SENSITIVITY OF THE SNOWMELT RUNOFF MODEL TO UNDERESTIMATES OF REMOTELY SENSED SNOW COVERED AREA

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ABSTRACT

Three methods for estimating snow covered area (SCA) from Terra MODIS data were used to derive conventional depletion curves for input to the Snowmelt Runoff Model (SRM). We compared the MOD10 binary and fractional snow cover products and a method for estimating sub-pixel snow cover using spectral mixture analysis (SMA). All three methods underestimated SCA and this contributed to underestimates in runoff modeled by SRM. The closest relationship between measured and computed runoff was achieved when SRM was run with conventional depletion curves derived from the MODIS binary snow cover product ($R^2 = 0.91$). Although the MODIS fractional snow cover product and SMA did not perform as well as the binary snow cover product ($R^2 = 0.70$ and $R^2 = 0.72$ respectively) we anticipate that either of these methods may be reworked to better account for forest cover in our study area and so improve SCA estimates.

Keywords: snow covered area, snowmelt runoff model, Terra MODIS

1. INTRODUCTION

In common with many of the major river systems in the interior Western United States, the streamflow of the Rio Grande and its tributaries is driven largely by melting winter snowpacks that accumulate annually in high altitude basins (figure 1). Over the last 40 years, records indicate earlier onset of spring with concomitant reduction in snowpack and melt season streamflow [1]. Annual snowmelt supplies around 50% of the surface water for the state of New Mexico so decreasing snowpack has serious implications for future management of water resources. The surface water supplied by the melting snowpack is vital for wildlife habitat, irrigated agriculture and for the conservation of the rural cultural landscape in the Rio Grande basin.

We are using the Snowmelt-Runoff Model (SRM) to forecast future water availability. SRM is a simple degree day model that simulates streamflow in high elevation basins where melting snow is a major contributor to runoff [2].

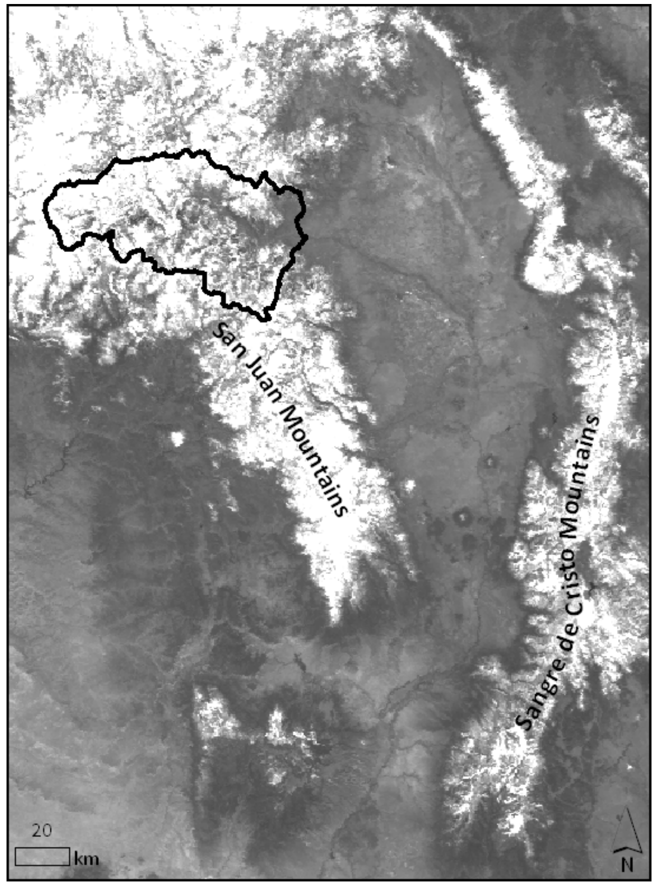

Figure 1. Terra MODIS view of snowpack in the upper Rio Grande Basin: April 13 2008. The Del Norte Basin is outlined in black.

Regular estimates of basin snow-covered area (SCA) are required over the snowmelt season to derive snow depletion curves for model input. Remotely sensed data are the most logical source for these regular, synoptic estimates of SCA. Given the size of our study area and the frequency with which we require cloud free imagery, the best sensors currently available for our research are the MODIS instruments onboard the Terra and Aqua platforms.

Various algorithms have been developed for SCA estimation from MODIS data. The most widely used is the normalized difference snow index (NDSI) [3] and variations thereof [4, 5]. The NDSI is analogous to the Normalized Difference Vegetation Index (NDVI) except that it uses shortwave infrared (SWIR: 1.628 μm to 1.625 μm) and green (0.545 μm to 0.565 μm) wavebands in its formulation. For Terra MODIS, the NDSI is calculated thus:

$$\text{NDSI} = (\text{Band 4} - \text{Band 6}) / \text{Band 4} + \text{Band 6}) \qquad (1)$$

The NDSI forms the basis of the binary and fractional estimates of SCA contained in the MODIS MOD10 snow cover products. For binary SCA, a pixel is mapped as snow if the NDSI is greater than 0.4, near infrared (NIR: band 4) reflectance is greater than 0.11 and band 4 reflectance is greater than 0.1 [6]. If NDSI is less than 0.4, a pixel can still be mapped as snow if it falls into a defined region in NDSI/NDVI feature space [4, 7]. For the fractional product, sub-pixel SCA is estimated using an empirical model that relates NDSI to sub-pixel snow-covered area [5].

Linear spectral mixture analysis (SMA) is an alternative to the fractional NDSI product for estimation of sub-pixel SCA. Linear SMA assumes that the spectral response of a pixel is a linear combination of the spectral responses of the ground cover elements (endmembers) sampled in that pixel, weighted by their relative abundance.

$$R_i = \sum_{k=1}^{n} f_j R_{ij} + \varepsilon_i \qquad (2)$$

R_i is the measured pixel reflectance in band 'i'; f_j is the relative abundance of endmember 'j' in the pixel. R_{ij} is the known reflectance value in band 'i' of endmember 'j'. ε_i is residual error in band 'i'.

2. METHODOLOGY

Terra MODIS daily snow products and daily reflectance data (MOD09GA) were acquired over the Upper Rio Grande Basin for 14 cloud-free dates spanning the 2001 snow melt season. SCA in the Del Norte Basin was calculated from the MOD10 binary and fractional snow products and from linear SMA of the reflectance data in bands 2, (NIR), 4 (green) and 6 (SWIR). Spectrally pure pixels were identified to select the 3 endmembers (rock, green vegetation and snow) for SMA [8]. SMA was carried out using the linear spectral unmixing module embedded in Envi™ software.

Snowmelt in a high elevation basin is more effectively modeled by SRM if the basin is separated into elevation zones. We divided the Del Norte into three elevation zones 'A' (2436–2926 m), 'B' (2926–3353 m) and 'C' (3353–4222 m). SCA was calculated for each zone, using each snow mapping method, for 13 of the 14 dates. Although small patches of snow were still present on the final date (July 16th, 2001), none of the snow mapping methods were able to detect it. Conventional depletion curves for each zone were interpolated from the SCA estimates derived from the three different methods (figure 2). For each zone, the binary NDSI product generally predicts the highest snow cover, followed by the fractional NDSI product and then SMA.

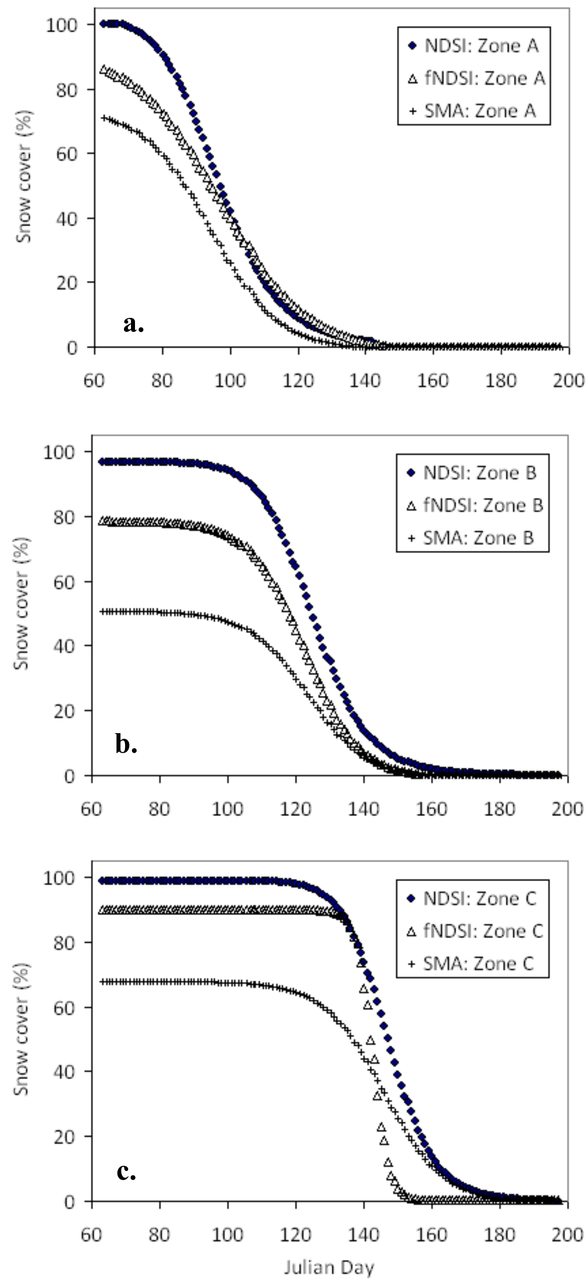

Figure 2. Conventional depletion curves interpolated from estimates of SCA for (a) Zone A, (b) Zone B, and (c) Zone C. SCA was estimated using the binary snow cover product, the fractional snow cover product and SMA.

SRM was input with precipitation and temperature data from two meteorological stations (Del Norte and Wolf Creek) and streamflow data recorded at the Rio Grande near Del Norte gage. The model was then calibrated for operation without input from snow depletion curves. Model parameters remained unchanged for each subsequent model run with the different conventional depletion curves.

3. RESULTS AND DISCUSSION

When SRM was run using the conventional depletion curves derived from the binary snow cover product, runoff volume was under-estimated by 4.2%. Regression analysis of the relationship between measured and computed runoff volumes yielded a coefficient of determination of 0.91. Superficially this appears to be a good result. However, the hydrograph (figure 3a) shows that the binary product fails to track the mid to late season runoff. From the end of May to mid July, measured runoff consistently exceeded computed runoff until the end of July. This result suggests that the MODIS binary snow cover product begins to underestimate snow cover just as the melt season streamflow peaks.

It is likely that the underestimation of SCA is due in part to the thresholding approach used to create the binary product. A pixel is classified as snow if it is 50% or more snow-covered [9]. When this rule is combined with the spatial resolution of the imagery (500 m), if a pixel contains less 0.125 km^2 of snow it will be classified as "not snow". Therefore, there is the potential for SCA to be underestimated as snow cover becomes patchier.

Running the same model with the depletion curves derived from the fractional snow cover product resulted in an estimate of runoff volume that was 22% below measured runoff volume and a coefficient of determination of 0.70. The hydrograph is similar to that produced for the binary product except that runoff is more severely underestimated between May and July (figure 3b). This result may arise from the empirical relationship used to model sub-pixel snow cover from NDSI [5]. This relationship was developed in areas of less complex terrain and with considerably less forest cover than our study area. For example, land covers where this model was developed included (i) glaciers in Alaska; (ii) relatively flat, snow-covered plains in Labrador, Canada; and (iii) taiga in Siberia. The model was validates in the sparsely vegetated North Slope of Alaska and Andes of Chile and Argentina. The translation of this empirical model to our study basin in the Southern Rockies is problematic. We know that the Del Norte basin should be 100% snow covered early in the season (before day 60). The depletion curves plotted in figure 2 show that the fractional snow cover product estimated only 80 to 90% snow cover. Also evident in Zone C (figure 2c) is the rapid drop-off of the fractional product depletion curve towards the end of May (day 140). It is probable that both the underestimation and the rapid decline in the zone C depletion curve are a function of the dense tree cover in the Del Norte Basin.

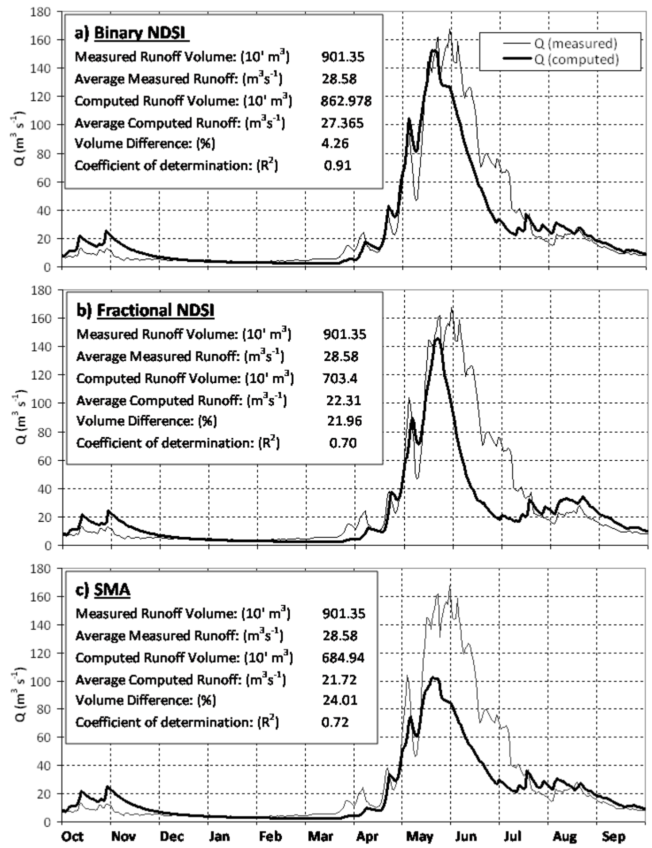

Figure 3. Runoff computed using SRM for conventional depletion curves derived from a) Binary NDSI product, b) Fractional NDSI product and c) Spectral mixture analysis

When the conventional depletion curves derived from the SMA were used as input for SRM, it was expected that the computed runoff would be substantially less than measured runoff. Snow cover and the resulting depletion curves from SMA were much lower than the depletion curves derived from the binary and fractional products (figure 2). Likewise, the hydrograph shows that computed streamflow is much lower than measured streamflow between mid-May and mid July. However, the statistics reported by SRM show that runoff was only underestimated by 24% and the coefficient of determination resulting from the regression of measured and computed runoff was 0.72, comparable to that for the fractional snow cover product.

The main reason why SMA underestimates SCA is because it does not account for snow cover under coniferous forest canopy. This problem is illustrated by the depletion curve computed for zone B (figure 2b). Evergreen forest covers 61% of the basin area in zone B. SMA predicts SCA to be

~45% of basin area at the beginning of the snowmelt season. This is less than half the SCA predicted by the binary NDSI.

4. CONCLUSIONS

Even though the MOD10A1 binary snow cover product underestimates patchy snow cover at high elevation at the end of the snowmelt season, our results indicate that this data product performs satisfactorily for estimating depletion curves for running the SRM for the Del Norte basin. The MOD10A1 fractional snow cover product is well-validated for several regions but it should be used with caution for estimating SCA in forested basins. A possible solution to the problem of underestimation of snow cover from the fractional cover product would be to develop an empirical model specifically for our study site that relates sub-pixel snow cover to the NDSI. The SMA approach yielded the lowest estimates of SCA and the lowest conventional depletion curves because we did not account for under-canopy snow cover. There is potential for using SMA to successfully estimate SCA because this approach also provides estimates of sub-pixel green vegetation cover. Combined with knowledge of the distribution of coniferous forest cover, estimates of sub-pixel green vegetation cover could be used to correct SCA to include the under-canopy snow cover.

5. REFERENCES

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