Integrating two remote sensing-based hydrological models and MODIS data to improve water supply forecasts in the Rio Grande Basin

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INTRODUCTION

Remotely-sensed data can be used with modern hydrological models to provide effective water supply forecasts and to evaluate water resource management options. MODIS, on both NASA TERRA and AQUA satellites, is likely the optimum sensor for snow mapping because it has a best resolution of 250 m (two bands), it passes over daily, it is free for downloading, and it provides a logical transition from 1 km NOAA-AVHRR data. Its worth for snow mapping has been proven both in the Rocky Mountains of the United States and the Pyrenees of Spain. Still, research to solve automated and operational problems is ongoing, including corrections for the 'Bow Tie' effect, mapping in shaded and heavily vegetated areas, and using bidirectional reflectance distribution functions to retrieve snow albedo. As the remote sensing improvements are made, the data are used in the Upper Rio Grande basin for improvement of the snowmelt forecasting system. Remote snow-water equivalent site data are acquired through the Natural Resources Conservation Service SNOTEL system employing meteor-burst relay. These data can be used for early season (November–December–January) volumetric forecasts that increase water management flexibility. The MODIS-derived snow cover data are input to the Snowmelt Runoff Model (SRM) for generating daily streamflow forecasts over the entire melt season. Because snowmelt runoff is not significant throughout the entire basin, SRM outflow from snowmelt basins is linked to the Semi-distributed Land Use-based Runoff Process (SLURP) model as an input. SLURP is a comprehensive distributed model now operating on the entire basin to assist in water management decision-making today and to evaluate future scenarios for improving long range planning. SLURP also used remote sensing inputs to establish current landcover thoughout the basin, and to derive the Leaf Area Index for use in evapotranspiration algorithms. Examples of forecasts for the 2001–2004 in the Upper Rio Grande basin are presented.

Information on snow water resources is a major concern in river basins where snowmelt runoff can be a significant contributor to total discharge, even in basins of the southwest United States, such as the Rio Grande, where desert makes up much of the lower elevation areas through which the river channel runs. Because the water resource is extremely limited in these basins, i.e. the water demand exceeds the water supply, the uses to which water is put must be carefully balanced. Many factors must be considered when making water management decisions in the Rio Grande basin such as:

- flood regulation
- irrigation demands
- municipal and industrial supplies
- Indian water rights
- compact and treaty obligations
- water quality parameters
- riverine and riparian habitat protection
- endangered and threatened species protection
- recreational uses
- hydropower generation

It is imperative that a prediction procedure be developed and available to users and water managers in the Rio Grande basin that is able to produce accurate forecasts along the length of the Rio Grande from both snowmelt-dominated and rainfall-dominated sub-basins. The basin is large scale in nature, and it seems well suited to incorporation of remote sensing data into the forecasting system.

BASIN CHARACTERISTICS

This Rio Grande basin is a large, international basin lying in North America, straddling the border between the United States and Mexico, and covering portions of the states of Colorado, New Mexico, Texas, Chihuahua, Durango, Coahuila, Nuevo Leon, and Tamaulipas (see Figure 1). In Mexico, the Rio Grande is known as Rio Bravo del Norte. The basin spans numerous climatic zones, but arid and semi-arid conditions predominate in most of the basin, and especially so in the

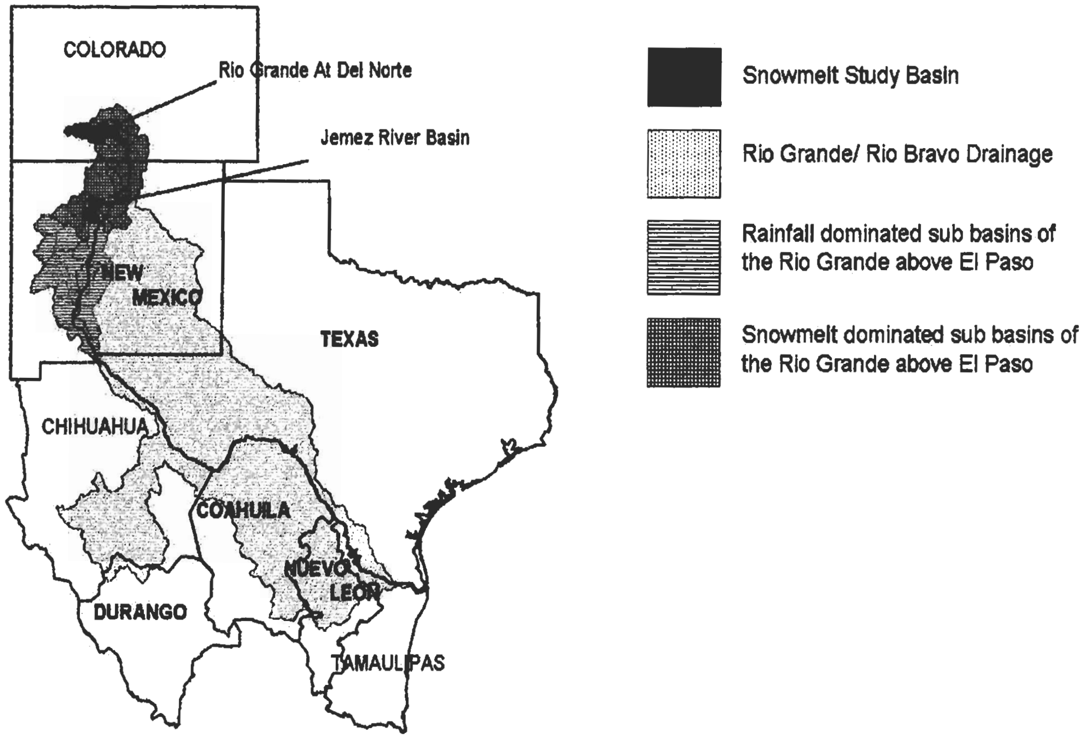

Fig. 1 Location of the Rio Grande in the United States and Mexico showing sub-basin areas dominated by snowmelt or rainfall above El Paso, TX.

urban regions. For the approximately 5 million people who live in basin, the primary sources of water come from snowmelt and rainfall in upstream tributaries.

The length of the Rio Grande is about 3058 km (1900 miles), making it the third longest river in the conterminous United States. The drainage area is about 870 235 km^2 (336 000 miles^2) which includes the major tributaries of the Pecos River in the United States and the Rio Conchos in Mexico. The lower two-thirds of the basin receive only 18–38 cm (7–15 inches) of precipitation annually on average. In the narrow mountainous rim region of the Rio Grande basin, average annual precipitation exceeds 65 cm (25 inches). In these areas, snow can make up to 75% of the annual precipitation, decreasing to the south. In the early stages of this project, we are concentrating on a smaller part of the basin, namely, the Rio Grande above El Paso, Texas, that has an area of about 102 280 km^2 (39 490 miles^2). The northern half of this area, about 50 675 km^2 (19 656 miles^2), has a very important snowmelt runoff component. In this area, we are first concentrating on the Rio Grande at Del Norte, Colorado (3417 km^2 or 1320 miles^2) and the Jemez River at Jemez Reservoir, New Mexico (2475 km^2 or 1060 miles^2).

REMOTE SENSING AND HYDROLOGICAL MODELS

Only two hydrological models have ever been designed with the input of remote sensing data as major elements. These two models are the Snowmelt Runoff Model (SRM) and the Semi-distributed Land Use Runoff Processes (SLURP) model. For this project, the operations of SRM and SLURP are being linked through a user-friendly interface.

SRM was originally designed (Martinec *et al.*, 1998) to operate in high elevation snowmelt runoff basins and has performed very well on over 100 basins worldwide. Since original development, SRM has also been shown to simulate flow accurately on large basins where rainfall dominates over snowmelt in addition to the high elevation basins (Seidel *et al.*, 2000). The original version of SRM is a degree day model with three primary input variables, namely, daily temperature, precipitation, and snow covered area (as obtained from satellite data). A modified version of SRM allows the input of radiation data in addition to temperature for melting the snowpack (Brubaker and Rango, 1997).

SLURP (Kite, 1998) has additional capabilities beyond SRM and, on specific sub-basins, SLURP has been modified to accept runoff output from SRM as input. SLURP can be divided into hydrological response units for operations. The land cover of each of these hydrological response units is

Table 1. Comparison between satellite sensors and snowcovered area

	Thematic Mapper	*MODIS*	*AVHRR*
Total Snow Covered Area	1,312.34 km²	1,255.89 km²	1,188.96 km²
Percent Snow Covered Area	38.43 %	36.78 %	34.82 %

determined from remote sensing data for use by SLURP in runoff generation. Another important use of remote sensing data in SLURP is for determining vegetation spectral indices for calculating leaf area indices and evapotranspiration. SLURP also takes into account man-made modifications to the hydrological cycle such as dams and reservoirs, diversions and irrigation schemes. The availability of both models working together will allow decision makers to test different scenarios concerning possible future conditions while adequately simulating existing conditions.

The reason for integrating these two models is to allow for the use of the best features of both models in a final, integrated product. For example, SLURP uses precipitation data from meteorological stations and distributes that information over the basin while SRM uses spatially defined precipitation data that are inherently already distributed over the basin. Both models can be used on large basins, interrogating each sub-basin individually; however, there is no mechanism within SRM, as there is in SLURP, to take into account reservoir operations, diversions and other details of interest to water managers. Both models can be and have been used in climate change analysis (e.g. Rango, 1992; Rango *et al.*, 1995; Kite *et al.*, 1994; Kite and Haberlandt, 1999)

A study of the various sensors available for snow mapping (Rango *et al.*, 2002) has led us to conclude that the MODerate resolution Imaging Spectroradiometer (MODIS) onboard both Terra and Aqua platforms of the Earth Observing System is the near ideal snow cover accumulation and depletion sensor. MODIS has moderately high resolution, especially when using the two most appropriate bands for snow mapping, namely, the 0.62–0.76 µm and the 0.725-1.0 µm channels which have a spatial resolution of about 250 m. The other channels have resolutions of either 500 m or 1 km. Frequency of observation is daily, with a morning overpass for Terra and an afternoon overpass for Aqua. Processing is usually rapid, with data generally being available the day after acquisition. MODIS data can be acquired free from NASA-DAAC or from direct broadcast facilities such as at Oregon State University. We have developed algorithms capable of correcting the MODIS data and rectifying it for snow mapping. For snow mapping, MODIS is currently the best sensor.

A comparison of snow distribution in the Rio Grande at Del Norte, Colorado study basin in which 30 m Landsat, 250 m MODIS, and 1 km NOAA-AVHRR data were evaluated demonstrates that MODIS, for all practical purposes, preserves the fine snow cover detail (in 100 m elevation bands) afforded by Landsat Thematic Mapper while viewing the target area daily as is characteristic of NOAA-AVHRR (Rango *et al.*, 2002). Typical results are shown in Table 1 for one particular day.

Using MODIS-derived snow cover values by elevation zones, snow cover depletion curves can be drawn without the need to have observations each day. The values for days in between the MODIS observations can be determined from the snow cover depletion curve. Those daily snow cover values are fed directly to SRM and combined with daily temperature and precipitation obtained from conventional climate stations to determine daily snowmelt values by elevation zone which are then converted to daily snowmelt runoff forecasts. Figure 2 shows the snow cover depletion curves for Rio Grande at Del Norte basin for the 2002 snowmelt season while Table 2 gives the zone characteristics.

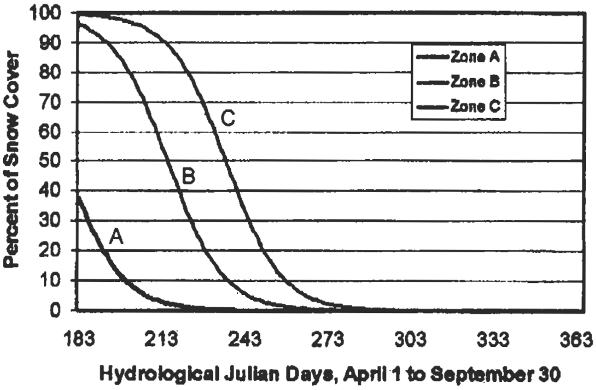

Fig. 2 Snow cover depletion curves for Rio Grande at Del Norte basin for the 2002 snowmelt season

Table 2. Zone characteristics for the Rio Grande at Del Norte basin

Zone	*Area (km²)*	*Mean elevation (a.s.l)*
A: 2,440-2,920 m	750.9	2,731.3
B: 2,940-3,340 m	1,248.4	3,162.3
C: 3,360-4,220 m	1,414.8	3,567.1

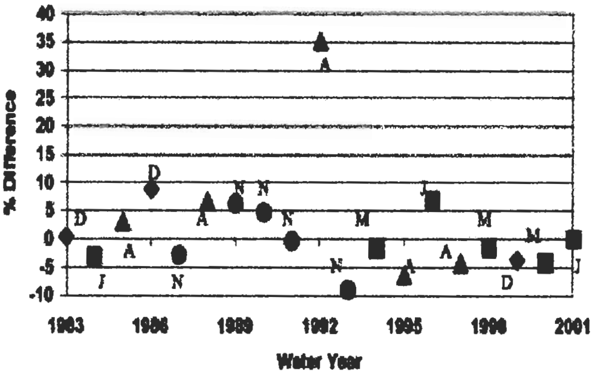

Fig. 3 Annual best prediction month (N=Nov, D=Dec, J=Jan, F=Feb, M=March, A=April) and prediction errors for April–September snowmelt runoff volumes in the Rio Grande at Del Norte, CO during 1983–2001.

EARLY SEASON FORECASTING PROCEDURES

Two types of early season forecasts are being developed in the Rio Grande basin. One type uses SNOTEL data for early-season statistical forecasting of spring snowmelt runoff volumes (April 1–September 30) for the Rio Grande at Del Norte (DeWalle *et al.*, 2003). Normally, forecasts of seasonal runoff volumes are not made until January 1, but earlier estimates of runoff could be quite useful in water resources planning in this perennially water short region. Runoff volumes predicted using snowpack water equivalents from selected SNOTEL sites on November 1 or December 1 of each year gave more accurate estimates than snowpack measurements in later months (January 1 to April 1) in 8 out of 19 years of available data (Figure 3). February 1 snowpack data never gave the best estimate in 19 years. Estimates based on March 1 or April 1 data were tied with November 1 and December 1 in frequency of best estimates for the 19-year period. Atmospheric circulation patterns affecting snowfall for entire winter seasons appeared to be reflected in early-season snowfall on this basin. Acquisition of early-season snowpack water equivalent data through the SNOTEL network, or some similar automated system, may be an underutilized asset in snowmelt runoff forecasting.

The other type of early season forecast of the April–September daily flows can also be made with SRM, using a prior reference year in which excellent temperature, precipitation and satellite data were available. This forecast is based mostly on average conditions, so progress is being made to link the seasonal volume forecast using SNOTEL to the SRM normalised forecast. Once accomplished, this will be a true early season forecast made before January 1 that will be of value to the agricultural sector in deciding crop plantings, grazing rotations, and irrigation planning.

On or about April 1, SRM can be used to make a daily streamflow forecast for the entire snowmelt runoff season. For the Rio Grande at Del Norte, Colorado, this was done in 2001, 2002, and now in 2003 as shown in Figures 4–6. The 2001 forecasts volume was within 15% of the actual volume and the timing of the hydrograph was good. The 2002 forecast volume was greater than observed, as were all forecasts in this extreme low flow year. However, SRM provided a forecast that showed a significant low flow year was expected. For 2003, we will have to wait until Fall of 2003 to evaluate the forecast accuracy. The 2003 forecast was updated in May using SNOTEL observations in the basin. The seasonal volume forecast was lowered from 423 428 ac-ft ($522.3 \times 10^6 m^3$) to 278 609 ac-ft ($343.6 \times x10^6 m^3$) based on very dry conditions prevailing after the initial forecast. Progress was also made on implementing SLURP on the basin. SLURP was used to divide the basin into the appropriate sub-basins and it has been modified to accept the direct input of SRM flows in all the

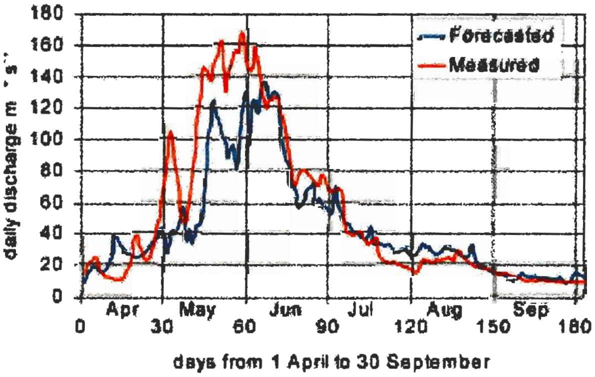

Fig. 4 SRM forecasted versus measured streamflow for 2001 for the Rio Grande at Del Norte.

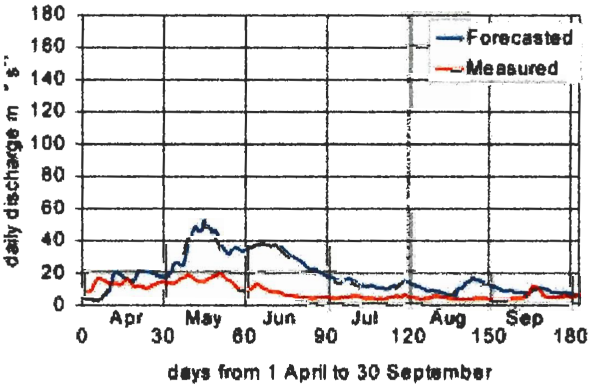

Fig. 5 SRM forecasted versus measured streamflow for 2002 for the Rio Grande at Del Norte

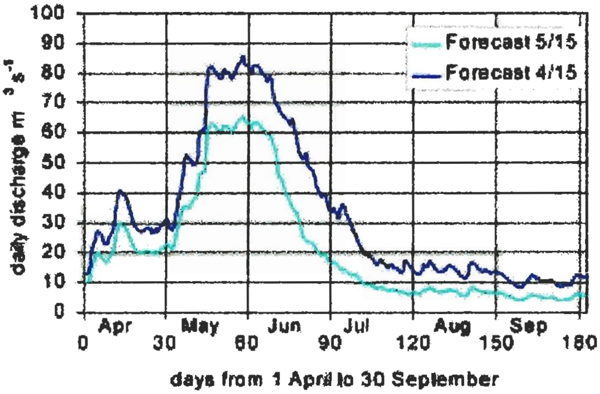

Fig. 6 SRM forecasted runoff for 2003

snowmelt runoff basins. Progress has been made on the SLURP compilation and implementation of the man-made structures and diversions along the Rio Grande channel network.

CONCLUSIONS

The Rio Grande basin is a large, complex international basin with many forecasting problems that need to be solved to improve water management. Both SRM and SLURP have been implemented on the Rio Grande, and these two models have been integrated with remote sensing data for development of a new and improve forecasting system. As most models do, SRM and SLURP require conventional climate inputs. These models differ from other hydrological models in that they require remote sensing input data in order to operate. MODIS data are optimum for mapping of snow covered areas required by SRM because of the spatial and temporal resolution, plus MODIS can be used for land use and evapotranspiration inputs required by SLURP. Although still early in the Rio Grande project, we have been able to forecast early season volumes and peaks as well as daily flows for the April 1–September 30 runoff season for the last three years. The forecast flow data have compared very well in most situations. We will do additional testing of the snowmelt forecasts and further integration of the models to result in a comprehensive water resource management system employing meteor-burst (SNOTEL) and remote sensing (MODIS) technologies.

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