The effect of sub-aqueous disposal of mine tailings in standing waters

Effet du rejet de résidus miniers au fond de plans d'eau stagnants

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ABSTRACT
Field observations provided the basis for a numerical model designed to quantify the vertical mass flux of material initially injected at the base of the water column in a small lake; a process called sub-aqueous disposal. Eddy diffusion estimation largely controlled the transport behaviour, highlighting the need for measurements of diffusion in deep strongly stratified environments. The model followed the contaminant development over 40 years and showed that (i) it is unlikely that any material can ever be completely disposed of over realistic scales and (ii) within the bounds limited by uncertainty in eddy diffusivity, turnover penetration and surface layer precipitation-driven flushing are the mechanisms most likely to have bearing on the contaminant distribution.

RÉSUMÉ
Des observations en nature ont fourni la base d'une modèle numérique destiné à quantifier le flux vertical de masse d'un matériau initialement injecté à la base de la colonne d'eau dans un petit lac; un procédé appelé rejet sub-aquatique. Le transport de matière est en grande partie contrôlé par la diffusion turbulente à grande échelle, ce qui met en évidence le besoin de mesure de diffusion dans milieux profonds fortement stratifiés. Le modèle a suivi le développement du polluant sur une période de 40 ans et il a montré que (i) il est peu probable qu'un matériau quel qu'il soit puisse jamais être considéré comme complètement éliminé à échelle de temps réaliste, (ii) à l'intérieur des limites définies par l'incertitude concernant la diffusion turbulente, les mécanismes qui semblent les plus concernés par la répartition du polluant sont les flux induits par les précipitations en surface.

Introduction

Sub-aqueous disposal is a mining industry technique whereby a mixture of water and finely ground rock is pumped to the bottom of a water body. Material from the slurry settles and consolidates forming a new lake bed with an overlying layer of water with high levels of dissolved material (the monimolimnion, see Fig. 1). These artificially created layers underlie the pre-existing lake structure which comprises, from bottom to top, the hypolimnion, thermocline and epilimnion. The premise is that the water forms an inert cap, effectively containing the injected material. Environmental considerations require that the effectiveness of this storage method be explored. Hence, the objective of this work is to quantifying transport rates (i.e. vertical mass fluxes) of dissolved material from the monimolimnion to the lake surface. We restrict our study to small lakes that are deep relative to the depth of seasonal stratification, so that wind-driven surface waves and horizontal motions are secondary effects. Furthermore, the various phenomena associated with the injection and consolidation are beyond the scope of this study (see Danielson & MacKinnon, 1990). Data from two lakes, one

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natural, the other man-made, are examined with regard to the impact of hypothetical sub-aqueous disposal. The observed scales provide a basis for computer modelling examining various types of transport and mass flux prediction.

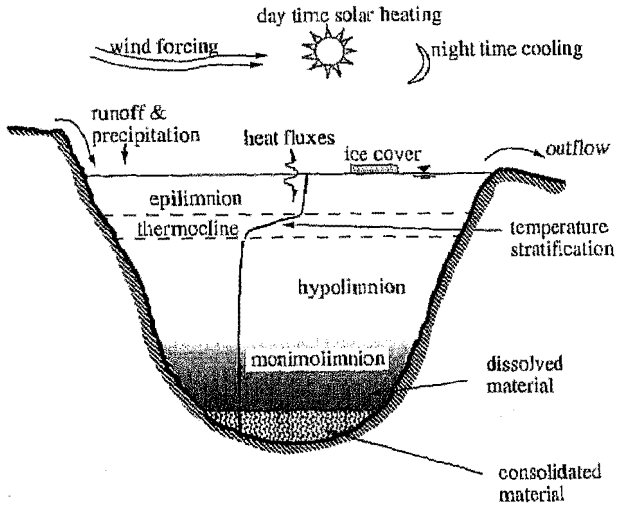

Fig. 1. Schematic of sub-aqueous disposal showing the epilimnion (surface mixing layer), the thermocline, hypolimnion, monimolimnion and consolidated material.

Entrainment of a monimolimnion

To a significant degree, entrainment of a monimolimnion into overlying water differs from entrainment across a thermocline. The barrier to vertical energy transport provided by natural stratification means that entrainment of the monimolimnion into the hypolimnion is generally an indirect process. In other words, energy fluxes at the surface must first drive intermediate processes that in turn drive the entrainment. Wetzel (1983) describes the seasonal cycle of a purely temperature-stratified lake that freezes over in winter (dimictic) as comprising two periods of stratification separated by the spring and autumn turnovers. The turnovers occur as the lake surface waters reach the temperature of maximum density (hereinafter TMD, ~4°C), at which point the water column is unstable to any small perturbation (Carmack & Farmer, 1982).

The addition of a monimolimnion induces meromixis whereby the turnover events do not penetrate to the base of the lake. Consequently, vertical transport of dissolved monimolimnetic material may be considered a twice yearly cycle alternating with the strength of the surface stratification. Near-surface stratification in summer and winter protects the hypolimnion from surface energy fluxes and so diffusion processes are indirect and lead to a slow thickening of the hypolimnion-monimolimnion interface (Fig. 2a, note that typical winter under-ice stratification sustains a much broader thermocline than indicated in this figure).

It is important to determine the rates of diffusion of the originally monimolimnetic material. Molecular transport, whereby Brownian motion leads to down-gradient transport, is a slow process relative to environmental factors likely to impact on a stratified lake. For example Sanderson *et al.* (1986) consider the diffusion of seawater trapped in Powell Lake in British Columbia 12,500 years ago, and show how even the very slow transport rates observed are still 4 times greater than that expected if only molecular mass transport occurred. While Sanderson *et al.* (1986) implicitly incorporate the effects of turnover, the elevated rate of diffusion over and above that of molecular diffusion is typically loosely described as being due to sporadic mixing processes within the interior of the fluid and benthic boundary-layer processes (Wüest *et al.* 1996). The most convenient way to parameterize transport due to turbulent fluctuations is through employment of an eddy diffusion coefficient whereby the displacements caused by turbulent motion are considered to act in the same manner as molecular diffusion, except faster. Eddy diffusion coefficients are consequently a function of the hydrodynamics and not the fluid so that a suitable average estimation must be derived in any given application.

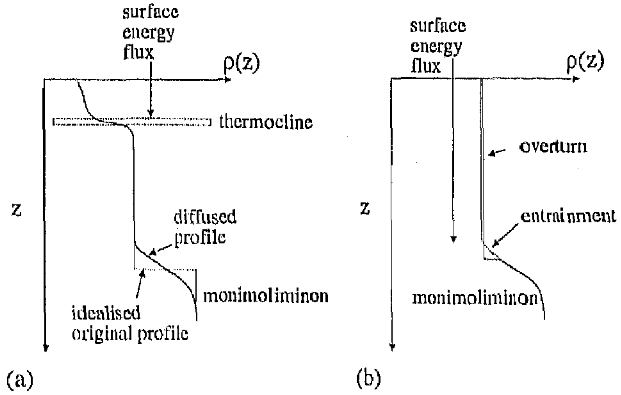

Fig. 2. Schematic of the two stage transport process where (a) stratification in winter and summer retards direct mixing below the thermocline and (b) at isothermal conditions in spring and autumn when the surface energy fluxes can penetrate to the monimolimnion.

At the end of the summer and winter stratified periods, autumn and spring turnover occur, respectively. The absence of thermal stratification allows the energy fluxes at the surface (Fig. 2b) to penetrate deep into the hypolimnion, retarded only by viscosity. Through entrainment the energy erodes and sharpens the thickened monimolimnion-hypolimnion interface. The material removed from the interface is not returned to the monimolimnion but, rather, distributed throughout the rest of the water column thereby increasing levels of contaminant concentration in the surface waters.

So far only stratification due to temperature and the monimolimnetic material has been considered. A third stratifying agent, such as dissolved salts, can be expected through runoff processes if there has been mining activity in the catchment. In all likelihood this stratifying agent will be similar material to that in the monimolimnion but its distribution is unlikely to be as well defined as the monimolimnion. Thus, with an overlying precipitation-generated fresh water epilimnion, the additional stratifying agent adds stability to the water column that is not affected by heat fluxes. Thus, turnover may be prohibited, or at least attenuated, by this stratification.

In addition to eddy diffusion and turnover, diurnal thermocline entrainment and freshet flushing must be considered. The thermocline acts as a transport barrier when a thermocline exists. Freshet flushing is caused by the increased run-off in spring due to snow melt, which dilutes the surface layer concentrations. In addition to these natural processes, some thought needs to be given to injection strategies such as repeated monimolimnion loading likely to occur in an operational mine. The following observations provide a basis for estimating their importance.

Site Description and Observations

Observations from Kitsault Lake are compared with those from the artificial Brenda Mines pit-lake to identify expected rates of transport. The lakes are both located in British Columbia, Canada, have similar volumes and both sustain ice cover for around 6 months of the year. The instrumentation deployed included thermistor chains and meteorological stations floating on the lake surface. In addition, conductivity, temperature, depth profiles (hereinafter CTD) were recorded.

Bathymetry

Kitsault Lake is small (2.6 km long, 500 m wide and a maximum depth of around 70 m, see Fig. 3a), and situated at an altitude of 790 m near Stewart in north-western British Columbia (55° 45'N, 129°30'E). The lake, because of its size and location, has been studied to determine the feasibility of any future sub-aqueous disposal. Generally speaking, a more likely application of sub-aqueous disposal is the Brenda Mines Pit-lake, located near Kelowna in South-central British Columbia at an altitude of 1450 m (lat. 49°53'N, long. 120°00'E, around 900 km South East of Kitsault Lake). This was formed from an open-cut mine pit that ceased operation in 1990 and was subsequently filled with water. At the time of data collection (1994–1995, see Stevens & Lawrence, 1997) the pit-lake was around 150 m deep and over 750 m in diameter at the water surface (Fig. 3b).

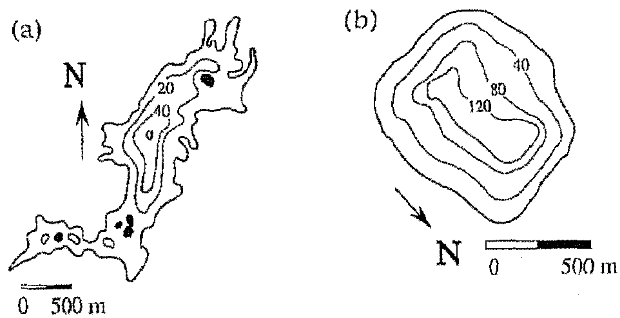

Fig. 3. Bathymetric contours of (a) Kitsault Lake with 20 m isopleths (60 m is not numbered) and (b) Brenda Pit-lake with 40 m isopleths.

Thermal structure

Isotherms recorded at the deepest point of Kitsault Lake from the ice-free period of 1994, shown in Fig. 4, illustrate a broad thermocline with only a shallow surface mixing layer until late in the stratified period. Wind energy must penetrate this region of stratification to have any direct impact upon any deeper hypothetical monimolimnion. Assuming the 6°C isotherm represents the maximum extent of the surface layer, then around day 190 the surface layer extended beyond 10 m and reached a depth of 15 m by day 280. The deepening continued so that, by day 305, the water column was isothermal down to the deepest measurement point at 55 m. Fig. 5a plots the raw temperature time-series recorded just before ice-on, showing the onset of autumn turnover. The isothermal condition resulted in a lake-wide temperature, not at the TMD, but at around 4.7°C. Wind, in conjunction with penetrative convection, was able to generate mixing to the maximum depth measured here (55 m) and was able to maintain isothermal conditions for around 6 days. By day 312 however, the stratification generated by the cooler, lighter, surface water was sufficiently strong so as to resist wind mixing. The hypolimnion then maintained its heat content at around 3.5 °C, somewhat less than the TMD (see Carmack and Farmer, 1982). These data provide a clear picture of the thickness of the thermocline and the duration of the isothermal conditions and associated turnover.

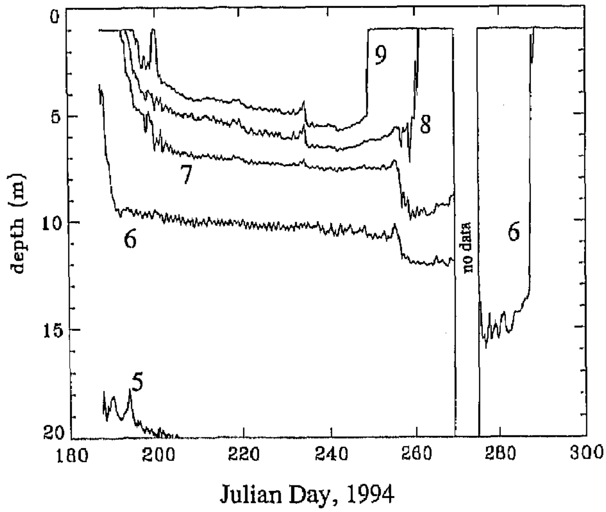

Fig. 4. The 5 (lower left), 6, 7, 8 and 9 °C isotherms from Kitsault Lake in 1994 recorded near the centre of the lake. The data were derived from thermistors recording 15 minute averages at depths of 1, 2, 3, 5, 8, 13, 21, 34 and 55 m. No contours were generated above 1 m or during the gap in the data.

An additional stratifying agent

The Kitsault temperature observations (Fig. 5a) are clearly different to equivalent temperature data from the Brenda Mines pit-lake (Fig. 5b). In the mine pit-lake the water deeper than 40 m remained at temperatures greater than the TMD and mixing was not sufficient to cross the chemocline generated by the salinity step of 0.23 PSU (Practical Salinity Units, see Dauphinee 1980) at 20 m found in the vertical profiles of temperature, salinity and density shown in Fig. 6. Thus, isothermal conditions and related mixing never occurred. The calculated vertical density gradients were only a factor of 2 smaller at the times of weakest thermal stratification (spring and autumn) than at the height of the summer temperature stratification.

Additionally, the profiles revealed a warm, salty layer at the base of the water column which was, in and of itself, stable. However, this layer was beneath a region of water slightly above the TMD, consequently, as heat diffuses faster than salt the bottom of the hypolimnion was effectively being heated by the bottom layer, resulting in it being lighter than the 100 m of water above it. The double-diffusion related mixing elevated the eddy diffusion to around 10^{-5} m^2s^{-1} (Stevens & Lawrence, 1997). Transport is 10^4 times more rapid than if molecular processes were solely responsible.

Annually, both Kitsault and Brenda Mines lakes receive inflow volumes due to precipitation and run-off of the same order of magnitude as the surface layer. Assuming this inflow is evenly mixed with the surface layer and that an equal volume flows out of the system then the inflow effectively dilutes the surface concentrations.

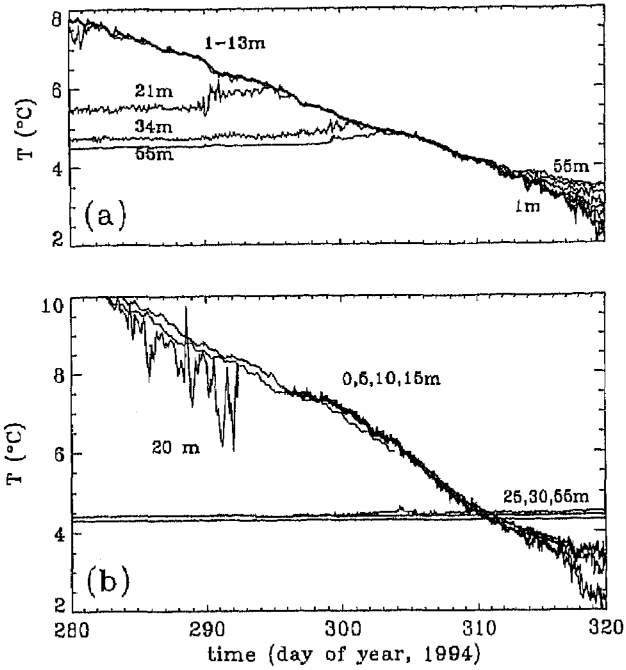

Fig. 5. Temperature time-series around the time of maximal surface densities during 1994 from (a) Kitsault Lake (depths of 1, 2, 3, 8, 13, 21, 34 and 55 m) and (b) Brenda Mines Pit-lake (depths of 0, 5, 10, 15, 20, 25, 30 and 38 m).

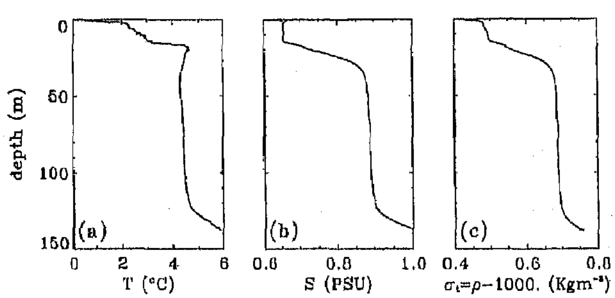

Fig. 6. (a) Temperature, (b) salinity and (c) density ($\sigma_T = \rho - 1000$) profiles from Brenda pit-lake, January 1995.

Modelling

Even though the magnitude of eddy diffusion implied by the field observations is greater than molecular diffusion, the time-scale for significant diffusive transport is of the order of decades. This makes direct comparison of model and observation unfeasible. However, analysis of a hypothetical basin, similar to Kitsault and Brenda Lakes, using parameters from the observations and the literature allows a sensitivity analysis of the model to inclusion of various mechanisms. Assuming that stratification results in much more rapid horizontal than vertical transport, a one-dimensional diffusion equation that incorporates a variable cross-sectional area is appropriate. Thus, any advective effects are implicit in the diffusion coefficient. The vertical transport is considered to be represented by

$$\frac{\partial C}{\partial t} = \frac{1}{A}\frac{\partial}{\partial z}\left(K_z A \frac{\partial C}{\partial z}\right) \quad (1)$$

where C is the concentration of material being considered, A is the cross sectional area as a function of depth z, and K_z is the eddy diffusivity characterising the effect of molecular and turbulent transport.

Realistically, the two boundary conditions associated with (1) are complicated. The epilimnion provides the upper boundary conditions where thermocline entrainment generates a flux and epilimnetic dilution controls the concentration level. The bed is defined as the interface between the consolidated material and the monimolimnion and was assumed to be a no-flux boundary. The possibility exists that the injection might be in stages spaced over many years or continuous. Two complicating factors are ignored in the model. First, if the consolidation time-scale is long then the bottom boundary condition is governed by a rate of release factor as more liquor is squeezed from the compacting slurry (Danielson & MacKinnon 1990). Second, the actual bed rises as material is injected and consolidated - displacing the entire water column into a new, wider, bathymetry.

A numerical approach was used to solve (1) because bathymetry and K_z distributions are unlikely to be well represented with simple functions. A centred-difference explicit time-domain scheme was chosen to solve (1) for $C(z,t)$ with spatial discretization chosen to represent at least the 1 m scale and time discretization chosen to match numerical stability criteria. Comparison with an analytic solution for constant K_z was within 0.7% after the first day of model time. In the absence of any outflow, mass was virtually conserved numerically by the model, with losses after 40 years of model time being of the order of 0.01% of the total initial mass. The hypothetical spatial domain was chosen as a 100 m deep basin with a radius varying linearly from 20 m at the base to 500 m at the surface (a volume of 2.7×10^7 m^3); this areal profile is comparable to both Kitsault and Brenda lakes. The monimolimnion itself was represented by initially setting $C = 1$ below a specified depth, while the remainder of the water column was set to $C = 0$. Here the half-depth was selected as the initial interface between monimolimnion and hypolimnion, so that with complete mixing the resultant average $C = 0.125$. The surface layer depth was fixed at 20 m and assumed well mixed. Improvement of this part of the model involves coupling it with a stratification simulation (e.g. DYRESM, Patterson *et al.* 1984) and is beyond the scope of this paper.

Any environmental system where this disposal technique is employed will likely be judged by tracer concentrations in the surface water. Consequently time-series of C at the surface (i.e. epilimnion) were used to compare model results.

Thermocline entrainment

The K_z at the base of the mixing layer was set to molecular levels ($K_z = 1 \times 10^{-9}$ m^{2}s^{-1}). This effectively retards gradient diffusion at the interface. The interfacial mixing was replaced by a bulk mechanism whereby a layer, centred about the thermocline, was homogenized at appropriate intervals. From the Kitsault and Brenda data we chose the thermocline mixing layer to be 3 m thick and well mixed every 7 days. Modifying the interfacial entrainment by realistic amounts had little effect on transport rates as the time-scales for diffusion adjacent the mixing region are much slower than the processes driving transport across the thermocline.

Constant K_z

Heinz *et al.* (1990) and Hondzo and Stefan (1994) collated observations of hypolimnetic eddy diffusion. Based on these data, the first simulation used a constant $K_z = 4 \times 10^{-6}$ m^{2}s^{-1} in the hypolimnion. The resulting C contours (Fig. 7a) show that, with this level of hypolimnetic eddy diffusion, the 0.1 solute contour reached the base of the epilimnion after 6.3 years and asymptoted to the homogeneous concentration of $C = 0.12$. These contours illustrate the rate of transport that should be expected in a hypolimnion. However under certain conditions elevated K_z's are possible. As described earlier, changes in density structure affected by groundwater inflow in the Brenda data implied that $K_z = 1 \times 10^{-5}$m^{2}s^{-1}. With this level of diffusion the model found that the $C = 0.1$ contour reached the thermocline after only 2.5 years.

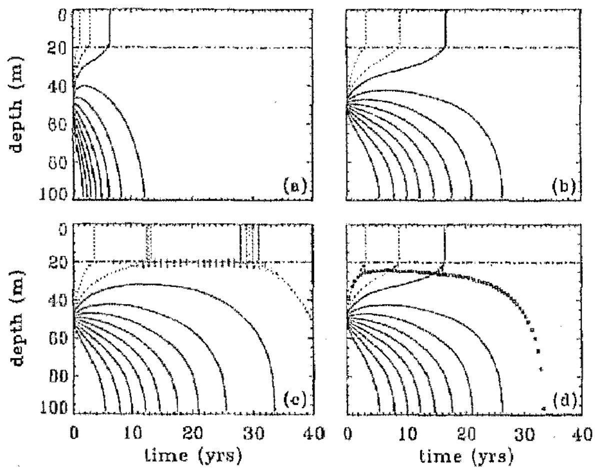

Fig. 7. Concentration contours for the modelled lake with diffusion modelled as (a) $K_z = 4 \times 10^{-6}$ m^{2}s^{-1}, (b) $K_z = \alpha N^{-\gamma}$ where $\alpha = 1.5 \times 10^{-7}$ and $\gamma = 0.8$, (c) $K_z = \alpha N^{-\gamma}$ with yearly surface layer refreshment and (d) $K_z = \alpha N^{-\gamma}$ with twice-yearly turnover. The depth of penetration of the turnover is marked by square symbols. The upper left hand dotted contour is $C = 0.01$, followed by 0.05, also dotted. The subsequent solid contours are at 0.1 intervals starting at 0.1 and increasing.

Variable $K_z = f(N)$

The dissolved chemicals from the introduced material elevate the density of the solution and consequent density gradients affect the magnitude of K_z. Heinz *et al.* (1990) related K_z to the stability of the density profile given by (e.g Turner, 1973)

$$N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z} \tag{2}$$

where $\partial\rho/\partial z$ is the vertical density gradient, g is downward gravitational acceleration and ρ_0 is average water density. These authors found that

$$K_z = \alpha N^{-\gamma} \tag{3}$$

and the present model followed Heinz *et al.* (1990) results and used $\alpha = 1.5 \times 10^{-7}$ and $\gamma = 0.8$. Note that N has dimensions of s^{-1} so that α is dimensional (here using m and s). Fig. 7b illustrates the scenario where the difference between $C = 0$ and $C = 1$ corresponds to a density step of 35 kgm^{-3} (Danielson & MacKinnon, 1990). From these contours it is apparent (Fig. 7b) that this new parameterization has a substantial impact, where the appearance of the 0.1 contour in the surface layer was delayed by 10 years relative to Fig. 7a. Note that the average N^2 were above the range of validating data collected by Heinz *et al.* (1990) by a factor of 5. The fact that the present scenario exceeds available observations highlights the lack of data pertaining to transport in deep, strongly stratified, waters.

Surface layer flow-through

High flow-through expected during the snow-melt induced spring freshet enters the surface layer and, under equilibrium, a similar amount of fluid exits through a surface outlet - thus the surface layer is flushed. Flushing was simulated by setting $C = 0$ in the surface layer once ever year in spring and represents a conservative estimate. Flushing forms a loss term in overall conservation of C. It had little impact on the appearance of the 0.01 contour in the surface layer (Fig.7c) but the 0.1 contour of C never reaches a level shallower than 30 m. Thus, the surface layer flushing, not limited by thermocline entrainment, removed mass at a rate greater than it arrived through diffusion. In fact, over the 40 year duration of the model, the total mass retained in the entire basin was reduced by 70%.

The effect of turnover

If there is no secondary stratification retarding turnover at the base of the surface layer (i.e. Kitsault Lake) then, upon cessation of thermal stratification, the hypolimnion is exposed to the effects of wind mixing and convective cooling. This was parameterized by assuming a fixed amount of energy is applied to the water column at the end of each stratified season. Through the use of a mixing efficiency it was possible to determine the resultant change in potential energy of the water column (Ward *et al.* 1990). The kinetic energy available for mixing was estimated as

$$E_k = A(0) d u_*^3 T \tag{4}$$

where d is a coefficient that converts u_* into the surface drift velocity, $A(0)$ is the water surface area and T is the duration of the isothermal period. Appropriate values chosen here were $d = 20$ (Monismith 1986), $u_* = 5 \times 10^{-3}$ ms^{-1} and, from Fig. 5a, $T = 10$ days. Inclusion of a mixing efficiency of 13% (Ward *et al.* 1990) provided the resultant change in potential energy.

Stepping down through the model water column and mixing successive discretization layers until E_k was fully exchanged into potential energy determined the depth to which turnover penetrated. Fig.7d illustrates the result, with symbols identifying the depth of the turnover. Note that the contouring smooths over the sharpened density structure created by the turnover so that if individual profiles are viewed the well-mixed region is clear. The turnover penetration initially deepened to the top of the monimolimnion but as diffusion spread the hypolimnion-monimolimnion interface, the penetration depth decreased to almost the base of the surface layer.

The depth of penetration was obviously sensitive to u_*, as modest increases in this value hastened the arrival of the 0.1 contour at the base of the surface layer. In fact, raising u_* to 0.01 ms^{-1} provided sufficient kinetic energy to mix the entire basin 9 years earlier than in the case where $u_* = 0.005$ ms^{-1}. Interestingly, if surface layer flushing was combined with the turnover mechanism, the turnover penetration was reduced because the chemocline at the base of the surface layer was renewed annually increasing the overall required change in potential energy. Also, the regeneration of the chemocline every year created an oscillation in the penetration depth because the autumn turnover would happen soon after surface water renewal, whereas diffusion had 6 months to act before the spring turnover. This regeneration did not appear to impact upon the C structure for $C > 0.1$.

Repeated loading

Finally, continuous production of storage material was examined by regenerating the original bottom layer at a selected frequency. As $C = 1$ represents the saturation concentration of the material that is dissolved from the tailings, refurbishment of the monimolimnion can not be additive (i.e. $C \geq 1$). As an example, reformation of the original monimolimnion every 5 years (Fig. 8a) elevated the surface layer concentration in a linear fashion so that $C(z = 0) = 0.4$ after 40 years and almost 3 times the initial mass was contained in the basin. The introduction of surface layer flushing and turnover into this situation (Fig. 8b) created an equilibrium where there were relatively high concentrations of C just beneath the surface layer.

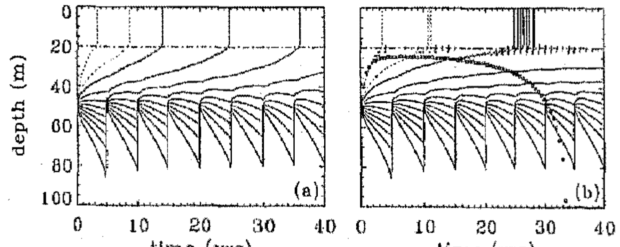

Fig. 8. Concentration contours for the modelled lake with diffusion modelled as (a) $K_z = \alpha N^{-\gamma}$, with 5 yearly monimolimnion replenishment and, (b) $K_z = \alpha N^{-\gamma}$, with 5 yearly monimolimnion replenishment and twice-yearly turnover and once yearly surface layer refreshment. The contours are the same as for Fig. 7.

Discussion

Apparently injecting material into the bottom of a lake to create an artificial monimolimnion can have varied effects on the stratification. The resulting concentration distribution depends on what type of material is injected (controlling the density) and, especially, how it is injected (controlling monimolimnion depths, leaching rates, refurbishment frequency). The fundamental idea to communicate to industry is that it is almost a certainty that some material stored at the bottom of the lake will eventually appear at the surface. Thus, if trace levels of the material being stored are hazardous, then sub-aqueous disposal is not a solution. If the appearance of small levels of the disposed material in the lake surface waters is acceptable then the factors described in the previous section should be considered to determine transport rates.

A plot of the epilimnion concentration $C(z=0)$ for all the model runs discussed above is shown in Fig. 9. Most of the curves fall within an order of magnitude of each other. Whilst time-scales for testing of material diffusion are long, estimates of K_z can be gauged with one year of hypolimnetic temperature time-series (e.g. see Heinz *et al.* 1990). The chemical stratification observed in the Brenda pit-lake (additional to that generated by a monimolimnion), as observed in the Brenda pit-lake data, appeared to minimise vertical transport in the turnover phase of the twice-yearly cycle.

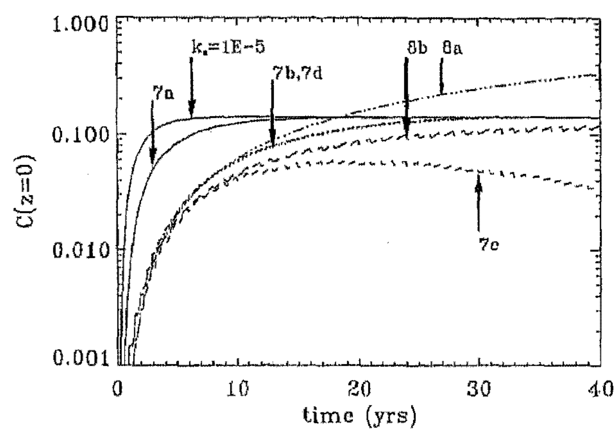

Fig. 9. Epilimnion concentrations, $C(z=0)$, as a function of time for the runs of Fig.7a-d and Fig. 8a-b. Also included are results from a model run with constant $K_z = 1 \times 10^{-5}$ m^{2}s^{-1}.

Surface layer flushing appears to be important in reducing concentrations of material, initially in the monimolimnion, that leave the system through the outflow. As diffusion will eventually bring dissolved material from the deep regions to the surface, the greater the dilution the better. Also, if the material stored is biologically non-accumulative then the sub-aqueous disposal facility might act as a slow diffuser of material such that it leaks into the external environment but at greatly reduced concentrations.

Whilst the emphasis here has been placed on long-term average mechanisms, and one dimensional ones at that, some comment on behaviour outside these bounds is merited. Wind-driven internal seicheing is a processes that can set the internal stratification oscillating vertically with amplitudes of several meters. With sufficient wind strengths it is possible that the thermocline region may actually reach the surface for a period at the upwind shoreline (Stevens & Imberger, 1996). Thus, consideration should be given to the position of the outflow relative to the direction of the strongest winds and also the magnitude of typical wind speeds relative to stratification. This wind-driven effect is especially important if the monimolimnion has evolved in a way similar to Fig. 8b whereby the annually stratification shows a strong gradient in C just beneath the epilimnion. If the thermocline region reaches the outflow for any period then high downstream concentrations of C will result.

Conclusions

This paper examined the likely impact of slurry injection into the bottom of a small deep stratified lake. At the scales considered here it is unlikely that total "disposal" of material is achievable. Accurate estimation of hypolimnetic eddy diffusivity was important and this highlights the need for more data on entrainment at deep strongly stratified interfaces. Furthermore, an additional stratifying agent had a marked effect when combined with precipitation-induced flushing of the surface layer. This combination served to increase the change in water column potential energy required for turnover and thus retards the penetration of turnover. In the modelling repeated loading of the monimolimnion, without surface flushing, resulted in relatively rapid increases in contaminant levels in the epilimnion. Repeating loading, with surface flushing, generated high contaminant levels just beneath the epilimnion. This presumably leaves the system susceptible to short-term effects such as wind-driven upwelling.

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Notations

$A(z)$	= area at depth z [m^2],
α	= dimensional coefficient for eddy-diffusion model,
C	= non-dimensional concentration,
d	= drift coefficient,
$\partial/\partial z$, $\partial/\partial t$	= partial derivative operators, with respect to depth, [m^{-1}] or time [s^{-1}],
E_k	= wind-imparted kinetic energy, [J],
g	= gravitational acceleration, [ms^{-2}],
γ	= exponent coefficient for eddy-diffusion model,
K_z	= coefficient of eddy diffusion, [m^2s^{-1}],
N	= buoyancy frequency, [s^{-1}],
ρ, ρ_0	= density, reference density, [kgm^{-3}],
σ_T	= perturbation density, [kgm^{-3}],
t	= time, [s],
T	= duration of unstratified mixing, [s],
TMD	= temperature of maximum density [C],
u_*	= friction velocity, [ms^{-1}],
z	= depth, [m].

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