Monitoring and Modeling Rain-Snow Dynamics Across an Elevational Gradient in a New England Montane Watershed

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INTRODUCTION

The Ranch Brook watershed in Vermont, USA exists in a temperate, humid climate in which spatial and temporal snow variability is highly sensitive to slight shifts in air temperature. Despite the importance of snow to regional hydrology, snowmelt dynamics remain understudied in this part of the world and historical data are scarce. Studying the at-risk snowpack of these low-elevation mountains is beneficial to understanding potential effects of climate warming. Monitoring infrastructure has recently been implemented in Ranch Brook to monitor snowpack, meteorology, soil response, and runoff at a high spatiotemporal resolution. Monitoring initiatives include: the Summit-to-Shore (S2S) network, which consists of 22 sites (13 of which are in Ranch Brook) with meteorological and snow monitoring equipment, nine soil moisture/temperature probe transects, stream pressure transducers at every tributary, and LiDAR snow depth measurements for a series of dates throughout the winter season. Using these data, data-driven analyses of snowmelt dynamics as well as physics-based models were developed and allow for an in-depth analysis of snow hydrology in Ranch Brook.

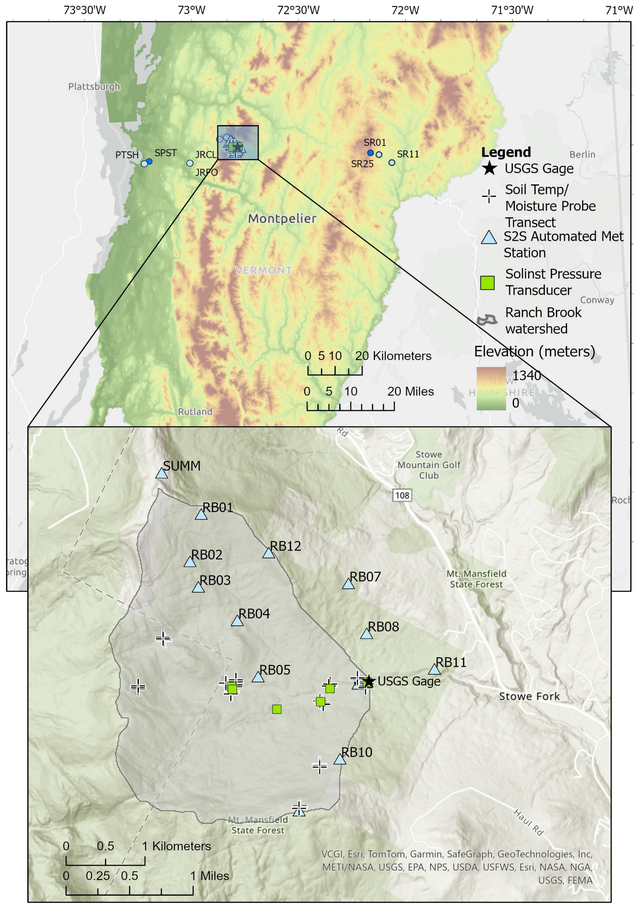

Fig. 1: Study domain with monitoring sites surrounding Ranch Brook.

STABLE ISOTOPE ANALYSIS

- **Objective:** Examine combinations of soil, snowpack, and meteorological conditions that control runoff generation during thaw events.
- **Methods:** Collect sequential stream samples using an ISCO automated pump and snowmelt/precipitation samples using passive wick snowmelt lysimeters during thaw events.
- Characterize events based on in-situ sensor data from Ranch Brook S2S stations
- Separate and quantify event flow using $\delta^{18}O$ and δD in a two-component isotope hydrograph separation.

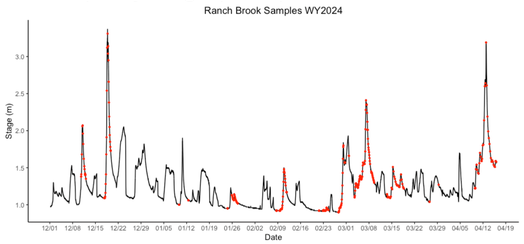

Fig. 2: Left—Stream and snowmelt lysimeter samples collected for isotope analysis during water year (WY) 2024. Right—Waterbury, VT after the December 18, 2023 rain-on-snow event (Photo: timesargus.com)

Event Analysis of Soil Conditions

- The distributed soil probe network allows us to quantify soil response and its spatiotemporal heterogeneity during each event.
- Antecedent wetness and temperature can help predict the percent of new water in Ranch Brook.

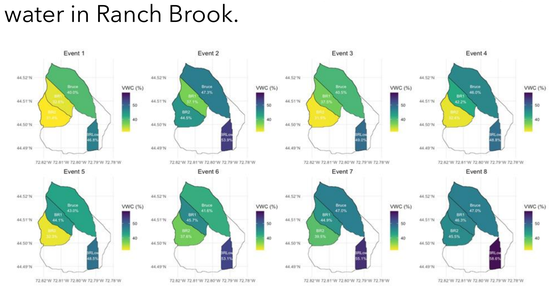

Fig. 3: Left—Antecedent soil moisture map by event within the watershed. Right—Pictures of a snowmelt lysimeter, soil probe, and ISCO installed in Ranch Brook.

Hydrologic Response

- Substantial new water variability by event: 9-54% for ROS and 18-38% for thermal melt events.
- In the two study years there was substantial interannual variability: 13-54% for WY2024 and 9-23% for WY2023.
- WY2024 had more frequent and intense events with two over 13.0 m^3/s, while WY2023 only saw the freshet rise to 6.7 m^3/s.

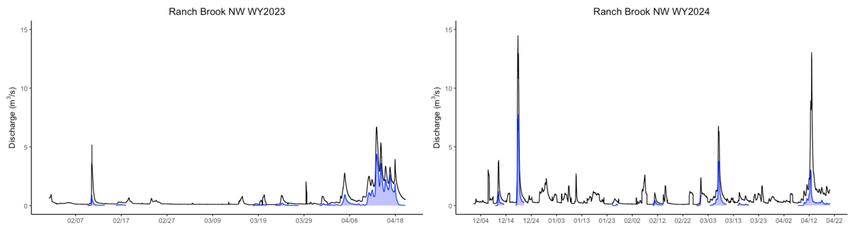

Fig. 4: The hydrograph for WY 2023 and WY 2024 separated into new (blue line) and old (black line) water components using an isotope hydrograph separation.

PHYSICS-BASED SNOWPACK MODEL

Using available historical data and the newly developed monitoring infrastructure (Figure 1 & 6), SnowModel (Liston & Elder, 2006), a physics-based distributed snowpack model, was calibrated and validated for a domain encompassing Ranch Brook and Mt. Mansfield. Snow depth and SWE were the primary calibration variables (Figure 5). To tailor SnowModel to the Vermont snowpack and climate, adjustments were made to code dictating the following processes: temperature lapse rates, densification, liquid water percolation routine, and the rain-snow threshold.

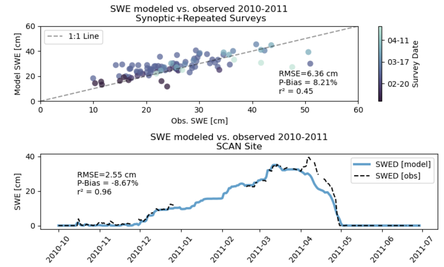

Fig. 5: Model calibration for winter 2010-2011. Top—modeled vs. observed SWE from synoptic (single day) and repeated (repeat measurements throughout the season) manual survey results. Bottom—modeled and observed SWE timeseries at the NRCS SCAN site on the West side of Mt. Mansfield. Error metrics are shown.

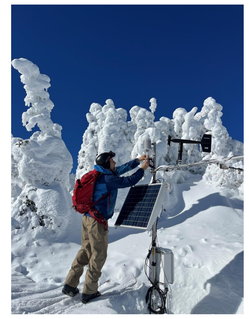

Fig. 6: Maintenance at the summit (SUMM) S2S meteorology and snowpack monitoring site.

Model output allows for spatiotemporally complete analysis of snowpack, energy balance, and meteorological variables. The calibrated model was used to conduct case study analyses on specific rain-on-snow events, such as one that occurred on February 25th, 2016 (Figure 7). Additionally, sensitivity analyses were implemented to study: 1) model sensitivity to methods of parameterizing the rain snow threshold, and 2) spatiotemporal snowpack sensitivity to perturbations in temperature and precipitation, representing future climate scenarios.

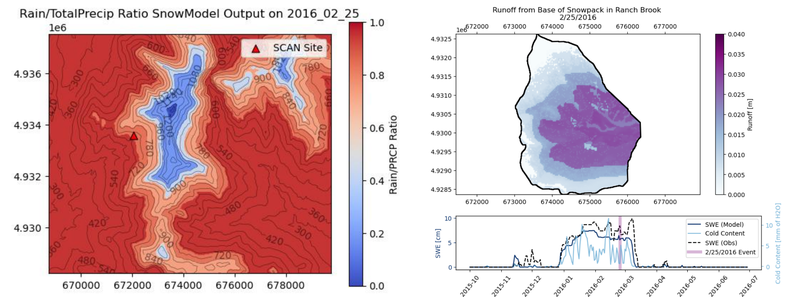

Fig. 7: Left—Model representation of the rain-snow line during 2/25/2016 event. Where the rain/total precipitation ratio is > 0.5, precipitation is rain, else it is snow. The rain-snow line is where the rain/PRCP ratio = 0.5.
Right, top—Model output showing runoff from the base of the snowpack in Ranch Brook. Right, bottom—Model SWE vs. observed SWE at SCAN site, as well as modeled cold content of the snowpack. The timing of this particular event is highlighted.

NEXT STEPS

- Since we've captured so much variability over the course of two seasons, we will work to integrate different datasets to test hypotheses and adjust for the upcoming isotope sampling season.
- Integrate SnowModel output and stable isotope analysis to investigate hydrologic response to rain-on-snow events, specifically during the December 18th, 2023 flood.