REMOTELY MONITORING SNOW WATER EQUIVALENT USING BASIC PHOTOGRAMMETRY

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ABSTRACT

Accurately monitoring the snow water equivalent (SWE) in watersheds and water supply areas is increasingly important in a changing climate as average temperatures are predicted to rise, resulting in diminishing mountain snowpacks. Recent research has shown that it is possible to accurately convert snow depth measurements to snow water equivalent using estimated bulk snow density; multiplying snow depth by the average density of the entire snowpack. Measuring snow depth is relatively simple and cost-effective in comparison to SWE measurements. This study describes a local-scale application of a snow density model with snow depth measurements taken using basic photogrammetry. The study site was situated at 1325 m on a sub-alpine ridge in the Capilano Watershed in British Columbia. Snow depth is estimated from images of a graduated snow depth pole, which is then converted to SWE. For this study, bulk snow density was calculated from historical (c. 1936) average monthly snowpack density at five nearby snow course sites. Calculated SWE values using this snow density model averaged 95% of the periodic manual validations, and proved to be more accurate and reliable than measurements from nearby automated SWE sensors. This technology can be used to fill data gaps and provide additional valuable information to water supply managers at a relatively low cost. (KEYWORDS: snow water equivalent, snow depth, snow density, photogrammetry, hydrology)

INTRODUCTION

Temperatures in Metro Vancouver, as in most parts of the world, are warming. Climate projections show an average increase of about 3°C in our region by the 2050s (PCIC, 2016). A change of 3°C would result in a 400-500 m increase in the average snow line elevation. As a result, more winter precipitation will fall as rain, with snow being confined to only the highest local mountains. The impacts from climate change highlight the importance of monitoring SWE and the need to re-evaluate Metro Vancouver's snowpack monitoring network.

Metro Vancouver has operated a snowpack monitoring network in its watersheds since 1936. The network consists of five manual snow courses and three automated snow-climate stations. These stations are situated within a 20 km radius at elevations between 900 and 1200 m. Snow station details are summarized in Table 1.

Table 1. Description of Metro Vancouver's snowpack monitoring network.

Name	Elevation(m)	Aspect(°)	Description
Palisade Lake	900	283	Manual snow course; snow depth (SR50) and scale (Sommer)
Dog Mountain	1040	221	Manual snow course
Disappointment Lk	1050	146	Manual snow course; snow depth (SR50) and scale (Sommer)
Grouse Mountain	1100	283	Manual snow course
Orchid Lake	1185	139	Manual snow course; snow depth sensor (SR50)
Macklin Peak*	1325	50	Camera and snow pole

Snow pillows have been used in the watersheds since the mid-1990s. More recently, snow scales replaced these aging snow pillows. These snow pillows and snow scales have historically underestimated SWE by an average of 15-20% compared to manual measurements. Consistent under-measurement has led to poor confidence in automated SWE readings. Local SWE routinely exceeds 2000 mm with a maximum value of nearly 4000 mm in 1999. Rain-on-snow events are frequent throughout the winter, which can lead to multiple ice crusts, often as thick as 20-30 cm. These conditions push the limits of any automated SWE sensor.

SWE can be accurately estimated from snow depth data by using estimated bulk snow density, largely thanks to the low variability of seasonal snow density values (Mizukami and Perica, 2008). This has led to the

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development of several snow density models (Jonas *et al*., 2009; Sturm *et al*., 2010; McCreight and Small, 2014). These models differ in some ways, but they all essentially use measured snow depth, the measurement date, and the snow climate classification to estimate the SWE. This study is an attempt to apply a snow density model using snow data from the comprehensive watershed manual snow survey data record.

Photogrammetry, or time-lapse photography, has been successfully used to monitor snow at various timescales (Currier, 2016; Garvelmann *et al*., 2013). Here, we use daily-scale time-lapse photogrammetry and ultrasonic snow depth sensors to measure snow depth. Snow depth is then converted to SWE using historical average snow density and day of the year. This is designed as a cost-effective remote monitoring system used to provide additional data to an existing snow monitoring network. It can, however, also be used as a simple stand-alone weather station. It is important to note that the estimated SWE values in this study are primarily used for long-term water supply forecasting and planning. Therefore, dynamic fluctuations in density from snow accumulation, rain-on-snow, or snow settlement are not considered.

BACKGROUND

Metro Vancouver's Water Services Department is responsible for providing drinking water to approximately 2.5 million residents. The region's water comes from rainfall and snowmelt and is collected and stored in reservoirs in three watersheds: Capilano, Seymour, and Coquitlam. These watersheds lie in the southern end of the rugged Pacific Ranges of the Coast Mountains. The mountaintops in this area are relatively low with most summits extending to between 1200 and 1700 m above sea level.

The weather conditions in Metro Vancouver's watersheds can be extreme. The watersheds receive 3000-4500 mm of precipitation annually, with most of this precipitation falling between October and April. The winter snowpack varies considerably from year to year given the relatively low elevation of the mountains and mild maritime climate. The maximum recorded snow depth was approximately 800 cm, with a SWE of around 3800 mm. Typically, snowmelt keeps the reservoirs at full capacity until July, at which point they gradually draw down until the first late-summer or fall storms arrive.

Metro Vancouver experienced a severe seasonal drought in 2015. This was a result of record-breaking winter temperatures, low snow depths, and record low spring precipitation. On April 1, 2015, only Orchid Lake (1185 m) had measurable snow (27 cm). Fortunately, the reservoirs were still able to refill completely during the spring, but the summer draw-down period began in the middle of May. By July 20, Metro Vancouver implemented Stage 3 water restrictions, which had not happened since 2003. In many ways, 2015 gave water managers a glimpse of what the future might look like in Metro Vancouver.

In 2016, a consultant was hired to evaluate the snow monitoring network and the proposed addition of a higher elevation snowpack monitoring site. This higher elevation site is intended to provide better SWE data for the watershed area above 1185 m, which is approximately 20% of the total watershed area. A site in the Capilano Watershed was selected and added to the manual snow survey circuit in late 2016. This site, called Macklin Ridge, is situated on a narrow wind-exposed ridge at approximately 1325 m. Manual snow surveys were conducted in the spring of 2016 and 2017; however, sampling in this location proved challenging due to the depth and density of the snow.

SNOW DENSITY MODEL

Studies have shown that SWE can be accurately estimated from snow depth measurements and snow density estimates, largely due to the low variability of seasonal snow density values (Mizukami and Perica, 2008). Snow density models are presented as cost-effective tools designed to improve local, regional, or global snowpack estimates. Snow depth measurements, date, and location are used as inputs to model the bulk snow density, which is then used to estimate the SWE. The location is primarily used to differentiate between snow classes and related differences in bulk snow density. All of these models produce accurate estimates of bulk snow density, with errors that are less than or equal to those resulting from manual observations.

For the purpose of this study, local historical snow data was used to calculate mean bulk snow density at a monthly or bi-weekly timescale (Figure 1). The mean snow density was then used to convert measured snow depth to SWE at a daily timescale. This process more closely followed a coarse snow density model (Sturm et al., 2010), even though a daily SWE estimate was used. Dynamic changes in snow density (daily-weekly timescale) were not necessarily relevant for long-term water supply forecasting. If necessary, these dynamic changes could be addressed during data processing by comparing values to nearby automated snow stations.

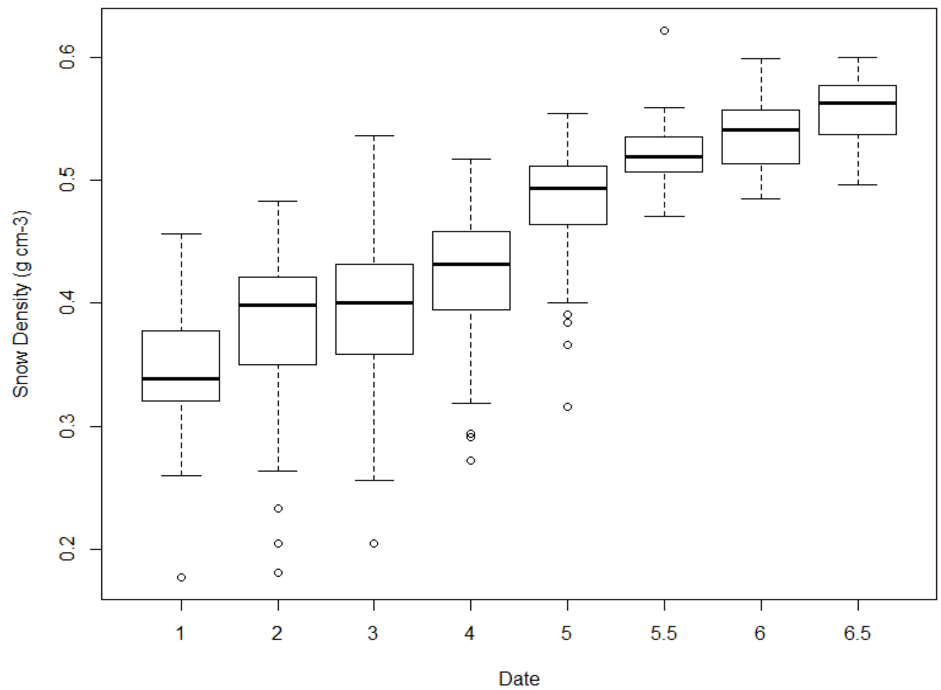

Figure 1. Monthly (Jan [1] to May [5]) and bi-weekly (May-15 [5.5] to Jun-15 [6.5]) bulk snow density from five watershed manual snow courses dating back to 1936. The solid black lines represent the median values, which are used in this snow density model. Top and bottom whiskers are calculated using the interquartile range (IQR)*1.5 rule, and outliers are shown with circles.

PROJECT SUMMARY

Site Selection

Macklin Ridge was selected as the study site for photogrammetry trial. This is a remote site with no cellular reception. As mentioned, in 2016 this site was identified as a reasonable higher elevation site to add to the existing manual snow course network. This site does provide valuable additional SWE data from a higher elevation band; however, there are concerns and challenges associated with it. The ridge is wind exposed, which could play a role in the challenging sampling conditions encountered here. There are also several large avalanche start zones immediately below the ridge crest; conditions common to upper elevation sites near ridgeline. Automating data from this site would reduce risk to field crews, alleviate the workload, and potentially improve data quality.

Camera System

A Nupoint Systems Remote Viewer™ camera system was chosen for this trial. Nupoint Systems is a Vancouver-based company that specializes in affordable satellite communication tools. The Remote Viewer™ is specifically designed for environmental monitoring in remote locations. These camera systems have been used in Metro Vancouver Watersheds to monitor conditions at snow-climate stations, alpine reservoir drawdowns, and streamflow response. The cameras have been valuable, reliable, and essentially maintenance free.

The Remote Viewer™ camera system transmits images via a Low Earth Orbit (LEO) satellite. The system consists of a camera and housing, satellite antenna, electronics box, and power supply. It operates on a 12V photovoltaic system and consumes less than 1 amp-hour per day. Images are sent directly to a pre-determined email distribution list at 0900 PST each day. Over-the-air commands via email are used to request additional images or change the camera settings.

The camera system was mounted approximately 10 metres up a large tree (Figure 2). The tree was limbed but was not topped in the hopes of increasing the lifespan of the tree. The overhanging tree limbs did not interfere with satellite communications. A 9 m tall tilt-up aluminum pole was installed in a relatively flat location 15 m from the base of the tree. The base of the pole was secured to bedrock and was anchored with two sets of guy wires at 5 and 9 m. The pole was marked at 1 m and 0.5 m increments using red (20 cm wide) and yellow bands (10 cm wide).

Figure 2. Study site on Macklin Ridge with the tree mounted camera system and snow depth pole. Manual validations were conducted intermittently.

In addition to providing snow depth information for a single point, the camera image paints a much better picture of the spatial distribution of the snow cover. The image itself is also invaluable for weather forecasting and flight planning.

Cost Comparison

This system is an inexpensive alternative to automated snow climate stations and manual snow courses in remote locations. Equipment and initial installation costs are approximately one tenth of the cost of nearby snow climate stations. For this study, monthly manual validations were performed; however, regular site visits may be unnecessary in the future. Ongoing costs, including a satellite data plan and maintenance, are considerably less than helicopter accessed manual snow courses and automated snow-climate stations.

CHALLENGES AND SOLUTIONS

Prior to February 2017, images were less reliable due to condensation on the housing window, which was later rectified by installing a heating element. When necessary, the heating element was turned on for 20-30 minutes using an over-the-air command, which was sufficient to clear the glass. A second image would then be requested and used to measure the snow depth.

Accessing the camera system for maintenance was difficult once it was installed in the tree. A 20-ft extension ladder was flown to the site in order to install the heating element. Once operating, the camera system is essentially maintenance free; however, camera access for maintenance and repairs should be considered during the initial installation. A fixed ladder or climbing system is recommended.

Lastly, the snow pole was significantly bent by snow creep and stress on the guy wires. No effort was made to correct the snow depth for the angle of the bent snow pole. Carefully selecting a site for the snow pole is critical in areas with a deep maritime snowpack. Guy wires may also a poor choice for securing the snow pole in this environment. Alpine infrastructure in Metro Vancouver's Watersheds has a long history of crumpling under the stress of a 4+ m snowpack, particularly as snow creep increases during the spring melt.

RESULTS

Snow depth was estimated from the daily image, and by reviewing the change in snow depth at nearby snow-climate stations. The snow density model was also applied to the Orchid Lake station, which has a snow depth sensor but no snow scale or pillow. Modelled values were compared to observed values from manual validations at Macklin Ridge and Orchid Lake.

For the model, the SWE error as a percentage of the observed value averaged –5.1%, and ranged from –11.4% to 2.8% (Table 2). This was considerably better than the comparison of automated snow sensors to observed values where the average error was –14.9% and the error ranged from –23.2% to –4.6%. A limited analysis of manual SWE measurements showed a range of ±15% for five and ten-point snow surveys within 100-200 m² snow course areas. The modelled SWE values certainly fell within this range of local variability.

Table 2. Comparison of snow depth model predictions and automated snow sensors to manual snow survey measurements in Metro Vancouver Watersheds.

Type of measurement	n	SD (cm)	SD std dev (cm)	Density (g cm^{-3})	Density std dev (g cm^{-3})	SWE (cm)	SWE std dev (cm)	Density error (g cm^{-3})	SWE error (cm)	SD error (cm)
Snow depth calculation	8	405.6	114.5	0.403	0.0357	166.8	57.4	-0.009	-5.1	-2.8
Automated sensors	7	265.7	72.0	0.351	0.0304	108.9	33.9	-0.054	-14.9	0.6
Measured values								Model results		

As expected, the snow density error decreased later in the season when the snowpack was deep and well settled and bulk snow density was more predictable. This provides confidence for water supply forecasting and planning, which focusses primarily on April 1 and May 1 snow data. However, it is important to note that this study was conducted over two winters where the mid-winter and spring snowpack exceeded 120% of historical average. The dataset is obviously very small. Results could differ with a shallow snowpack or a late-arriving winter season. Adjusting the bulk snow density with nearby manual observations should help reduce this potential error.

FUTURE CONSIDERATIONS

Configuring a Snow Depth Sensor

It is possible to connect a digital snow depth sensor to the camera system directly using SDI-12 or RS-485 communication protocols. Alternatively, a small datalogger (e.g. Campbell Scientific CR300) could be used to process the data and transmit it via the Remote Viewer™. The Lufft SHM31 laser snow depth sensor shows promise for this application. This sensor uses a laser rangefinder to measure snow depth up to 10 m from distances of 30 m away. It can be angled out from the tower or tree, eliminating the need for a horizontal mounting arm. The camera image would display the air temperature and snow depth measurement. The addition of a snow depth sensor to the camera system would eliminate the need for a snow depth pole, which would reduce maintenance costs.

Applying the Model at Snow-Climate Stations

For 2019, the snow density model will be incorporated directly into the dataloggers used at the three snow-climate stations. Metro Vancouver uses Forest Technology Solutions (FTS) Axiom dataloggers. It is possible to write a simple script that utilizes the snow depth data from the ultrasonic snow depth sensor and the average historical bulk snow density using the day of the year. For this application, bulk snow density increases from 0.25 g cm^{-3} to 0.58 g cm^{-3} in bi-weekly increments beginning as soon as the snow depth exceeds 50 cm.

This additional modelled SWE data should improve accuracy for long-term water supply planning, but is not intended to replace existing snow scales. Snow scales remain valuable for monitoring shorter timescale changes in snow conditions, particularly during rain-on-snow flood events.

CONCLUSIONS

This study is an example showing the efficacy of using historical bulk snow density to convert measured snow depth to SWE. Estimated bulk snow density for this project was calculated by averaging monthly manual snow samples from five local snow courses over the past 80 years. Here, snow depth was measured using ultrasonic snow depth sensors and a satellite-enabled web camera directed at a 9 m tall snow pole.

This is a very small-scale study; however, the method and results show promise for enhancing an existing snow monitoring network. The modelled SWE was considerably more accurate than nearby automated SWE sensors. Models values averaged 95% of the observed SWE values. The model accuracy also improved as the winter season progressed.

The snow density model, as used in this application, is a valuable tool for organizations with a dense network of snow stations, a long historical data record, and a need to fill data gaps or provide higher resolution data. The camera system is presented as an innovative tool in snowpack monitoring. Enhancing the camera by installing an automated snow depth sensor makes this system an affordable, low-maintenance, standalone snow and weather monitoring station.

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