Postimpoundment Winter Sedimentation and Survival of Lake Whitefish (*Coregonus clupeaformis*) Eggs in Southern Indian Lake, Manitoba[1]

R. J. P. Fudge and R. A. Bodaly

Department of Fisheries and Oceans, Freshwater Institute, 501 University Crescent, Winnipeg, Man. R3T 2N6

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Flooding of Southern Indian Lake for hydroelectric power development has resulted in extensive wave erosion of glacio-lacustrine clay shore material and greatly increased suspended sediment levels. Winter sedimentation on spawning grounds of lake whitefish (*Coregonus clupeaformis*) ranged from 0.03 to 0.14 g dry wt sediment·cm^{-2}. This deposited a layer 1–4 mm in depth. The sediment, low in organic content, was categorized as silty clay. The effect of this winter sedimentation on survival of whitefish eggs was tested at four sites over a range of winter sedimentation rates. Three of the sites were whitefish spawning areas. Egg survival was significantly higher for eggs incubated in cages designed to minimize exposure to sedimentation compared with survival in cages allowing full exposure to sedimentation. Winter sedimentation rates and whitefish egg survival were negatively correlated for cages designed to minimize exposure to sedimentation, while egg survival in the exposed cages was uniformly low.

Une conséquence de l'inondation du lac Sud des Indiens en vue de développements hydro-électriques a été une forte érosion, sous l'action des vagues, du matériel argileux glacio-lacustre du rivage et une forte élévation des niveaux de sédiments en suspension. La sédimentation hivernale sur les frayères de grands corégones (*Coregonus clupeaformis*) a varié entre 0,03 et 0,14 g de poids sec de sédiment·cm^{-2}. Il en est résulté la déposition d'une couche de 1–4 mm d'épaisseur. Ce sédiment, faible en teneur organique, a été classé comme argile vaseuse. Nous avons étudié l'effet de cette sédimentation hivernale sur la survie des œufs de grand corégone à quatre sites, dans une gamme de taux de sédimentation hivernale. Trois de ces sites étaient des frayères de cette espèce. La survie des œufs a été nettement plus élevée parmi des œufs incubés dans des cages conçus de façon à minimiser l'exposition à la sédimentation, comparativement à la survie dans des cages où les œufs étaient complètement exposés à la sédimentation. Il y eut corrélation négative entre les taux de sédimentation hivernale et la survie des œufs de corégone dans des cages où la sédimentation était moindre, tandis que celle des œufs dans les cages exposées a été extrêmement faible.

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The purpose of this study was to determine the amount of sedimentation on postimpoundment spawning beds of lake whitefish (*Coregonus clupeaformis*) in Southern Indian Lake over the period between spawning and hatching and, second, to determine whether this sedimentation affected survival of lake whitefish eggs.

The detrimental effects of depositions of fine sediment on the egg survival of stream-spawning salmonids are well documented (Shaw and Maga 1943; Gangmark and Bakkala 1960; Cooper 1965; Shelton and Pollock 1966; Peters 1967). In general, moving water is necessary for the supply of oxygen to and for the removal of metabolic wastes from developing eggs. Siltation, which restricts water flow through gravel interstices and around eggs, can inhibit normal metabolic function and result in increased egg mortality (Cooper 1965). Much less is known about the effects of siltation on the eggs of lake-spawning salmonids. Work on lake whitefish and vendace (*Coregonus albula*) has indicated that egg survival is low when eggs are deposited over soft mud bottoms (Zawisza and Backiel 1970; Ash 1975; Mikkola et al. 1976; Lahti et al. 1979). Ash (1975) separated the effects of sedimentation and substrate type and concluded that siltation acting alone contributed to high mortality of incubated whitefish eggs. In contrast, Zawisza and Backiel (1970) attempted to test the effect of sedimentation but found no difference in survival of eggs using roofed and nonroofed cages and concluded that siltation was not a significant cause of egg mortality.

Study Area

Southern Indian Lake (SIL) is located on the Churchill River in north-central Manitoba (57°N, 99°W) (Fig. 1). Although located within the Precambrian Shield, surficial deposits of glacio-lacustrine origin cover bedrock over much of the drainage basin. The lake level was raised 3 m in 1976 for diversion of the Churchill River for hydroelectric power production. SIL has a surface area of 2391 km^2 compared with 1977 km^2 before impoundment (McCullough 1981). The length of flooded shoreline is 3788 km (Cleugh et al. 1974), of which 86% is composed of unconsolidated material, particularly

[1]This paper is one of a series on the effects of the Southern Indian Lake impoundment and Churchill River diversion.

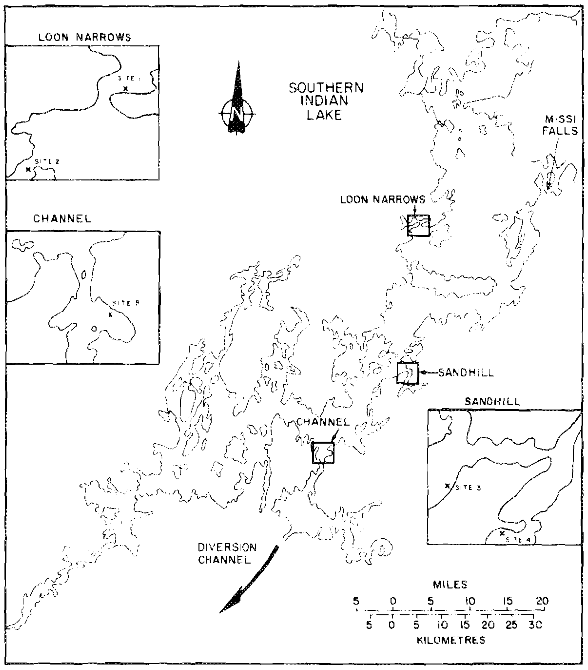

FIG. 1. Southern Indian Lake showing experimental site locations.

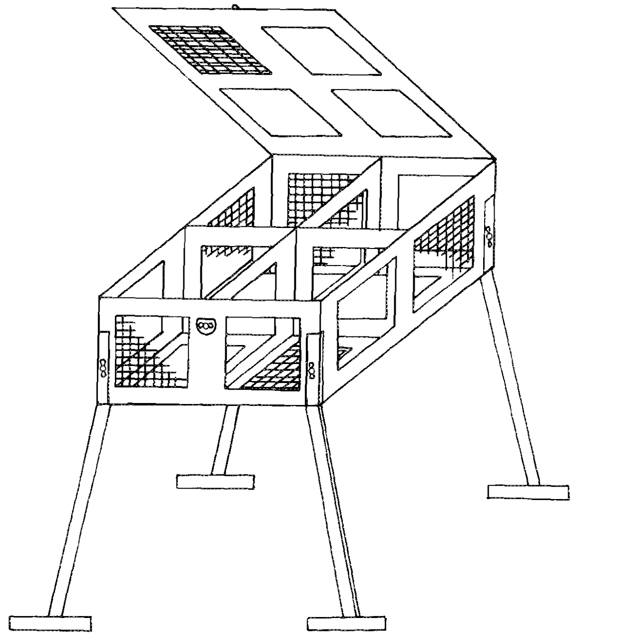

FIG. 2. Egg incubation cage showing screened bottom (protected) design.

varved silty clay, sensitive to permafrost melting and wave erosion. Newbury and McCullough (1984) observed shoreline erosion rates of fine-grained materials as high as $20\,m^3 \cdot m^{-1} \cdot yr^{-1}$. An average of 3.97×10^6 t of sediment was added to the open lake areas each year during the postimpoundment period, 1976–78 (Newbury and McCullough 1984). Filterable (nominal pore size 1 μm) suspended solids concentrations have increased from $\sim 2\,g \cdot m^{-3}$ prior to impoundment to $5–10\,g \cdot m^{-3}$ after impoundment in the lake basin adjacent to Loon Narrows (Fig. 1) (Hecky et al. 1979).

Materials and Methods

Postimpoundment spawning locations of lake whitefish were determined by gillnetting (R. A. Bodaly, unpubl. data). These areas averaged 5 m in depth and the substrates were composed predominantly of rock cobble and boulder. Known spawning sites tended to be in areas exposed to wave action. In 1978–79 and 1979–80, sediment traps were placed at two known spawning areas (sites 2 and 5) and in 1980–81, sediment traps and egg cages were placed at four sites (sites 1, 2, 3, and 4) chosen to represent a range of sedimentation conditions (sites 1, 2, and 3 are spawning locations) (Fig. 1).

Winter sedimentation was determined by placing sediment traps on the lake bottom for the approximate period of lake whitefish egg incubation (October–May). Traps were constructed to hold four 250-mL glass jars (with round mouths 4.8 cm in diameter) upright about 25 cm above the lake bottom. After air-drying in the jar the total weight of settled sediment was divided by the mouth area of the jar to give a measure of sedimentation. Analysis of particle size and organic content of sediment was determined according to McKeague (1978).

The effect of siltation on whitefish egg survival was determined by incubating fertilized eggs at the four lake locations. At each site, eggs were held in cages of two designs; the first allowed sediment to collect on eggs (exposed cage), while the second minimized sediment buildup (protected cage). The cages were constructed of Plexiglas (6.35 mm thick) with aluminum legs (Fig. 2). Both cage designs had nitex screen (1.6-mm bar) attached with silicone seal over precut holes on the top, sides, and internal partitions of the four separate compartments per cage. They differed in that the bottom of the protected cage was screened, allowing sediment to pass through, whereas the exposed design had a solid bottom causing sediment to accumulate.

Fish in spawning condition were captured by gill net in early October 1980 at Loon Narrows and Sandhill (Fig. 1). Eggs were stripped into a clean, dry tub and fertilized in a 3:1 (male to female) ratio followng the dry method (Wood and Dunn 1948). Fertilized eggs were put in cages and held in the lake until the cages were placed at test sites at depths of 4–6 m. On October 11, 1980, two protected and two exposed cages, containing eggs from fish captured near Loon Narrows, were placed at each of sites 1 and 2 by scuba divers. Similarly, on October 18, 1980, one protected and one exposed cage were placed at each of sites 3 and 4, containing eggs from fish captured near Sandhill Bay. The initial number of eggs placed in each of the four compartments of each cage was determined by actual count or estimated from 10 counts of 15-mL volumes of eggs as 492 ± 14 ($\bar{x} \pm 95\%$ C.I.).

The cages were recovered through the ice on March 20, 1981, by scuba diving. The eggs were cleaned and preserved in 10% Formalin (4% formaldehyde) solution the same day. Status of the eggs was evaluated within 1 mo. Eggs were classified as alive (eyed or in some cases hatched, probably due to mechanical agitation) or dead (eggs opaque or degenerated).

Significant loss of eggs through decomposition of dead eggs was evident for both cage designs, but loss was higher for the protected design (range 51–71%) than for the exposed design (23–48%). In both designs, large numbers of decomposed eggs lay in clumps; no attempt was made to count them, as individual eggs could not be discerned. Larger numbers of dead yet nondecomposed eggs were found, buried in sediment, in the exposed cage. Shaw and Maga (1943) had similar findings; they

TABLE 1. Mean dry weight of sediment accumulated in sediment traps and particle size analysis. Sediment weight presented as mean of three replicates, after air-drying and correction for area of trap opening.

Year	Site	No. of days on bottom	Mean dry weight sediment ($g \cdot cm^{-2}$)	% organic matter	% sand	% silt	% clay	Textural designation
1978–79	5	183	0.088	3.4	2	47	51	Silty clay
	5	183	0.088	3.1	1	46	53	Silty clay
1979–80	2	163	0.127	4.0	1	40	59	Silty clay
	2	163	0.138	4.2	0	40	60	Clay
	5	161	0.083	3.3	1	39	60	Clay
	5	161	0.088	3.3	1	41	58	Silty clay
1980–81	1	162	0.055	5.0	—	—	—	—
	2	162	0.033	2.9	—	—	—	—
	3	155	0.077	4.1	—	—	—	—
	4	155	0.017	3.9	—	—	—	—

TABLE 2. Number of eggs placed at the start of the experiment, number of eggs found alive and dead at the end of the experiment, and percent survival for each compartment with 500 eggs in protected and exposed cages at sites 1, 2, 3, and 4, Southern Indian Lake, 1980–81.

	Loon Narrows (egg cross)						Sandhill (egg cross)			
	Site 1		Site 2				Site 3		Site 4	
No. of eggs	Protected cage	Exposed cage	Protected cage	Protected cage	Exposed cage	Exposed cage	Protected cage	Exposed cage	Protected cage	Exposed cage
Initial	492	492	492	492	492	492	492	492	492	492
Live	19	2	59	44	0	0	2	0	44	2
Dead	264	285	202	201	328	383	129	400	148	187
% survival	3.86	0.41	11.99	8.94	0	0	0.41	0	8.94	0.41
Initial	492	492	492	492	492	492	492	492	492	492
Live	16	0	34	52	0	0	5	0	14	3
Dead	203	173	80	124	352	373	125	375	53	225
% survival	3.25	0	6.91	10.57	0	0	1.02	0	2.85	0.61
Initial	492	492	492	492	492	492	492	492	492	492
Live	15	0	85	52	0	0	4	0	27	0
Dead	235	287	149	147	345	389	181	330	76	191
% survival	3.05	0	17.28	10.57	0	0	0.81	0	5.49	0
Initial	502	—	492	492	492	492	—	—	—	—
Live	15	—	81	56	0	0	—	—	—	—
Dead	217	—	116	139	457	413	—	—	—	—
% survival	2.99	—	16.46	11.38	0	0	—	—	—	—
Mean % survival	3.29	0.14	13.61	10.37	0	0	0.75	0	5.76	0.34

noted an apparent resistance to decomposition of dead eggs covered by a protective layer of silt.

Results

Winter sedimentation at known lake whitefish spawning areas ranged from 0.033 to 0.138 $g \cdot cm^{-2}$ (Table 1). Sediment accumulation at site 4, a nonspawning area, was 0.017 $g \cdot cm^{-2}$. These amounts of sediment represented accumulations approximately 1–4 mm in thickness. Sedimentation at site 5 was similar during 1978–79 and 1979–80, while sedimentation at site 2 was approximately four times greater in 1979–80 than in 1980–81. In 1980–81, a lake drawdown in excess of 1 m occurred, resulting in exposure of more stable bedrock shorelines and an overall reduction in shoreline erosion. The organic content of sediment tested never exceeded 5% (Table 1). Sediment was predominantly clay (51–60%) and silt (39–47%). Observations by divers of the study areas during recovery of cages from under the ice indicated that a layer of sediment several millimetres thick coated the outside of the traps and cages as well as the rocky areas of the substrate.

Whitefish egg survival was significantly greater in cages that protected eggs from sedimentation as compared with survival in cages that exposed eggs to sediment (Table 2). Although overall egg survival was low, never exceeding 18% in protected cages, one-way analysis of variance of data for all sites indicated that survival of protected eggs was significantly higher than for exposed eggs (arcsin transformed data: $F_{1,33} = 74.5$, $P <$

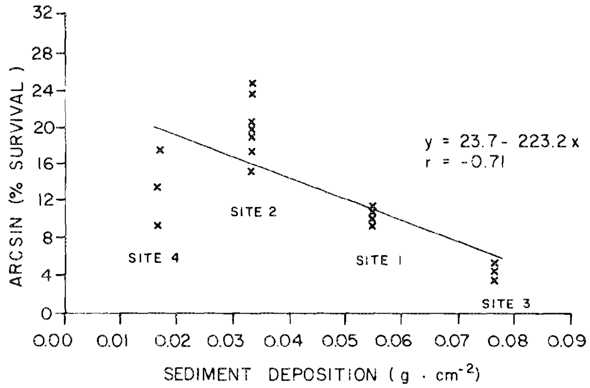

FIG. 3. Arcsin percent survival of lake whitefish eggs in protected cages versus mean dry weight of accumulated sediment as measured by sediment traps, 1980–81.

0.001). Analysis of variance for individual sites where nonzero survival was observed (sites 1 and 4) also indicated that egg survival was significantly higher in protected cages (arcsin transformed data, site 1: $F_{1,4} = 54.5$, $P < 0.005$; site 4: $F_{1,5} = 17.7$, $P < 0.025$).

Survival of eggs from the protected cage design was affected by the amount of sedimentation over the four different sites. There was a significant negative correlation between the amount of sediment and egg survival ($r = -0.71$, $P < 0.005$) (Fig. 3). Survival in exposed cages was very low with only three compartments having nonzero survival.

Although the protected cage design allowed sediment to pass through the central screened area of the cage bottom, some silt was deposited along the unscreened bottom edges. Low egg survival was associated with sediment in this region of the cage. Nearly all live eggs were found on the screened area. The eggs in exposed cages were almost completely covered with sediment. Fungal growth binding both live and dead eggs was found in both cage designs but always in association with sediment. Few eggs bound in fungus were found in the clear central areas of the protected cages.

Discussion

This study demonstrates that under postimpoundment conditions in SIL, significant sedimentation occurred on lake whitefish spawning beds over the winter egg incubation period and that observed levels of sedimentation were sufficient to cause decreased egg survival. Conclusions concerning the effect of sedimentation on egg survival are based on the incubation of eggs in actual lake conditions but in artificial chambers. The possibility that observed differences in egg survival were caused by differences in cage design and were unrelated to sedimentation was eliminated by the observation that within one cage design, egg survival was related to the amount of sedimentation at different sites within the lake. Variation in egg survival unrelated to amount of sedimentation was probably associated with variation in water temperature and chemistry at the experimental sites and to differences in the survival characteristics of the two different batches of eggs used in the experiment. Laboratory incubation of these two batches of eggs indicated that their survival characteristics differed (R. J. P. Fudge and R. A. Bodaly, unpubl. data).

Observed differences between egg survival in protected and exposed cages are not necessarily equivalent to differences between egg survival before and after SIL impoundment. For this to be true, conditions in the egg cages would need to mimic actual pre- and post-impoundment conditions on spawning beds very closely. However, the cage designs employed were not unrealistic models for actual conditions on spawning beds. Natural spawning areas of lake whitefish in SIL generally consisted of large broken rock, and the eggs that survive fish predators are probably those that fall into crevices between rocks. Thus, a certain degree of confinement and crowding of eggs in natural conditions probably is common. Egg survival in exposed cages never exceeded 10% of survival in protected cages. If the experimental conditions approximated actual egg incubation environments, then postimpoundment reductions in lake whitefish egg survival may be substantial.

Studies of the effects of stream siltation on salmon and trout eggs have led to the conclusion that increased egg mortality associated with siltation is due to reduced oxygen transport to the eggs (Cooper 1965; Shelton and Pollock 1966). Alderdice et al. (1958) calculated critical oxygen levels for salmon eggs ranging from 1 ppm in early developmental stages to 7 ppm just prior to hatching, while lethal oxygen levels ranged from 0.4 ppm in early developmental stages to 1.0–1.4 ppm just prior to hatching. Alderdice and Wickett (1958) found that egg mortality was a function of the inhibition of oxygen uptake by increased concentrations of carbon dioxide. Wolf (1957) found that when metabolic wastes were not adequately removed from the egg environment an osmotic imbalance occurred that was ultimately lethal. It is presumed that the blanket of silt deposited over eggs in SIL acted to inhibit oxygen uptake and to inhibit dispersion of carbon dioxide and other metabolic wastes. The organic content of winter sediment in SIL was quite low, and this combined with winter water temperatures approaching 0°C suggests that the oxygen demand of the sediment itself was probably low. The sediment thus acted mainly as a physical barrier to oxygen and waste transport to and from the eggs. It was noted that fungal growth was often associated with dead eggs in the presence of sediment, but occasionally live eggs were found matted with fungus. Hall (1925) found that fungal growth was rapid on dead eggs and that surrounding live eggs were engulfed, causing death in a few days. Ash (1975) indicated that increased fungal growth was promoted primarily by higher temperature and secondarily by soft mud substrates. In our experiments, fungal growth was likely associated with already dead eggs and promoted by sediment buildup. However, the extent to which fungus is involved in causing whitefish egg mortality is unknown.

The results of this study confirm those of Ash (1975) who assessed the effects of sedimentation on lake whitefish eggs and found reduced egg survival in open trays compared with that in covered trays. Water temperatures in Ash's study were elevated (4–9°) due to heated effluent. In SIL, bottom water temperatures at whitefish spawning beds ranged from 0.4 to 4.0°C over winter (Hecky et al. 1979) associated with shallow water depths and lack of thermal stratification. Yet even at these low temperatures the metabolic requirements of incubating eggs are apparently great enough to result in increased mortality from a sediment coating.

The present studies were designed to assess the effects of winter sedimentation on eggs incubating on hard substrate. It is known that salmonid egg mortality is increased by incubation on soft bottoms as compared with hard bottoms (Zawisza and Backiel 1970; Ash 1975; Mikkola et al. 1976; Lahti et al. 1979). Significant winter sedimentation will continue for at least a number of decades because present estimates for shoreline stabilization in the Southern Indian Lake reservoir are approximately 50 yr (Newbury and McCullough 1984). Because continued sedimentation on whitefish spawning beds may eventually transform the rocky substrate into soft bottoms, egg mortality may increase as the reservoir ages.

The effect of increased postimpoundment egg mortality on recruitment of lake whitefish into the adult population is difficult to predict from present results. Very high mortality from egg to adult is characteristic of fish species with high fecundity such as the lake whitefish. It is possible that lake whitefish populations could compensate for increased mortality at the egg stage with increased fecundity or decreased mortality in later stages and thereby maintain adult abundance. However, from the evidence available to us, we would conclude that a substantial decrease in the lake whitefish population of Southern Indian Lake is likely because of anticipated low egg survival and diminished recruitment to the adult population.

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