Fixed Wing LiDAR Snow Mapping in the Upper Englishman and Little Qualicum River Watershed: 2020 Progress Report

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Table of Contents

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Introduction

One of the key limitations in snow science is the lack of extensive snow observations specific to both the depth and density of snow, due in part to the effort required to collect this type of information and the lack of technology to collect these data at a large scale. Traditional methods of measuring snow volume and density are largely limited to manual snow course measurements and small footprint, automated weather stations. In BC, we have extensive snow course data, in some cases dating back to the 1920's. These data are supplemented with a network of automated weather stations run by various government agencies, industry and academia; the stations can provide SWE data on an hourly basis using snow pillows, which weigh the mass of snow above them, in addition to other microclimate information at the site. Because the stations generally only provide information about local conditions, it is difficult to scale these observations to the watershed level. However, they do provide accurate indications of current snow conditions, a historical record to track change through time, and invaluable observations for both driving and validating hydrological models.

In the last decade, LiDAR has been used to map snow depth at the watershed scale around the world (e.g. Deems et al, 2017). Within BC, LiDAR acquisition related to snow depth is still in its infancy and, until recently, LiDAR has not been used extensively for operational uses due to the cost of acquiring such data and the lack of research in forested watersheds where snow is an important component of the water balance. To help fill this critical knowledge and data gap, the Cryosphere Node was established in 2018 at UNBC in partnership with Vancouver Island University and Hakai Institute and the Ministry of Forests, Lands, Natural Resource Operations and Rural Development with a primary objective of quantifying the contribution of ice and snow in freshwater flux to the marine environment. A key component of this project is to develop methods to better measure snow and ice in coastal BC. To accomplish this, the Airborne Coastal Observatory (ACO) was launched by UNBC and the Hakai Institute in 2019, consisting of a Navajo Piper operated by Kisik Aerial Surveys Inc, a dedicated LiDAR unit and both hyperspectral and optical cameras.

The ACO began winter survey operations in Feb 2020 focusing on three key watersheds on Vancouver Island (Tsitika, Cruickshank and Englishman) and one in the lower mainland (Seymour), partnering with the Comox Valley Regional District, Metro Vancouver and the Regional District of Nanaimo. All partners in the greater cryosphere project contributed to the overall methods and improvements to the workflow of the LiDAR acquisition, processing, field work to validate measurements, and methods to estimate density and snow water equivalent (SWE). Preliminary estimates of snow and water volume will be provided in this report, with a brief overview of sources of uncertainty and a plan for the 2021 LiDAR snow survey acquisition.

Methods

Two primary data collection methods were used for this project, aerial LiDAR and orthophotos, and field based ground validation. We used the LiDAR acquisition to produce surface digital elevation models (DEM) of one bare earth (snow free) and five separate snow models covering approximately 30km^2 The LiDAR survey focused on the area around Mt Arrowsmith and Mount Cokely draining into both the Englishman River and Little Qualicum watersheds (Figure 1). Table 1 provides dates of acquisition for the snow surface and bare earth LiDAR. These snow surface DEM's were used to create snow depth models by subtracting them from the bare earth DEM. DEM pixel resolution was 3m for all acquisitions and was based on the average ground return over the scene collected with a minimum of 3 returns per unit area. All DEM's are in NAD_1983_CSRS_UTM_Zone_10N, ellipsoidal height.

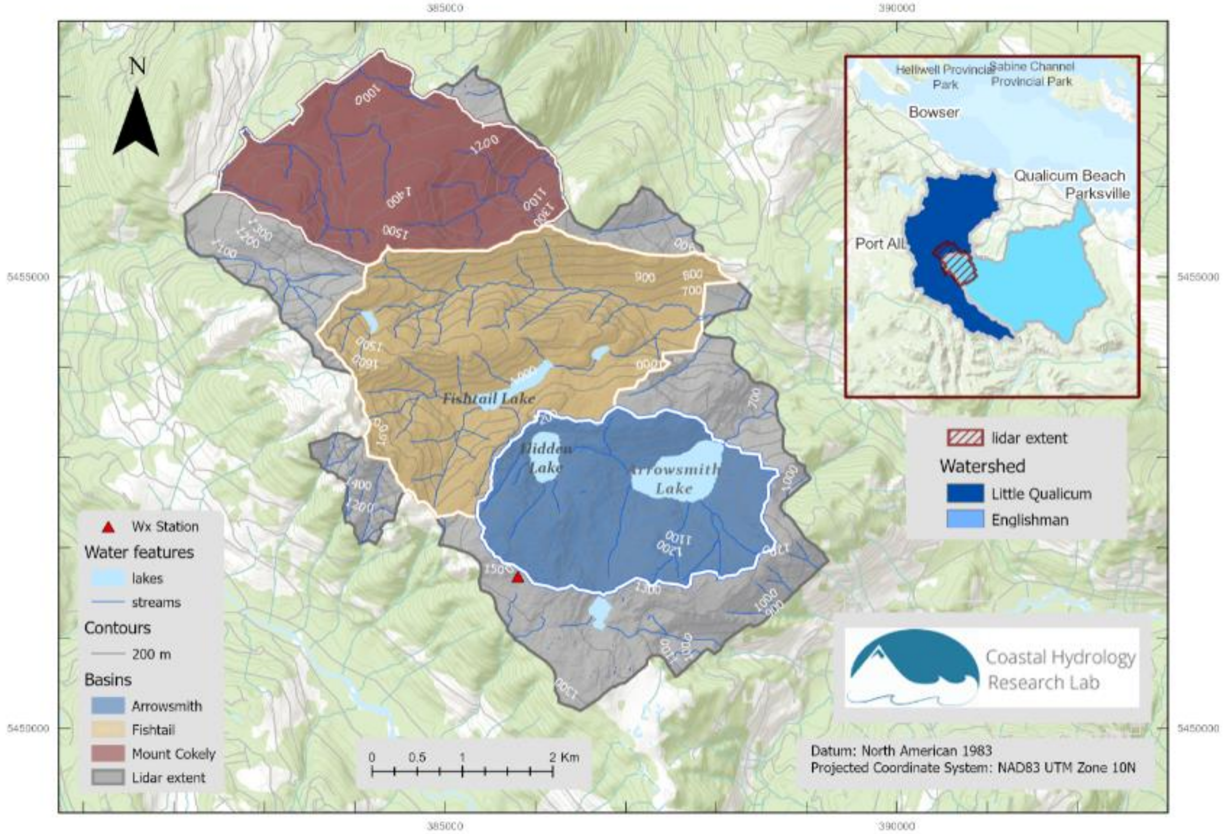

Figure 1. LiDAR acquisition extent for 2020 LiDAR snow surveys and watershed areas covered.

Table 1. Date of LiDAR acquisition in the Upper Englishman River Watershed.

area	phase	julian day	date
Englishman	phase 01	Day075	15-Mar-20
	phase 02	Day097	06-Apr-20
	phase 03	Day128	07-May-20
	phase 04	Day148	27-May-20
	phase 05	Day170	18-Jun-20
	Bare Earth	Day 272	29-Sept-20

Field data Collection of SWE and Snow Depth Data

The original plan for 2020 was to acquire field data in the survey area within a few days or day of the LiDAR acquisition to use as validation data for depth measurements, which could subsequently be used for vertical co-registration, and also to collect snow density data for use in estimates of snow water equivalent (SWE) over the study area. Due to the CoVID pandemic we had to cancel all field acquisition from the survey area in 2020, however we were still able to collect data from the general region during the subsequent surveys around Mount Washington after the start of April and the Upper Cruickshank Watershed in early March prior to the lockdown. These data were used, along with automated weather stations and the greater manual snow survey network (Table 2) to create regional relationships between snow depth and SWE and to calculate average densities by survey period. The Arrowsmith High Elevation weather (Wx) station was also within the study area, so we were able to include SWE and snow depth data in our regional analysis, as well as using it as a single point for validation of snow depth. It should be noted that no snow surveys were completed in 2020 at the Cokely snow survey site due to CoVID.

Table 2. Provincial snow course locations, weather station and snow survey data used to estimate SWE in study watersheds

Snow Course Name	Number	Elev. meters	March regression	April regression	Early May regression	Late May June regressio
DOG MOUNTAIN	3A10	1080	2/25/2020			6/1/2020; 6/15/2020
GROUSE MOUNTAIN	3A01	1100	2/26/2020		5/1/2020; 5/11/2020	
PALISADE LAKE	3A09	640	3/1/2020			
ORCHID LAKE	3A19	880	3/1/2020		5/1/2020; 5/14/2020	6/1/2020
ELK RIVER	3B04	1190	3/1/2020	04/01/2020	5/1/2020	
UPPER THELWOOD LAKE	3B10	270	3/1/2020	04/01/2020	5/1/2020	
WOLF RIVER (MIDDLE)	3B18	990	3/1/2020	04/01/2020	5/1/2020	
WOLF RIVER (LOWER)	3B19	990	3/1/2020	04/01/2020	5/1/2020	
CALLAGHAN CREEK	3A20	1040	3/2/2020			
FORBIDDEN PLATEAU	3B01	1100	3/2/2020	04/01/2020		
CHAPMAN CREEK	3A26	1022	3/4/2020		5/1/2020	
EDWARDS LAKE	3A27	1070	3/4/2020		5/1/2020	
South Circlet	1001	1236	3/11/2020			
East Circlet	1003	1219	3/11/2020			
Jutland Ridge	1005	1605	3/12/2020			
Moat Lake Hut	1007	1207	3/12/2020			
South Moat Lk	m3p3	1267	3/11/2020			
Castlecrag Rg	m3p4	1449	3/11/2020			
Whiskey Mdws	md2p2	1203	3/10/2020			
MLakeWest	1008	1234	3/12/2020			
Paradise meadows	NA	1070			5/8/2020	5/27/2020
PdseMdws	NA	1070			5/8/2020	5/27/2020
Sunrise 1	NA	1450			5/8/2020	5/27/2020; 6/18/2020
Sunrise 2	NA	1230			5/8/2020	5/27/2020
Mt.Arrowsmith Wx	NA	1462	03/01/2020; 03/15/2020	03/06/2020	05/07/2020; 05/22/2020	5/27/2020
Jump Creek	NA	1190	03/01/2020; 03/15/2020	03/06/2020	05/07/2020; 05/22/2020	5/27/2020

LiDAR Derived Snow Depth Maps

Watershed boundaries were delineated in ARC GIS using hydrotools and a TRIM 20m DEM. We used a courser DEM than the one created with the bare earth LiDAR data to reduce complexities associated with delineation using fine spatial scale DEM's. Snow depth was only calculated on Arrowsmith Lake because we had information on water level; all other lakes were excluded from depth calculations. DEMs for each LiDAR acquisition were co-registered to a bare earth model following the methods in Nuth and Kääb (2011). Ortho photos were also created to assess snow free and snow covered zones during the validation and co-registration process. The bare earth DEM was used as a master and all snow surface DEM's were co-registered to it using stable terrain such as open areas with no vegetation, roads and natural openings that were visible during all periods. In addition, a ground control point was included in all surveys to aid in co-registration

Prior to depth calculations, an assessment of vertical noise from each survey was completed by comparing snow free areas from each survey. These are assumed to be stable terrain and were identified using ortho-imagery from each survey. From this analysis we were able to identify a negative vertical bias in the April 06 acquisition, and using these data, along with snow depth data from the Arrowsmith weather station, applied a 60cm positive vertical offset to the data. Based on work elsewhere we assumed an approximately 20cm threshold for identifying a change in snow depth between surveys. We will do a more formal assessment of this threshold using data from all surveys from the Cryosphere node in early 2021 to identify change detection thresholds based on forest cover and canopy densities.

Snow depth rasters (3m resolution) were created within ArcGIS Pro initially by subtracting from the bare earth raster. All values below -0.2m and greater than 8m were removed from the dataset. These holes were filled using the average of the 8 neighboring cells, and when no neighboring cells were available, plane fitting using the IDW methods was used with greater weight given to the closest cells based on a search area of $9m^2$. A combination of Sentinel 2 snow free masks and high resolution ortho images (using a reflection value) were used to identify snow free areas that were set to zero depth in the snow depth rasters. As a final process to identify snow free areas where forests were present and the ground could not be seen, snow free masks were applied to all elevations below 1000m for the May 07 survey, 1150m for the May 27 survey and 1275m for the June 18 survey.

Once snow depth maps were created, the snow depth to SWE linear regressions were applied to each snow depth pixel across the survey area. Snow volumes were also calculated and summed by elevation and aspect.

Results and Discussion

Snow Depth and Snow Water Equivalent Relationships

Despite having to curtail field work specific to the Englishman River, there were enough data from the existing Provincial Snow survey network and data collected for the greater Cryosphere project to develop linear regressions for snow depth and SWE that could be applied to the LiDAR derived snow depth gridded products for this project. All regressions were significant to the .05 level, with R^2 ranging from 0.73 to 0.97 (Figure 2). April had the least data available across the region due do curtailment of work due to CoVID. Regression multipliers used to convert depth to SWE increased through the melt season, which corresponded to a general increase in density from March to June, with mean densities from each survey period ranging from 0.36 to 0.43, with the standard deviation increasing as the melt season progressed (Figure 3.). This increase in variation through the melt season corresponds with the effects of elevation, forest cover, slope and aspect on solar radiation inputs.

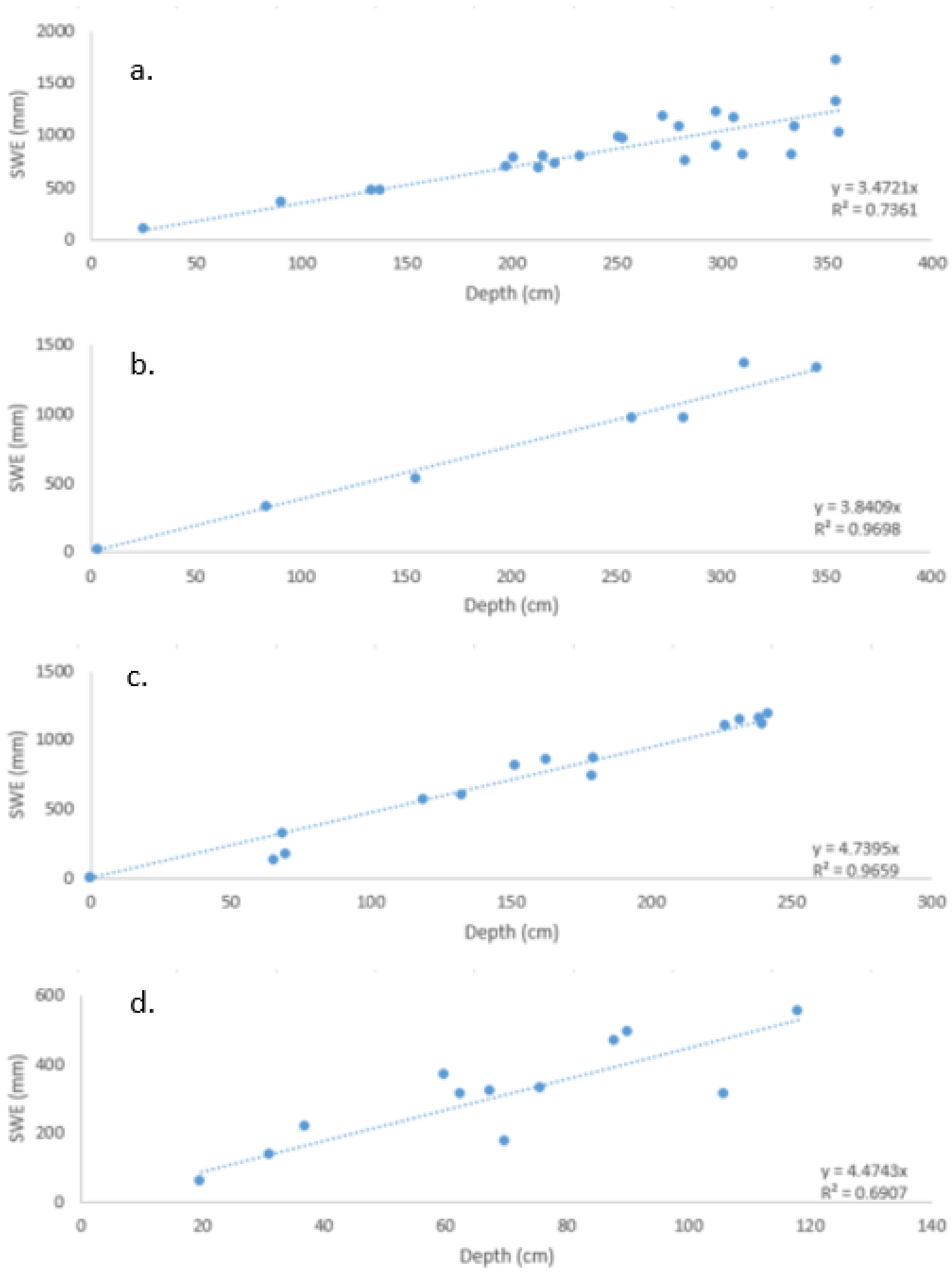

Figure 2. Snow depth (cm) and snow water equivalent (SWE) (mm) linear regressions for a selection of snow courses and weather stations across Vancouver Island and the South Coast from 2020 for **a**. mid-March, 2020 (Phase 01); **b**. early April (Phase 02); **c**. early May (Phase 03) and **d**. Late May-Mid June (Phase 04 and 05).

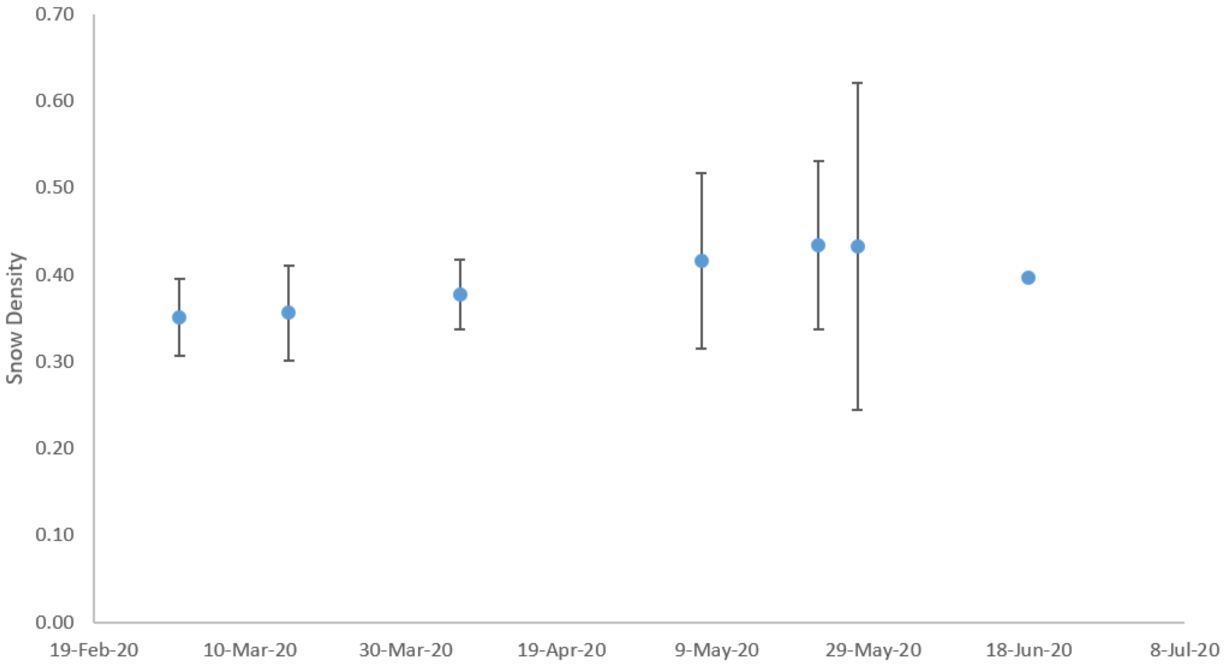

Figure 3. Mean density from snow surveys taken from specific dates used to develop regression equations. Error bars are based on standard deviation. Note that June 18 data is from a signal survey location.

Basin Wide SWE and Water Volumes

The LiDAR derived SWE raster dataset provided detailed information that was previously unavailable for the area surrounding Mt Arrowsmith and Mt.Cokely. The five surveys from 2020 captured part of the accumulation phase from March 15th to April 6th (which also corresponded to the peak snow depth and SWE at the weather station), and the subsequent melt period over the final three surveys. The entire survey area at peak snow storage on April 6th, 2020 had almost 19,000,000 m^3 of water stored as snow (Figure 4a), with snow covering the entire survey area down to an elevation of 600m (Figure 10)

Specific to watersheds within the Englishman River, the Arrowsmith Lake drainage peaked at just over 3,200,000m^3 of water stored as snow on April 6th, 2020. Within Arrowsmith Lake Watershed, almost 95% of the water stored as snow was below 1500m, with 50% below 1200m. The majority of the snow is stored on northerly aspects which provides some buffering capacity through the melt season from solar radiation induced melt, although the effect of solar radiation driven melt is evident in the SWE maps from May through June (Figures 11-13). Water stored as snow on April 06, 2020, represents approx. 40% of the water drawn from Arrowsmith Lake in 2020 (data not shown), however it should be noted that the lake filled up in early January and did not begin release of water until early July when most of the snow was gone from the watershed (in the June 18 survey there was approximately 26mm of SWE stored as snow across the watershed). It is likely that the 2020 snowpack delayed the date of water release from Arrowsmith Lake.

The Fishtail Lake watershed had very similar patterns of snow storage and melt as Arrowsmith Lake waetrshed, but certain characteristics, such as higher overall elevation, resulted in a greater storage of snow per unit area compared to Arrowsmith Lake. Water stored as snow on April 06 was just over 7,400,000 m^3 (Figure 4.), which was over 2.3 times as much as Arrowsmith Lake watershed, despite being approximately 1.5 times the size. There is generally more snow stored at higher elevation than in Arrowsmith Lake watershed, with 95% of the snow stored below 1600m and just over 50% stored below 1300m. It is also notable that the SW and W aspects do not hold nearly as much snow as in Arrowsmith Lake watershed, with the SE and S holding considerably more, which may be due to the more rugged/steeper terrain and deeper valleys which would hold less snow and shield aspects from direct solar radiation. The high amount of snow stored in Fishtail Lake watershed provides a downstream source of water to the Englishman which also likely delays the date of release from Arrowsmith Lake. It is notable that there was approximately 115mm of water stored as snow in Fishtail Lake watershed on June 18th, almost 4 times the amount as in Arrowsmith Lake watershed.

The Cokely sub-basins survey showed different patterns than either Arrowsmith or Fishtail, however it should be highlighted that the April 06 survey appeared to have a negative offset that was not fully accounted for with the offset we applied from the weather station depth data. Due to this we were not able to objectively adjust this depth and the subsequent SWE and water volume estimates are likely low for April 06. The water volumes for the other survey dates were generally higher than Arrowsmith Lake Watershed (Figure 4) which corresponds to the slightly larger contributing area and higher overall elevation. Melt and storage patterns were similar across the survey period to both Arrowsmith and Cokely, with most of the snow stored below 1500m and just over 50% stored below 1300m.

The numbers presented in this section have a degree of uncertainty which has not been fully quantified. There is uncertainty associated with measurements of SWE and density used to estimate snow water volume across the watersheds. The data from the provincial snow survey program tend to be located at treeline elevations and on sheltered and level terrain, and thus do not fully describe snow patterns across the landscape. A component of the greater Cryosphere Project is to collect additional data that takes into account elevation, aspect and slope to gain a better understanding of how snow density varies in more complex terrain. The results of collecting data across different terrain attributes can be seen in Figure 2a that included data from our field campaign in the Cruickshank where we sampled in wind exposed areas and over different terrain attributes. In the 2021 field season we plan to sample across these same attributes in both the Arrowsmith and Fishtail Creek watersheds to better describe this variation.

Another component of the uncertainty is the depth measurements derived from the LiDAR. Past work in open terrain by the project team suggests an approximate 20cm threshold for change detection. Within forested areas it is expected to be higher due to the difficulties with getting ground returns to build both a bare earth and snow surface DEM. These uncertainties are especially important in the watersheds surveyed in the project, especially Arrowsmith Lake watershed which is more than 50% forested. The next step in our analysis will be to identify areas with low ground returns and determine if more intense LiDAR is required, and also to do more on the ground validation in these areas. We will use the snow depth maps to help design the 2021 field validation methods to ensure we focus on areas with the most amount of snow and highest degree of uncertainty.

Even with the uncertainty associated with density estimates and snow depth calculations, these data represent a major advancement in snow measurement and estimates of water storage. Rather than having to scale up estimates from a single weather station or snow survey location to the watershed, we can now measure depth across the entire area. While the absolute values presented for water storage and SWE across the basins may change as we better quantify errors, we can with a high degree of confidence identify what elevations and aspects hold the most amount of snow and use this information for planning purposes for things like climate change. It is notable that even though Mt Arrowsmith is over 1800m in elevation, the bulk of the water is stored below 1400m across the surveyed area. From a climate change perspective with most of the water being stored at these lower elevations, warming winters may significantly decrease snowpacks as snow shifts to rain. A positive aspect of the watersheds surveyed is that much of the snow is stored on northerly and easterly aspects, which will reduce the effects of solar radiation that can drive melt rates during the spring and summer and potentially mitigate spring and summer droughts.

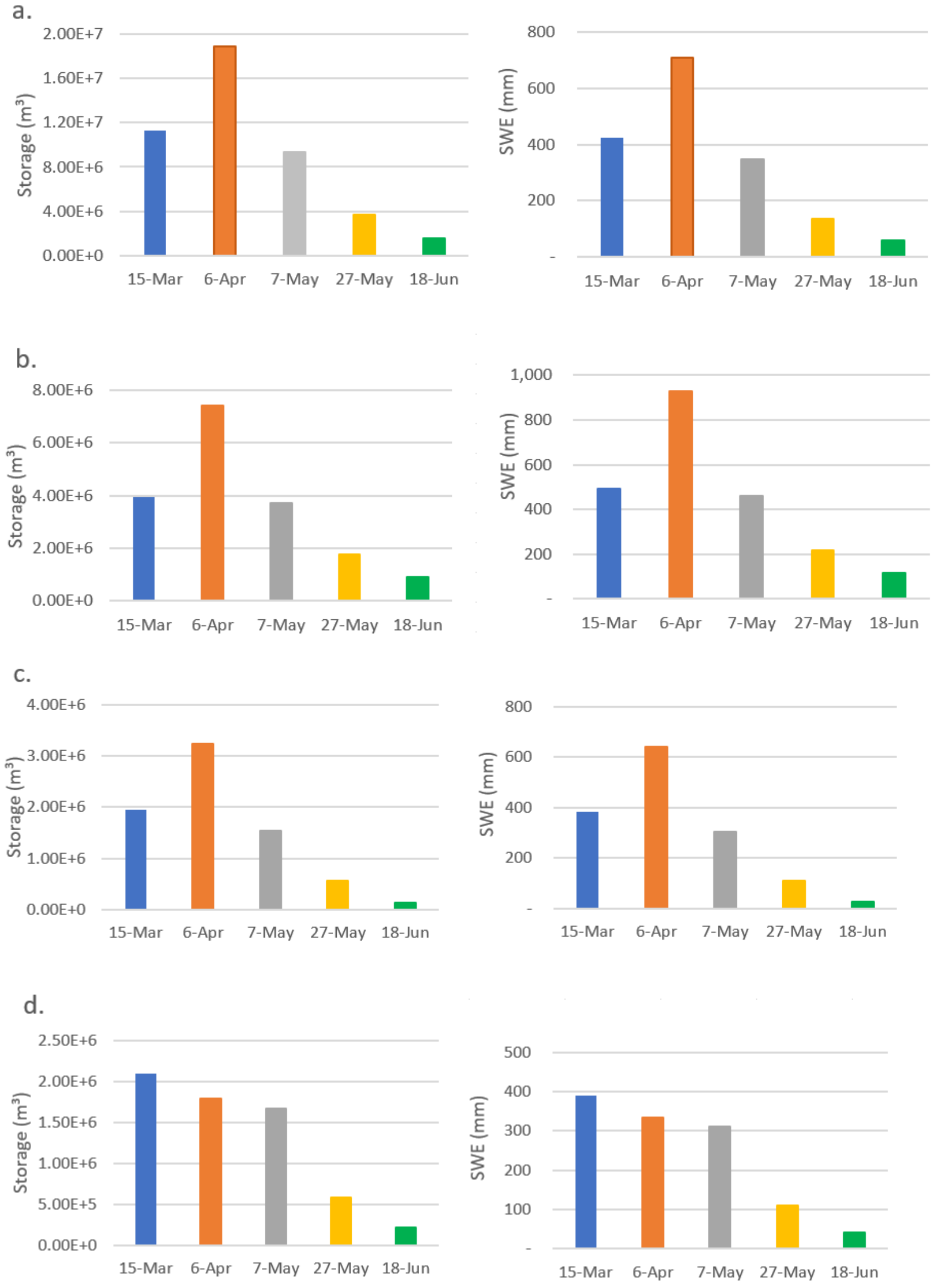

Figure 4. Water storage and snow water equivalent (SWE) in 2020 for a. the entire survey area; b. Fishtail Lake; c. Arrowsmith Lake, and; d. Cokely sub-basins. Note that the April 06 survey at Cokely ws negatively biased and the water storage and SWE is likely higher.

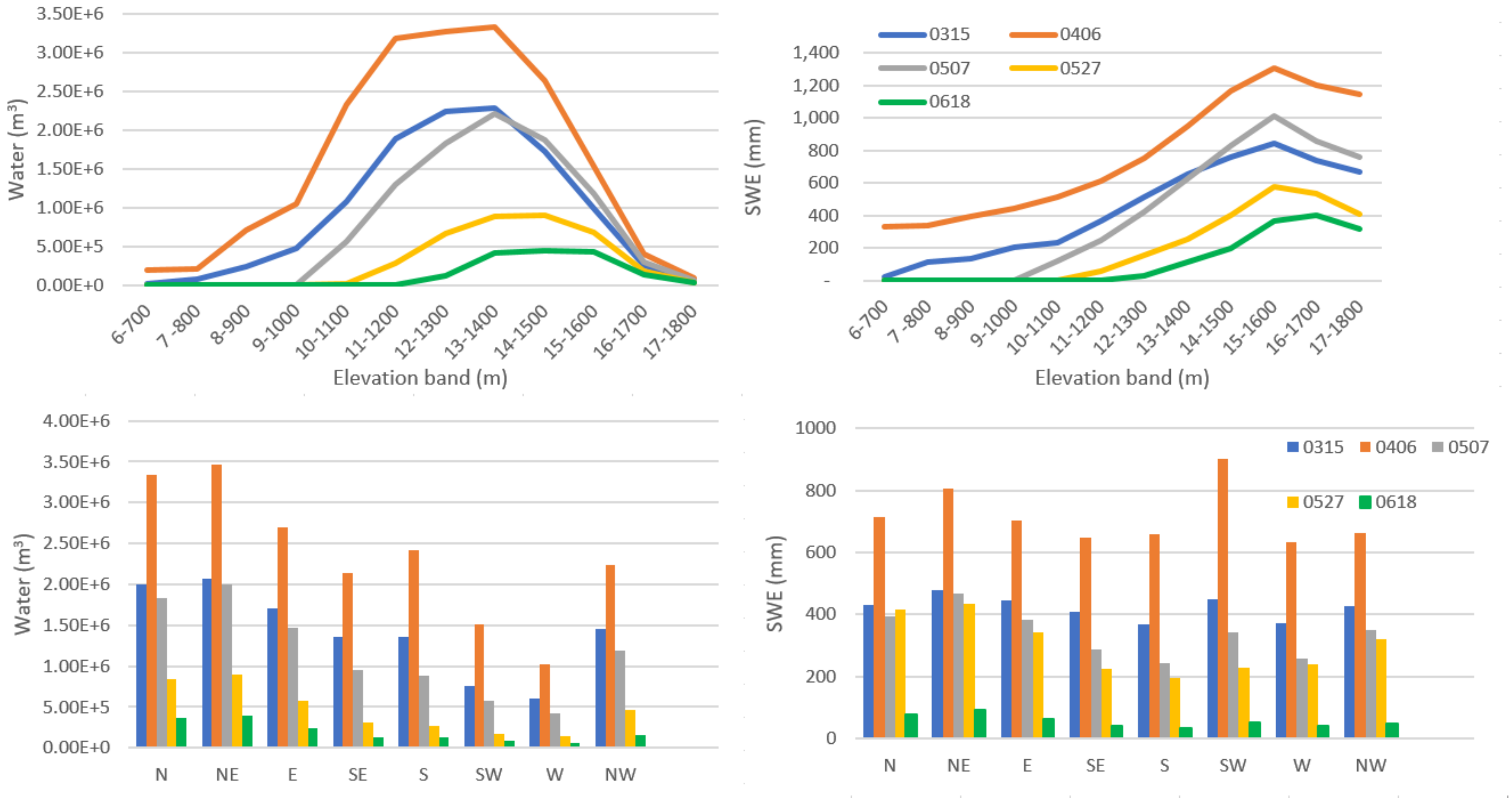

Figure 5. Water volume and snow water equivalent (SWE) by aspect and elevation for the entire area surveyed in the Englishman River and Little Qualicum watersheds over 5 survey dates from March 15th to June 18th, 2020.

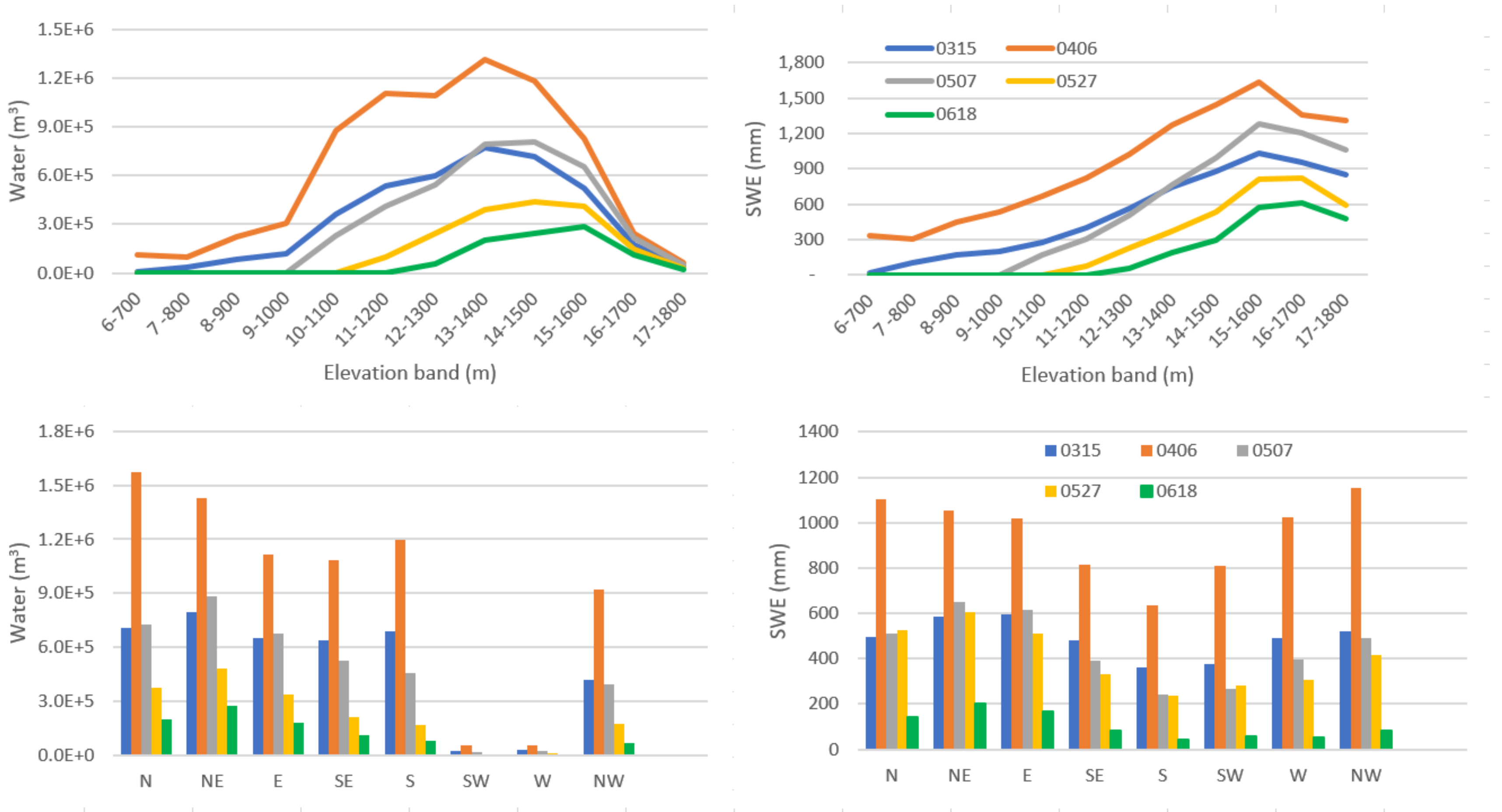

Figure 6. Water volume and snow water equivalent by aspect and elevation for the Fishtail Lake watershed over 5 survey dates from March 15th to June 18th, 2020.

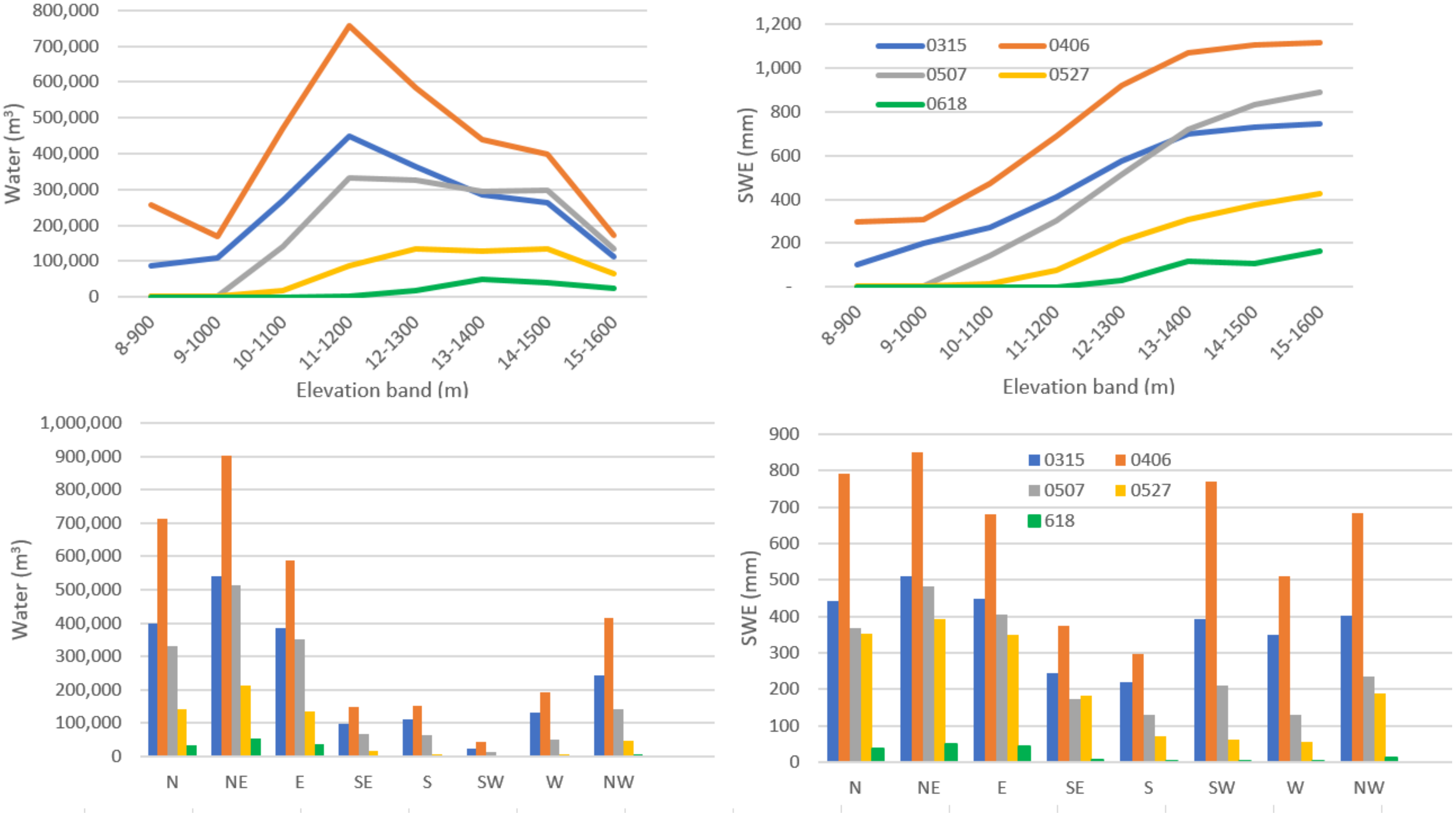

Figure 7. Water volume and snow water equivalent by aspect and elevation for the Arrowsmith Lake watershed over 5 survey dates from March 15th to June 18th, 2020.

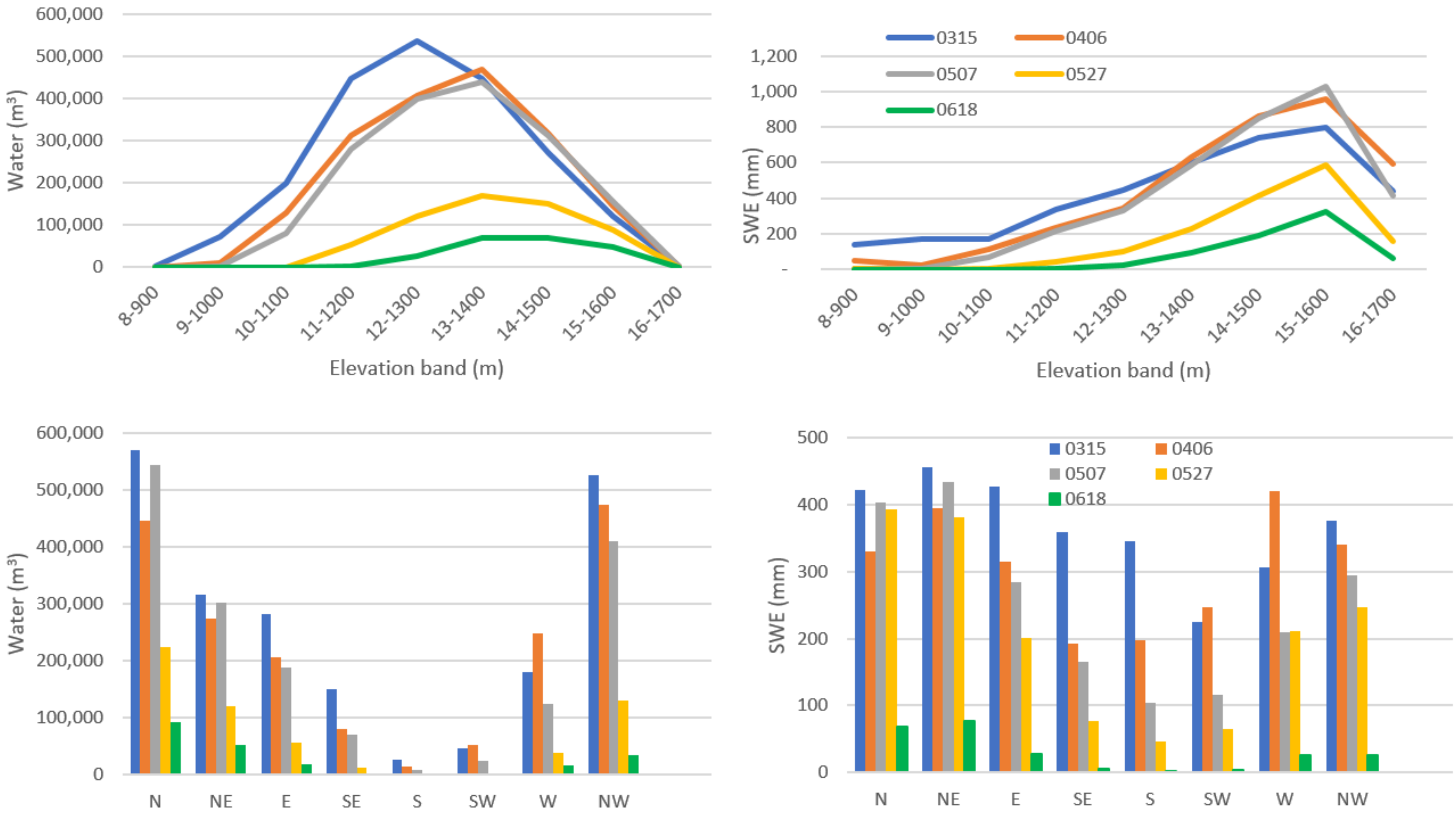

Figure 8. Water volume and snow water equivalent by aspect and elevation for the Cokely watersheds over 5 survey dates from March 15th to June 18th, 2020. Note that the April 06 survey was negatively biased and water volumes and SWE are likely higher.

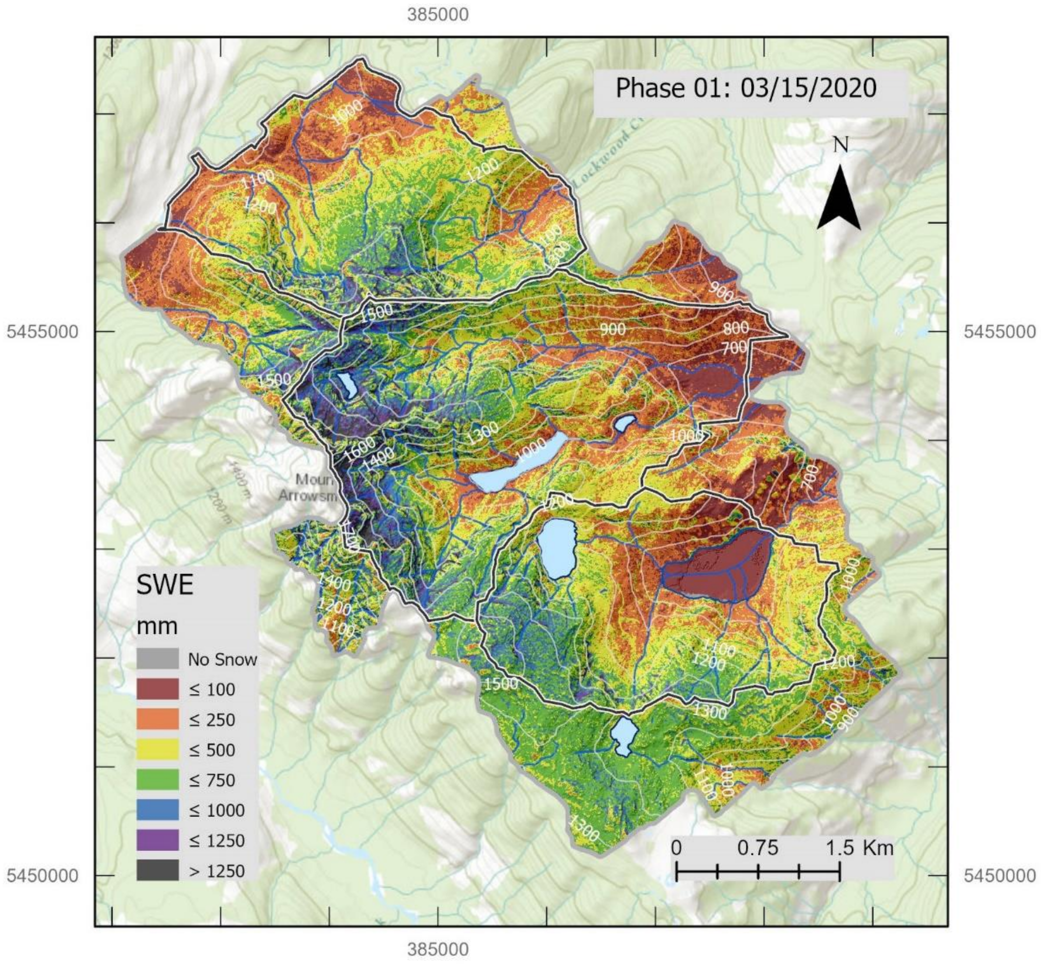

Figure 9. Snow water equivalent (SWE) over the study area for March 15, 2020.

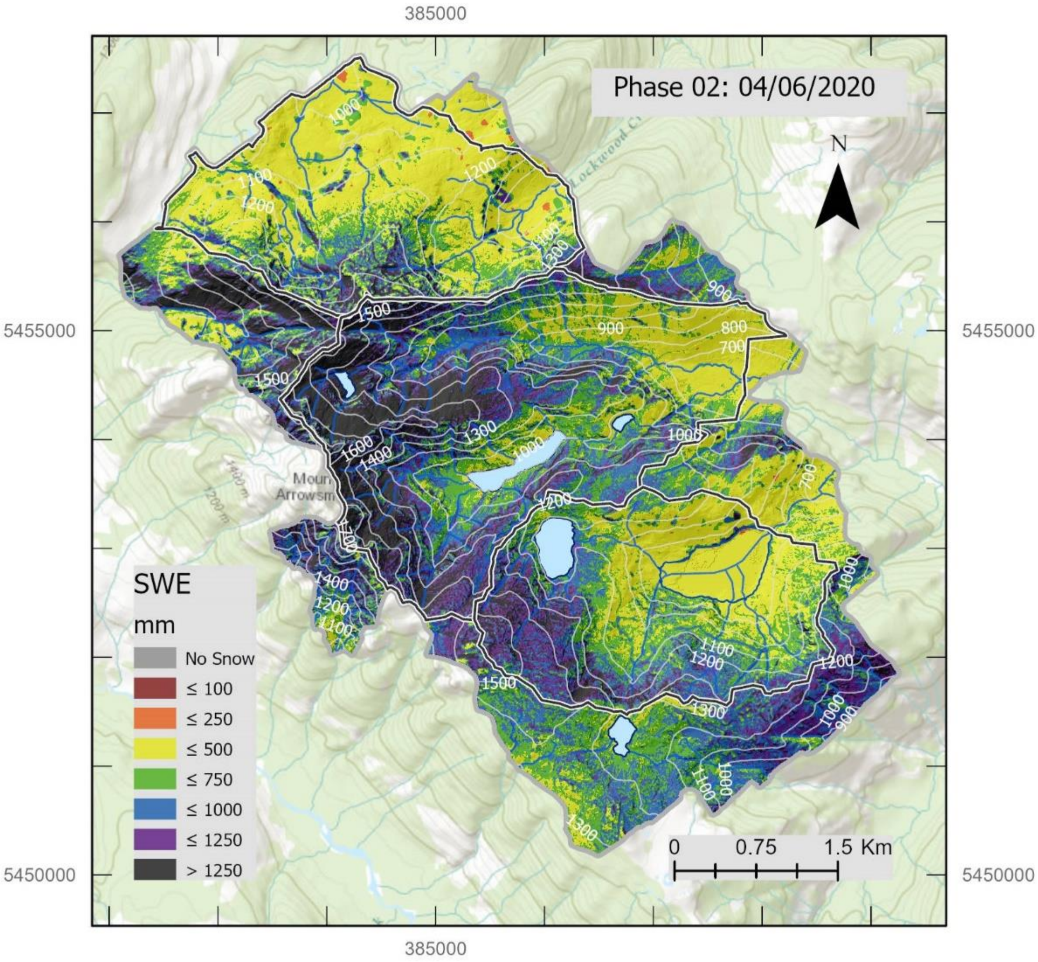

Figure 10. Snow water equivalent (SWE) over the study area for April 06, 2020.

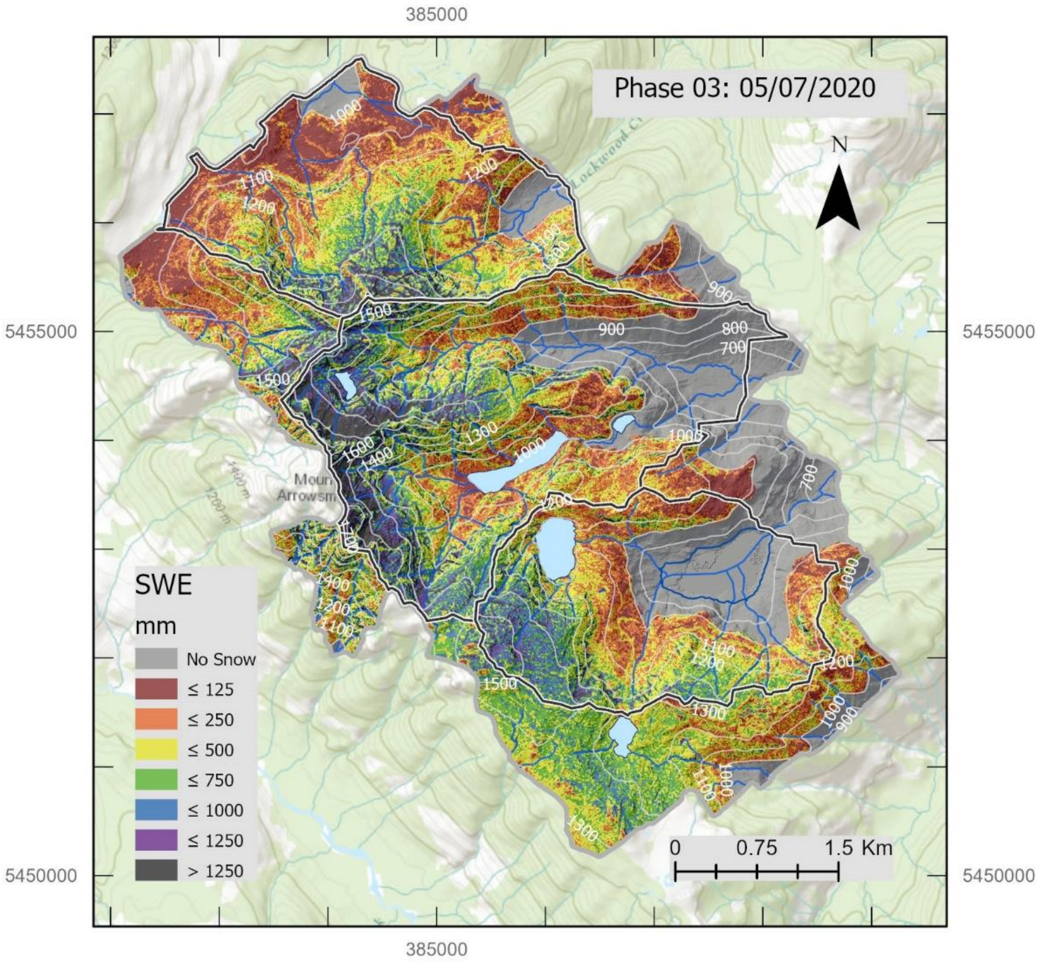

Figure 11. Snow water equivalent (SWE) over the study area for May 07, 2020.

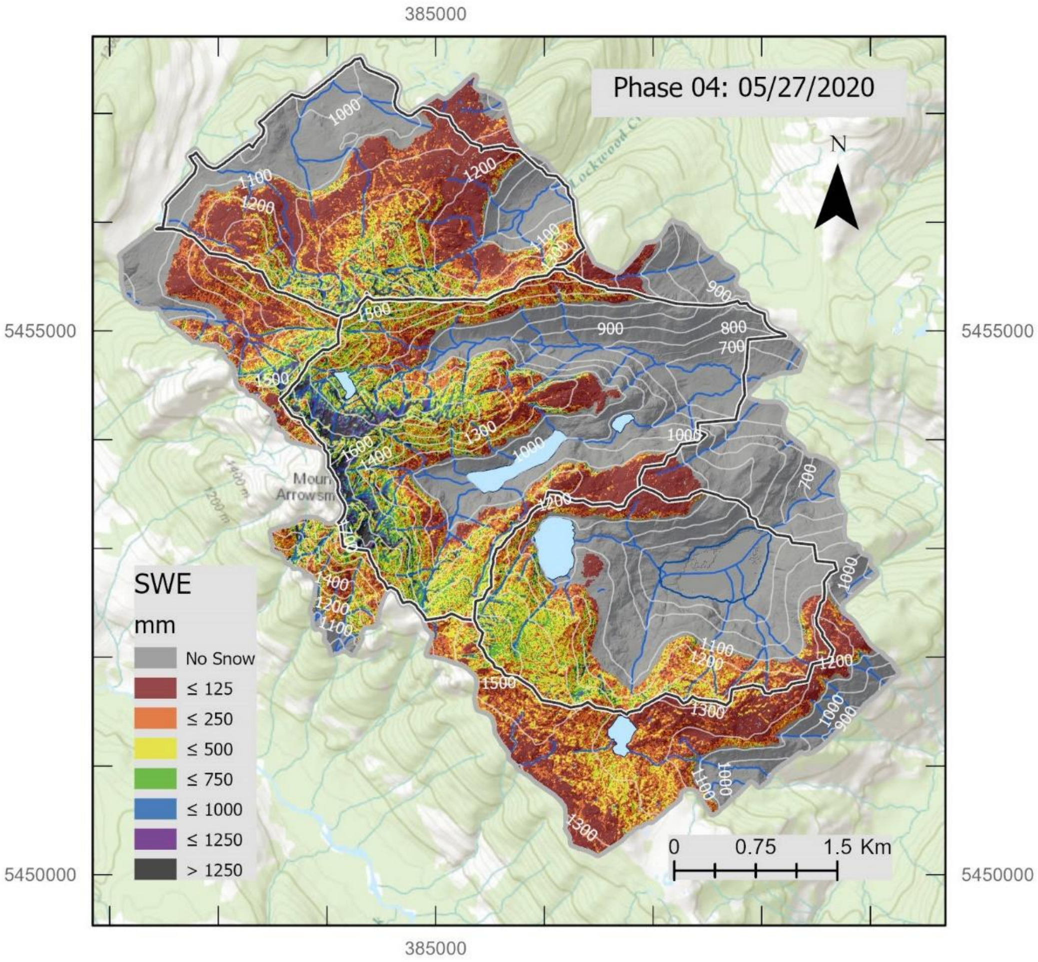

Figure 12. Snow water equivalent (SWE) over the study area for May 27, 2020.

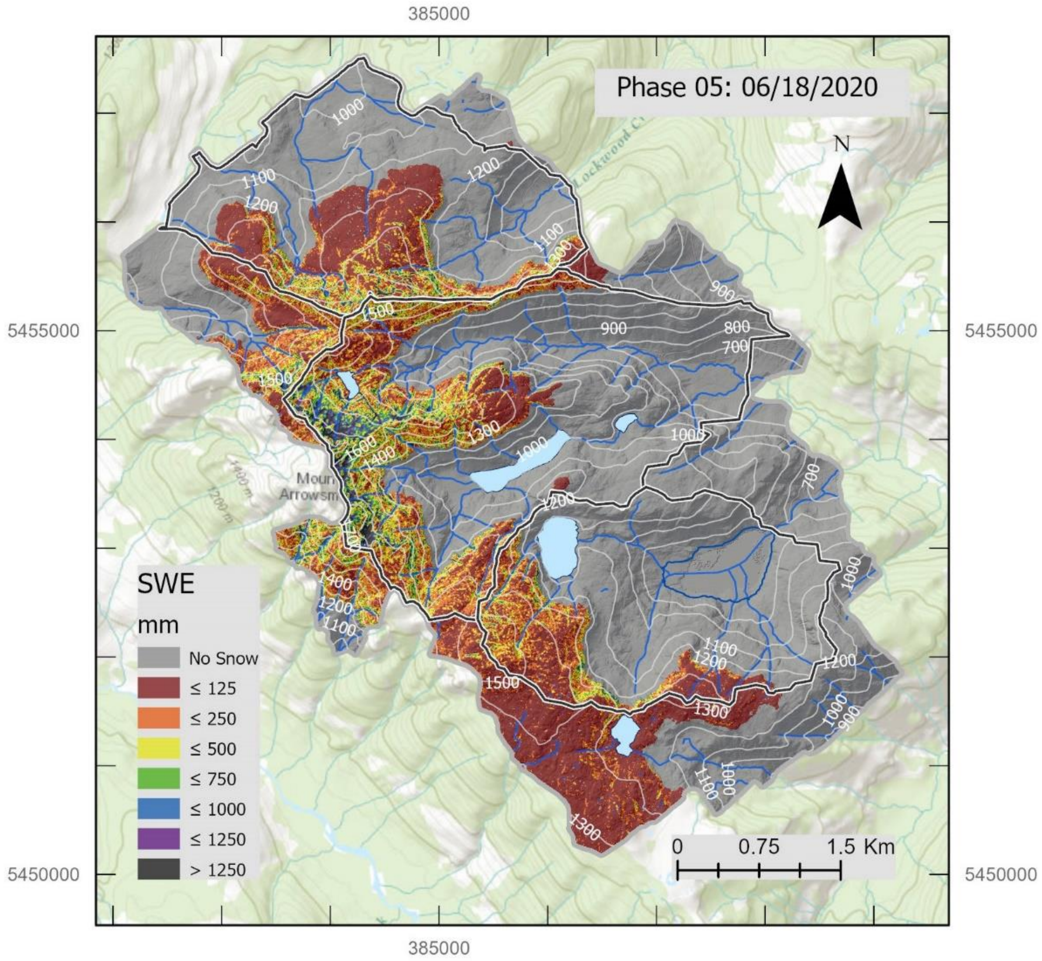

Figure 13. Snow water equivalent (SWE) over the study area for June 18, 2020.

2021 Snow Season Plans

The greater Cryosphere Project will continue winter snow surveys starting in March 2021 with a target of 3 to 5 surveys depending on weather conditions. We propose covering the same area for the Englishman River and Little Qualicum as in 2020. We have had to adjust planning due to CoVID, but with protocols in place, we plan to do field campaigns in the same window, over a 3 to 4 period as the LiDAR based snow surveys. We plan to have a team of 3 people based on Mt Arrowsmith near the weather station who will survey the area by foot. We will also install up to three time lapse cameras and snow stakes to measure snow depth in between surveys to track the snow pack through time, and to increase the depth validation points for the LiDAR surveys. The overall goal for the 2021 season is to create a larger snow depth validation dataset and collect snow density data across varying terrain types to further refine the SWE estimates derived from this project. These same measurements will be completed in the three other survey areas (Tsitika, Cruickshank and Upper Seymour) to create a regional dataset to improve modelling of SWE.

We are also planning to recruit a PhD student and a Post Doc to work on the greater Cryosphere Project to work along with the team of technicians and scientists already focused on this work. It should be noted that the Post Doc we hired to support this work has yet to be issued a Visa, which is related to CoVID, despite making the hire a year ago. We have a VIU GIS Intern doing their practicum focusing on depth uncertainty from LiDAR measurements starting in Feb 2020. Funding from the RDN will be used for the LiDAR surveys, travel for field work and supporting students and technician salaries. Below is a proposed timeline (Table 3) and Budget (Table 4). Please note that the final budget includes approximately $20,000 that was not spent in 2020 due to a reduction in the planned field work.

Proposed Timeline and Budget:

Table 3. Timeline

Item				
	Q1	Q2	Q3	Q4
LiDAR Survey (3 to 5)	🟦	🟦		
Ground Validation (3 to 5)	🟦	🟦		
Snow density modelling and maps	🟦	🟦	🟦	
Final project report			🟦	🟦

Table 4. Budget

Item:	Description:	Budget:
LiDAR Surveys	Acquisition of LiDAR data and derived products (DEM, point cloud, orthophotos) – 5 surveys total of Upper Englishman Watershed	$20,000
Ground Surveys	Ground teams of 3 people, including prep, data collection and compilation for 3 to 5 trips	$11,000
Data analysis and post-processing	Create snow depth and density maps using multiple methods to model snow water equivalent for periods between surveys(cost shared among partners)	$8,000
Materials and Supplies	General field supplies, misc equipment	$1,500
Travel	Travel to and from site (mileage), per diems	$3,500
Access	Helicopter access (cost shared among partners)	$8,000
Lab Fees	Equipment, software, etc	$3,000
University Overhead	Administrative overhead	$6,000
Total		**$61,000**

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