Nutrient mixing in a submerged surfzone

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Nutrient Pollution
Lakebed pollution removal (denitrification)

Removal of NO$_3^-$ pollution
⇒ creation of N$_2$ in bed
⇒ Elevation near-bed N$_2$

Chemical flux = $\frac{\partial C}{\partial z}$

Turbulent diffusivity (Henderson)

Vertical gradient in concentration (Harrison and Deemer)

Outline

1. Description of internal waves
2. Influence of waves on nearbed mixing
3. Influence of waves on lakewide transport
Examples of internal waves

Mediterranean
Columbia River
Australia
Puget Sound
Australia
China

Lacamas Lake

- lake map with depth contours
- inlet
- impoundment
- impound location

Lake depth:
- 0-4.5m
- 4.5-9m
- 9-13.5m
- 13.5-18.3m
- 18.3-19.8m
Internal waves visible as tilted temperature contours

Next, will show data from near where thermocline meets lakebed.

Full-depth velocity profiles
Tripods deployed on Lakebed

Acoustic Doppler Profiler (ADP)
Acoustic Doppler Velocimeter (ADV)
PME fast temperature
Chemical sampling
Not shown: Temperature loggers

Temperature fluctuates owing to internal waves

Temperature $T$ ($^\circ$C)

Time (yearday)

17 May 15 July
Temperature fluctuates owing to internal waves

- Lake warms $1^\circ C$ in 60 days.
- Waves propagate upslope at about $0.04 \text{ m/s}$.

Dissolved oxygen fluctuates owing to internal waves
Internal bores

Overturning
Breaking

Undular Bores

Temperature

Backscatter

Upslope velocity

Vertical velocity

% overturns

(counts)

(m/s)

(m/s)

(m/s)
Undular Bores

Other examples of undular bores
Outline

1. Description of internal waves
   - Influence of waves on nearbed mixing
2. Influence of waves on lakewide transport

Mixing varies owing to internal waves

Chemical flux = \(-D \frac{\partial C}{\partial z}\)
Mixing varies owing to internal waves

Chemical flux = \(-D \frac{\partial C}{\partial z}\)

Chemical fluxes

Time (yearday)

Temperature (°C)

Backscatter

Upslope velocity

Vertical velocity

Turbulent diffusivity

log_{10} [D (m^2 s^{-1})]

Turbulent diffusivity

<table>
<thead>
<tr>
<th>Yearday</th>
<th>Backscatter (counts)</th>
<th>Upslope velocity (m/s)</th>
<th>Vertical velocity (m/s)</th>
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Chemical fluxes

Inferred Total N_2 Flux (mmol m^{-2} h^{-1})

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Temperature (°C)

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Eulerian mean currents flow downslope

- Should carry warm water downslope, but rapid warming not observed – why?
• Particles spend more time moving upslope under wave crests than downslope under troughs.
• Resulting velocity correction called Stokes drift:
  mean $u$ for particle = $u_{sd} + \langle u \rangle$
• If wave propagates steadily at known speed, can calculate $u_{sd}$.
Slow variability of $u_{sd}$ and $<u>$ correlated

Intermediate temperature water transported to deep lake (rate appears sufficient to explain summer thickening and deepening of thermocline base).

Particle transport < Eulerian mean. Owing to cancelation by Stokes drift.

Mass transport

Under certain conditions, isothermal mean velocity = Eulerian mean velocity + Stokes drift, i.e. isothermal velocity = mean velocity of water particles.
Summary

1. Internal waves pitch forward near lakebed, sometimes “breaking” or forming undular bores.
2. Mixing rates vary by orders of magnitude through wave cycle.
3. Chemical fluxes estimated from turbulence measurements and near-bed chemical gradients appear sensible (more work required).
4. Upslope Stokes drift from waves appears to roughly cancel Eulerian downslope flow.
5. Net transport of intermediate temperature water away from internal surfzone appears to make significant contribution to mixing/deepening lakewide stratification (more work required).

Ongoing work

• Flow through mangroves in New Zealand and Mekong.
• Analysis of surfzone eddies data.