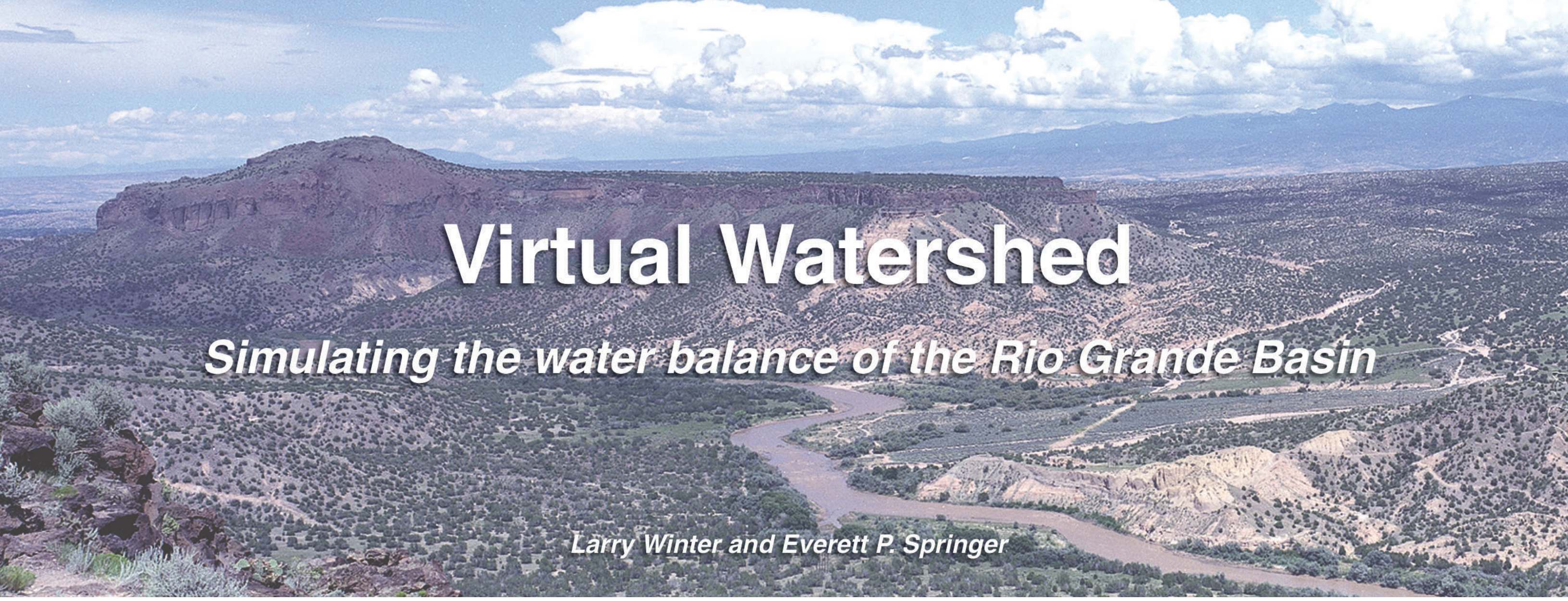

Virtual Watershed

Simulating the water balance of the Rio Grande Basin

Larry Winter and Everett P. Springer

Reliable supplies of clean, fresh water are essential to life and economic growth. It is not surprising then that demands for water increased dramatically during the last century as human populations grew, and energy consumption and industry expanded. As demand approaches supply, societies will become vulnerable to even minor variations in the climate and use of the land. Ironically, we now need to critically manage a resource that had almost no value less than a generation ago.

Scarce water resources *can* be managed objectively if decisions are based on the best available science and realistic computational models of complex watersheds. Detailed physics-based models, running much faster than real time on high-performance computers, can be used to test hypotheses about the performance of watersheds facing inevitable land use changes, climate change, and increased climate variability. Decision makers can use such models to evaluate management alternatives or the effects of alternate climate regimes and to support decisions about allocations of water between agriculture, ecosystems, industry, and municipalities.

Los Alamos National Laboratory and the National Science Foundation Science and Technology Center for Sustainability of Semi-Arid Hydrology and Riparian Areas are developing a high-resolution, physics-based computational model, known as the Los Alamos Distributed Hydrology System (LADHS). The model can be used to assess water resources at scales that are relevant to science and to decision makers. It is composed of four interacting components: a regional atmospheric model that is driven by global climate data, a land surface hydrology model, a subsurface hydrology model, and a river-routing model. When coupled together, these four components represent the complete hydrosphere. Our scientific and engineering goals are to retain the essential physics of all the separate components and to include realistic feedback among them. Because several alternative application codes (legacy codes) exist for each of these components, two of our key software goals are to link existing applications together with minimal code rewriting and to provide a software environment that is flexible enough to accept different alternatives.

We describe our progress in using the LADHS by means of a concrete example: quantifying the water balance of the Rio Grande Basin.

The Rio Grande Watershed

The Rio Grande is a major river system in the southwestern United States and northern Mexico. Our interest is in the upper Rio Grande, which extends from headwaters in the San Juan and Sangre de Cristo Mountains of southern Colorado to Fort Quitman, Texas (about 40 miles downstream from El Paso and Juarez), where it runs dry (see Figure 1). The upper basin covers about 90,000 square kilometers and includes the cities of Santa Fe and Albuquerque, New Mexico, and the El Paso–Juarez metropolitan area. The Rio Grande system provides water for flora, fauna, agriculture, domestic consumption, recreation, business, and industry.

Water moves through the basin along multiple natural pathways, the most important of which are precipitation, surface runoff, infiltration, groundwater recharge and discharge, and evapotranspiration, as seen in Figure 2. Spring snowmelt and summer monsoon storms are the main sources of water in the basin (Costigan et al. 2000). The northern Rio Grande and its tributaries are dominated by snowmelt runoff, but streamflow in the southern tributaries is dominated by summer rain from the North American monsoon.

The atmosphere and river discharges are the main mechanisms for transporting water out of the basin—indeed, out of any basin. Annual river flows have averaged about a million acre-feet per year in the upper Rio Grande, but variability is quite high. The basin has also been subjected to lengthy drought periods, such as the one in the 1950s that caused a rapid shift in forest and woodland zones on the Pajarito Plateau (Allen and Breshears 1998). We may be entering another such drought period now.

Apart from its land, sky, and rivers, the other major feature of the Rio Grande Basin is groundwater, which is the primary source of water for metropolitan areas. Losses from the river to the groundwater are localized, as are gains to the river from the groundwater. In some areas, streamflow is even supported by groundwater. Typically, the groundwater is recharged through mountain blocks and in streams along mountain fronts.

Increasing demands from competing uses may eventually deplete groundwater resources and affect surface-water resources. Indeed, water availability is already an important issue throughout the basin. Sustainability of water resources in the upper Rio Grande Basin requires an understanding of the conjunctive use of ground and surface water, especially groundwater recharge from different sources.

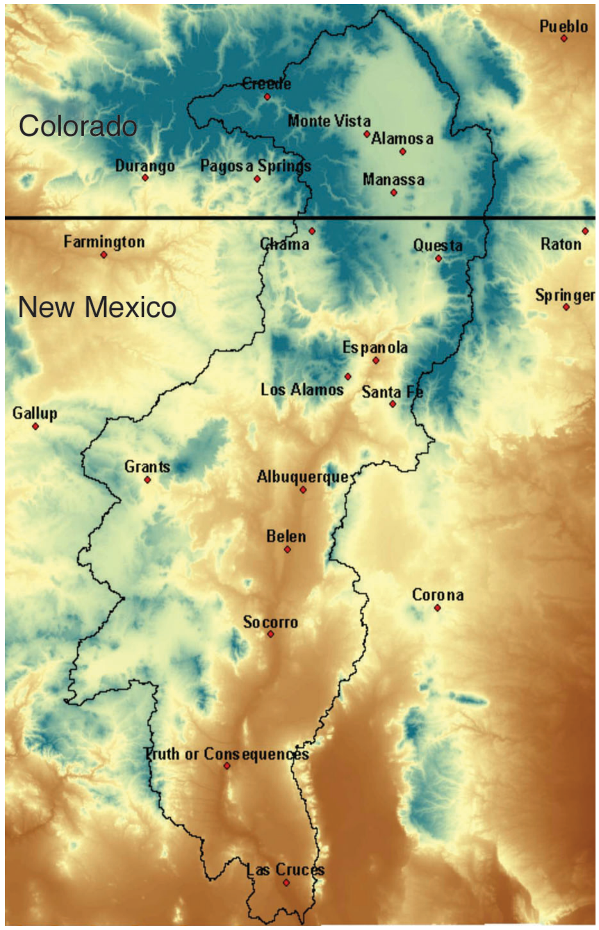

Figure 1. The Upper Rio Grande Basin
The upper Rio Grande runs from southern Colorado to the western-most tip of Texas. The black boundary defines the basin. All ground and surface water within the basin eventually flows towards the river.

Regional Atmosphere. The regional atmosphere component of our model is currently represented by the Regional Atmospheric Modeling System (RAMS). It provides precipitation, temperature, humidity, radiation, and wind data to the surface-water hydrology component. RAMS solves the Navier-Stokes equations with finite-differencing methods to estimate potential temperature, mixing ratio of water, atmospheric pressure, and horizontal and vertical components of wind (Pielke et al. 1992, Cram et al. 1992). The model consists of modules that allow for many possible configurations of parameterizations for processes such as radiation calculations and cloud microphysics. RAMS can use telescoping, interactive, nested grids to represent a large area with relatively coarse resolution and smaller areas within this domain with greater resolution. For each time step, the coarse-grid information is interpolated to the fine grid and the fine-grid variables are averaged back up to the coarse grid to provide the two-way interaction. We can enter nonstationary global climate effects into RAMS via global boundary conditions. These would be set by observed sea-surface temperatures and atmospheric fields or by output from a global climate model.

The LADHS

Our computational approach is to link a regional atmospheric process with surface and subsurface hydrologic processes in a data flow that corresponds to regional water cycles. The detailed physics of the physical processes are summarized in Table I, along with the resolutions that we employ in our model. The flow of data through the model reflects mass and energy exchanges among the four domains in our representation of the hydrosphere. Fluxes are basically driven by dissipative waves operating at different scales.

It should be noted that like every major river in the West, the Rio Grande is highly regulated; thus, the measured streamflow reflects the operation of diversion and storage dams as well as natural forces. Reservoirs and their operations are critical to determining regional effects of climate variation, because management of the water resource can alleviate or modify the impact of variability through storage and operation (Lins and Stakhiv 1998). At present, the LADHS emphasizes interactions among natural processes, although the system is modular enough to accept components representing human demands and resources.

Land Surface. The Los Alamos Surface Hydrology (LASH) System is a grid-based water balance model (Xiao et al. 1996, Ustin et al. 1996) that represents land surface hydrology and, in particular, the hydrology of river basins. It also represents some processes in high resolution to account for soil erosion, contaminant transport, and biogeochemical cycling. The model simulates surface and subsurface flows in two dimensions. Surface flows are routed using a diffusive wave approximation to the momentum equation with an explicit finite-difference scheme solution (Julien et al. 1995). Subsurface flow is routed using a finite-difference form of Darcy's law to determine the amount of flow between adjacent elements. The soil profile consists of two layers, plus a third if a saturated zone is present. Evapotranspiration, or the process by which plants extract water from a subsurface layer and "secrete" it through their leaves into the atmosphere, is based on the incomplete cover model presented by Ritchie (1972).

River Routing. Our initial approach was to use the National Weather Service's Dynamic Wave Operational Model (Fread 1988) to model how rivers and channels would flow, given our land contours, since we planned to simulate basins under natural (unregulated) flow conditions. However, those conditions do not provide the data needed by water resource managers. We are evaluating other codes for their ability to include reservoirs and dendritic drainage patterns.

Subsurface Hydrology. Groundwater represents a major water resource that is not included in current climate models. The Finite Element Heat and Mass (FEHM) code is a three-dimensional multiphase flow code that we use to model both the shallow subsurface aquifers and regional aquifers (Zyvoloski et al. 1997). FEHM solves mass- and energy-flow equations in a porous medium using control-volume finite elements.

So far, we have concentrated on coupling RAMS and LASH together, because the land surface–atmosphere interface controls most hydrologic exchanges on time scales of less than a few years. LASH requires meteorological data from RAMS, such as precipitation, temperature, wind speed, short- and long-wave radiation, and air pressure, whereas RAMS must receive evapotranspiration and related quantities from LASH. However, both RAMS and LASH are legacy codes that were not designed to be coupled to other codes. The scale and size of the data structures used by each code are different; two- and three-dimensional arrays must be exchanged; RAMS runs in a master/slave style and has a user-defined distribution of data that depends on the number of processors; and the two applications have different grid orientations.

The Parallel Applications Workspace (PAWS), developed at Los Alamos, provides a flexible software environment for connecting these separate parallel applications. PAWS can also accept any alternate application codes we wish to incorporate into the model. A central PAWS controller coordinates communications between applications so that they can share parallel data structures, such as multidimensional arrays. Applications can have unequal numbers of processors, use different parallel data layout strategies, and be written in different languages. After the workspace is established before runtime, PAWS does not interfere with processing. The PAWS controller coordinates the creation of connections between components and data structures.

Originally developed through the DOE Accelerated Strategic Computational Initiative and Office of Science DOE 2000 Advanced Computational Testing and Simulation Toolkit, PAWS has been extended and generalized by the requirements of LADHS. New capabilities include handling multiple grid orientations and data with strides greater than 1, transmitting local data within guard-cell-bound memory, interacting with a

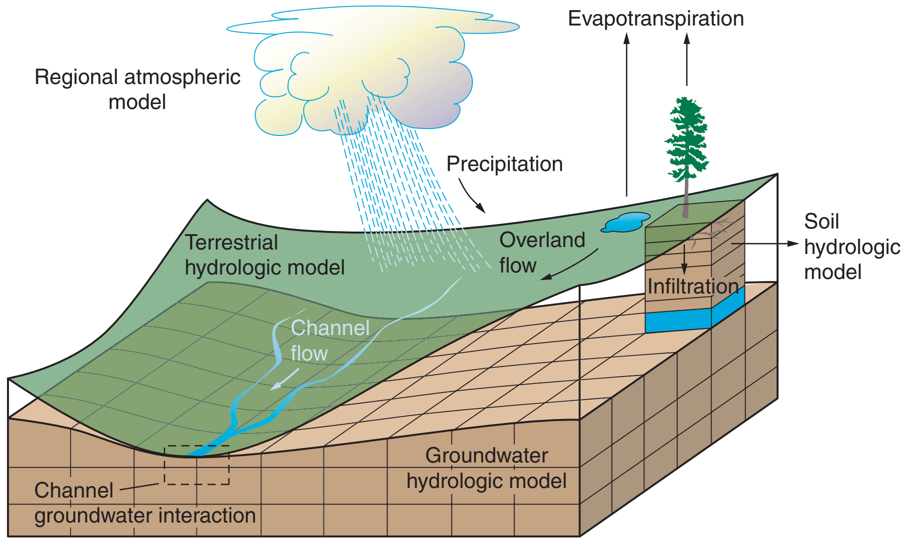

Figure 2. The Hydrologic Cycle
A river basin is a dynamic region, with water entering and leaving along multiple natural pathways. Precipitation (primarily rain, hail, or snow) brings fresh water into the basin. The water can flow overland (surface runoff) and make its way to small channels, streams, and tributaries before becoming part of the river. Water also enters the ground, where it can flow beneath the land surface and eventually feed the river, or it can recharge (resupply) aquifers. The major process that returns water to the atmosphere is evapotranspiration, a dual process consisting of evaporation from surface areas, and transpiration, wherein plants absorb and subsequently evaporate groundwater. The LADHS couples these processes, providing a complete water balance for the river basin.

Table I. LADHS Physical Processes and Model Resolutions

Component	Physics	Characteristic Scales	Model Resolution
Groundwater	Darcy's equation	mm-m/day	~100 m
Unsaturated subsurface	Multiphase flow	mm-cm/min	100 m
Atmosphere	Navier-Stokes equations	mm-m/s	1–5 km
Overland flow	Saint-Venant equations	cm-m/s	100 m
Snowmelt	Diffusion (heat and mass)	m/hr	100 m
Stream	Saint-Venant equations	m/s	By reach
Evapotranspiration	Diffusion	m/s	100 m

master/slave component model, and using multiple communication strategies. These capabilities are also of interest to the Common Component Architecture Forum, of which the PAWS project is a member and which is working on defining standardized component interfaces for high-performance computing.

One of our next steps will be to implement in PAWS the entire LADHS—RAMS, LASH, FEHM, and river-routing applications.

Initial Studies and Results

In our initial studies, we have been especially interested in how the spatial extent and timing of precipitation influences soil moisture, a metric that is of particular interest to farmers. We have chosen the 1992–1993 water year (October 1992–September 1993) as our test period and the northern half of the Rio Grande Basin (southwestern Colorado and northern New Mexico) as our test area. The 1992–1993 water year was an El Niño year with higher than normal precipitation in the Southwest, especially during the winter season.

Precipitation is notoriously difficult to simulate because it is highly localized. Nonetheless, its timing and extent are critical to regional and local water budgets. Our precipitation estimates are based on high-resolution simulations using RAMS with three nested grids. The largest grid, 80 kilometers on a side, covers most of the western United States, along with parts of Canada, Mexico, and the Pacific Ocean. This grid is necessary to simulate the flow features in the region. A medium-scale grid contains the states of Utah, Arizona, Colorado, and New Mexico and has a horizontal grid spacing of 20 kilometers. Given that resolution, large terrain features, such as mountain ranges, are resolved well enough to be recognized by the model. A third grid, 5 kilometers on a side, is also used in many of the simulations to better resolve smaller terrain features.

Our initial results indicate that the RAMS model can reproduce the pronounced year-to-year variability observed in precipitation patterns across the western United States (Costigan et al. 2000). Simulated and observed monthly precipitation totals compare fairly well, although they are far from perfect (see Figure 3). In general, the 1992–1993 water year was wetter then normal, and our model had a tendency to overestimate precipitation at some high-elevation locations.

Figure 4 shows an example of output from the coupled land surface/atmosphere model, in which we simulated the effect of snow-water equivalent on soil moisture. Snow-water equivalent is the amount of water contained in snow, and its extent is the same as the snowpack. Snow accumulation is based on the RAMS definition of snow, with snowmelt determined by temperature. It is produced by RAMS at 5-kilometer resolutions, and the blocky nature of the snow distribution in Figure 4(a) is evident. LASH operates at a much finer, 100-meter resolution. RAMS and LASH were coupled by a statistical down-scaling technique based on kriging, which is an estimation procedure used in geostatistics (Campbell 1999). The highly resolved land surface (modeled by 9,307,500 grid cells) results in a smooth, detailed map of soil moisture. That level of detail is important when simulating local processes such as soil erosion and contaminant transport.

Conclusion

Although we cannot experiment with a system as large and valuable as the hydrosphere of the Rio Grande Basin, computer hardware and software have advanced until simulations of river basins can be highly realistic. Gaps in the data and inadequacies in coupling the components of the model are now the main limits on basin-scale simulations. In some cases, coupling is simply a matter of scaling one process to another while conserving mass and energy. In other cases, new science is required. This is especially true of "ecohydrology" and "agrohy-

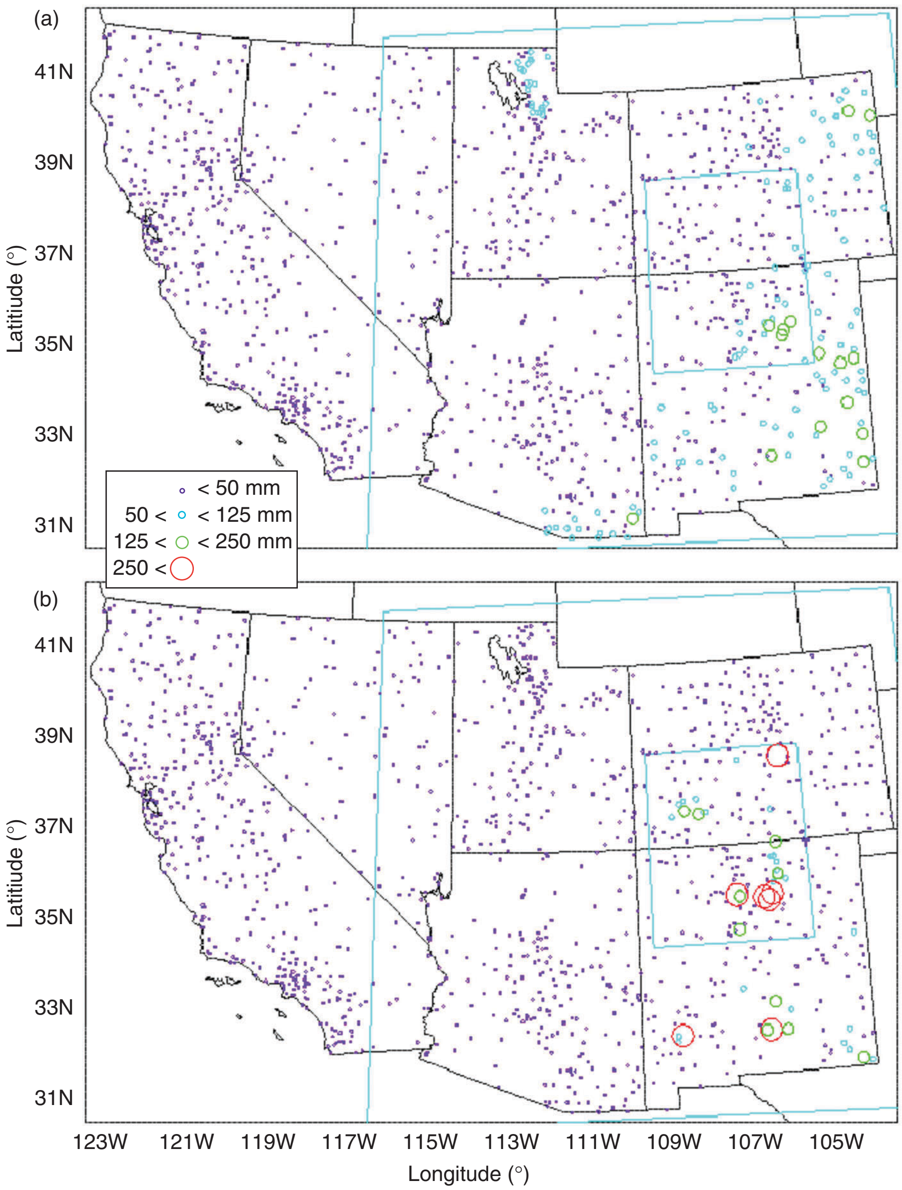

Figure 3. Precipitation from RAMS

The plots are a comparison of (a) observed data and (b) RAMS output for July 1993. The blue lines mark the approximate location of nested grid boundaries. Circles are centered on the observation sites with their size representing the accumulated precipitation (in millimeters) for the month. Model results were bilinearly interpolated to the observation sites in order to facilitate comparisons. While not perfect, the RAMS estimate of the seasonal precipitation agrees with the measured data.

drology,” where the effects of riparian areas and farming on processes like aquifer recharge and evapotranspiration must be quantified.

We also need new science to represent the impacts of municipalities and industry. Although large networks exist for observing some data, such as temperature and precipitation, they are the exception. Remote sensing, especially satellite based, and new geological and geophysical characterization techniques may eventually fill many data gaps. However, the theory of coupled basin-scale modeling will need methods of quantifying uncertainty because no data set will ever be exact.

As human activity pushes against the margins of available water supplies, we may soon need a crystal ball to assess the effects of even small increases in demand or small variations in supply. What does a crystal ball look like? One version may be a large computer, a computational model, and a team of scientists that can apply the model and interpret the results. ■

Further Reading

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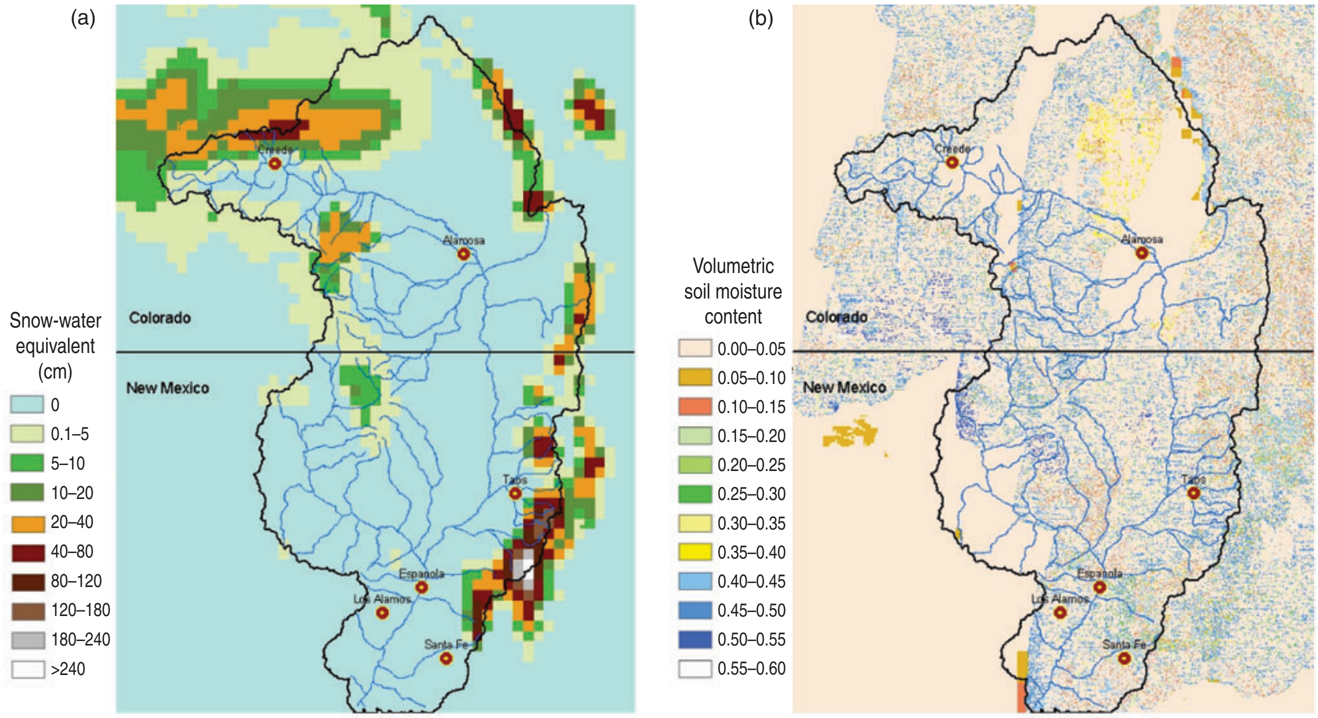

Figure 4. Examples of Snow Pack and Soil Moisture Results from LADHS
Panel (a) shows the RAMS estimates of snow-water equivalent. Snow is mainly found in the San Juan and Sangre de Cristo Mountains during this October-November period. The snow distribution is not resolved very well because of the coarseness of the RAMS grid (5-km grid cells). (b) The plot shows the surface soil moisture estimates from LASH. Coupling between RAMS and LASH, which uses a finer grid (100-mm cells), smoothes the snow distribution. The distribution of soil moisture ranges from very dry in the San Luis Valley around Alamosa, Colorado, where there is little precipitation on an annual basis, to very wet conditions in higher-elevation zones where snow accumulation and melt usually occur.

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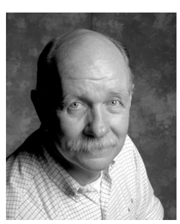

Everett Springer graduated from the University of Kentucky in 1975 with a bachelor's degree in forestry and received his Ph. D. in watershed science from Utah State University in 1983. Everett was a hydrologist with the Agricultural Research Service of the U.S. Department of Agriculture from 1982 to 1985, when he became a staff member in the Environmental Science Group at Los Alamos. He is currently a member of the Atmospheric, Climate and Environmental Dynamics Group. He has worked on characterizing and modeling vadose zone and surface hydrology as well as contaminant transport. For the past 6 years, he has worked on applying high-performance computing to simulating coupled hydrologic systems.