TEMPORAL AND SPATIAL SWE PREDICTIONS FOR HYDROLOGIC MODEL INPUT

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ABSTRACT

A multiple regression equation was developed to describe temporal and spatial variability of daily snow water equivalent (SWE) in Lake Tahoe's Incline Basin. SWE maps of the basin are needed for the parameterization of the physically-based Alpine Hydrochemical Model (AHM) to simulate basin hydrology and solute transport. SWE data collected during 2002's peak snow accumulation were used in conjunction with data from three local SNOTEL stations to calibrate the regression equation. Calibration was conducted during a dry and average water year using the sum of least squares. The multiple-regression was dependent on elevation, aspect, slope, vegetation density and solar radiation and was normalized by the average SWE measured at the three SNOTEL sites. Basin-wide computations were done at 30 m resolution in ArcView to generate daily SWE maps. Verification was performed at the three SNOTEL sites for a wet year and another average year. While errors in prediction were relatively low (approximately 0.3%), the regression over predicted peak accumulations for upper elevations, under predicted SWE at lower elevations and allowed greater attenuation of SWE into the summer months for lower elevations. In contrast, the mid-elevations were extremely well predicted in both timing of peak accumulation and overall SWE volume. SWE maps allow for calculation of snow covered area (SCA), snowfall and potential snowmelt needed for AHM input.

INTRODUCTION

Snowmelt processes primarily control the magnitude and timing of spring runoff in alpine watersheds with estimates of snow water equivalent (SWE) distribution throughout the catchment actively controlling patterns of snow disappearance (Anderton et al., 2002). Therefore, SWE is an important input to any hydrologic model of a high mountain watershed. Unfortunately, spatial and temporal estimates of SWE are limited by our understanding of how snow is actually distributed over an entire watershed and measurement of SWE at the basin and multi-year scale is hindered by time, effort and financial constraints. While remote sensing techniques are emerging as a valuable tool for SWE prediction (Bales and Harrington, 1995), these methods are not routinely used due to problems in sensor sensitivity (Rango and Shalaby, 1999), validation of SWE retrieval algorithms (Cline, 1998) and scale appropriate measurements. Currently, intensive field sampling of snow depth and SWE coupled with interpolation techniques are generally used to estimate SWE. Several SWE models have relied on geostatistical approaches (Hosang and Dettwiler, 1991; Phillips et al., 1992; Carroll et al., 1995; Carroll and Cressie, 1996), statistical relationships (Elder et al., 1991) and binary regression tree methods (Elder, et al., 1995; Elder et al., 1998). Many studies use a combination of elevation, slope, aspect, net solar radiation and/or vegetation cover as the independent variables in computing SWE distribution across a watershed (Elder and Dozier, 1990; Elder, et al., 1995; Elder et al., 1998; Erixleben et al.,2002).

This study represents the first phase in parameterizing the Alpine Hydrochemical Model (AHM) by describing temporal and spatial snow distributions within an alpine basin over a wide range of climatic conditions (i.e. dry, average and wet). Maps of snow water equivalent (SWE) are used to compute snow covered area (SCA), incremental snowfall and potential snowmelt rates needed by the hydrochemical model.

METHODS

Alpine Hydrochemical Model (AHM)

While numerous hydrologic models for watershed assessment exist (e.g. HEC-1, PRMS, SLURP), only a few couple both hydrologic and chemical characteristics in response to atmospheric deposition (HSPF, AGNPS) and these were developed primarily for low elevation agricultural sites. More appropriate for alpine basins, the Alpine Hydrochemical Model (AHM) is a general material-balance algorithm developed by the University of

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Arizona, Tucson for detailed, compartmental modeling of seasonally snow-covered watersheds (Wolford, 1992). It is an integrated hydrologic and chemical model that can simulate the magnitude, timing and chemical composition of watershed runoff. AHM has been used primarily to model alpine watersheds in the Sierra Nevada (Wolford et al., 1996), with more recent attempts in the Rocky Mountains of Colorado (Meixner et al., 2000). In the present study, AHM is being employed to model the hydrology and chemistry in the Incline Creek watershed, Nevada. This is part of a multidisciplinary project that is integrating regional airflow, atmospheric chemistry and hydrochemical models into a comprehensive framework.

Incline Creek Watershed

The Incline Creek watershed is 17.4 km^2 located in the Carson Range of the Sierra Nevada, with its stream draining into Lake Tahoe (Figure 1). The maximum, average and minimum basin elevations are 2812 m, 2347 m and 1901 m, respectively. Slope in the Incline Creek basin ranges from zero degrees to 44 degrees with an average of 23 degrees. Aspect is generally west-south-west with stream flow draining into Lake Tahoe at the exit of the basin. Vegetation throughout the Incline watershed is primarily large conifer stands, dominated by Lodgepole Pine in the upper elevations, a combination of Red Fir and mixed conifer in the middle elevations, and mostly Jeffrey Pine in the Lower elevations. Only small groves of Aspen and Alder exist in the basin. Huckleberry Oak and montane mixed chaparal are prolific along the creek banks at the upper and middle elevations of the basin.

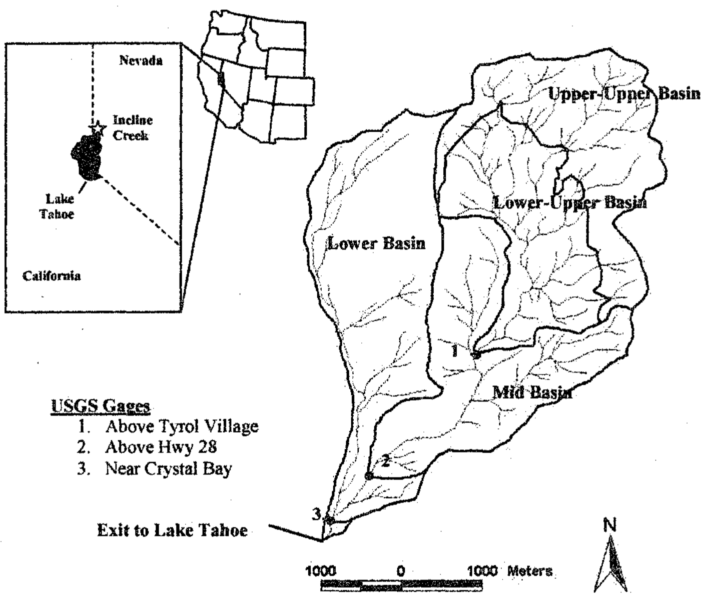


Figure 1. Location of Incline Creek and its division into four sub-basins with USGS gaging stations marked.

The basin hydrology and solute transport are dominated by snowmelt processes making it mandatory to adequately describe both the spatial and temporal distribution of snow in the basin in order to quantify basin runoff characteristics. For the purposes of this study, the basin is divided into four sub-basins. The designated sub-basins allow for systematic calibration of the AHM model with respect to stream flow and chemistry at each of the three United States Geological Survey (USGS) stream gages located in the study site. The Upper basin drains into the USGS gage "Above Tyrol Village" and is further sub-divided based on the mean elevation into the Upper-Upper and Lower-Upper basins. The division of the Upper basin was done after initial modeling efforts with AHM as a means to better attenuate stream flow. The Upper basin is primarily undisturbed with little development. Development that does exist occurs as a recreational ski resort (Diamond Peak). The resort resides on the south-eastern flank of the Upper basin and extends downward into the Mid basin. The Mid basin was determined by the area that contributes additional flow to the USGS gage "Above Hwy 28" while the Lower basin contributes additional flow to the USGS gage "Near Crystal Bay". Residential and urban development, in addition to a golf course, occupies much of the Mid and Lower basins.

Snow Data

A snow survey was conducted on March 26, 2002 at peak snow accumulation for the year. Fourteen locations were sampled in the Upper basin where a majority of the snow is located. These locations were chosen prior to the survey to represent different major classes of elevation, slope, aspect and vegetation density. All locations were registered to the 30 m USGS DEM. A Federal Sampler was used to measure SWE (from three replicate samples) at the center point of each location while a probe was used to measure depth at 20 m increments along a 100 m transect each side of the center point. SWE for each location was then computed by multiplying the snow density calculated from the Federal Sampler measurements by the average depth of the location.

Three local SNOTEL sites were used in conjunction with the snow survey data. These sites include the Mt Rose Ski Area (Western Regional Climate Center (WRCC) number 260024) at an elevation of 2697 m, Marlette Lake (WRCC number 260023) at an elevation of 2438 m and Tahoe City Crossroads (WRCC number 040023) at an elevation of 2062 m. All three sites are located within the Lake Tahoe basin between 3 to 20 km from Incline Creek watershed. Their elevations span the elevations found within the Incline watershed.

Regression Analysis

While binary tree models offer the best existing model at present (Erxleben et al.,2002), the preliminary snow survey did not provide enough data points to properly characterize a model. Therefore, a multiple regression using the independent variables found significant in other studies (Elder, 1995; Elder et al., 1998) of elevation, slope, aspect, potential global solar radiation and vegetation density was established. Elevation, slope and aspect were obtained from a 30 m DEM and vegetation density was categorized from a Tahoe Regional Planning Agency (TRPA) shapefile into zones of less than 20% cover and 20% - 60% cover. Monthly averages of potential global solar radiation (W/m^2) were computed at the 30 m scale using Solar Analyst, a Third-Party extension for ArcView developed by the University of Kansas (Fu and Rich, 1999). In an attempt to capture daily variations in SWE, the function was normalized by the average SWE value found at the three SNOTEL sites. The following equation was used to predict SWE across the entire basin,

$$SWE_t^i = \overline{SWE_t}^{SNOTEL} \left(aE^i + bS^i + cA^i + dV^i + eG_m^i + f\right) \quad (1)$$

where SWE is Snow Water Equivalent (cm); SWE^{SNOTEL} is the average SWE between the three SNOTEL sites; E is elevation (m); S is slope (degrees); A is aspect (degrees); V is a vegetation density code (1 = 0-19%, 2 = 20-60%); G is potential global radiation (W/m2); i is cell designation on 30x30m grid; t is day of prediction; m is month of prediction and a,b,c,d,e,f are multiple regression calibration parameters. Calibration was accomplished by minimizing least squares for prediction of snow survey data as well as SNOTEL data for a dry water year (2001) and an average water year (2002). Verification of the model was then conducted for a wet water year (1999) and another average water year (2000).

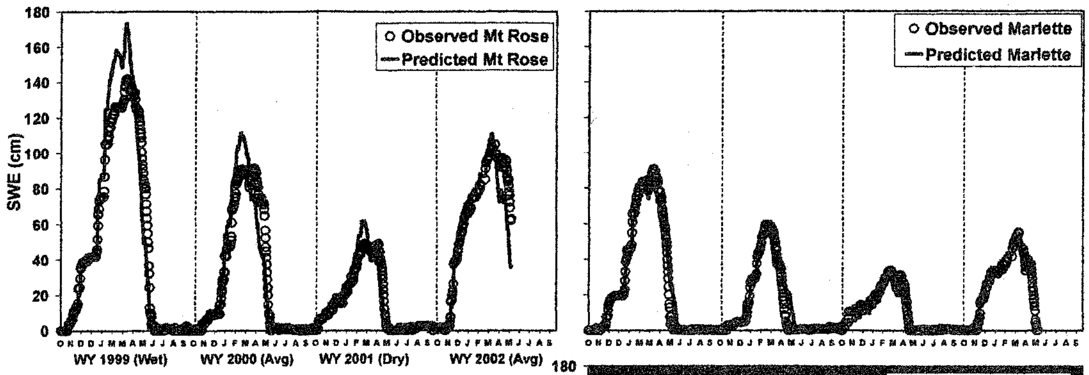
RESULTS AND DISCUSSION

Snow Water Equivalent Prediction

Calibrated results (n = 1450) explained nearly 92% of the observed variation in SWE and produced an average error of 0.06 cm and a RMSE equal to 0.18 cm SWE. Verification was performed at the three SNOTEL sites for a wet year (WY1999) and another average year (WY 2000). The average residual and RMSE for the wet water year (n = 1068) was 0.07 cm and 0.35 cm SWE, respectively with 93% of the observed variation explained by equation (1). The average residual and RMSE for the average water year (n = 1056) was 0.05 cm and 0.25 cm SWE, respectively with 90% of the observed variation explained. While errors in prediction were relatively low (approximately 0.3%), Figure 2 shows that in general the regression over predicts peak accumulations for upper elevations, under predicts SWE at lower elevations and allows greater attenuation of SWE into the summer months for lower elevations. In contrast, the mid-elevations are extremely well predicted in both timing of peak accumulation and overall SWE volume.

AHM Inputs Derived From SWE Maps

Temporal and spatial distribution of SWE is needed to parameterize snow-covered area (SCA), incremental snowfall and potential snowmelt inputs to AHM. Using the regression equation (1), at a30 m resolution, the average SWE values were computed for each of the four sub-basins shown in Figure 1. From these SWE estimates, SCA was calculated in ArcView as the ratio of 30 m cells within a given sub-basin that had any amount of snow cover to the total number of cells in that sub-basin. In all four sub-basins SCA increases rapidly (i.e. days) to a value of 1.0 and likewise decrease rapidly (i.e. days) to a value of 0.0.



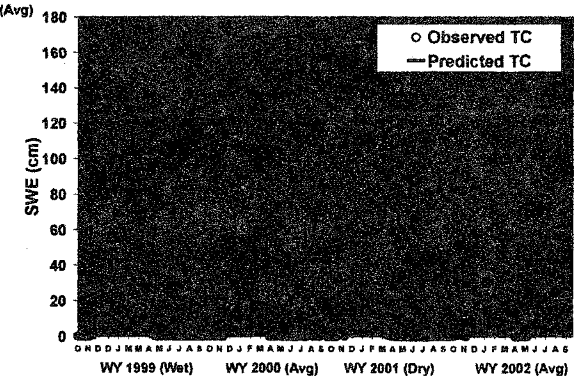


Figure 2. Comparison of observed and predicted SWE values at all three SNOTEL locations. While calibration of the SWE model was conducted during water years 2001 and 2002, verification of the model is shown for water years 1999 and 2000.

AHM uses equation (2) to compute snowfall through out the basin where P_S is snow precipitation in the sub-basin, $P_{S,B}$ is snow precipitation at a base site, E is elevation of the sub-basin, E_B is the elevation of the base site and Fs, analogous to a lapse rate, is the AHM input parameter used to scale snowfall from the base site to each of the four sub-basins.

$$P_S = P_{S,B}\left[1 + F_S\left(\frac{E - E_B}{1000}\right)\right] \qquad (2)$$

The Marlette SNOTEL location was used as the base site and F_S was calibrated to match predicted accumulated snow for each sub-basin each modeled year as predicted by equation (1). Potential snowmelt for each sub-basin was computed by subtracting SWE(t) from SWE(t-1) and assuming that potential snowmelt is zero if SWE(t) is larger than SWE(t-1). Figure 3 is an example of modeled snowfall and snowmelt volumes compared to stream gage information, in this case for USGS gage "Above Tyrol Village". Timing and relative magnitude of melt volumes during an average water year (2000) appear to correlate well with the rising and falling hydrograph. This correlation suggests that melt rates are reasonable.

CONCLUSIONS

A simple regression using independent parameters of elevation, slope, aspect, potential global solar radiation and vegetation density to predict both temporal and spatial distributions of SWE for a 17.4 km^2 alpine basin appear reasonable yet not entirely realistic. The failure of the model to melt snow fast enough at lower elevations causes SWE values to attenuate later into the summer than casual observation would suggest and may cause distortion in the SCA estimates. The model also appears to over predict SWE values at the upper elevations, and this may have an impact on AHM model interpretation of the real system. However, SWE appears to be well estimated for mid elevations within the watershed. This ability may over-ride model limitations at the extremes. Future snow surveys and continued AHM development and analysis will allow further evaluation of the SWE interpolation technique.

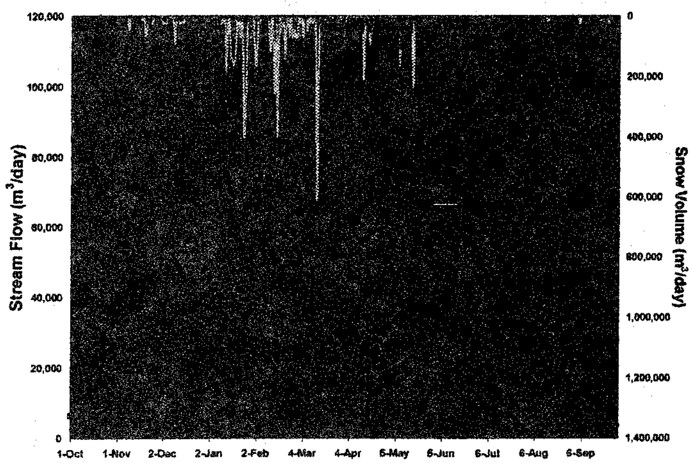


Figure 3. A comparison of modeled snowfall and snowmelt volumes to observed stream flow out of the Upper basin during an average water year (WY 2000).

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