Snow Water Equivalent (SWE): Progression of Snowpack SWE Measurements and the Use of a GIS Environment for Spatial Analysis

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Abstract

Modern computers and the development of geographic information systems (GIS) have had a great impact on the collection and spatial processing of point data. GIS has developed significantly, especially in the field of earth sciences. A GIS is defined as "a system which analyses and displays spatially referenced data" (Hinton, 1996). GIS has been increasingly beneficial in snow hydrology. Snowpack parameters can be tested for spatial significance and correlation, and can be visually represented with topographic features. In this literature review, three methods for calculating snow water equivalent (SWE) will be summarized. Each method integrates GIS to provide spatial representation of SWE through spatial analysis and interpolation. To date, there has been no integration of snow course, Snow Telemetry (SnoTel), and remote sensing measurements with topographic variables and vegetation, found within a GIS environment or GIS research. I believe that using GIS to incorporate metrological parameters, topography, slope, aspect, and vegetation with snow course, SnoTel, and remote sensing measurements would develop a structure of characteristics that could be used to better represent spatial distribution of SWE in mountain regions.

Keywords: snow water equivalent (SWE), snowpack telemetry (SnoTel), snow course, remote sensing, and geographic information system (GIS)

I. Introduction

Modern computers, the development of geographic information system (GIS), and technology based on precise global poisoning systems (GPS) are revolutionizing areas of environmental science and human endeavors (Tim, 1995). Since its beginning over 35 years ago with the Canadian Geographic Information System (CGIS) for computer spatial data analysis and modeling, GIS has become an important spatial analysis tool used in a variety of research fields (Peuguet and Marble, 1993). GIS applications allow better visual understanding in environmental studies by comparing and summarizing complex spatial relationships. Accomplishments made in GIS have allowed users to quickly perform analyses such as queries, distance measurements, transformations, optimization, and basic statistics, which at one time were very time-consuming to perform.

In the research field of snow hydrology, GIS applications have become extensive. Currently a GIS –based Snow-Cover Comparison Tool (SCCT) is being developed for analysis to make comparisons between simulated and remotely sensed snow cover data (Koczot, K.M., and M.D. Dettingger,). A GIS-based Geographic Resources Analysis Support System (GRASS) is in use that will interpolate observations of snow water equivalent (SWE) and produce gridded estimates of SWE, stores, analyzes, and displays point, line and gridded data (McManamon et al., 1993).

Three different components are discussed in this literature review. The first component provides a basic background and review of snow course data, snowpack telemetry data (SnoTel), and remote sensing data used to measure SWE. Also, a discussion of techniques, methods, and problems associated with each of these applications will be reviewed. The second component highlights ways in which GIS has been used to aid in image analysis, and how it has been used as a base in snow hydrology models. The final component discusses applications of GIS in snow hydrology, particularly how a GIS can be used to compile a spatial dataset of SWE distribution within the Colorado Rocky Mountain Region.

II. Background

The most important snow data for a snow hydrologist is the snow water equivalent (SWE) content of the surrounding snowpack (Dingman, 2002). Snow water equivalent is defined as the mass of a standing column of water resulting from the melting of a snow sample of a cross section and height equal to the snowpack depth, and is expressed as a unit of length, i.e. mm (Paul et al., 1994). Snow on the ground is a dynamic medium where the properties and characteristics of fallen snow change continuously as a function of energy fluxes, wind, moisture, water vapor, and atmospheric pressure (Williams, 2002). The bulk of western United States surface water resources comes in the form of solid precipitation, and is naturally stored in mountain snowpack at high elevations. The majority of western water flow is derived from the melt of winter snowpack, so it is important to monitor snowpack properties throughout the winter months. Yearly water consumption in the west averages around 44% of renewable supplies, compared to only 4% for the rest of the country (Serreze et al., 1999). For this reason, understanding physical location and amount of water held within mountain snowpack is of great importance for water supplies, power production, and flood control. Three common techniques for measuring SWE are derived from snow course field data, snow telemetry data (SnoTel), and remote sensing data.

A. Snow Course Data collection of SWE

A snow course is a path between two fixed end points over which a series of measurements of snow depth, snow density, and water equivalent are measured (Derksen et al., 2002). Site selection for snow course measurements depends on the research purpose. For example, when the data is to be used as an index parameter for correlation of physical parameters, a different site may be more appropriate than when an absolute SWE value for a specified watershed or geographic region is desired (Goodison et al., 1981). However, a few general rules are applied in site selection for all research purposes: a consistent location over time, accessibility by foot or skis, and sampling away from ground irregularities and slightly sloping terrain (Goodison et al., 1981). Depending on terrain and aspect, a snow course is in the range of 150 to 250 m, with measurements made at six to eight locations along the transect (Dingman, 2002). Snow course data provide informative information at the local scale; selected site locations mimic the average local topography and vegetation of the research region.

Methods used to determine SWE from snow course measurements are basic and straightforward. Snow course measurements focus on the second half of the water year (December – May) in order to attain estimates of pre-snowmelt SWE (Derksen et al., 2002). At each sampling point a coring tube (snow tube) is inserted vertically into the surface. After the snow tube contacts the ground, the snow sample is extracted and weighed on a calibrated scale that is pre-tared and reads in centimeters or inches of water equivalent (Dingman, 2002). The depth is also measured at each site by reading the depth scale on the side of the snow tube, and snow density can be calculated using equations described in Lawrence Dingman's Physical Hydrology Textbook (2002). Snow course measurements are done twice a month during winter months: once on the first day of the month, and the second on the fifteenth day of the month.

Many problems are associated with snow course SWE measurements. For example, snow course methods only provide point data, snow tubes underestimate SWE when ice lens and depth hoar are present, cause deconstructive sampling of *in situ* snowpack, are labor intensive, have limited spatial distribution, and they can cause biased sampling (Derksen et al., 2002). The most common error associated with snow course SWE measurements is manual measurement error, due to extreme weather conditions in the field. Snow course measuring methods require physically strong field personnel to collect and maintain remote snow course sites.

B. Snowpack Telemetry (SnoTel) Data Collection of SWE Data

Snowpack telemetry (SnoTel) involves meteor burst telemetry for sending remote snow data to a main database. Meteor burst telemetry relies on the reflectance of radio signals from ionized meteorite trails 50 to 75 miles above the earth's surface (NRCS, 2003). Meteor burst technology allows communication between two locations up to 1,200 miles apart. This technique allows a better spatial representation of remote mountain terrain SWE and provides hourly to daily values of SWE as compared to bimonthly values provided by snow course data. In 1977, the Natural Resource Conservation Service (NRCS) began implementing SnoTel measurements and transmitting snowpack, precipitation, and temperature data on a daily basis (NRCS, 2003). SnoTel data is transmitted everyday from over 600 sites located within the 11 western states including Alaska. SnoTel sites are selected to represent the local topography and vegetation of the selected research region.

Methods used to determine SWE at SnoTel sites relies on the measurement of the overlying snowpack weight. Since SnoTel stations are fully automated and unattended, SWE measurements are made using snow pillows that are filled with an antifreeze solution. As snow accumulates on the snow pillows, the weight applies a pressure on the snow pillow, which is then read by a monometer and converted to SWE in inches from a pressure transducer (Serreze, 1999). Cumulative daily SWE values are obtained through the snow pillow, and incorporate responses to gain by precipitation of rain and snow or to a loss by snow percolation and snowmelt.

Although SnoTel stations provide daily SWE, temperature, and precipitation data, there are problems associated with this method. There are four main problems associated with SnoTel SWE measurements: bridging, snow pillow interaction with snowpack, wildlife impacts, and structural changes in antifreeze solution. Bridging occurs when the snowpack creates a dense layer (ice lens) that connects with the snowpack outside of snow pill region. This reduces the pressure on the snow pillows, thus contributing to an under-estimation of SWE content. The presence of snow pillows within a snowpack alters temperature and vapor pressure interactions between the snowpack and the soil surface, which can adversely affect the SWE measurement (Williams, 2002). Wildlife can affect the SWE measurement by walking across or lying down on the snow pillows, which alters the pressure measurement on the snow pillow. Also, structural changes of antifreeze solution with temperature can allow changes in pressure readings on snow pillows (Williams, 2002). Another important aspect to remember is that SnoTel sites measure weight and convert the value into SWE, so sensor error due to calibration can be variable due to site location and site characteristics.

C. Remote Sensing of SWE

In mountainous regions large variations of SWE and snow depth are due to variations in slope, aspect, elevation, exposure, and surface cover (Goodison et al., 1981). These variations cause discrepancies in ground-based measurements derived from snow course and SnoTel data. With the first successful launch of the Earth Resources Technology Satellite (ERTS-1 or Landsat-1) on the 23 July 1972, scientists have been able to gain valuable information on hydrologic systems and processes (Pietroniro and Prowse, 2002). Remote sensing of snowpack characteristics can account for the SWE variations to provide an enhanced spatial representation of snowpack properties. To date, there are several ways in which remote sensing data can be used for snow monitoring applications (Schjodt-Osmo and Engeset, 1996). The most common method of satellite-acquired data used for snow monitoring is derived from optical, passive, and active microwave sensors. The National Operational Hydrologic Remote Sensing Center (NOHRSC) is part of the National Weather Service (NWS), and provides remotely sensed and modeled hydrology products for the United States.

This review focuses on remote sensing of snowpack properties through airborne electromagnetic radiation (EMR) measurements: microwave and gamma. Passive microwave data has the capability to penetrate clouds and snow cover and provides dual polarization at different frequencies (Trait, 1998). Microwave radiation is read in wavelengths of 0.1 to 50 cm, and the microwave radiation flux from a snowpack is dependent on temperature within the snowpack, grain size, and soil conditions (Dingman, 2002). Gamma radiation is naturally emitted from the ground surface and attenuates through the snowpack. To obtain remote sensed EMR data, flight lines over the research area are done prior to snowcover (bare ground) and when ground is snow covered. As EMR up-wells from the ground through the snowpack, it is scattered by snow grains, which attenuates the radiation signal. The degree of attenuation by the snowpack shows a positive correlation with snowpack depth (Konig et al. 2001). The deeper the snowpack the less radiation is emitted and a lower brightness temperature is detected by the sensor, which in turn allows the derivation of algorithms for determining snowpack depth and SWE (Konig et al., 2001). Special Sensor Microwave Imager (SSM/I) is a unique sensor created for estimating SWE.

Microwave radiation sensors such as SSM/I provide excellent representation of SWE distribution for large areas (15 x 13 km to 65 x 43 km), but are limited in use for small areas (Bernier et al., 1999). Carroll et al. (1999) found several problems with the SSM/I sensor. They stated that the SSM/I resolution is to course, the SSM/I algorithms are not good in forested area, and the SSM/I signal is affected by small amounts of liquid water on the snowpack surface. Konig et al. (2001) found agreement between satellite derived snow depth and individual ground measurements to be poor, and algorithms for SWE and snow mass to be poor.

D. Comparison of the Three Methods for Estimating SWE

Table 1 presents a comparison of time series, synoptic sensitivity, advantages, and disadvantages for SWE measurement methods derived from snow course, SnoTel, and Remote Sensed data. The table is derived from Derksen et al. (2002), but modified to add SnoTel information and to remove non-pertinent data.

Table 1. Summary of snow course, SnoTel, and Passive microwave data.

	Snow Course	SnoTel	Remote Sensed
Time Series	1933 to present	1977 to present	1978 to present
Synoptic Sensitivity	Commitment of field personnel. Data biased to second half of water year.	Daily and 6 to 12 hour intervals.	Daily, weekly, and monthly.
Advantages	Provides information at local scale. Snow course can be selected to represent vegetation and terrain.	Provides information at local scale. Can be selected to represent vegetation and terrain. Cost-effective data.	All-weather imaging. Rapid scene revisit. One of the longest satellite records.
Disadvantages	Labor intensive. Limited spatial distribution.	Snowpack bridging. Snow pillow interaction with snowpack. Antifreeze solution. Wildlife.	Problems mapping SWE during wet snow periods. Large pixel dimensions. Land cover complications.

III. Integration of GIS and Snowpack Data In Snow Hydrology

Using GIS for snowpack data analysis in snow hydrology research can greatly enhance the spatial representation of snow data (i.e. SWE), incorporate spatial analysis, and enhance snowmelt forecast. Most literature is focused on pursuing and enhancing performance of remote sensing of snowpack properties, whereas snow course data and SnoTel data are considered to be a reference to calibrate remotely sensed data. Most remotely sensed data is not used to measure SWE, but instead is used to determine the snow covered area (SCA) of a specified region. Applying the analytical and visualization tools found in a GIS can enhance physically based hydrological models, which has been the main application of GIS in snow hydrology. Kozcot and Dettinger (1999) designed a comparison tool for remotely sensed snow data and simulated snow cover data to improve watershed models in the Sierra Nevada region. Orndorff and Van Hoesen

(2001) used GIS to look at shading, slope, and curvature of the landscape in the Snake Range, Nevada in combination with a climate-driven model to simulate past spatial distribution of perennial snow during the modern and late Pleistocene. NOHRSC provides GIS data sets, snow information, snow analyses, and airborne gamma snow survey information for federal, private, and public users.

Limited literature is found on incorporating a GIS for use with SWE data. Literature found on this subject focuses on comparison analysis and using point source data from snow course and SnoTel data to create SWE layouts. Derksen et al. (2002) compared snow course data, passive microwave SWE data, and a developed snow model. Their results showed that snow course data by location have a high degree of variability between data sets, and that a stronger agreement is achieved when resolution of data are spatially and temporally coarsened. Klein and Barnett (2003) validated a snow cover map created by Moderate Resolution Imaging Spectroradiometer (MODIS) by comparing a MODIS snow cover map and a NOHRSC snow cover map against *in situ* SnoTel data for the 2000-2001 snow season. Klein and Barnett's (2003) comparison of both snow cover maps with *in situ* SnoTel measurements reveal good overall accuracies of 94% and 76% for the MODIS and NOHRSC maps respectively.

GIS has been used for interpolating point data from snow course and SnoTel measurements to create visual representations of changes in measured SWE. McManamon et al. (1993) use the Geographic Resources Analysis Support System (GRASS) GIS to store, analyze, and display point, line and gridded data for use in interpolating observations of SWE. The end result is gridded SWE estimates to aid in better forecasting of seasonal water supplies. Fassnacht et al. (2001) and Parajka et al.

(2003) both used GIS for mapping layouts of their respective study areas using DEM data and interpolation of SWE point measurements as input data for their hydrologic models to aid in predicting future water resources.

IV. Discussion

Much research has been done managing point measurements of snow course and SnoTel data and interpolating these points across a watershed or designated region. SWE layouts of point measurements help reveal spatial distribution, but are susceptible to errors due to site selection, elevation, vegetation, and aspect. Remote sensing of SWE yields the same outputs as point measurements, but provides a better representation of SWE distribution. Remotely sensed measurements are not accurate at a fine resolution, but show good spatial and temporal trends in SWE content (Bernier et al., 1999).

Manual SWE measurements by snow course and automated SWE measurements by SnoTel can provide a beginning toward regression equations that can be used in a GIS (McManamon et al. 1993). Derived equations can be obtained from SWE historical data, which then can be applied in a GIS to represent average SWE values with fewer point measurements. This is a practical application if continuous data is available for derivation of regression equations.

Remotely sensed measurements are good when coarse resolution data is adequate, but many factors need to be known or assumed while measurements are collected. For example, considerable information on ground conditions such as temperature, grain size, and soil conditions need to be acquired in order to create reliable algorithms for interpretation of SWE (Dingman, 2002). Problems associated with land cover are not modeled correctly using SSM/I. Derksen et al. (2002) used the International Geosphere-Biosphere Programme (IGBP) land cover classification of four land cover types (open, coniferous, deciduous, and sparse forest cover) to provide better SWE representation in forested and non-forested regions.

As stated above, little work has been done to incorporate SWE measurements from snow course, SnoTel, and remote sensing into one spatially distributed SWE layout. Rapid improvements in remote sensing and historical records of snow course and SnoTel data provide an opportunity to use high temporal and spatial resolution data to produce a better representation of spatially distributed SWE.

V. Conclusion

Snow course measurements beginning in the 1930's and SnoTel measurements beginning in the 1970's both represent measurement methods that have remained the same for years, generating representative data sets for long-term SWE studies at each site location. Since the first Earth sensing satellites were launched, the quality and quantity of remotely sensed data has increased. With recent technological advances in remote sensing and computer software, applications combining snow course, SnoTel, and remotely sensed snow data can be attainable within a GIS. Combining these data sets will provide a better understanding of SWE and its spatial distribution by comparing it to other variables such as slope, aspect, vegetation, and metrological parameters. Future work needs to use GIS to integrate snowpack, vegetation, topographical, and meteorological data to better characterize SWE distribution in mountain environments.

VI. References

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