USING GROUND PENETRATING RADAR TO ASSESS THE VARIABILITY OF SNOW WATER EQUIVALENT AND MELT IN A MIXED CANOPY FOREST

Ryan Webb[1]

EXTENDED ABSTRACT

Snow is an important environmental variable in headwater systems that controls hydrological processes such as streamflow, groundwater recharge, and evapotranspiration. These processes will be affected by both the amount of snow available for melt and the rate at which it melts. In complex mountainous terrain, a number of factors can affect snow water equivalent (SWE) and melt including slope, aspect, canopy type, and canopy density.

This study assesses variability of SWE and melt during the melt season using ground penetrating radar (GPR) to survey multiple plots in northwestern Colorado near the Dry Lake snow telemetry (SNOTEL) as further detailed in Webb (2017). This station is at an elevation of 2510 m asl in an open area near deciduous trees (Figure 1). The SNOTEL data show peak SWE tends to occur here on average on April 5 with a 35 year median peak SWE

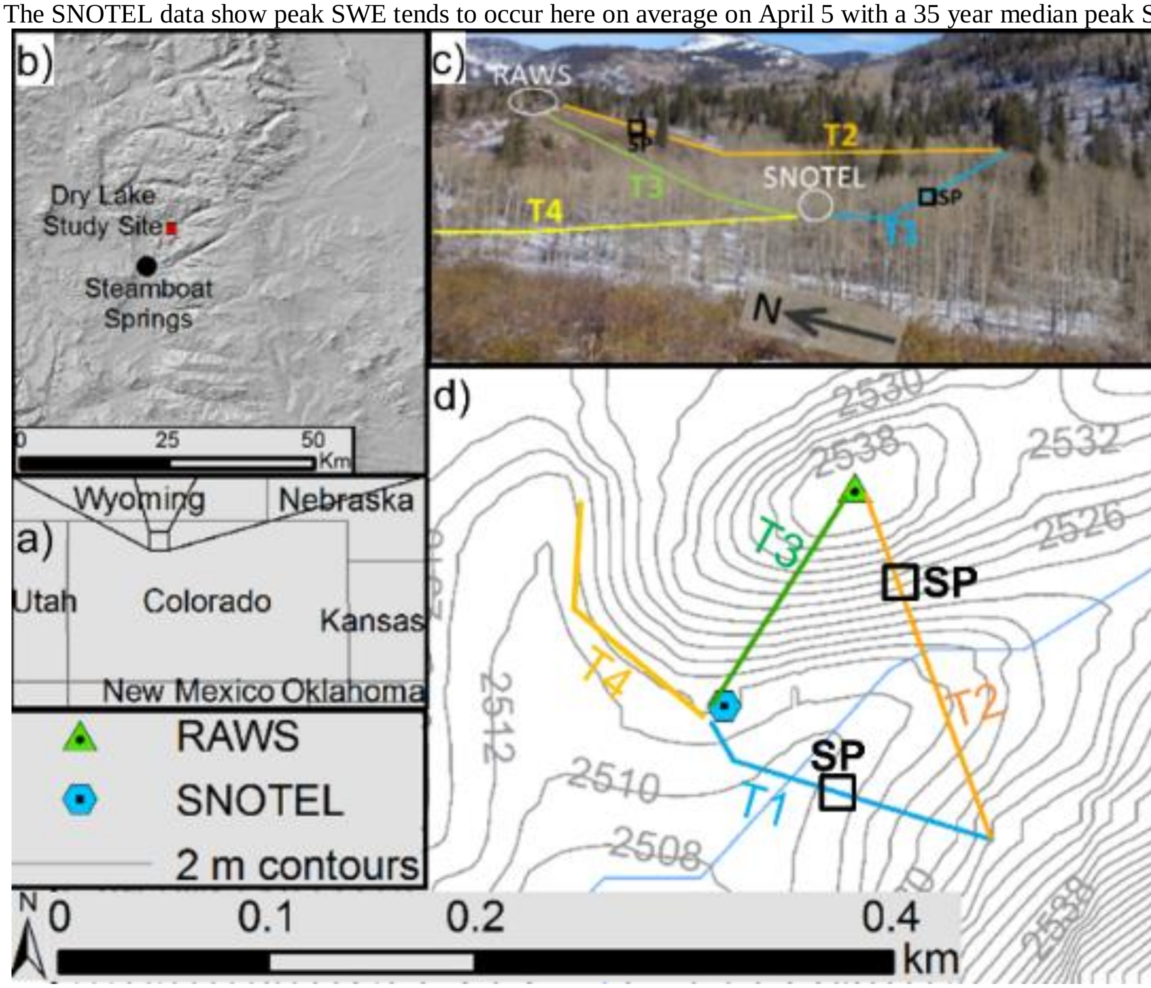

Figure 1. The location of the Dry Lake study site and transects are shown as a) the relative location in Colorado, b) hillshade of nearby surrounding terrain, c) a photograph of the study site, and d) transects T1 through T4 shown with two meter contours. Locations of snow pits (SP) used to calibrate GPR velocity are indicated with boxes. (Webb, 2017)

Paper presented Western Snow Conference 2017
[1] Ryan Webb, 4001 Discovery Drive, University of Colorado-Boulder, Boulder, CO, 80303, ryan.w.webb@colorado.edu

of 570 mm. The plots around this station include south aspect and flat aspect slopes with open, coniferous (subalpine fir, *Abies lasiocarpa* and Engelman spruce, *Picea engelmanii*), and deciduous (aspen, *populous tremuloides*) canopy cover. Plots with specific aspect and canopy types were identified as flat and open (FO), flat deciduous (FD), flat coniferous (FC), and south open (SO). Four transects were then established that crossed through all plots at lengths from almost 120 m up to 200 m.

The GPR data was analyzed using the two-way travel time (TWT) of the radar wave from the reflected ground surface (Lundberg et al., 2006; Heilig et al., 2009; Mitterer et al., 2011). The wave speed will depend upon the dielectric properties of the snow through:

$$v = \frac{c}{\sqrt{\epsilon_r}} \tag{1}$$

Where v is the velocity of the electromagnetic wave (m/ns), c is the speed of light in a vacuum (0.3 m/ns), and ε_r is the relative dielectric permittivity of the snow. Depth was estimated from the velocity using:

$$d = \frac{TWT \cdot v}{2} \tag{2}$$

Where d is the snow depth in meters. For this study, observed snow depths at three snow pits were used to calibrate the GPR data. One depth measurement utilizes the SNOTEL station data for FO conditions whereas the other two were from snow pits dug along transect 1 under FD conditions and transect 2 under SO conditions (Figure 1). SWE was then estimated from bulk density measurements at these snow pits and SNOTEL station by multiplying depth and density.

The GPR unit used was the pulseEKKO pro with 1.0 GHz antennas, manufactured by Sensors & Software, placed in a sled for travel across the snow surface. Step sizes for measurements were 10 cm with six times stacking of recordings. Distances along all transects were measured using a “big wheel odometer” from Sensors & Software that was calibrated along a 50 m distance of snow surface. Processing of data was accomplished through EKKOView Deluxe software. Filtering using the dewow function that removes the long waved part of the signal caused by electromagnetic induction was followed by spherical and elliptical correction (SEC) to compensate for losses and dissipation of energy. SWE estimates were confirmed from SNOTEL observations, snow pit measurements at two locations directly adjacent to transects, seven more snow pits with variable canopy cover within 500 m as part of a separate study (Webb and Fassnacht, 2016), and radar wave velocity estimates from hyperbolic diffraction curvature at the ground surface.

SWE profiles were created for each transect and then segregated into datasets for each individual survey plot. Loss of SWE profiles were calculated for melt period 1 (May 4 SWE profile subtracted from April 20 profile) and melt period 2 (May 18 SWE subtracted from May 4). This creates two datasets for statistical analysis using variograms to estimate correlation lengths of SWE and loss of SWE for each individual survey plot.

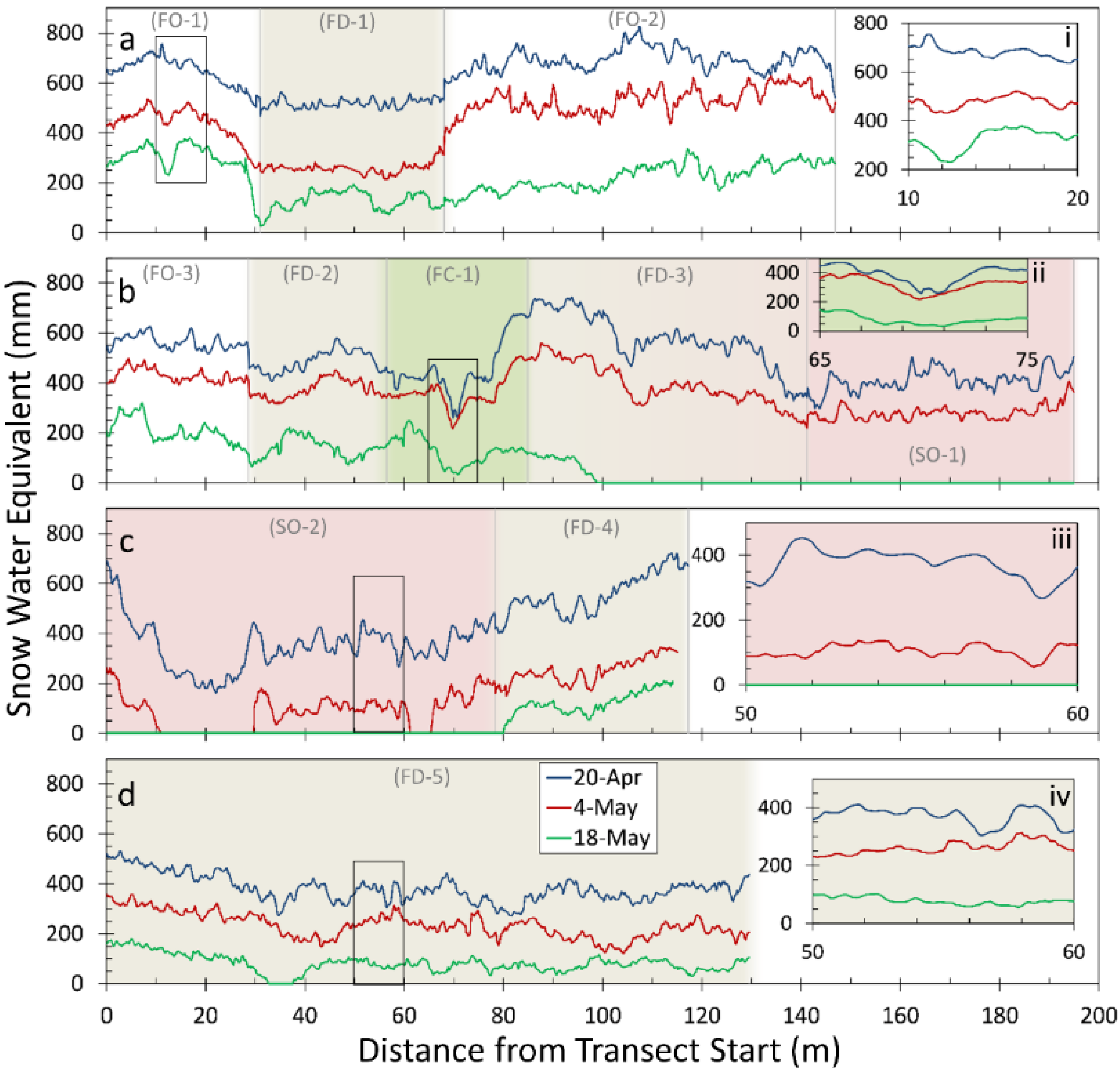

Figure 2. Interpreted snow water equivalent (SWE) for a) Transect one, b) Transect two, c) Transect three, and d) Transect four. Color shading is associated with the land cover and slope aspect types with flat aspect with open cover (FO) shaded white, flat aspect with deciduous cover (FD) shaded tan, flat aspect with coniferous cover (FC) shaded green, and south aspect with open cover (SO) shaded pink. Each transect has a boxed area that is expanded for an enlarged view of the SWE profile in panels i-iv. (Webb, 2017)

Results from this investigation show the high variability for SWE and loss of SWE during spring snowmelt (Figure 2). In the observed study, locations with similar aspect and canopy type show different spatial patterns. The variability in spatial patterns of SWE was shown to increase with time during spring snowmelt whereas the variability in loss of SWE remained similar. These observations show a pattern of melt variability increasing in flat open areas and decreasing in flat areas with deciduous cover. SWE was shown to have correlation lengths between two and five meters and the loss of SWE showed correlation lengths between two and four meters. These are lesser correlation lengths than those found in alpine regions due to the added complexity of snowmelt from the sky view factor of tree canopies (Williams et al., 1999). The SNOTEL station regularly measured higher SWE than survey plots, but did capture the loss of SWE reasonably well. Hydrological investigations can benefit from the non-destructive nature of GPR methods that will improve SWE surveys and melt flux estimates in the future. Recommendations for future investigations include utilizing differential GPS and LiDAR systems that would enable more accurate measurements at greater spatial resolution. Additionally, more snow pit observations with measured liquid water contents would enhance observations of meltwater distribution within the snowpack. These recommendations for future research will improve our understanding of the controls on melt distribution and variability in subalpine terrain that is driven by complex physical processes. For more detailed information on this study, see Webb (2017). (KEYWORDS: ground penetrating radar, Colorado, SNOTEL, SWE, spatial variability)

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