Sublethal Responses of Coho Salmon (*Oncorhynchus kisutch*) to Suspended Sediments

James A. Servizi and Dennis W. Martens

Department of Fisheries and Oceans, Cultus Lake Salmon Research Laboratory, Cultus Lake, B.C. V0X 1H0, Canada

Servizi, J. A., and D. W. Martens. 1992. Sublethal responses of coho salmon (*Oncorhynchus kisutch*) to suspended sediments. Can. J. Fish. Aquat. Sci. 49: 1389–1395.

Underyearling coho salmon (*Oncorhynchus kisutch*) were exposed to sublethal concentrations of Fraser River suspended sediments (SS) in the laboratory. Comparisons with other rivers indicated that Fraser River sediments caused the lowest turbidity for a given SS value. Blood sugar levels (*y*) were elevated and directly proportional to SS exposure (*x*) according to $y = 5.79 + 4.23(x)$. Published blood sugar data for adult sockeye salmon (*O. nerka*) exposed to Fraser River SS were in agreement with the linear relationship for underyearling coho. Cough frequency was elevated approximately eightfold over control levels at 0.24 g SS·L^{-1}. No increase in cough frequency was observed at 0.02 g SS·L^{-1}. Avoidance was defined by movement to the surface to escape higher SS at depth. Mean avoidance (*y*) was related to SS by $y = 0.077 + 4.457(x) - 1.547(x^2) + 0.202(x^3)$. Mean avoidance was less than 5% up to the inflection point at 2.55 g SS·L^{-1} but rose to approximately 25% at 7.0 g SS·L^{-1}. Laboratory results indicated that sublethal responses could be expected at naturally occurring SS levels in the Fraser River.

Des saumons coho (*Oncorhynchus kisutch*) de moins d'un an ont été exposés en laboratoire à des concentrations sublétales de matières en suspension (MS) du fleuve Fraser. Des comparaisons portant sur d'autres cours d'eau ont montré que les matières en suspension du fleuve Fraser étaient celles donnant lieu à la plus faible turbidité à valeur égale. Les teneurs sanguines en sucre (*y*) étaient élevées et directement proportionnelles à l'exposition au MS (*x*); elles s'exprimaient par la formule $y = 5{,}79 + 4{,}23(x)$. Les données publiées sur la teneur sanguine en sucre de saumons rouges (*O. nerka*) exposés à des matières en suspension du fleuve Fraser concordaient avec la relation linéaire déterminée pour les cohos de moins d'un an. La fréquence de la toux était de huit fois supérieure à celle des témoins quand la concentration de MS atteignait 0,24 g·L^{-1}. Aucune augmentation de la toux n'a cependant été notée à la concentration de MS de 0,02 g·L^{-1}. Le comportement d'évitement a été défini comme un déplacement vers la surface effectué afin d'éviter la plus forte concentration de MS en profondeur. L'évitement moyen (*y*) a été relié à la concentration de MS par l'équation $y = 0{,}077 + 4{,}457(x) - 1{,}547(x^2) + 0{,}202(x^3)$. L'évitement moyen était inférieur à 5% jusqu'au point d'inflexion, situé à 2,55 g MS·L^{-1}, mais atteignait 25% environ à 7,0 g MS·L^{-1}. Les essais en laboratoire ont montré que les concentrations naturelles de MS du fleuve Fraser pouvaient donner lieu à des réactions sublétales.

Received October 31, 1991
Accepted January 23, 1992
(JB288)

Reçu le 31 octobre 1991
Accepté le 23 janvier 1992

The Fraser River is one of the world's major salmon (*Oncorhynchus* sp.) producers (Northcote and Larkin 1989) and it also carries a suspended sediment (SS) load which varies with season (Servizi and Gordon 1989). While much of the Fraser River sediment originates from bank erosion in the upper reaches, some tributaries also contribute. In addition, anthropogenic activities may add SS directly or indirectly through alterations to the landscape. Juvenile salmon utilize habitat throughout the Fraser system where they are exposed to a range of SS levels. Acute lethal toxicities for exposure to Fraser River SS have been reported for sockeye (*O. nerka*; Servizi and Martens 1987), chinook (*O. tshawytscha*; Servizi and Gordon 1990), pink (*O. gorbuscha*; Servizi 1990), and coho salmon (*O. kisutch*) (Servizi and Martens 1991).

The objective of this study was to measure sublethal responses of underyearling coho to Fraser River SS by using tests for blood sugar, cough frequency, and avoidance.

Materials and Methods

Test sediment and particle size distribution were described in Servizi and Martens (1987, 1991). Turbidity and SS were both measured on 115 samples and included data from an earlier study (Servizi and Martens 1991). A nephelometric turbidimeter (HF Instruments Ltd., model DRT 100) was used to measure turbidities. Suspended solids were collected and measured according to Servizi and Martens (1991).

Turbidity and SS of Fraser River sediments were related by the following equation ($p < 0.01$, $r = 0.952$, df $= 113$; Fig. 1):

$$(1) \quad T = 113(\mathrm{SS})^{0.916}$$

where T is nephelometric turbidity units (NTU) and SS is suspended sediment (grams per litre). For various rivers in Alaska, Lloyd et al. (1987) reported that

$$(2) \quad T = 0.44(\mathrm{SSmg})^{0.858}$$

$$(3) \quad T = 1.103(\mathrm{SSmg})^{0.968}$$

where SSmg is milligrams per litre and T is NTU. The expression for Fraser River sediment given in milligrams per litre becomes

$$(4) \quad T = 0.188(\mathrm{SSmg})^{0.916}.$$

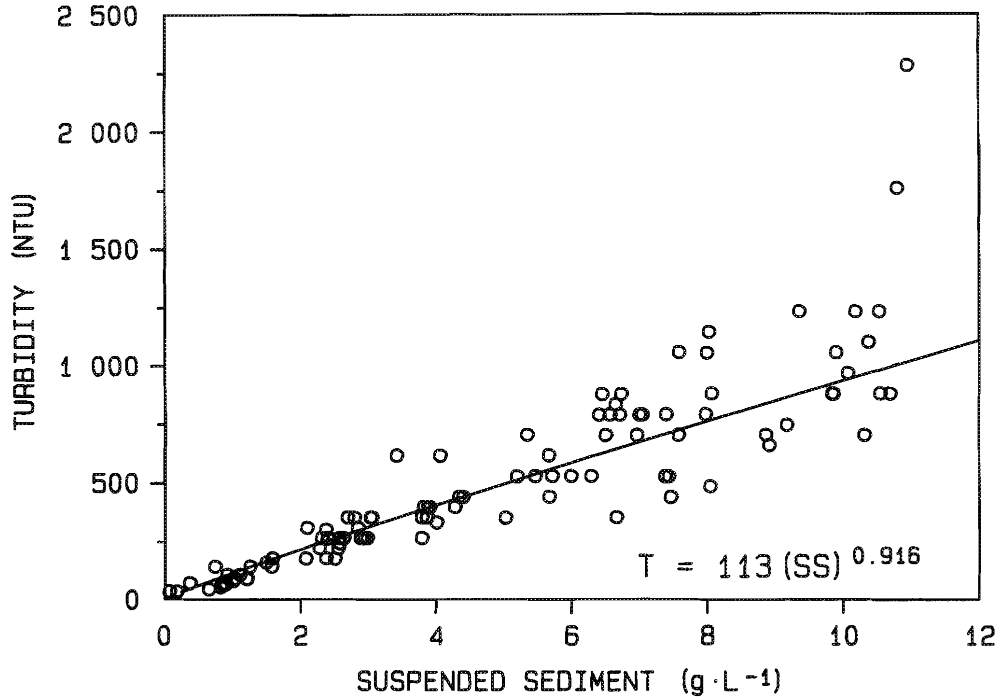

FIG. 1. Relationship between turbidity and SS for Fraser River sediments.

Sigler et al. (1984) reported

(5) $T = 5.49 + 0.162(\text{SSmg})$

for water dosed with clay. Comparison among these equations indicates that Fraser River sediments used in biological testing caused the lowest turbidity for a given SS value.

Test fish were Chilliwack River Hatchery coho reared from eggs (Servizi and Martens 1991). Illumination during rearing and testing was via incident daylight from north-, east-, and west-facing windows. Fish were reared at 6–7.5°C and were tested at the rearing temperature. Fish of similar size, as described below, were used in each test. Fish were reared on Oregon Moist Pellet (OMP) but were not fed within 24 h of testing. In all cases the experimental area was screened to prevent disturbance of fish during testing.

Serum glucose was measured in three groups of 10 coho (17.4 ± 2.2 g, 11.9 ± 0.5 cm) following 96 h of exposure to two concentrations of SS and a sediment-free control at 6°C. Fish were confined to cylindrical cages (30 × 8 cm high) suspended 8 cm below the surface in 217-L conical test vessels. Samples were drawn twice daily at the top of cages for measurements of SS. At 96 h the cages were quickly transferred one at a time to an anaesthetic bath (2-phenoxyethanol, 0.5 $g \cdot L^{-1}$). Blood was collected in micro serum separators immediately following severance of the caudal peduncle. Serum glucose was measured by the hexokinase enzymatic procedure (Anonymous 1974).

A total of 93 coho (20.1 ± 5.5 g, 12.3 ± 1.1 cm) were exposed to four SS concentrations and a control for measurements of cough frequency at 6°C. The numbers tested at each concentration are reported in Table 1. Fish were confined to individual cages (15 × 3 × 4 cm) submerged at a depth of 8 cm in 35-L test vessels (Servizi and Martens 1991) during measurements of cough frequency. Samples for SS were collected twice daily at the top of cages.

Coughs were monitored using a buccal cannula (Saunders 1961) connected via polyethylene tubing (Clay-Adams PE60 Intramedic) to one of two physiological pressure transducers (model P23BB, Statham Laboratory) and then to a recorder (model 321, Sanborn dual-channel carrier amplifier). Fish were monitored by attaching the free end of the polyethylene tubing to one of the two transducers, recording, disconnecting, and connecting the next specimen in turn. Generally, fish were handled in groups of four in the following way. Four freshly cannulated fish were placed in cages and rested for 18 h in sediment-free water, when baseline ventilation measurements were made. Two of these fish were transferred in their cages, submerged in a basin of water, to a SS concentration where they rested until ventilation measurements were made, while two fish served as controls. Control cages were lifted, also submerged in a basin of water, and replaced to simulate transfer. Ventilation rates were measured after transfer (real and simulated) according to the schedule in Table 1. For each fish, the baseline and experimental measurements were made on the same transducer and the same recorder channel. Following transfer in their cages, fish were allowed to rest for approximately 1 h before baseline or experimental ventilation was measured. On the average, ventilation was measured for approximately 11 min and was about equally divided between baseline and experimental conditions. Coughs were identified as prominent spikes among uniform pressure recordings of ventilation (Schaumburg et al. 1967). Elapsed time between coughs was used to calculate cough frequencies.

Avoidance tests used 30 fish (1.0 ± 0.1 g) in each 35-L test vessel (Servizi and Martens 1991). Avoidance was based upon the tendency of coho to swim at the surface to avoid higher SS at depth. Twenty-five SS concentrations and five controls were tested at 7°C. The same operator made all observations but only after several days of practise to assure objectivity. Observations commenced within 10 min of transferring fish to test vessels and continued for 96 h. The observer looked at the water surface and immediately counted all the fish seen. Owing to turbidity, only fish within approximately 1 cm of the surface could be seen in experimental vessels. In controls, the observer

TABLE 1. Mean cough frequencies (SE, maximum) of underyearling coho prior to and during exposure to Fraser River SS. Means followed by the same letter are not significantly different.

Group	No.	Baseline coughs·min^{-1}	SS (g·L^{-1})	Turbidity (NTU)[a]	SS exposure 1 h (coughs·min^{-1})	SS exposure 24 h (coughs·min^{-1})
A	30	0.14a (0.05, 0.81)	0.00	0	—	0.19a (0.05, 0.94)
B	19	0.17a (0.06, 1.00)	0.02	3	—	0.19a (0.06, 0.78)
C	10	0.27a (0.13, 0.80)	0.24	30	—	1.51b (0.36, 3.32)
D	18	0.09a (0.04, 0.45)	2.46	260	5.31d (0.171, 11.7)	3.32c (0.82, 11.70)
E	16	0.13a (0.05, 0.67)	6.78	666	6.70e (0.84, 13.20)	—

[a]Calculated from equation 1.

counted only fish within approximately 1 cm of the surface. Fifty observations were made of each test vessel at approximately equally spaced intervals during each 7.5 h working day. The proportion of fish at the surface was calculated for each observation and the mean calculated for the 200 observations made at each concentration. All 6000 observations were used to calculate analysis of variance and 95% confidence intervals. Samples for SS measurements were collected twice daily at 8 cm depth. Two hundred and forty SS measurements were made during avoidance testing and these were used to calculate 95% confidence intervals for SS. A suspended solids gradient was based upon 199 measurements at depths from 2 to 25 cm in identical test vessels without fish present.

Temperatures in test vessels were maintained by water bath and were measured daily. Dissolved oxygen exceeded 90% of saturation in all cases. Water from Cultus Lake was used for rearing and for dilution water (Servizi and Martens 1991).

Analysis of variance was computed by the GLM procedure (SAS Institute Inc. 1985). We compared means using Duncan's multiple range test (SAS Institute Inc. 1985) and the Tukey–Kramer test (Sokal and Rohlf 1981).

Results

Mean blood sugar of underyearling coho was elevated above control levels following 96 h of exposure to SS (Fig. 2). Mean glucose levels at 0, 0.53, and 1.36 g SS·L^{-1} were not statistically different by ANOVA (GLM) but the regression between glucose (y, millimoles per litre) and SS (x, grams per litre) was significant ($p < 0.05$, $r = 0.384$, df $= 27$):

$$(6) \quad y = 5.79 + 4.23(x).$$

Cough frequencies were measured for cannulated coho in the four exposure groups and the control before and during SS exposure (Table 1). Prior to SS exposure, mean cough frequencies ranged from 0.09 to 0.27 cough·min^{-1} but there were no statistical differences among the groups. The weighted mean was 0.15 cough·min^{-1}. Ninety percent of the fish had a baseline cough rate of 0.50·min^{-1} or less. The mean cough frequency of Group A (control) was unchanged after 24 h as was that of the 0.02 g SS·L^{-1} exposure group (B). However, after 24 h of exposure to 0.24 g SS·L^{-1} or more, mean cough frequencies were elevated above control values (ANOVA, GLM, $p < 0.05$). In addition, cough frequencies increased with SS concentration to a maximum observed value of 13.20·min^{-1} measured in 6.78 g SS·L^{-1}. One hour after exposure to 2.46 g SS·L^{-1}, mean cough frequency was significantly increased to 5.31·min^{-1} but declined to 3.32·min^{-1} at 24 h (t-test, $p < 0.05$).

When coho were kept in clear water without confinement to a particular depth, they usually schooled just above the screen (20 cm depth) and were seldom seen at the surface. However, when coho were exposed to SS in test vessels, their normal behaviour was altered within minutes and some fish swam at the surface at intervals apparently to take advantage of lower SS. Evidence of a SS gradient was confirmed by measurements. Quadratic regression of the data yielded equation 7 ($p < 0.01$, $r = 0.693$, df $= 196$):

$$(7) \quad y = 100 + 2.6(x) + 0.1(x^2)$$

where y is percent of SS at the surface and x is depth (centimetres). For example, according to equation 7, SS at 18 cm depth is estimated to be 170% of the value at the surface. Typically, fish could only be seen in the turbid waters when their backs were within approximately 1 cm of the surface. The fish avoided the jet of recirculated water in exposure vessels and selected eddies at either side of the jet. The fish which could be seen were often within 1 cm of each other. There was no evidence of acute oxygen deprivation, such as gulping, among fish observed at the surface. We interpret swimming at the surface in turbid water as demonstrating avoidance of higher SS at depth. Close observation indicated that individual fish did not stay at the surface constantly, but appeared at the surface for minutes and then submerged. As one fish submerged, another would often surface at a different point. Percent avoidance was calculated for each observation and ANOVA (GLM) of all avoidance and SS data yielded $p < 0.005$, confirming that significant differences exist between means. Linear and third-order polynomial regressions yielded r values of 0.940 and 0.966, respectively. In addition, visual comparison confirmed that the polynomial gave a better fit to the data (Fig. 3). Accordingly, we concluded that avoidance was represented by equation 8 ($p < 0.01$, $r = 0.966$, df $= 28$):

$$(8) \quad y = 0.077 + 4.457(x) - 1.547(x^2) + 0.202(x^3)$$

where y is percent avoidance and x is grams SS per litre measured at 8 cm depth. Figure 3 suggests low-level avoidance to the inflection point (defined by $d^2y/dx^2 = 0$) at 2.55 g SS·L^{-1} (NTU = 270). For SS beyond this value, the slope of the curve (dy/dx) increased steadily, passing through 1:1 at 3.45 g SS·L^{-1}, and avoidance rises to about 25% at 7.0 g SS·L^{-1}. Equation 8 predicts a 96-h EC50 for avoidance at 8.5 g SS·L^{-1} (EC50; median effective concentration causing a response for 50% of fish). The narrow 95% confidence intervals for SS in Fig. 3 indicate low temporal variability of exposure conditions. Confidence intervals for SS ranged from 0.01 to 0.50 g·L^{-1} and are typical for all the experiments reported herein and compare favourably with SS data previously reported for this apparatus and methodology (Servizi and Martens 1991).

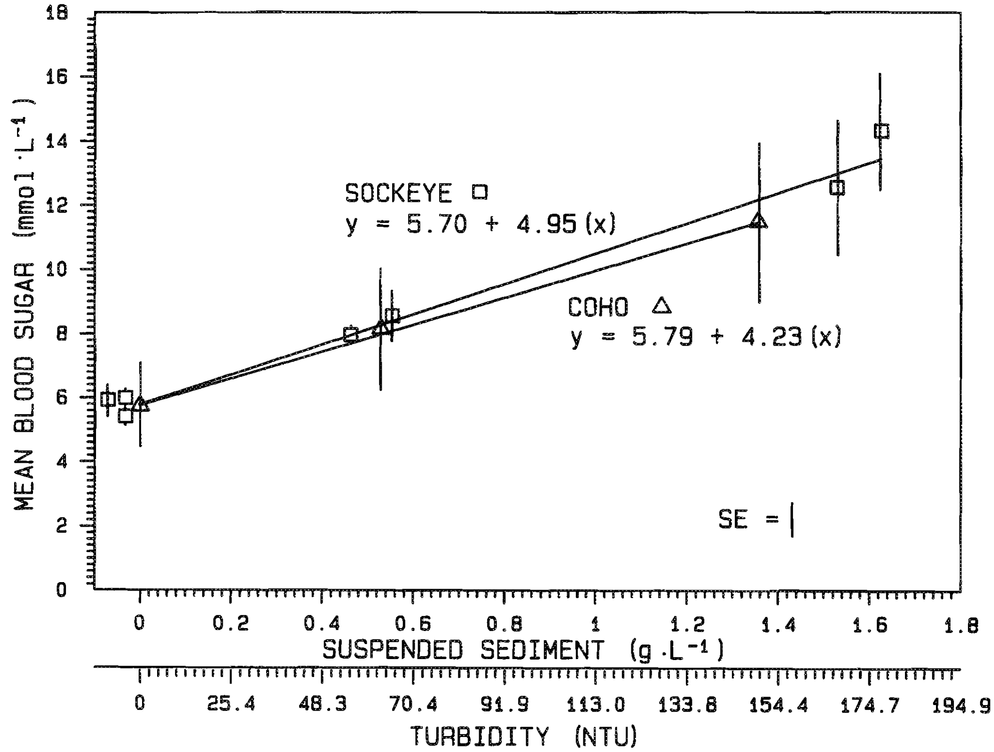

FIG. 2. Responses of blood sugar to SS exposure for underyearling coho (this study) and adult sockeye (from Servizi and Martens 1987).

Discussion

Increased blood sugar was one of the responses of underyearling coho to SS. Similar increases in blood sugar were reported for adult sockeye exposed to Fraser River SS for 9 and 15 d (Servizi and Martens 1987) at temperatures in the range 7.5–14.5°C (Fig. 2). Mean blood sugar levels for sockeye exposed to 1.53 and 1.63 g SS·L^{-1} were different from those at 0.55 and 0.46 g SS·L^{-1} and from controls (ANOVA, GLM, $p < 0.05$) and regression yielded equation 9 ($p < 0.01$, $r = 0.689$, df $= 59$):

(9) $y = 5.70 + 4.95(x)$.

Equation 9 differs only slightly from equation 6 (coho blood sugar) and for most purposes they could be considered equal. Mean glucose levels were not statistically different for coho exposed to SS but the regression was significant ($p < 0.05$). Sokal and Rohlf (1981) noted that the regression test is more powerful than ANOVA and a significant regression is sometimes found when means change only slightly, as is the case for coho mean bood sugar. Elevation of blood sugar is cited as a secondary stress indicator (Wedemeyer et al. 1984). McLeay et al. (1987) reported increases in blood sugar and blood sugar variance among Arctic grayling (*Thymallus arcticus*) exposed to SS for 24 and 96 h but no mathematical relationship was obtained, since increases were highly variable. These authors concluded that the 24-h EC50 was less than 0.05 g·L^{-1} for organic sediment (placer mining "overburden"). According to equation 6, 0.05 g Fraser River SS·L^{-1} would elicit only a 3.6% increase in mean plasma glucose after 96 h. This change would not be detectable from control values. An increase in blood sugar variance among groups of salmonids was also considered a stress response (Wedemeyer and McLeay 1981). It is noteworthy that variance, in the form of standard error, increased with SS for coho and sockeye (Fig. 2). For underyearling coho, variance was noticeably increased at the 0.52 g SS·L^{-1} exposure level. This value is a 17% increase over the baseline and is 2.4% of the 96-h LC50 for coho in Fraser River SS at 6°C (Servizi and Martens 1991). Redding et al. (1987) used cortisol levels to detect primary stress responses among yearling coho exposed to suspended topsoil in the 0.3–0.6 and 2.0–4.0 g·L^{-1} ranges. Although cortisol levels were initially elevated fivefold, they decreased within 96 h, indicating physiological compensation.

The foregoing comparisons indicate that blood sugar consistently responds to the stress induced by sublethal SS exposure. For the study reported herein the relationship between blood sugar and Fraser River SS is linear up to 1.4 g·L^{-1}. However, beyond this range, blood sugar may rise faster than linear until toxic actions impair this response. This speculation is based on our analysis of published data (McLeay et al. 1983) which indicates that blood sugar (y, millimoles per litre) and the toxic substance pentachlorophenol (x, micrograms per litre) are related exponentially ($y = 3.73e^{0.0164x}$) over a 50-fold range for Arctic grayling.

Response to a stressor is dependent on environmental factors such as duration of exposure and temperature. Blood sugar values responded equally for underyearling coho and adult sockeye exposed to Fraser River SS but exposure times and temperatures differed for the two species. Furthermore, adult sockeye were undergoing physiological changes associated with maturation. Given these differences, the nearly identical equations for underyearling coho and adult sockeye responses may be coincidence. Further testing would be required to resolve the question of coincidence.

The maximum cough frequency observed for coho exposed to SS was 13.20·min^{-1} (Table 1). This maximum is slightly less than the 15–20 cough·min^{-1} maximum estimated for rainbow trout (*O. mykiss*), no matter what the extent of stimulus

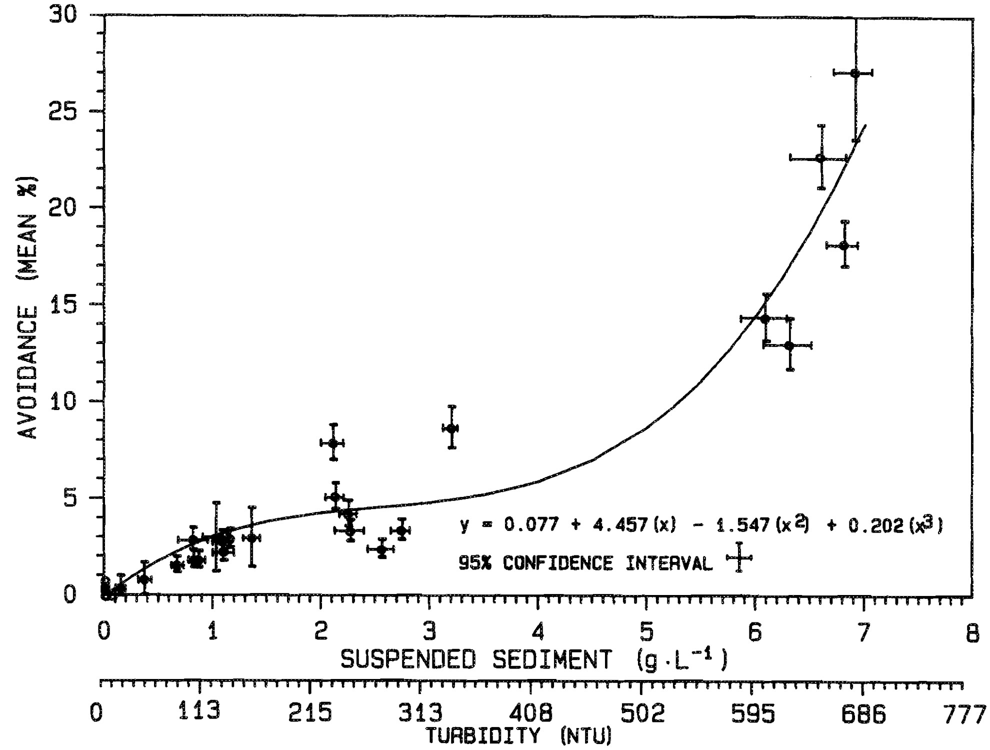

FIG. 3. Avoidance of SS by underyearling coho calculated from the percentage of the population observed at the surface during 96 h.

(Bass and Heath 1977). Mean cough frequency was less at 24 h than at 1 h during exposure to 2.46 g SS·L^{-1}. This result is consistent with reports of an overnight decrease following an initial rise in cough frequency during exposure to a stressor. Specifically, cough frequencies decreased for sockeye (Davis 1973) and rainbow trout (Walden et al. 1970) after overnight exposure to bleached kraft mill effluents.

Increased cough frequency has been reported for fish exposed to various chemicals (Heath 1987) and effluents (Walden et al. 1970; Davis 1973) but there are limited observations for exposure to SS. Cough reflex is the mechanism by which fish expel foreign matter from gills (Fry 1957). Bams (1969) reported that sockeye alevins used the cough reflex to clear buccal cavities of suspended particles. MacLeod and Smith (1966) made an early attempt to quantify cough reflex when they made visual counts to calculate cough frequencies for fathead minnows (*Pimephales promelas*) exposed to pulp fibers. They reported that coughing was elevated within minutes following exposure to 25 ppm pulp fibers. In our tests, 0.02 g SS·L^{-1} (20 ppm) did not cause an increase in cough frequency at 24 h (Table 1). The difference in response may be related to the nature of the suspended particles and species differences. Visual counts of "gill flaring" indicated that cough frequency was significantly elevated when underyearling coho were exposed to SS (gravel pit fines, largely 0.02–0.06 mm) for 1–48 h at 30 NTU (Berg and Northcote 1985). More than 90% of particles in Fraser River SS were 0.05 mm and smaller, based upon geometric mean diameter (Servizi and Martens 1987, 1991). A turbidity of 30 NTU is equivalent to about 0.24 g Fraser River SS·L^{-1} (equation 1), which caused a significant increase in cough frequency at 24 h. These results are supportive of a threshold between 3 and 30 NTU for elevation of cough frequency.

Although swimming at the surface has been reported during exposure to SS for Arctic grayling (McLeay et al. 1987) and underyearling sockeye (Servizi and Martens 1987), our results are the first attempts to quantify this behaviour. The tendency of coho in control vessels was to remain submerged several centimetres below the surface. Less than 1% of the fish were observed at the surface in clean water. At SS exceeding 0.3 g·L^{-1} (37 NTU), coho exhibited first signs of avoidance behaviour in the vertical plane. This point is 1.3% of the 96-h LC50 (Servizi and Martens 1991) and is close to 0.24 g SS·L^{-1}, at which significant elevation of cough frequency occurred. Thus, avoidance may be a response to the stress associated with increased cough frequency. Mean avoidance was less than 5% up to the inflection point at 2.55 g·L^{-1} (NTU = 269). Continuous increase in the slope of the avoidance curve as SS increase beyond the inflection point (Fig. 3) may be an indication that the need for relief from SS stress increasingly overcomes the preference to stay submerged. Each time coho swim near the surface in a natural setting there is risk of avian predation (Peterson 1982). If the behaviour observed in the laboratory occurred in nature, avian predation may cause a significant loss.

Reports of salmonid avoidance behaviour in the horizontal plane can be compared with the three sublethal responses observed herein. Sigler et al. (1984) reported emigration of juvenile coho and steelhead (*O. mykiss*) from rearing channels containing 11–49 NTU. These authors suggested that this emigration was evidence that turbidity was stressful to the fish. We estimated that the threshold for avoidance in the vertical plane was 37 NTU. Our results for elevation of blood sugars, cough rate, and avoidance response support the contention by Sigler et al. (1984) that turbidity was stressful in the range 11–49 NTU. Bisson and Bilby (1982) reported a 13% decrease ($p < 0.05$) in numbers of naive coho in the turbid side of a horizontal trough at 70 NTU. On the other hand, in the vertical plane, mean avoidance was only 2% at 70 NTU (Fig. 3). This comparison suggests that coho may be more inclined to move laterally than to the surface to avoid stresses imposed by SS. Avoidance in the vertical plane may be attenuated by the preference shown for depth in clear-water controls.

Newcombe and MacDonald (1991) have proposed a ranked response, derived from a stress index, as a means of predicting sublethal and lethal effects on salmonids caused by SS episodes of known intensity. The model is based upon episodes ranging from 1.2 min to 361 d in duration and SS concentrations from 0.7 to 207 000 $mg \cdot L^{-1}$. The ranking is calculated from an equation based upon the natural logarithm of the product of exposure concentration (milligrams per litre) and duration (hours). The model imposes no constraints on exposure duration or SS concentration. The stress index model predicts that increased coughing would occur at 0.202 and 0.008 $mg\ SS \cdot L^{-1}$ after 1 and 24 h, respectively. Our results indicate that coughing rate was not affected at 20 $mg \cdot L^{-1}$ and was elevated at 240 $mg \cdot L^{-1}$ (Table 1). The stress index model predicts avoidance in the range 4.7–18.2 $mg\ SS \cdot L^{-1}$ at 10 min and at 0.032 $mg \cdot L^{-1}$ after 24 h, but we found that mean avoidance in the vertical plane did not exceed threshold values until SS exceeded 300 $mg \cdot L^{-1}$ (Fig. 3). The model also predicts physiological stress (elevated blood sugar) at 27.7 $mg\ SS \cdot L^{-1}$ after 96 h. An SS value this low has no detectable effect on blood sugar according to our equations 6 and 7. For the cases cited above, the stress index model predicts SS values one to four orders of magnitude below the values at which sublethal effects were observed. The stress index model also predicts 40–60% mortality during 96 h at 6900 $mg \cdot L^{-1}$. This concentration was the highest used in avoidance tests (Fig. 3). Even if the test fish stayed at the surface (1 cm) where mean SS would have been 5600 $mg \cdot L^{-1}$ (equation 8) the stress index model predicts 20–40% mortality. However, no mortalities occurred during avoidance tests at 6900 $mg \cdot L^{-1}$ or any other concentration. Furthermore, the mortality ranges predicted above by the stress index model compare poorly with the 96-h LC50 for coho (23 000 $mg \cdot L^{-1}$) exposed to Fraser River SS at 7°C (Servizi and Martens 1991). We believe that the use of open-ended exposure time and SS concentration without regard to threshold effect levels or other factors such as temperature and fish size causes the model to be an unreliable predictor of sublethal and lethal effects.

Underyearling coho responded to SS by increasing blood sugar and cough frequency and by avoiding SS at depth. Could sublethal responses be expected in the Fraser River, one of the world's major producers of salmon? Coho bound for the sea use the Fraser River in spring when typical SS are in the 0.3–0.6 $g \cdot L^{-1}$ range and occasionally may exceed 1.0 $g \cdot L^{-1}$ according to records for 1967–87 (Servizi and Gordon 1989; Anonymous 1985, 1988, 1989). There is no reason to believe that the SS regime varied historically from these values. Coho smolts spend 1–25 d traversing the Fraser River from the various natal tributaries (C. Levings, Department of Fisheries and Oceans, West Vancouver, B.C. V7V 1N6, pers comm.). The highest SS value is about 5% of the 96-h LC50 for underyearling coho exposed to Fraser River SS. Thus, outright mortality would not occur. According to Fig. 2 and 3 and Table 1, SS levels typical of the Fraser River could be expected to elicit sublethal responses. In fact, blood sugar and cough frequency are probably elevated over baseline levels at the SS concentrations which occur in the Fraser River. However, coho could avoid high SS by travelling in the upper layers of the river where SS are least (Anonymous 1985, 1988, 1989). Outmigrant juvenile Pacific salmon showed strong preferences for surface waters in the lower Fraser River where approximately 63% occurred in the upper 25% of the water column (0–1.4 m) (Anonymous 1981). While average and maximum SS in the Fraser River may evoke sublethal responses among juvenile salmon, the historical evidence for major salmon runs suggests that the response levels probably did not exceed homeostatic capacity.

In this paper we have reported a relationship between SS and turbidity (equation 1) and compared it with regressions reported in the literature for rivers in Alaska (equations 2 and 3) and a natural water dosed with clay (equation 5). Fraser River SS produced the least turbidity for a given level of SS. Since turbidity is based on light scattering, and very fine particles would scatter more light than coarser particles of the same total weight, it is probable that Fraser River SS particles are larger than those referenced. Particle size has biological implications, since acute lethal tolerance of SS by juvenile sockeye decreased as SS particle size increased (Servizi and Martens 1987). Turbidity (light scattering) probably has no direct effect on lethal tolerance, but a sublethal response such as avoidance may be influenced by both turbidity and particle size. In order to facilitate comparison of research results, we recommend that investigators characterize the sediments which they study as to their particle size distribution and the relationship between SS and turbidity.

Acknowledgements

We are pleased to acknowledge the diligence and dedication shown by Sherrie Waal who made all avoidance measurements. We also thank Steve MacLellan for processing our statistical analyses.

References

ANONYMOUS. 1974. *In vitro* diagnostic products for human use, proposed. Establishment of product class standard for detection and measurement of glucose. U.S. Dep. Health, Educ. Welfare Food Drug Admin. Fed. Reg. 39, No. 126: 24136–24147.

1981. Environmental impact of proposed improvements to the Fraser River shipping channel. Report prepared for Public Works Canada by Beak Consultants. Chap. V. 615 p. (Available from Public Works Canada, Vancouver, B.C. V6E 3W5, Canada)

1985. Sediment data. 1983. Canadian rivers. Water Survey of Canada, Ottawa, Ont. 233 p.

1988. Sediment data. 1986. British Columbia. Water Survey of Canada, Ottawa, Ont. 37 p.

1989. Sediment data. 1987. British Columbia. Water Survey of Canada, Ottawa, Ont. 23 p.

BAMS, R. A. 1969. Adaptations in sockeye salmon associated with incubation in stream gravels, p. 71–88. *In* T. G. Northcote [ed.] Symposium on salmon and trout in streams. University of British Columbia, Vancouver, B.C.

BASS, M. L., AND A. G. HEATH. 1977. Cardiovascular and respiratory changes in rainbow trout (*Salmo gairdneri*) exposed intermittently to chlorine. Water Res. 11: 497–502.

BERG, L., AND T. G. NORTHCOTE. 1985. Changes in territorial, gill-flaring and feeding behaviour in juvenile coho salmon (*Oncorhynchus kisutch*) following short-term pulses of suspended sediment. Can. J. Fish. Aquat. Sci. 42: 1410–1417.

BISSON, P. A., AND R. E. BILBY. 1982. Avoidance of suspended sediment by juvenile coho salmon. N. Am. J. Fish. Manage. 4: 371–374.

DAVIS, J. C. 1973. Sublethal effects of bleached kraft pulp mill effluent on respiration and circulation in sockeye salmon (*Oncorhynchus nerka*). J. Fish. Res. Board Can. 30: 369–377.

FRY, F. E. J. 1957. The aquatic respiration of fish, p. 1–63. *In* M. E. Brown [ed.] The physiology of fishes. Vol. 1. Academic Press, Inc., New York, NY.

HEATH, A. G. 1987. Water pollution and fish physiology. CRC Press Inc., Boca Raton, FL. 245 p.

LLOYD, D. S., J. P. KOENINGS, AND J. D. LAPERRIERE. 1987. Effects of turbidity in fresh waters of Alaska. N. Am. J. Fish. Manage. 7: 18–33.

MacLeod, J. C., and L. L. Smith, Jr. 1966. Effect of pulpwood fibre on oxygen consumption and swimming endurance of the fathead minnow, *Pimephales promelas*. Trans. Am. Fish. Soc. 95: 71–84.

McLeay, D. J., I. K. Birtwell, G. F. Hartman, and G. L. Ennis. 1987. Responses of Arctic grayling (*Thymallus arcticus*) to acute and prolonged exposure to Yukon placer mining sediment. Can. J. Fish. Aquat. Sci. 44: 658–673.

McLeay, D. J., A. J. Knox, J. G. Malik, I. K. Birtwell, G. F. Hartman, and G. L. Ennis. 1983. Effects of Arctic grayling (*Thymallus arcticus*) of short-term exposure to Yukon placer mining sediments: laboratory and field studies. Can. Tech. Rep. Fish. Aquat. Sci. 1171: xvii + 134 p.

Newcombe, C. P., and D. D. MacDonald. 1991. Effects of suspended sediments on aquatic ecosystems. N. Am. J. Fish. Manage. 11: 72–82.

Northcote, T. G., and P. A. Larkin. 1989. The Fraser River: a major salmonine production system. *In* D. P. Dodge [ed.] Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Sci. 106.

Peterson, N. P. 1982. Population characteristics of juvenile coho salmon (*Oncorhynchus kisutch*) overwintering in riverine ponds. Can. J. Fish. Aquat. Sci. 39: 1303–1307.

Redding, J. M., C. B. Schreck, and F. H. Everett. 1987. Physiological effects on coho salmon and steelhead of exposure to suspended solids. Trans. Am. Fish. Soc. 116: 737–744.

SAS Institute Inc. 1985. SAS/STAT guide for personal computers, vers. 6 ed. SAS Institute Inc., Cary, NC. 378 p.

Saunders, R. L. 1961. The irrigation of the gills of fishes. I. Studies of the mechanism of branchial irrigation. Can. J. Zool. 39: 637–653.

1962. The irrigation of the gills of fishes. II. Efficiency of oxygen uptake in relation to respiratory flow activity and concentrations of oxygen and carbon dioxide. Can. J. Zool. 40: 817–862.

Schaumburg, F. D., T. E. Howard, and C. C. Walden. 1967. A method to evaluate the effects of water pollutants on fish respiration. Water Res. 1: 731–737.

Servizi, J. A. 1990. Sublethal effects of dredged sediments on juvenile salmon, p. 57–63. *In* C. Simenstad [ed.] Effects of dredging on anadromous Pacific coast fishes: workshop proceedings, Seattle, September 8–9, 1988. Washington Sea Grant Publication WSG-W090-1. University of Washington, Seattle, WA.

Servizi, J. A., and R. W. Gordon. 1989. Turbidity and selected water quality characteristics of the Fraser River at Hell's Gate, 1965–85. Can. Data Rep. Fish. Aquat. Sci. 755: 131 p.

1990. Acute lethal toxicity of ammonia and suspended sediment mixtures to chinook salmon (*Oncorhynchus tshawytscha*). Bull. Environ. Contam. Toxicol. 44: 650–656.

Servizi, J. A., and D. W. Martens. 1987. Some effects of suspended Fraser River sediments on sockeye salmon (*Oncorhynchus nerka*), p. 254–264. *In* H. D. Smith, L. Margolis, and C. C. Wood [ed.] Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96.

1991. Effect of temperature, season, and fish size on acute lethality of suspended sediments to coho salmon (*Oncorhynchus kisutch*). Can. J. Fish. Aquat. Sci. 48: 493–497.

Sigler, J. W., T. C. Bjornn, and F. H. Everest. 1984. Effects of chronic turbidity on density and growth of steelheads and coho salmon. Trans. Am. Fish. Soc. 113: 142–150.

Sokal, R. R., and F. J. Rohlf. 1981. Biometry. The principles and practice of statistics in biological research. 2nd ed. W. H. Freeman and Company, New York, NY. 859 p.

Walden, C. C., T. E. Howard, and G. C. Froud. 1970. A quantitative assay of the minimum concentrations of kraft mill effluents which affect fish respiration. Water Res. 4: 61–68.

Wedemeyer, G. A., and D. J. McLeay. 1981. Methods for determining the tolerance of fishes to environmental stressors, p. 247–268. *In* A. D. Pickering [ed.] Stress and fish. Academic Press, Toronto, Ont.

Wedemeyer, G. A., D. J. McLeay, and C. P. Goodyear. 1984. Assessing the tolerance of fish and fish populations to environmental stress: the problems and methods of monitoring, p. 163–196. *In* V. W. Cairns et al. [ed.] Contaminant effects on fisheries. John Wiley & Sons, Toronto, Ont.