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Internal Wave Generated Temperature Fluctuations in Stratified Lakes

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Management Perspective

Internal Wave Generated Temperature Fluctuations in Stratified Lakes

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Kootenay Lake was overenriched in the 1970s but is now nutrient poor with reduced fish production. Further complicating lake management are sporadic fishkills. It is thought that fishkills may be caused by rapid temperature fluctuations which affect the sensitive Kokanee salmon. As well as fisheries concerns, temperature fluctuations have more general water quality implications in proposed hydroelectric projects in British Columbia such as the Kemano Completion Project.

A partnership of NWRI and UBC researchers studied the temperature fluctuations in extensive data gathered by NWRI in 1976-78. Of particular importance was that the data were maintained in machine readable format despite several changes in computer technology over the years. Maintenance of the data made further fieldwork unnecessary for the purposes of this preliminary diagnostic effort. Internal waves were found in the summer thermocline which is the transition zone between warm surface water and cold bottom water. Modeling these waves revealed that a fish maintaining its depth could experience a temperature change of 1°C per hour. A more sophisticated measurement and modeling effort were recommended to enable prediction of thermal effects in any one year.

INTERNAL WAVE GENERATED TEMPERATURE FLUCTUATIONS IN STRATIFIED LAKES

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Abstract:

Rapid fluctuations of temperature in lakes have the possibility of seriously stressing some piscean species. Here we describe how the temperature stratification forms and what causes it to fluctuate as internal waves. A basic mechanistic approach to the prediction of temperature variations associated with internal waves is given, with a caveat that the system is likely always at some transient stage in its development.

INTRODUCTION

Vertical temperature stratification is an important factor in the ecological status of inland standing waters such as lakes and reservoirs. Essentially it controls mixing of nutrients and oxygen and transport into regions where there is light. In addition the stratification has direct impact on the physiological well-being of resident piscean species. This paper reviews some of the basic features of thermal stratification relevant to standing waters of the Columbia system with particular examples from Kootenay Lake, British Columbia.

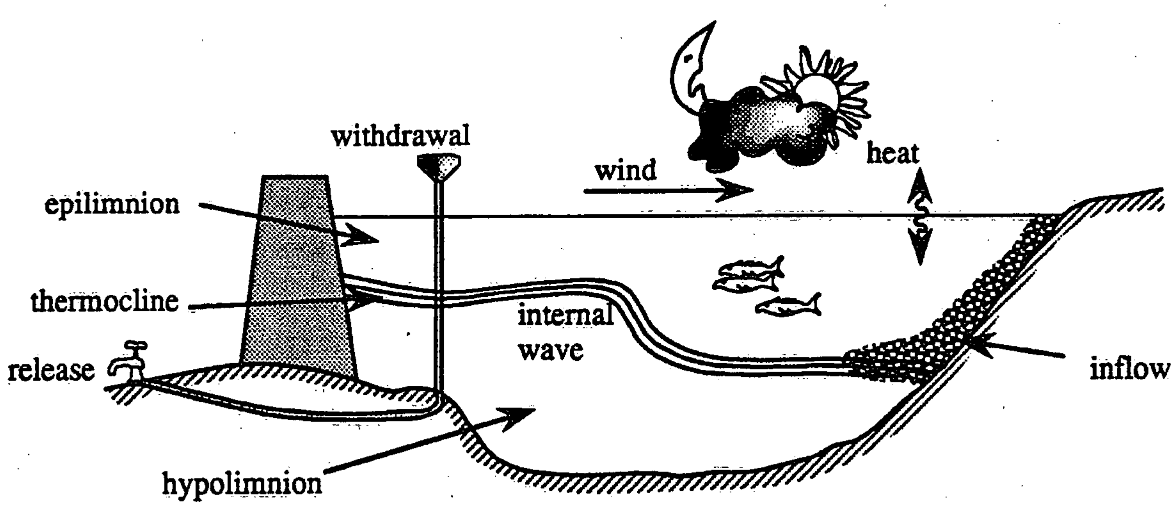

Figure 1. A sketch of basic mechanisms controlling the stratification

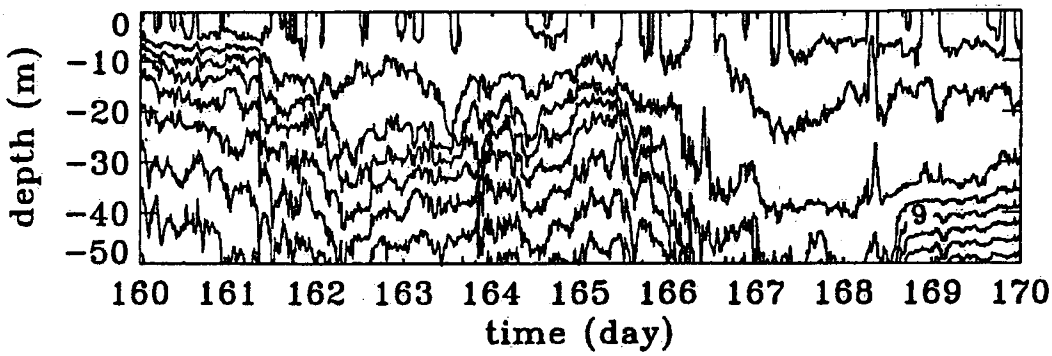

Figure 2. Isotherms from Kootenay Lake, 1992.

cation. As is generally necessary for the purposes of simplification, certain aspects of the physics must be ignored or, at best, calibrated for. Unfortunately internal waves have largely fallen into this category. Certainly, models of internal waves exist, but these in turn do not feedback and affect the vertical temperature structure. Thus it is important to describe some basic facets of internal wave modelling.

The first approximation in determining the period of the gravest internal wave (T_1) is to assume the lake is a two layer box of arbitrary width (Heaps and Ramsbottom, 1966). The internal wave speed is given as

$$c = \sqrt{g'(h_1 h_2)/(h_1 + h_2)}$$

where h_1 and h_2 are the thicknesses of the epilimnion and hypolimnion respectively, g' is the modified gravity defined as $g' = (\Delta\rho/\rho_0)g$ where g is gravitational acceleration, ρ_0 is the average density of water and $\Delta\rho$ is the density difference between the top and bottom layers. As mentioned earlier this wave speed can be as great as 0.5 ms^{-1}. The time taken for the wave to travel down and back up the lake is the period $T_1 = 2L/c$ where L is the length of the lake.

Two assumptions are worthy of scrutiny here, firstly, lakes are rarely well represented by a rectangular box; although lakes in long glacially formed valleys are about as close as one can get, and secondly, the stratification is poorly represented by two layers. Successful efforts have been made in improving predictive analyses for internal wave periods. However, the resultant methodology is complex and might be considered a first order correction, especially given that the stratification is ever changing and so in a numerical model any period analysis will need to be repeated at every timestep.

An estimate of the amplitude of these internal waves is made through the Wedderburn number (Imberger, 1985) which, again uses a two layer model. The Wedderburn number is defined as

$$W = \frac{g' h_1^2}{u_*^2 L}$$

where u_* is the friction velocity related to the wind speed by a drag coefficient. Fischer *et al.* (1979), for example, presents an explanation of the determination of u_*. The quantity defined by W is non-dimensional and effectively represents h_1/ζ where ζ is the internal wave amplitude. Thus, $W \gg 1$ implies very small amplitudes and $W \ll 1$ indicates very large amplitudes.

An additional assumption made in the formulation of W is that it is a steady state model where the wind must blow for at least $T_1/4$ for it to be applicable. This implies

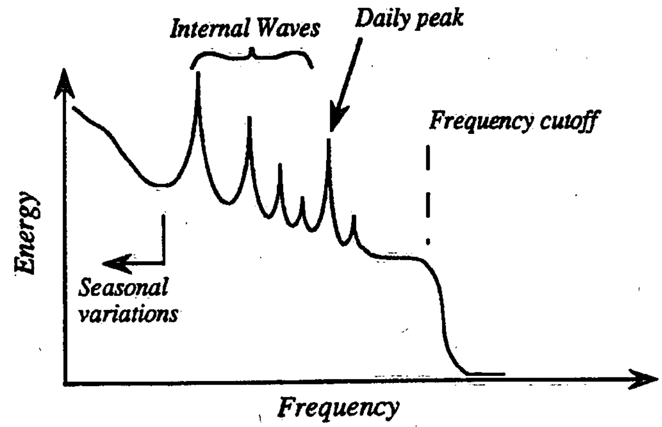

Figure 3. Idealised Energy spectrum.

that, for example in the case of Kootenay lake where, at the peak of summer $T_1 \approx 7$ days, a half-hour long storm cannot be used to calculate a u_* and then a W, but rather, the wind record must be filtered with a cut-off at $T_1/4$ and then the W history maybe calculated.

Spectral analysis identifies the frequencies at which the energy is greatest. As is typical with almost any natural system, energy is found in a number of frequency bands. The schematic frequency spectrum of Fig. 3 illustrates how the energy is distributed in the frequency domain. Meteorological forcing manifests itself in a daily peak and energy at very low frequency is due to seasonal fluctuations. The stratification itself has an intrinsic frequency limit related to the temperature stratification, above which buoyancy related fluctuations are not possible. In addition to these regions in the energy spectrum are the internal waves. A two layered two-dimensional box supports only one family of internal waves; a continuously stratified irregularly stratified basin will support an infinite number of waves. Thus, between the seasonal fluctuations and the buoyancy cutoff several peaks are observed in the energy spectrum and they represent different types of internal waves. In any given situation, analysis of typical geometry, stratification and forcing using parameters like T_1 and W is necessary to determine the most likely internal waves.

Practical Implications

Through simple rearrangement using arguments implied by the derivation of W it is possible to show that the maximum rate of temperature change likely to be experienced is given by

$$\left(\frac{\partial T}{\partial t}\right)_{\max} = \frac{1}{\alpha \delta g}\frac{c u_*^2}{2h_1}$$

where α is the coefficient of thermal expansion, and δ is the thickness of the thermocline. The linearity implicit in the development of c implies that the wave is a true half-sinusoid with a node at mid-lake. However, small W conditions and observations indicate the reality is otherwise and the waves, propagating as internal bores, can generate displacements anywhere along the lake. In addition if $W \approx 1$ or less this fluctuation can be expected to occur throughout the water column.

Using typical values of $\alpha = 10^{-4}{}^\circ C^{-1}$, $\delta = 5$ m, $c = 0.3\text{ms}^{-1}$, $u_* = 0.01\ \text{ms}^{-1}$ and $h_1 = 10$ m, the calculation indicates that the temperature can change by a degree an hour. The values used in this example are not exceptional in any way, a strong storm will create a much greater u_*, significantly enhancing the estimated temperature change. This simple model indicates the importance of internal waves to systems that have no means of avoiding undesirable temperature changes.

For a given situation, having established the relevance of thermal fluctuations to the problem at hand through approaches like the one described above, we recommend the following procedure for determination of the thermal dynamics of the system. Using guessed data and/or a single observation, examine the literature for similar systems and calculate basic properties such as T_1 and W. Based on this analysis and experience, design a field monitoring program. This involves the deployment of a meteorological station and at least 1 thermistor chain (a string of thermistors at different depths in the water column). Lakes of the Columbia system, by their very nature, are found in valleys and have their own micro climate so that transferral of wind speed and temperature properties from meteorological stations located even only a few kilometers away may be misleading. The cost of data logging devices and thermistor chains are decreasing in price constantly making them a reasonably cost-effective field tool. Logging data every 10 minutes will provide a valuable time series that is infinitely more informative than irregular manually recorded temperature profiles.

This data should reveal the dominant mechanisms and their relevance to the problem at hand. At this point modelling techniques can be applied. The options here are to employ packaged general models that are designed to cover a wide range of conditions (e.g. Imberger and Patterson, 1990, §XII) or build process oriented models (e.g. Killworth and Carmack, 1979) that can be tailored to the specific conditions at hand. Notwithstanding the philosophical arguments associated with these options, the important phase after the success or failure of this first pass at the modelling is to iterate the procedure. Thus, the data collection should be fine tuned and augmented with additional data and the process repeated with a suitably modified model. A model that appears to provide correct results the very first time probably hasn't had its output examined sufficiently.

Irrespective of the choice of packaged or process-orientated models, an experienced data collection/modelling group will still probably need to be employed, at least in the first instance. However, technological advances and recognition of the importance of the physical mechanisms operating are continually making this option more attractive.

References

FARMER, D.M., 1978 Observations of long nonlinear waves in a lake. J. Phys. Oceanogr., 8, 63-73.

HAMBLIN, P.F., 1978 Internal kelvin waves in a fjord lake. J. Geophys. Res., 83, 2409-2418.

HEAPS, N.S. AND A.E. RAMSBOTTOM, 1966 Wind effects on water in a narrow two-layered lake. *Phil. Trans. R. Soc. Lond.*, **A259**, 391-430.

IMBERGER, J., 1985 The diurnal mixed layer. *Limnol. Oceanogr.*, **30**(4), 737-770.

IMBERGER, J. AND J.C. PATTERSON, 1990 Physical Limnology. *Advances in Applied Mechanics*, **27**, 303-473.

KILLWORTH, P.D. AND E.C. CARMACK, 1979 A filling-box model of river-dominated lakes. *Limnol. Oceanogr.*, 24(2), 201-217.

STEVENS, C.L., G.A. LAWRENCE, P.F. HAMBLIN AND E.C. CARMACK, 1994 Wind forcing of internal waves in long narrow stratified lakes. Fourth International Symposium on Stratified Flows, Grenoble, Vol. 3.

WIEGAND, R.C. AND E.C. CARMACK, 1986 The climatology of internal waves in a deep temperate lake. *J.Geophys.Res*, **91**(C3), 3951-3958.

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