RESEARCH AND DEVELOPMENT IN ADVANCING FLUIDLESS SNOW WATER CONTENT MONITORING

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ABSTRACT

The U.S. Department of Agriculture (USDA) has coordinated the cooperative effort in snow surveying and water supply forecasting in the Western States since 1935. This initially involved the Research and Development (R&D) of progressive snowpack monitoring techniques, eventually bringing automated measurements that transmitted data directly to their office. The advances in snowpack monitoring provided more reliable and timely forecasts vital for farmers, business owners, and communities. The technology that is currently used to continuously measure Snow Water Equivalent (SWE), the snow pillow, was developed in the 1960's, over 50 years ago. The snow pillow has been the only reliable SWE sensor despite the inherent limitations. With limited improvements in SWE monitoring to date, Alpine Hydromet set out to develop technology towards bringing a better solution for operators. This summarizes the R&D of two SWE sensors that aim to phase out the traditional fluid snow pillow while developing more reliable and robust technologies; the Fluidless Snow Pillow (FSP) and Cosmic Ray Detector (CRD). This analysis presents an in-depth analysis of comparative data from the winter of 2016-17 and 2017-18 (partial winter through April, 2018) as tested at the UC Berkeley Central Sierra Snow Laboratory (CSSL). (KEYWORDS: snow water content, snow pillow, fluidless snow pillow, cosmic ray)

INTRODUCTION

The western United States is confronting a critical situation associated with climate variability that produce challenges with water supply and managing extreme events. Trending decrease in snowpack and an increase in water security concerns is creating economic concerns for many states. Snow Water Equivalent (SWE) monitoring instrumentation was developed over 50 years ago. The snow pillow has been the only reliable SWE sensor despite many limitations. SWE and snow depth is measured to calculate the density of snow. The density of the snow is used to forecast when spring runoff will begin. SWE is also used to quantify the amount of water which are both fed into river forecast models. These models are derived from regression analysis of snow course data, precipitation, soil moisture, and observed streamflow in the basin where more than 20 years of data has been used (Palmer, 1986).

The technical, economic, social, and other benefits are vast for all operators in water supply management, flood warning systems, farmers, and climatologist. Improved data gives agencies more reliable and timely forecasts vital for farmers, business owners, and communities. The estimated cost is relatively low while expected ongoing benefits of providing more reliable data reaches every aspect of the economy, especially in the western half of the U.S. The need has been identified by both Federal and State agencies, but both lack sufficient resources to research, develop, fabricate, and commercialize the needed scientific instrumentation.

USDA Natural Resources Conservation Service (NRCS) analyzed the importance of SWE for agriculture, recreation, flood management, and power generation. Their findings revealed that 50 - 80 % of water supply in the western United States comes from the snowpack (United States Department of Agriculture, n.d.). In recent years, rain-on-snow events have proved increasingly problematic with flooding. Understanding the snowpack and its water content is critical for adjusting models used for river forecasting and reservoir operations.

THE PROBLEM: SNOW PILLOWS AND THE INHERENT LIMITATIONS

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Snow pillows are installed with slight variations, but all with the same principle based on the weight of the snowpack over the sensor. A standard NRCS SNOw TELemetry (SNOTEL) snow pillow is a polypropylene (rubber) bladder that is 10 ft in diameter. The SNOTEL pillows are installed with a 165-gallon 50-50 solution of propylene glycol-ethanol and water (United States Department of Arigulture, Natural Resources Conservation Service, 2015). A pipe fitting near an edge on the bottom of the pillow is plumbed to a structure that houses the electronics. The pressure line is connected to a pressure transducer to determine weight and converted to SWE.

There are many limitations to the traditional snow pillow developed in the 1960's. There are environmental concerns and local land owners have placed increasing pressure on the agencies to discontinue the use of the propylene glycol-ethanol solution. The Forest Service will not allow the use of any new measurement technology using bulk chemicals to be installed within a national forest. The fluid must be transported to the site location. Many stations do not have or allow vehicle access which means barrels must be sling loaded on helicopters or strapped to horses and packed in on multi-day expeditions. Both items limit the expansion of the water supply forecasting network where needed.

Site maintenance is difficult largely due to damage of the sensor caused by human and animal activity. NRCS states that over 12 snow pillows are damaged by bears every year (United States Department of Agriculture, n.d.). Damage by insects and other animals can damage the pillow or plumbing. Sometimes pin-hole leaks are created that go undetected until the pressure of the accumulating snowpack causes the pillow to leak. This leads to the snow pillow going flat which results in loss of record for that winter (Osterhuber et al., 1998). The pillow must then be replaced with a new bladder and more barrels of fluid.

Finally, snow pillows operate on a weighing principal. Snow accumulates over time, the increase in weight is representative of added water content in the snowpack. Storms arrive with varying conditions and complicate the measurement process. Some events are cold and some warm, weather between snowfall will affect the top layer of snow to then be covered by fresh snowfall. Each layer creates a new dynamic/structure within the snowpack. If a solid ice layer forms, it acts as a bridge, referred to as bridging, and will not allow the transfer of weight of new snow down the snowpack and onto the pillow. In addition, the formation of strong basal layers in deep snowpack also causes bridging. Once these bridges are formed, the subsequent snowfall may not be detected until later in the season when warming occurs and the bridge collapses (Osterhuber et al., 1998). Prior to the bridge collapsing, incorrect measurement of SWE degrade water supply forecasts.

RESEARCH & DEVELOPMENT (PRE-2015)

Solid State Snow Pillow/Fluidless Snow Pillow

The principle research for a fluidless snow pillow based on loadcells was first researched by Jerome B. Johnson who at the time worked for the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Wainwright, Alaska. Over the winters of 2005-06 and 2006-07 CRREL and NRCS tested an electronic, solid state, FSP prototype referred to as the e-SWE sensor. This first design was 3.2-meters square (surface area of 10.24 m^2) and consisted of 1 center weighing panel measuring 1.2-meters square (measurement area of 1.44 m^2) and 8 outer panels. Measurements were also made from one of the outer panels to determine how side stress affects the measurement. In 2008, Jerome Johnson of CRREL began working as a Research Professor at the University of Alaska, Fairbanks where he continued efforts to produce a loadcell-based snow pillow. In 2012-13 two smaller e-SWE sensors were installed, 1.8 m^2 and 1.2 m^2, to determine any variation in sensor performance due to size (Johnson et al., 2015).

The results of the research and development funded by the NRCS were promising; however, there were several areas requiring improvement that were never addressed prior to the defunding of the program. First, maximum range tested for the design never exceeded 1200 mm of SWE and there are many locations in the Western United States, and specifically west coast mountain ranges, that get higher values up to 3000 mm SWE. Based on research and development of the fluid snow pillow, it is known that a 4.88 m^2 area would be inadequate for deep snowpack (USDA NRCS, 2015). Second, sensor calibration was done in the field or postprocessed based on manual snow core measurements. Field calibration requires transportation of weights to the measurement location to perform calibration in the field, which is not practical. Manual snow core measurements have accuracies of 9 % to 11 % which limits the e-SWE accuracy to that of the snow core measurement (Johnson et al., 2015). Third, the sensor construction had each panel isolated from the adjacent panel which resulted in an uneven measurement surface by the end of winter. Over the winter the panels settled unevenly from the pressure of the snow and created an uneven surface that needed to be adjusted. A second field calibration would be required after the settling of the panels (Johnson et al., 2015). It is not known at what point during the winter the settling of the panels occurred and the effect on the measurement.

There were other developments that the NRCS wanted incorporated into an optimal system, such as improved signal output, inbuilt signal processing, and solid frame design which remained unaddressed. These concerns were brought to the attention of Alpine Hydromet and became design objectives.

Cosmic Ray Attenuation

The cosmic ray attenuation sensor is an innovative approach to SWE monitoring. The initial research and development was performed at the UC Berkeley CSSL. The CSSL and California Cooperative Snow Surveys at DWR were approached by researcher Ken Condreva from Sandia Laboratories. Mr. Condreva was tasked to find civilian uses for radiation detection and telemetry systems which had been applied for military use. Radiation detection methods had the capacity to measure the quantity of water, regardless of state, and therefore could measure the amount SWE in a snowpack.

During the winter of 1996-97, the collaborators installed a test sensor at the CSSL. Osterhuber et al. (1998) showed promising results and outlined key areas that require additional research. During the summer of 1997, the sensor was also tested in a body of water and achieved measurements up to a depth of 7600 mm of water.

RESEARCH AND DEVELOPMENT CONTINUED BY ALPINE HYDROMET (2015-PRESENT)

FSP5 & FSP9 - Fluidless Snow Pillow

Alpine Hydromet began the design process for a fluidless snow pillow based on the preliminary research efforts by CRREL and NRCS. As necessary results were not being achieved by research and other commercial agencies to date, Alpine Hydromet decided to pursue solutions that it believed had promise. Alpine Hydromet visited the NRCS National Water and Climate Center in November of 2015 to review initial designs with key NRCS individuals and began prototype fabrication in Auburn.

The initial objective was to continue research carried out to date and answer one simple question: is measurement area or total surface area more important for SWE measurement in a solid state SWE sensor? Alpine Hydromet began to build the FSP5 (1.5-meter square) and FSP9 (2.7-meter square), both with a 0.9-meter square measurement area. Table 1 shows the comparison of measurement area and surface area in square meters for the FSP5, FSP9 and SNOTEL snow pillow at the CSSL. This design was modeled after the CRREL design but with key design objectives; (1) keep signal conditioning electronics out of the snow, (2) have no single piece longer than 4 feet (1.2 m) or weigh more than 35 lbs. (about 16 kg), (3) have the sensor mounted on a single rigid base and (4) have SDI-12 output for simple data connectivity to the existing data collection network.

In the spring of 2016, a beta test for proof-of-concept for the FSP design was tested in a dug-out and reconstructed snowpack. The success of the beta test led to a full design by fall of 2016 for a pilot study of two fluidless snow pillow models, the FSP5 and FSP9. The objective of this study was to compare snow water equivalent (SWE) monitoring sensors at the CSSL over the winter of 2016-17 and 2017-18. There are three in-situ measurement devices; 1) Alpine Hydromet FSP5, 2) Alpine Hydromet FSP9, and 3) Stainless Steel Snow Pillow. The snow tube measurement, commonly used as the standard for ground truthing SWE, was used as a reference to the automated in-situ sensors in the study.

CRD – Cosmic Ray Detector

Alpine Hydromet worked in collaboration with CSSL to deploy a beta cosmic gamma detector during 2016-17. The sensor cable connector was not sufficiently durable and disconnected with the first rain-on-snow event. Limited data were collected for a small range of SWE. The results were consistent with the findings from the studies performed in the mid-1990's and the relationship between the cosmic ray attenuation can be used calculate SWE. A new housing was engineered and fully tested submerged in 168 cm of water for 48 hours. The unit was also raised and lowered to varying depths to verify the measurement of water content tracked the known depth of water. A more robust design was installed and captured a full winter of data in 2017-18.

STUDY LOCATION & INSTRUMENTATION

Study Location and Data Acquisition

The study location, CSSL, near Soda Springs, on the Western side of the Donner Summit at 2,100 m elevation. A layout of the Central Sierra snow lab facility and SWE monitoring sensors are displayed in Figure 1 for 2016-17 and in Figure 2 which included the CRD in the test field study.

Data used in this study are provided in the form of monthly reports and real-time data by: 1) CSSL for manual SWE measurements, cumulative Precipitation, percentage and amounts of rain and snow, snow depth, and outside temperature; 2) NRCS snow pillow SWE and ambient temperature; and 3) Alpine Hydromet for FSP5, FSP9 and CRD.

Figure 1. 2018 UCB Central Sierra Snow Lab 2016-17 sensor configuration

Figure 2. UCB Central Sierra Snow Lab 2017-18 with the addition of the CRD ground and reference detector

Alpine Hydromet FSP5 and FSP9

The Alpine Hydromet FSP5 and FSP9 is a modular fluidless snow pillow that uses four load cells to measure the weight of snow over a 0.84 m² measurement area. The load cells come with a 20 m cable which is run to an electronics box (where the load cell signals are processed) that is in a water tight enclosure next to a data logger. The purpose of the long cable lengths is to meet the first objective of removing any electronics enclosures from beneath the snow, eliminating potential failure from water intrusion damage to the electronics box. The electronics box provides an SDI-12 digital output to the data logger. There is only one major difference in the FSP5 and FSP9. The FSP5 comes with four 0.3 m perimeter stress panels while the FSP9 comes with eight 0.91 m perimeter stress panels. A comparison of the measurement area, surface area, and buffer panels for the FSP and SNOTEL snow pillow can be found in Table 1. The perimeter stress panels are designed to help with differential thermal conductivity between the soil and the aluminum measurement area and help to eliminate perimeter side stress from the snowpack. The measurement range of the FSP5 and FSP9 are 3000 mm with an accuracy of 0.3 % and a resolution of 1 mm.

Table 1. Weighing principle SWE monitoring sensors comparison

Manufacturer	Model	Type of Measurement	Anti-freeze	Total Surface Area (m²)	Measurement Area (m²)	Side Buffer Width (m)
Alpine Hydromet	FSP5	Load Cells	No	2.3	0.84	0.3
Alpine Hydromet	FSP9	Load Cells	No	7.5	0.84	0.91
CRREL/Johnson	E-SWE	Load Cells	No	10.24	1.44	0.9
Stainless Steel Snow Pillow	150” Druck	Pressure Transducer	Yes	5.95	5.95	N/A

Alpine Hydromet CRD

Gamma rays routinely enter the earth's atmosphere as primary cosmic radiation. Primary cosmic radiation collides with nuclei sending a shower of secondary charged and neutral particles known as secondary cosmic radiation into the earth's environment. The cosmic radiation detection that Alpine Hydromet is studying is the measurement of secondary cosmic gamma radiation. Osterhuber et al. (1998) explains that gamma rays penetrate many terrestrial objects including snow, where the signal is reduced based on the quantity of water in the snow. Alpine Hydromet incorporates an instrument to measure the incoming cosmic radiation above and below the snowpack and developed an equation to convert the attenuation of the gamma radiation through the snowpack to the quantity of water present in the snowpack (SWE).

The CRD is about 107 cm long, 20 cm wide, and 13 cm high. The application of a reference sensor above the snowpack assures that fluctuation in atmospheric conditions are cancelled out to measure the attenuation of the snowpack below. Further research is being done to see if the reference detector can be removed with specific site calibration or correction for known meteorological conditions.

Stainless Steel Snow Pillow

The stainless-steel snow pillow is a large bladder with a surface area of 5.95 m^2 (Anderson, 2017). The bladder is filled with antifreeze and plumbed to a pressure transducer that is in a nearby shed (about 23 m away). The pressure transducer provides a signal to a data logger as pressure associated with the accumulation of snow over the snow pillow. The surface of the pillow is covered with gravel. The range of sensor is 3800 mm with a stated accuracy of 0.15 % and resolution of 2.54 mm.

DATA REVIEW

All data shown is raw data that have not been corrected or edited. Prior to SWE analysis it is important to understand that for the weighting-based solutions the accuracy of the sensing device does not necessarily relate to accuracy of snow water content because of the influence of snow dynamics. Accuracy is based on applied weight to the sensors. Deeper snow packs may develop uneven pressure areas resulting in different applied forces to the sensors (Natural Resource Conservation Service, 2014). Snow tube measurements are the closest measurement to ground truthing though they are also known to have measurement errors. The measurement error is not only caused by the ability to drive the snow tube down orthogonal to the horizontal plane but can also be a function of "snow height, snow layer hardness and density, cutter sharpness and temperature gradients within the snowpack" (Osterhuber, 2014).

Winter 2016-2017

The winter of 2016-17 produced historic precipitation and snowpack accumulations at the CSSL. According to CSSL records, 2016-17 was the wettest winter on record and 9th most in snowfall accumulation. Through April, 2938 mm of precipitation with 1429.5 cm of snow fall was measured. There were also ten rain-on-snow events, and four of these ten rain-on-snow events were significant events ranging from 98 mm to 247 mm of rainfall. The four-major rain-on-snow events all occurred relatively early in the season, between December 7th and February 11th. This contributed to changes in the snow dynamics, runoff, and malfunction to the NRCS snow pillow. Figure 3 provides an overview of the winter. The left axis represents millimeters (mm) for daily precipitation accumulation, hourly SWE measurements from FSP5, FSP9, SNOTEL snow pillow and incremental manual SWE measurements. The right axis represents degrees Celsius for the hourly temperature readings. Table 2 shows the dates of the four events along with the quantities and percentages of precipitation in rain and snow.

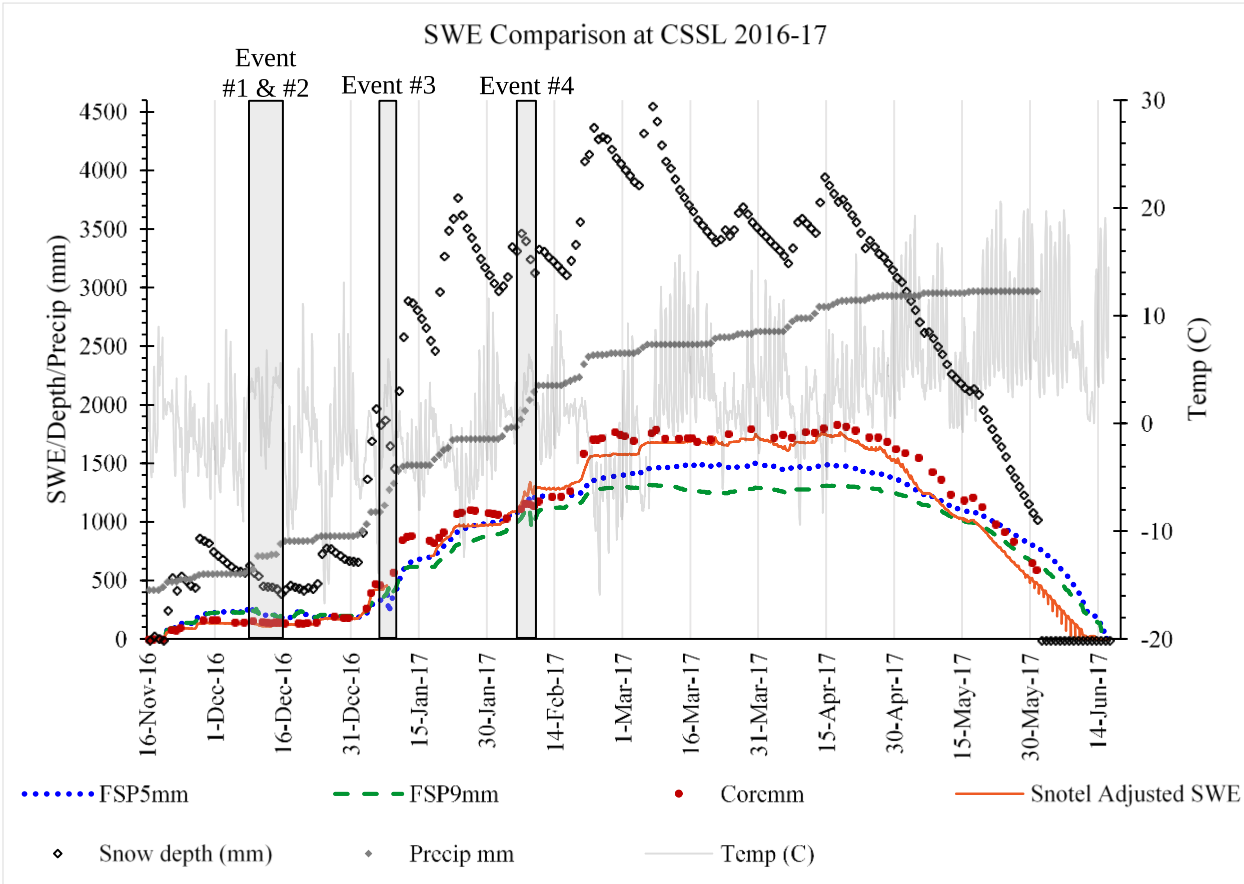

Figure 3. Winter 2016/2017 Cumulative Precipitation, Temperature and SWE and snow depth. Chart also includes identification of the four-significant rain-on-snow event periods.

Table 2. Four major rain-on-snow events, including precipitation totals and percentages. Event precipitation quantities provided by the CSSL

Event	Date	Event Precipitation (mm)			Rain (%)
		Total	**Rain**	**Snow**	
#1	Dec. 7th-10th	152	141	11	92
#2	Dec. 13th-17th	128	98	30	76
#3	Jan. 7th-12th	399	184	215	46
#4	Feb. 2nd-11th	456	247	209	54

The first two rain-on-snow events occurred within a ten-day period (December 7th -17th) and only three days apart, resulting in 239 mm of rainfall. The first event caused the data cable of the prototype CRD to disconnect from the ground sensor and no further data was collected past December 10th, 2016 with the CRD. Figure 4 shows the CRD, core measurements, and SNOTEL snow pillow SWE data. The CRD was initially installed on the south side of the house in a shaded area away from the main exposed test bed.

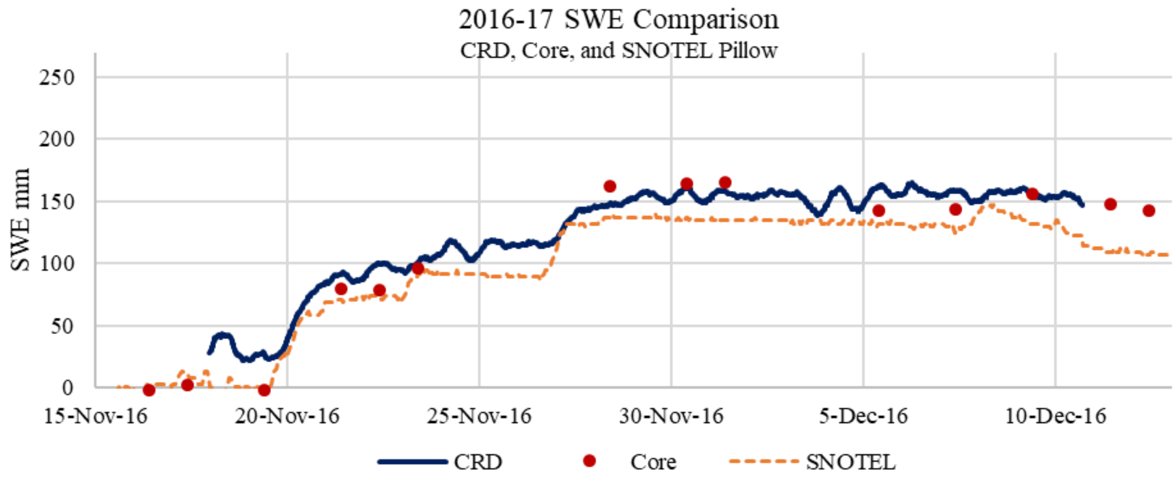

Figure 4. Comparison of CRD, manual core measurements and SNOTEL snow pillow SWE data.

Rain-on-snow Event #3 occurred between January 7th-12th resulting in 399 mm of precipitation, 184 mm in rainfall. Event #3 was an extreme event in which a channel of water flowed into the ground floor of a nearby structure which housed the pressure transducers for the stainless-steel snow pillow. Fortunately, the structure was accessible, and the pressure transducers were able to be replaced, limiting the data loss to only 10 days.

Rain-on-snow Event #4, the largest rainfall event of the winter occurred between February 2nd-February 11th, resulting in 456 mm of precipitation, 247 mm being in the form of rainfall. This is the same event that resulted in the near failure of the Oroville Dam. Following Event #4, FSP5 and FSP9 began to undermeasure. It is believed that snow dynamics influenced by Event #4 contributed to the undermeasurement of FSP5 and FSP9. Figure 5 shows a graph of the February events. Table 2 provides daily values and percentages of precipitation (snow and rain) along with temperature highs and lows for Event #4.

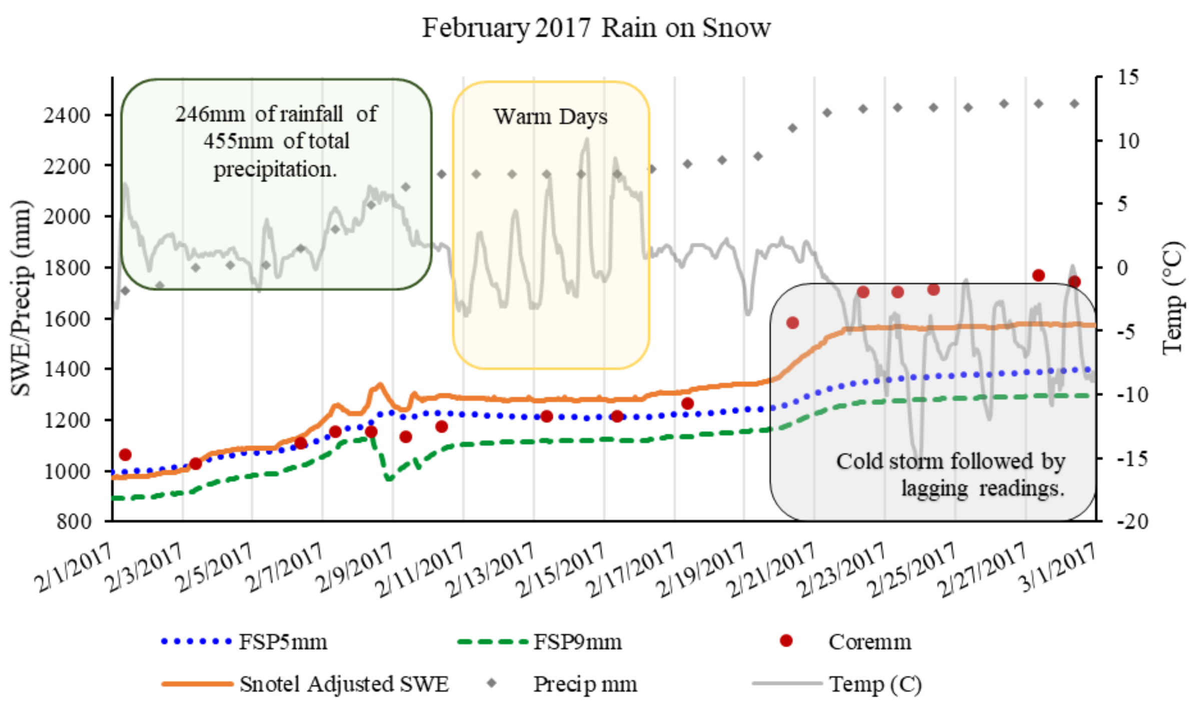

Figure 5. February rain-on-snow and following weather indicative of crust formation.

Change in snow layer density, hardness, or the formation of a bridge may have occurred over the FSP5 and FSP9. As seen in Figure 5, Event #4 rain-on-snow event was followed with three consecutive days of warmer weather, with daily high temperatures between 9 °C to 11 °C. This warmer weather was followed by a cold snow event where 234mm of snow fell over eight days and temperature stayed below 0 °C with lows ranging from -9 C to -14 °C.

Sensors based on a weighing principle can be impacted by differential pressure caused by lack of uniformity of the snowpack and bridging. Rain-on-snow events and warm temperatures followed by cold temperatures can impact the snow dynamics of the snowpack. Snow layer density, snow hardness and ice lenses can all influence the pressure distribution of the snow on weight measurement devices. Ice lenses can cause an under measurement as future snowpack accumulates by supporting the weight accumulation. One way to attempt compensation for variation in snow pressure and bridging is to increase the surface area of the snow pillow. Though differences may occur between each sensor based on the location of installation and how snow water channels form within the snowpack, it was seen that the larger surface area of the traditional snow pillow may have helped with more reliable measurements than the smaller measurement area sensors.

Winter 2017-2018

For the winter of 2017-18 Alpine Hydromet reinstalled the Cosmic Ray Detector (CRD). Over the summer or 2017 Alpine Hydromet redesigned the CRD housing with an all-aluminum, powder coated and gasketed enclosure with IP68 rated, marine grade, stainless steel cable glands. The sensor was then tested submerged in 168 cm of water for 48 hours prior to the installation in 2017-18 winter. This also allowed for the verification of the attenuation to SWE curve against known quantities of water content.

The 2017-18 winter started off dramatically different from the previous winter with signs of a dry year until March. The snowpack entered February at about 33% of average and 50 mm of cumulative precipitation (100 % snowfall) for the entire month of February. In contrast, "Miracle March" as the media proclaimed, brought 530 mm of precipitation bringing peak snow height to 76 % of average at 2320 mm on March 17th and peak SWE to 72 % of average at 670 mm on March 26th (Osterhuber, Personal Communication, UCB Central Sierra Snow Laboratory, 2018). An overview of the 2017-18 winter is shown in Figure 6.

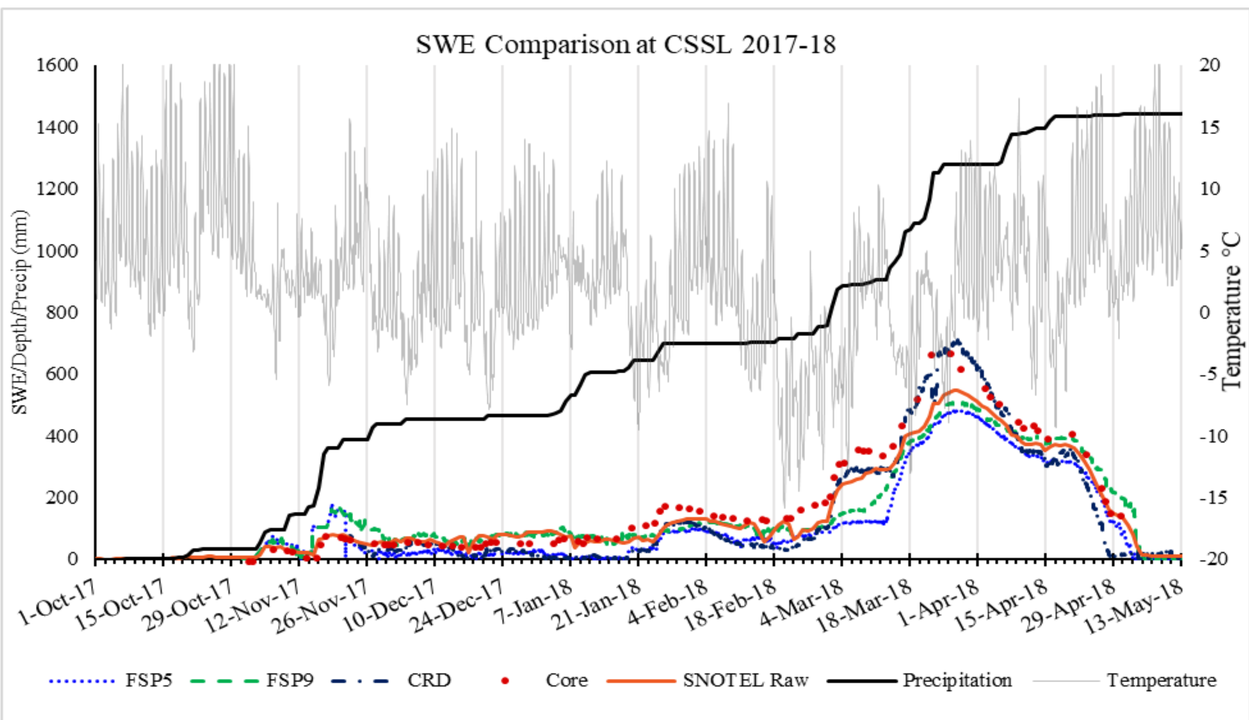

Figure 6. 2017-18 SWE comparison at the CSSL of the Alpine Hydromet FSP5, FSP9, and CRD, and manual core measurements with a federal sampler, and NRCS SNOTEL snow pillow edited SWE data, precipitation and air temperature (left axis).

The installation location of the FSP5 and CRD were the first sensor locations to melt out. The CRD was placed near a tower which likely affected snow melt by welling during ablation periods. The FSP9 and SNOTEL snow pillow both stay covered with snow longer than the FSP5 and CRD. The winter of 2017-18 had a mid-winter melt out at the CSSL due to warmer weather and rain-on-snow events. The snow height December 20th, 2017 was 32 cm and dropped to 18 cm by January 18th, 2018 at the location of the snow core measurements. However, at this time due to the nature of the melt pattern at the CSSL, the CRD and FSP5 locations had both melted out completely and left both sensors exposed.

There was one more significant snow event at the end of January which brought 56 mm of snowfall followed by about two weeks of maximum temperatures above 10 °C. The warmer weather was followed but a cold snap with lows reaching -18 °C at night and a total 184 mm of snowfall in the next two storms that both the FSP5 and FSP9 were not able to register. The warm weather followed by the cold front and snowfall lead to crust formation. It is very likely that the crust affected the distribution of the weight of snow on to both the FSP5 and FSP9. Following the cold snow events two rain-on-snow events occurred. The first was March 10th and the second on March 14th. These events broke the crust layer allowing for the snow weight to be transferred onto the sensors and both sensors resumed normal measurement of the snowpack.

The 2017-18 data collection was successful since all four SWE sensors measured peak SWE at the same time and, minus the CRD which was installed next close to a tower and subject to effects of welling, the sensors all came to zero SWE within a day or two of each other. The CRD has proved successful and the most reliable sensor of the winter as the SNOTEL data also became subject and was edited to correct errors in the sensor that were experienced around the same time the FSP measurements were not experiencing effects of complex snow dynamics.

CONCLUSIONS

The 2016-17 winter was the wettest on record at the UCB Central Sierra Snow Lab and ranked 9th historically for snowfall. Ten rain-on-snow events impacted the snow dynamics and tested the durability and accuracy of the automated SWE measurement devices. 2017-18 brought a different type of snowpack formation with early snow turned crust, mid-winter partial melt-out followed by substantial snow in March, and late winter rain-on-snow events. The FSP5, FSP9 and redesigned CRD sensors appeared robust and reliable in providing representative SWE data.

Research in the FSP concluded that while a sensor buffer perimeter may be necessary, the important area for data correlation was the measurement area. A larger total surface area (increased size of side panels) did not provide increased data accuracy as the data indicates limitation with deeper snowpack in both FSP5 and FSP9 models. There remains a question on the relationship between optimal measurement area and maximum SWE, and this likely also varies with not only the depth of snow, but the density of snow and the formation of crust layers. It is likely that the optimal measurement area may vary by region, with the maritime coastal environment requiring larger measurement area, and the inland continental air mass areas requiring smaller measurement area. Continued research in collaboration with network operators would be beneficial for the develop a sensor with a larger measurement area.

The inherit limitation with any weighing-based principle are addressed with the CRD. It is expected that continued research into the measurement can add value in the snow data by potentially recognizing rain-on-snow accumulation and drainage in the snow pack. There is also potential in minimizing the effects of bridging by increasing the measurement area of the FSP to be like that of standard snow pillows for locations with complex snow dynamics and structures.

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