***Albert Rango** is a research hydrologist with the USDA-ARS Jornada Experimental Range in Las Cruces, NM. He has B.S. and M.S. degrees from Penn State University and a Ph.D. from Colorado State University. Al has over 350 publications in the fields of remote sensing, rangeland applications, watershed management, and snow hydrology. He is a past president of the IAHS International Commission on Remote Sensing, the American Water Resources Association, and the Western Snow Conference.*

FUTURE CLIMATE CHANGE IMPACTS ON NEW MEXICO'S MOUNTAIN SOURCES OF WATER

Albert Rango
USDA-ARS-Jornada Experimental Range, Las Cruces, NM
Enrique Vivoni, New Mexico Tech, Socorro, NM
David Gutzler, University of New Mexico, Albuquerque, NM
Brian Hurd, New Mexico State University, Las Cruces, NM
Stephanie Bestelmeyer, Chihuahuan Desert Nature Park, Las Cruces, NM

I am going to talk to you about a project Dave Gutzler mentioned earlier whose goal is to study the possibilities of what is going to happen as a result of future climate change and how that is going to impact New Mexico's mountain sources of water. I hope to tell you why that is important. I do want to point out, based on earlier discussions at this conference, that the three major research universities in New Mexico are just working together happily—Aggies, Lobos, and for want of a better word, the Techsters. The reason I don't know their nickname is because they, surprisingly, have no NCAA varsity sports at that school. I've also discovered when going to meetings there that they have no requirement for parking permits on campus. I don't know what this world is coming to with no nickname and no parking permits. In any event, we are working well together and hoping that this project goes forward. It is an EPSCoR project, which is being submitted to the National Science Foundation, so it is not yet finalized. If successful, it will be funded for a five-year period. I am going to outline to you what that involves and show you some early results because we have been working on this research topic.

You saw this slide already from Dave Gutzler. I don't have to go over it. I will just confirm what others have said: it is going to get warmer here in New Mexico. Dave has explained this quite nicely. He has also shown you this slide (see Figure 1). I just want to indicate that this is the Del Norte basin in Colorado on the Rio Grande and the most highly productive tributary in the Rio Grande basin. As a result of this increase in warmth, the snowline is going to retreat to higher elevations. As Dave Gutzler mentioned, the depletion curve of snow covered area in the lowest elevation zone in the Del Norte basin—will go from what it is today in this particular year to virtually zero snow cover in future years. All these other elevation zones higher up will experience decreasing snow cover. This was generated from a test, with a model that I will talk about later, using a two and a half degrees Celsius warming. It is going to become very important, and as we have seen earlier, this warming has already begun and will continue.

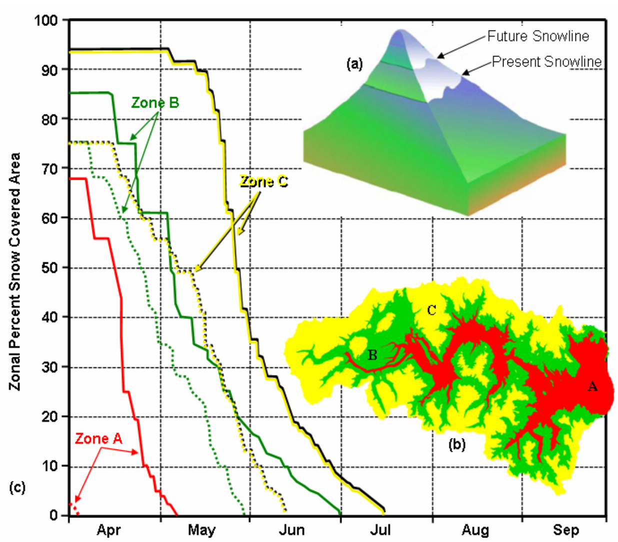


Figure 1. Remote sensing and the Snowmelt Runoff Model have been used to analyze climate change impacts on snow covered area and the resultant effects on water supply derived from the snowmelt.

There are a number of important aspects of this problem of water supply forecasting as shown in Figure 2 (courtesy of R. Abramovich, NRCS, Boise, ID). Water forecasters have a problem early on in any particular year coming up with volume forecasts. Following the volume forecasts, they are then asked to do peak-flow forecasts and then eventually low flow forecasts. The users are very dependent on these forecasts. When they reach the time of low-flow forecasts, people are starting to ask what will happen next year. Water users and managers have a real problem in knowing what the water supply will be in the future, and we would hope to help in this area as well. One of the things that forecasters do is look at the El Niño/La Niña phenomena. In Figure 3 (Courtesy of D. Gutzler, UNM), you can see that it means different things in different parts of the west. In the Idaho area and in other parts of the northwest, El Niño means a very dry year for them, whereas, in New Mexico and parts of Arizona and Utah, an El Niño year is a nice thing if you like above normal runoff. The forecasters have told me that they do not want to put all of their eggs in one El Niño basket when forecasting, so they need additional techniques. I'll show you a little bit of what happens here.

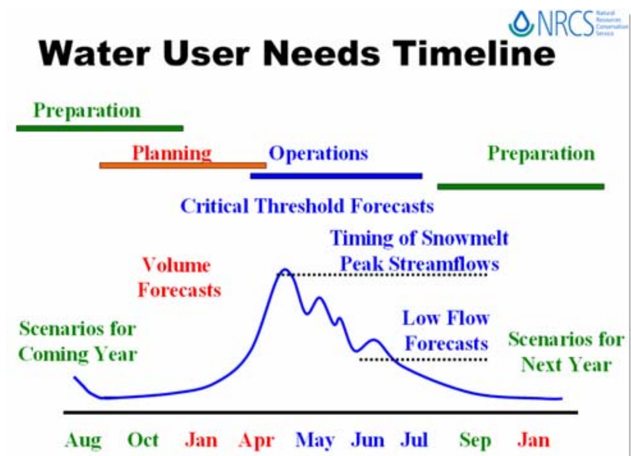


Figure 2. Water user needs timeline that results in different types of forecasts.

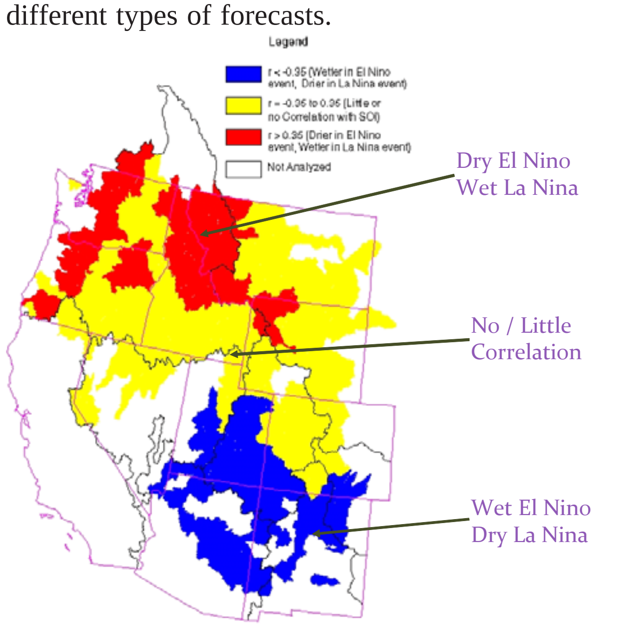


Figure 3. El Niño phenomena in the West as it impacts water availability.

We've mentioned throughout this conference that the snow cover is going to decrease, and we might be more reliant on the monsoon season in the summer for some of our water supply. If we look at this particular map, also from Dave Gutzler, it shows that we are very reliant on the snowpack accumulation, but we have learned to be flexible in the summer as well. This slide (Figure 4) shows the percent of annual average precipitation that occurs in July through August. You see that less than ten percent occurs in the upper northwest and Idaho, whereas parts of Colorado and Arizona and most of New Mexico can experience up to 40, maybe even 50, percent of their total annual precipitation during this time of year. As an example, back in 2006, it was an extremely good monsoon year in New Mexico. You can see that New Mexico in the monsoon season was 150 to 200 percent of normal. What resulted from the high monsoon precipitation was a lot of runoff. It blew out arroyos in Hatch and caused a lot of turmoil in the form of flood damage. During that period, Elephant Butte Reservoir, which is usually releasing water then so that the water level is going down, actually stabilized and experienced a slight increase in the water volumes stored there. We need to take a look at this for a lot of the streams in the southern part of the state to see if we can be ready to catch this flow. It was mentioned in a couple of the talks earlier.

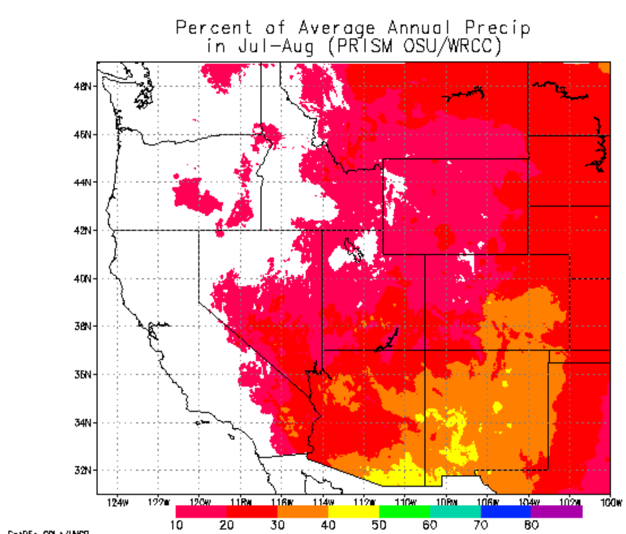


Figure 4. Percent of average annual precipitation occurring in July - Aug (PRISM OSU WRCC) for different western states.

Let's look at the Rio Grande in Figure 5. This is the area that we are focused on. It covers two countries and eight different states, including the Mexican states. The river length is about 1,900 miles, the third longest in the U.S. The drainage area is about 336,000 square miles. It includes the Pecos and a major tributary in Mexico, the Rio Conchos. The lower two-thirds or three-quarters of the basin receives only seven to fifteen inches of precipitation a year. Another look at this in Figure 6 shows that the major population areas are somewhere near or along the Rio Grande. If we overlay the Chihuahuan Desert, which is North America's largest desert, we see that the Rio Grande actually flows through a lot of the Chihuahuan Desert and past these high population areas. If we look further, we see that along the northern perimeter of the basin, the red area, is where a large portion of our runoff comes from that makes its way down the Rio Grande. It does dry out below El Paso, but because of the tributaries coming in southeast of El Paso, the flow of the river resumes. There is a public misconception of the importance of snow to the water flow because few people live in the snowmelt areas, whereas a preponderance of people lives in the desert portion of the Rio Grande.

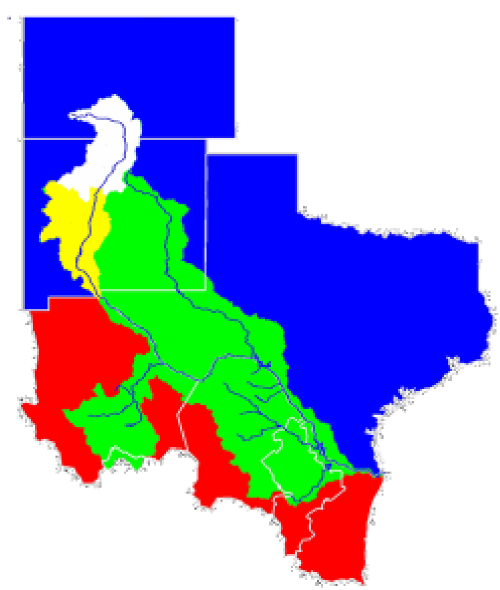


Figure 5. Characteristics of the Rio Grande: 2 countries, 8 states; river length 1,900 miles; 3rd longest in the U.S., 21st longest worldwide; drainage area: 336,000 mi^2; which includes Pecos River and Rio Conchos; lower 2/3 of the basin receives only 7-15 inches of annual precipitation

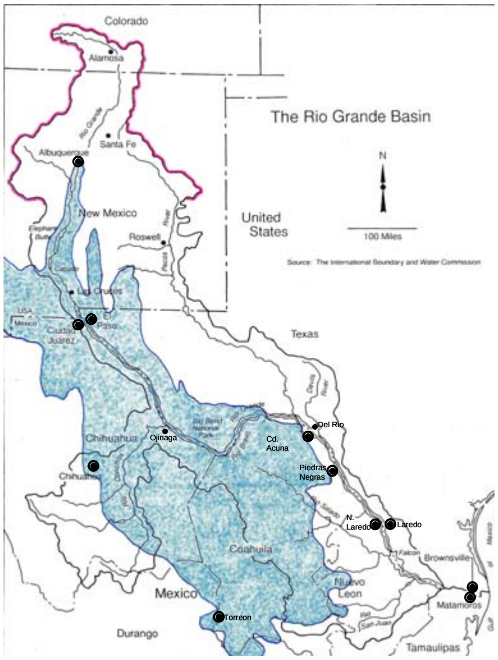


Figure 6. The relative locations of population centers (20,000-100,000 and over 100,000) and water supply source areas (in red) in relation to the Rio Grande main channel and the Chihuahuan Desert (in blue) results in a public misconception of the importance of snow.

The reason that snow is so important is that it accumulates for the entire winter and then it melts off in a very short period of time, from several weeks to a month or month and a half. The snowmelt runoff, because of this, is a very efficient runoff process, more efficient than rainfall runoff. In the mountainous areas, the soils are relatively thin, and as a result, not much of the water percolates to the groundwater reservoir at the higher elevations. Most of the high mountain snowmelt makes its way to surface runoff. In the Rocky Mountains, about 90 percent of the total runoff results from snowmelt. In the upper Rio Grande, it is down to about 75 percent because we are further south. Around the world, some of the mountain basins have 99 percent of their runoff coming from snowmelt. The contribution of snowmelt is going to change here in New Mexico first, actually. If we examine different parts of the basin, in the Colorado portion, the snowmelt contribution averages about 51 percent and can exceed 75 percent in specific tributaries. If you go further south into the northern New Mexico tributaries of the Rio Grande, about 35 percent of the runoff comes from snowmelt, which could vary between 16 and 60 percent. There is even a small snowmelt component down around Elephant Butte.

Figure 7 shows the basins we are going to study. You'll see that the Colorado-New Mexico boundary is here. These are the basins, the Rio Chama and the Rio Hondo, that we are going to look at in great detail with additional instrumentation and field studies. We will investigate all the shaded basins because they have a significant snowmelt component at present. Using remote sensing data, we will be looking at the tributaries in Colorado as well. The most productive tributary is the Rio Grande near Del Norte, Colorado. The Conejos River basin is another very important snowmelt runoff basin, and then all these other basins that I identified in Figure 7. The study basins where we will be doing extensive instrumentation will be the Rio Chama, the Rio Hondo, and, because of prior studies there, the Jemez River basin. You will see that different watershed models will be running in these different areas.

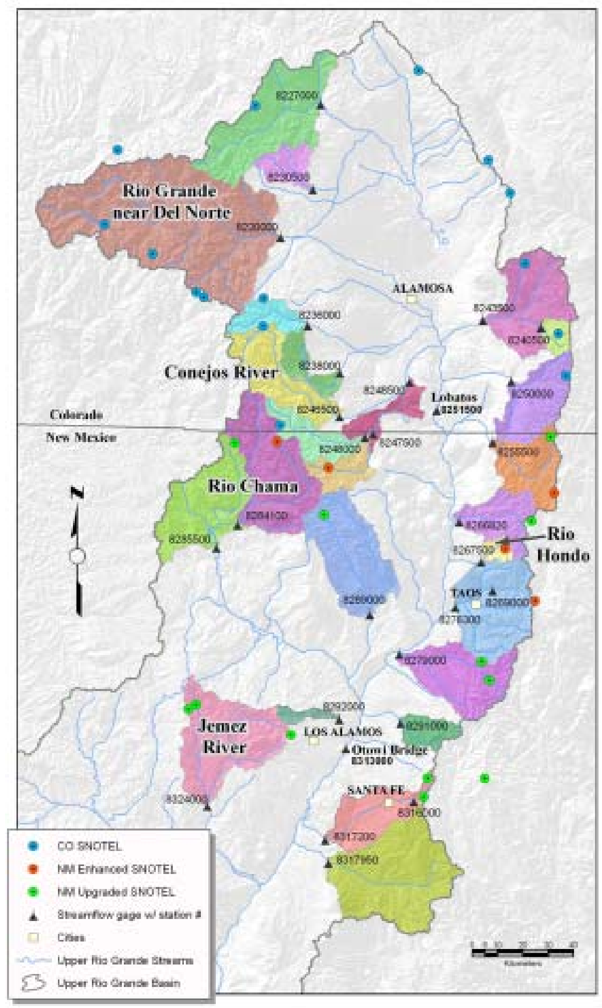


Figure 7. Significant snowmelt runoff basins in the upper Rio Grande used to evaluate the potential effects of climate change

We are going to be using remote sensing data as input to several of the different models. The first model (shown in Figure 8, courtesy of Enrique Vivoni, NMT) is one that is being developed at New Mexico Tech, tRIBS, which is a distributed hydrologic model that is very detailed and works on a very small grid size and requires a lot of data on soil moisture, infiltration, heat fluxes, radiation and energy balances, interception, and evaporation. Because of that, it is a very data-intensive model, and it can only run currently on relatively small tributaries. In addition to streamflow generation, we learn a lot from this model about the different processes that are important in a particular basin and what is happening to them as the environment changes. Enrique Vivoni has recently also modeled the winter part of the hydrologic cycle with tRIBS. This particular portion of the model is what we will be testing in these snowmelt basins.

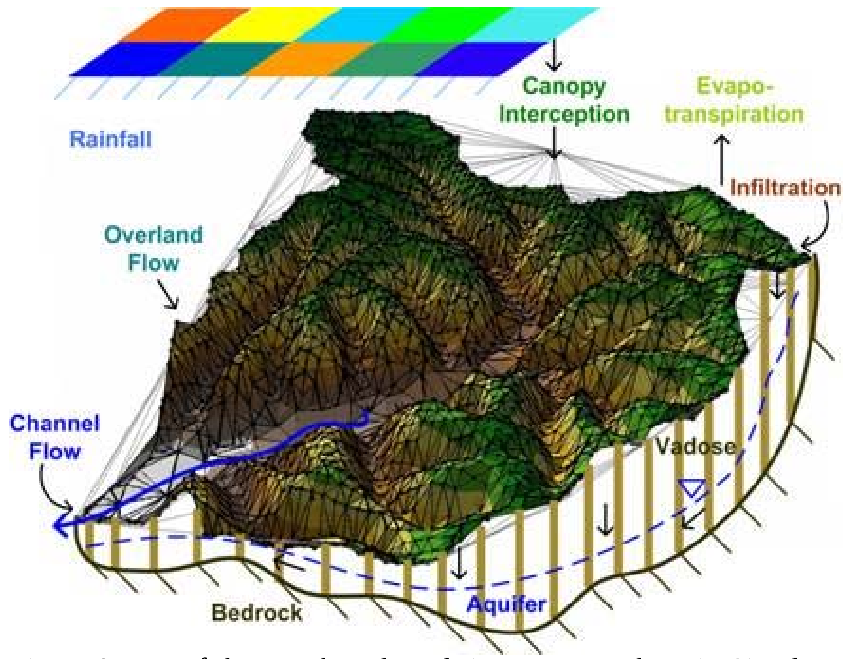


Figure 8. Use of the TIN-based Real-time Integrated Basin Simulator (tRIBS) for distributed modeling of coupled hydrologic processes in complex basins.

Another one that I know more details about is this snowmelt runoff model (SRM) shown in Figure 9. It is a model that requires three major inputs: temperature, precipitation, and remotely sensed snow covered area. In addition, it was one of the few models that was designed with remote sensing in mind. In recent years, it has added a formalized climate change algorithm. If you give me a scenario of how the precipitation and temperature would change in a new climate regime, the model can then run a climate change scenario for you and give you a change in basin runoff as a result of climate change. We have done this on a number of basins. First of all, SRM has been tested mostly on basins, like the basins chosen for this study that I showed you in Figure 7 that range from 100 square kilometers to about 10,000 square kilometers in area. It has been tested around the world on about 120 basins. It is capable of producing for the user the percent of runoff coming from seasonal snowmelt, from new snow melting, from rain, and from ice melt as shown in Figure 10. This particular model in Switzerland has a glacial component that we do not need here. When working with SRM, we are using the MODIS satellite sensor data. It is input for deriving the snow cover depletion curves that we talked about earlier that will change with warmer conditions. The snow cover is directly input into the SRM model along with the temperature and precipitation.

Figure 11 shows a comparison of the MODIS snow mapping for the Rio Grande near Del Norte. It shows you that in the middle of March in 2003, there was relatively little snow cover in the upper elevations, more snow in 2004, and 2005 in this particular basin was a relatively good runoff year. It shows about 59 percent snow covered area. It shows you that snow cover can vary from year to year. It can be very important generating runoff.

Not going into all of the details here, it is sometimes asked why we use snow cover and not snow water equivalent. We use snow cover from existing satellites on a very repetitive basis, so we chose to go that route because we can keep track of the snow with time in the basins and you can only melt so much snow on a given day. If the satellite passes are relatively frequent, we keep up with the changes in the snow covered area. The problem with trying to do it for snow water equivalent is that it is very difficult to get areal coverage of snow water equivalent. Secondly, models that calculate snow water equivalent do it in a flawed way

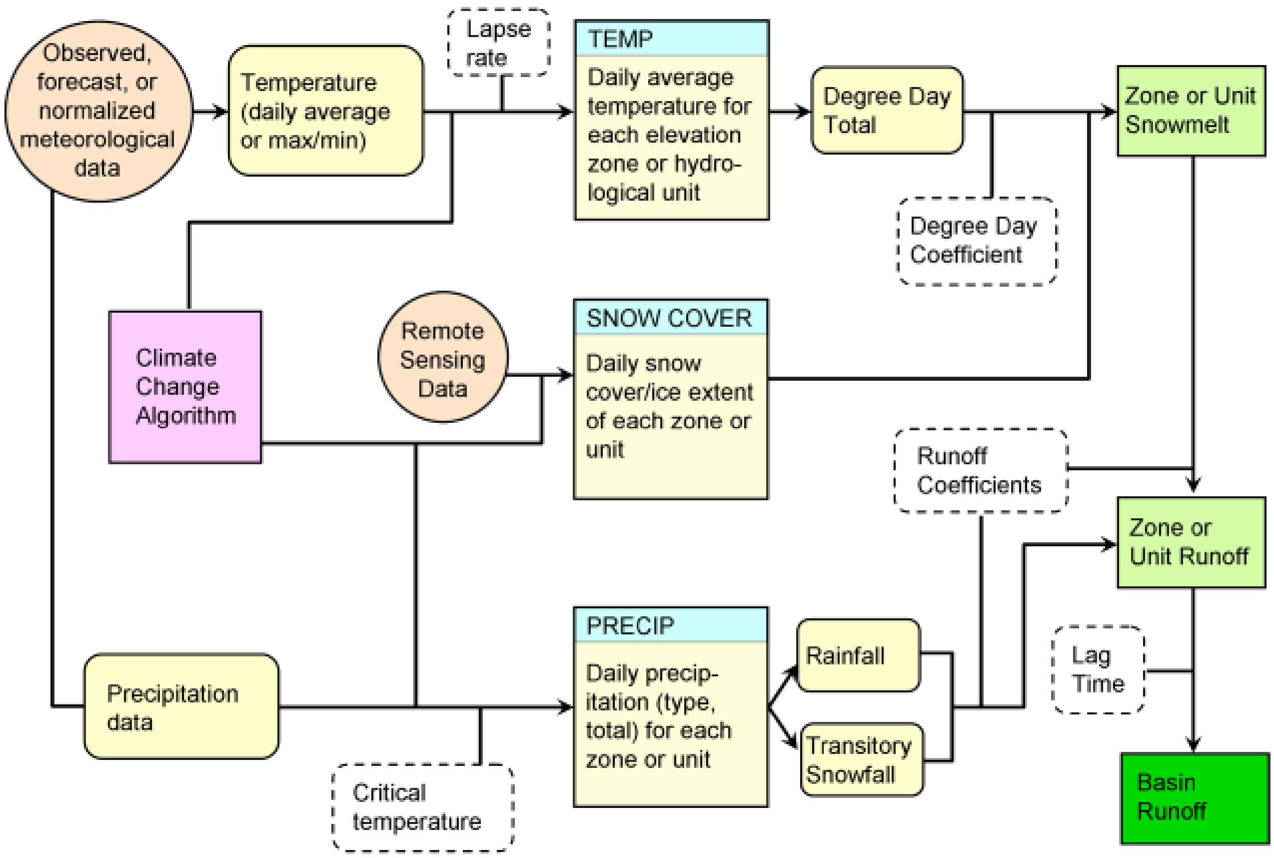


Figure 9. Schematic diagram of the organization of the Snowmelt Runoff Model (SRM)

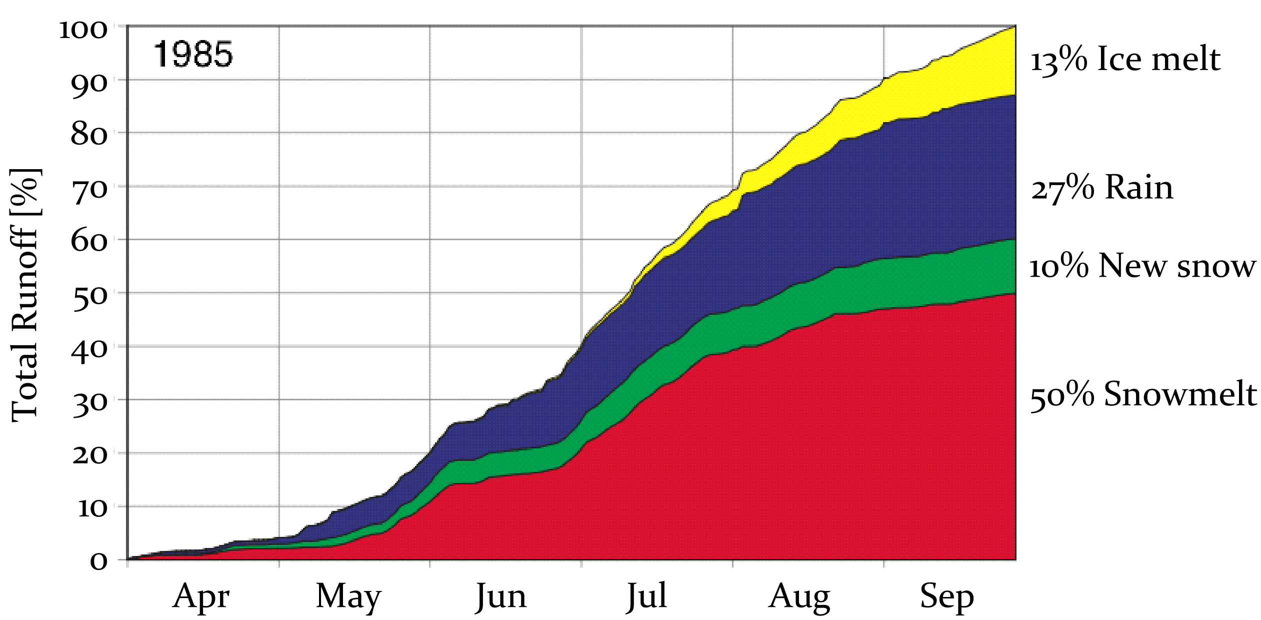


Figure 10. Contributions of runoff components in the basin Rhone-Sion (3371 km^2, 491-4634 m a.s.l.) as determined by SRM

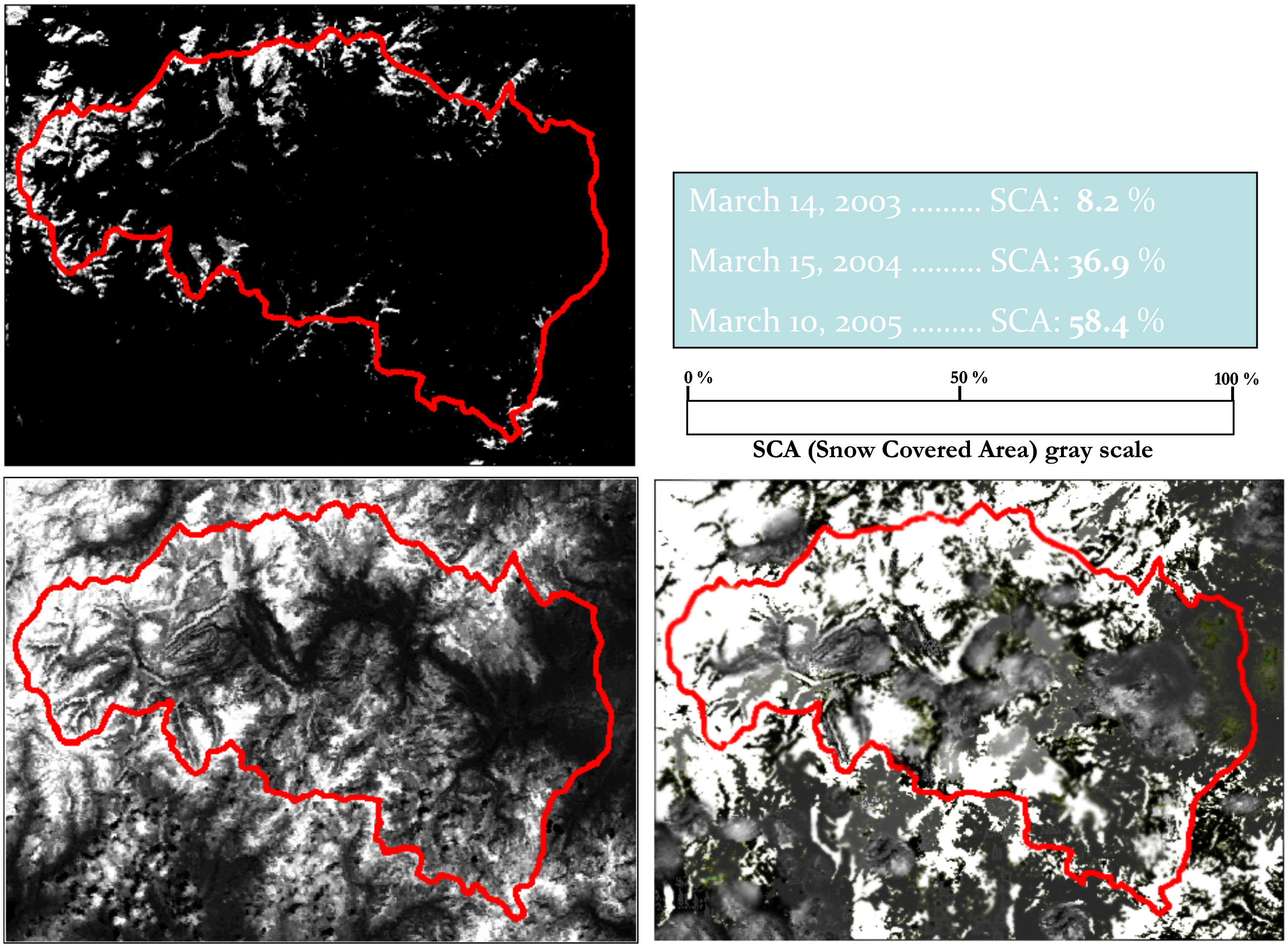
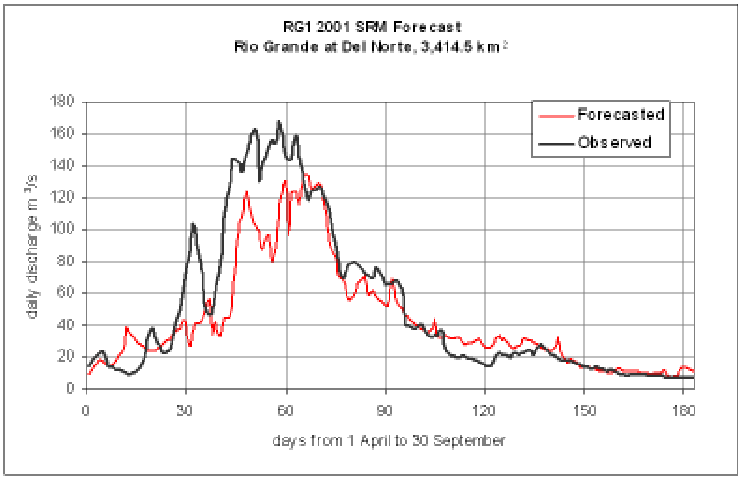


Figure 11. MODIS snow mapping for the Rio Grande at Del Norte Basin (3,415 km^2) near March 15

because they use precipitation data they have at gauging stations and do not correct for the wind-caused undercatch that these gauges experience up in the higher elevations. Without the catch-deficit correction, the model parameters then have to be tweaked later to account for that. We prefer to use the real data from snow cover rather than generate snow water equivalent and have to correct the model later.

In any event, we used the model for forecasting in 2001 on the Del Norte basin as shown in Figure 12. The dark line in this slide is the actual flow, and the red line is the forecasted flow starting on April 1 and never updated after that date. We were able to explain about 77 percent of the variation in the daily runoff through this six-month period with SRM. If we updated it with the actual flow from the day before, we, of course, get a much better fit at about 97 percent of the variation explained. We think that we can do this on nearly all of the snowmelt basins here in Colorado and New Mexico because SRM has been tested in this manner around the world in basins just like this. It has worked in every case. We are hoping to expand this to the other basins when the ESPCoR project starts.

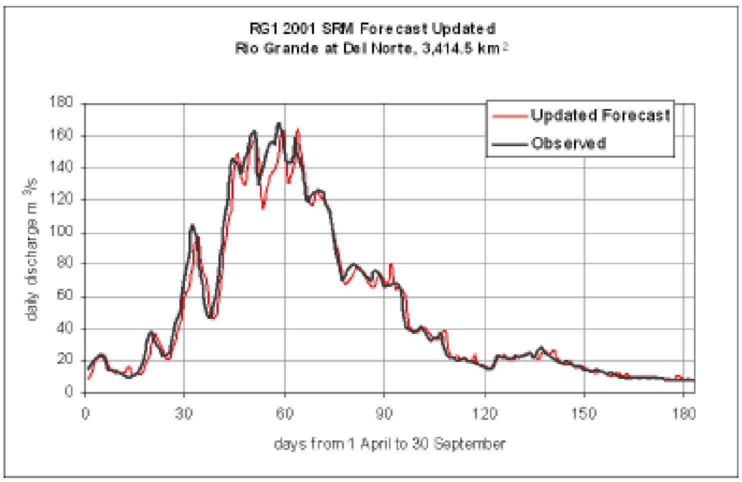
Climate change can be evaluated using the model, and if we put in various climate scenarios, in this case an increase in temperature of 4 degrees Celsius and a decrease in the diurnal range in temperature, the model parameters need to be shifted because spring snowmelt will occur earlier and earlier. It is this shift to earlier snowmelt (see Figure 13) that is going to cause problems. We have also input a ten percent increase in precipitation to SRM for this scenario which is sort of an optimistic future scenario. We are thinking, as Dave Gutzler pointed out, that the precipitation is going to go down considerably while warming occurs. By 2050 from the year 2000, this is what the hydrograph will look like. You'll see more runoff in April and May and a lot less runoff in June and July when we need the water the most. By year 2100, there is going to be a major change. You will see twice as much runoff in



1 April to 30 September:

Forecasted vol. = 692.1 Hm³
Observed vol. = 808.2 Hm³

R^2 = 0.773
Dv = 16.78 %



1 April to 30 September:

Updated forecast vol. = 786.9 Hm³
Observed vol. = 808.2 Hm³

R^2 = 0.971
Dv = 2.70 %

Figure 12. 2001 SRM Forecasting: Rio Grande at Del Norte

April and May as we got before. This reduction in flow in June-August is pretty significant. We're going to have to figure out how the reservoir storage capabilities, releases, and operating rules are going to cope with this kind of new scenario.

This is something we see in almost all of the studies that have been done on future warming effects on snowmelt runoff. There is a shift towards earlier runoff. And for some reason that we haven't quite been able to figure out yet, when this total of four degrees kicks in as opposed to two degrees, we also had this peak that exceeded the existing peak in 2000. A threshold could have been exceeded here. This is the kind of situation that scientists are saying could lead to an increase in significant events like flooding and drought.

The final model that we will use is the SLURP model, which is the total river basin model that accounts for irrigation diversions, endangered species requirements, urban diversions, and industrial water supplies. Any changes that we put into this basin can be accounted for. In addition, SLURP, which covers the entire Rio Grande, has been modified to take outputs directly from SRM as an input at the various gauging locations. They are working in tandem. As I mentioned, it is a total basin model. It is good for "what-if" management scenarios. It has been applied to many basins throughout the world as well. It actually was developed outside the United States. It can model linkages between farm and irrigation schemes at relatively small scales as well as very large basin scales, diversions into the basin, and so on. It also uses remote sensing data and is another of the few models that were designed to work with remote sensing data. We will probably run it for future scenarios either using the climate stations on a grid like this or perhaps with input from general circulation models running into the future that would provide the temperature and precipitation that we need at these grid points across the basin.

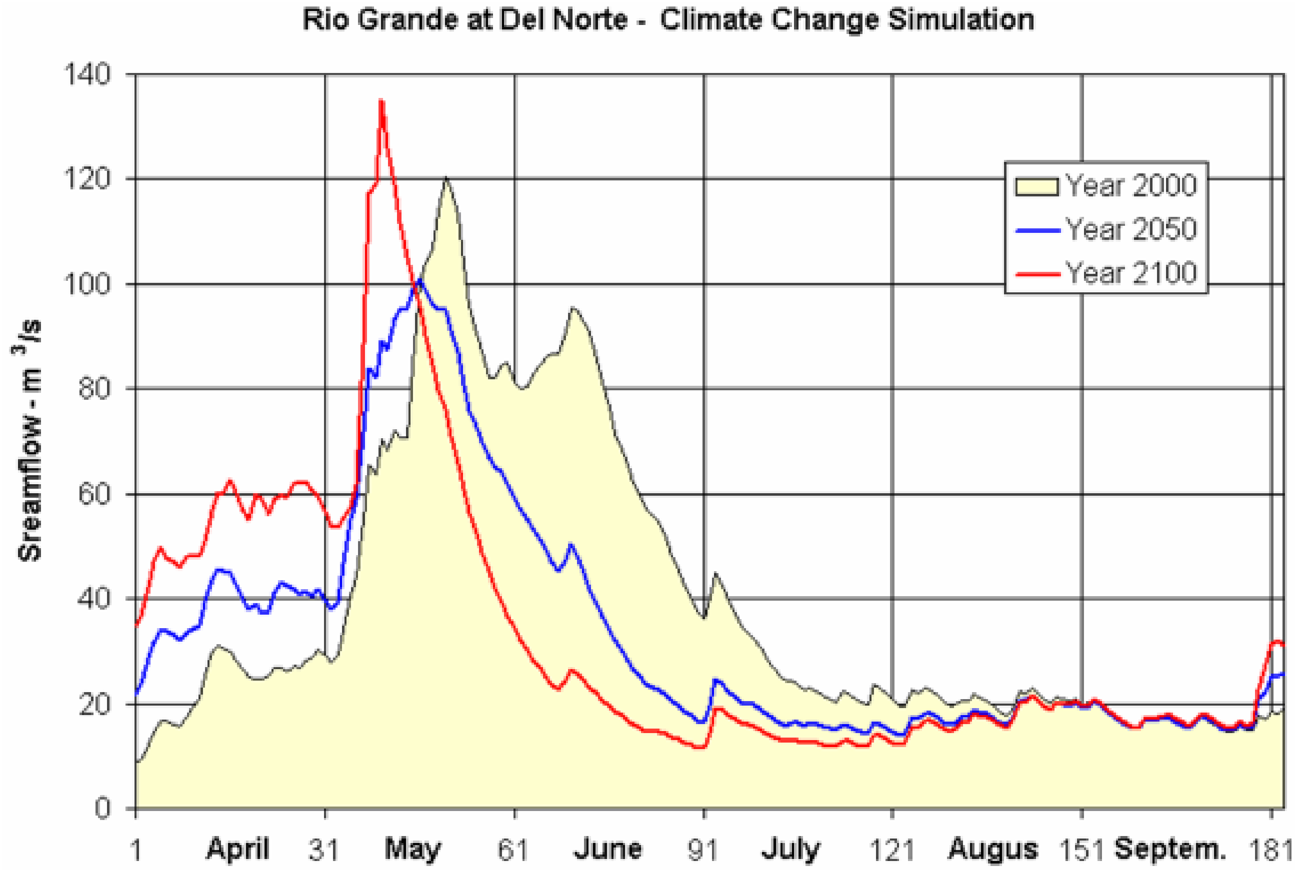


Figure 13. Climate change simulation Rio Grande at Del Norte with periodic changes throughout the 21st century. By 2100, temperature has increased by 4 degrees C, the diurnal temperature range has decreased by 1.4 degrees C, model parameters are shifted, and a 10% increase in precipitation is expected.

I will not talk about this because we saw it yesterday, but all of these models will be linked to the RioGEM model, which is the hydroeconomic model for the Rio Grande that Brian Hurd has developed and Julie Coonrod reported on yesterday. We will be looking at the economic side. We are also linking the model results to education and outreach in the project. We have a method for taking the results from the science and climate change impacts on mountain sources of water and getting the information to various state and tribal entities, science educators, who of course then will address the K-12 community, undergraduates, and graduates. We hope to be working very closely with the educators to get this out.

The major objective here is to continuously measure the spatial distribution of key variables that affect the water quantity in New Mexico's mountains: snowfall, snowmelt, rainfall, evapotranspiration, soil moisture, and runoff. To do the snowmelt portion, we will be increasing the number of SNOTEL sites in the mountains by five. We will also be upgrading 12 of the SNOTEL sites that exist to provide more relevant data from these particular locations. The climate networks will be upgraded, at least in the northern part of the state. SCAN stations from the NRCS will be installed to measure soil moisture at four new locations in the north. We are hoping to install a few more runoff stations where the tRIBS model will be tested. We have these three models that I mentioned in addition to the economics model and the climate models that feed these models. These will be semi-operational basin models from fine resolution all the way up to the river basin scale. They will allow the climate change impacts to be assessed. We hope that the research will provide a better understanding of how the hydrologic processes will be susceptible to climate change. We will also have cyberinfrastructure money in this project, along with high performance computing in order to be able to run the models very efficiently.

We have three hydrologic models that are already operating in some way in New Mexico. They can be used to improve the forecasting of flow over employing just the current methods. That is a start. Improving forecasting is important. We have the methodology being developed that will allow projections into the future that will allow assessment of the effects of climate change on our water supply. We need, from what we have seen in prior model runs, to start adapting now to new climate and a changing water supply. We have the chance with this NSF-EPSCoR project to upgrade our instrumentation networks, improve our computational power, storage capabilities, and develop our remote sensing capabilities to understand better what is going to happen with this new climate. Based on that—and these objectives get progressively more optimistic or tough to achieve—we will have new forecasting approaches. We need to, based on that and the climate scenarios, adapt our water use. That will be difficult. What will be more difficult is modifying reservoir operating rules and the Rio Grande Compact. In a new climate, one would hope that these would change to be able to cope with the hydrologic effects of new climate. One goal that will probably be very difficult to do is to establish moratoriums on unrestricted development based, now and in the future, on water availability. I think that we have a chance to do all these, but if we can accomplish some of them, I think we will be pretty happy.

From the early runs that we have done in a couple of basins, this is what we have learned. In extreme years, droughts are very likely going to be intensified, especially if precipitation decreases. Floods will become more common because of the dramatic nature of the monsoon events. We will probably have more problems like we had recently in the southern part of the state in future years. The gap between water supply and water demand will grow even faster than it is now because of development and population coming into the state. Even without a volume reduction, the temporal redistribution of runoff shows runoff moving from June and July into April and May. It is going to cause a major problem for the various reservoirs to cope with. Although we don't have glaciers in this basin, there will be effects on them as well in other parts of the western U.S. Reservoir operating rules will have to change. Particularly, old and weakened water systems will fail if we have more of these flashy kinds of events. We have to think about new or reinforced reservoirs and distribution systems that will be needed. We might need to put some small reservoirs on some of the tributary streams. The general circulation model generates climate change as inputs to the hydrologic models. We need to come to a consensus on these climate changes so that we can impact a particular basin with the best available information. We think hydrologic models are the only way to forecast hydrologic responses to climate change, but a consistent method of application is needed between the models.

Question: My question has to do with the upper Rio Grande and some of those areas and water management. We work pretty closely particularly with Colorado and NRCS on their similar runoff forecasts for that basin of March and April. Have you linked into that? I would just suggest that you do. Have you talked with Tom Pagono about the work that he is doing?

Rango: I visited with Tom last week as a matter of fact. We will work closely with them. NRCS is a very important cooperator in this project because not only do they have experience forecasting in those basins you referred to, they also are quite agreeable to our upgrading their SNOTEL sites and putting in additional SNOTEL sites. Once we have done that with this project, NRCS will continue to maintain those sites and run them for however long they are viable. We feel that is very important. The SCAN sites, which are in the lower elevations for soil moisture, will also be maintained by NRCS. They will do the same things for those sites. We will work with them in the forecasting mode, but particularly with the data instruments that go in to provide better infrastructure in both northern New Mexico and the southern Colorado portions of the basin, where we will be restricted to remote sensing data. Of course, we will be using remote sensing on all of the basins that I showed you today.

Question: Is there inadequate coverage of the NRCS and the weather bureau water equivalent sites right now?

Rango: There are a lot of gaps in the network. We hope to fill those gaps. In addition, I don't know if you are familiar with the fact that there is a basic SNOTEL site, which has snow depth, water equivalent, temperature, and precipitation; the enhanced sites add radiation budget instrumentation and soil moisture and so on, which turn out to be extremely good if you are using a very high powered model. They are also important for forest fire susceptibility forecasts. Those are the kind of instruments that will be added. NRCS also hopes to answer those questions.

Question: What has the weather bureau used for decades to predict water elevation in the floods?
Rango: For decades they were using, when they used NRCS data, manual snow surveys once a month. The SNOTEL sites that were starting to be installed about 25 years ago make those measurements every day on an automated basis; those data as well as data on precipitation, snow depth, and temperature are bounced off of meteor trails in the ionosphere and reflected down to three central receiving stations in the United States. Those data are available online to everybody within a day. That is why they are very important. The National Weather Service uses that data as well in their forecasts.

Question: The picture you had of the runoff against the models showed that the end of the runoff shifted earlier, but the start of the runoff didn't seem to shift at all.
Rango: I showed you the six-month snowmelt season from April through September. We run it year round as well, and if I had shown you that, you would have seen the snowmelt starting in March, even in February in the southern part of the basin. We have the twelve month hydrograph capability as well, and you could see that.