Mountain Hydrology, Snow Color, and the Fourth Paradigm

The world’s mountain ranges accumulate substantial snow, whose melt produces the bulk of runoff and often combines with rain to cause floods. Worldwide, inadequate understanding and a reliance on sparsely distributed observations limit our ability to predict seasonal and paroxysmal runoff as climate changes, ecosystems adapt, populations grow, land use evolves, and societies make choices.

To improve assessments of snow accumulation, melt, and runoff, scientists and community planners can take advantage of two emerging trends: (1) an ability to remotely sense snow properties from satellites at a spatial scale appropriate for mountain regions (10- to 100-meter resolution, coverage of the order of 100,000 square kilometers) and a daily temporal scale appropriate for the dynamic nature of snow and (2) The Fourth Paradigm [Hey et al., 2009], which posits a new scientific approach in which insight is discovered through the manipulation of large data sets as the evolutionary step in scientific thinking beyond the first three paradigms: empiricism, analyses, and simulation. The inspiration for the book’s title comes from pioneering computer scientist Jim Gray, based on a lecture he gave at the National Academy of Sciences 3 weeks before he disappeared at sea.

Water From the Mountain Snowpack

Of the seasonal changes that occur on Earth’s land surface, the most profound are accumulation and melt of snow, filling rivers and recharging aquifers that support downstream ecosystems and supply water for 20% of Earth’s population. These high, midlatitude snowpacks are at risk because a warming climate would change some snowfall to rainfall and deliver runoff months before demand. Management of this water for competing requirements (flood control, irrigation, hydropower, recreation, and habitat) now uses assessments of the snow storage and the plausible rate of melt. Even in well-instrumented basins, seasonal forecasts are sometimes wrong. In the Sierra Nevada’s American River, for example, the median error of the 1 April forecast of the April–July runoff is 18%; 1 year out of every 5 exhibits an error that reaches nearly 40%. Comparison between forecasts and river flows shows that the maximum error from 1990 to 2011 was 129% (Figure 1). Worldwide, mountain ranges like the Hindu Kush, Tien Shan, Karakoram, Himalayas, and Andes pose formidable difficulties even for rough estimates.

Manual and automated ground measurements of snow water equivalent—all on nearly flat ground and many in forest clearings—do not represent snow on the landscape. Historically, water managers assumed that ground measurements provide some index to the actual volume of water, but established forecasting methods depend on statistical relations developed while land use and climate have been changing. Rich, hard-won, long-term data do show trends already, but statistical uncertainty will get worse as the past becomes less representative of the present [Milly et al., 2008]. Thus, scientists and water managers need physically based approaches that account for topographic heterogeneity and estimate the volume of water in basin-wide snow, relative to historical trends and extremes. Some mountain regions where snow falls contain austere infrastructure, meager gauging, challenges of accessibility, and emerging or enduring insecurity related to water resources. Remote sensing, models, and data-intensive analyses offer opportunities to address this need. Similar methods can be applied to Earth’s polar and subpolar regions.

The Significance of the Color of Snow

If human eyes were sensitive to radiation through the whole solar spectrum, snow would be one of nature’s most “colorful” surface covers, whose spectral reflectivity varies as snow crystals change size and shape and gather dust or soot [Dozier et al., 2009]. Satellite-borne sensors such as the Landsat...
Thematic Mapper and the Moderate Resolution Imaging Spectroradiometer (MODIS) can see this temporal, spectral, and topographic variability from space.

In measuring any variable from satellites, one faces a choice between different “resolutions”—temporal, spatial, spectral, radiometric, coverage, dynamic range, etc. For mapping the extent and reflectivity of mountain snow, the Landsat Thematic Mapper provides 30-meter spatial resolution at 16-day intervals, whereas MODIS on two satellites sees the whole Earth at a 500-meter resolution, at least 4 times daily depending on latitude, with half of those observations at night. Snow changes more rapidly and frequently than other surface covers, and neither sensor can see through clouds, so scientific understanding benefits from the frequent opportunities offered by MODIS to track waxing and waning snow. Spatially, however, snow in mountainous terrain varies with topography, so 500-meter MODIS pixels (and even 30-meter Landsat pixels) smear together reflections from snow, soil, and vegetation. To get around this conundrum of needing information in detail and frequently, measurements at multiple wavelengths enable calculation of the fraction of snow (Figure 2) and its reflectivity, along with soil and vegetation, that match the spectral mixture in each pixel [Painter et al., 2009].

**Spatially Distributed Snow Water Equivalent Based on Snow Extent**

With currently available technology the task of reckoning snow water equivalent everywhere in a drainage basin has three independent but not mutually exclusive options, as Figure 3 shows for California’s Sierra Nevada in 2006. First, interpolation combines maps of snow extent with ground observations of snow water equivalent [Fassnacht et al., 2003]. Covering location and elevation and constrained by fractional snow cover and tapered near the snow line, interpolation produces a physically realistic (but not necessarily correct) value for snow water equivalent. Second, time-resolved physical snow model assimilates observations from weather stations and remote sensing [Lehning et al., 2006]. Over the conterminous United States the Snow Data and Assimilation System (SNODAS) integrates the National Oceanic and Atmospheric Administration’s Rapid Update Cycle Version 2 (RUC2) numerical weather model with surface and remotely sensed measurements to estimate snow water equivalent at 1-kilometer spatial resolution and 1-hour temporal resolution. Third, reconstruction combines the satellite-observed rate of snow depletion with a calculation of the melt rate to retroactively estimate, as the snow melts, how much had existed everywhere earlier in the season [Martinec and Rango, 1981]. To drive the snowmelt model, the computation in Figure 3 uses data from the National Land Data Assimilation System about solar radiation, longwave radiation, temperature, and humidity. It adapts these estimates to the terrain to account for differences in illumination, shadowing, elevation, and vegetation.

The three methods give different answers, but reconciling them would improve snowmelt runoff forecasts even in basins with sparse hydrological measurements. Figure 3 shows similar patterns and significant differences among the methods. The physical model accumulates snow in the northwest where neither interpolation nor reconstruction shows any. Interpolation and models methods produce real-time values, but the calculations lack information from the high elevations. Snow in those calculations increases from 1200 to 3000 meters in elevation but then levels off or decreases, whereas reconstructed snow, available only as it disappears, increases to 3600 meters before leveling off. Reconstruction indicates substantially more snow.

A sequence of similar figures would show variability in the melt-out dates. According to the available ground measurements, snow appears to be gone by 1 July 2006, so the interpolation method has nothing to interpolate even though snow is visible in satellite imagery and to hikers. The physical model melts out about 28 July. In the reconstruction method, patches of snow persist into September, but most of it melts by early August.

Interpolation is the easiest method to apply in areas where surface measurements are available, so it can serve as a benchmark against the more elaborate schemes. Interpolation and weather-driven models produce some implausible artifacts, whereas reconstruction matches values at snow pillows and shows variability at the topographic scale related to solar illumination, vegetation, and wind redistribution. Data from the 18 Sierra Nevada rivers with reliable, full, natural flow measurements show that in 2006 neither interpolation nor SNODAS accumulates enough snow to account for the volume of water. The reconstruction method is probably the most accurate, accumulating enough snow to account for the runoff and leave 20% for evaporative losses, but its estimates come only as the snow melts. Knowing the spatial distribution of snow as it disappears clarifies implications for soil moisture and vegetation, but that knowledge does not help forecast runoff.

**Ways Forward**

The predicament brings researchers back to The Fourth Paradigm and data-intensive science. A spaceborne sensor that directly measures snow water equivalent in the mountains will not be available soon. Meanwhile, data sets of large size or complicated structure that could illuminate this problem exceed the human capacity to search, validate, analyze, visualize, synthesize, store, and curate the information. The complexity of the transformations that must be applied to render some kinds of observations useful to scientists makes better infrastructure imperative so that scientists can build on others’ work and the population of people with useful insight can expand as they construct products of successively higher levels of integration and synthesis. Specific data-intensive research questions for this specific problem of estimating the heterogeneous distribution of snow in the mountains include these: Can discoverable patterns in the reconstructed time-space distribution of snow water equivalent help improve the accuracy of models that assimilate ground and spaceborne observations to estimate the amount of snow in the early spring?
before melt has begun? Can scientists use such methods to predict runoff by methods beyond simple correlation? Could people with different knowledge sets help discover such patterns? How can researchers pose the problem, provide the infrastructure to make such cross-disciplinary collaboration feasible, and best enable comparison and validation of models? How can literature be efficiently searched to identify which papers have analyzed which data sets? Should AGU or other scientific societies publish a data journal to make data accessible, not just available, and provide a mechanism for reuse and citation?

In short, will advances in data-intensive science cause an incremental change in how science is done, or will they transform science? [Collins, 2010]

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Author Information

Jeff Dozier, Bren School of Environmental Science and Management, University of California, Santa Barbara; Email: dozier@bren.ucsb.edu