AN EVALUATION OF THE SPECTRAL MIXTURE ANALYSIS TECHNIQUE APPLIED TO MODIS DATA

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ABSTRACT

Satellite images of snow-covered area (SCA) have become increasingly useful tools in hydrologic and climatological studies. SCA images are used to help estimate snow water equivalence, a critical input variable for modeling in these fields. Two techniques have been used to map SCA from satellite data: 1) binary, which applies a snow/no-snow threshold to a normalized difference snow index and 2) fractional, which uses spectral mixture modeling. Fractional SCA images are able to map areas of less than 50% snow cover which the binary SCA products show as 0% SCA. The MODIS binary SCA product includes a correction for vegetation cover, whereas fractional SCA does not. The objective of this work is to assess the differences between the MODIS SCA product and fractional SCA images computed using MODIS surface reflectance data, and identify the importance of vegetation correction. We compared SCA images at peak and mid-melt snowpack in two meso-scale watersheds with mixed land cover in the Pacific Northwest. The spectral mixture model estimated a much lower percent SCA at peak snowpack in comparison to the MODIS SCA images. During mid-melt, snow cover existed only in the forested upper portions of the basin. In this case, the mixture model and the standard MODIS image predicted similar amounts of SCA. At peak snowpack, the spectral mixture model calculated low SCA in forested areas above the snowline in both study basins. These results suggest that the spectral mixture modeling method, as applied here, is inadequate for identifying snow cover beneath a forest canopy where adjoining open areas are also snow-covered. For areas with a more homogeneous snow reflectance conditions, the current MODIS algorithm may estimate SCA as accurately as the spectral mixture method.

INTRODUCTION

Satellite images of snow-covered area (SCA) have become a useful tool in hydrologic and climatological studies (Schmugge, 1002). Distributed models in these fields are used to investigate the effects of land use and climate change on basin hydrology (Alila, 2001). The efficiency of these models depends on the accuracy of the forcing parameters and the certainty of the results depends on adequate validation data. Remotely measured data can augment the few in-situ measurements are available.

Validating physically based hydrologic models requires extensive in-situ measurements. These measurements are typically sparse, but can be augmented using remote sensing data. Snow covered area images can be used to help estimate the snow water equivalence. This is especially important in snowmelt-dominated watersheds throughout western North America.

The Moderate Resolution Imaging Spectroradiometer (MODIS) provides daily snow covered area images at 500-meter resolution. The MODIS SCA product uses a binary snow classification based on the normalized difference snow and vegetation indices (Hall, 2002). We applied a spectral mixture modeling technique (Nolin, 1993) to determine if this method could produce more accurate SCA results. This technique uses the spectral signatures of image-defined spectral end-members to determine the relative percentages of each constituent within a pixel. The final snow covered area image estimates the percentage of snow coverage within each pixel. In this study, we compared two binary SCA techniques: the normalized difference snow index (NDSI) and the standard MODIS SCA product (which has a vegetation correction), with fractional SCA estimated by spectral linear unmixing in two meso-scale watersheds. The objectives of the investigation are as follows:

1. Apply the spectral linear unmixing model to MODIS surface reflectance data
2. Evaluate the ability of the spectral linear unmixing model to estimate below-canopy snow coverage
3. Compare the amount of SCA estimated by a binary snow product with and without a vegetation correction,

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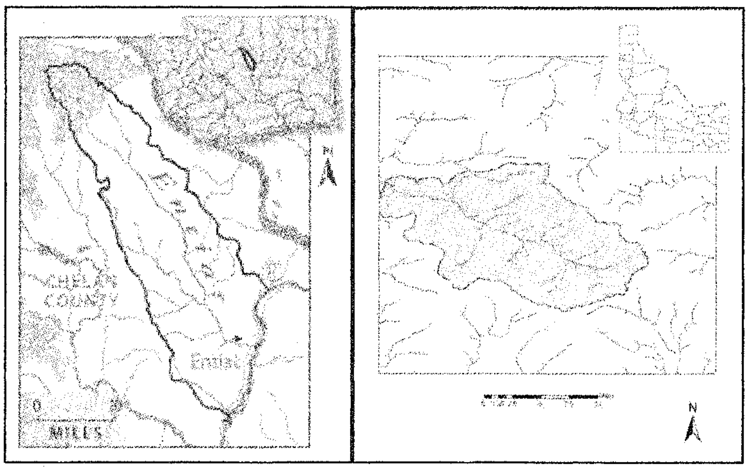
and a fractional SCA product calculated using the spectral linear unmixing model

4. Investigate the limiting factors off the spectral linear unmixing model

METHODS

Background and Description of Study Area

An understanding of the effects of land use change on the hydrology of a region has become increasingly important for land managers. These changes may be caused by wildfires, forest management practices, or land rehabilitation. The Entiat Basin in the Eastern Cascades of Washington (Fig. 1) has an active wildfire history. This activity has spurred interest to investigate the effects wildfire has on snow hydrology (VanShaar, 2002), sediment production (Lanini, 2005), and streamflow. Land use in the upper Hangman Creek Basin in northern Idaho has substantially changed in the past 75 years. A thorough understanding of the hydrologic controls in the basin is important in determining appropriate restoration measures. The well-documented land coverage history of both basins allows a thorough investigation of hydrologic changes. A major difficulty confronting these investigations is a lack of in-situ snow measurements. Augmenting the available measurements with remote sensing data will expand these studies and validate hydrologic modeling efforts (Turpin, 1999).



Figures 1 and 2. The Entiat Basin, WA, and the Upper Hangman Creek Basin, ID.

Entiat River Basin (Figure 1)

- Area: 1,075 km^2
- Topography: The valley is deeply incised with extremely steep slopes (250-2800 m)
- Vegetation: upper elevations are alpine environments, which progress to forest and agricultural fields.

Upper Hangman Creek Basin (Figure 2)

- Area: 280 km^2
- Topography: rolling loess hills and low, forested mountains (650-1500 m)
- Vegetation: upper elevations are forested, valley floor is mainly dry-land agricultural.

Description of Data and Methods

The MODIS SCA product and MODIS surface reflectance data were obtained for peak snowpack in each basin (Entiat: 5 March 2003, Hangman: 12 January 2004). In addition, data for the regional peak snowpack for the Hangman basin (10 March 2004) were acquired. The surface reflectance dataset consists of seven bands, which were used to calculate the NDSI (Equation 1) and the fractional SCA (Equation 2). For a pixel to be considered snow-covered, band 2 (xxxx μm) must be great than 11% and the NDSI value must be greater than 0.4 (Hall, et. al., 1995).

$$NDSI = \frac{band4 - band6}{band4 + band6}$$

Equation 1. NDSI calculation (band 4: 0.545-0.565 μm, band 6: near-infrared 1.628-1.652 μm).

The fractional SCA estimates were calculated using Equation 2. The spectral end-members define the boundaries within which total pixel spectral radiance, L_c, must fall. Snow, vegetation, and open-water/shadow were defined end-members in each image. The fraction of each end member, F_i, was then determined for each pixel, using the ENVI (Research Systems, Inc) spectral unmixing tool. The fraction of the snow end-member in a given pixel defines the percent SCA within that pixel. Figure 3 depicts how this equation is applied to each pixel within the image.

$$L_c = \sum_{i=1}^{N} F_i L_{i,c} + E_c$$

Equation 2. Spectral mixture model; L_c, pixel radiance pixel, F_i, fraction of the end-member, $L_{i,c}$, radiance of the end-member, E_c, error.

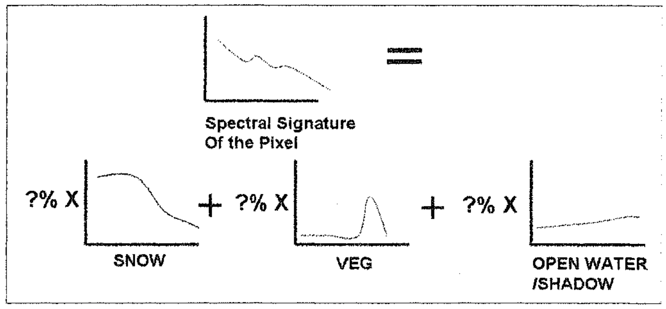


Figure 3. Depiction of the spectral unmixing model

Additional data was acquired to evaluate the effectiveness and the limitations of these algorithms. Digital elevation models and forest canopy images were obtained for both basins to evaluate geographical trends in snow covered area. Forest density data for the Entiat Basin were provided by the Chelan County Soil and Water Conservation District. Forest density data for the Hangman Basin were obtained from the Landsat-based National Land Cover Database. Additionally, in-situ snow measurements from SNOTEL sites and other informal surveys provide approximate ground-truth for the SCA estimates. Using these data we can identify where and why each calculation has difficulty identifying snow covered area.

RESULTS

In both basins, the spectral unmixing model's SCA results were considerably different from both binary methods. In the Hangman Basin, the basin perimeter is higher-elevation forested land which tests the application of the algorithms in a diverse environment. The January 12 analysis followed a series of snow events which covered the entire basin with snow. The canopy-corrected MODIS SCA delineated extensive snow in these higher elevations on January 12, whereas the uncorrected NDSI and fractional estimate did not (Figure 4). The fractional method estimated the lowest amount of snow basin-wide and especially underestimated forested portions of the basin (Figure 5). Overall, the binary techniques estimated a higher SCA in the Hangman basin; Figure 4 shows the SCA trend over the elevation range. The binary technique including the vegetation correction estimated 80% of the basin to be snow covered. The fractional SCA model approximates 26%, a much lower percentage then both binary techniques. The in-situ measurements indicate that the basin was 100% snow covered.

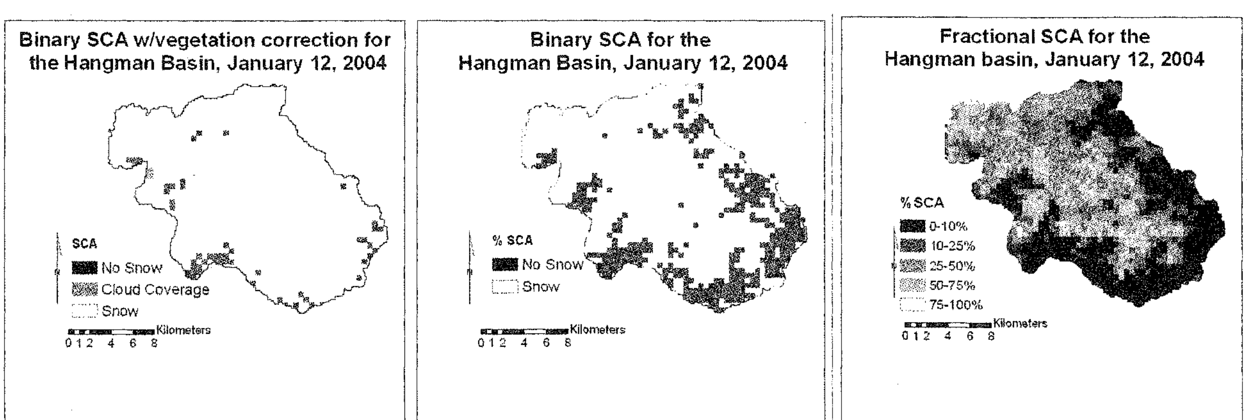


Figure 4. Snow covered area (SCA) for the Hangman Basin, Idaho using three techniques (12 January 2004).

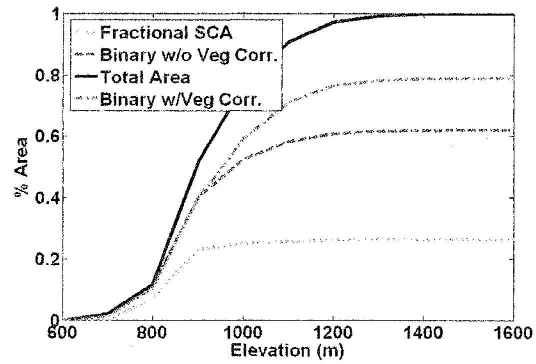


Figure 5. Total area and estimated SCA using three methods versus elevation in the Hangman Basin (12 January 2004).

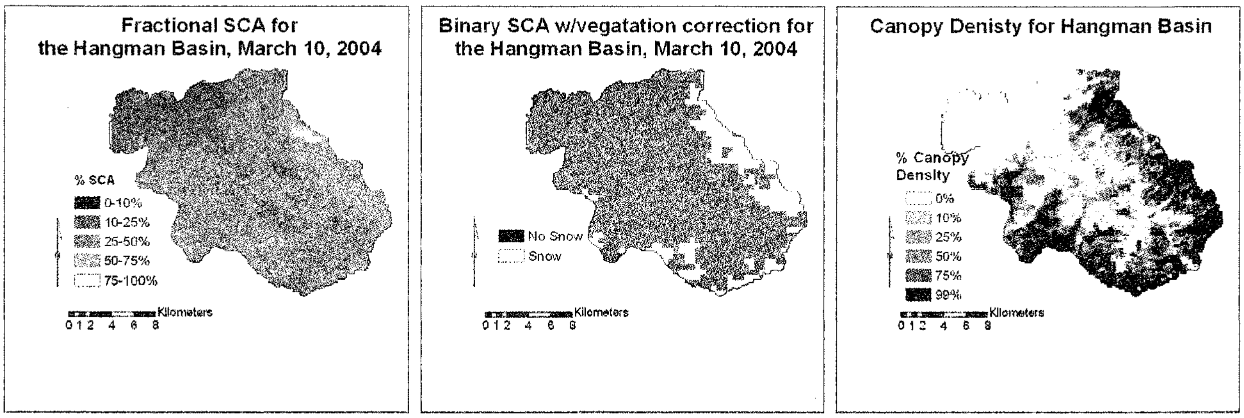


Figure 6. Snow covered area (SCA) using two techniques (March 10, 2004), and canopy density for the Hangman Basin, Idaho.

Hangman Basin SCA was also estimated on a date for which snow was known to exist in the upper elevations of the basin, but not the valley floor (March 10, 2004). The MODIS and fractional method SCA estimated both show snow coverage in the upper elevations (Figure 6). MODIS may have underestimated SCA in the upper forested areas, whereas the fractional method overestimated SCA on the valley floor (center of the basin). Canopy density (Figure 6) has a significant role in determining the efficiency of the algorithm. A similar pattern of a canopy density image and fractional method images (Figure 4) show that denser forested areas received lower SCA estimates.

The patterns observed in SCA estimates in the Hangman Basin were also observed in the Entiat Basin. In areas with high canopy density, the uncorrected binary and fractional methods apparently underestimated SCA (Figure 8). In contrast to the results found in the Hangman Basin, snow was predicted in the upper elevations, due to the low canopy density in the sub-alpine environment. The Entiat Basin contains a greater diversity of vegetation types and densities, which is reflected in the fractional results. There are clear consistencies with the fraction snow cover estimate and the canopy density image. Overall, the binary product including the vegetation correction estimated 70% of the basin was snow-covered, while the fractional product estimated 20% of the basin to be snow covered (Figure 7). The large differences in these estimates indicate that the vegetation cover plays a significant role in identifying snow-covered area.

Snow-covered area estimates were compared to elevation in each basin (Figures 7-8). The MODIS SCA product estimates 70% of the Entiat basin and 95% of the Hangman basin (12 January) were snow covered. In contrast to the standard MODIS product, the spectral unmixing model predicted much lower SCA in both basins: 25% in Entiat, and 26% in Hangman. In situ-measurements infer 100% snow cover at 1500 m in the Entiat and 650 m in Hangman.

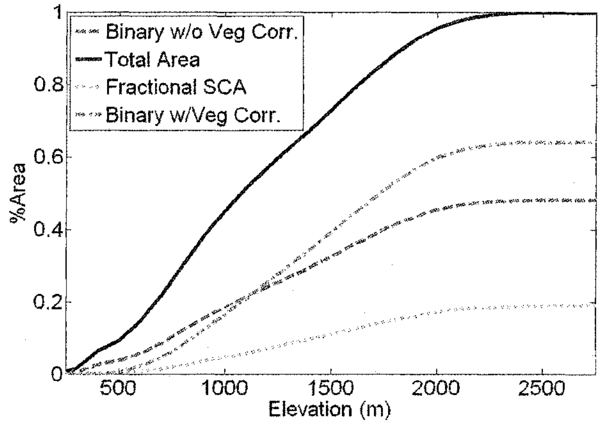


Figure 7. Total area and estimated SCA using three methods versus elevation in the Entiat Basin.

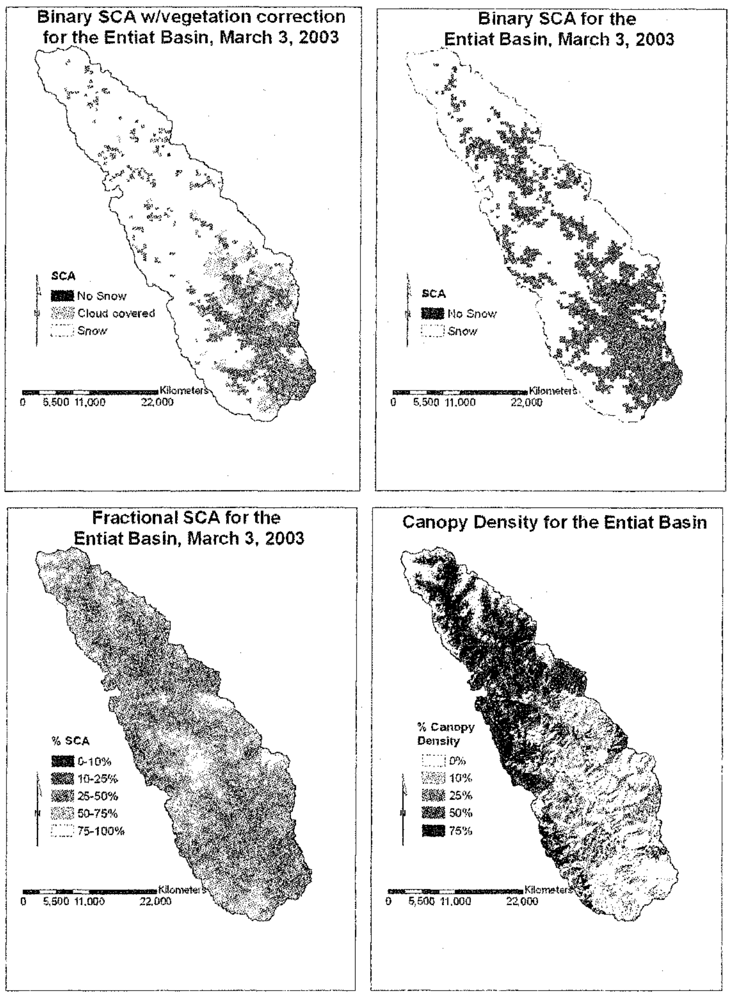


Figure 8. Snow covered area (SCA) using three techniques (3 March 2003), and canopy density for the Hangman Basin, Idaho.

DISCUSSION AND CONCLUSIONS

The spectral linear unmixing model estimated a much lower percent SCA at peak snowpack in comparison to the MODIS SCA images at both sites. The patterns of snow distribution estimated by spectral linear unmixing model suggest that this technique, as applied here, is inadequate for measuring below-canopy SCA. The binary technique including the vegetation correction estimated greater snow-covered area underneath the forest canopy. These results highlight the importance of including a vegetation correction in mapping snow-covered area using remote sensing data. In future applications of fractional SCA mapping, a vegetation correction factor should be included.

The estimates of SCA using the MODIS SCA binary product including the vegetation correction compare well to in-situ estimates. This result suggests that the MODIS product is appropriate for in meso-scale watersheds. Use of this product will improve modeling results where SCA measurements are required. Increasing the certainty of remote sensing products will expand the application of the data to areas with few or no measurements—a situation commonly confronted by streamflow forecasters in mountainous environments.

The similarity between the spectral linear unmixing model and MODIS SCA in the March 10 image at Hangman Creek suggests that the spectral linear unmixing model and MODIS SCA estimates will be similar when snow cover has a uniform spectral signature across the basin. The spectral signature of snow across a basin can be uniform following snow events. Over large elevation ranges, with varying microclimates, the snow surface can have multiple reflectance signatures. This complicates the application of the spectral unmixing model, which relies on a uniform signature for each end-member. The combination of these end-members can then be non-linear. The result is a poor estimate of SCA. Spectral unmixing models applied to images with near-uniform spectral signatures of snow will have better results as shown in the Hangman Creek January 12 analysis.

Results suggest that spectral unmixing of remote sensing data for determining snow extent is hindered by the presence of a moderate-density forest canopy. This technique may provide enhanced snow cover information in open areas; however, a high level of error in forested areas limits the usefulness of the technique as applied here. Further evaluation of this technique over snow with uniform reflectance could provide insight into whether variability in snow reflectance in the test images caused inaccurate results in the spectral linear unmixing model.

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