SNOW: THE REAL WATER SUPPLY FOR THE RIO GRANDE BASIN

Albert Rango[1]

ABSTRACT

The Rio Grande basin in Colorado, New Mexico, Texas, and Mexico is an important drainage in southwestern North America, vital for water consumption by a rapidly growing population, irrigated agriculture, economic development, preservation of endangered species, and energy generation. The most important source of water in the Rio Grande drainage results from snowmelt in the mountains of the upper basin. The gap between water supply and water demand is continually increasing as the population increases, and long term climate change further will affect the amount and timing of streamflow. The criticality of these problems will continue unabated through the 21st Century. Planning to cope with these water management problems needs to move now from relying on projections derived from current storage in reservoirs to additionally incorporating new technologies for measurements and hydrological modeling to allow the development of likely scenarios in both the short and long term. Models that can accept and integrate all types of measurements need to be utilized. Such models exist and are ready to be used operationally. Examples are given of both daily flow forecasts for an entire snowmelt season in the basin as well as predictions of future changes in streamflow to be expected under conditions of climate change. These types of data are vital in deciding among various future options which include the determination of the cost of water, controls on industrial and domestic development, new water distribution and storage systems, and the implementation of water conservation measures.

The Rio Grande meanders through the entire length of New Mexico from the Colorado border in the north to the Texas border in the south. It is by far the most important river in the nation's fifth largest state (by area). It is also one of the two most important rivers of the Southwest (the other being the Colorado River) because it transports water, the world's most unusual substance and the essence of life, through North America's largest desert which produces little water of its own. The Rio Grande has had many names throughout history, but translation of some of the names reveals the importance of the river—"big river," "turbulent river," "angry or fierce river," and "great river" (Reid 2004). Although 50–75% of the flow of the Rio Grande is sustained by melting snow in the mountains of southern Colorado and northern New Mexico, the public perception of

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[1] Corresponding author: alrango@nmsu.edu Research Hydrologist, USDA-ARS Jornada Experimental Range, Las Cruces, NM

the source of Rio Grande water is not clearly defined. This lack of a clear public perception of the role of snow versus the role of rain in generating the flow in the Rio Grande can lead to uncertainties in decision-making when priorities are set for improving forecasting and management of the scarce water resource in the Rio Grande basin. The true importance of snow in the basin is masked by a combination of factors including geography, climate, demography, water supply and demand, groundwater availability, and diverse political and social issues.

BACKGROUND

The Rio Grande is a long river in a relatively narrow basin with only two major tributaries (Rio Conchos and the Pecos River) (See Figure 1). It runs approximately 1900 mi (3058 km) making it the third longest in the United States and 26th longest in the world (Wikipedia 2006). These statistics are somewhat variable between publications because determinations of the mouth of a river and also the source is somewhat subjective, and different authors may use different map scales in their determination of length. Another variation can be seen in drainage area. The drainage area of the Rio Grande is 336,000 mi^2 (870,236 km^2), but the figure can vary even more widely than length because of exclusion or inclusion of internal drainage basins having no outlet to the river and differences in determining the watershed divide at different map scales. Van der Leeden *et al.* (1990) reports a drainage area of 870,236 km^2 whereas Wikipedia (2006) reports a drainage area of 570,000 km^2, a difference about 300,000 km^2, but Wikipedia (2006) also shows a drainage area map that presents the area of internal drainage that is excluded that reduces the effective area to 570,000 km^2.

Because the Rio Grande is so long compared to its relatively small drainage area (due to the limited number of tributaries), activities and knowledge in the lower basin are not closely linked to similar information in the upper basin. Because of different interests in different parts of the basin, knowledge is not easily transferred and, in some cases, is not even pertinent in all parts of the basin. Figure 1 also delineates the snowmelt dominated sub basins in southern Colorado and northern New Mexico that deliver the majority of flow in the Rio Grande. When geography (drainage basins, stream length, topography), demography (locations of population centers), and climate (in the mountains as opposed to the vast expanse of arid lands) are superimposed, it becomes evident why most of the public does not think “snow” when the source of water is discussed. Figure 2 superimposes the Rio Grande basin outline, the area of the Chihuahuan Desert, the location of major population centers, and the mountains on the basin perimeter where a major snowpack accumulates in winter.

It can easily be seen that the majority of the basin's approximately 13 million inhabitants (Van Metre *et al.* 1997; Rio Grande/Rio Bravo Basin Coalition, 2006) reside in or near North America's largest desert (Chihuahuan) and very few people live in the vicinity of mountain snow fields. Being more familiar with the desert than mountain snowpacks, the general public has some misconceptions about the most dependable source of Rio Grande water supplies. The climate experienced by the majority of the basin populace has no significant snowfall, and snow is regarded as a novelty or a nuisance rather than a vital source of water supply. Not many people from the desert region travel to the mountain rim areas where vast amounts of snow persist in cold storage throughout the winter. Population in the Rio Grande basin is growing at one of the fastest rates in the United States. The same is true of the Mexican part of the basin. As we know now, global population and industrial growth is the root cause of climate change, and the Rio Grande basin will experience marked increases in temperature in future years. At the same time, population growth and demand for water tend to increase together. As a result, the water supply in the basin, which is already exceeded by the water demand, will remain fairly constant. The gap between water supply and demand will continue to grow. Even in an above normal runoff year, the water demand will exceed the water supply for the foreseeable future. Even more important, as the climate changes, the timing of water supply availability will shift to earlier in the year and water management flexibility for current water users will decrease. Associated with this growing demand for water is an ill-conceived public notion that when surface water is in short supply, groundwater supplies can be tapped to make up the deficit. Even if the monetary resources are available to pay for pumping water for irrigation and domestic supplies, this solution is very shortsighted because the groundwater reservoir is already being heavily mined or depleted in the basin. The small amounts of water infiltrated and percolated to the water table in any year can't serve to replenish the groundwater reservoir in a realistic time frame, even if no further pumping occurred. As further pumping takes place, the quality of water will decrease as mineral-laden groundwater is encountered.

THE EFFECTS OF TREATIES AND COMPACTS ON INTERSTATE FLOWS

The Rio Grande basin has both international treaties and an interstate river compact in force to apportion the flow of the river between countries and states. As is true of other river basin compacts in the West, e.g. the Colorado River Compact, the average flows that are usually used to calculate water rights to receive water in an average year may not be representative averages. In fact, the precipitation and streamflow totals in the first part of the 20th Century in the Southwest United States were well above normal as long term reconstructions have shown (Dole 2003, Redmond 2003). As a consequence, the so-called averages result in false expectations of what normally will be flowing in the Rio Grande and other western streams. This discrepancy naturally has a significant affect on water management in the basin and how many water rights can reasonably be satisfied from year to year. Western river basin compacts have been based on different methods to divide water in interstate basins. DuMars (1999) points out that the Rio Grande Basin Compact approach to allocations (which is based on the amount of water delivered at one or more upstream gauging points to determine the amount to be delivered further downstream, along with a sliding scale for those amounts between low and high flows) may be preferable to other approaches. Other basins use different methods, which include delivery of the same volume of water at a particular streamgauge every year, apportionment of the annual total water yield in a basin by a fixed percentage, and establishment of a specific cap on consumption by upstream states (DuMars 1999). The Rio Grande Basin Compact approach seems more flexible than these others, but as King and Maitland (2003) point out, it is impossible for one state to exactly meet its delivery obligation to a downstream state (presumably for various reasons including transit losses, errors in calculation, extreme drought, forecast problems, and Federal government priority water requirements that are unknown until late in the runoff season). As a result a system of credits and debits was included in the Rio Grande Basin Compact that can be used to adjust for water deliveries that are over and under the mandated amounts.

There are a number of streamgauges in the Rio Grande basin that are key to determining the amounts of water to be delivered downstream. For Colorado deliveries to New Mexico, those gauges are Conejos at Mogote, Los Pinos near Ortiz, San Antonio at Ortiz, and the Rio Grande near Del Norte. For deliveries by New Mexico to Texas (in actuality to Elephant Butte Reservoir), the index streamgauge is the Rio Grande at Otowi Bridge. King & Maitland (2003) provide excellent examples of Rio Grande Basin Compact accounting between the states to facilitate understanding of the calculation of deliveries in a given year. Improvement of forecasts of streamflow at the key gauging sites would help improve water management planning and reduce the absolute amount of credits/debits.

USE OF MODELING TO AID IN IMPROVING FORECASTS

It is somewhat mystifying that there has not been strong lobbying for a well coordinated effort to improve forecasts in the Rio Grande basin that would help each state meet their Compact water delivery requirements more precisely; and, at the same time, allow water users to determine earlier if, when, and how much water they will receive. Many hydrologic models exist that could be employed in this effort ranging from extremely simple statistical models to very complex, deterministic models. For the most part, statistical models have serious weaknesses in operating well in extreme runoff years, and highly complex models have a problem acquiring the necessary data to run continuously over a basin as large as the Rio Grande or even its sub basins. Compromises between statistical and complex models may very well be the answer in this and similar basins. The model or models eventually used need to forecast ahead by several days, weeks, months, and an entire year as well as provide long-range runoff scenarios under conditions of future climate change. Without developing new models, existing models could provide an improvement over a conservative approach currently used which relies primarily on the amount of water stored in reservoirs on a given date. Such an approach does not consider future flow contributions to the river or to reservoirs.

The most important area for water yield is where mountain snowpack accumulates year-to-year in winter in preparation for spring snowmelt runoff. In these mountain snow areas, the Natural Resources Conservation Service has established SNOw TELemetry (SNOTEL) automated sensors to acquire snow water equivalent and snow depth information in addition to temperature and precipitation data. Although the SNOTEL sites and data were established for use in statistical seasonal runoff forecasts, these data also have merit for inputs to other hydrological models, if placed in representative locations. Because the location of the snowpack in the basin can vary and determines where snowmelt can occur, another type of data has gained favor, namely, satellite snow cover data. Satellite snow cover data based on elevation zones has been used in the Rio Grande for simulation and forecasting of snowmelt runoff since the mid-1970s (Rango 1980; 1983).

Initially Landsat data (80m resolution, 18 day repeat interval) were employed, but subsequently, because of a need for more frequent observation, NOAA-AVHRR data (1000m, daily) were utilized and more recently, the MODIS data products were found to be optimum (250m, daily) (Rango *et al.* 2004). Figure 3 shows an example of MODIS derived snow cover over the Rio Grande near Del Norte, CO on about March 15 in three different runoff years (2003 drought year; 2004 below average year; and 2005 above average). The first attempts to incorporate Landsat data were for seasonal runoff volume forecasts using regression analysis on both Rio Grande near Del Norte, CO and the South Fork of the Rio Grande (Shafer *et al.* 1981). Subsequently, the snow cover data from Landsat, NOAA-AVHRR, and MODIS were input into the Snowmelt Runoff Model (SRM), the first model designed to accept remote sensing data inputs directly (Martinec *et al.* 1998). Snow cover area is mapped for input to SRM by elevation zones as is shown in Figure 4 for the Rio Grande near Del Norte, CO. Through remote monitoring of the declining area of snow cover in the basin or in an elevation zone, the daily amount of snowmelt available for runoff can be calculated through use of either a degree-day approach or a radiation balance approach, depending on the input data available. The degree-day SRM approach is more simple and probably more suited to operational implementation in river basins. SRM has been evaluated independently against other snowmelt runoff models by the World Meteorological Organization and found to perform equally well or better than the other hydrological models evaluated (World Meteorological Organization 1986). Figure 5a shows the comparison of the forecast and observed flows on the Rio Grande near Del Norte, CO for 2001 with no updating after April 1. Figure 5b shows the resulting comparison with a daily updating with the observed flow at the streamgauge. The R^2= 0.773, which is the amount of variation in the daily flows explained by SRM, and the difference in season volume (Dv) of 16.78% in Figure 5a are reasonable considering that no updating was done after the April 1 forecast. Updating serves to improve this result.

SRM has several advantages for operations. It uses only real observed data: precipitation, temperature and snow cover. It does not use synthetic data derived by models for use in other models. It is not a calibration model so that no optimization of model parameters takes place. Model parameters are obtained from actual observations or from hydrologic knowledge of the investigator. This permits SRM to be used effectively in climate change analysis or long term projections; according to Becker & Serban (1990) and Klemes (1985), calibration models are not well suited for evaluating the hydrological effects of changing climate. SRM is the only model that currently incorporates a formalized climate change algorithm. Finally, SRM is simple to understand and operate by a wide variety of users. It also has significant documentation of how to apply the model as evidenced by its User Manual (Martinec *et al.* 1998) and the fact that it has been applied successfully in over 100 basins worldwide with over 80% of these applications having been performed by independent users (Rango, unpublished data). SRM is efficient with an annual daily simulation or forecast being accomplished in seconds so that multiple runs are possible, and it has performance evaluation criteria imbedded in the model to assist the user in interpreting the model results.

Not all parts of the Rio Grande basin produce snowmelt runoff. SRM can operate in a rainfall dominated basin, but because SRM does not possess a capability to incorporate the effects of diversions and reservoirs on flow, it is probably wise to select a model that takes account of water management decisions while also being able to operate in the rainfall dominated lower reaches of the Rio Grande basin where most water management takes place. SRM has been linked to such a model, the Semi-distributed Land Use Runoff Processes (SLURP) model (Kite, 1998) which has been modified to accept runoff output from SRM as input. SLURP can be divided into hydrological response units for operations where remote sensing is also used to provide input variables. The landcover of each of these hydrological response units is determined from remote sensing data for use by SLURP in runoff generation. Remote sensing also is used to determine vegetation spectral indices for SLURP calculations of vegetation leaf area and evapotranspiration. After calculating runoff from the hydrological response units and receiving channel inputs from SRM in snowmelt basins, SLURP 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 management scenarios concerning possible future conditions while adequately simulating existing conditions. The linkage of SRM and SLURP has been successfully tested (Rango *et al.* 2004).

POTENTIAL WATER YIELD CONSEQUENCES OF CLIMATE WARMING ASSESSED WITH A SNOWMELT RUNOFF MODEL

A number of studies have been performed to assess how water supply and management will be affected by future climate change, generally employing hydrological models (Leavesley, 1994; Stewart *et al.* 2005, Rango *et al.* 2003, Rango & Martinec 2000, Rango 1992, 1995, 1997). The results of these studies are fairly consistent qualitatively in that warmer temperatures will convert some snowfall events to rainfall, thereby reducing snowpack accumulation, more runoff will occur during winter and less during summer than previously observed, and the snowmelt runoff peak flows will be shifted to earlier in the year. In all cases, the increase in temperatures in response to an enhanced greenhouse effect is commonly agreed upon, whereas changes in precipitation are much debated with both increases and decreased predicted.

The primary water supply catchment in the Rio Grande basin is the Rio Grande near Del Norte, CO (3219km^2) (Figures 3 and 4), which is also a key gauging point for determination of Colorado water deliveries to New Mexico under the Rio Grande Basin Compact. To illustrate the changes in flow that might occur in this important basin, just two scenarios were selected: Scenario 1—Temperature increase of +2.5°C, precipitation increase of 7%; Scenario 2—Temperature increase of +5°C, precipitation increase of 7%. Scenario 1 seems most likely to occur by 2050-2060 and Scenario 2 by 2100-2110. After inputting these changes to SRM, the model automatically calculates the changed hydrograph based on a normalized year using data from 1957-1994. Figure 6 shows the change in snow cover depletion by zone in the Del Norte basin to be expected under the climate conditions of Scenario 1 applied to the normalized year. It is evident that two upper elevation zones (B and C) will have diminished snow cover, whereas the lowest elevation zone (A) loses its snow cover almost entirely by April 1 and must rely on rainfall to produce runoff. Figure 7 presents the SRM simulation of the annual runoff hydrograph compared with the SRM climate change hydrograph under both the conditions of Scenarios 1 and 2. It is evident that more snowmelt runoff occurs during winter, much more runoff occurs during April and early May as a result of an earlier melting of the snowpack, and that for the rest of the summer after about May 15, the runoff is reduced considerably by the early removal of the mountain snowpack during the exact time when basin water demand is the highest. Figure 7 shows that by the 22nd Century when Scenario 2 is likely, the effects on the hydrograph are markedly enhanced as temperatures continue to rise and peak flows are significant in April when the Del Norte basin has relatively modest flows under current conditions. In fact the snowmelt runoff peak for Scenario 2 is about 5 weeks earlier than for the normalized year, whereas the onset of snowmelt has moved from mid-April to the beginning of March. Table 1 shows the change in monthly flow volumes on the Rio Grande near Del Norte, CO for both scenarios. The largest increase in percent of monthly flow occurs in April for Scenario 1 and in March for Scenario 2. The largest decrease occurs in July in both scenarios.

These effects will definitely change how agencies manage water supplies to meet the needs of users with prior appropriation rights (while the owners of the rights are also changing as water right purchases increase). Compact deliveries will also change if only by the fact that water flowing in the stream channel throughout the year will be different and delivery timing will change. Will water users be able to use their water rights earlier in the year, perhaps as early as winter? Will water managers be able to continue operations as normal without affecting reservoir storages and releases and not changing reservoir operating rules? Can the states continue to operate the Rio Grande Basin Compact without incurring large deficits and surpluses that will require changes to the Compact itself? Future planning needs to use scenarios like those here in a whole range of water years in addition to a normalized year in order to develop a plan of how management strategies and infrastructure will need to change as the climate changes to meet the requirements of New Mexico. Tributary basins to the Rio Grande in New Mexico, like the Jemez basin, will be affected to an even greater extent because of the more southerly location compared to Del Norte. As a result, snow accumulation in the New Mexico basins will be reduced even more and snowmelt will occur earlier in the year.

DISCUSSION

It is evident that conditions are changing in the Rio Grande basin. Population is increasing at one of the fastest rates in North America. Prior appropriation water rights are changing hands as agricultural rights are purchased for domestic water supply. The gap between water supply and water demand continues to grow. The climate is also changing, and even more severe problems than today will occur in the next 50-100 years. Water management agencies need better information about what is happening today as well as better forecasts for the future, both short and long term. Hydrologic models are the logical vehicle to use to improve forecasts. All models are not equal, however. In general, most models are best used for specific purposes and each individual model may be able to clear up part of a water resources problem, but not the entire problem or set of problems. Statistical regression models are good for a particular problem, e.g., seasonal runoff volume forecasts early in the year, even before snowmelt has started (DeWalle *et al.* 2003). Physically based, deterministic models work best on small basins where adequate data exist to drive the model. These types of models are best for determining the potential effects of treatments that will change different hydrologic processes in the basin. The size of the basin is critical because of the sometimes major data load required by many of these models. In snowmelt runoff areas, a proven model, e.g. SRM, that accurately produces snowmelt runoff that has been validated is very critical for operational use. Channel models are required for moving virtual water downstream through a complex series of structures, divisions, and storage dams. In order to take all these types of models into consideration, an overall hydrologic model that can integrate these various functions in required. A model like SLURP that can incorporate output from some of the specific models as well as calculate various hydrologic components unaddressed by other models is very valuable to make progress in forecasting as well as address the consequences of difference management strategies.

CONCLUSIONS

The Rio Grande basin is a large and complex catchment extending from high alpine snow accumulation and significant snowmelt runoff generation areas to low elevation deserts where rainfall generated streamflow is only available for short time periods and distances characteristics of scattered connective rainfall events. In the upper Rio Grande basin mountains, from 50–75% of the annual flow is generated by snowmelt depending upon the year. Because the majority of the population lives in or near the lower Chihuahuan Desert, the critical role of snow as a major resource is not widely recognized. To improve water management, improved forecasts and simulations are needed using a combination of new measurement technologies like remote sensing, SNOTEL data relay, and hydrological models. All these elements are currently in place and validated and should be exploited to the maximum. The use of these approaches can also be employed to evaluate the future effects of climate change on the water supply of the Rio Grande. The improvement of both current and long range forecasts are vital to assisting water management decision making for the benefit of the rapidly growing population in a time of increasing water supply / water demand deficit. Once an improved system is in place, we can use the improved hydrologic information to objectively make decisions regarding controls on population growth, cost of water, and the type of conservation measures that need to be implemented.

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FIGURES AND TABLES

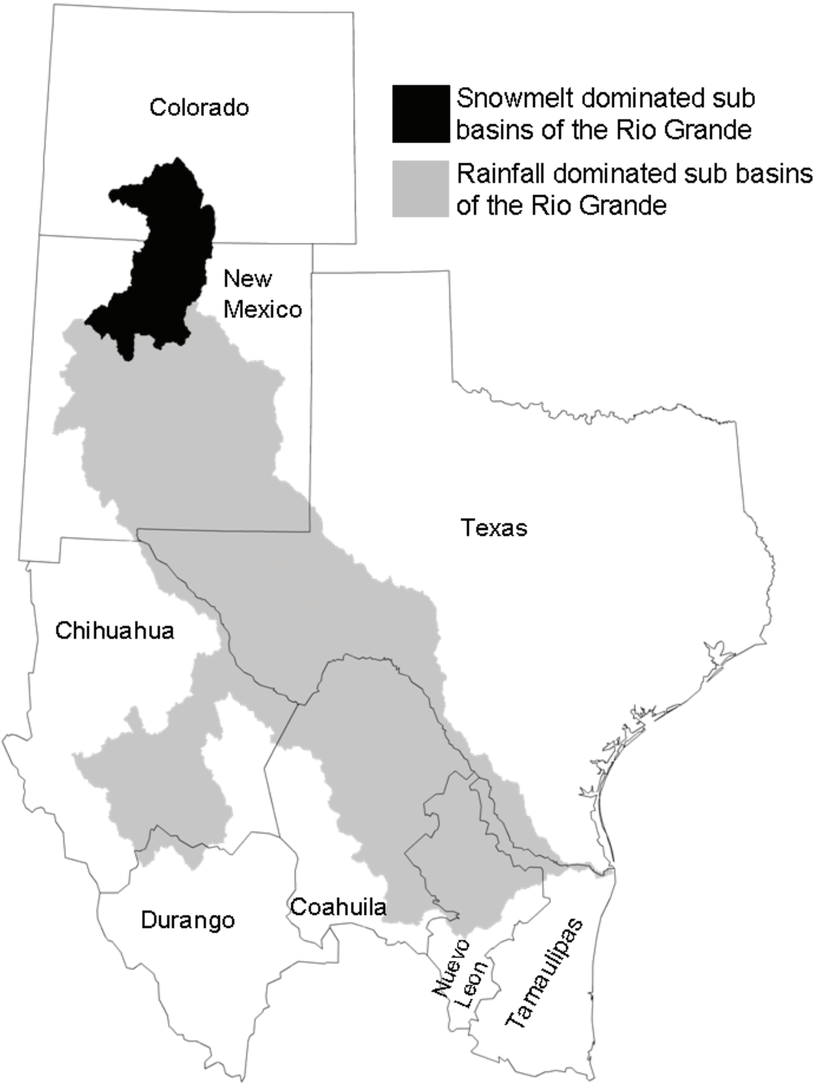
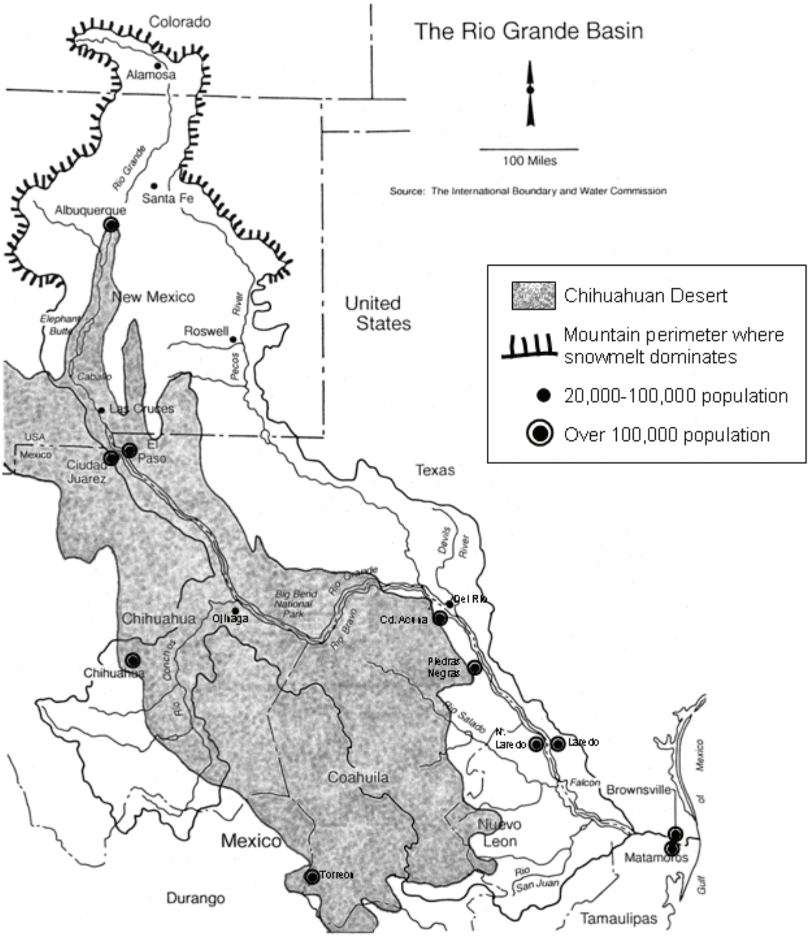


Figure 1. Snowmelt vs. rainfall dominated runoff areas of the Rio Grande in the United States and Mexico. The upper shaded part of the basin in southern Colorado and northern New Mexico supplies 50–75% of the total streamflow in the Rio Grande, primarily derived from snowmelt.


The Rio Grande Basin

Source: The International Boundary and Water Commission

Figure 2. The superimposition of the Chihuahuan Desert, the Rio Grande watershed, population centers, and the mountain perimeter where snowmelt dominates highlights why more emphasis is needed on snowmelt runoff forecasting.

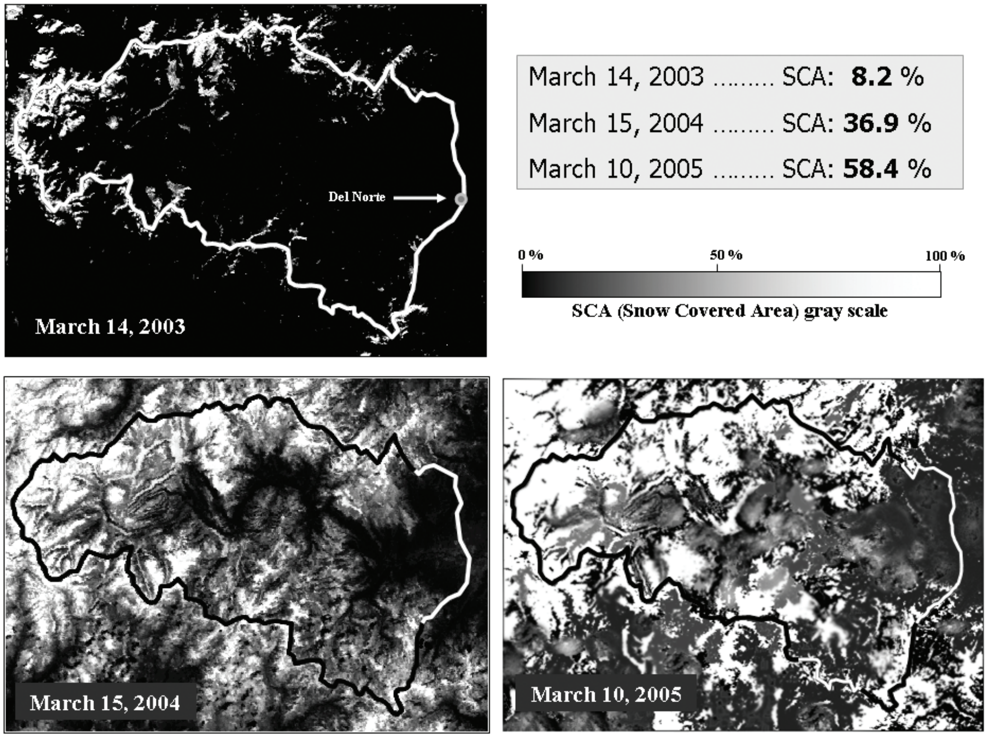


Figure 3. Comparison of MODIS snow cover maps on the Rio Grande near Del Norte, CO around March 15 for consecutive years 2003, 2004, and 2005 shows the variability possible in years ranging from drought (2003) to above average runoff (2005).

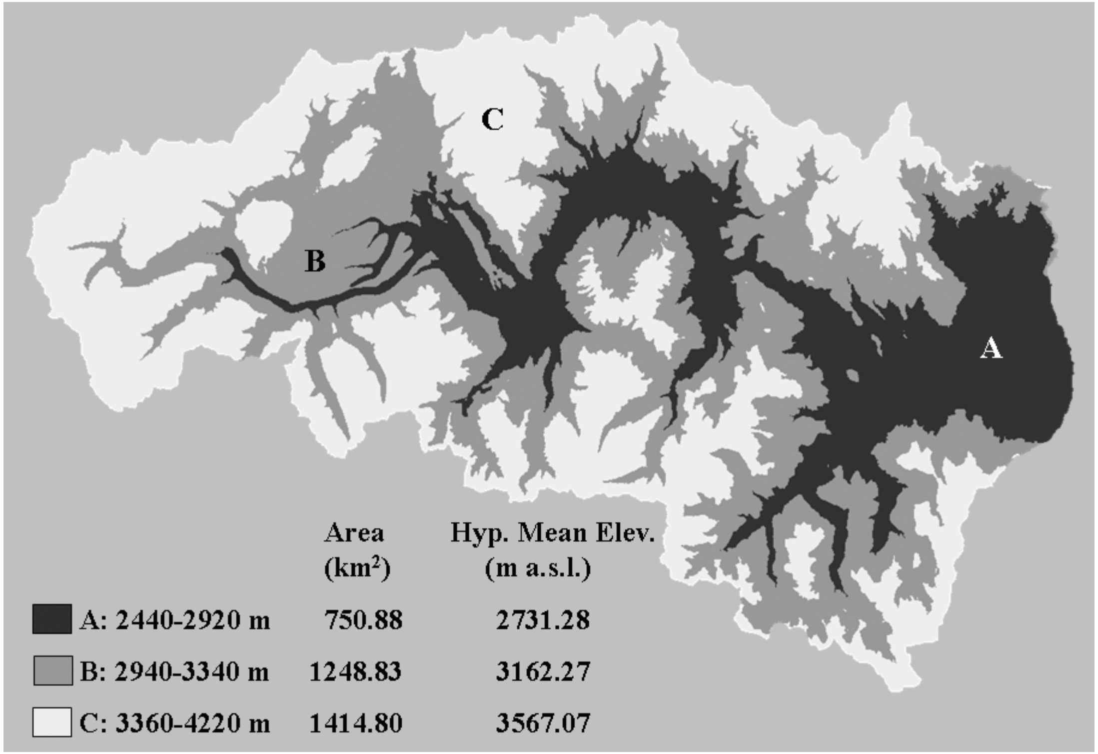
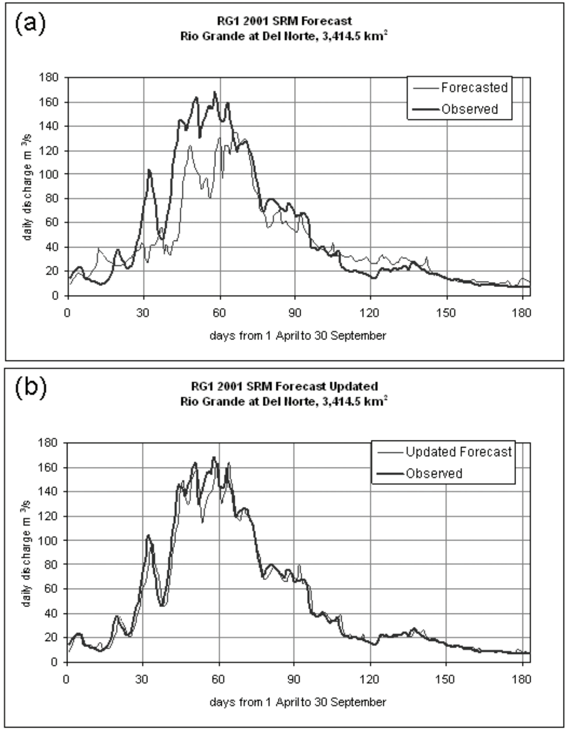


Figure 4. Elevation zones in the Rio Grande near Del Norte, CO (area=3415km^2) used for mapping snow covered area for input to SRM.



1 April to 30 September:

Forecasted vol. = 692.1 Hm^3
Observed vol. = 808.2 Hm^3

$R^2 = 0.773$
Dv = 16.78 %

1 April to 30 September:

Updated Forecast vol. = 786.9 Hm^3
Observed vol. = 808.2 Hm^3

$R^2 = 0.971$
Dv = 2.70 %

Figure 5. SRM forecasts of snowmelt streamflow on the Rio Grande near Del Norte for (a) starting on April 1, 2001 with no updating for six months, and (b) with updating every day using observed daily streamflow.

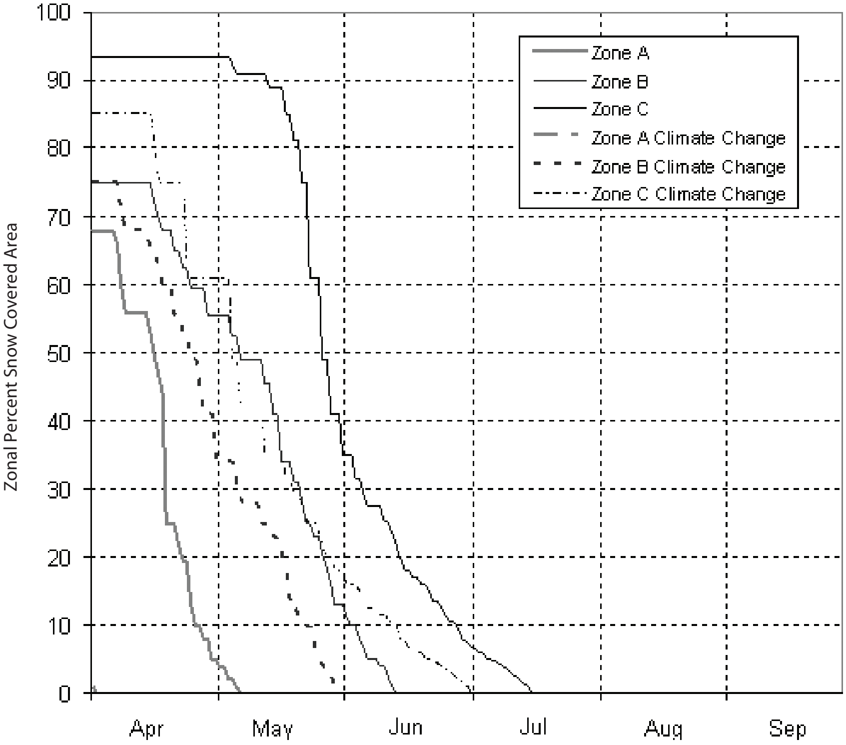


Figure 6. Snow cover depletion curves of a normalized year versus the same year modified by a climate change of +2.5°C and +7% precipitation for elevation zones A, B, and C on the Rio Grande near Del Norte, CO.

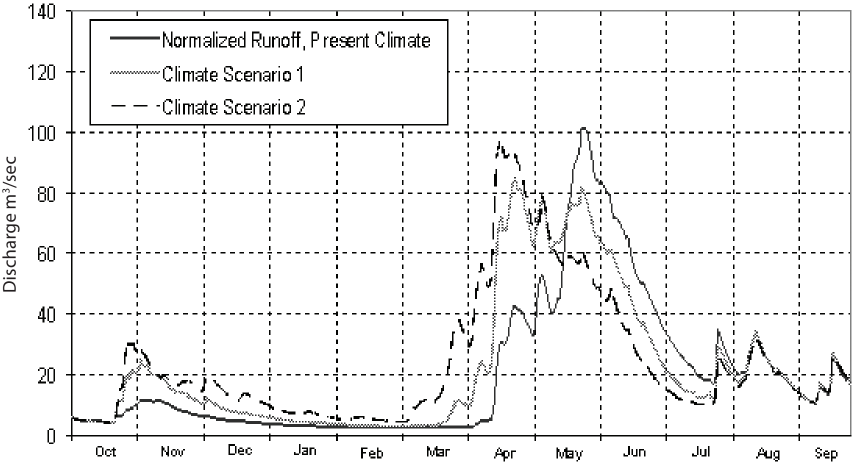


Figure 7. Comparison of the daily measured or simulated hydrograph for a normalized water year with the hydrograph resulting from climate changes of +2.5°C and +7% precipitation (Scenario 1) and +5° C and +7% precipitation (Scenario2).

Month	**Normalized Yr. Volume**	**Scenario 1 Volume**	**Scenario 1 % Change**	**Scenario 2 Volume**	**Scenario 2 % Change**
October	15.30	22.72	+ 48%	28.91	+ 89%
November	24.61	43.42	+ 76%	50.39	+ 105%
December	12.81	21.96	+ 71%	36.51	+ 71%
January	8.64	12.17	+ 41%	19.72	+ 128%
February	6.53	7.84	+ 20%	12.70	+ 94%
March	6.77	11.83	+ 75%	37.33	+ 451%
April	47.21	113.62	+ 141%	171.77	+ 277%
May	164.71	189.57	+ 15%	170.17	+ 3%
June	172.03	130.04	- 24%	94.09	- 45%
July	70.73	47.01	- 36%	35.30	- 50%
August	66.18	62.83	- 5%	59.10	- 11%
September	40.79	42.06	+ 3%	41.41	+ 2%

Table 1. Normalized year monthly volume (106m^3) of flow at the Rio Grande near Del Norte, CO compared to the monthly flow from climate change Scenarios 1 and 2 and the percent change.

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