COMPARATIVE SATELLITE CAPABILITIES FOR REMOTE SENSING OF SNOW COVER IN THE RIO GRANDE BASIN

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ABSTRACT

From 1972 until near the end of the 20th century, the use of satellite data for snow cover mapping was a viable approach under certain conditions. The spatial resolution of Landsat and the temporal frequency of NOAA-AVHRR (National Oceanic and Atmospheric Administration – Advanced Very High Resolution Radiometer) were optimum or possibly better than required individually, but seldom could they be exploited together. Now, with the launch of Terra, the forthcoming launch of Aqua, and numerous private satellites, both adequate spatial resolution and temporal frequency is available for mapping most size basins. When these data are used in sub-pixel mapping algorithms, detailed snow cover representations in basins smaller than 10 km^2 are possible. Probably the best snow cover mapping sensor for combining reasonably high resolution (250 m) and frequent coverage (daily) is MODIS (Moderate Resolution Imaging Spectroradiometer), on board both Terra and Aqua platforms, but the choices of sensors or satellites are numerous with most of the data being readily available to users. Comparison of the spatial resolution, observational frequency, feature detection, suitability for snowmelt runoff models, and cost will be illustrated using different size sub-basins of the Rio Grande.

INTRODUCTION

Snow maps are being obtained from satellite data by a linear combination of a visible and a near-infrared channels. (Gómez-Landesa and Rango, 2002). The snow cover percent is used as an input variable for SRM (Snowmelt Runoff Model), used to simulate and forecast the daily streamflow of each basin (Martinec, Rango and Roberts, 1988). Both the snow covered area and the snowmelt runoff forecasts of the Pyrenees are being sent to the Spanish hydropower company ENHER (Energía Hidroeléctrica del Ribagorzana) for decision making in water management, and for distribution among other local water resources users.

The linear combination method can potentially be applied to any satellite and airborne imagery, as long as its instruments include a visible and near-infrared channels. Traditionally it was applied to NOAA-12 and NOAA-14 AVHRR channels 1 and 2, and Landsat-5 TM (Thematic Mapper) channels 2 and 4 (Gómez-Landesa, 1997), but since the Terra platform was launched in 1999, the MODIS channels 1 and 2 are being used, therefore improving the spatial resolution of the snow maps from 1.1 km resolution of AVHRR to 250 m of MODIS.

Other remote sensor capabilities can be used, such as SSM/I (Special Sensor Microwave/Imager), GOES (Geostationary Operational Environmental Satellites), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), SPOT (Satellite Pour l'Observation de la Terre), IKONOS, Quickbird, and many additional sensors scheduled for deployment in the near future. Comparison of the spatial resolution, observational frequency, feature detection, suitability for snowmelt runoff models, are among the criteria considered to select the suitable sensors for snow mapping on a regular basis. The appropriate sensor or sensors will be used in a methodology being developed for improved water supply forecasts in the Rio Grande basin of New Mexico and Colorado as well as in the Pyrenees of Spain.

AVHRR, MODIS and TM

Based on the spatial resolution, the observational frequency and data availability, the NOAA-AVHRR, Terra-MODIS and Landsat-TM instruments are considered the most suitable for snow mapping. Table 1 summarizes the comparison between these three instruments.

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NOAA-AVHRR:	
Channel 1 : 0.58-0.68 μm (visible)	**Frequency: Daily**
Channel 2 : 0.725-1.0 μm (NIR)	**Resolution: 1 km**
Terra-MODIS:	
Channel 1 : 0.62-0.67 μm (visible)	**Frequency: Daily**
Channel 2 : 0.841-0.876 μm (NIR)	**Resolution: 250 m**
Landsat-TM:	
Channel 2 : 0.52-0.6 μm (visible)	**Frequency: each 16 days**
Channel 4 : 0.76-0.9 μm (NIR)	**Resolution: 30 m**

Table 1. Visible and near-infrared channels of NOAA, Terra and Landsat satellites.

The MODIS instrument has 36 channels, of which channels 1 and 2 have 250 m resolution, channels 3 to 7 are 500 m and the rest are 1 km. Precisely channels 1 and 2 are visible and near-infrared, respectively, as required by the linear combination method used for snow mapping. This fact, together with the free availability of data in Internet, points to MODIS as the perfect candidate to substitute the traditional AVHRR data, though in fact both instruments are being used simultaneously. As for Landsat-TM, even when it has 30 m resolution, the frequency of images (16 days) is too low for operational snow mapping on a regular basis, and it is considered only as complementary to the regular data sources from MODIS and AVHRR.

Fig. 1(a). Location of Finger Mesa (rectangle) inside the Upper Rio Grande Basin at Del Norte

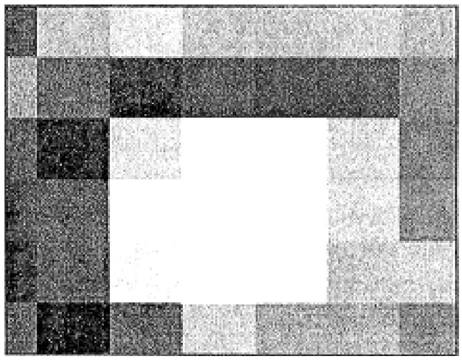

Fig. 1(b). Finger Mesa as seen by AVHRR

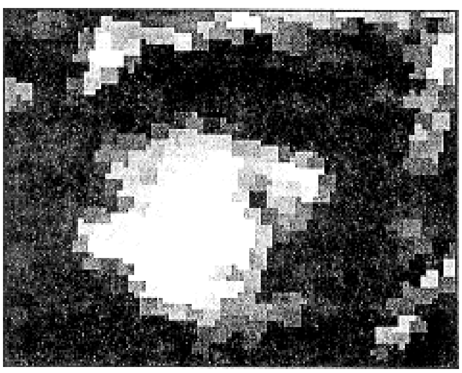

Fig. 1(c). Finger Mesa as seen by MODIS

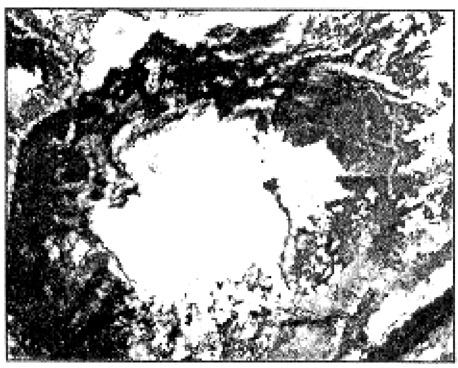

Fig. 1(d). Finger Mesa as seen by Landsat TM

Figure 1(a) shows the location of Finger Mesa, an area of 7.1 x 5.7 km located inside the Upper Rio Grande basin at Del Norte (3,414 km^2), chosen to compare the spatial resolution of AVHRR, MODIS and TM. The rectangle shows the position of Finger Mesa inside the basin on a Landsat-7 TM image of March 3, 2002. Figure 1(b) shows the NOAA-16 AVHRR version at 1.1 km resolution, 1(b) shows the Terra-MODIS version at 250 m, and 1(c) shows the Landsat-7 TM version at 30 m, the three of them taken on March 3, 2002. Spatial resolutions are slightly higher than those indicated due to off-nadir location of the target.

Basin as small as Embalse de Llauset, in the central Pyrenees, with only 8.3 km^2, are even smaller than Finger Mesa area, with 40.5 km^2. An AVHRR snow map of these small basins can only be accomplished by using a sub-pixel approach, such as the linear combination method, thus obtaining percents of snow within each pixel.

SOLAR ILLUMINATION EFFECT

Digital values of pixels belonging to shaded slopes of the basin are strongly diminished because the two channels used in this combination are located in the solar reflective region of the spectrum. Therefore, an algorithm was developed to simulate the shaded areas inside a basin. The simulation was tested using a Digital Elevation Model (DEM) of the Upper Rio Grande basin as static input and using the solar azimuth and zenith angles as dynamic inputs. The spatial resolution of the DEM grid is 90 m x 90 m, and 20 m in elevation. The solar zenith and azimuth angles were obtained from decomposition in Fourier series of the hour angle and the solar declination, following the indications of the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) User's Guide (Vermote et Al., 1995).

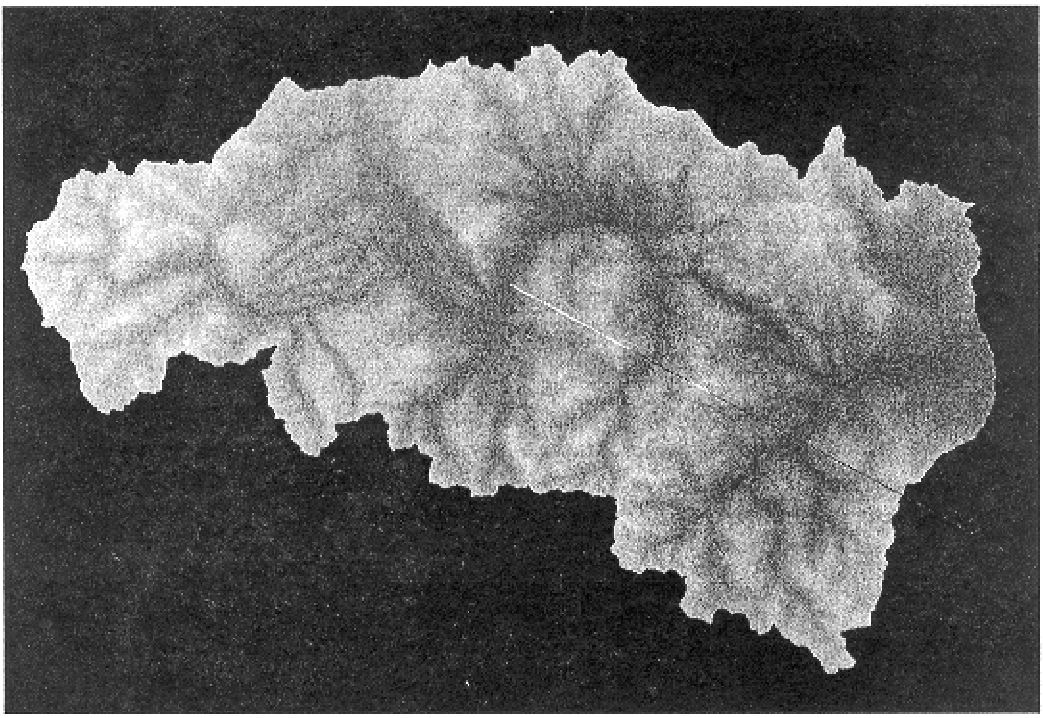

Fig. 2.- DEM analysis of the illumination conditions

To develop the simulation algorithm the following conditions were assumed:

1.- The solar azimuth and zenith angles are constant throughout the whole basin.
2.- The surface of the earth is plane, so that the curvature of the earth is neglected.
3. – There is no terrain outside the basin boundaries that can affect the illumination conditions inside the basin.

Under these assumptions, the algorithm decides whether or not each pixel *p* of the DEM, with an altitude *Zp*, is illuminated. The solar direction is examined from the position of pixel *p* to the end of the basin boundaries, and the pixel is illuminated only if there is no terrain obstructing the solar direction.

Let the vector *(i,j)* be the position of the examined pixel *p*, where *i* is the row and *j* the column of the DEM raster file, and let *Zij* be the altitude of that pixel. A secondary loop runs from the position *(i,j)* to the basin boundary, following the direction of the solar azimuth angle φ, to find the altitude of each pixel *p'* located at *(i'j')*, with an altitude *Zi'j'*. The illumination condition is then:

$$Zij + \Delta Zi'j' > Zi'j' \qquad (1)$$

Where *ΔZi'j'* is the altitude increment of the solar direction from the position *(i,j)* to *(i'j')*, given by:

$$\Delta Zi'j' = \frac{90\sqrt{(i'-i)^2 + (j'-j)^2}}{Tan\theta} \qquad (2)$$

Where θ is the solar zenith angle, and the factor 90 is the grid resolution of the DEM in meters. Therefore, the altitude increment is also expressed in meters. Finally, a primary loop repeats the process for all the DEM pixels, obtaining the illuminated areas of the whole basin.

In Fig. 2 we can see the algorithm applied to the Upper Rio Grande at Del Norte. The red line means that the solar direction is over the terrain, and the white line means that the solar direction is under the terrain, so we can conclude that this particular spot is under the shade. For this simulation the solar zenith angle is 87° 54' and the azimuth is –61° 32', corresponding to 26 November, 2001, at 7:15 am, local Arizona time (GMT-7). The elevation of the simulated spot is 2,720 m.a.s.l. Figure 3 shows a simulation of the Upper Rio Grande basin in 26 November, 2001, at different times of the day. The red color corresponds to illuminated areas.

THE NDSI APPROACH

The snow covered area can also be obtained by means of the Normalized Difference Snow Index (NDSI), which can discriminate snow from most types of clouds, and the widely used Normalized Difference Vegetation Index (NDVI). The result is a two category snow map in which pixels are snow covered or snow free. This method was developed by NASA's Hydrology Sciences Branch for global snow cover mapping using the MODIS instrument. It considers the snow cover in forested areas (Klein *et al.*, 1998), being able to discriminate a snow covered forest from a snow free forest.

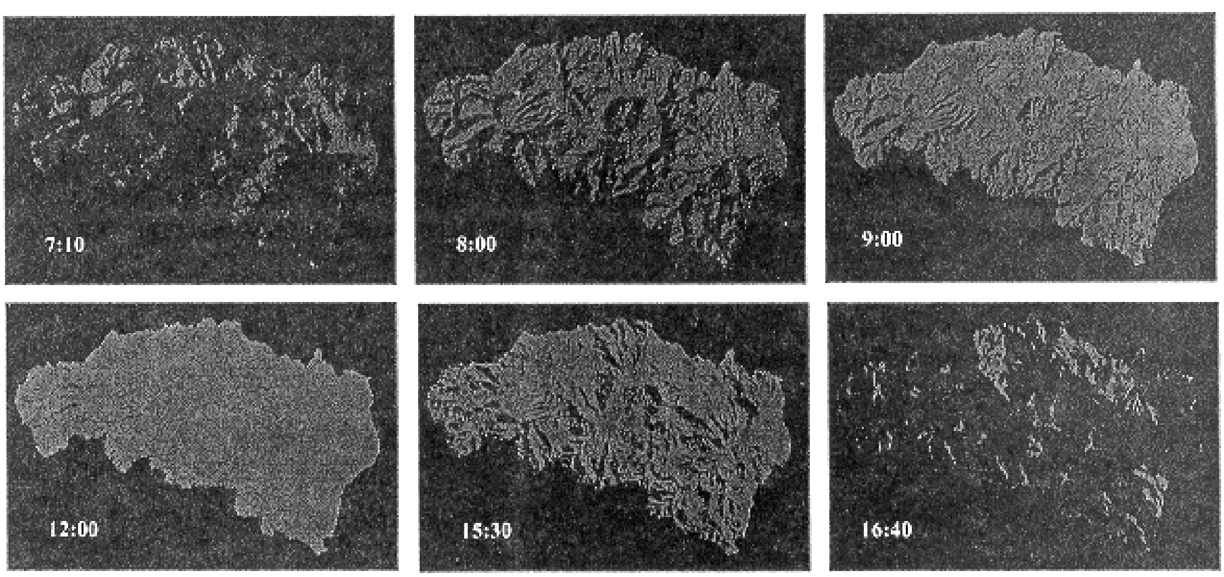

Fig. 3.- Solar illumination simulation, 26 November, 2001, Rio Grande at Del Norte

$$\text{NDSI} = \frac{\text{TM channel 2 - TM channel 5}}{\text{TM channel 2 + TM channel 5}} \quad (4)$$

The MODIS version of the SNOMAP algorithm will use channel 4 (0.545 – 0.565 μm) as the visible channel, instead of TM channel 2, and channel 6 (1.628 – 1.652 μm) as mid-infrared, instead of TM channel 5. Snow is discriminated from water by means of TM channel 4 (near infrared); pixels with an albedo lower than 11% in this channel are not considered snow pixels. For this decision, MODIS channel 2 (0.841 – 0.876 μm, near infrared) will substitute TM channel 4. Also, a minimum pixel reflectance of 10% in TM channel 2 (MODIS channel 4) is required to be considered snow pixels. The accuracy of this approach is estimated to be 91 – 95 %, being slightly lower in forested areas and higher in tundra type areas (Hall, *et al.*, 1998).

The linear combination method was compared with the NDSI method have been applied independently to Landsat TM scenes of BOREAS project (Canada), 6 February, 1994, and Glacier National Park (GNP), Montana, 14 March, 1991. Correlation coefficients between snow maps generated by the two methods were in the range from 0.89 to 0.93.

SNOWMELT RUNOFF MODEL

Snow cover maps are used as an input variable for the Snowmelt Runoff Model (SRM). Each basin is divided into a number of elevation zones, typically five in the Pyrenees case, with an elevation range of 500 m. For each elevation zone the daily snow cover percent is obtained as input data together with daily temperature and precipitation. Daily values of snow cover are interpolated from the satellite measurements. To run SRM in forecasting mode, a total of eight basin parameters must be obtained using hydrological criteria, and with the help of discharge simulation of previous years.

Figure 4 shows the SRM daily forecasted streamflow compared with the measured streamflow. The temperature and precipitation were obtained from the average year 1976, and the snow cover data was obtained from satellite measurements of the year 2001. The forecasted accumulated volume from 1 April to 30 September is 682.1 Hm^3, while the measured volume is 808.2 Hm^3, so that the relative difference is 16.9 %.

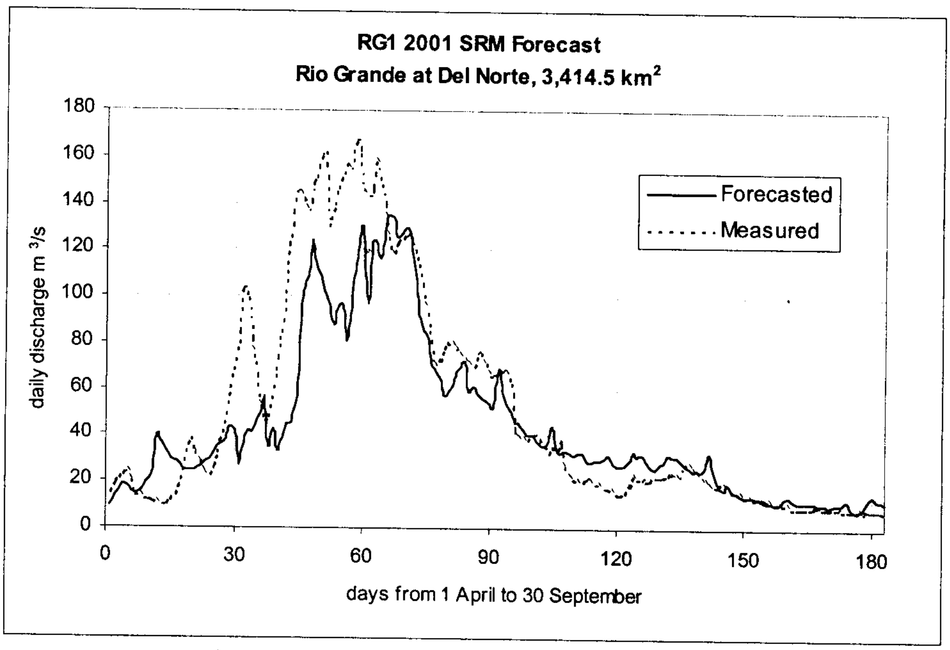

Fig. 4.- SRM forecasted streamflow compared with measured streamflow.

CONCLUSIONS

There are three instruments suitable for snow mapping; NOAA-AVHRR, Terra-MODIS and Landsat-TM. Considering the spatial resolution, frequency of observations and data availability, the MODIS instrument is the best for snow mapping on a regular basis.
Snow maps can be obtained by a linear combination of visible and near-infrared channels at a sub-pixel level, giving percents of snow covered area, and allowing mapping basins as small as 10 km^2. Effects like the low response of snow under a forest canopy and the illumination condition of the basin are also to be considered.
With the use of accurate snow maps and the SRM model, and taking the snow percents as an input, it is possible to simulate and forecast the daily streamflow of the snowmelt season, with relative errors in the accumulated volume smaller than 20%.

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