APPLICATION OF A SNOWPACK WATER-EQUIVALENT MODEL TO RAIN-ON-SNOW EVENTS IN THE CENTRAL SIERRA NEVADA

By

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INTRODUCTION

A multitude of processes interact to create changes in the seasonal snowpack of mountainous regions. Various topographic and atmospheric factors determine snowpack accumulation and ablation rates. Snowpack accumulation depends upon precipitation amount, type and duration, and upon windspeed and direction. The snowmelt process depends on radiant, latent, and sensible heat exchanges. Site elevation affects peak snowpack variability (Caine, 1975) and elevation, slope, and aspect influence snow accumulation and ablation (Meiman, 1968). In the northeastern United States, cumulative precipitation and snow depth have been used for predicting snow water-equivalent (Steyaert, et al., 1980).

Knowledge of snowpack water-equivalent is critically important in determining the reaction of the snowpack to rainfall. Deep, high water-equivalent snowpacks may retain some portion of the rainfall. In contrast, flood flows are more likely to result from rainfall on shallow, saturated packs.

This paper describes a set of multiple regression equations that estimate snowpack water-equivalent in the central Sierra Nevada of California, and the result of application of the equations to several recent rain-on-snow events.

DEVELOPMENT OF THE REGRESSION EQUATIONS

The regression equations incorporate near real-time snow water-equivalent information from the Forest Service's Central Sierra Snow Laboratory (CSSL), 2100 m elevation, near Soda Springs, California, and Blue Canyon weather station, 1600 m elevation on the Sierra Nevada west slope, in combination with specific site descriptor variables. Thirteen years of data (1967 to 1979) from snow courses in the Mokelumne, American and Yuba River basins were analyzed. Snow water-equivalents at CSSL and Blue Canyon were related in the equations to water-equivalent and site descriptor variables at 54 snow courses throughout the three-basin area. The data were collected from isotopic profiling snow gage observations at CSSL (Kattelmann, et al., 1983) and Federal snow tube measurements at Blue Canyon and the snow courses.

Although many variables are considered, only those showing definite promise as predictor variables are discussed. Site descriptors examined were geographic location, distance from CSSL, elevation, aspect, and slope. Hydrometeorologic variables included observation date and real-time snow water-equivalent at both CSSL and Blue Canyon. Several "interaction" terms generated as products of the primary variables and logarithmic or exponential transformations of the site descriptor or hydrometeorologic variables were examined.

Selection of the final equations is based upon these criteria: a small number and meaningful set of predictor variables, a reasonable level of explained variation (R^2), low standard errors, and minimal multicollinearity problems. We formulated 19 equations, each developed with and requiring English units. Equation 1 combines 2433 observations and spans all elevations in the three basins:

$$WC = (ELE*0.0063)+(LNG*16.63425)+(I1*0.16298)-(I2*0.00628)-2040.24 \quad (1)$$

$$R^2 = 0.77; \text{ standard error} = 20.8 \text{ cm}$$

in which
WC: snowpack water-equivalent (inches) at site in question on day DA
ELE: site elevation (feet)

DA: number of calendar days since December 24 (e.g., January 3 has DA = 11)
XWC: snowpack water-equivalent (inches) at CSSL on day DA
DIST: airline distance (statute miles) from CSSL to site. CSSL is about one-half mile west of Norden and 1 mile east of Soda Springs, California, at geographical coordinates of 39° 19' N. latitude and 120° 22' E. longitude.
BC: snowpack water content (inches) at Blue Canyon.
LAT: site latitude in decimal form (e.g., 39.02)
LNG: site longitude in decimal form (e.g., 120.85)
I1: ELE * XWC / 1000
I2: XWC * DIST
DS2: DIST squared

The other 18 equations (Table 1) stratify the basins by elevation and date. These stratified equations can, at the expense of added complexity, estimate water-equivalent that is closer to observed values than can equation 1.

Table 1. Stratified regression equation coefficients.

Basin	Elev[1]	Date[2]	Constant	XWC[3]	DA[3]	BC[3]	I2[3]	ELE[3]	LAT[3]	DIST[3]	LNG[3]	DS2[3]	R^2	Stnd Err (cm)	N[4]	CV[4]
Yuba	Hi	LE 85	4.5	1.31244	--	--	-	-	-	--	-	-	.93	11.9	72	.15
	Hi	GT 85	-2.4	1.33725	.14015	--	-	-	-	--	-	-	.89	18.8	71	.16
	Med	LE 85	3.3	1.04954	--	.25349	.01142	-	-	--	-	-	.89	12.5	145	.20
	Med	GT 85	8456.9	1.08528	--	--	-	.01719	218.088	2.9625	-	-	.89	15.8	165	.17
	Low	LE 85	-35.1	-	--	1.0624	.01275	.00704	-	--	-	-	.81	15.0	160	.31
	Low	GT 85	-4158.2	.61594	--	.57585	-	.02031	-	--	33.5386	-	.78	20.3	149	.35
American	Hi	LE 85	1.9	.97594	--	--	-	-	-	--	-	-	.90	11.2	231	.19
	Hi	GT 85	-40.7	.88188	.12648	--	-	.00452	-	--	-	-	.81	15.5	176	.18
	Med	LE 85	10.5	.79645	--	.21079	-	-	-	--	-	.00661	.92	9.7	242	.17
	Med	GT 85	20.0	.74374	--	.31837	-	-	-	--	-	.01119	.88	13.2	175	.16
	Low	LE 85	-36.2	.60617	--	.58015	.01012	.00646	-	--	-	-	.86	9.7	152	.27
	Low	GT 85	.3	.75314	--	.63693	.01782	-	-	--	-	-	.78	15.8	148	.41
Mokel.	Hi	LE 85	10358.3	1.0149	--	.26305	-	.00890	236.604	--	10.1848	.02465	.92	11.9	142	.16
	Hi	GT 85	17883.8	1.1059	.20084	-	-	.01341	413.482	--	16.0433	.04091	.84	19.6	151	.19
	Med	LE 85	-3087.3	.45716	.04499	.51304	.01772	-	-	--	25.6867	-	.94	6.6	72	.11
	Med	GT 85	-8225.2	-	.08370	.41231	.01227	-	-	--	68.2759	-	.89	10.9	72	.23
	Low	LE 85	-.3	2.7896	--	.71438	.05074	-	-	--	-	-	.86	6.4	57	.39
	Low	GT 85	-.3	1.7759	--	.54744	.03180	-	-	--	-	-	.89	4.8	53	.51

[1]: Elevation range code: Hi = higher than or equal to 2195 m; Med = between 1905 m and 2195 m; Low = lower than 1905 m
[2]: LE signifies equation appropriate for day numbers equal to or less than 85; GT signifies day numbers greater than 85; Day 85 is March 18 in non-leap years
[3]: See text for definition
[4]: N is sample size, CV is the coefficient of variation

All regression slopes are significant at the 0.0001 level. Water equivalent at CSSL, XWC, is the dominant predictor variable. XWC, or its associated interaction term, I2, occurs in all equations, with XWC explaining more of the total variance in the high and mid-elevation sites than any other variable. Blue Canyon water-equivalent becomes increasingly important for the lower elevation sites. These results were expected. Real-time water equivalent values at CSSL and Blue Canyon intuitively should correlate more strongly with site water-equivalent than such static properties as site elevation or location. Variability of the snow course aspect and slope is low, the sites usually being in flat, valley locations. This situation accounts for the absence of slope and aspect terms in the equations. In future analyses an enlarged geographical area will be used in the slope and aspect determinations for evaluation of mesoscale slope and aspect influences. The hypothesis that Mokelumne River basin sites, those most distant from CSSL and thereby potentially being influenced by different meteorological conditions, was only partially borne out. DS2 makes only minor R^2 improvements at Mokelumne locations.

The equations perform well at high elevation sites and during the main snow accumulation period. For the January to March period, fewer variables are needed to generate high R^2 values and both standard error and coefficient of variation values are lower than for low elevation or melt season observations. The generally greater late season water-equivalent variability contributes to the poorer correlation during that period.

To evaluate the equations, we did residuals analysis, cross validation checks, and multicollinearity tests. Data plots of the residuals versus the independent or dependent variables show no evidence of non-random patterns. Cross validation checks do not produce a significant difference between the training and cross validation data sets (Dixon and

Brown, 1979). The highest correlation between independent variables included in the equations equalled 0.70, with most values being in the range of -0.2 to 0.5. As we anticipated, the higher r values were between the interaction terms, variables I1 and I2, and their component individual variables, ELE, XWC and DIST. Tolerance values parallelled the correlation values and were large enough so as to not suggest substantial multicollinearity (Dixon and Brown, 1979).

The regression equations were evaluated by applying them to two independent data sets. In 1979, we measured water-equivalent each week with a portable isotopic density gage at four American and Yuba River basin sites ranging in elevation from 1735 to 2250 m (Blincow and Dominey, 1974). In comparison to the Federal snow sampling tube, the portable isotopic gage undermeasures water-equivalent. And so on the basis of Soil Conservation Service tests (US Dep. Agric., 1975), we augmented the recorded values by 16%. Estimated and observed values were plotted (Figure 1) and the root mean square error, calculated by

$$RMS = [\Sigma (O - P)^2/(N - 1)]^{0.5},$$

in which O is the observed water equivalent, P is predicted water equivalent and N is sample size, equals 15 cm for this comparison. The coefficient of variation equals 0.33. Predicted and observed values were reasonably close, but there was an over-prediction bias.

During the 1980 water year, we recorded water-equivalent data from American River basin snow course sites ranging in elevation from 1600 to 2600 m. These observed values were plotted with water equivalent values predicted by the stratified equations (Figure 2). The RMS error for this 107-observation comparison equalled 17 cm, with monthly RMS values increasing from 6 cm in January to 25 cm in May. Mean RMS error and coefficient of variation values were 14 cm and 0.25, respectively.
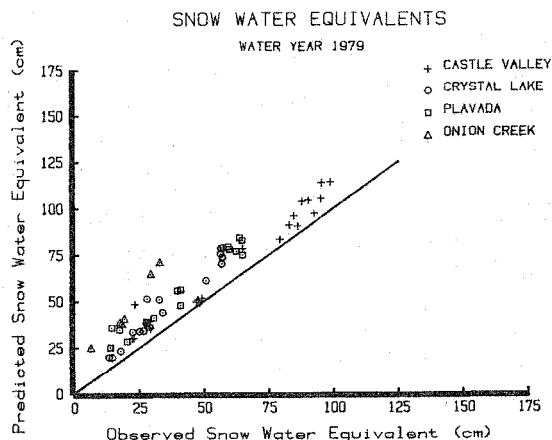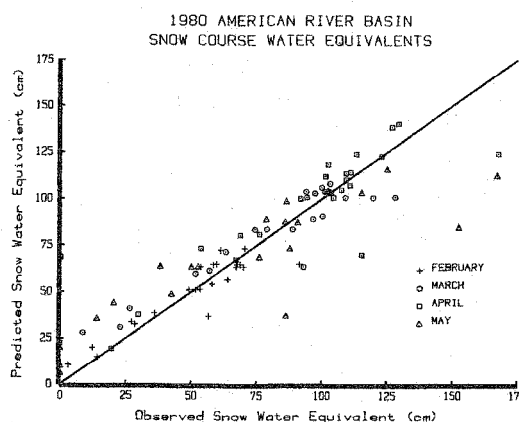

Figure 1

Figure 2

A potential use of the regression equations is the assessment of the adequacy of the current snow course network. In particular, would use of this method allow elimination of snow courses, and if so at what price in water-equivalent estimation accuracy? Although the equations produced a reasonably good fit overall, input sample sizes are inadequate for precise evaluation of the snow course network. In general, water-equivalent changes at the high elevation sites were well estimated, suggesting that consideration should be given to eliminating some high altitude courses. On the other hand, the relatively poor regression fits to low elevation sites suggest the need for more courses at these elevations. Establishment of courses at sloping locations with varying aspects would make the snow course network more representative of the Sierra Nevada snow accumulation zone.

SNOWPACK WATER-EQUIVALENT AFTER RAINFALL

Observed and predicted post rain-on-snow water-equivalent values were plotted for the four American and Yuba River basin sites (Figure 3). Only observations made within 4 days after rainfall were included. Modelled and observed values were reasonably close for high water-equivalents, but there was over-prediction in the range of 10 to 60 cm. Bias is evident, in particular, for the two low elevation sites, Crystal Lake and Onion Creek. The RMS error was 22.5 cm and the coefficient of variation equalled 0.42 for this comparison.

Predicted and observed water-equivalents at 40 snow courses throughout the American, Yuba and Mokelumne River basins were plotted for rain-on-snow events during January, February and April, 1980 and April, 1982 (Figure 4). A slight overprediction bias

RAIN-ON-SNOW WATER EQUIVALENTS
WATER YEARS 1978-1982

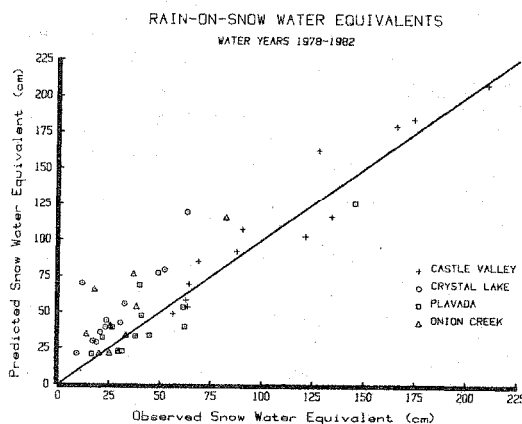RAIN-ON-SNOW WATER EQUIVALENTS

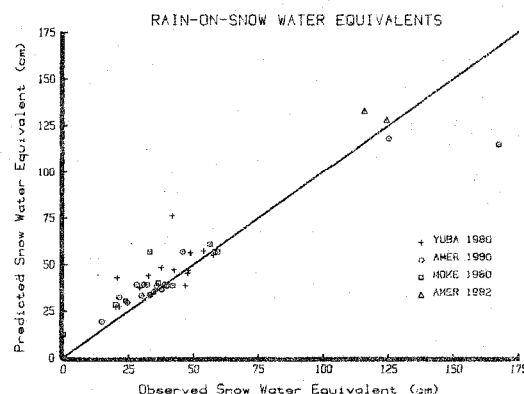Figure 3   Figure 4

was evident. The 13-cm RMS error and 0.30 coefficient of variation for this test were substantially smaller than the first rain-on-snow evaluation (Figure 3). The closer fit is due partially to the difference in measurement equipment.

CONCLUSIONS

A set of multiple regression equations predict snowpack water-equivalent at moderate to high elevation central Sierra Nevada sites more precisely than at low altitude locations. Prediction is also better during the accumulation period than during the melt season. The equations estimate post-rain-on-snow snowpack water-equivalent with root mean square errors in the range of 13 to 22 cm. The equations are applicable to sites spanning the 1500 to 2750 m altitudinal range within the Mokelumne, Yuba and American River basins, in northern California. The propriety of their use beyond this area has not been evaluated.

ACKNOWLEDGMENT

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