Satellite and Geographic Information System Estimates of Colorado River Basin Snowpack

James S. Ferris and *Russell G. Congalton*
Department of Forestry and Resource Management, University of California, Berkeley, CA 94720

ABSTRACT: Mountain snowmelt accounts for the majority of streamflow in many areas of the world. The timing and volume of this critical resource can be economically forecast for optimal use from satellite observations of spring snowpack. A geographic information system (GIS) was created for the Colorado River watershed to estimate snowpack water volume from topographic and satellite (AVHRR) data. Digital PC-based cloud removal techniques, a regression model, and the program SNOWPAC were developed to facilitate pixel-by-pixel snow water equivalent (SWE) estimates. The model, regressed on 312 satellite observations, predicts SNOTEL ground measured SWE with a correlation of 0.70. Given SWE prediction error averaging and complete two-dimensional basin-wide coverage at over 50,000 data locations, the satellite and GIS estimates point to improved snowmelt streamflow forecasting accuracy over conventional methods.

INTRODUCTION

SNOWMELT ACCOUNTS FOR 50 to 80 percent of the annual streamflow in many mountainous areas of the world including the Sierra Nevada, Rocky Mountains, Alps, and Himalayan Mountains. In the western United States, the annual value of snowmelt water for hydropower and irrigation is $6.60 billion (Castruccio *et al.*, 1980).

The area of interest in this project is the Colorado River Basin, a 644,000 km^2 watershed of major importance to the southwestern United States (Figure 1). The Colorado's average yearly flow of 15.0 million acre-feet (MAF) is fully allocated and consumed among the seven basin states and Mexico. Accurate forecasts of snowmelt streamflow are critical because of the importance of the Colorado River as a water resource and because its annual flow is so variable – ranging from 5.8 MAF to 24.5 MAF in the last 12 years alone.

Current forecast techniques for the Colorado River Basin rely heavily on 182 snow course point measurements taken monthly from January through June (Tom Perkens, personal communication, July 1987). However, snow survey measurements are highly site-specific and not subject to extrapolation. In addition, there is no simple relationship or model to classify the unique and dynamic characteristics of mountain snowpack (Smith and Berg, 1982).

Daily satellite coverage can be a valuable input variable for synoptic mapping of recent storm activity or changes in melting patterns. The use of satellite imagery provides two-dimensional data which can only be inferred from ground-based measurements (Shafer *et al.*, 1984).

In recent research, the snowpack parameter most frequently estimated using remote sensing is the amount of snow covered area (SCA) expressed as percent of a basin under snow cover (Rango and Peterson, 1980; Makhdoom and Solomon, 1986). A more important parameter for estimating snowpack water volume is snow density or snow water equivalent (SWE). SWE is the vertical depth of water which would be obtained by melting a column of snowpack. For example, if a site had 200 cm of snow depth with a density of 0.40 or 40 percent, the SWE at this site would be 80 cm. Because the visible and near infrared portions of the electromagnetic spectrum do not penetrate snow, but rather measure surface reflectance, it is not possible to directly estimate SWE using these wavelengths. The microwave wavelengths are sensitive to the presence of water and can remotely sense SWE. However, microwave remote sensing cannot currently be used for operational snowpack water volume estimation due to inadequate resolution and difficulty in data interpretation, particularly over mountainous terrain and forested areas where the microwave emission from forest cover tends to override that of snow (Hall *et al.*, 1985).

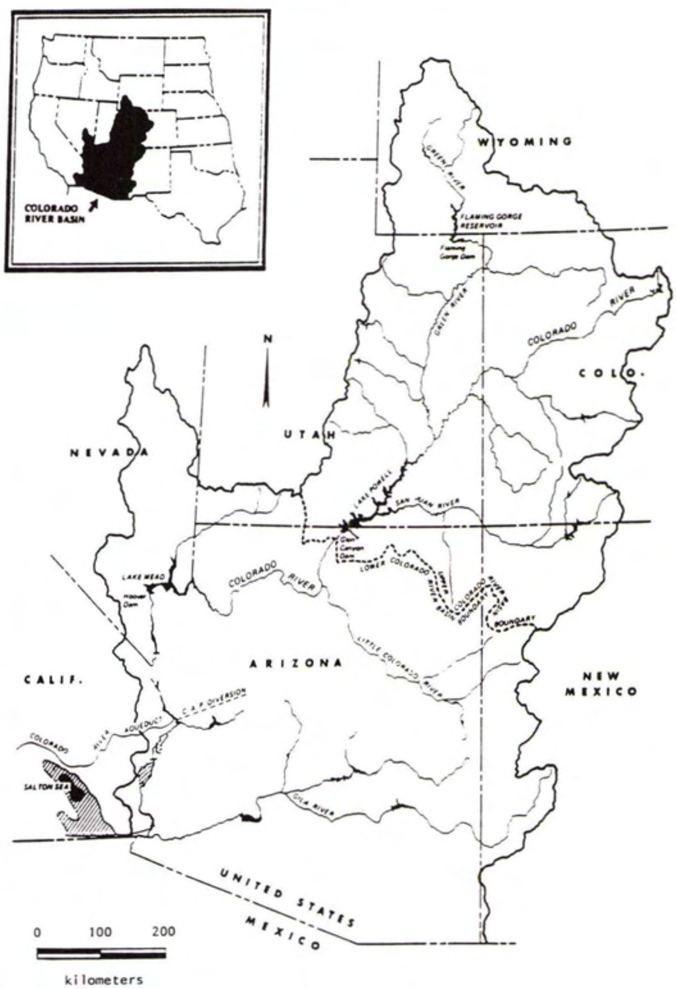

FIG. 1. The Colorado River Basin. Note upper and lower basin boundary. (from Erlenkotter and Scherer, 1977).

The objective of this study was to utilize topographic data and remotely sensed digital satellite data in a geographic infor-

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 55, No. 11, November 1989, pp. 1629–1635.

0099-1112/89/5511–1629$02.25/0

mation system (GIS) to produce low-cost and improved estimates of Colorado River Basin snowpack water volume. This was attempted through indirect measurement of SWE for each snow covered pixel. Techniques were developed in consultation with river forecasting agencies to be compatible with, but not repetitive of, current forecast procedures. Snowpack water volume estimates derived from methods set forth in this study can be input into existing hydrological and forecast models.

The use of remotely sensed satellite data is advantageous in providing low-cost, repetitive, multispectral, synoptic, and uniform observations over large areas. Recent advances in satellite, microcomputer, and GIS technology make this research undertaking possible. The development of methods taking advantage of this new technology is critical because a mere 1.5 percent increase in Colorado River forecast accuracy would result in a net economic benefit of $5.1 million (Castruccio *et al.*, 1980).

GIS DATA BASE

A raster data base containing 36 informational layers, precision registered in a 900- by 618-pixel grid, was created (Table 1). Because a pixel is represented by a digital number (DN) of 0 to 255 and is stored in one byte, the disk space requirement for the GIS is 900 × 618 × 36 = 20.03 megabytes. Decision Images commercial software was utilized for analysis, supplemented by a FORTRAN program (SNOWPAC) written to compute snowpack water volume. The authors of this paper developed SNOWPAC for automatic cloud recognition and pixel-by-pixel SWE estimates based on the optimal regression model. Although this program was developed for the Colorado River Basin GIS database, it could be modified for use on other watersheds.

SATELLITE DATA

One kilometre Advanced Very High Resolution Radiometer (AVHRR) imagery is utilized in this study (Figures 2 and 3). The use of this imagery is preferred over other remote sensing satellites for a number of reasons: (1) imagery is collected over the western United States twice daily and is available for distribution on computer tape the following day; (2) the resolution of AVHRR Local Area Coverage (LAC) 1 km imagery is appropriate for snowmelt streamflow forecasting on a basin of this size because it is not of such high resolution as to create excessive data handling problems; and (3) the cost of each scene covering the entire basin is only $100. Neither the Landsat nor SPOT satellite systems provide any of these benefits. Another available data product, GOES satellite imagery, has poor spectral coverage, resolution, and viewing geometry.

AVHRR satellite imagery over the Colorado River Basin was previewed from photographic archives at the NOAA Weather Service Forecast Office and receiving station in Redwood City, California. Six high quality scenes, 98 to 100 percent cloud free, were selected. These scenes cover the entire Upper Colorado River Basin (Figure 1) where about 75 percent of the river's flow originates from snowpack (U.S. Department of Interior, 1970).

TABLE 1. GIS DATA LAYERS.

Visible Reflectance (six dates)
Near Infrared Reflectance (six dates)
Thermal Infrared Reflectance (six dates)
Normalized Difference Vegetation Index (six dates)
Elevation
Slope
Aspect
Aspect Factor
Shade (six dates)
Sub-Basin
SNOTEL Ground Site Locations

(The common measurement point for Colorado River flow is near Lake Powell; for the rest of the river's course [lower basin], the minimal additional inflow is balanced by evaporation from the river and its reservoirs.) Each scene covers 35 to 44°N and 105 to 113°W at a pixel resolution of 1.11 km on a side; this creates an image of 900 rows by 618 columns. (1.11 km resolution AVHRR data are typically referred to as simply 1 km data.) Spectral channels 3 and 5 were not used; channel 3 is subject to excessive noise, and the spectral range of channel 5 is similar to channel 4.

To allow for quicker and more flexible GIS manipulation, the ten-bit AVHRR data were geometrically corrected and scaled to eight bits by the Sea Space lab in San Diego. This was a straight linear rescaling accomplished by converting the ten-bit DN to percent reflectance using NOAA pre-launch calibration as per the *NOAA Polar Orbiter Data Users Guide* (Kidwell, 1986). Because raw ten-bit DN never exceeded an equivalent 64 percent reflectance, the generated eight-bit data were assigned the value (reflectance × 4). This allowed for 0.25 percent reflectance resolution in the eight-bit data as opposed to 0.10 percent resolution in the original ten-bit data. Raw ten-bit DN thermal infrared reflectance was within a range of 64°C, so likewise it was converted to eight bits with 0.25°C resolution (Robert Bernstein, personal communication, August 1988).

The six scenes were loaded onto the Decision Images image processing software system and displayed on a 1024 by 1024 monitor. Near infrared images displayed on different color guns were overlayed and registered to each other by shifting some images one row or one column. Lake shores and steep mountain valleys delineated on channel 2 were used for precise pixel registration.

The Normalized Difference Vegetation Index (NDVI), described by Goward *et al.* (1987), was included as a GIS data layer in an attempt to account for the vegetation response. In simple terms, NDVI is a ratio of two satellite channels: (near infrared - visible) / (near infrared + visible). If vegetation response could be quantified or separated from snow cover response, perhaps better estimates of pixel SWE might be developed. The elevation and aspect variables also indirectly account for vegetation because these topographic features characterize vegetation type. Because of the size of the Upper Colorado River Basin and the incompatible scale of existing vegetation maps, the vegetation indices were used instead of actual vegetation information.

TOPOGRAPHIC DATA

An elevation database of the study area was compiled at the EROS Data Center by degrading 1:250,000-scale digital elevation data to populate a 960 by 960 array over the Upper Colorado River Basin. Although this elevation model covered the same land area as the satellite scenes, each elevation pixel did not represent a square area on the ground. Therefore, the elevation model was resampled, using a nearest neighbor algorithm, to register with the 900- by 618-pixel satellite scenes. Elevations are digital values ranging from 53 to 207 which, when multiplied by 20, give elevation in metres. Decision Images software was used to generate slope and aspect data layers from the elevation data. Slope is reported in degrees and aspect is coded from 0 to 8: 0 is flat, 1 is north, 2 is northeast, 5 is south, and so on.

A mask of the Upper Colorado River Basin had to be digitized to exclude snowpack outside the watershed. Because the basin covers 875 km north to south, and each pixel covers a square area on the ground, the satellite image is wider in the north and narrower in the south than standard conic projection maps. In addition to this correction, a watershed mask covering this large an area would have to be digitized in segments from large scale maps to be accurately represented. Accuracy at this point was critical because it is the basin boundary pixels, at the highest elevations, that often contain the most snow and water volume

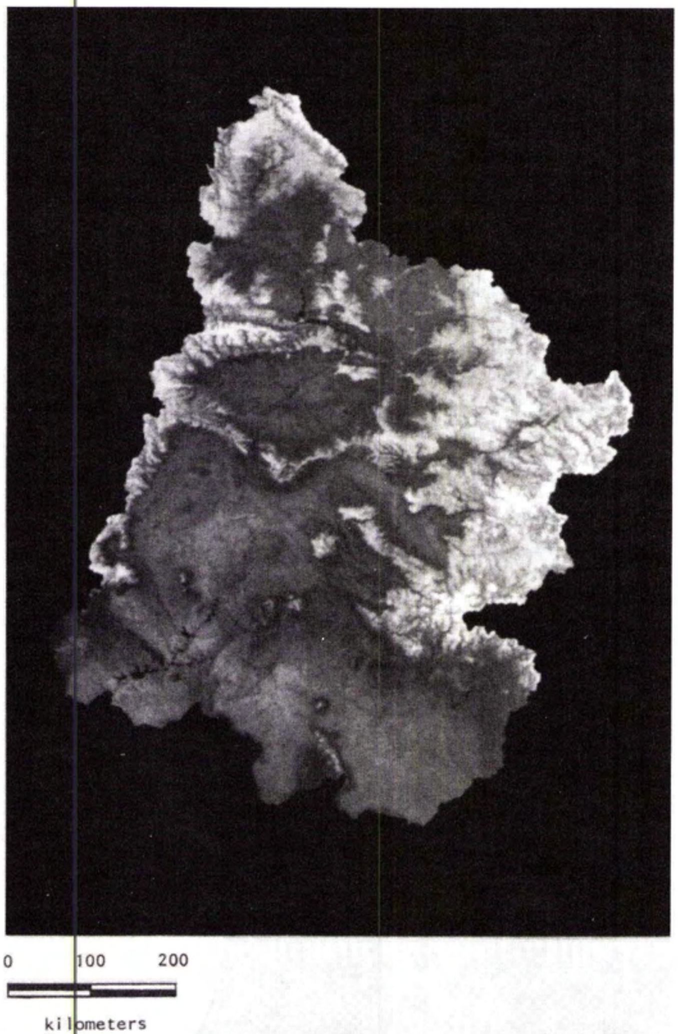

FIG. 2. 14 April 1984 AVHRR channel 2 near infrared satellite image of the Upper Colorado River Basin.

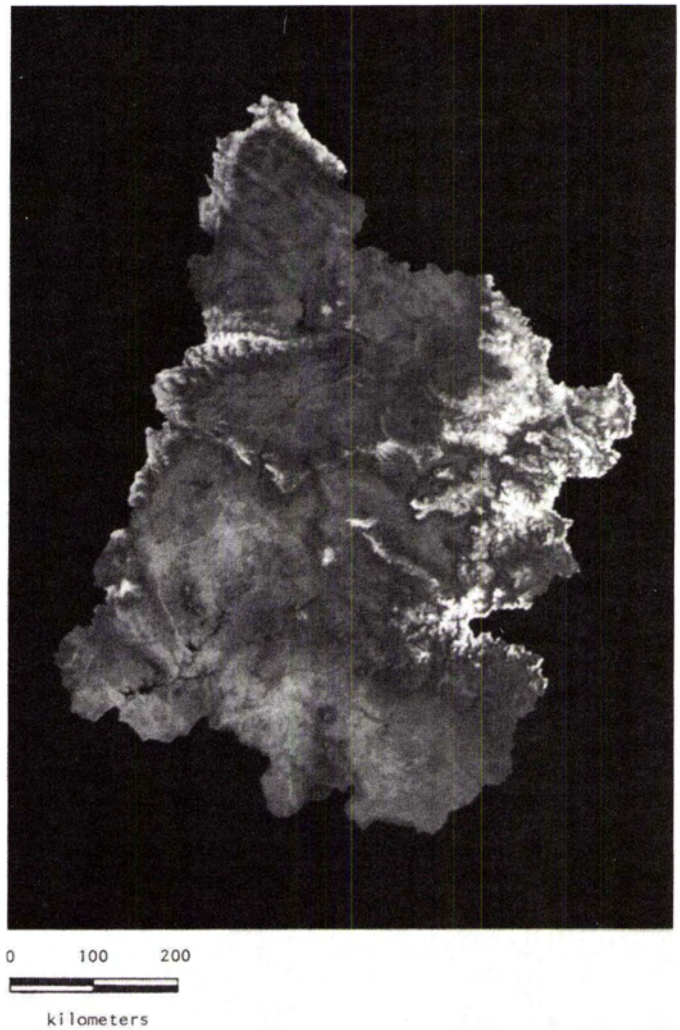

FIG. 3. 12 April 1988 AVHRR channel 2 near infrared satellite image of the Upper Colorado River Basin.

(Figures 2 and 3). An alternative approach was developed. The elevation model was displayed, enlarged, and enhanced to pinpoint mountain crests at the watershed boundaries. From each enlarged area the Upper Colorado River Basin was digitized on the monitor to mask off areas outside the watershed. This method worked quite well – each reiteration indicated the watershed was indeed masked along the highest pixel (mountain crest).

The aspect factor GIS data layer is a modification of the aspect data. The aspect number assignments are arbitrary: for example, aspect 8 (northwest) lies next to aspect 1 (north). In order to use aspect as an independent variable in regression modeling, an aspect factor was developed after Beers *et al*. (1966). Initially, assumptions about the effect of aspect had to be hypothesized. Visible and near infrared satellite response for the 312 observations at SNOTEL sites were high in the southeast and low in the northwest. SNOTEL sites, at 2,360 to 3,740 metres, are largely in forest zones of the Upper Colorado River Basin. Given the semiarid climate, hot southern exposures, and rain shadows on eastern slopes, ground and forest cover may be greatest on the west to north aspects (Paul Zinke, personal communication, October 1988). This assumption was supported by aerial photograph observations. Not only might vegetation cover reduce the response of snow in the north, but southern sun exposures might enhance response in the south. The aspect factor we used is equal to $\mathrm{Cos}(\mathrm{Amax}-\mathrm{A})+1$ where Amax is 315° (northwest) and A is the arbitrary aspect number to be converted (Beers *et al.*, 1966). This conversion gives the following aspect factor coefficients:

	1.7	
2.0	N	1.0
1.7 – W –		– E – 0.3
1.0	S	0.0
	0.3	

These values were eventually multiplied by ten to make all of the variables and coefficients in the regression equation the same order of magnitude.

The shade GIS data layer was developed using formulas given by Kaufmann and Weatherred (1982) for determination of potential direct beam solar irradiance. By taking the sun's position at the time of the satellite overpass, and the pixel's slope and aspect, the percent of potential reflectance was determined. This coefficient in the regression equation is designed to subtract out the effect of varying sun reflectance based on time of day, date, and pixel and satellite orientation. One step beyond this would be to include the effect of shadows caused by topographic relief. Such a transformation, generated from elevation data and sun position, is often called a shade image. Unfortunately, this image processing feature was not available for this study.

The sub-basin GIS data layer divides SNOTEL sites into clusters based on mountain range to minimize weather variation over the 282,000 km² Upper Colorado River Basin. The six sub-basin areas are Wyoming, Uinta, Wasatch, North Colorado, Central Colorado, and San Juan.

GROUND TRUTH DATA

Ground-based SNOwpack TELemetry (SNOTEL) SWE readings taken the same day as each satellite overpass were available for 63 sites in the upper basin. From the latitude and longitude of each site, and with the aid of elevation information, SWE measurement sites were matched with the proper pixel in the 900 by 618 array. These sites represent not only a wide geographic distribution, but also a variety of elevations, slopes, and aspects. For this study there are 315 simultaneous ground measurements of SWE taken at the 63 SNOTEL sites on five image dates. The sixth image date, from 1988, was not part of the modeling but was used to test the model.

Snow/Cloud Discrimination

Several dates had a maximum of 2 percent cloud cover. Cloud cover was visually discriminated from snow by color, shape, and shadows. The color difference in the thermal infrared reflectance proved to be due to colder cloud temperatures registered on channel 4.

Image processing enhancement techniques showed that clouds can be automatically distinguished from snow on the AVHRR scenes. The weather regime in the Upper Colorado River Basin on each image date produced colder brightness temperatures for clouds than for any ground features – including snow. However, occasionally warmer cloud edges and extremely thin cloud cover gave an overlapping DN response with the peak elevations in the basin. Both the snow and cloud temperatures depended on time of day and the time of year of the satellite overpass and the weather.

By using density slicing and color coding of thermal imagery, the coldest scene temperatures produced highlighting of only clouds. The temperature was increased until maximum cloud cover was flagged without picking up the coldest ground response pixels over mountain peaks. In this manner a threshold temperature, between −20 and 0°C, was determined for each scene date for automatic computer discrimination and removal of nearly all pixels with cloud cover.

Regression Modeling

The next step was to estimate SWE for each snow covered pixel so snowpack water volume could be summed over the entire basin. To establish a relationship between SWE and the GIS data layers, information from the 315 ground truth sites was entered into a LOTUS 1-2-3 spreadsheet. Automatic cloud discrimination and visual varification indicated three data points had cloud cover; therefore, regression modeling was done using a data set with 312 observations.

Regression analysis and residual plots were run on all the GIS test parameters to find the best correlation with SWE ground truth sites. The optimal regression equation allows SWE and consequent snowpack water volume, in acre-feet, to be estimated for each snow covered pixel.

The regression equation was written into a FORTRAN computer program called SNOWPAC. SNOWPAC queries the user for the satellite image date to be analyzed and the scene snow/cloud discriminating temperature. The program accesses the appropriate GIS data layers and computes output information based on over one-half million pixels. Percent cloud cover and percent snow cover is reported for each thousand-foot (305-metre) elevation zone in the snow accumulation zone of 8,000 feet (2,438 metres) and greater. The elevation zone of 7,000 to 8,000 feet (2,134 to 2,438 metres) was not included because the regression model was developed from SNOTEL data which had site elevations of 2,360 to 3,740 metres. Extrapolation could not be justified; in addition, Weisbecker (1974) indicates that the snow accumulation zone may be as high as 9,000 feet (2,743 metres). The selected regression equation (i.e., model) is used by the FORTRAN program SNOWPAC to calculate water volume in million acre-feet (MAF) by elevation zone. The total estimated volume of water for the basin snowpack can then be used by river forecasting agencies in hydrological models to estimate actual river flows for the remainder of the snowmelt season.

RESULTS

Results of the regression and residual plot analysis reveal near infrared reflectance, thermal infrared reflectance, and the aspect factor to be the significant variables for remotely sensed estimates of snow water equivalent. One-km resolution AVHRR pixels and aspect factor could predict ground-based SNOTEL SWE with a correlation of 0.70.

A correlation matrix was produced to analyze the relationship among each of the ten GIS variables and the actual and predicted SWE (Table 2). The single most important predictor was AVHRR channel 2 – the near infrared band. The percent near infrared reflectance gave a correlation of 0.62 with SWE. AVHRR channel 1, the visible band, was nearly as useful a predictor but, because its correlation with the near infrared band is 0.98, it provided no additional information. AVHRR channel 4, the thermal infrared band, and the aspect factor contributed about equally in bringing the correlation from 0.62 to 0.70. Although aspect gave a higher correlation than aspect factor, the former was not used in modeling because coefficients assigned to each aspect could not be explained in terms of the data; this is why the aspect factor was developed.

Vegetation response or density could not be ascertained from the Normalized Difference Vegetation Index. NDVI had a correlation of −0.48 with SWE because it is derived from the highly correlated visible and near infrared reflectance variables.

The elevation data had a weak correlation (0.24) with SWE. The inclusion of the elevation variable in the model did not improve overall correlation because the information it contained

Table 2. Correlation Matrix.

	%VIS	%IR	TEMP	NDVI	ELEV	SLOPE	ASPCT	ASFAC	SHADE	BASIN	SWE	PRED
%VIS	1											
%IR	.98	1										
TEMP	−.17	−.09	1									
NDVI	−.74	−.61	.49	1								
ELEV	.21	.22	−.26	−.21	1							
SLOPE	−.09	−.06	−.01	.09	.22	1						
ASPCT	.28	.22	.10	.38	.21	.48	1					
ASFAC	.04	.05	−.06	−.03	.04	.14	.98	1				
SHADE	−.32	−.40	−.48	−.05	−.01	.04	.22	.12	1			
BASIN	.13	.11	.16	.21	.58	.37	*	.32	.06	1		
SWE	.61	.62	−.33	−.48	.24	−.10	.27	.20	−.06	.20	1	
PRED	.90	.89	−.45	−.71	.29	−.01	.36	.31	−.14	.20	.70	1

* both row and column have multiple independent variables (indicator variables) and a correlation is not feasible.

was accounted for by the thermal infrared variable; the elevation verses thermal infrared correlation was −0.26.

Slope was not directly helpful in predicting SWE. It seemed logical that slope, along with aspect as a factor in pixel orientation, might affect the intensity of solar reflectance based on sun and satellite position. This hypothesis led to the shade algorithm. However, the addition of this algorithm did not improve the correlation.

Using indicator variables for the six sub-basins did not significantly improve the ability to predict SWE. What small benefit this approach provided was offset by requiring an additional GIS data layer, increased computer run time, and loss of six degrees of freedom.

The three useful parameters of near infrared reflectance, thermal infrared reflectance, and aspect factor were then tested in a series of non-linear regressions. No significant improvement was found.

The final regression model is the linear equation

$$\mathrm{SWE} = 0.959R - 0.372T + 0.310\mathrm{A}$$

SWE is the predicted snow water equivalent in inches, R is the percent near infrared reflectance from AVHRR channel 2, T is the thermal infrared brightness temperature in °C from AVHRR channel 4, and A is the aspect factor. SWE divided by 12 (inches/foot) times the 305-acre (123 hectare) pixel size gives the estimated water volume per pixel in acre-feet.

Table 3 shows the output summary data for SNOWPAC computer runs on each of the six image dates. Percent cloud cover, percent snow covered area (SCA), and snowpack water volume in million acre-feet (MAF) is estimated by elevation zone. Snow zone cloud cover and SCA are presented as weighted average totals along with total estimated basin-wide snowpack water volume.

Cloud cover is not a problem; the number of pixels removed in the snow zone due to cloud cover is at most 1.8 percent. The removed pixels tend to be from higher elevations where clouds form around mountain peaks (Table 3). Estimates of water volume include estimation of water volume by elevation zone for pixels with cloud cover. For example, an elevation zone with 1.2 percent cloud cover has its water volume, as calculated from cloud free pixels, increased 1.2 percent. High interbasin correlation found by Shafer and Leaf (1980) allows estimates of snow cover in adjacent topographically similar areas to be used for characterizing pixels under cloud cover. The final figures for basin-wide snowpack water volume represent the goal of this study. These figures cannot be readily compared for accuracy against actual subsequent snowmelt streamflow volumes. Hydrologic models must be employed to account for loss due to soil retention, upper basin withdrawals, and evaporation, or for additional flow due to subsequent precipitation.

Although four of the five image dates used in regression equation development had exceedingly high water volumes, the equation still did an excellent job of estimating water volume on the sixth image date used to test the model-drought year 1988. The results in Table 3 for 14 April 1984 (one of the wettest years on record) and 12 April 1988 can be compared with Figures 2 and 3.

DISCUSSION

The factors contributing to 1-km pixel response over the Colorado River Basin are complex and highly variable. Topographically, a single pixel can include elevation changes of 500 metres, several slopes and aspects, and shadowing problems. Cover type can span dense forest, scrub, water, and bare rock. Snow cover can be spotty, drifted, windswept from exposed rock, weathered, or freshly fallen and laden on trees. In spite of this variability, snowpack reflectance remotely sensed over a 123 hectare area as a single response enabled a correlation of 0.70 with SWE to be achieved.

As discussed earlier, the near infrared and thermal infrared wavelengths cannot penetrate snow. However, several researchers found a decreased near infrared response for snow undergoing melt due to increased water content and grain size

Table 3. Snowmelt Water Volume Analysis.

FEET ELEVATION	4 APRIL 1984 %CLOUD	%SCA	MAF WATER	30 APRIL 1986 %CLOUD	%SCA	MAF WATER
8-9000	0.1	48.7	7.94	1.1	25.1	3.71
9-10000	0.1	34.3	3.23	2.5	55.5	5.07
10-11000	0.2	33.8	2.16	1.8	79.0	5.40
11-12000	0.9	65.7	2.41	1.9	92.2	3.83
>12000	0.5	96.5	1.40	4.0	93.8	1.56
TOTAL	0.2	45.3	17.15	1.8	50.3	19.56
	14 APRIL 1984			7 MAY 1987		
FEET ELEVATION	% CLOUD	%SCA	MAF WATER	%CLOUD	%SCA	MAF WATER
8-9000	0.0	73.9	11.05	0.0	0.5	0.06
9-10000	0.0	78.2	6.88	0.1	5.1	0.36
10-11000	0.0	86.0	5.24	0.1	24.3	1.27
11-12000	0.0	97.8	3.73	0.2	54.0	1.69
>12000	0.1	99.8	1.63	0.3	75.8	0.93
TOTAL	0.0	80.0	28.51	0.1	12.8	4.31
	8 MAY 1984			12 APRIL 1988		
FEET ELEVATION	%CLOUD	%SCA	MAF WATER	%CLOUD	%SCA	MAF WATER
8-9000	1.2	46.5	6.08	0.0	8.0	1.00
9-10000	1.1	74.3	6.05	0.0	11.4	0.85
10-11000	2.1	87.9	5.25	0.1	21.4	1.15
11-12000	3.0	95.7	3.61	0.4	47.7	1.45
>12000	1.9	97.9	1.52	0.2	76.4	0.85
TOTAL	1.5	66.8	22.51	0.1	16.8	5.30

(Rango, 1983; Hall and Martinec, 1985). A decreased response is thought to be associated with increasing SWE. Results of the research presented here indicate exactly the opposite: increasing near infrared response is in a positive linear correlation with increasing SWE. The most likely conclusion is that the dominating factor in near infrared response is the proportion of an individual pixel covered with snow.

A pixel's reflectance value is the weighted average of the reflectance of all the elements in the pixel's field of view. Deeper highly reflective snowpack, sometimes up to five metres deep, means more low reflectance soil, rock, and vegetation is covered. Although ground cover is extremely variable, local relief on the order of 0 to 5 vertical metres seems to be a key in remotely sensed estimates of SWE on a 1-km scale. This is due to a decrease in horizontal cross sectional area of terrain and vegetation features as snowpack depth increases. For example, assume a site near timberline has a stand of four metre fir trees with 40 percent crown closure. The AVHRR channel 2 near infrared reflectance for fir is about 20 percent and for snowpack it may be 55 percent. If the snowpack is two metres deep at the site, and all snow has melted from the tree crowns, remotely sensed pixel reflectance would be 0.4 (proportion trees) $\times$ 0.20 (tree reflectance) + 0.6 (proportion snow) $\times$ 0.55 (snow reflectance) or 41 percent. With a deeper snowpack of four or more metres, the pixel reflectance would be 1.0 $\times$ 0.55 or 55 percent. The role of the trees – or any ground relief less than the depth of maximum snowpack – is like that of a snow course measurement marker. Thousands of such markers are simultaneously measured and averaged in each snow covered pixel of the entire watershed.

The vegetation index variable NDVI did not improve correlation, but vegetation cover was indirectly accounted for in the aspect factor variable. The model would be improved with the incorporation of a detailed vegetation data layer in the GIS. Full hydrological modeling would also require a soils GIS data layer with information on water infiltration capacity.

The correlation between actual SWE and SWE predicted from the model at 312 data points (pixels) is 0.70. An even higher basin-wide correlation can be expected because summing individual pixel SWE estimates over the entire basin tends to average out individual pixel SWE underprediction and overprediction errors. The average residual SWE (error) for the 312 data points is near zero.

Satellite imagery is valuable for providing weekly forecast updates. Imagery can be analyzed in a few hours using the models developed here and a geographic information system in the personal computer (PC) environment. Several researchers have stressed the importance of monitoring short-term weather variation in SWE during the April through June period when snowmelt patterns can drastically alter the magnitude and timing of runoff (Shafer and Leaf, 1980; Kattelmann *et al.*, 1985).

For example, on 1 April 1984 the Colorado Basin River Forecast Center estimated the 1 April – 31 July seasonal runoff for the Colorado River Basin at 11.5 MAF. The 4 April 1984 estimate of basinwide snowpack water volume, based on AVHRR imagery interpreted in the FORTRAN program SNOWPAC, was 17.2 MAF. These two estimates measure different entities; yet reasonable agreement exists when compensating for evaporation, withdrawals, and other sources of loss. Satellite imagery taken just ten days later (Figure 2) and analyzed by SNOWPAC indicated basinwide snowpack water volume had jumped to 28.5 MAF. At this point a mid-month forecast update could have been made to revise significantly upward the 11.5 MAF 1 April - 31 July seasonal runoff estimate. In fact, the actual runoff for this period reached a near record 15.3 MAF. In this historical case, if the methods described in this paper had been employed, the major 1984 runoff event could have been predicted sooner and more accurately.

CONCLUSION

This study reveals the potential of low-cost, synoptic, and daily AVHRR 1-km satellite imagery in a GIS for snowpack water volume estimation. Ground-based estimates are difficult because of vast and inaccessible terrain, and because SWE is so site-specific that relationships do not hold along contour or by elevation zone. AVHRR satellite imagery samples over 50,000 data points in the snow zone of the Upper Colorado River Basin, accounts for a large amount of the SWE variability, and provides two-dimensional information which can only otherwise be inferred from the ground.

Although cloud cover can be a problem in a basin the size of the Upper Colorado spanning five states, methods have been set forth to computer detect and remove cloud cover.

The dominant factor for remotely sensed estimates of SWE is the proportion of snow – verses other ground features – sensed in an individual pixel. The DN response contribution from local terrain and vegetation relief on the order of 0 to 5 vertical metres is related to snowpack depth. In essence, every such relief feature acts as an aerial snow course measurement marker.

The objective of this research was met in demonstrating the potential of digital AVHRR 1-km data in a GIS for pixel SWE and basin-wide snowpack water volume estimation. The GIS includes satellite and topographic data layers accessed by the FORTRAN program SNOWPAC for automated analysis in the PC environment. The methodology described here could be smoothly and economically integrated into current snowmelt streamflow forecasts for improved Colorado River forecast accuracy. The result could be a GIS providing multi-million dollar savings in water resources management due to increased efficiency and conservation in reservoir storage, flood control, hydroelectric power generation, irrigation, wildlife and fisheries management, water quality, and water supply planning.

ACKNOWLEDGMENTS

Funding for this research was provided by the California Water Resources Center, project W-704.

REFERENCES

Beers, T. W., P. E. Dress, and L. C. Wensel, 1966. Aspect Transformation in Site Productivity Research. *Journal of Forestry*, Vol. 64, pp. 691–692.

Castruccio, P. A., H. L. Loats, Jr., D. Lloyd, and P. A. B. Newman, 1980. Cost/Benefit Analysis for the Operational Applications of Satellite Snowcover Observations. *Operational Applications of Satellite Snowcover Observations*, NASA CP-2116, pp. 185–200.

Erlenkotter, D., and C. R. Scherer, 1977. *An Economic Analysis of Optimal Investment Scheduling for Salinity Control in the Colorado River*. University of California, Water Resources Center Project No. UCAL-WRC-W-474, 267 p.

Goward, S. N., D. Dye, A. Kerber, and V. Kalb, 1987. Comparison of North and South American Biomes from AVHRR Observations. *Geocarto International*, Vol. 2, pp. 27–40.

Hall, D. K., and J. Martinec, 1985. *Remote Sensing of Ice and Snow*. Chapman and Hall Ltd., New York, 189 p.

Hall, D. K., J. L. Foster, and A. T. C. Chang, 1985. Microwave Remote Sensing of Snow Cover in Forested and Non-Forested Areas. *Pecora 10 Proceedings*, pp. 262–271.

Kattelmann, R. C., N. H. Berg, and M. K. Pack, 1985. Estimating Regional Snow Water Equivalent with a Simple Simulation Model. *Water Resources Bulletin*, Vol. 21, No. 2, pp. 273–280

Kaufmann, M. R., and J. D. Weatherred, 1982. *Determination of Potential*

Direct Beam Solar Irradiance. USDA Forest Service Research Paper RM-242, 23 p.

Kidwell, K. B. 1986. *NOAA Polar Orbiter Data Users Guide*. NOAA; National Environmental Satellite, Data, and Information Service; National Climatic Data Center; Satellite Data Services Division. 184 p.

Makhdoom, M.T.A., and S. I. Solomon, 1986. Attempting Flow Forecasts of the Indus River, Pakistan Using Remotely Sensed Snow Cover Data. *Nordic Hydrology*, Vol. 17, No. 3, pp. 171–184.

Rango, A., 1983. A Survey of Progress in Remote Sensing of Snow and Ice. *Hydrological Applications of Remote Sensing and Remote Data Transmission*, IAHS Publ. No. 145, pp. 347–359.

Rango, A., and R. Peterson, Eds., 1980. *Operational Applications of Satellite Snowcover Observations*. NASA CP-2116, 301 p.

Shafer, B. A., and C. F. Leaf, 1980. Landsat Derived Snowcover as an Input Variable for Snowmelt Runoff Forecasting in South Central Colorado. *Operational Applications of Satellite Snowcover Observations*, NASA CP-2116, pp. 151–169.

Shafer, B. A., D. T. Jensen, and K. C. Jones, 1984. Analysis of 1983 Snowmelt Runoff Production in the Upper Colorado River Basin. *Proceedings of the 52nd Annual Western Snow Conference*, pp. 1–11.

Smith, J. L., and N. H. Berg, 1982. Historical Snowpack Characteristics at the Central Sierra Snow Laboratory, a Representative Sierra Nevada Location. *The Sierra Ecology Project*, Volume 3, Office of Atmospheric Resources Research, 44 p.

U. S. Department of Interior, 1970. *Project Skywater*. Bureau of Reclamation, Atmospheric Water Resources Program, 16 p.

Weisbecker, L. W., 1974. *The Impacts of Snow Enhancement, Technology Assessment of Winter Orographic Snowpack Augmentation in the Upper Colorado River Basin*. Stanford Research Institute, 624 pp.

SPECIAL NOTICE
GIS/LIS '89 Opening Session

Welcome

Opening and Keynote
Marriott Crystal Ballroom, Salons J-Q
Tuesday, November 28, 1989
10:00–11:00 am

Join us for an exhilarating multi-media presentation introducing you to the beautiful state of Florida. Secretary Tom Pelham, of the Department of Community Affairs, will address topics regarding Florida's environment. This exciting opening is followed by a special plenary session, "Status of Federal GIS/LIS Activities." The speakers are Dr. Dallas Peck, Director, U.S. Geological Survey; John J. Moeller, Assistant Director, Bureau of Land Management' and George Leonard, Associate Chief, Forest Service, U.S. Department of Agriculture.