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Glacial meltwater modeling to simulate streamflow and lake levels in Taylor Valley, Antarctica

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I. Introduction

Three closed-basin, perennially ice-covered lakes occupy the valley floor: lakes Bonney, Hoare, and Fryxell. Glacial meltwater accounts for nearly the total inflow to these lakes. Groundwater flux is essentially non-existent. Outflow is through sublimation of the frozen lake surface. Lake levels are highly sensitive to changes in climate and are mediated by the surface energy balance of the glaciers. With mean summer air temperatures below 0°C, glacier ablation shows a complex sensitivity to solar radiation and wind speed. (Fountain et al. 1999)

II. Methods

The distributed ICEMELT model (Hoffman et al. 2016) is applied to simulate streamflow and lake level from 1995 to 2013 at a grid resolution of 250 m. The model is:
- a distributed, physically-based energy balance model
- driven by gridded local weather measurements
- calibrated using ablation measurements at Taylor and Canada glaciers
- tuned specifically to local ice and meteorological conditions
- assumes direct (same-day) meltwater routing

Additionally, the model accounts for solar radiation penetration into the ice, the spatial variability of albedo, and glacier topography that affects microclimate.

Objectives:
- Simulate modern streamflow and lake level change in Taylor Valley.
- Test meltwater and lake water balance model assumptions.
- Can these models be used to study paleo-lakes in the MDV?

Glacier Energy Balance Equation:

\[ \dot{E} = Q_{\text{direct}} + Q_{\text{stream}} + Q_{\text{ground}} + P - S - E_{\text{A}} \]

Simplified to:

\[ \frac{dV}{dt} = Q_{\text{glacier}} = S \times A \]

III. Streamflow Results

Figure 3. Simulated (dashed) versus observed (solid) daily runoff totals at Canada Stream (7) for the 2001-02 melt season. Associated daily streamflow measurement uncertainty (±25%) is shown as the grey shaded area. This season was an anomalously ‘flood year’.

Figure 4. Top panel (A) shows model efficiency in predicting total daily discharge using the Nash-Sutcliffe Efficiency (E) for all 15 streams by year. The left most column shows E values for each stream across all 10 modelled seasons and the bottom row shows E values for each season all at once.

Figure 5. Stacked bar plot of observed (A) and predicted (B) total annual runoff for all streams. Stacked bar plot of observed (C) and predicted (D) percent of total annual runoff for all streams. Blue colors represent streams that flow into Lake Bonney, red colors for streams flowing into Lake Hoare and green colors for streams flowing into Lake Fryxell. The beige color represents Commonwealth Stream, which flows to McMurdo Sound.

IV. Lake Level Results

Figure 7. Simulated versus observed lake level change. Modelled using a sublimation rate of 0.35 m yr⁻¹ before 2004 and 0.27 m yr⁻¹ after 2003. Red arrows show ‘flood years’.

Figure 9. Sutcliffe Efficiency (E) of each season (1995 to 2010) for the 2001-02 melt season. A. Nash-Sutcliffe Efficiency (E) of each season (1995 to 2010) for the 2001-02 melt season. B. Coefficient of determination (\(R^2\)) and mean absolute error (MAE) for each season (1995 to 2010) for the 2001-02 melt season.

V. Conclusions

• With an adjustment of ~0.85 to albedo, the meltwater model can predict streamflow moderately well.
• Predicted runoff results show higher efficiency in simulating dynamics but lower efficiency in simulating observed flow magnitudes.
• Some meltwater sources are being neglected, e.g. ablation zone size or high elevation snow melt (low magnitude efficiency).
• Meltwater model results are better for Canada and Taylor (Bonney basin) glaciers.
• Increased model bias on Commonwealth and Kukri Hills glaciers suggest that unaccounted ice surface properties, e.g. surface roughness length, are present.
• Lake model results show that under-predicting melt inflow limits ability to model lake level change.
• Particularly at Lake Fryxell and during flood years of 2001-02, 2008-09 and 2010-11.

Lake surface sublimation rates required to fit lake level rise (0.27 to 0.35 m yr⁻¹) are less than estimated, real-world values (0.35 to 1 m yr⁻¹).

References
Hoffman et al. 1999: Physical Controls on the Taylor Valley Flows, Antartica. Reference

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