The Effects of Log Salvage Operations on Aquatic Ecosystems; predicting the change in oxygen regimes.

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The Effects of Log Salvage Operations on Aquatic Ecosystems; Predicting the Change in Oxygen Regimes

By

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ABSTRACT

Smokorowski, K.E., K.J. Withers, and J.R.M. Kelso. 1999. The effects of log salvage operations on aquatic ecosystems; predicting the change in oxygen regimes. Can. Tech. Rep. Fish. Aquat. Sci. No. 2297: vi + 31 p.

Removing logs from lakes and rivers will cause a loss of habitat diversity for fish and invertebrates, change the morphology of stream beds, and may affect the aquatic organisms that depend upon logs as cover or as a substrate for food production. The major concern with removal of logs is the effects on water quality and sediment composition. Direct effects from log removal on fish spawning and health can be minimized using mitigation methods e.g. silt screens, limiting the time of year to avoid disrupting spawning, regulating proximity to outflows, etc.

Oxygen depletion is a concern in slow flowing or sedentary water where logs will be salvaged. A steady state oxygen model (Clark et al.1999) is presented which can be used to predict end-of-summer dissolved oxygen (DO) profiles in lakes without sediment disturbance. A screening method to determine a lake's suitability for log removal was created by estimating sediment respiration rate, assuming a sediment surface area that will be affected, and assuming a pool of available oxygen. Lake size and the amount of disturbed sediment were found to be important factors controlling effects of log removal upon lakes.

RÉSUMÉ

L'enlèvement des billots des lacs et des rivières entraînera une perte de la diversité des habitats du poisson et des invertébrés, modifiera la morphologie du lit des cours d'eau, et risque d'affecter les organismes aquatiques qui se servent de ces billots comme couvert ou comme substrat pour la production de nourriture. Les effets sur la qualité de l'eau et la composition des sédiments sont le principal problème que pose l'enlèvement des billots. Les effets directs de cette opération sur la reproduction et la santé des poissons peuvent être minimisés par l'application de méthodes d'atténuation des impacts, p. ex. filtres à limon, établissement, période réservée pour éviter de perturber la fraye, réglementation de la distance aux exutoires, etc.

L'épuisement de l’oxygène est un problème dans les eaux à écoulement lent ou les plans d'eau stagnante où les billots seront récupérés. Les auteurs présentent un modèle d'oxygène à l'équilibre (Clark *et al.*, 1999) qui peut être utilisé pour prévoir les profils d'oxygène dissous à la fin de l'été dans des lacs où il n’y a pas de perturbation des sédiments. La méthode de sélection établie permet de déterminer si un lac convient à l'enlèvement des billots en estimant le taux de respiration des sédiments, à partir d’une superficie supposée de sédiments touchés et du bassin d'oxygène supposé disponible. La dimension du lac et le volume de sédiments perturbés sont considérés comme des facteurs importants qui régissent les effets sur les lacs de l'enlèvement des billots

INTRODUCTION

Logs have become submerged in lake and river systems over the last century as a result of logging activities. The Fish Habitat Management Division (FHM) of DFO has recently received requests for approval of log salvage operations in inland lakes and rivers. While there is no question that the sunken logs have economic value, few of the requests for salvage operations have been approved. Preventing or restricting log salvage operations is a precautionary option in the face of uncertainty in the management and science community regarding the environmental impacts of log salvage on lakes and rivers. Since the guiding principle for fish habitat managers is to achieve no net loss of the productive capacity of fish habitats, information is needed on the effects of log removal from these systems to ensure compliance with the mandate. Concerns related to log removal from aquatic systems include: the loss of physical habitat structure and diversity, the impact of disturbed sediments on spawning, survival and development of fishes, changes to the oxygen regime, phosphorus concentrations, thermal budgets, and contaminant concentrations.

We searched the literature in an attempt to summarize the impacts of log removal on lentic and lotic aquatic systems that will help fish habitat managers assess consequences and apply mitigation measures to minimize the impact on our fisheries. Keywords used in the search included log salvage, log removal, woody debris, debris removal, sedimentation, sediment disturbance, fetch, suspended sediment, sediment respiration, oxygen, oxygen regimes and models, phosphorus, DOC, temperature and models thereof. No attempt was made to limit the search criteria by system type or effect, as obtaining all relevant information was of interest. An overview of the potential effects of log salvage information on lakes and rivers is presented.

Ultimately, however, our interest focused on deep-water log removal from lakes because these impacts are among the least understood, and this was the most likely scenario to receive management approval. Although applications have been received by DFO for the salvage of logs from rivers, this review will only briefly address these concerns. We felt that a useful tool for managers would be to develop a method to assist in selecting lake sites for approval. Thus, models predicting oxygen and temperature regimes in lakes were reviewed for use in predicting the effects of sediment disturbance induced by log removal on oxygen/phosphorus profiles and temperature gradients.

POTENTIAL EFFECTS OF LOG REMOVAL

LOSS OF STRUCTURAL HABITAT

Fish

Spatially heterogeneous fish communities have been shown to be correlated with a greater diversity of habitats within lakes (Benson and Magnuson 1992). Millions of dollars have been invested in creating habitat for fish in streams and near-shore areas of lakes (Smokorowski et al. 1998). Many of these dollars have gone towards adding log piles, log jams, brush bundles, log overhangs, log reefs, etc. to increase habitat diversity in hopes of benefiting target fish populations. A few of these projects have shown a localized increase in fish abundance and biomass, though there have been minimal monitoring efforts (Smokorowski et al.1998).

Consequently, removing logs that have been submerged for a period of time may result in a loss of structural habitat for fish. Removing woody debris from stream/river channels affects bank stability and channel morphology, and releases previously stable sediments to be transported downstream (Bilby and Ward 1989, Elliott 1986, Beschta 1979). The presence of coarse woody debris (CWD) in stream channels could benefit fish by decreasing competition through visual isolation, thereby reducing aggressive interactions and energy expenditure (Sundbaum and Naslund 1998). Submerged logs in rivers can result in increased pool volumes, decreased current velocity, and increased water depth and cover (Riley and Fausch 1995; Cullis 1995; Hunt 1976; Nickelson et al. 1992; Milton and Towers 1990; Crispin et al. 1993; White et al. 1992; and Slaney et al. 1994). These stream characteristics can increase abundance and biomass of target species such as trout in localized areas (House 1996; Riley and Fausch 1995; Cullis 1995; Slaney et al. 1994; Crispin et al. 1993; and Nickelson et al. 1992). Fewer fish were found in areas without CWD (Moore and Gregory 1988; Hunt 1976). Dolloff (1986) found lower carrying capacities for juvenile coho salmon and dolly varden in stream sections cleaned of wood, regardless of the technique of removal.

Log structures in the littoral zones of lakes are utilized by species such as yellow perch, smallmouth bass, and young brook trout as cover and habitat (Bassett 1994; Moring and Nicolson 1994; Moring et al. 1989; Biro and Ridgway 1995). Removal of logs from the littoral zones in lakes will reduce cover and habitat diversity for lentic species. Cottage development is often coupled with the removal of near-shore CWD and the clearance of most shoreline vegetation, thus eliminating the source of CWD and precluding replacement. If tree planting does occur, the replenishment of CWD in the near-shore areas of lakes could also occur, but the process may take up to two centuries due to slow tree regeneration and mortality rates (Christensen et al. 1996). In many instances replacement of existing woody debris would not be feasible. Dendrochronological dating of eastern white pine in the littoral zone of Swan Lake, Algonquin Park, Ontario, demonstrated that the average germination date of this CWD was approximately 600 years ago (Guyette and Cole 1999). While the average calendar date of annual rings was 1551, evidence indicates that accelerated CWD input occurred 100-200 years ago when extensive logging cleared the area of all merchantable eastern white pine. Today, 30 – 90 m buffer strips exist around lakes wherein logging activity is strongly discouraged; Guyette and Cole (1999) estimate that no pine CWD entered the lake beyond 1893.

There has been little documentation of the effects of removal of logs from deep water in lakes. While logs in deep water may not be as important as habitat for fishes, they still provide structural diversity and are potentially important to the ecosystem. Moring et al. (1986) found longnose suckers, white suckers and golden shiners were more abundant in areas with submerged logs. The study sites ranged from three to 16 meters deep. However, Moring et al. (1986) also found that yellow perch were not clearly associated with submerged logs. This study indicated that invertebrates were more abundant in the sediment than on logs; however, some groups of invertebrates, Gastropoda, Plecoptera, Neuroptera, and some genera of Ephemeroptera and Trichoptera, consumed by yellow perch were only found on logs. As sedimentation is a continuous process in lakes, the role of submerged logs in the ecosystem will be continually changing.

Invertebrates

Coarse woody debris provides refuge for invertebrates as well as epibenthic fish, especially when vegetation or other types of physical structures are absent (Everett and Ruiz 1992). Harmon et al. (1986) reported that of 100 taxa identified from snag (standing dead tree), sand and mud habitats, 63 occurred on snags. Also the biomass of insects on snags was 20-50 times higher than in sandy habitats, and 5-10 times greater than in mud habitats. Boulton et al.(1988), Tikkanen et al. (1994) and Reice (1985) found that although macroinvertebrates are immediately negatively affected after a disturbance in a stream, they are able to recover rapidly if stable physical structure is accessible. Predictable disturbances caused by anthropogenic activities should be completed in times when minimal damage will be caused to the existing communities (Tikkanen et al. 1994). Pulp logs salvaged from Wyman Lake in Maine were found to have no bark, therefore making them unsuitable environments for invertebrates and other organisms (Moring et al. 1986). Bowen et al. (1998) found invertebrate communities on CWD lacking bark and small twigs supported fewer, yet more diverse populations of invertebrates; however, there was a higher biomass of macroinvertebrates on introduced wood in the littoral zone than on naturally occurring CWD (Table 1). Moring et al. (1986) found significantly higher invertebrate biomass in the sediment than on logs in deep water areas (Table 1). Removing the logs in some instances is not likely to limit critical habitat for macroinvertebrates; however, species composition may be affected.

Table 1. Comparison of macroinvertebrate biomass (mg/m^2) in different habitats.

Substrate	**Macroinvertebrate Biomass (mg/m^{-2}) (±SE)**	**Site Description**	**Reference (location)**
CWD	Scott Lake:134(18) Mykiss Lake: 302(29)	Littoral	Bowen et al. 1998 (Algonquin Park, Ontario)
Introduced wood	Scott Lake: 387(31) Mykiss Lake:698(71)	Littoral	
Pulpwood logs	May:259(72) June:101(17) July:165(45) August:120(21)	5 to 16 m deep, log holding area	Moring et al. 1986 (Wyman Lake, Maine)
Sediment	May:1893(453) June:3035(350) July:2889(452) August:2869(1384)	5 to 16 m deep, log holding area	

After a disturbance, sediment eventually settles affecting the meiobenthic community. The meiobenthic community is able to recover in a relatively short period of time. Colangelo et al. (1996) found that copepods and nematodes were able to recover from an artificial disturbance in sediment that was defaunated/reduced sand through organic enrichment, within fifteen days. Fine sediment settling on top of coarser sediment changes the sediment composition therefore altering the benthic species composition, which may alter benthic trophic interactions (Wulff et al. 1997).

SPAWNING

It has been well documented that fine sediment settling on fish spawning beds will be detrimental to the success of emerging fry. Depending on the characteristics of the sediment that is disturbed, the settling rate will vary; the timing of the disturbance may be crucial to successful spawning by resident fishes. Reducing the flow of water in a gravel spawning bed reduces the amount of oxygen reaching the eggs. Fine sediment can also obstruct the movement of emerging fry. Phillips et al. (1975) found an inverse relationship between the survival of coho fry and the quantity of fines; premature emergence of fry was related to higher concentrations of fines. Hausle and Coble (1976) found sand in redds slowed and reduced the number of brook trout fry emergence. Crouse et al. (1981) found that increasing sedimentation suppressed fish production (juvenile coho salmon).

HEALTH AND BEHAVIOUR

Suspended sediments have been shown to directly affect fish health and behaviour, a finding mainly generated from research in lotic environments. Herbert and Merkens (1961) studied the relationship between suspended sediment concentration and survival of rainbow trout. They found that, in fish exposed to high concentrations of suspended sediments, wounds were more likely to become infected and there was an increase in the occurrence of fin rot and abrasion to the gills from sediment particles, inducing the thickening of the gills, in turn degrading the health of the fish. Berg and Northcote (1985) observed the behaviour of juvenile coho when exposed to short-term pulses of suspended sediment, and found that behaviour modifications, for example as changes in territorial, gill-flaring, and feeding behaviour, will affect the fitness of the population. Chiasson (1993) also found a fleeing response in golden shiners when exposed to suspended sediments at 20 °C and 15, 75 and 150 JTU(Jackson Turbidity Units). Servizi and Martens (1991) found that tolerance to suspended sediment by coho salmon was independent of season but affected by temperature and size. Tolerance of, or survival of, fishes was further reduced if the fish had viral kidney infections.

Fish and other mobile organisms are able to migrate from and subsequently re-colonize disturbed areas. Magnuson et al. (1985) found different responses to sediment disturbances between species and between age classes within a species. Young-of-the-year redbelly dace and fathead minnows immigrated to areas with higher dissolved oxygen, while older individuals remained while oxygen levels declined (Magnuson et al. 1985). This induced movement could result in fish moving from safe, covered areas to open areas, potentially increasing vulnerability to predation, in turn expending more energy and increasing mortality. Less mobile or sessile organisms would more likely be affected by increased anoxia. The energy expended to move to more oxygenated areas, or the inability to move far enough, may result in mortality (Breitberg 1992).

WATER QUALITY

Disturbances always have ecological effects (Poff 1992). A change in water quality due to a disturbance causes a response in fish, invertebrates and other aquatic organisms, some of which were outlined above. Phosphorus levels affect phytoplankton abundance because phosphorus is often the limiting nutrient in freshwater aquatic ecosystems (Schindler 1978). Resuspension of sediment may result in increased phosphorus in the water column. An increase in external nutrient input, or an increase in the release of internal nutrients, would stimulate algae and macrophyte growth thus increasing biomass of decaying organic matter, resulting in a reduction of oxygen in the system. An anoxic condition at the sediment water interface induces the release of previously sequestered phosphorus into the water column further exacerbating the situation (Wetzel 1983). Therefore, the effect of log removal on the oxygen regime is of major environmental concern.

Several models predicting oxygen concentrations in lakes were reviewed with the goal of finding or developing a model that could predict the suitability of cold-water, well-oxygenated pelagic habitat during and following log salvage operations. Models have been developed to predict O_2 concentrations, hypolimnetic O_2 deficits, phosphorus levels, O_2 depletion rates, and thermocline depths. Because most requests for log salvaging operations in lakes will be for deep-water log removal, the focus of our review will be toward a model that predicts the area of suitable cold-water habitat (Lake Trout as benchmark) in stratified lakes in summer.

<u>Phosphorus</u>

When sediment is re-suspended following a natural disturbance (i.e. wind) chlorophyll *a* initially increases possibly due to increased release of phosphorus from disturbed sediment (Schindler 1978; Ogilvie and Mitchell 1998). The time required to return to initial levels depends on the size of particles in the sediment, the presence or absence of macrophytes and other, primarily physical, parameters that affect the amount of sediment that may be re-suspended. Much research has been conducted on the oxygen-phosphorus interactions in the hypolimnion of lakes (Nürnberg 1984;1987; 1995a; 1995b). Anoxic lakes have lower retention rates for phosphorus than oxic lakes (Nürnberg 1984). External phosphorus inputs result in greater primary production, which leads to a greater quantity of organic matter sedimentation. Organic accumulation in turn causes a greater rate of hypolimnetic oxygen depletion through aerobic decomposition processes. The same sequence is true for internal nutrient loading, which can occur from regeneration of nutrients from the sediments (Lind and Davalos-Lind 1993). Agitated solutions of sediment have been shown to release nearly twice the phosphorus than sedentary solutions (Wetzel 1983). Measuring the phosphorus concentrations available for release from lake sediments could be a useful tool in predicting the change to an ecosystem due to disturbance.

Dillon and Rigler (1974) developed a simple model that predicts the average summer chlorophyll-*a* concentration from a single measurement of phosphorus concentration at spring turnover:

$$\mathrm{Log}_{10}\,[\mathrm{Chl}\ a] = 1.449\ \mathrm{Log}_{10}\,[\mathrm{P}] - 1.136 \qquad \text{(Eqn. 1)}$$

This model was created using data from 19 lakes with two measurements of phosphorus taken within five days of ice-off. Using this model can save considerable time and money by reducing samples and fieldwork requirements. Components of this model could be used in other models predicting oxygen levels. Dillon et al. (1988) showed that 80% of the variability in chlorophyll *a* can be explained by total phosphorus (TP). More recent research demonstrated that total phosphorus has a lesser, but still significant, effect on chlorophyll *a* in lakes that contain large herbivorous zooplankters (i.e. large *Daphnia sp*.), than those that do not (Mazumder 1994). Dillon and Rigler (1975) show an inverse relationship between measured or predicted chlorophyll-*a* concentrations and Secchi depth readings.

<u>Temperature</u>

If the disturbance is severe enough to decrease water transparency for a prolonged period of time, temperature may be affected. A change in the temperature regime could have multiple effects on the lake. Transparency (largely determined by DOC and Chl *a*) is a key factor in determining mixed layer depths and metalimnetic oxygen concentrations in lakes less than 500 ha in size (Mazumder and Taylor 1994; Stefan et al. 1995; Fee et al. 1996). Changes in stratification depths will alter the distribution, and potentially survival, of temperature sensitive organisms, which may ultimately affect species composition. Changes in the thermal structure will also have an impact on chemical exchanges in sediment-water interactions, for example, temperature is the most significant determinate of NH_4+ flux (Cerco 1989).

Many researchers have created models that predict temperature budgets in aquatic ecosystems (Fee et al. 1996; Mazumder and Taylor 1994; Clark et al. 1999; Nürnberg 1988; Gorham and Boyce 1989; and Cerco 1989). Nürnberg (1988) developed a simple model that predicts fall turnover date (useful if anthropogenic activities effect the thermal budgets). The model predicts fall turnover date using an average midsummer hypolimnetic temperature, mean depth and latitude (adjusted for altitude). Pérez-Fuentetaja et al. (submitted) found dissolved organic carbon (DOC) to account for 74% (out of 84% total for the model) of the variability in the thermocline depth. In this model chlorophyll-*a* accounted for only 1% of the variability. Other significant variables were lake area and maximum depth. Gorham and Boyce (1989) developed a model to estimate the depth of the thermocline (h) at the time of maximum heat content in lakes less than 5,000 m crossbasin width, by measuring: surface area, wind stress from storms, gravitational acceleration and the density contrast between the epilimnion and the hypolimnion. This model could be used to detect the change, if any, in the thermocline after a disturbance. Clark et al. (1999) developed a temperature model that predicts the depth at which 10°C will occur at end-of-summer; this model is discussed in detail later.

Oxygen

One of the most important concerns regarding the impacts of log salvage is the increased oxygen depletion as a result of the sediment disturbance. Oxygen is one of the most fundamental parameters of lakes, because dissolved oxygen (DO) is essential to the metabolism of all aerobic aquatic organisms. Any disturbance that affects the oxygen regime in an aquatic system will have a severe effect on these types of organisms. It is well known that water at the sediment interface can easily become anoxic by the loading of organic matter to the hypolimnion and sediments, thereby increasing the consumption of dissolved oxygen (Wetzel 1983). The water above the profundal sediment is the first to become anoxic because the oxygen demand is highest at the sediment surface (Cornett and Rigler 1987). Sediment moving into the water column will have two possible effects in the water column: 1) the water oxygen consumption (WOC) will increase due to decomposition of suspended sediments, and 2) a new sediment layer will be exposed, therefore increasing the oxygen demand at sediment-water interface which could in turn reduce the DO. Wulff et al. (1997) found an initial decrease in oxygen concentration in the sediment after settling of fine sediment; however, within a day, the upward migration of benthic diatoms were able to start restoring the oxygen levels, although the oxygenated layer was thinner. This effect may cause the system to be less resistant to disturbances in the future.

REVIEW OF OXYGEN MODELS

Modelers have focused on predicting hypolimnetic oxygen concentrations (Charlton 1980; Cornett and Rigler 1987; Vollenweider and Janus 1982; Nürnberg 1984; Burns 1995; etc.). Because sediment disturbance is an important issue for log removal operations, we were interested in finding a model that would account for the sediment oxygen demand (SOD). However, because the data collection could be the responsibility of the proponent, the model must have straightforward data needs and be relatively easy to use. A number of oxygen models are presented below, some of which are potentially more suitable for predicting the effects of log salvage but are relatively complex, and others which are more simple yet have lower predictive power.

It is not uncommon for lakes to become seasonally anoxic. Many hypolimnetic oxygen deficit models have been developed to measure seasonal anoxia. The AF (anoxic factor) was developed by Nürnberg (1987) to measure the intensity of anoxia in stratified lakes in the summer or winter periods.

$$AF = (\text{duration of anoxia} * \text{anoxic sediment area})/A_0 \qquad \text{(Eqn. 2)}$$

Where A_0 represents the surface area of the lake, and the anoxic factor (AF) represents the number of days sediment is overlain with anoxic water.

Stefan and Fang (1994a,b) created, tested and applied a deterministic, one-dimensional, unsteady numerical model to simulate mean daily dissolved oxygen (DO) characteristics in 27 lake classes in Minnesota. The model was validated using 11 years of data from seven lakes. The oxygen sinks in the model are sediment oxygen demand (SOD), water column biochemical oxygen demand (BOD), and plant respiration, while reaeration at the water surface and photosynthesis are the oxygen sources. The DO transport model is a differential equation:

$$\frac{\partial C}{\partial t} - \frac{1}{A}\frac{\partial}{\partial z}\left(AK_z \frac{\partial C}{\partial z} \right) + \frac{1}{YCHO2} k_r \theta_r^{T-20} CHLa - P_{\max} Min[L] CHLa + k_b \theta_b^{T-20} BOD + \frac{S_b}{A}\frac{\partial A}{\partial z} = 0$$

(Eqn. 3)

Where: C(z,t) = dissolved oxygen concentration (mg/L)

T(z,t) = water temperature (°C)

A(z) = horizontal area (m^2)

CHLa = chlorophyll-*a* concentration (mg/L)

BOD = water column biological oxygen demand

K = light limitation

$P_{\max}$ = the maximum specific oxygen production rate by photosynthesis at saturating light conditions

k = total attenuation coefficient

YCHO2 = ratio of mg chlorophyll-*a* to mg oxygen utilized in respiration

k_r = respiration rate coefficient (day^{-1})

S_b = sedimentary oxygen demand coefficient

θ = temperature adjustment coefficient

Min[*L*] = light limitation function as a function of depth and time

The sensitivity analysis showed the sedimentary oxygen demand (S_b) to be the most important parameter in the regional DO model. There was a weak sensitivity to water column oxygen demand (BOD). The DO simulations were very close to the measured values and were better for stratified lakes than non-stratified lakes (Stefan and Fang 1994b).

Clark et al. (1999) developed a steady state model designed to predict the optimal habitat boundaries for lake trout (i.e. temperature <10°C; DO>6mg/L). To determine these boundaries, lake morphometry, total phosphorus concentration (TP) and initial O_2 concentrations at spring turnover, and mean summer Secchi depth or dissolved organic carbon (DOC) are measured. The upper and lower habitat boundaries are predicted for the same date (end of summer) using two models. The upper boundary is determined by a temperature model (developed by Clark et al. 1999) that predicts Z_{10} (the depth at which 10°C occurs):

$$Z_{10} = 3.52 + \frac{11.3}{DOC} + 0.139 \times \sqrt{A_0} \quad (1) \qquad \text{(Eqn. 4)}$$

or

$$Z_{10} = 3.35 + 0.956 \times Secchi + 0.33 \times MD \quad (2) \qquad \text{(Eqn. 5)}$$

Where: A_0 = surface area
DOC = dissolved organic carbon
MD = maximum distance from shore

Either model may be used. Model 1 (Eqn. 4) gave the better fit; however, Secchi depth and maximum distance data are generally more available and easier to collect. A_0 may also be used in place of MD in the second model (Eqn. 5).

The lower boundary ($Z_{6mg/L}$) is determined using an oxygen model developed by Molot et al. (1992) which predicts DO levels at different strata:

$$Log_{10}O_2(f)_z = 1.89 - \frac{1.88}{VSA_z} - \frac{7.06}{O_2(i)_z} - 0.0027TP_{epi}^2 \qquad \text{(Eqn. 6)}$$

R^2 = 0.88, MSE = 0.027, F = 124.9, P<0.0001.

If TP (TP_{so}) at spring turnover is available it can be used instead of TP_{epi}:

$$Log_{10}O_2(f)_z = 1.83 - \frac{1.91}{VSA_z} - \frac{7.06}{O_2(i)_z} - 0.0013TP_{so}^2 \qquad \text{(Eqn. 7)}$$

R^2 = 0.88, MSE = 0.029, F = 116.9, P<0.0001.

Where: VSA = volume/sediment surface area ratio
TP_{epi} = mean epilimnetic total phosphorus
TP_{so} = total phosphorus concentration at spring overturn
$O_2(i)_z$= initial oxygen concentrations at the start of each summer period

The temperature model (Eqns. 4 and 5, Clark et al. 1999) was developed using data from 37 lakes and tested using independent data from 50 lakes in the Gull River watershed (Haliburton County, Ontario), over a mean sampling period of 13 years (range from 3 to 19 years of data). The hypolimnetic oxygen model (Eqns. 6 and 7, Molot et al. 1992) was developed using data from 15 lakes in central Ontario, and tested on an independent set of 17 lakes in the same region. This model predicts the DO concentration in 2 meter strata at end of summer in a steady state system; thus, it could be useful in predicting available cold-water habitat in lakes proposed for log salvage, but can not be used to predict what changes may occur upon disturbance. Measurements of DO or TP at spring turnover is essential to use this model. The major parameter missing from this model that is important to our needs is SOD, which is included in Stefan and Fangs (1994) more complicated yet more precise model (Eqn. 3).

Lind and Davalos-Lind (1993) developed a relative areal hypolimnetic oxygen deficit model:

$$RAHOD = \frac{AHOD}{2^{[(T-4)/10]}} \times \frac{Z}{500+Z} \qquad \text{(Eqn. 8)}$$

Where: T = the mean hypolimnion temperature (°C)
Z = hypolimnion mean depth (cm)
AHOD is the slope of the regression of the areal oxygen content on each date plotted against successive days.

The Lind and Davalos-Lind (1993) model is intended to monitor changes in trophic state. It was used to monitor the eutrophication of Douglas Lake in Michigan, and demonstrated that the oxygen deficits in regions of the lake farthest from development averaged 60% of those near the developed areas. This model would be useful in measuring a change due to disturbance; however, it would not predict the changes. The parameters used in this model are easy to measure and could be done by laypersons.

Another method to detect changes in trophic state is to calculate volumetric hypolimnetic oxygen depletion caused by the decomposition of organic material in the hypolimnion ($VDHR_{org}$) (Burns 1995). Burns (1995) reviews nine processes that affect the observed VDHR ($VDHR_{obs}$) which can account for the difference between the $VDHR_{org}$ and $VDHR_{obs}$. These processes are: the effects of ambient dissolved oxygen concentrations, sites of DO uptake and effect of hypolimnion thickness, variations in the fraction of production reaching the hypolimnion, within-season variation in depletion rates, temperature effects on oxygen uptakes, downward transport of oxygen, photosynthesis in the hypolimnion, effects of inflows, and delayed decomposition of organic matter.

Welch et al. (1976) developed a model that can be used to predict aerial sediment respiration rates ($R\ m^{-2}$) in Ontario lakes using only lake morphometry.

$$R\ m^{-2} = (0.105) + (0.004) * \max.depth \qquad \text{(Eqn. 9)}$$

The predicted rate ($gO_2\ /m^2\ /day$) can be used as an estimate of the sediment respiration rate in a given system with relatively little data and effort.

SIMULATED EFFECTS OF DISTURBING SEDIMENT

The objective of the review of oxygen models was to find a simple model that would predict effects of sediment disturbance on oxygen regimes in lakes. Because no simple model was found which incorporated sediment oxygen demand, we opted instead to use existing models in ways to estimate the impact of the predicted increase in oxygen demand in lakes. The methods demonstrated below could be used by fish habitat managers in choosing candidate sites for log salvage approval by demonstrating which lakes would be most vulnerable to an increase in oxygen demand. In this manner managers would be adopting a precautionary approach by minimizing the impact on fisheries pending suitable research/monitoring of log salvage operations.

Using Increased Phosphorus

Our first attempt was to use the Molot et al. (1992) oxygen model (Eqn. 5) to predict oxygen concentrations in 2 m strata under conditions of increased phosphorus, assuming that a disturbance in the sediment will increase total phosphorus in the system (Table 2). The data were obtained from Molot et al. (1992), using lakes in central Ontario in Haliburton County or in the district of Muskoka. Model simulations indicate that habitat available to cold water species such as lake trout would be lost with an increase in phosphorus, based on the optimal habitat criteria of below 10 °C and at least 6mg/L of oxygen (Table 2). All optimal habitat for cold water species in the two smaller lakes was lost in our simulation. The larger lake, Solitaire, showed a decrease in available habitat; however, there was less of an impact than on the two smaller study lakes since optimal habitat still remained.

Table 2. Oxygen concentrations predicted using Molot et al. (1992) showing effects of increased phosphorus.

Lake (area)	**Depth (m)**	**Measured Oxygen (mg/L)**	**Predicted Oxygen**		
			Measured TP_{so} (µg/L)	**1.5 x Measured TP_{so} (µg/L)**	**2.0 x Measured TP_{so} (µg/L)**
Blue Chalk (52.4 ha)	15	5.6	5.5	4.9	4.1
	17	3.1	1.9	1.6	1.4
	19	0.9	2.6	2.3	1.9
Basshaunt (47.3 ha)	5	8.5	5.9	4.7	3.5
	7	6.3	5.6	4.5	3.4
	9	5.4	5.4	4.3	3.2
	11	5.1	4.7	3.8	2.9
	13	4.5	3.7	3.0	2.2
	15	4.2	2.4	1.9	1.4
	17	3.5	4.2	3.4	2.5
	19	2.0	3.1	2.4	1.8
	21	0.8	1.1	0.9	0.7

Lake (area)	Depth (m)	Measured Oxygen (mg/L)	Predicted Oxygen		
			Measured TP_{so} (µg/L)	1.5 x Measured TP_{so} (µg/L)	2.0 x Measured TP_{so} (µg/L)
Solitaire (124 ha)	15	9	8.6	7.6	6.5
	17	8.1	8.2	7.3	6.2
	19	7.5	7.9	7.0	5.9
	21	6.9	7.5	6.7	5.7
	23	5.6	6.9	6.1	5.2
	25	4.3	5.7	5.1	4.3
	27	3.3	2.9	2.6	2.2

Using Sediment Oxygen Demand

Our second endeavor involved devising a method to use a predicted aerial sediment respiration rate (based on the Welch et al. 1976 model, Eqn. 9), along with the volume of each stratum and an oxygen profile, to estimate oxygen depletion in a disturbed system. This method involves calculating the amount of oxygen available in each stratum and amount of oxygen that will be lost daily through sediment oxygen demand. The disturbed area (m^2) multiplied by the aerial respiration rate (g O_2/m^2/day) gives the daily oxygen loss. Thus, oxygen loss depends on the proportion of the lake bottom that is disturbed, and the duration of the disturbance. For example: if we disturb 10% of the sediment surface area for a period of 10 days we would multiply 10% of the total lake area by the respiration rate (giving a daily rate) and then by 10 days to give an estimated amount of oxygen lost. Then, starting at the bottom of the lake, subtract the amount of oxygen lost due to sediment respiration from the oxygen available in each stratum until the total lost oxygen is accounted for. Comparing the temperature profile and available oxygen determines how much suitable and optimal habitat is left for cold water species. The procedure is outlined in more detail in Appendix 1.

This method could underestimate the loss of oxygen in the system because: 1) we are using an estimated respiration rate (Welch et al. 1976) to determine the impact due to disturbance from log removal, and 2) we do not include the daily loss of oxygen that is naturally occurring, 3) we do not account for a likely increase in the respiration rate that would be caused by a disturbance, and 4) we used the surface area of the lake, which is readily available for most lakes, instead of sediment surface area. However, an overestimate of the actual hypolimnetic oxygen depletion may occur by not accounting for additional oxygen inputs, such as from groundwater upwellings. The use of this method requires an oxygen profile, lake morphometric data, and the area and volume of each depth stratum, which can be calculated from a bathymetric map.

We compared respiration rates provided by Johnson and Brinkhurst (1971), range from 0.15 to 0.35 $gO_2 /m^2 /day$, to rates obtained from using the Welch et al. (1976) model and were within the range specified. Using our respiration rate method we simulated the effects of sediment disturbance on two lakes in Wishart township in the Algoma district - Little Turkey Lake and Turkey Lake. The estimated respiration rates were calculated for the two lakes using morphometric data from Jeffries and Semkin (1982), oxygen and temperature data were obtained from Semkin (unpublished). The available oxygen in each stratum was calculated and compared to a temperature profile to predict available habitat for cold water species. By multiplying the respiration rate by the sediment surface area, the amount of oxygen depleted per day was calculated for increments of area disturbed up to a whole lake disturbance. Calculations were made in both lakes simulating the oxygen demand with different percentages of the area disturbed.

Using this method of calculating the effects of sediment disturbance, by disturbing 50% of the sediment for a period of 10 days in Little Turkey Lake in June, three meters of optimal habitat were lost (Table 3a). In September in the same lake, using the same methods, no habitat was lost; however, only one meter of optimal habitat was available with no disturbance (Table 3b). If the disturbance had occurred in June, depleting the available habitat early in the season, by September there would not likely be any suitable habitat available for salmonids. In Turkey Lake, using the same criteria, three meters of available habitat were also lost in June, however 20 m of suitable habitat remained (Table 4a). In September, again, no additional habitat was lost, leaving 14 m of optimal habitat remaining in Turkey Lake (Table 4b).

Table 3. Predicted oxygen concentrations (mg/L) after 10 days of sediment disturbance in Little Turkey Lake. Calculations based on the percentage of sediment surface area disturbed (% shown), predicted respiration rate, and available oxygen in Little Turkey Lake (21.3 ha) in a) June and b) September. The sediment respiration rate was calculated using the Welch et al. (1976) model (z_{max} = 13 m, R = 0.16 gO_2/m^2/day)

a) Little Turkey Lake – measured temperature and oxygen data from June 11, 1997.

Depth (m)	**Temp (°C)**	**Measured DO (mg/L)**	**Dissolved Oxygen (mg/L)**				
			100%	50%	30%	20%	10%
0	22.3						
1	21.6	9.26	9.26	9.26	9.26	9.26	9.26
2	20.5	9.34	9.34	9.34	9.34	9.34	9.34
3	15.3	10.83	10.83	10.83	10.83	10.83	10.83
4	12.0	11.34	11.34	11.34	11.34	11.34	11.34
5	9.7	11.7	11.7	11.7	11.7	11.7	11.7
6	8.0	10.82	10.82	10.82	10.82	10.82	10.82
7	7.0	10.53	10.53	10.53	10.53	10.53	10.53
8	6.1	7.93	7.93	7.93	7.93	7.93	7.93
9	5.7	6.07	4.39	6.07	6.07	6.07	6.07
10	5.4	4.97	0	3.00	4.97	4.97	4.97
11	5.3	4.58	0	0	0.37	2.18	4.00
12	5.2	5.11	0	0	0	0	0

b) Little Turkey Lake – measured temperature and oxygen data from September 3, 1997

Depth (m)	**Temp (°C)**	**Measured DO (mg/L)**	**Dissolved Oxygen (mg/L)**				
			100%	50%	30%	20%	10%
0	20.2						
1	20.2	9.40	9.40	9.40	9.40	9.40	9.40
2	20.2	9.46	9.46	9.46	9.46	9.46	9.46
3	20.1	9.37	9.37	9.37	9.37	9.37	9.37
4	19.9	9.13	9.13	9.13	9.13	9.13	9.13
5	18	9.48	9.48	9.48	9.48	9.48	9.48
6	12.9	11.28	11.28	11.28	11.28	11.28	11.28
7	10.3	11.36	11.36	11.36	11.36	11.36	11.36
8	8.7	7.56	7.15	7.56	7.56	7.56	7.56
9	7.8	4.24	0	3.16	4.24	4.24	4.24
10	7.4	3.03	0	0	0	1.69	2.78
11	7.1	1.14	0	0	0	0	0
12	6.8	1.09	0	0	0	0	0

Table 4. Predicted oxygen concentrations (mg/L) after 10 days of sediment disturbance in Turkey Lake. Calculations based on the percentage of sediment surface area disturbed (% shown), predicted respiration rate, and available oxygen in Turkey Lake (54 ha) in a) June and b) September. The sediment respiration rate was calculated using the Welch et al. (1976) model (z_{max} = 37 m, R = 0.25 gO_2/m^2/day).

a) Turkey Lake – measured temperature and oxygen data from June 12, 1997

Depth (m)	**Temp (°C)**	**Measured DO (mg/L)**	**Dissolved Oxygen (mg/L)**				
			100%	50%	30%	20%	10%
0	20.8						
1	20.7	9.36	9.36	9.36	9.36	9.36	9.36
2	17.2	9.66	9.66	9.66	9.66	9.66	9.66
3	14.5	9.64	9.64	9.64	9.64	9.64	9.64
4	10.8	9.31	9.31	9.31	9.31	9.31	9.31
5	9	9.18	9.18	9.18	9.18	9.18	9.18
6	7.8	9.22	9.22	9.22	9.22	9.22	9.22
7	7.2	9.09	9.09	9.09	9.09	9.09	9.09
8	6.4	8.86	8.86	8.86	8.86	8.86	8.86
9	5.9	8.4	8.4	8.4	8.4	8.4	8.4
10	5.6	8.6	8.6	8.6	8.6	8.6	8.6
11	5.4	8.23	8.23	8.23	8.23	8.23	8.23
12	5.2	8.07	8.07	8.07	8.07	8.07	8.07
17	4.6	7.6	7.6	7.6	7.6	7.6	7.6
21	4.4	6.77	6.77	6.77	6.77	6.77	6.77
25	4.3	6.39	5.30	6.39	6.39	6.39	6.39
29	4.2	5.91	0	2.65	4.52	5.46	5.91
32	4.1	5.72	0	0	0	0	1.94

b) Turkey Lake – measured temperature and oxygen data from September 4, 1997

Depth (m)	Temp (°C)	Measured DO (mg/L)	Dissolved Oxygen (mg/L)				
			100%	50%	30%	20%	10%
0	21.6						
1	21.6	9.22	9.22	9.22	9.22	9.22	9.22
2	21.6	9.15	9.15	9.15	9.15	9.15	9.15
3	21.6	8.9	8.9	8.9	8.9	8.9	8.9
4	21.3	7.6	7.6	7.6	7.6	7.6	7.6
5	17.9	7.83	7.83	7.83	7.83	7.83	7.83
6	12.9	9.59	9.59	9.59	9.59	9.59	9.59
7	9.6	9.53	9.53	9.53	9.53	9.53	9.53
8	8.4	9.13	9.13	9.13	9.13	9.13	9.13
9	7.6	8.84	8.84	8.84	8.84	8.84	8.84
10	6.8	8.26	8.26	8.26	8.26	8.26	8.26
11	6.2	7.86	7.86	7.86	7.86	7.86	7.86
12	5.7	7.98	7.98	7.98	7.98	7.98	7.98
17	4.5	5.39	5.39	5.39	5.39	5.39	5.39
21	4.2	5.52	5.52	5.52	5.52	5.52	5.52
25	4.1	4.99	2.42	4.93	4.99	4.99	4.99
29	4	3.67	0	0	1.76	2.69	3.63
32	4	3.61	0	0	0	0	0

SUMMARY

Lake size, morphometry, available oxygen, type of sediment, species of fish present, and time of year of the disturbance, are parameters that are important to consider for log salvaging. Salvaging logs from lakes creates concerns of oxygen depletion by increasing sediment oxygen demand and internal phosphorus loading. Table 5 outlines the concerns related to log removal in lake versus stream habitats.   We suspect that, among the effects of log removal, the change to oxygen regimes in lakes is likely to be one of the most serious impacts.

Table 5. Summary of concerns related to log removal from lakes and streams.

Lake	Stream
Sediment resuspension effects on TP and O_2	Downstream settling of resuspended sediment
Thermal alteration	Stream morphometry changes
Physical and behavioural effects on fishes	Physical and behavioural effects on fishes
Near-shore changes to production of macroinvertebrates	Alteration of substrates for macroinvertebrate production

We propose a method that could be used by habitat managers as a screening tool to determine which lakes would be less affected by log salvage operations. The initial screening tool is the Clarke et al. (1999) model, used to predict suitable habitat available to cold water species at the end of the summer. If cold water habitat is predicted to be limited under static conditions, then a disturbance of the sediment by log removal will have a greater effect.

The possible effects of disturbing sediment can be calculated using sediment respiration rate, the surface area and the oxygen concentrations using the methods described above. By comparing two lakes of different size we found that there was a more detrimental effect on the small lake, which had little available habitat for salmonines to begin with. The larger lake (Turkey Lake) would probably be able to absorb the disturbance without causing a major loss of available habitat for cold water species. We also found that there was less habitat lost if the disturbance took place in the fall. However, conditions of limited cold-water habitat may already exist at this time, and authorization of log salvage activities would further degrade conditions in these systems.

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