REPRINT

FROM

# World Resource Review

volume 15 number 1

Send all correspondence regarding WORLD RESOURCE REVIEW to WORLD RESOURCE REVIEW, PO BOX 5275, WOODRIDGE IL 60517-0275, USA *WWW.GlobalWarming.Net*

*World Resource Review Vol. 15 No. 1*

# IMPROVED SATELLITE SNOW MAPPING, SNOWMELT RUNOFF FORECASTING, AND CLIMATE CHANGE SIMULATIONS IN THE UPPER RIO GRANDE BASIN

Albert Rango and Enrique Gómez-Landesa
USDA-ARS Jornada Experimental Range
2995 Knox St.
Las Cruces, NM 88003 USA
Max Bleiweiss
NMSU Department of Entomology
Plant Pathology and Weed Science
945 College Ave.
Las Cruces, NM 88003 USA
Kris Havstad
USDA-ARS Jornada Experimental Range
2995 Knox St.
Las Cruces, NM 88003 USA
Koli Tanksley
Department of Agricultural and Biosystems Engineering
University of Arizona
1200 E. South Campus Dr.
Tucson, AZ 85721 USA

**Keywords:** Remote sensing, snow mapping, climate change, streamflow forecasting

## SUMMARY

The knowledge of snow water resources is a major concern in high elevation basins, where snowmelt streamflow can be a significant contribution to the total discharge. This information is especially useful for irrigation, hydropower and water supply management. In this paper we present a system for snow water resources evaluation, based on satellite data, that generates three products; snow cover distribution with altitude, snowmelt runoff forecasts, and simulations of the expected future snowmelt seasons using the climate change scenarios indicated by international agencies. The new generation of satellites is providing scenes of the earth with increasing quality, more spectral bands, and better spatial resolution. To take advantage of these improvements, it has been necessary to solve new problems associated with the design of the new instruments, such as the so-called Bowtie Effect of the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument. The system developed is being currently applied to the Upper Rio Grande basin in the Colorado Rocky Mountains and to several basins in the Spanish Pyrenees. As an example, a six month daily hydrograph was forecasted for the Upper Rio Grande at Del Norte, CO, for 2001 that was 14.4% different from the observed flow and had an $R^2$=0.768. Furthermore, hydrographs were produced under conditions of changing climate progressively through the 21st century.

## INTRODUCTION

The USDA-ARS (United States Department of Agriculture – Agricultural Research Service) is currently operating a system for snow cover mapping and snowmelt runoff forecasting (at the Jornada Experimental Range, New Mexico State University, Las Cruces, NM) that is being applied in the United States and Spain. The system originally used 1 km resolution NOAA-AVHRR (National Oceanic and Atmospheric Administration – Advanced Very High Resolution Radiometer) channels 1 and 2, visible and near infrared, respectively. Recently, the AVHRR data has been replaced by the data from the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument on board the Terra satellite.

Formerly known as EOS-AM1, Terra was launched on 18 December 1999, as part of NASA's Earth Science Enterprise (ESE). The MODIS instrument is currently providing images in 36 channels, covering the portion of the spectrum from 0.4 to 14.4 μm. Snow cover and characterization of other snow properties are among the aims of the MODIS design (Kaufman et al., 1998). MODIS swaths are 2,300 km wide and achieve a global coverage of the earth every 1-2 days. Channels 1 (visible) and 2 (near infrared), with 250 m resolution, are equivalent to NOAA-AVHRR channels 1 and 2. Channels 3 to 7 are 500 m resolution and the remaining 29 channels are 1 km. This means that, for the visible and near infrared region, MODIS is providing 16 pixels for each AVHRR pixel, but even with this resolution improvement, sub-pixel snow mapping is needed at local scales (Hall, 1995).

A linear combination of visible and near infrared channels is used to generate the snow maps (Gómez-Landesa and Rango, 2002). Table 1 shows the channels used for the Terra-MODIS, NOAA-AVHRR and Landsat TM instruments. Correlation coefficients between the snow maps obtained from these different instruments were always higher than 0.9 (Gómez-Landesa, 1997; Rango et al., 2002).

**Table 1** Channels used with different instruments for the generation of snow maps

| Instrument | Spatial Resolution | Visible Channel | Near Infrared Channel | Frequency |
|---|---|---|---|---|
| **NOAA-AVHRR** | 1,000 m | Channel 1<br>0.57 - 0.70 µm | Channel 2<br>0.72 - 0.99 µm | 1 day |
| **Terra-MODIS** | 250 m | Channel 1<br>0.62 - 0.67 µm | Channel 2<br>0.84 - 0.88 µm | 1 day |
| **Landsat TM** | 30 m | Channel 2<br>0.52 - 0.60 µm | Channel 4<br>0.76 - 0.90 µm | 16 days |

For each basin, the snow cover distribution is derived from the satellite snow maps together with a Digital Elevation Model (DEM), and used as an input for the Snowmelt Runoff Model (SRM). SRM simulates and forecasts the daily streamflow in mountain basins. A recently-issued version of the computer program includes the simulation of the runoff for a changed climate (Martinec et al., 1998). The SRM model has been applied to over 100 basins worldwide and has performed successfully in different tests carried out by the World Meteorological Organization (WMO, 1986 and WMO, 1992).

## BOWTIE EFFECT CORRECTION

The so-called "Bowtie Effect" of the MODIS instrument has complicated the implementation of the recently available MODIS data. Geometrically, this effect is due to an overlap of the satellite field of view, producing a data repetition. MODIS receives data in groups of swaths, each of which is approximately 2,300 km wide by 10 km long at nadir, and about 20 km long at the edge of the scene, as illustrated in Figure 1. The result is an increasing overlap of the consecutive swaths with distance from nadir and can be especially dramatic at the edge of the image.

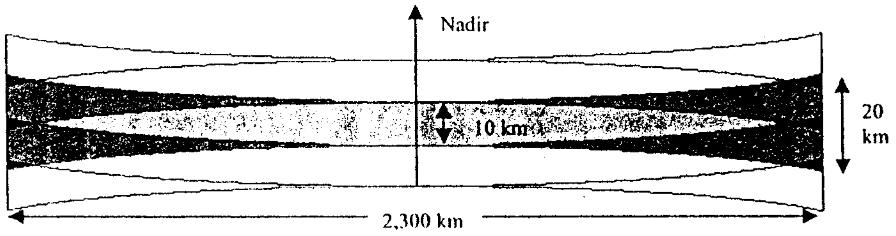


**Figure 1** Geometry of the MODIS Bowtie Effect in three consecutive swaths.

Figure 1 shows three consecutive MODIS swaths. The center swath has been filled with three gray levels: light gray, corresponding to single data which is present only in the center swath; dark gray, corresponding to duplicated data which is present in two swaths (either the previous or the next one); and black, corresponding to data shared by the three displayed swaths. Actually, the triplicated data is only for a few pixels. The swath dimensions in Figure 1 are not proportionally correct for purposes of illustration.

When this project was initiated, there was no software available to correct the "Bowtie Effect" for a PC platform on the Windows environment. The Modis Swath to Grid Toolbox (MS2GT) is a collection of software tools, including the MODIS Bowtie Effect correction, for UNIX environment only (Haran, 2001). In order to use the MODIS data in our snow mapping system we designed a correction algorithm and developed the corresponding software to be used in the Windows environment. This software is available free of charge upon request to the authors.

In order to address this problem, an algorithm was developed and tested with several MODIS scenes. The basic idea is to resample the MODIS scene in latitude and longitude coordinates. In case of correcting the 250 m bands, there is one longitude and latitude value for each group of 4 x 4 image pixels, so the algorithm reads groups of 40 rows of image pixels and groups of 10 rows of latitude and longitude values, and it places each image pixel in the corresponding position of an output file in latitude and longitude coordinates.

Each pixel has its final position determined by two linear bidimensional interpolations in the latitude and longitude space, defining two planes that approach the local variations of latitude and longitude (Equation 1) for the pixel located in row i, column j. The equations of these planes are derived independently for latitude and longitude, and for each case it uses three values of latitude and longitude, *a*, *b* and *c*, as shown in Figure 2.

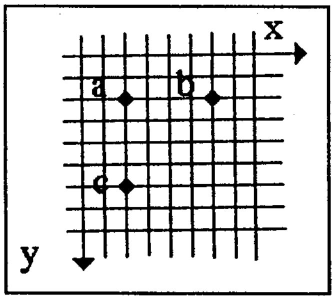


**Figure 2** Three points used to obtain the latitude and longitude plane on the pixel grid.

Further explanations on how these equations were obtained and how the algorithm performs, can be obtained from Gómez-Landesa et al. (2002).

$$lat(P_{ij}) = lat(a) - \frac{1}{4}\left[j\Delta_{ab} + i\Delta_{ac} + R_{abc}\right]$$

$$lon(P_{ij}) = lon(a) - \frac{1}{4}\left[j\Delta'_{ab} + i\Delta'_{ac} + R'_{abc}\right] \qquad [1]$$

Where:

$$\Delta_{ab} = lat(a) - lat(b) \qquad \Delta'_{ab} = lon(a) - lon(b)$$

$$\Delta_{ac} = lat(a) - lat(c) \qquad \Delta'_{ac} = lon(a) - lon(c)$$

$$R_{abc} = \frac{5}{2}\left[lat(b) + lat(c) - 2\,lat(a)\right] \qquad R'_{abc} = \frac{5}{2}\left[lon(b) + lon(c) - 2\,lon(a)\right] \qquad [2]$$

The size of the output file is fixed to keep the relation:

$$\delta_{lon} = \frac{\delta_{lat}}{\sin\theta_m} \qquad [3]$$

Where $\theta_m$ is the local mean latitude, and $\delta_{lon}$, $\delta_{lat}$ are the local increments of longitude and latitude respectively.

A comparison between a MODIS scene before and after running the algorithm can be seen in Figures 3 and 4. Figure 3 shows the surroundings of the Upper Rio Grande Basin before the Bowtie Effect correction, on 25 April 2001. It was extracted from a channel 1 MODIS scene far from nadir, close to the edge of the scene. Figure 4 corresponds to the same area after the correction.

## SNOW COVER DISTRIBUTION

A linear combination of visible and near infrared channels is used to obtain fractional snow cover maps, consisting of pixels with a digital level proportional to the percent of snow covered area. These fractional snow maps allow the study of small basins (as small as 10 times

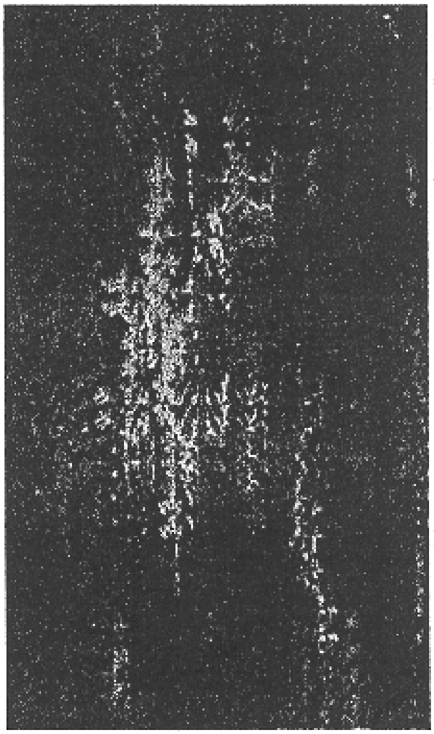


**Figure 3** MODIS view of the Upper Rio Grande basin on 25 April 2001 before the Bowtie Effect correction.

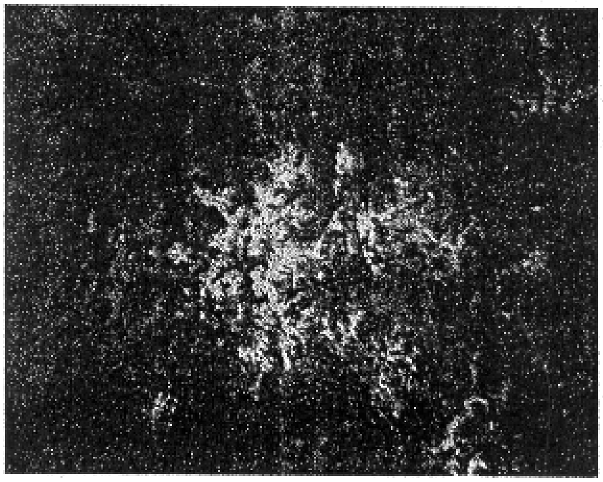


Figure 4 MODIS view of the Upper Rio Grande basin on 25 April 2001 after the Bowtie Effect correction.

the pixel size); whereas a two category snow map, i.e., snow and non snow, does not give enough information to find a reliable snow cover distribution. Other methods use the values of NDVI (Normalized Difference Vegetation Index) and NDSI (Normalized Difference Snow Index) as criteria to obtain fractional snow maps (Barton, et al., 2000).

Based on the snow and ground pixel response, the linear combination for MODIS channel 1 ($C_1$) and channel 2 ($C_2$), is given by the simple relation $a_1C_1+a_2C_2$. To obtain the combination coefficients $a_1$ and $a_2$, the following condition is imposed:

$$a_1\begin{pmatrix} S_1 \\ G_1 \end{pmatrix}+a_2\begin{pmatrix} S_2 \\ G_2 \end{pmatrix}=\begin{pmatrix} Max \\ 0 \end{pmatrix} \qquad [4]$$

Details on how to find the snow and ground values $S_1$, $S_2$, $G_1$ and $G_2$ can be found in Gómez-Landesa and Rango (2002). The *Max* value is the maximum digital value of the snow map pixel. For an 8-bit snow map it would be 255, for 10-bits it would be 1023, and for a 16-bits it would be 65535. In this study we considered that 256 digital levels is enough to discriminate snow cover extent, so our snow maps are in 8 bits.

Figures 5(a), 5(b), 5(c), and 5(d) show the DEM's of the four sub-basins of the Upper Rio Grande in Colorado considered in this study; the Rio Grande at Del Norte, the Rio Grande at Wagon Wheel Gap, South Fork, and Pole Creek. Figure 5(e) shows the location of the sub-basins within the main basin. Combining the satellite snow maps with these DEM's produces snow cover tables. A comparison between the snow cover tables obtained from MODIS and AVHRR instruments can be seen in Figure 6, in a graphical mode, and Table 2 in a numerical mode. This comparison was done on the Noguera Ribagorzana basin, in the central Spanish Pyrenees, on April 7, 2000.

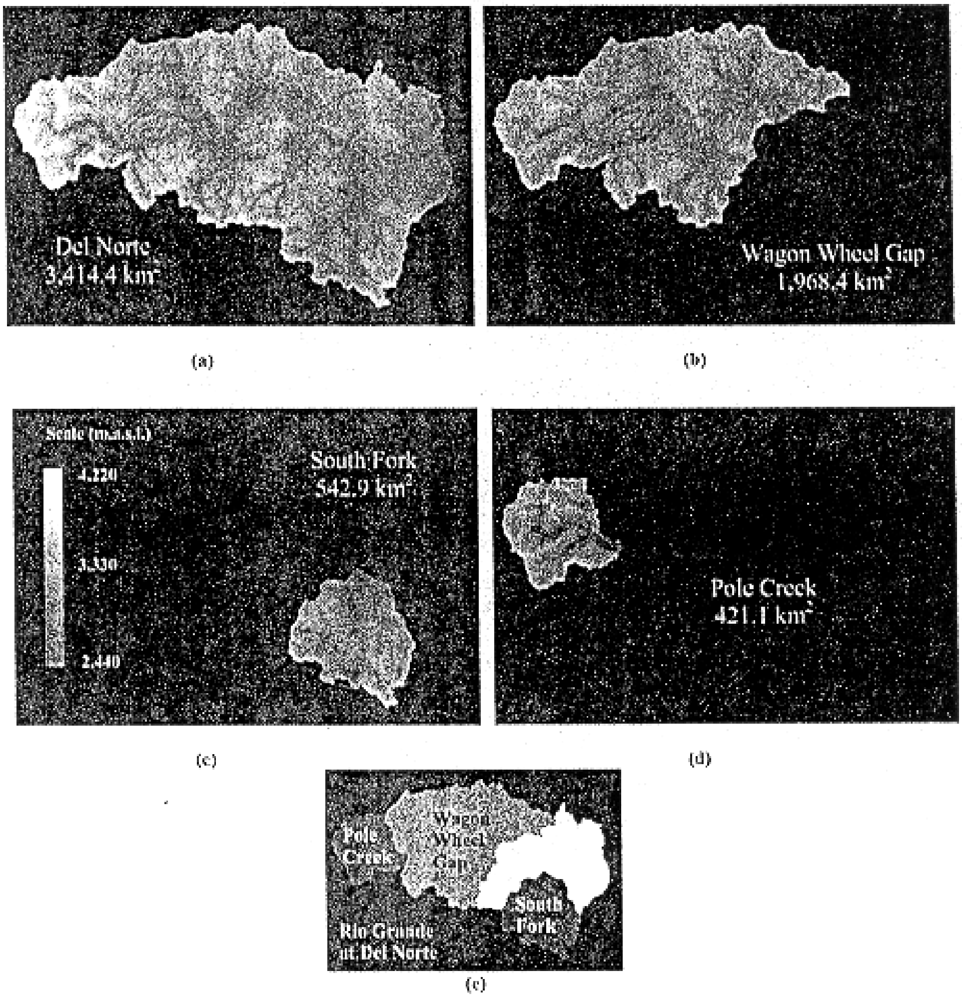
## SNOWMELT RUNOFF FORECAST

For each of the four sub-basins of the Upper Rio Grande, the snowmelt runoff for the year 2001 has been forecasted using the SRM model. SRM was designed to simulate and forecast the daily discharge in basins where the snowmelt runoff is considered to be an important contribution to the total streamflow. The basin was divided into elevation zones and a hypsometric mean altitude was assigned to each zone (Martinec et al., 1998). SRM has eight parameters related to the basin features, and three input variables; temperature, precipitation and snow cover extent. Though not necessary, the DEM's can be helpful in running SRM, providing the snow depletion curves of each elevation zone (together with the satellite snow maps), the zone areas, and the zone hypsometric mean altitude.

**Table 2** Numerical values of snow covered area obtained by MODIS and AVHRR instruments for the Noguera Ribagorzana basin, central Pyrenees, 7 April 2000.

| **Altitude** (m) | **AVHRR snow** ($km^2$) | **MODIS snow** ($km^2$) |
|---|---|---|
| 800 to 900 | 0 | 0 |
| 900 to 1000 | 0 | 0 |
| 1000 to 1100 | 0 | 0 |
| 1100 to 1200 | 0 | 0 |
| 1200 to 1300 | 0 | 0 |
| 1300 to 1400 | 0 | 0 |
| 1400 to 1500 | 0.5 | 0.7 |
| 1500 to 1600 | 0.9 | 1.2 |
| 1600 to 1700 | 1.9 | 2.2 |
| 1700 to 1800 | 4.5 | 3.7 |
| 1800 to 1900 | 7.1 | 6.6 |
| 1900 to 2000 | 8.7 | 9.1 |
| 2000 to 2100 | 10.6 | 10.3 |
| 2100 to 2200 | 13.5 | 13.5 |
| 2200 to 2300 | 16 | 16.8 |
| 2300 to 2400 | 19.7 | 21.6 |
| 2400 to 2500 | 20.9 | 22.2 |
| 2500 to 2600 | 22.7 | 23.3 |
| 2600 to 2700 | 20.7 | 20.3 |
| 2700 to 2800 | 16.4 | 16.2 |
| 2800 to 2900 | 10.9 | 10.5 |
| 2900 to 3000 | 4.9 | 4.5 |
| 3000 to 3100 | 1.2 | 1.1 |
| 3100 to 3200 | 0.3 | 0.2 |
| 3200 to 3300 | 0.1 | 0 |
| 3300 to 3400 | 0 | 0 |
| 3400 to 3500 | 0 | 0 |
| 3500 to 3600 | 0 | 0 |
| **Total** | **181** | **184** |

SRM computes the runoff on a daily basis, and it needs daily values of it's three input variables; snow cover extent, temperature and precipitation. Even when MODIS and AVHRR data can not be obtained daily because of cloud cover, the available satellite



(a) (b)

(c) (d)

(e)

Figure 5 Digital Elevation Models of the (a) Upper Rio Grande at Del Norte, Colorado, basin and the three sub-basins considered in this study; (b) Wagon Wheel Gap; (c) South Fork; and (d) Pole Creek. The sub-basin locations in the Upper Grande at Del Norte, Colorado, are shown in (e)

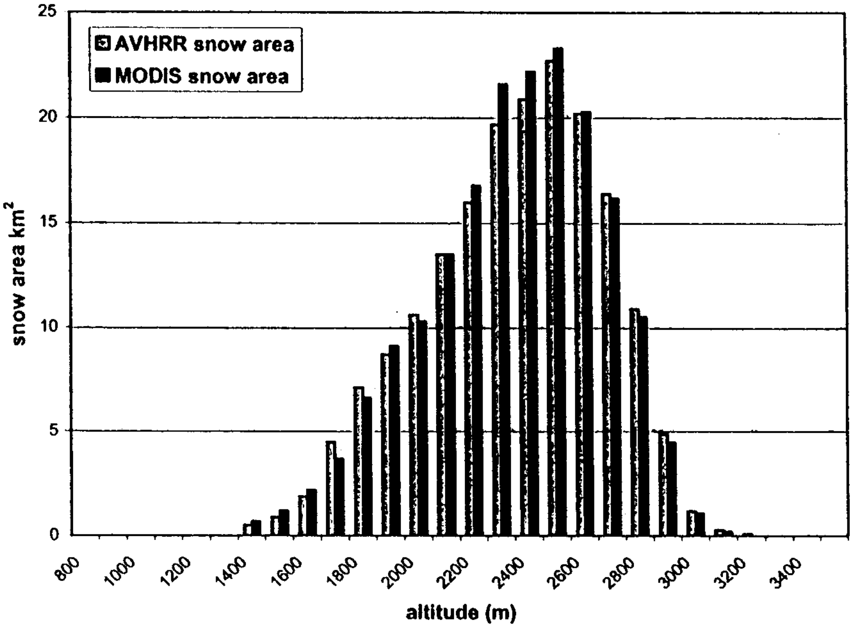


**Figure 6** Graphic of snow-covered area obtained by MODIS and AVHRR instruments for the Noguera Ribagorzana basin (572.9 km$^2$), central Pyrenees, 7 April 2000, in 100 m elevation zones

measurements are interpolated to get a daily snow percent value for the elevation zones.

In the forecasting mode, the daily snow cover curves are extrapolated until the end of the forecasting season (typically September 30) and are designated as Conventional Depletion Curves (CDC). In these forecasts we used the following exponential function to extrapolate the CDC's:

$$S(n) = \frac{100}{1 + e^{a(n-b)}} \qquad [5]$$

Where S(n) is the snow cover percent on day n, and *a* and *b* are two parameters to be determined from the available satellite measurements. In particular, *a* is the "smoothness" of the curve and *b* is the "shift" factor, representing the day in which the snow cover is 50%.

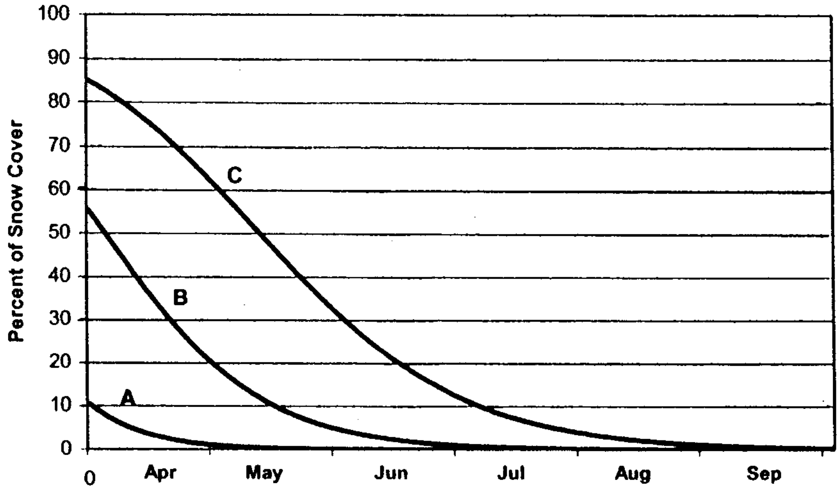


**Figure 7** 2001 Conventional Depletion Curves (CDC) of the Rio Grande at Del Norte basin for elevation zones A (2431-2926 m), B (2926-3353 m), and C (3353-4215 m).

An example of CDC's used in the forecast for the year 2001, can be seen in Figure 7 for the three elevation zones of the Rio Grande basin at Del Norte, Colorado. The lower curve corresponds to zone A (mean elevation of 2,719 m and area of 779.5 km$^2$), the intermediate curve to zone B (mean elevation of 3,155 m and area of 1,282.1 km$^2$), and the upper one to zone C (mean elevation of 3,566 m and area of 1,354.5 km$^2$).

Because the year 2001 was a near average year up to the time snowmelt began, and because the forecasts were made over a period of six months, the daily precipitation and temperature values for the six-month period were taken from the Rio Grande basin for a year also considered to be a near average year, namely, 1976. It would be a great improvement to have a daily meteorological forecast for the entire snowmelt runoff season; but this is impossible at the moment, so a more empirical approach is used. Results of the forecast can be seen in Figures 8(a) to 8(d). These graphics show both the total expected discharge of the basin and the snowpack melt contribution obtained running SRM in absence of precipitation input.

In order to compute the exclusive contribution of the snow, we must consider the existence of the recession flow of the basin, and that can be obtained running the model in absence of both precipitation and snow covered area. This contribution is represented in Figures 9(a) to 9(d); the black solid line is the snowmelt runoff and the gray dotted line is the

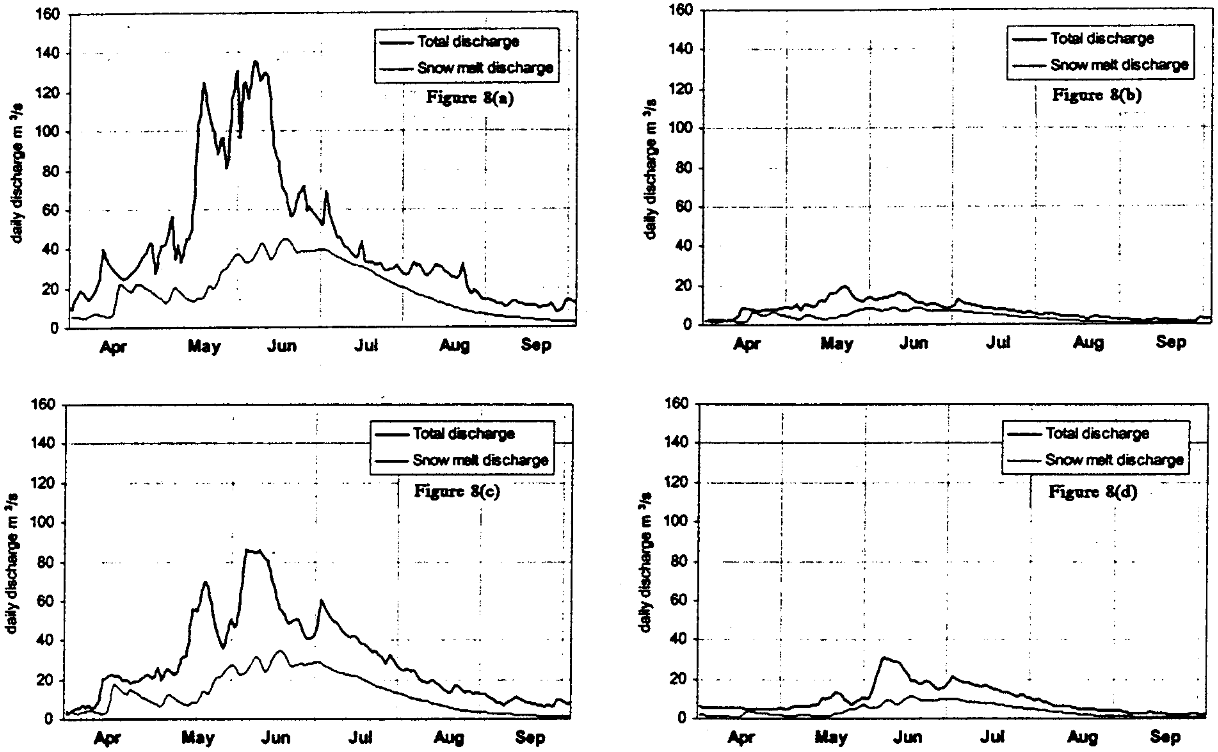


**Figure 8** Runoff forecast for the: (a) Rio Grande at Del Norte basin (3,414.5 $km^2$), 2001; (b) South Fork basin (542.9 $km^2$), 2001; (c) Wagon Wheel Gap basin (1,968.4 $km^2$), 2001; and (d) Pole Creek basin (421.1 $km^2$)

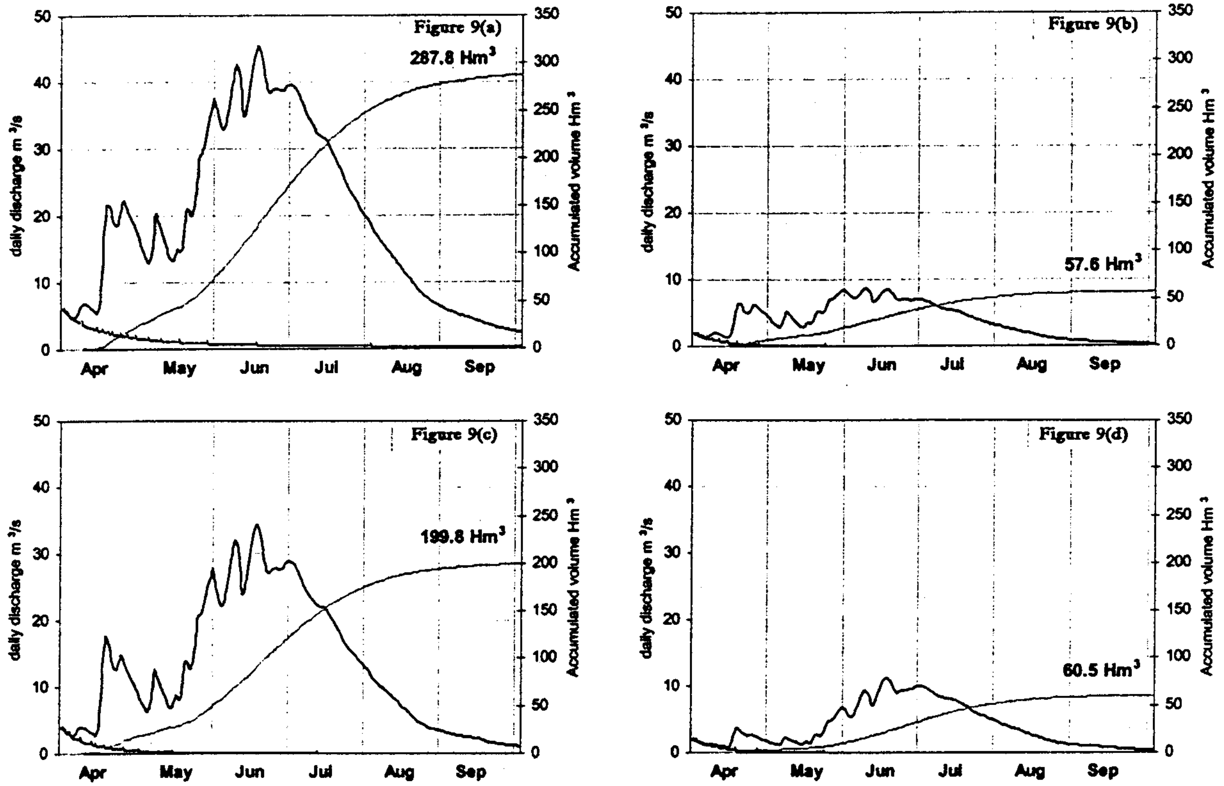


**Figure 9** Accumulated snowmelt discharge for the: (a) Rio Grande at Del Norte basin 2001; (b) South Fork basin, 2001; (c) Wagon Wheel Gap basin, 2001; and (d) Pole Creek basin, 2001

recession flow of the basin. If we integrate the snowmelt runoff *Qa*, over the recession flow *Qb*, we obtain the accumulated snowmelt volume *V(t)* that flows out from the basin as a function of time, as shown in Equation 6.

$$V(t)=\int_{0}^{t}[Qa(s)-Qb(s)]ds \qquad [6]$$

This accumulated snowmelt volume can be seen in Figures 9(a) to 9(c) plotted as a gray solid line. At the end of September, it converges to the total Snow Water Equivalent (SWE) that flows through the closing point of the basin during the snowmelt season. Another way to interpret this value is the total SWE stored in the basin at the beginning of the snowmelt season.

Forecasts of streamflow of four sub-basins of the Upper Rio Grande were made during the first week of May 2001. The measured streamflow of the Del Norte basin was not obtained until March 2002 from the U.S. Geological Survey. Figure 10 shows a comparison between the forecasted and measured total streamflow of the Rio Grande at Del Norte basin, which includes recession flow, snowmelt runoff and rainfall runoff.

The total forecasted volume is 692.1 Hm$^3$ (1 Hm$^3$ = $10^6$ m$^3$) and the measured volume is 808.2 Hm$^3$, which is a 14.4% over the forecasted amount. This result is considered to be satisfactory, taking into account that the daily discharge was forecasted over a period of six months with no updating. We obtained a satisfactory coefficient of determination $R^2 = 0.768$, where:

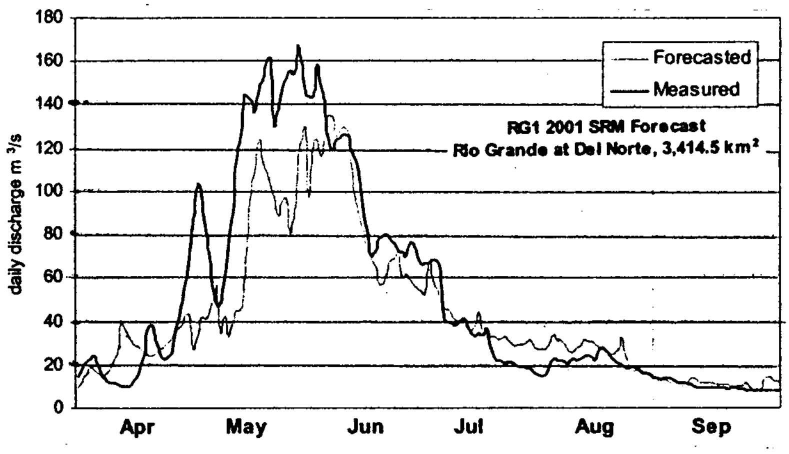


**Figure 10** Upper Rio Grande at Del Norte (3,414.5 km$^2$) measured vs. forecasted daily total streamflow, from 1 April to 30 September 2001.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q'_i)^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2} \qquad [7]$$

and where $Q_i$ is the measured daily streamflow, $\overline{Q}$ is the forecasted daily streamflow, Q is the average measured streamflow, and n is the number of streamflow values.

## CLIMATE CHANGE SIMULATIONS

Five climate change scenarios were selected for the Rio Grande basin, based on the deliberations of the Intergovernmental Panel on Climate Change (IPCC, 1996). Table 3 shows the five selected years, starting from 2000 and progressively advancing 25 years at a time to 2100. These scenarios include, apart from a temperature increase, an effective temperature increase, caused by a predicted reduction in the diurnal temperature range. Actually the nighttime minimum temperature is expected to rise faster than the daytime maximum temperature over the next 100 years, causing an increased average temperature for melting snow (Karl et al., 1993). There is also a precipitation increase and a parameter shift in time that reflects the fact that the expected characteristics of the basin, such as runoff coefficient and other parameters, are shifted towards the winter due to the increased temperature in the new climate. A near-average year (1976) was used as the base year for evaluation of the effect of the climate change.

**Table 3** Climate change simulation on the Rio Grande at del Norte basin.

| Year | Temperature Increase /Effective Temperature Increase | Precipitation Increase | Parameter Shift |
|---|---|---|---|
| 2000 | 0°C / 0°C | 0% | 0 Days |
| 2025 | 1°C / 1.175°C | 2.5% | 5 Days |
| 2050 | 2°C / 2.350°C | 5.0% | 13 Days |
| 2075 | 3°C / 3.525°C | 7.5% | 20 Days |
| 2100 | 4°C / 4.700°C | 10.0% | 28 Days |

Three of the five hydrographs are shown in Figure 11, corresponding to the years 2000, 2050 and 2100. From this graphic, the shift of the snowmelt and runoff seasons towards the winter months can be seen clearly. SRM can automatically produce these hydrologic-climate change scenarios given inputs of the changed temperature and precipitation

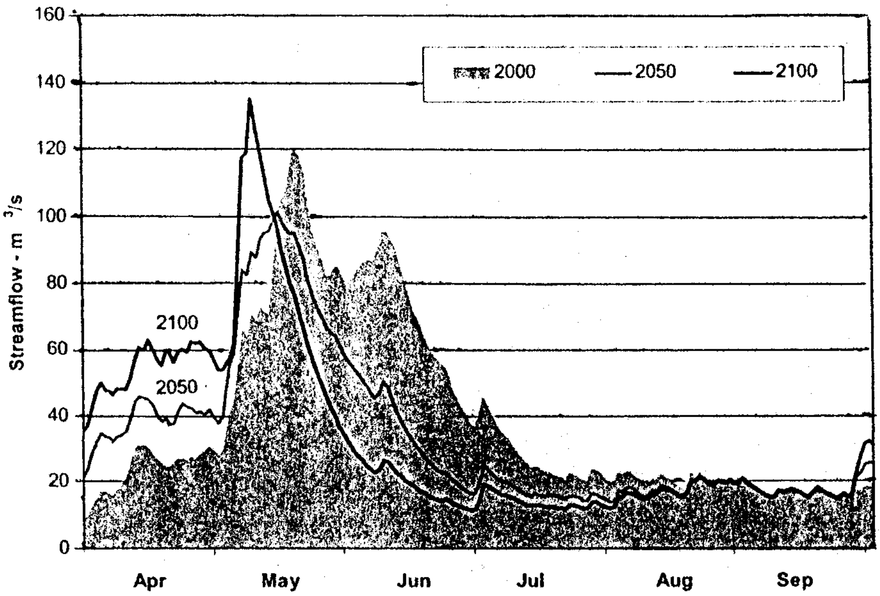


**Figure 11** Climate change simulation for the years 2000, 2050 and 2100 for the Rio Grande at Del Norte basin.

to be expected. This capability is very valuable for water resources planning and management, especially when plans for future structures and rules of operation must be made.

## CONCLUSIONS

After correcting the MODIS "Bowtie Effect", by means of the algorithm highlighted in this paper, snow mapping of the Upper Rio Grande basin is now possible on a regular basis using a personal computer. This enables possible users of the snow maps, such as hydropower companies and irrigation districts, to systematically make use of this information for better water resources management. A linear combination of channels 1 and 2 of the new MODIS instrument provides daily snow maps with 250 m resolution, thus improving the accuracy of the snow distribution results (formerly based on the 1 km resolution NOAA-AVHRR imagery). Because of the sub-pixel snow mapping approach, this information content is indicative of a resolution less than 250 m. A information content is indicative of a resolution less than 250 m. A comparison between MODIS and NOAA-AVHRR snow mapping capabilities was performed using a basin in the Spanish Pyrenees.

Snow depletion curves derived from the satellite snow maps are being used as an input to the SRM model, which successfully simulated the daily streamflow of the Upper Rio Grande basin and many other basins worldwide. SRM can be operated in the forecasting mode to estimate the future streamflow, therefore providing users with valuable information for decision making in water management.

Comparison between the daily streamflow forecast of the Upper Rio Grande basin at Del Norte with the measured streamflow for the year 2001 gave a coefficient of determination $R^2 = 0.768$ and a volumetric difference of 14.4% (the forecasts of the rest of the sub-basins of the Upper Rio Grande at Del Norte were not verified due to the measured data not being available). If long-term meteorological forecasts can be improved, the snowmelt streamflow forecasts should also be improved over the use of temperature and precipitation from a past year with similar streamflow.

The forecast of Pole Creek basin, shown in Figure 8(d), indicates that the contribution of the snowmelt to the total streamflow is higher than in the Del Norte case, shown in Figure 8(a). The reason is that Pole Creek is a sub-basin of Del Norte, with it's elevation being the highest in the basin, so that a majority of the discharge is from snowmelt, as is to be expected in any extreme headwater basin.

Once the SRM basin parameters are known, through the assessment of the SRM simulation performance, climate change simulations can be generated to describe the future snowmelt season regime. In this paper we simulated the streamflow of the Upper Rio Grande basin for five years in 25 year intervals, from 2000 to 2100. The general tendency is to have a shorter snowmelt season, with less snowmelt runoff, and also peaks concentrated in the first half of May, instead of during late May and June, as it happens today.

## REFERENCES

Barton, J.S., D.K. Hall and G.A. Riggs, Remote Sensing of Fractional Snow Cover using Moderate Resolution Imaging Spectroradiometer (MODIS) Data. In: *Fifty-seventh Eastern Snow Conference (Syracuse, New York, May 2000)*, Eastern Snow Conference, USA (2000).

Gómez-Landesa, E., A. Rango and M. Bleiweiss, *Addressing the MODIS Bowtie Effect for Snow Mapping* (manuscript in preparation) (2002).

Gómez-Landesa, E. and A. Rango Operational Snowmelt Runoff Forecasting in the Spanish Pyrenees Using the SRM Model, *Hydrological Processes*, **16**, 1583-1591 (2002).

Gómez-Landesa, E., *Evaluación de Recursos de Agua en Forma de Nieve mediante Teledetección usando Satélites de la Serie NOAA,* (Estimation of snow water resources using remote sensing with NOAA satellites) Doctoral Thesis, ETS Ingenieros de Caminos, Canales y Puertos, Universidad Politécnica de Madrid (UPM), Madrid, Spain (1997).

Hall, D.K., *First Moderate Resolution Imaging Spectroradiometer (MODIS) Snow and Ice Workshop*, NASA Conference Publication 3318, NASA Goddard Space Flight Center, Greenbelt, Maryland (1995).

Haran, T., MS2GT: The MODIS Swath-to-Grid Toolbox (2000).
<http://nsidc.org/PROJECTS/HDFEOS/MS2GT/>

Intergovernmental Panel on Climate Change (IPCC), Climate Change 1995, *The Science of Climate*, Cambridge University Press, New York, pp. 572 (1996).

Karl, T.R., P.D. Jones, R.W. Knight, G. Kukla, N. Plummer, V. Razuvayev, K.P. Gallo, J. Lindseay, R.J. Charlson and T.C. Peterson, A New Perspective on Recent Global Warming; Asymetric Trends of Daily Maximum and Minimum Temperature, *Bulletin of the American Meteorological Society*, **74**(6), 1007-1023 (1993).

Kaufman, Y., D. Herring, J. Ranson and J. Collatz, Earth Observing System AM1 Mission to Earth, *IEEE Transactions on Geoscience and Remote Sensing*, **36**(4) (1998).

Martinec, J., A. Rango and R. Roberts, *Snowmelt Runoff Model (SRM) User's Manual*, Geographica Bernensia P-29, Department of Geography, University of Bern, Switzerland, pp. 65 (1998).

Rango, A., E. Gómez-Landesa and M. Bleiweiss, Comparative Satellite Capabilities for Remote Sensing of Snow Cover in the Rio Grande Basin, *Proceedings of the 70th Western Snow Conference*, Granby, Colorado, (in press)(2002).

WMO, *Intercomparison of Models of Snowmelt Runoff*, Operational Hydrology Report No. **23**, World Meteorological Organization, Geneva (1986).

WMO, *Simulated Real-time Intercomparison of Hydrological Models*, Operational Hydrology Report No. **38**, World Meteorological Organization, Geneva (1992).