niveau plus favorable à la croissance de ces poissons (en supposant que la nourriture ne soit pas un facteur limitant). On a enregistré une réduction du taux de croissance des jeunes saumons kétas lors des expériences mettant en jeu de grandes concentrations d'eaux de refroidissement, ce qui produisait des températures typiques de la saison estivale et donc caractéristiques d'une période postérieure à celle prédite pour le séjour des jeunes saumons dans le bras Port Moody. Ce type d'effets devrait probablement être limités à un secteur très restreint du bras (une concentration en eaux de refroidissement supérieure à 50% ne se rencontre que dans un secteur dont la superficie est inférieure à 300 m^2).

Il a également été conclu que les effets du déversement des eaux de refroidissement de la centrale ne pouvait avoir qu'un impact négligeable sur la croissance des jeunes saumons kétas qui fréquentent le bras Port Moody.

Réponses comportementales aux changements de température et à la nourriture

Entre mai et août 1997, les réponses comportementales des jeunes saumons kétas ont été étudiées en laboratoire pour déterminer si ces poissons sont susceptibles de fréquenter des eaux dont la température a été élevée par les déversements des eaux de refroidissement de la centrale thermique Burrard. L'activité et la position des saumons kétas ont été examinées dans des bassins d'eau de mer isothermes (10 °C) et dans des bassins non isothermes (24 °C - 10 °C), avec ou sans nourriture. Les conditions expérimentales ont été choisies pour reproduire au plus près les changements qui peuvent se produire au début du déversement des eaux de refroidissement réchauffées de la centrale Burrard.

Les jeunes saumons se sont tenus dans les eaux proches de la surface et ne s'en sont éloignés qu'au fur et à mesure que la température augmentait. Les réponses des poissons témoins ont été utilisées pour définir les niveaux d'attraction (12.2 °C), de préférence (de 13.7 °C à 17.9 °C) et de répulsion (20.2 °C). Quatre-vingts dix pour cent des poissons ont évité les températures supérieures ou égales à 22.9 °C. L'exposition des saumons kétas à une eau de mer à 25 °C s'est traduite par une survie médiane de 150 et 157 minutes suivant que la pression des gaz totaux était élevée (109%) ou pas. Dans leur quête de nourriture, les saumons kétas pénétraient cependant régulièrement dans des eaux suffisamment chaudes (25 °C et 30 °C) pour les mettre en danger de mort. Les comportements auto-protecteurs consistants à éviter de telles eaux étaient alors supplantés par l'attirance que suscitait la présence de nourriture et la motivation de se nourrir.

Effets des eaux de refroidissement réchauffées de la centrale thermique Burrard sur la distribution verticale des jeunes saumons kétas dans le bras Port Moody

Des cages de stratification verticale ont été déployées sur 4 sites au cours du printemps et de l'été 1997 pour déterminer si les déversements d'eaux réchauffées modifiaient l'attirance innée des saumons kétas pour les eaux de surface et la distribution verticale de ces poissons dans le bras Port Moody. Les poissons pouvaient se déplacer librement dans une colonne d'eau de 6 m à l'intérieur d'une cage mesurant 6 x 0.5 x 0.5 m. Après 24 h, la position choisie par les poissons était déterminée en fermant simultanément des portes qui divisaient la colonne en compartiments de 1 m de hauteur chacun. Dans l'ensemble, on a trouvé moins de poissons dans les eaux de surface à proximité (70 m) du déversoir de la centrale, mais aucune différence statistiquement significative n'a pu être relevée entre les distributions des saumons kétas relevées d'un site à l'autre à plus de 1200 m du déversoir.

Les températures maximums enregistrées en juillet étaient respectivement de 22.5 °C, 23.5 °C, 23.3 °C et 24.0 °C pour le site de référence et les endroits situés à 70 m, 250 m et 1200 m du déversoir.

Pendant toute la durée de l'étude, la PGT dépassait 100% aux profondeurs supérieures à 4.5 m et différait peu d'un site à l'autre. Les valeurs les plus élevées ont été enregistrées en juillet et le maximum (125.2%) a été mesuré à 1200 m du déversoir des eaux de refroidissement. Pour l'instant, les valeurs moyennes restent cependant entre 110% et 115% à tous les sites.

Compte tenu des conditions qui prévalaient dans le bras Port Moody entre juin et août 1997, il apparaît que le déversement d'eau réchauffée par la centrale thermique Burrard n'a eu à cette époque aucun effet statistiquement significatif sur la distribution verticale des jeunes saumons kétas. Les saumons kétas ont eu tendance à occuper leur habitat situé proche de la surface où la température a parfois dépassé les valeurs optimales déterminées en laboratoire.

Conséquences d'une exposition à des températures et à des PGT sub-létales chez les jeunes saumons kétas

Les études comportementales menées sur le terrain ont révélé que les jeunes saumons kétas pouvaient pénétrer dans des eaux dont la température et la PGT pouvaient être potentiellement dangereuses lors d'un séjour prolongé. Il a été établi que les jeunes saumons kétas restaient dans le bras Port Moody pendant une période variant de quelques jours à quelques semaines au cours de leur première rencontre avec l'eau salée. Ces poissons peuvent donc rencontrer les effluents de la centrale thermique Burrard lorsqu'ils résident dans le bras. Les conséquences possibles d'une telle exposition ont été étudiées en laboratoire (mai et août 1998). Des jeunes saumons kétas ont été exposés à des niveaux sublétaux de température et de sursaturation gazeuse et on a évalué dans quelle mesure ils étaient alors plus susceptibles d'être capturés par les poissons marins piscivores. On a trouvé des différences importantes entre les témoins et les spécimens exposés pour ce qui est de l'incidence et de la gravité des symptômes associés à l'embolie gazeuse, en particulier au niveau des yeux, de la ligne latérale, de la nageoire caudale et des ouies.

Ces expériences ont mis en évidence une augmentation de la vulnérabilité des jeunes saumons kétas vis-à-vis de leurs prédateurs après une exposition à de l'eau de mer tiède et à une sursaturation gazeuse. Cet accroissement de la vulnérabilité à l'égard des prédateurs provenait probablement d'un déclin des performances des poissons à mettre au crédit des bulles de gaz qui réduisent leurs capacités sensorielles et leur circulation sanguine. L'augmentation de la vulnérabilité est peut-être également due aux effets débilitants des niveaux élevés de température et de pression des gaz totaux sur la nage des poissons et la réduction connexe des capacités de récupération après les attaques de prédateurs et les manœuvres de fuites répétées.

Une analyse statistique a permis de mettre en évidence une augmentation, par rapport aux témoins, de la vulnérabilité aux facteurs de stress sublétaux liés à une eau de mer tiède (20.7 °C) et à une PGT de 120% pendant 24 h (la prédation a augmenté de 22.8% dans le cas des sébastes cuivrés et des sébastes à dos épineux, de 9.8% dans le cas des chabots armés et des sourcils de varech); ou à une PGT de 130% pendant 12 h (augmentation de 10.7% de la prédation par les sourcils de varech et les chabots armés).

L'exposition des saumons kétas à une eau de mer tiède (20.7 °C) et à une PGT de 115% pendant 48 h n'a pas entraîné de surcroît important de prédation par rapport aux témoins (la prédation a augmenté de 6.5% dans le cas des sébastes et de 0.3% dans le cas des sourcils de varech et des chabots armés).

RISQUES ENCOURUS PAR LES JEUNES SAUMONS EXPOSÉS AUX EAUX DE REFROIDISSEMENT RÉCHAUFFÉES DE LA CENTRALE THERMIQUE BURRARD

Dans les secteurs côtiers voisins des rivages, la densité des jeunes saumons décroît habituellement entre la fin du printemps et le début de l'été. Durant cette période, la température de l'eau en surface et la pression des gaz totaux dans le bras Port Moody ont tendance à monter à des niveaux qui, lorsqu'ils agissent de concert, peuvent conduire à augmenter la vulnérabilité des

jeunes saumons kétas vis-à-vis de leurs prédateurs (en particulier lorsque les jeunes saumons sont en contact avec de telles conditions pendant des périodes excédant 48 h), à réduire leur taux de croissance et à affecter leur condition.

La tendance innée des jeunes saumons à résider pendant des jours ou des semaines près de la surface au début de leur vie marine peut augmenter le risque qu'ils soient exposés à des températures et à des PGT élevées dans les eaux de surface du bras Port Moody. L'action des courants et des marées qui emportent 80% des calories déversées limite cependant la possibilité que la température de l'eau dépasse de beaucoup les valeurs saisonnières normales. La température et la PGT dans le bras Port Moody n'atteignent par conséquent que rarement des niveaux qui pourraient être dangereux pour les saumons kétas pendant la période où ces saumons fréquentent le bras.

Nous en déduisons que les risques encourus par les saumons kétas face aux déversements de la station thermique Burrard, risques dus à l'élévation de la température et de la PGT, sont certainement minimes. Ces risques doivent concerner plus particulièrement les quelques rares spécimens qui restent dans le bras Port Moody entre la fin du printemps et le début de l'été avant d'entamer leur migration naturelle vers l'océan Pacifique. Nous concluons donc que les déversements actuels d'eaux de refroidissement réchauffées par la station thermique Burrard de BC Hydro ne sont pas en mesure d'affecter de façon négative les populations de saumons kétas qui fréquentent le bras Port Moody.

Mots clés : *Oncorhynchus keta*, eau de mer, bilan thermique, température, croissance, comportement, distribution, préférence thermique, répulsion, nourriture, prédation, migration.

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

BURRARD GENERATING STATION AND ENVIRONMENTAL IMPACT STUDIES

The studies reported herein were initiated in relation to potential increases in the thermal discharge from British Columbia Hydro and Power Authority's (BC Hydro's) Burrard Generating Station (BGS), into the marine waters of Port Moody Arm (PMA) which is situated at the eastern end of Burrard Inlet, BC. The gas-fired steam-electric BGS operates under a permit from the provincial government [Permit (No. PE-07178) issued by the BC Ministry of Environment, Lands and Parks (BCMELP 1995)], and utilizes a once-through seawater system to cool its steam condensers. The permit allows for the daily discharge of up to 1.7 million cubic meters of cooling water (CW) at a temperature of ≤ 27 °C. The volume and temperature of this effluent fluctuates below, and to, these levels in relation to the operating conditions of the BGS. Seawater is drawn into the BGS from PMA and subsequently discharged in a strong jet which is directed eastward along the northern shoreline. This input of seawater "causes a clockwise gyre located south and east of the outfall pipes that is not naturally present in the arm" but it has "no net effect on the total flushing characteristics of Port Moody Arm" (Seaconsult Marine Research Ltd. 1995).

Chum salmon (*Oncorhynchus keta*) is the most prevalent species of Pacific salmon in the arm. However, in addition to the natural production of juvenile salmon in 1997, 528,000 juvenile salmon were released from hatcheries into the waters of PMA and Indian Arm, in Burrard Inlet. These releases comprised 66,000 coho salmon, 184,000 chinook salmon and 278,000 chum salmon. Because of the known sensitivity of salmon to temperature changes, there was concern for their health. Aside from the potential for sublethal effects, the temperature of the BGS cooling water that these fish may encounter in the surface waters of PMA exceeds the laboratory-derived upper lethal limits (Brett 1952) for juvenile salmon. The potential also exists for supersaturated levels of dissolved gases [an elevation in total gas pressure (TGP)] to be produced during the heating of the seawater water within the BGS, in addition to that produced naturally. Elevations in TGP can lead to gas bubble trauma (GBT) in fish and thereby affect their health and performance. Furthermore, and although a number of studies (Hodgins and Webb 1991; Hodgins 1993) had been conducted previously on the thermal regime of the receiving waters of PMA in relation to the heat discharged from the BGS, concern remained over the hydrodynamic model of heat dispersion within PMA that was used to assess the thermal effects of the BGS under a variety of BGS operating scenarios (Seaconsult Marine Research Ltd. 1995). This concern related to insufficient water temperature data at various depths (including the surface water habitat of juvenile salmon), and uncertainties in the thermal contribution to PMA from solar radiation and the tidally exposed mudflats towards its eastern end.

Studies to assess potential environmental effects in PMA due to the BGS cooling water discharge were required for an amendment to the provincial permit under which the BGS operates. Federal and provincial government regulatory authorities considered it important to examine the effects of the thermal discharge from the BGS. Accordingly, BC Hydro submitted a plan to these authorities in December 1996 that identified a number of studies to be initiated in 1997 as part of a 2-3 year environmental assessment (BC Hydro 1996). The study plan was approved in 1997 and resulted in research on the effects of the thermal discharge on the growth (Greenbank et al. 1998, 2001a), behavior and survival (Birtwell et al. 1998, 2001a, b; Korstrom et al. 1998) of chum salmon, the potential effect on planktonic organisms (Duval 1998; M. Henry, University of British Columbia, unpublished data), the species of fish and their distribution in Port Moody Arm (Aquatic Resources Ltd. 1998), adult and juvenile salmon migration (Greenbank et al. 2001b), and the heat budget for Port Moody Arm (Fissel et al. 1998; Taylor et al. 1999, 2001).

The intention of this report is to summarize the findings of the primary studies on the heat budget for PMA, and on the biology, physiology and behavior of chum salmon, and to present the deductions from, and the conclusions of, the research. Detailed information (i.e., materials and methods, results and discussion) is available in the specific reports identified above.

REPORT SUMMARIES

HEAT BUDGET FOR PORT MOODY ARM

The overall goal of the study was to develop an improved understanding of the thermal regime for PMA, and thus provide information that would be useful to other studies concerned with the potential effects of the operation of the BGS on sensitive species and life stages of aquatic life therein. Figure 1 shows the location of temperature monitoring stations in Port Moody Arm (from Taylor et al. 2001).

The specific objectives of this study were to extend BC Hydro's temperature database, to improve the temperature monitoring program, based on the analyses and evaluation of 1995-1997 data sets, through improved horizontal resolution of the temperature network, by increasing the number of monitoring stations, improving vertical resolution of the network, and to determine the amount of heat exchanged between PMA and Burrard Inlet proper in relation to the total heat budget for the arm. Additional objectives were to undertake continuous measurements of ocean current profiles over a one month period near Gosse Point in 1998 (the realization of this objective would allow the first direct computation of the effective tidal exchange and hence the horizontal heat exchanges), to further the current understanding of the role of the mudflats on the thermal regime, and to improve the understanding of the near-field area of the BGS thermal plume.

Water temperature data were available for varying periods from 14 stations at depths to 27 m around PMA. During the course of data analysis the analytical techniques were designed and implemented in order to distinguish temperature effects attributable the BGS discharge from those due to natural sources, to the extent possible.

During the study, extensive monthly and 14-day statistics (mean, standard deviation, minimum and maximum) were calculated for the water temperature and meteorological parameters representative of PMA. Contour maps of monthly mean water temperature for PMA were prepared for depths 0.5 m, 2 m and 5 m, for the period February to September, and for noon

October 29, 1998. These maps depict graphically the variation of temperature throughout the arm, particularly the higher temperature in the main body of the arm and the lower temperature in the western channel around Carraholly Point. Slightly elevated monthly mean temperatures (no more than a few tenths of a degree) observed within 100 m of the BGS discharge were more obvious on these contour maps in non-summer months, and only in the upper few meters water depth, because of the greater contrast between BGS CW discharge temperature and ambient seawater temperature. Contour plots of monthly mean water temperature with water depth for a transect along the length of the arm were prepared for the period June to September and noon October 29, 1998. It was evident from these data that any influence of the BGS thermal plume on water temperature within the arm was discernible only in the upper few metres of these vertical sections.

The deployment of an acoustic Doppler current profiler for the month of October 1998 in the narrow entrance to PMA was a significant feature of the present study. Precision measurements of current velocities (needed for the heat transport calculation and detailed water currents) were measured with this installation, and data from nearby water temperature stations enabled the first well-constrained calculation of the heat transport in and out of the arm by currents and tides. The results for October 1998 confirm that currents and tidal action play a dominant role in the removal of heat from the waters of PMA; this heat loss occurred via currents and tidal action in the upper 6 m, amounting in this layer alone to about twice the BGS heat discharge. However, at mid-depths, the arm gained heat by currents and tidal action between 6 m and 10 m, and to a lesser degree at greater depths. The cumulative result of the heat exchange calculation over the entire water column was a large net export of heat from PMA to Burrard Inlet. The calculations for the overall heat budget for PMA for October 1-27, 1998 "balanced" to within 531,000 GJ. This residual comprises smaller heat sources and sinks not accounted for in the analysis, and errors. About half of this amount was the estimate of errors. The heat budget calculations indicated that a quantity of heat equivalent to more than 80% of the BGS heat discharged to PMA in October 1998 left the arm due to currents and tidal action. Figure 2 depicts the natural thermal exchanges with Port Moody Arm and the heat discharged by the BGS (from Taylor et al. 2001).

Calculations of the atmospheric heat exchanges for October 1998 showed that there was an additional loss of heat from the water body to the atmosphere, sufficient not only to account for the "remaining 20%" of the BGS discharge heat, but also to remove heat from the water body resulting in the decreasing water temperatures observed in the arm over this month. The integrity of the results is assured in this study through achieving, for the first time, a balancing of the overall heat budget for the waters of PMA. For the month of October 1998, the contribution of various atmospheric heat exchanges were calculated from the local meteorological and water temperature data, and the heat discharged to the arm by the BGS was available from operational data. The estimated error in these calculations was a quantity of heat equivalent to about 12% of the BGS heat discharge.

During summer, monthly mean water temperature at a depth of 2 m at eastern stations is 2 °C - 3 °C higher than that at the western entrance to the arm. Summer maximum monthly temperature at these stations and depth was up to 5 °C - 6 °C higher. These observations reflect the mixing with the adjacent Burrard Inlet and Indian Arm to the west, while the summer water temperature gradient to the east and towards the head of the arm may be ascribed largely to the distance and lessening exchange with Burrard Inlet, and the effects of the major mudflats. The role of the mudflats in PMA is considerable and heat from the atmosphere is accumulated on the flats while they are exposed in summer, and then it is taken up by the seawater during tidal immersion. Fourteen-day mean water temperature measured on the mudflats (i.e., not including mud surface temperature when the mudflats are drying) was up to 1.37 °C higher than nearby sea surface temperatures in non-mudflat areas from June to October 1997. The heat budget calculation for summer 1997 showed that the additional heat provided to PMA by the twice-daily export of the tidal prism overlying the shallows and mudflats was greatest during early August, being about 80% of the heat discharged to the arm by the BGS operating at typical summer levels. Cumulatively over the mid-June to early September 1997 period, the shallows contributed additional heat to the arm equivalent to about 25% of the heat discharged by the BGS.

The cumulative heat budget for the summer period, mid-June to early September, was calculated for 1998 and compared to the previous two years. BGS power levels were very different for each of these three summers. Yet, there was a lack of basin-wide response to operating conditions at the BGS and heat did not appear to be sequestered within the water body for longer than a tidal cycle. The water temperature-monitoring program provided strong observational evidence that natural processes regulate arm water temperature. In the summer, the arm starts losing heat through natural processes in late July to early August, regardless of BGS operational levels.

Mid-winter monthly mean temperature is similar throughout the arm, although some winter minimum temperature values are lower in the arm than at its' entrance. Water temperature to depths of 8 m in mid- to late-winter 1997-1998 was about 2 °C higher than in the two previous years. This trend continued in 1998 to the spring and summer, and was possibly due to strong *El Nino* conditions, resulting in a warming of the north Pacific Ocean and adjoining inland waters.

It was deduced that the thermal discharge from the BGS at normal operating levels has a limited impact on the temperature of surrounding waters of PMA. Within 100 m of the BGS, mean monthly water temperature was no more than a few tenths of a degree higher than surrounding background water temperature and only within the upper few meters of the water column. Water temperature measured half-hourly within 70 m of the BGS discharge point may be as much as 1 °C - 3 °C higher than BGS intake temperature; however, these values are consistent with the daily variation in water temperature observed throughout the arm. Using a simple cross-correlation technique and using 4-hour BGS heat discharge data (Taylor et al. 1999) variations in heat discharged by the BGS were shown not to be correlated with changes in water temperatures throughout the water column at nearby stations. This suggested that mixing of the BGS discharge with the surrounding water in the "near-field" occurs quickly and efficiently.

Current and tidal heat transport alone is capable of removing most of BGS discharge heat when the latter is operating at approximately 60% (575 MW) of its generating capacity, as shown by the October 1998 calculations. There is evidence that tidal heat loss in the summer may be substantially higher than calculated in October, under present BGS loading. This suggests that PMA could cope with the thermal discharge resulting from the BGS operating at 100% capacity through much of the year, except possibly in summer.

CHUM SALMON IN PORT MOODY ARM

The purpose of this sudy was to gather quantitative data on species, numbers, and timing of juvenile and adult migrating salmonids in Port Moody Arm. Surveys were conducted to enumerate adult salmon in the fall of 1998 and 1999. The trapping of downstream migrating juvenile salmon was carried out in Mossom Creek in the spring of 1999 and 2000.

The main tributaries to Port Moody Arm (Mossom, Noons, Sutterbrook as well as Schoolhouse North and South Creeks) were surveyed over the 1998 and 1999 fall spawning season. Figure 3 shows the location of the creeks (from Greenbank et al. 2001b). Chum salmon (*Oncorhynchus keta*) was the dominant species of Pacific salmon found in all of the systems; coho salmon (*Oncorhynchus kisutch*) and chinook salmon (*Oncorhynchus tshawytscha*) were also observed. Total escapement estimates of chum salmon for Mossom Creek were 1803 in 1998 and 658 in 1999; low numbers of chum salmon were also recorded in the other systems that were monitored. Relatively low numbers of adult coho salmon were observed in Mossom, Noons, Schoolhouse North and Sutterbrook Creeks.

Adult chum salmon were first noted in Mossom Creek on October 5 and 6 in 1998 and 1999 respectively. The last fish was observed in early December in both years. The peak migration period extended from October 16 through November 9. It was estimated that the majority of the chum salmon moved through Port Moody Arm in the latter half of September and into October.

Water temperature data collected during September and October 1998 at 5-m depth in Port Moody Arm were used to determine if the temperature regime in the arm was suitable for adult salmon. The maximum temperature in September was 16.6 °C and was lower in October. Although no information was readily available on the preferred "migration water temperature" range for adult chum salmon in salt water, the fresh water value has been reported to be between 8.3 °C and 15.6 °C (Bjorn and Reiser 1991). It was concluded that the BGS cooling water effluent would not have an adverse effect on the migrating salmon.

A trap was deployed in Mossom Creek during the spring of 1999 and 2000 in order to enumerate the numbers of downstream migrating juvenile salmon. A total of 13,252 and > 18,000 chum salmon were captured and released in 1999 and 2000 respectively. The downstream migration period started in early March and was almost complete by the first week of May in both years. A total of 331 coho salmon fry were captured in 1999 and 875 in 2000. The majority of these fish were captured in March and April. Low numbers of coho smolts, cutthroat trout (*O. clarki clarki*) parr and sculpin species were also captured in the trap.

Based on the results of these surveys and other pertinent information, juvenile chum salmon are likely present in Port Moody Arm from March to July.

EFFECTS OF TEMPERATURE, TGP, AND BGS COOLING WATER ON CHUM SALMON

Particular attention has been focused on the significance of temperature changes due to thermal discharges from nuclear and electric generating stations into fresh and marine waters (Neill and Magnuson 1974; Coutant 1975, 1977; International Atomic Energy Agency 1975; Spigarelli 1975; Spigarelli et al. 1982; Langford 1990). In particular, the responses of fish to temperature has been studied extensively due to its' fundamental importance in the life of poikilothermic aquatic organisms as a controlling, limiting, and directive factor (Fry 1947; Brett 1952; Coutant 1977; Reynolds 1977; Olla et al. 1980; Houston 1982; Coutant 1987; Langford 1990). However, the determination of the effects of thermal discharges on fish is difficult to do under natural circumstances for the complexity of variables encountered in the wild make cause and effect relationships difficult to isolate. But to conduct all experiments within the controlled environment of the laboratory could result in erroneous information unless care is taken to mimic conditions in nature so as to improve the relevance of the findings. To address the potential for the thermal discharge from the BGS to affect juvenile chum salmon in Port Moody Arm we employed complementary laboratory and field studies on the behavior of the fish (Birtwell et al. 1998, 2001a), attempted to reveal significance to survival of the likely exposure of the fish to elevated levels of dissolved gases and temperature in surface waters through laboratory studies that mimicked conditions the fish may experience in the wild (Birtwell et al. 2001b), and also utilized the thermal effluent from the BGS diluted with water from Port Moody Arm in studies on the growth of the fish (Greenbank et al. 2001a).

Growth of chum salmon in dilutions of BGS cooling water

Brett's (1952) work revealed that the ultimate upper lethal temperature for chum salmon in fresh water was 23.8 °C, that their preferred temperature was between 12 °C and 14 °C, and that optimal growth in fresh water occurred at around 15 °C (Brett 1995). Birtwell et al. (2001a) determined that the preferred temperature in seawater lay between 13.7 °C and 17.9 °C, that the 50% avoidance level response to increasing temperatures was 20.2 °C. Given that the temperature of the thermal discharge from the BGS is ≤ 27 °C and that temperature of the surface waters of PMA frequently exceed the laboratory-derived avoidance threshold in summer (Birtwell et al. 1998), the potential is present for adverse effects on juvenile chum salmon due to temperature alone. Although it would have been possible to manipulate water temperature within a laboratory and examine the effects of this variable alone on the growth of chum salmon, we considered another alternative that provided greater relevance to the natural situation. An on-site laboratory facility was utilized at the BGS for this purpose and effluent from the BGS was supplied to the facility together with water from Port Moody Arm. Accordingly, stock fish were supplied with water that they would otherwise have encountered in the wild upon their release from the hatchery, and all variables inherent to the effluent (such as variation in dissolved gases) were incorporated in the experiments. Figure 4 shows the main components of the apparatus that was used to examine the effects of dilutions of BGS CW on juvenile chum salmon (from Greenbank et al. 2001a).

During the late spring and summer of 1997 (June 10 to September 10) three consecutive experiments were conducted to examine the potential effects of BGS CW on the growth of juvenile chum salmon. In each of these controlled growth studies, of 20 - 28 days in duration, fish were placed in the indoor test facility and exposed to CW [0% (control), 6%, 12%, 25% or 50%] diluted with sea water drawn from 3 m depth in Port Moody Arm (away from the influence of the thermal discharge). In each growth study there were two replicates of 30 - 50 fish for each treatment group. The number of fish per group was reduced over time to maintain an acceptable loading density of ≤ 10 $kg \cdot m^{-3}$ (Environment Canada 1990). Research efforts focused on identifying relationships between fish growth, temperature, TGP and the concentration of CW to which the fish were exposed.

Overall growth rates of juvenile chum salmon fry averaged from 2.38% to 6.38% body weight per day, and decreased significantly with increasing concentration of CW in the second and third studies (July 15 - August 7, and August 7 - September 10, 1997 respectively). Most of these differences occurred in the groups exposed to the 50% CW treatment. Overall, growth rates for all groups, including the controls, were substantially lower in the third study. This may have been due to a size-related phenomenon (i.e. slower growth rate in larger fish) or perhaps a loading density/social interaction effect (i.e. fewer but larger fish in the tank).

For the temperature/CW regimes that were examined, the decrease in growth rate of chum salmon was linear with respect to the number of degree·hours of exposure above a temperature of 18.7 °C. This temperature is 0.8 °C higher than the laboratory derived upper-level boundary of the "preferred" range for chum salmon and 1.5 °C lower than the 50% avoidance threshold (Birtwell et al. 2001a). This relationship was valid for second and third studies but not for the first (June 16 - July 10, 1997). The result in the first study was attributed to high stress levels related to the experimental design (e.g. insufficient overhead and in-tank cover for the fish).

The decrease in growth with respect to increasing exposure to TGP was also determined to be a linear relationship for the range of CW concentrations to which fish were exposed in all three studies. However, linear and multiple regression analysis applied to the data determined that almost all of the differences in growth could also be explained by temperature alone, for these two variables were highly correlated with each other.

Another series of growth experiments was conducted in 1998. The intent of these investigations was to characterize the effect of different concentrations of dilutions of the cooling water on the survival, growth and condition of underyearling chum salmon and to confirm, if possible, the results obtained during the latter two 1997 experiments. An additional objective was to distinguish the effects on growth due to high temperature from those related to possible interactive effects with elevated levels of dissolved gases (high TGP), and to relate any observed effects to potential interactions between the operation of the BGS and chum salmon juveniles occupying Port Moody Arm.

In 1998, four consecutive experiments, each of 16 to 20 days in duration, were performed from May to August. During each experiment, groups of 30-50 fish were exposed to CW [0% (control), 6%, 12%, 25%, 35% and 50%] diluted with seawater pumped continuously from a 5-m depth at a station removed from the influence of the CW discharge. In the final growth study conducted in August, tanks supplied with CW concentrations of 65% and 75% were incorporated in the experiment. In addition, two tanks were supplied with 50% CW at low TGP (i.e. the high dissolved gas levels removed) and two tanks were supplied with water pumped continuously from a 1-m depth from Port Moody Arm (removed from the influence of the CW discharge plume). The latter treatments enabled a separation of the effects of elevated dissolved gases from those of elevated temperature alone, and the seasonal effects of shallow surface water on the growth and condition of juvenile chum salmon during a time when water temperature within Port Moody Arm peaks naturally.

The first three experiments conducted in the spring and early summer of 1998 (May through July) identified a positive relationship between fish growth rates and their exposure to BGS cooling water at CW concentrations as high as 50%. In the fourth experiment, conducted in August, exposure to ≤ 35% BGS CW did not affect fish growth significantly, whereas the higher concentrations of 50% and 65% CW retarded growth. A reduction in the dissolved gases to levels that were equivalent to those at air saturation in the 50% treatment group did not prevent the growth retardation evident during this time period.

Overall mortality of juvenile chum salmon used in the four 1998 growth studies (up to and including 50% cooling water exposures) was less than 1%. There were no deaths in the control tanks. Mortality was 9.1% (average over four experiments) in the shallow Port Moody Arm waters (contrasting with the average mortality of 2.9% due to exposure to 50% CW). However, the high mortality (28% and 30%) in the shallow-water treatment (PMA surface water) during the second experiment coincided with turbid waters which were considered to be indicative of seasonal algal blooms. Mortality in the 65% CW treatment (22.6 °C) was 13.3% while that in the 75% CW (23.4 °C) was 100% in approximately 5 days.

The condition of all fish in the 1998 studies deteriorated slightly during the course of the experiments, as evidenced by increasing incidences and severity of external signs of ill health. These signs (including cataracts, split cornea, scale loss, dot hemorrhages in the lateral line, subcutaneous lesions and torn fins, as well as classical GBT signs such as exopthalmia, bubbles in the eye, lateral line and unpaired fins) increased from the first to the third study at which time nearly all fish, including the controls, showed signs of deteriorating health. There was a significant increase in the signs of ill-health which was correlated positively with increasing CW concentrations in the second study; however, by the third study all treatment groups had similar levels of health-related signs. This coupled with the antibiotic treatment delivered to stock tank populations suggests that fish used in the second experiment may have had a low level infection which could have contributed to the overall reduction of growth rates observed in that study. The only experimental treatment to show a statistically significant increase in the signs of GBT relative to control fish, occured in the first study and used tanks supplied with shallow water drawn from Port Moody Arm.

Based on the results of the two year study on the effects of BGS CW on the survival, condition, and growth of juvenile saltwater-adapted chum salmon in Port Moody Arm, the overall effect of this heated-water discharge would appear to be small. Retarded growth rates were observed for those fish that were held in high concentrations of CW which resulted in elevated temperatures similar to those recorded in the surface waters of Port Moody Arm, outside of the predicted main chum salmon utilization period (Birtwell et al. 1998). However, a benefit to the growth of juvenile chum salmon could accrue earlier in the year due to an elevation in temperature more favorable to metabolic function relative to temperature in waters not influenced by the BGS CW discharge plume and outside Port Moody Arm. The importance of increasing temperature on growth rate in salmonids has been well-established (Weatherley and Gill 1995; Brett 1995). Provided food is not limiting, growth rate in many salmon species increases to a maximum between 15 °C and 20 °C, and then rapidly decreases as the incipient lethal limit is approached (Weatherly and Gill 1995). Wissmar and Simenstad (1988) state that the metabolic costs of maintenance are in delicate balance with food intake and growth. If food was impoverished in the preferred, yet thermally heated surface waters, the energetic costs of capturing food in high temperature waters could limit growth. Donaldson and Foster (1941) found that juvenile sockeye salmon refused to feed when temperatures increased from 17.2 °C to 25.6 °C, but resumed feeding when temperatures returned to 21.1 °C. Similarly, Brett et al. (1982) found that 19.0 °C was the optimum temperature for the growth of juvenile chinook salmon fed on maximum ration, but above this level feeding and growth decreased. They also state that at 60% of maximum daily ration, the optimum temperature for growth decreased to 14.8 °C. Their studies did not permit opportunity for the fish to balance the thermoregulatory requirements against the energetic and metabolic demands of feeding and growth. Accordingly, feeding in higher temperature waters (as could occur for chum salmon in PMA) may not be as detrimental in thermally stratified environments that permit fish to thermoregulate and maximize performance. In this context, the movement of sockeye salmon into warmer surface waters to feed followed by a return to colder waters in lakes, is considered to be adaptive and energetically advantageous (Biette and Geen 1980). This apparent advantage is attributed to the lower maintenance requirements at colder temperatures and a concomitantly greater proportion of food available for conversion to growth (Brett 1971).

While the dispersion of food in the wild is unlikely to be available only in the surface waters (1 -2 m) where the juvenile chum salmon prefer to reside, their presence there suggests proximity to food. It has been suggested by Coutant (1987) that there may be marked differences in feeding behavior in steep gradients and that fish may feed on uncharacteristic prey. Spigarelli and Thommes (1979) documented the reduced growth and condition in ictalurids due to strong thermal attraction and inadequate food in "thermally-enriched" areas. However, Spigarelli and Smith (1976) found no evidence of such an effect on rainbow trout from thermal plume and reference areas implying an ample supply of food for "plume-resident" fish. Quite obviously there are site-specific differences among the reported findings, but the pattern of attraction of fish to thermal discharges at certain times of the year is common to all.

It is our conclusion that the combination of the thermal avoidance behavior determined by Birtwell et al. (1998, 2001a), the documented and expected utilization period of juvenile chum salmon in Port Moody Arm (MacDonald and Chang 1993; Hwang et al. 1994; Greenbank et al. 2001b) as well as the results of this investigation, provide sufficient evidence to indicate that the discharge of CW from the BGS will have a minimal effect on populations of juvenile chum salmon that utilize these waters.

Behavioral responses to temperature change and to food

As part of the research studies reported here, a Water Column Simulator (WCS; Birtwell and Kruzynski 1987), was employed to study aspects of the behavior of juvenile chum salmon under controlled conditions in the laboratory. Figure 5 shows the main apparatus components used in this study. Experimental conditions were chosen to mimic chum salmon entry to marine waters and their potential encounter with the thermal plume in Port Moody Arm created by the CW discharged from the BGS. Seawater used in these experiments was drawn from the contiguous waters of English Bay. A series of acute lethality tests with juvenile chum salmon in seawater was undertaken to determine the ability of the fish to survive short-term (few hours) exposure to a single high temperature (~25 °C) with or without dissolved gas supersaturation (elevated levels of TGP). The results, which were similar between the treatments and revealed the lethality of such conditions (median mortality time 150 - 157 min), were used to assist in the interpretation of the findings of fish behavior studies conducted within the WCS in response to thermal change.

We anticipated that the chum salmon would avoid heated seawater, but that this avoidance could be mediated through the presence of food and the motivation to feed. Accordingly, we examined the behavior and distribution of a population of juvenile chum salmon with and without the presence of food under isothermal (acclimation) conditions followed by a transition to stable, vertically-stratified conditions in which heated water (24 °C) was separated from cooler waters at the 10 °C acclimation temperature, by a narrow thermocline. The volitional position of fish in the water column was determined together with swim speed, and duration of time spent in heated surface waters relative to baseline isothermal conditions. The complete set of experimental data pertaining to these experiments is presented in the report by Korstrom et al. (1998).

The response of chum salmon to thermal change and food followed a trend that has been recorded for fish proximal to thermal plumes and during other laboratory investigations. That is, fish were attracted to warmer waters and preferred a particular temperature range (13.7 °C – 17.9 °C), avoided higher temperatures (see Figure 6), and were motivated to feed in waters with temperatures which approached or exceeded those which could be acutely lethal if exposure was sustained.

Based on this information, the temperature of waters in which this species resides during their early sea life would be expected to be less than that which induced avoidance behavior: temperature would be below ~20 °C, and most probably <18 °C, (the 50% avoidance response level, and the upper limit of the preferred range, respectively). The preferred temperature range in seawater for this species and life stage would lie, approximately, between 14 °C and 18 °C, and favor optimal metabolic and physiological functions. Behavioral thermoregulation would be expected to favor survival, and the broader the range of the preferred temperature, the greater the scope for exploiting habitats. Similarly, the greater the resistance to temperatures outside this range, the higher the opportunity for extending this range into "sub-optimal" regions for transitory and important activities such as feeding. In this regard, chum salmon displayed behavioral flexibility and showed that they are capable of briefly using waters approximately

6 °C and 15 °C higher than their lethal limit and optimum (i.e. at 25 °C and 30 °C, respectively) in order to feed.

The consequences of the behavioral traits demonstrated in these studies to the survival of chum salmon in the waters of Port Moody Arm are not known with any degree of certainty, although they may be speculated upon based on this knowledge, and that from other research on thermal discharges. In the marine environment, the imposition of thermal regimes elevating temperatures above ambient to those in the preferred range would be expected to encourage fish occupancy from cooler waters; a situation that could occur in the spring and early summer. Assuming adequate food supplies, these conditions would favor growth (survival), but at the same time extended residence could result in exposure to elevated TGP if and when such conditions were present. This latter effect may be mediated behaviorally through the occupation of deeper waters, but this would remove the fish from their preferred surface water habitat.

Increasing the temperature of the surface waters of Port Moody Arm above the preferred range would be expected to result in their avoidance by juvenile chum and other species of salmon, as temperatures approached potentially lethal limits, typically in summer when fewer juvenile salmon are present. However, the innate behavioral trait to occupy surface waters during estuarine residence and early sea life may compromise survival if other non-thermal cues are dominant factors. In this circumstance, they could override thermal stimuli that would otherwise favor survival and the optimization of metabolic and physiological functions. Although chum salmon demonstrated an avoidance of potentially lethal high temperatures in the laboratory, they were also motivated to feed in such waters (to 30 °C). To this extent we do not know the effects of repeated excursions into waters that are potentially lethal. However, the consequences of longer occupancy of waters that may be stressful at the sub-lethal level (e.g. combined effects of temperature and elevated TGP) on the health and performance of individuals and the crucial link to survival was examined by Birtwell et al. (2001b).

Intermittent operation of the BGS would impose a fluctuating thermal regime in Port Moody Arm because of the rapid (1 to 2 d) tidal-induced replacement of water (Waldichuk 1965). Such a scenario would probably reduce potential impacts on chum salmon during the early spring and summer, but might increase the risk of adverse effects such as thermal shock in winter and temporary habitat displacement for those few salmon that may be in Port Moody Arm in summer.

Effects of the BGS cooling water on the vertical distribution of juvenile chum salmon in Port Moody Arm

This study was undertaken because of the paucity of specific information on the behavior of chum salmon in relation to thermal change in seawater, and the documented potential for juvenile salmon to occupy waters of "sub-optimal" quality. We speculated that the fish would tend to occupy surface waters in the marine environment of Burrard Inlet, as documented in other locations (e.g. Birtwell and Harbo 1980), and that their dispersion in the water column would be related to the prevailing conditions. Because of the variable nature of the waters around the thermal discharge from the BGS, and the tendency of the heated water to occupy surface waters (Seaconsult Marine Research Ltd. 1995), we employed an experimental cage technique (Birtwell

1977; McGreer and Vigers 1983). Each rectangular mesh-enclosed cage was 6 m in length, 0.5 m deep and 0.5 m wide. The cages were partitioned into six 1 m compartments interconnected by gates that provided separation of, or access to, the enclosed water column. Figure 7 is a diagram of the apparatus (from Birtwell et al. 1998). By placing equal numbers of juvenile chum salmon into each compartment of the apparatus and permitting them access to the enclosed 6 m water column for approximately 1 d before closing the gates, we were able to determine their vertical distribution within the waters of Port Moody Arm. The cages were deployed, during June – August 1997, at a reference location and at 3 other sites 70 m, 250 m, and 1200 m in distance from the BGS thermal discharge location. The results of these studies have been reported by Birtwell et al. (1998).

The vertical distribution of chum salmon was not affected in a statistically significant manner with proximity to the discharge of thermal effluent from the BGS during July and August 1997. These fish prefer to occupy the shallow waters close to the surface during their early marine life and we anticipated that warm water from the plant would rise to the surface and disrupt this adaptive behavior, thereby displacing them from their preferred habitat. In this way we expected that the distribution of fish would be affected depending not only on the climatic conditions and proximity to the discharge location, but also on the operating conditions at the BGS. Although fewer fish were in the uppermost surface waters close to the thermal discharge there was sufficient variation in the data to negate any potential statistical significance. However, a seasonal component to their distribution was recorded as the larger fish tended to be in deeper and cooler waters in August at all study locations including the reference site.

The waters of Port Moody Arm were typically supersaturated with dissolved gasses reflective of the primary productivity and thermal input from both natural (solar) and other sources. However, adjacent to the discharge of cooling water, TGP was occasionally reduced to levels approaching optimal values for salmon. Thus, there did not appear to be a direct effect of the BGS heated water discharge on TGP in Port Moody Arm at this location.

Relative to the reference site, water temperature was elevated at sites close to the discharge (70 m and 250 m east), and in general at sites towards the shallow head of Port Moody Arm. Throughout most of the study period (June to August) temperature levels preferred by chum salmon (13.7 °C to 17.9 °C) were present within 6 m of the water surface, and were frequently less than that which caused 50% avoidance (20.2 °C) in laboratory studies (Birtwell et al. 2001a). At the reference site, temperatures in the uppermost 1 m of the water column that were favored by the chum salmon, were always less than the upper lethal limit of 23.8 °C that was determined by Brett (1952) in laboratory experiments, and rarely at levels that would have been expected to evoke avoidance behavior. Temperature levels in waters to the east of the outfall were generally higher than the reference site, exceeded the laboratory-derived avoidance threshold more frequently, and approached the potentially lethal level in July. At the site 1200 m east of the thermal discharge location, the potentially lethal level was exceeded briefly, perhaps reflecting the shallowness of the area and the possible thermal input from extensive mudflats towards, and at the head of Port Moody Arm (Taylor et al. 2001). Even though the temperature of surface waters in Port Moody Arm were frequently higher than those that were found to cause avoidance responses in laboratory experiments, juvenile chum salmon continued to use these waters. It is unclear as to whether this use represented brief excursions into these waters to feed, an ability to tolerate the warmer water due to progressive thermal acclimation, a response to natural ambient stimuli or a combination of all of these. While experiments conducted in the laboratory by Brett (1952) and Birtwell et al. (2001a) did not mimic all the cues likely to be found in the wild, they did reveal that elevated temperatures, such as the highest ones recorded in Port Moody Arm, are likely avoided by juvenile chum salmon, and that prolonged occupation of such waters can result in their death. Irrespective of the reasons why juvenile chum salmon chose to occupy the waters close to the surface, concern is warranted if these fish continue to reside in depths <1 m due to the potential for harmful effects on their health caused by the interaction of temperature and TGP (notwithstanding the potential protection from TGP in shallow waters which occurs due to the presence of supersaturated levels of dissolved oxygen).

At each of the four stations in Port Moody Arm investigated in this study, including a reference station removed from the direct influence of the BGS cooling water discharge, chum salmon continued to use surface waters despite supersaturated conditions for TGP and temperatures which were frequently 18 °C to 21 °C. The innate behavioral trait to occupy surface waters during estuarine residence and early sea life may compromise survival if other non-thermal cues become dominant factors. In this circumstance, they could override thermal stimuli that would otherwise favor survival and the optimization of metabolic and physiological functions. Although chum salmon demonstrated an avoidance of potentially lethal high temperatures in laboratory experiments (Birtwell et al. 2001a), they were also motivated to feed in such waters. It is possible that a thermal discharge could elevate temperatures above ambient to those in the preferred range during certain times of the year. Under these circumstances fish would be encouraged to move from cooler waters, as may occur in the spring and early summer. Assuming adequate food supplies, these conditions would favor growth (a conclusion also reached by Greenbank et al. (2001a) and possibly survival. However, at the same time, extended residence could result in exposure to elevated levels of TGP and the development of gas bubble trauma (refer to Birtwell et al 2001b). This latter effect may be mediated behaviorally through the occupation of deeper waters, but this would remove the fish from their preferred surface water habitat.

Consequences to juvenile chum salmon survival following exposure to sublethal temperature and dissolved gas supersaturation

Whether the occupancy of the thermally-elevated and dissolved gas-supersaturated surface waters of Port Moody Arm would be harmful to juvenile chum salmon required resolution as either one of these variables has the potential to harm fish given a sufficient exposure time and level. There was, however, no information available on the combined effects and significance of these variables at the sublethal level on juvenile chum salmon. To address this deficiency we designed a study to provide information on the effects of exposure of juvenile chum salmon to sublethal temperature and dissolved gas supersaturation (DGS) in seawater. The main components of the apparatus used in the study are shown in Figure 8 (from Birtwell et al. 2001b). The focus of the research was on the potential of a combination of these variables to compromise the performance and behavior of chum salmon to the extent that their survival may be jeopardized through increased vulnerability to predation.

Although it would have been possible to study the combined effects of temperature and TGP on juvenile chum salmon through a series of laboratory assays that indicated effects within the organism (Wedemeyer et al. 1991), a whole organism response was considered more appropriate. Furthermore, we required a test that had an end point that was not only relevant to the survival of the individual but also one that was ecologically meaningful. A fish that is less fit, and therefore is less able to effectively compete for food and avoid predators is, potentially, likely to be selectively preyed upon (Bams 1967). No one test can measure the vitality of a fish better than the survival of an individual after a life time under natural conditions, but shorter-term whole organism tests that have a direct link to the survival of the individual, and that at the same time are ecologically meaningful, have value in environmental assessments. Accordingly, we chose a predator challenge test to assess the fitness of juvenile chum salmon after exposure to the combined stressors of elevated temperature and dissolved gas supersaturation.

Clearly, death in the wild is an expected end point to an individual's life, and one would logically expect visible corpses from the death of all organisms were it not for the actions of predators and scavengers. Research has shown that fish can survive exposure to a range of potentially lethal compounds, effluents, and circumstances, but may be physiologically and behaviorally compromised as a consequence. Without knowledge of the potential consequences of such compromises to the survival of these fish when faced with the additional rigors associated with life in the wild, it would be easy to overlook indirect mortality or "ecological death" (Sprague 1971; Coutant et al. 1979; Kruzynski and Birtwell 1994; Mesa et al. 1994). That few dead organisms are visible at times other than those in which catastrophic events occur is testimony to the natural consumption and assimilation of organisms, and the fitness and fortunes of others. Fish live in a competitive environment in which their survival is related to the maintenance of health and performance. Because predation is a major source of juvenile salmon mortality during their early marine life (Parker 1968; Bax 1983; Mace 1983; Healey 1982) and that predators generally attack prey in sub-standard or unusual condition (Neill and Cullen 1974; Coutant et al. 1979; Landeau and Terborgh 1986; Temple 1987; Gadomski and Hall-Griswold 1992; Kruzynski and Birtwell 1994; Mesa and Warren 1997), we considered that the use of predator challenge tests had merit in not only assisting in the elucidation of the effects of temperature and supersaturated TGP on juvenile chum salmon, but also in providing a potentially highly relevant and ecologically meaningful result.

Previous studies determined that juvenile chum salmon would continue to occupy the surface waters of Port Moody Arm in the early summer even when temperatures and dissolved gases were potentially stressful to them with prolonged exposure (Birtwell et al. 1998). Because an increase in temperature also coincided with increases in dissolved gases in surface waters of the arm during the late spring and early summer, we considered that the well being of juvenile chum salmon might, in some instances, be compromised at such times. It is well known that the effects of stress can lead to a reduced performance in fish and that the effects of an imposition of multiple stressors is cumulative. Both elevated temperature and dissolved gas supersaturation have the capacity to debilitate fish and accordingly a combination of these variables could potentially exert an indiscriminate and cumulative effect on the chum salmon that use Port Moody Arm prior to their migration to the Pacific Ocean.

In the predator challenge experiments, groups of equal numbers of control chum salmon exposed continuously to seawater at cool temperatures (12.8 ± 1.0 °C) and 100% TGP as well as those which had been exposed to 20.7 °C seawater and 115% (T+115), 120% (T+120), or 130% (T+130) TGP for 48 h, 24 h, or 12 h respectively, were exposed to the risk of predation from locally occurring copper and quillback rockfish, kelp greenling, and Pacific staghorn sculpin in apparatus at the West Vancouver Laboratory. Temperatures above 20.7 °C, and to a maximum of 24 °C, and TGP values to a maximum of 125.2%, were recorded in the surface waters of Port Moody Arm in July 1997 (Birtwell et al. 1998).

Statistical analysis revealed the significantly increased vulnerability of juvenile chum salmon to the combined sublethal stressors of warm (20.7 °C) seawater and elevations of TGP of 120% for 24 h (22.8% increase with rockfish; 9.8% increase with Pacific staghorn sculpin and kelp greenling predators), or 130% TGP for 12 h (10.7% increase with kelp greenling and Pacific staghorn sculpin predators) relative to controls. However, exposure of the chum salmon to warm (20.7 °C) seawater and 130% TGP for 12 h did not result in a significant increase in susceptibility to predation by rockfish (11.3% increase) relative to control fish, nor did 115% TGP for 48 h (6.5% increase with rockfish; 0.3% increase with kelp greenling and Pacific staghorn sculpin predators).

The predators fed more efficiently on the fish that received the T+120 and T+130 treatments than they did on those exposed to T+115, and signs of the effects of exposure to TGP (i.e. gas bubble trauma) were most evident in the groups that were most heavily preyed upon. These results indicated that the performance of the juvenile salmon was compromised by the T+120 and T+130 treatments they received, thereby rendering them more susceptible to predation. We speculated that this performance deficit was possibly associated with the effects of gas bubbles on the sensory capabilities of the fish, but more so to the effects of temperature and TGP on swim performance and a reduced ability to recover from fatigue brought on by predator attacks and the need for repetitive escape responses.

CONCLUDING COMMENTS

Table 1 displays the significant findings of the studies reported in this document.

RISK OF HARM TO JUVENILE CHUM SALMON FROM EXPOSURE TO COOLING WATER FROM THE BURRARD GENERATING STATION

It is possible to speculate on the significance of these findings to the populations of juvenile chum salmon that use Port Moody Arm. The numbers of juvenile chum salmon typically decline in near shore coastal areas during the late spring and early summer. At this time, surface water temperatures and dissolved gases in Port Moody Arm tend to increase to levels that, in combination, could lead to an increased vulnerability of juvenile chum salmon to predation [especially so with prolonged (>48 h) residence], reduced growth rates and condition.

The innate tendency of juvenile salmon to reside for days to weeks in the uppermost surface waters during their early marine life potentially increases the risk of exposure to elevated temperatures and TGP in the surface waters of Port Moody Arm. Because the concomitant effects of elevated temperature and TGP increased the vulnerability of chum salmon to predation, the potential exists for an increase in mortality within those populations that use Port Moody Arm under the circumstances where the duration of exposure to the combination of temperature and dissolved gas supersaturation in the surface waters is sufficiently stressful and debilitating (as was evident here for the 24-h T+120 and the 12-h T+130 treatments). The mortality of juvenile salmonids is typically high during their early sea life (40% to 50%) due primarily, to size-selective (discriminate) predation (Bax 1983; Mace 1983; Healey 1982). Because elevated temperatures and TGP have the potential to affect all members of a population, these water quality variables may be viewed as indiscriminate stressors whose effects are additive to those of the natural predation events. Thus the potential is present in Port Moody Arm for juvenile chum salmon to suffer increased predation during the late spring and early summer when elevated temperatures and TGP occur in combination at levels which reach and or exceed those which were shown in the present studies to cause such an effect, or exposure for a greater duration to lower, yet still elevated, levels of temperature and/or TGP. The magnitude of any effect on the population of chum salmon at these times will be diminished because of the natural decrease in numbers of chum salmon that occur in near shore marine waters during this same period in time.

Intuitively one may expect that these fish would avoid potentially harmful conditions in their environment, but the choices that we deem to be appropriate are not always those that are made by the fish. There are numerous examples of fish occupying sub-optimal waters and suffering as a consequence. In this regard the chum salmon could move deeper in the water column to obtain the benefit of increased hydrostatic pressure and thereby reduce the effects of TGP (a movement to 1-m depth is equivalent to a reduction of 10% TGP), and a reduction in temperature. Such movements would take the fish from their preferred surface water habitat, and it is likely that any such movement would be of increased risk to their survival (predators tend to be in deeper water). The behavior to occupy the surface waters is probably adaptive and has contributed to the perpetuation of the species over time. Because of this, it is unlikely that movement to depth would override this seemingly strong innate behavior for protracted periods of time.

Because Port Moody Arm tends to be eutrophic, dissolved oxygen levels are frequently above air-saturated levels during daytime due to photosynthetic activity. Elevated levels of dissolved oxygen have been found to reduce the effects of nitrogen supersaturation (which can occur through the enclosed heating of air-saturated waters) on fish. However, at night the potential exists for hypoxic conditions to occur in eutrophic waters due to the respiratory requirements of phytoplankton and other organisms. If this were the case, the hypoxic waters themselves could impair performance of fish thus negating the benefit of increased oxygen levels during daytime. Fortunately, the dissolved oxygen levels in the water drawn from depth in Port Moody Arm into the BGS are usually below air saturated values and the heating that occurs prior to its discharge does not always result in supersaturated levels of dissolved gases.

An effect of increased and rapid growth of chum salmon upon entry to seawater would probably enhance their chances of survival, for as they grow they are able to swim faster and become progressively less available to some predators. Increased surface water temperatures in parts of Port Moody Arm during the spring could enhance the growth rate of chum salmon in these waters assuming adequate food supplies were available (Greenbank et al. 2001a). There is evidence that the waters of Port Moody Arm are naturally warmer in the spring and summer than the contiguous waters of Burrard Inlet to the west (Taylor et al. 2001), and this situation alone would favor a relatively earlier and more rapid growth in juvenile fish when temperature is metabolically optimal. Thus the continuous operation of the BGS and the discharge of cooling water, together with the natural heating of this shallow water body, could promote the growth of the chum salmon. This thermal change could raise the temperature in Port Moody Arm to that which is in the metabolically-optimal range for the salmon at an earlier date than that which would occur under natural circumstances (intermittent operation, however, could be potentially stressful to the fish due to rapidly fluctuating ambient conditions). The net result of the increased growth could, therefore, be an increased chance of survival.

In conclusion, it was determined that the combined effect of elevated temperature and DGS at levels similar to, and exceeding, those which have been recorded on occasion (maxima for surface waters) in Port Moody Arm during early summer, has in such instances, and over ≤ 24 h, the potential to increase the susceptibility of juvenile salmon to predation. Juvenile chum salmon that remain in the waters of Port Moody Arm in summer would be expected to incur additional predation pressure commensurate with the duration of their exposure to, and the respective levels of, the combined stressors of elevated temperature and dissolved gas supersaturation. Furthermore, the increased temperature in surface waters would be expected to retard growth rates relative to that which occurs at lower and more optimal temperatures. Despite these concerns, the rapid removal of >80% of the heat entering the arm through tidal action and currents limits the elevation of temperature above seasonal ambient levels. Accordingly, temperature (and TGP) rarely attains a level that would be acutely harmful to chum salmon during the time of year that they reside in Port Moody Arm.

We deduce that the risks to the wellbeing of chum salmon due to the indiscriminate effect of exposure of the chum salmon population in Port Moody Arm to the combination of elevated temperature and dissolved gas supersaturation (elevated TGP) would be minimal. Such risks will be restricted to any individuals of the chum salmon population that may remain to utilize these waters during the early summer before their migration to the Pacific Ocean.

It is concluded that the current discharge of cooling water from the BC Hydro Burrard Generating Station will not adversely affect chum salmon populations that utilize Port Moody Arm.

ACKNOWLEDGEMENTS

We are especially grateful to BC Hydro who provided the primary funding for these research projects. Administrative tasks were facilitated by Peter Calder and Tony Cohen of BC Hydro, and John Pringle, Richard Addison, Julie Henderson, Gail Huscroft, and Gus Cormier of Fisheries and Oceans Canada. We are also grateful for the assistance of BC Hydro staff at the Burrard Generating Station and for their interest in the project. We appreciate the efforts of Mark Johnson and Lee Nikl who assisted in the procurement of fish, and the staff of the Seymour River Volunteer Hatchery and the Mossom Creek Hatchery, who cared for them and ensured that they were in good health. We are especially grateful for the help we received from Rod McVicker, Ruth Foster, and their students at Centennial High School, Coquitlam, for their data collection and operation of Mossom Creek Hatchery. The interest and cooperation of the Port Moody Ecological Society members is also appreciated. Lee Nikl and Barb Wernick (Fisheries and Oceans Canada) assisted in the capture and transport of predatory fish to the West Vancouver Laboratory. Sirjit Nizzar of the Greater Vancouver Regional District (GVRD) Air Quality Department, provided meteorological data from the Rocky Point station in Port Moody. Mike Henry, Department of Earth and Ocean Sciences, University of British Columbia, supplied mid-channel water temperature and salinity profiles. Numerous staff of ASL Environmental Sciences, Inc., assisted in the studies: Rick Birch and Dave English deployed the acoustic Doppler current profiler, Jeff Hibbs, Alan Tsoi, Dave Billenness, Ward Cartier and Keath Borg assisted with data processing, and Rene Chave assisted with programming and software. Gordon Miller and Pam Olsen (Fisheries and Oceans, Canada) efficiently supplied literature. Disease diagnostics staff at the Pacific Biological Station, Nanaimo, BC, provided an assessment of the health of the stocks of chum salmon. Brett Hodson (Hodson Consulting, Gibsons, BC) and Jonathan Burkowikz (University of British Columbia) provided invaluable assistance with statistical analyses. Don McLeay (McLeay Environmental Ltd., Victoria, BC) meticulously and thoroughly reviewed and critically edited drafts of the project reports on behalf of BC Hydro, and provided valuable insights and comments.

REFERENCES

Aquatic Resources Ltd. 1998. Distribution of fish in Burrard Inlet, Port Moody Arm, and potential effects on migration of adult salmon. A report prepared for B.C. Hydro, Burnaby BC.

Bams, R.A. 1967. Differences in performance of naturally and artificially propagated sockeye salmon migrant fry, as measured with swimming and predation tests. J. Fish. Res. Board Can. 24: 1117-1153.

Bax, N.J. 1983. Early marine mortality of marked juvenile chum salmon (*Oncorhynchus keta*) released into Hood Canal, Puget Sound, Washington, in 1980. Can. J. Fish. Aquat. Sci. 40: 426-435.

BC Hydro 1996. Plan for Environmental Impact Study: Receiving Waters Associated with Cooling Water Discharged by the Burrard Thermal Generating Plant (Permit PE-07178). Prepared for BC Ministry of Environment Lands and Parks, and Burrard Inlet Environmental Review (BERC) Subcommittee. December, 1996.

British Columbia Ministry of Environment, Lands and Parks (BCMELP). 1995. Permit PE-07178. Amended (December 29, 1995). Permit issued March 1, 1985 by the BC Ministry of Environment Lands and Parks under the provisions of the Waste Management Act, governing the discharge of effluent to Burrard Inlet from BC Hydro's Burrard Generating Station. Surrey, BC.

Biette, R.M., and G.H. Geen. 1980. Growth of underyearling salmon (*Oncorhynchus nerka*) under constant and cyclic temperatures in relation to live zooplankton ration size. Can. J. Fish. Aquat. Sci. 37: 203-210.

Birtwell, I.K. 1977. A field technique for studying the avoidance of fish to pollutants. *In* Proc. 3rd aquatic toxicity workshop, Halifax, NS, Nov. 2-3, 1976. Envir. Prot. Serv. Tech. Rep. No. EPS-5-AR-77-1. pp. 69-86.

Birtwell, I.K., and R.M. Harbo. 1980. Pulp mill impact studies at Port Alberni and Port Mellon, BC. Transactions of the Technical Sections Vol: 6(4) TR 85-89.

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

Birtwell, I.K., R.P. Fink, J.S. Korstrom, B.J. Fink, J.A. Tanaka, and D.I. Tiessen. 1998. Vertical distribution of juvenile chum salmon (*Oncorhynchus keta*) in relation to a thermal discharge into Port Moody Arm, Burrard Inlet, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. No. 2235.

Birtwell, I.K., J.S. Korstrom, R.P. Fink, J.A. Tanaka, D.I. Tiessen, and B.J. Fink. 2001a. Distribution and feeding responses of juvenile chum salmon (*Oncorhynchus keta*) to thermal change in seawater. Can. Tech. Rep. Fish. Aquat. Sci. 2342: 93 p.

Birtwell, I.K., J.S. Korstrom, M. Komatsu, L.I. Richmond, B.J. Fink, and R.P. Fink. 2001b. The susceptibility of juvenile chum salmon to predation following sub-lethal exposure to elevated temperature and dissolved gas supersaturation in seawater. Can. Tech. Rep. Fish Aquat. Sci. 2343: 149 p.

Bjornn, T.C. and D.W. Reiser. 1991. Habitat requirements of salmonids in streams. Amer. Fish. Soc. Spec. Pub. 19: 83-138.

Brett, J.R. 1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. J. Fish. Res. Board Can. 9: 265-323.

Brett, J.R. 1971. Energetic response of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). Am. Zool. 11: 99-113.

Brett, J.R. 1995. Energetics. *In* Physiological ecology of Pacific salmon. *Edited by* C. Groot, L. Margolis, and W. C. Clarke. UBC Press, Vancouver, BC. pp. 3-68.

Brett, J.R., W.C. Clarke, and J.E. Shelbourn. 1982. Experiments on thermal requirements for growth and food conversion efficiency of juvenile chinook salmon, *Oncorhynchus tshawytscha*. Can. Tech. Rep. Fish. Aquat. Sci. No. 1127.

Coutant, C.C. 1975. Temperature selection by fish – a factor in power-plant impact assessments. *In* Environmental effects of cooling systems at nuclear power plants. IAEA-SM-187/11, Vienna, Austria. pp.575-597.

Coutant, C.C. 1977. Physiological considerations of future thermal additions for aquatic life. Volume 3. *In* Proceedings of the world conference towards a plan of action for mankind. *Edited by* M. Marois. Biological balance and thermal modifications. Pergamon Press, New York, NY. pp. 251-266.

Coutant, C.C. 1987. Thermal preference: when does an asset become a liability? Envir. Biol. Fish. 18: 161-172.

Coutant, C.C., R.B. McLean, and D.L. DeAngelis. 1979. Influences of physical and chemical alterations on predator-prey interactions. *In* Predator-prey systems in fisheries management. *Edited by* H. Clepper. pp. 57-68.

Donaldson, L.R., and F.J. Foster. 1941. Experimental study on the effect of various water temperatures on the growth, food utilization, and mortality rate of fingerling sockeye salmon. Trans. Am. Fish. Soc. 70: 339-346.

Duval, W. 1998. 1997 cooling water effects study. A study of entrainment of planktonic organisms at the intake and effects of the thermal discharge. A report to B.C. Hydro, Burnaby, BC.

Environment Canada. 1990. Biological test method: acute lethality test using threespine stickleback (*Gasterosteus aculeatus*). Report EPS 1/RM/10, Environmental Protection Series, Conservation and Protection, Ottawa, ON.

Fissel, D.B., M. MacNeil, and A.E. Taylor. 1998. A study of the thermal regime of Port Moody Arm in relation to the Burrard Thermal Generating Station. Volume II: Appendices. Report to BC Hydro, Burrard Thermal Generating Station, Burrard Upgrade Project Office, Port Moody, BC.

Fry, F.E.J. 1947. Effects of the environment on animal activity. Univ. Toronto Stud. Biol. Ser. 55. Publ. Ont. Fish. Res. Lab. 68: 1-62.

Gadomski, D.M., and J.A. Hall-Griswold. 1992. Predation by northern squawfish on live and dead juvenile chinook salmon. Trans. Am. Fish. Soc. 121: 680-685.

Greenbank, J.D., R.P. Fink, and M.Z. Lu. 1998. Burrard Generating Station cooling water effects study: effect of cooling water on growth of juvenile chum salmon (*Oncorhynchus keta*). Report for BC Hydro, Burrard Generating Station.

Greenbank, J.D., R.P. Fink, M.Z. Lu, S.L. Rendek, and I.K. Birtwell. 2001a. Effect of thermal effluent on the survival, growth, and condition of juvenile chum salmon, (*Oncorhynchus keta*). Can. Tech. Rep. Fish. Aquat. Sci. 2341: 90 p.

Greenbank, J.D., S.L. Rendek, and I.K. Birtwell. 2001b. Salmonid migration in tributaries of Port Moody Arm, Burrard Inlet, BC. Can. Man. Rep. Fish. Aquat. Sci. 2557: 47 p.

Healey, M.C. 1982. Timing and relative intensity of size-selective mortality of juvenile chum salmon (*Oncorhynchus keta*) during early sea life. Can. J. Fish. Aquat. Sci. 39: 952-957.

Hodgins, D.O. 1993. Temperature and residual chlorine measurements in Port Moody Arm, September 16, 1993. Prepared for BC Hydro, Burnaby, BC.

Hodgins, D.O. and A.J. Webb. 1991. Determination of residual chlorine in Burrard Inlet originating from the Burrard Thermal Generating Plant. Prepared for BC Hydro, Vancouver, BC.

Houston, A.H. 1982. Thermal effects upon fishes. NRCC Associate Committee on Scientific Criteria for Environmental Quality, Ottawa, Ontario. NRCC No. 18566.

Hwang, J., B.A. Clark, and B.G. Naito. 1994. Timing and distribution of juvenile salmonids in Burrard Inlet: February to August 1992. Unpublished data report, Department of Fisheries and Oceans.

International Atomic Energy Agency. 1975. Environmental Effects of Cooling Systems at Nuclear Power Plants. IAEA-SM-187, Vienna, Austria.

Korstrom, J.S., R.P. Fink, J.A. Tanaka, D.I. Tiessen, B.J. Fink, and I.K. Birtwell. 1998. The influence of lethal temperature and food on the behavior of juvenile chum salmon (*Oncorhynchus keta*) under simulated marine conditions. Can. Data Rep. Fish. Aquat. Sci. No. 1040.

Kruzynski, G.M., and I.K. Birtwell. 1994. A predation bioassay to quantify the ecological significance of sublethal responses of chinook salmon to the antisapstain fungicide TCMTB. Can. J. Fish. Aquat. Sci. 51: 1780-1790.

Landeau, L., and J. Terborgh. 1986. Oddity and the "confusion effect" in predation. Anim. Behav. 34: 1372-1380.

Langford, T.E.L. 1990. Ecological effects of thermal discharges. Elsevier Applied Science, London, England.

Macdonald, J.S., and B.D. Chang. 1993. Seasonal use by fish of nearshore areas in an urbanized coastal inlet in south-western British Columbia. Northwest Sci. 67: 63-77.

Mace, P.M. 1983. Predator-prey functional responses and predation by staghorn sculpins (*Leptocottus armatus*) on chum salmon fry (*Oncorhynchus keta*). Ph.D. thesis, University of British Columbia, Vancouver, BC.

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. *In* Aquatic toxicology and hazard assessment: 6th symposium. *Edited by* W. E. Bishop, R. D. Cardwell, and B. C. Heidolph. ASTM STP 802, American Society for Testing and Materials, Philadelphia, PA. pp. 519-529.

Mesa, M.G. and J.J. Warren. 1997. Predator avoidance ability of juvenile chinook salmon (*Oncorhynchus tshawytscha*) subjected to sublethal exposures of gas supersaturated water. Can. J. Fish. Aquat. Sci. 54: 757-764.

Mesa, M.G., T.P. Poe, D.M. Gadomski, and J.H. Petersen. 1994. Are all prey created equal? A review and synthesis of differential predation on prey in substandard condition. J. Fish Biol. 45 (Suppl. A): 81-96.

Neill, S.R.St.J. and J.M. Cullen. 1974. Experiments on whether schooling by their prey affects the hunting behavior of cephalopods and fish predators. J. Zool., Lond. 172: 549-569.

Neill, W.H., and J.J. Magnuson. 1974. Distributional ecology and behavioral thermoregulation of fishes in relation to heated effluent from a power plant at Lake Monona, Wisconsin. Trans. Am. Fish. Soc. 103: 663-710.

Olla, B.L., W.H. Pearson, and A.L. Studholme. 1980. Applicability of behavioral measures in environmental stress assessment. Rapp. P.-v. Réun. Cons. int. Explor. Mer 179: 162-173.

Parker, R.R. 1968. Marine mortality schedules of pink salmon populations in British Columbia. J. Fish. Res. Board. Can. 25: 757-794.

Reynolds, W.W. 1977. Temperature as a proximate factor in orientation behavior. J. Fish. Res. Board Can. 34: 734-739.

Seaconsult Marine Research Ltd. 1995. Receiving water impact assessment for the Burrard Thermal Generating Plant. Vancouver, BC.

Spigarelli, S.A. 1975. Behavioral responses of Lake Michigan fishes to a nuclear power plant discharge. *In* Environmental effects of cooling systems at nuclear power plants. IAEA-SM-187/18, Vienna, Austria. pp. 479-498.

Spigarelli, S.A., and D.W. Smith. 1976. Growth of salmonid fishes from heated and unheated areas of Lake Michigan – measured by RNA-DNA ratios. *In* Thermal ecology II. *Edited by* E.G.W. Esch, and R.W. McFarlane. RDA Symposium Series, CONF-750425, Augusta, GA. pp. 100-105.

Spigarelli, S.A., and M.M. Thommes. 1979. Temperature selection and estimated thermal acclimation by rainbow trout in a thermal plume. J. Fish. Res. Board Can. 36: 366-376.

Spigarelli, S.A., M.M. Thommes, and W. Prepejchal. 1982. Feeding, growth, and fat deposition by brown trout in constant and fluctuating temperatures. Trans. Am. Fish. Soc. 111: 199-209.

Sprague, J.B. 1971. Measurements of pollutant toxicity to fish - III. Sublethal effects and "safe" concentrations. Water Res. 5: 245-266.

Taylor, A.E., D.B. Fissel, J. Hibbs, and A. Tsoi. 1999. Burrard Thermal Generating Station cooling water impact study: thermal regime of Port Moody Arm, 1998. Volume II: Appendices E-J. Report to BC Hydro, Port Moody, BC.

Taylor, A.E., D.B. Fissel, and I.K. Birtwell. 2001. A study of the thermal regime of Port Moody Arm, Burrard Inlet, BC. Can. Tech. Rep. Fish. Aquat. Sci. 2344: 128 p.

Temple, S.A. 1987. Do predators always capture substandard individuals disproportionately from prey populations? Ecology, 68: 669-674.

Waldichuk, M. 1965. Water exchange in Port Moody, British Columbia, and its effect on waste disposal. J. Fish. Res. Board Can. 22: 801-822.

Weatherley, A.H. and H.S. Gill. 1995. Chapter 3: Growth. *In* Physiological ecology of Pacific salmon. *Edited by* C. Groot, L. Margolis, and W.C. Clarke. UBC Press, Vancouver, BC. pp. 101-158

Wedemeyer, G.A., B.A. Barton, and D.J. McLeay. 1991. Stress and acclimation. *In* Methods for fish biology. *Edited by* C.B. Schreck, and P.B. Moyle. American Fisheries Society, Bethesda, MA. pp. 451- 489.

Wissmar, R.C., and C.A. Simenstad. 1988. Energetic constraints of juvenile chum salmon (*Oncorhynchus keta*) migrating in estuaries. Can. J. Fish. Aquat. Sci. 45: 1555-1560.

Table 1. Significant findings of studies related to the operation of Burrard Generating Station and its impact on Port Moody Arm.

Study	Findings
Heat Budget	Heat is generally not sequestered in PMA for longer than a tidal cycle
	More than 80% of BGS thermal discharge to PMA left due to currents and tidal exchanges with Burrard Inlet proper
	Dominant loss of heat in upper 6 m of water column
	Summer maximum monthly water temperatures 5 °C - 6 °C higher at eastern end of PMA compared with temperature at entrance
	Mudflats at eastern end accumulate heat when exposed, which is transferred to seawater during tidal immersion (equivalent to 80% of heat from BGS at summer operating levels)
	PMA starts losing heat in late July/early August through natural processes irrespective of BGS CW discharges
	PMA could accommodate the BGS operating at 100% capacity through most of the year
Chum Salmon	Downstream migration commenced in early March in 1999 and 2000
Juveniles	13,252 and >18,000 downstream migrating juveniles in 1999 and 2000, respectively.
	Predicted use of PMA from March to July
Adults	Escapement into Mossom Creek 1803 in 1998, and 658 in 1999
	First adult in Mossom Creek October 5 (1998) and October 6 (1999)
	Water temperature at 5 m depth in PMA was not at a level considered to impede migration
	No adverse effect of BGS discharge on migration expected
Growth and Condition	Growth rate of fish in dilutions of BGS CW over 16-28 days, during spring and summer was related to concentration of CW and temperature/dissolved gas supersaturation
	Growth rate declined above 18.7 °C and reflected seasonal heating of the PMA water
	Reduction in dissolved gases in 50% CW to air saturated levels did not influence growth rate
	Condition of fish deteriorated during experiments and some fish in all treatments, including controls, displayed signs of "ill health" possibly due to disease

Table 1 (cont'd). Significant findings of studies related to the operation of Burrard Generating Station and its impact on Port Moody Arm.

Study	Findings
Growth and Condition (cont'd)	In shallow surface water drawn from 1 m depth in PMA fish mortality was up to 30%. The cause was speculated to be related to seasonal algal blooms
	Mortality in 65% (22.6 °C) and 75% (23.4 °C) CW was 13.3% and 100% in approximately 5 days
	Effect of BGS CW predicted to increase growth rate in early spring if food not limiting
	Effect of BGS CW on populations of juvenile chum salmon in PMA minimal due to their natural emigration prior to acutely adverse temperatures and TGP occurring in surface waters
Behavior: Laboratory Experiements	50% mortality occurred in approximately 160 minutes
	Attraction of 50% to seawater at 12.2 °C
	Preference by >83.5% for seawater temperature between 13.7 °C and 17.9 °C
	Avoidance of 50% to 20.2 °C, and 90% to 22.9 °C
	Briefly and rapidly fed in waters at 25 °C, and 30 °C
	Predicted fish use of BGS CW effluent plume in spring to occupy waters in which temperature is in preferred and metabolically optimum range
	Juvenile chum salmon expected to feed in thermal plume from the BGS
Field Experiments	Natural surface water orientation of juvenile chum salmon was not affected in a statistically significant manner with proximity to the BGS CW discharge
	Potentially stressful levels of temperature and dissolved gases (levels of TGP in surface waters of PMA typically <115%) occurred in surface waters in summer and particularly towards the head of PMA closest to mudflats
	Juveniles continued to use surface waters in which temperatures (typically between 18 °C and 21 °C) exceeded those determined in the laboratory to evoke avoidance responses
	Temperatures within the range preferred by juvenile chum salmon were present within 6 m of the water surface in PMA during summer

Table 1 (cont'd). Significant findings of studies related to the operation of Burrard Generating Station and its impact on Port Moody Arm.

Study	Findings
Susceptibility to Predation:	Exposure of juvenile chum salmon to warm (20.7 °C) seawater and 115% TGP for 48 hours did not result in an increased vulnerability to predation
Laboratory Experiments	Exposure of juvenile chum salmon to warm (20.7 °C) seawater and either 120% or 130% TGP for 24 and 12 hours respectively increased susceptibility to predation (<23%) by local piscivorous marine fish
	Signs of GBT (a consequence of exposure to elevated levels of TGP) most evident in those groups of fish that were most heavily preyed upon
	It is speculated that increased predation was related to performance deficits due to the effect of warm seawater and TGP on the sensory capabilities of juvenile chum salmon and on their impaired swim performance due to reduced ability to recover from fatigue caused by predator attacks
Impact of Burrard Generating Station Cooling Water	Juvenile chum salmon typically occur close to the water surface (<2 m) for days to weeks during their early sea life
	During the early spring the relatively warmer waters of PMA could encourage a more rapid growth of juvenile chum salmon relative to those outside the arm in cooler waters and thereby favor survival
	Surface waters of PMA become stressful and potentially harmful to juvenile salmon during summer primarily through increases in temperature and dissolved gas supersaturation
	The natural movement of juvenile chum salmon to the Pacific Ocean to complete the oceanic phase of their life cycle typically occurs in late spring and early summer before acutely stressful conditions occur in surface waters of PMA
	Removal of >80% of the heat entering the arm through tidal action and currents moderates increases in temperature and thereby facilitates the maintenance of water quality
	Despite the potential of the surface waters of PMA to be acutely stressful and debilitating to juvenile chum salmon with prolonged residency in the summer, the natural tidal flushing and atmospheric heat loss coupled with the seasonal movement of juveniles out of the arm minimizes the risk of harm to the populations that use these waters
	The current discharge of BGS CW is not expected to adversely impact the populations of chum salmon that utilize PMA

BGS - Burrard Generating Station; PMA - Port Moody Arm; CW - Cooling Water; TGP - Total Gas Pressure; GBT - Gas Bubble Trauma

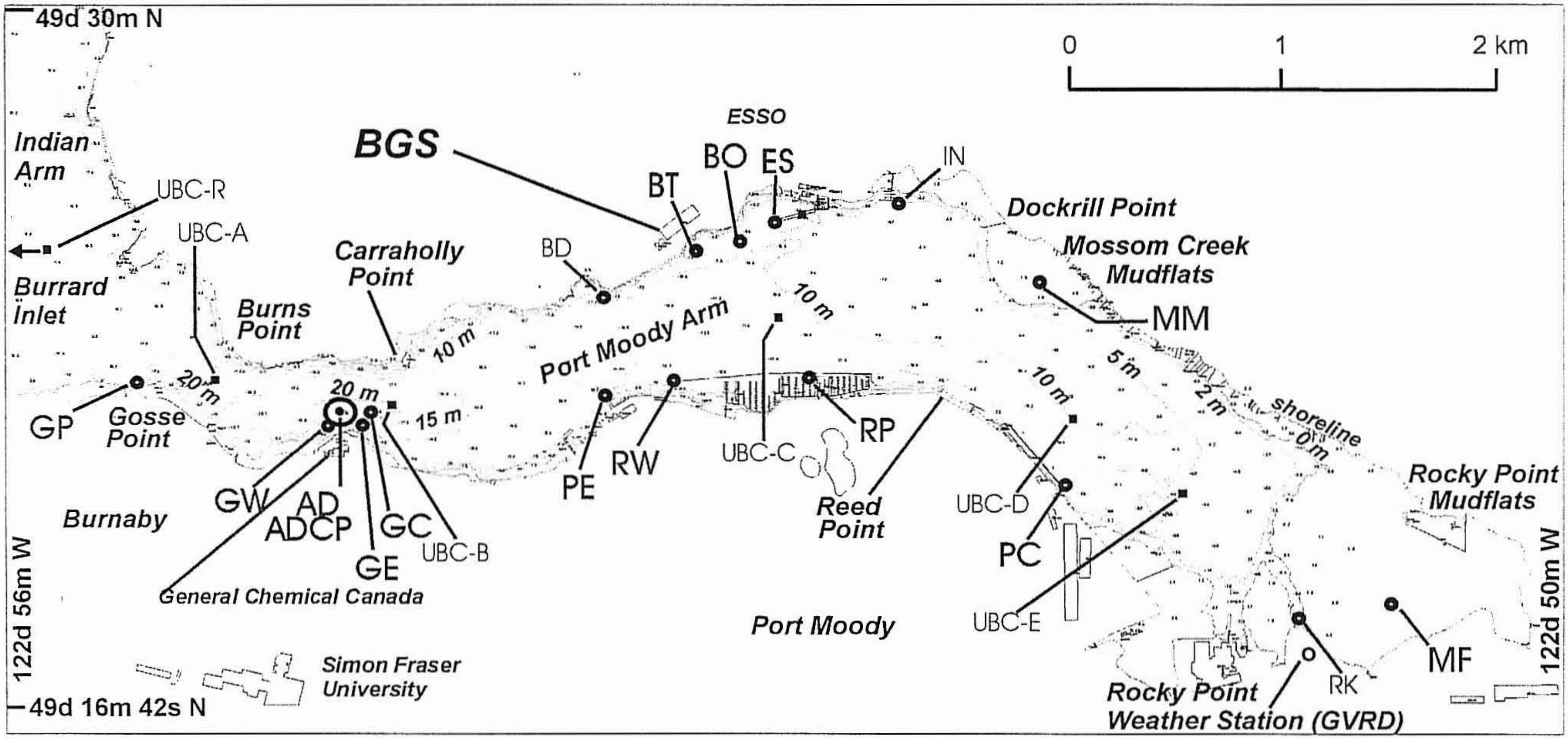


Figure 1. Location of temperature monitoring stations in Port Moody Arm (after Taylor et al. 2001).

BD, BT, ...: operated by BC Hydro (various times after August 1995);
UBC-x, ...: profiling stations operated by UBC (Summer 1998-);
ADCP: Acoustic Doppler Current Profiler station (October 1998)

Depths on map are in metres reduced to Chart Datum (3.1 m below mean water level).
Based on Canadian Hydrographic Service (1992), chart 3495.

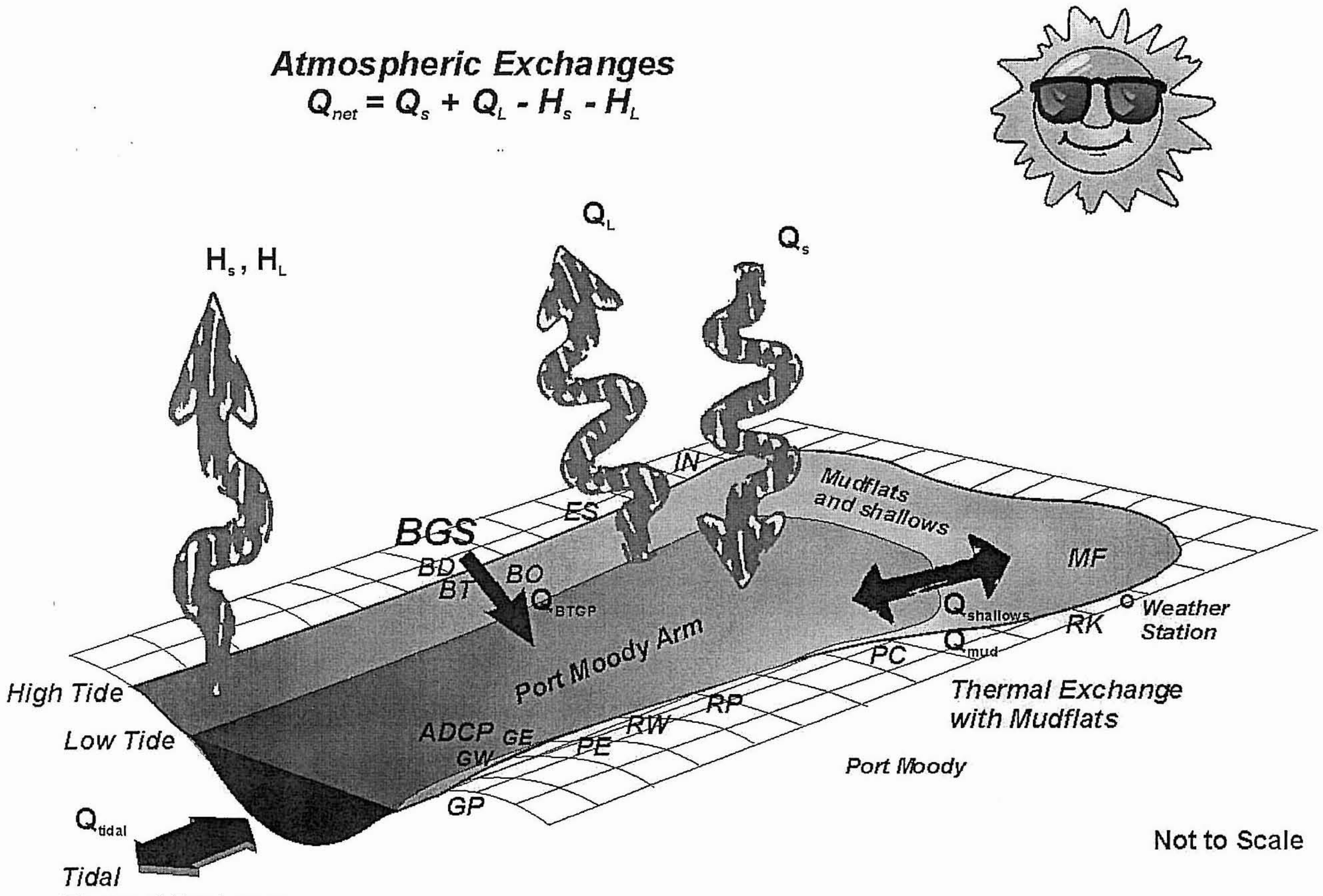


Figure 2. Illustration of the natural thermal exchanges with Port Moody Arm and the heat discharged by the Burrard Generating Station (after Taylor et al. 2001).

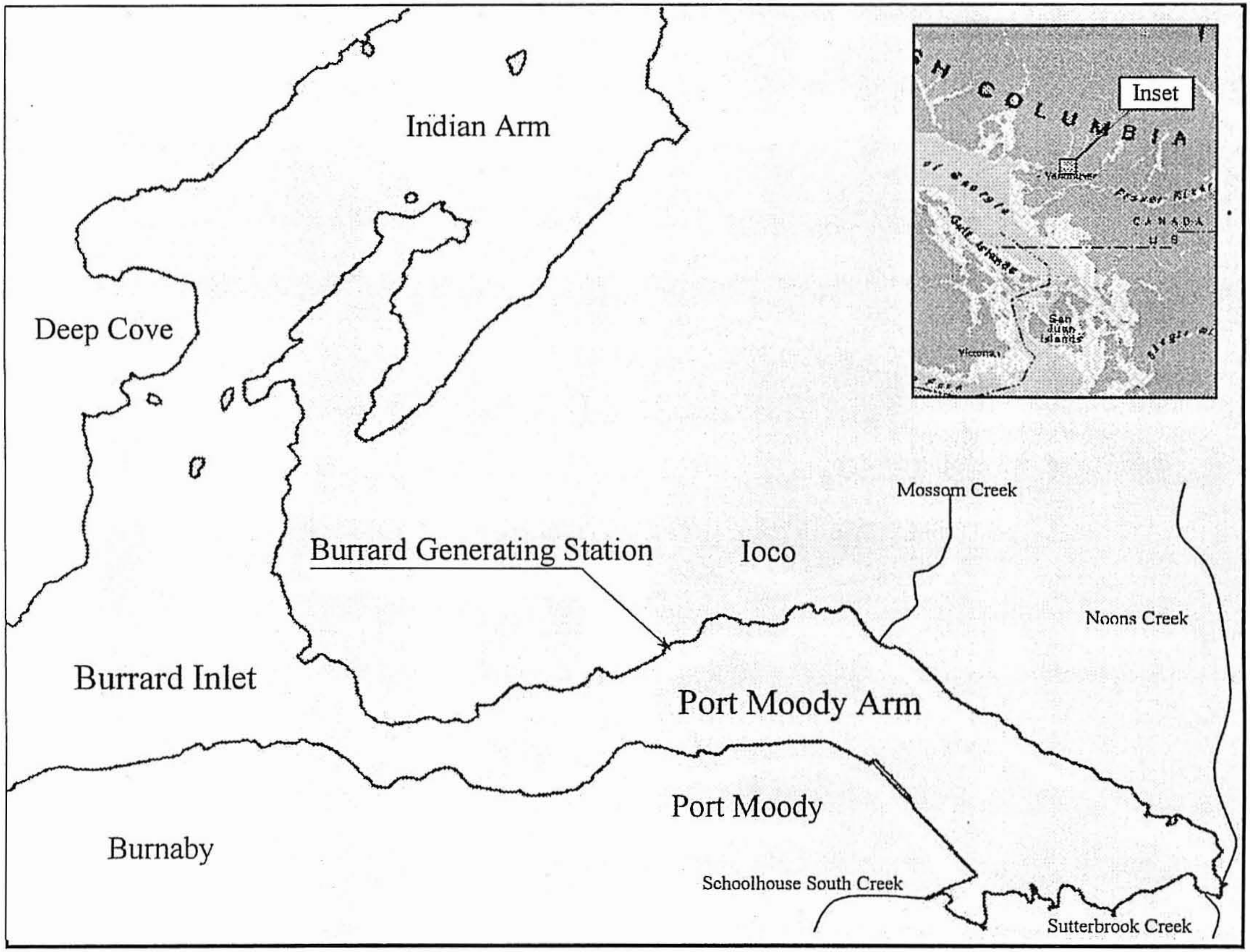
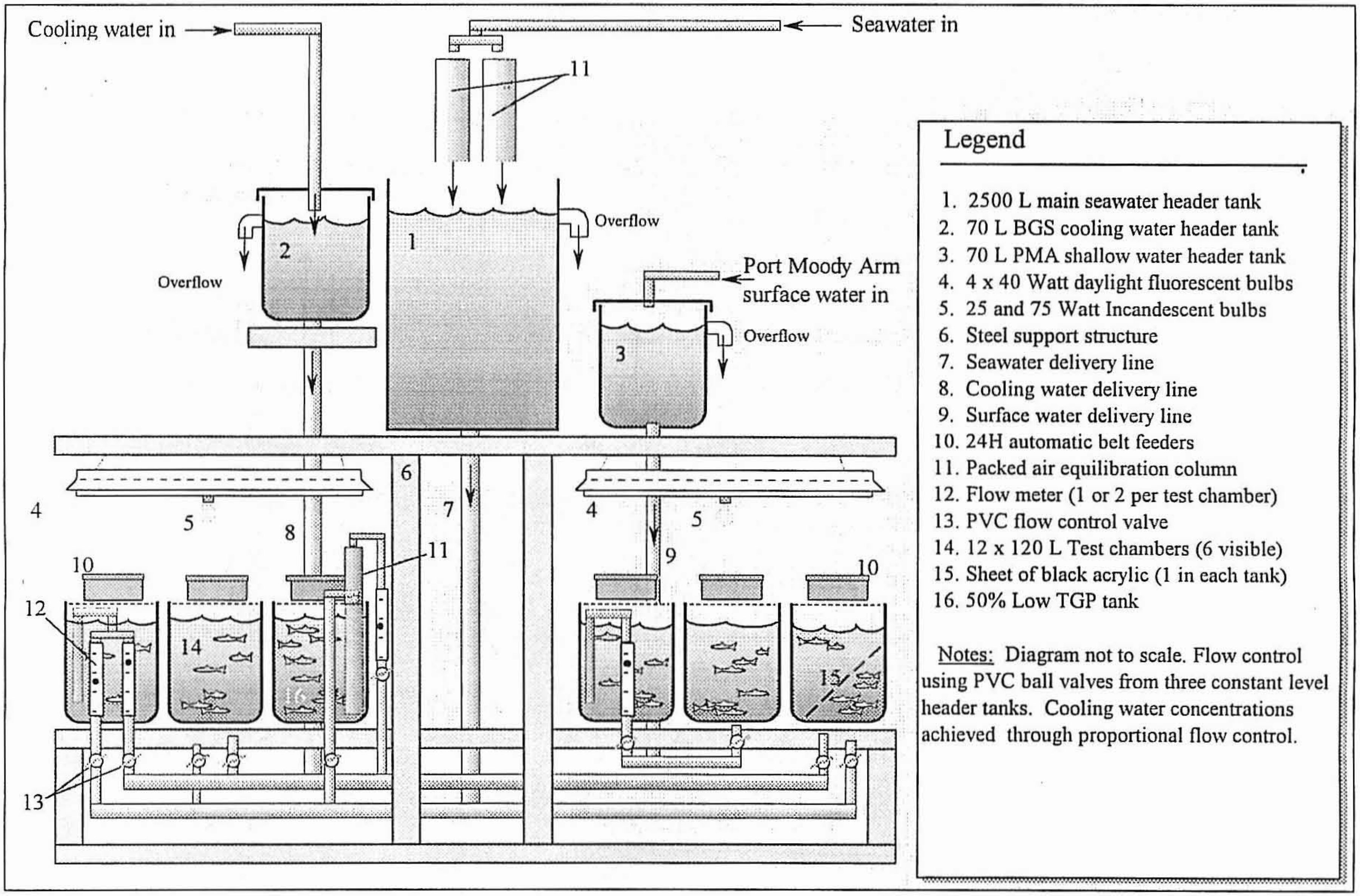


Figure 3. Location of BGS and tributaries surveyed on Port Moody Arm, British Columbia (from Greenbank et al. 2001).



Legend

1. 2500 L main seawater header tank
2. 70 L BGS cooling water header tank
3. 70 L PMA shallow water header tank
4. 4 x 40 Watt daylight fluorescent bulbs
5. 25 and 75 Watt Incandescent bulbs
6. Steel support structure
7. Seawater delivery line
8. Cooling water delivery line
9. Surface water delivery line
10. 24H automatic belt feeders
11. Packed air equilibration column
12. Flow meter (1 or 2 per test chamber)
13. PVC flow control valve
14. 12 x 120 L Test chambers (6 visible)
15. Sheet of black acrylic (1 in each tank)
16. 50% Low TGP tank

Notes: Diagram not to scale. Flow control using PVC ball valves from three constant level header tanks. Cooling water concentrations achieved through proportional flow control.

Figure 4. Main components of the apparatus used to examine the effects of dilutions of BGS CW on juvenile chum salmon (from Greenbank et al. 2001).

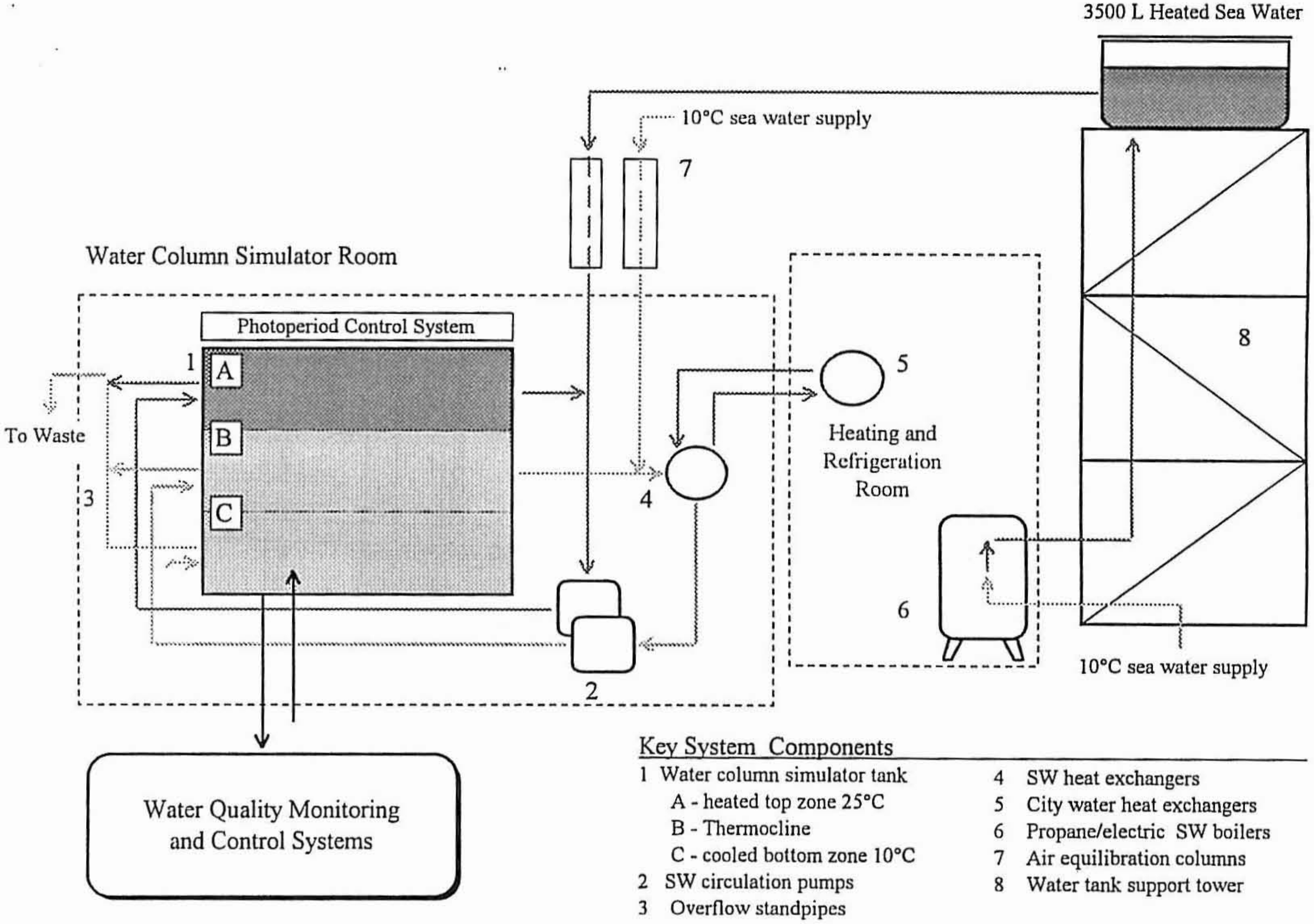


Figure 5. Main apparatus components used to examine the behavior of juvenile chum salmon to temperature change and food (from Birtwell et al. 2001a).

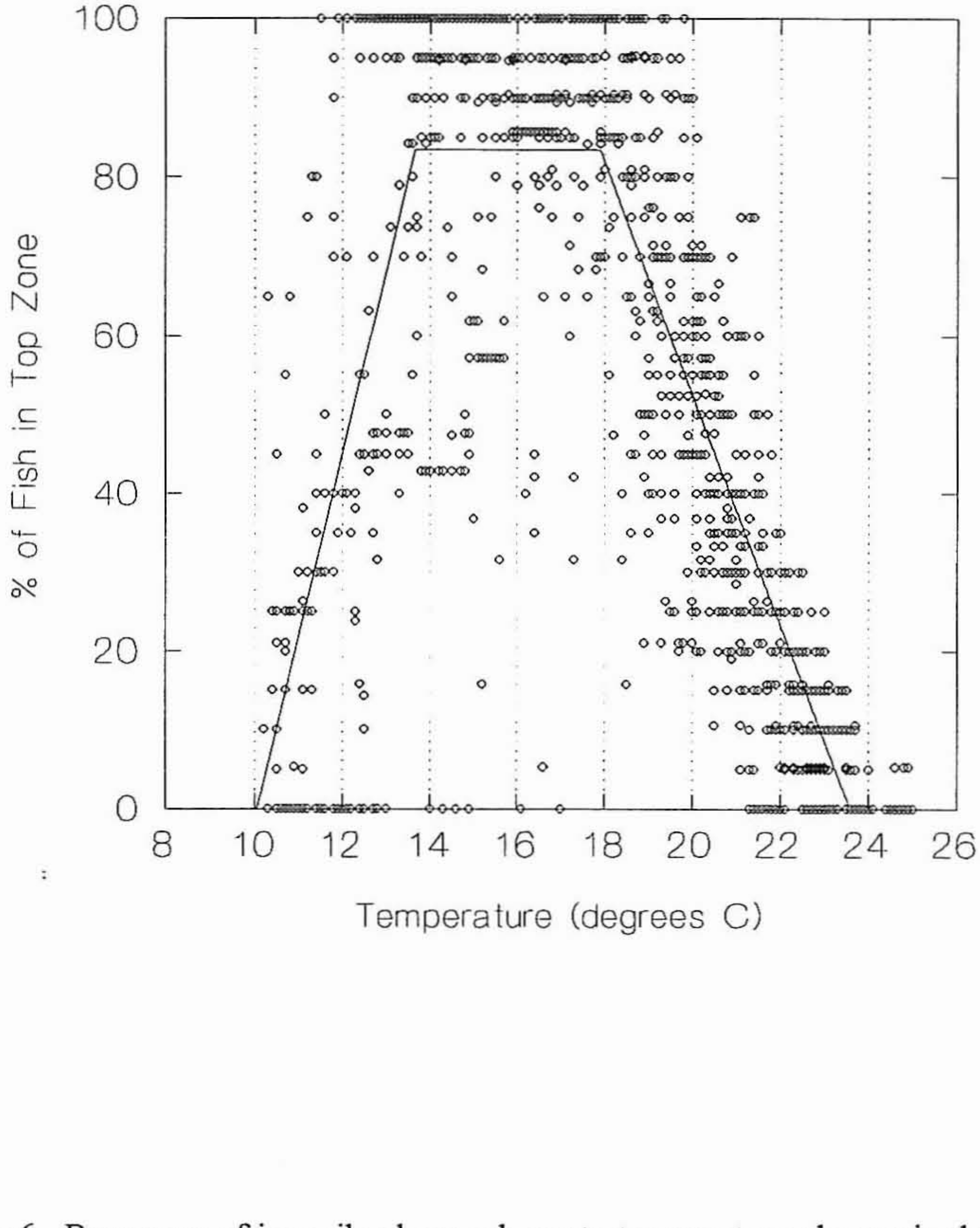


Figure 6. Response of juvenile chum salmon to temperature change in the surface waters of the WCS aquarium, estimated by piece-wise non-linear regression (from Birtwell et al. 2001a)

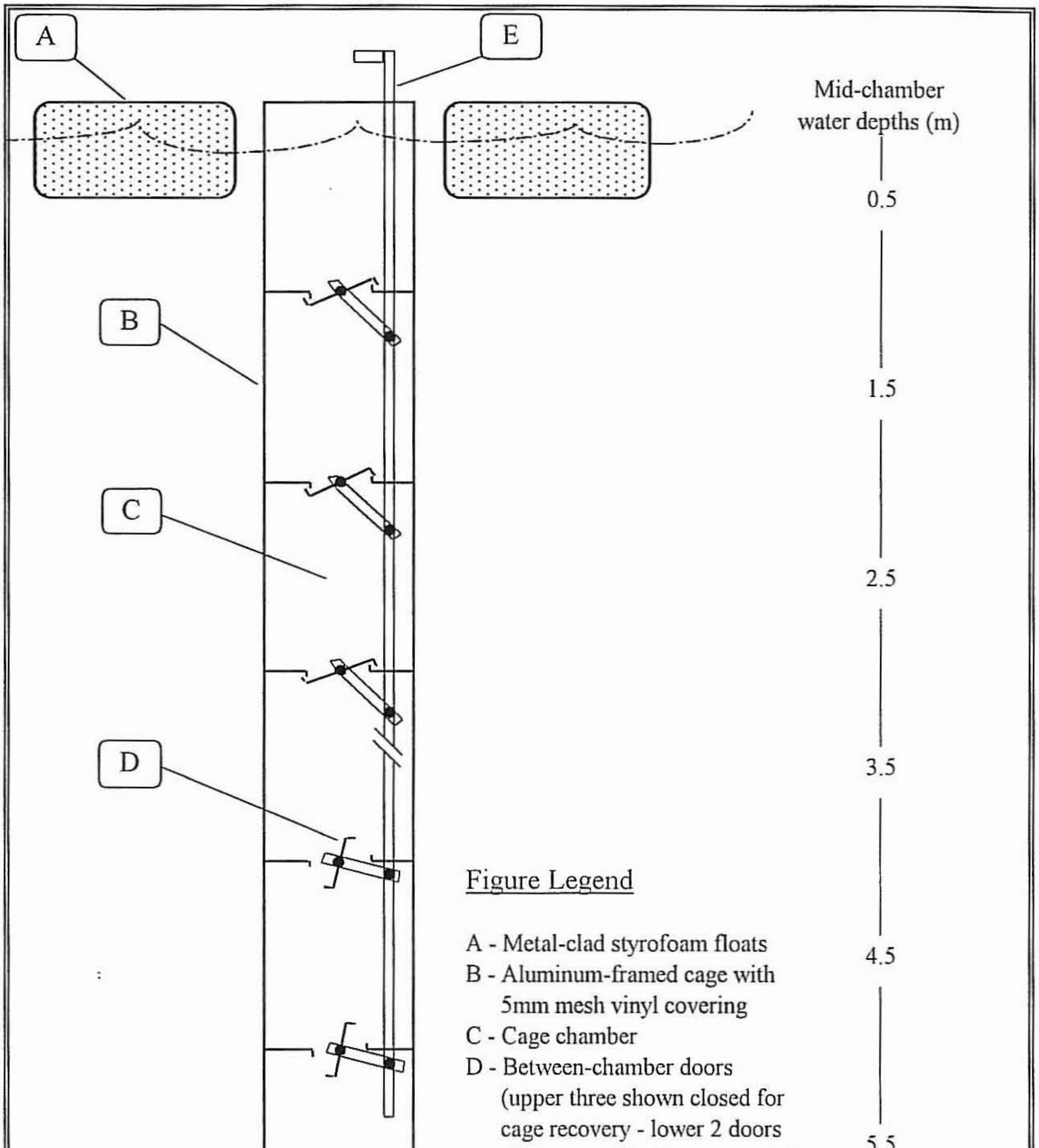


Figure Legend

A - Metal-clad styrofoam floats
B - Aluminum-framed cage with 5mm mesh vinyl covering
C - Cage chamber
D - Between-chamber doors (upper three shown closed for cage recovery - lower 2 doors shown open for free movement of fish between chambers)
E - Aluminum door-control arm

Figure 7. A diagram of the preference-avoidance apparatus used to examine the vertical distribution of juvenile chum salmon in Port Moody Arm (from Birtwell et al. 1998).

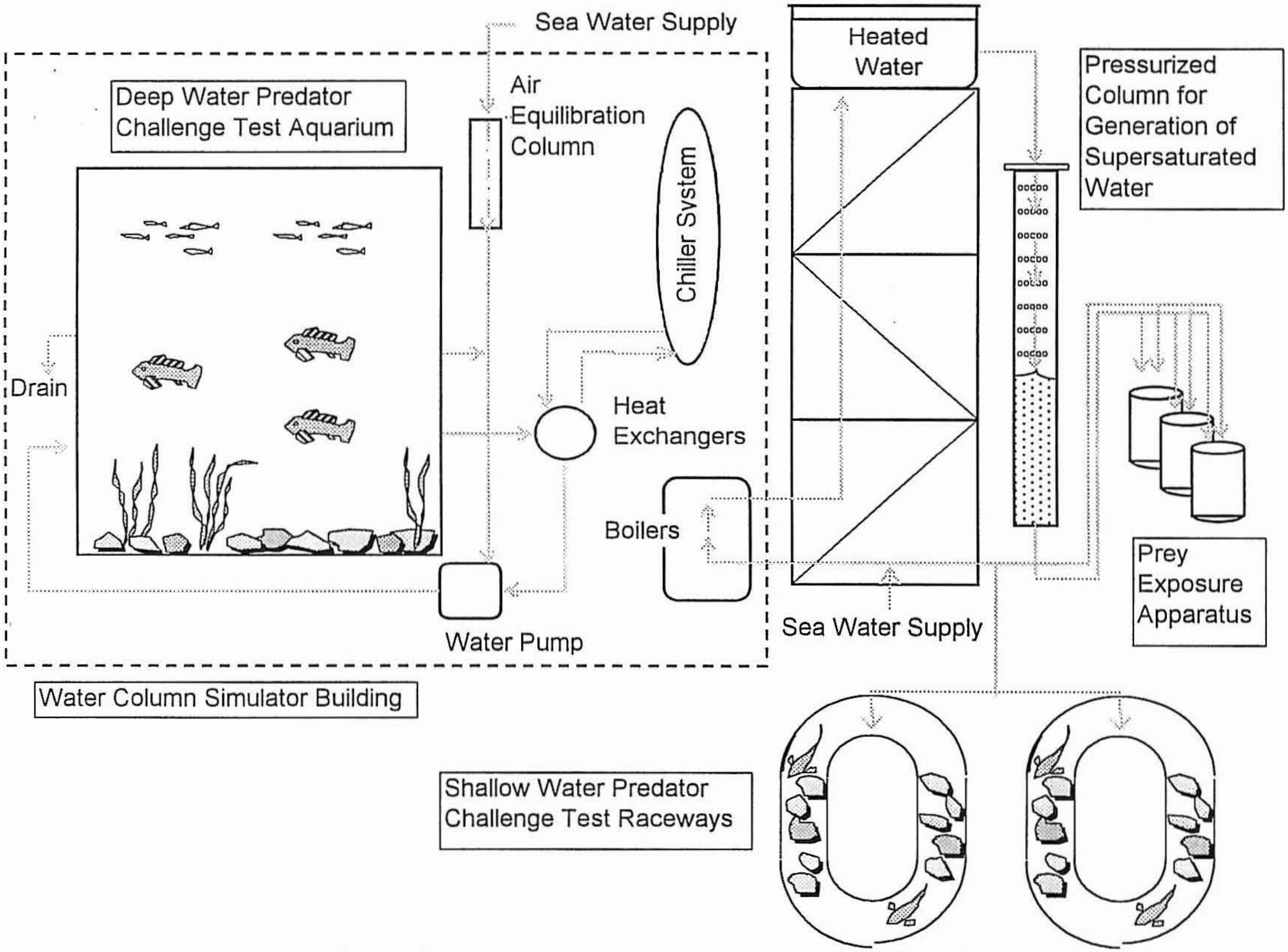


Figure 8. Schematic of experimental apparatus used to examine the susceptibility of juvenile chum salmon to predation (from Birtwell et al. 2001b).