In a region already prone to water shortages, researchers now forecast that rising temperatures threaten the American West's hidden reservoir: mountain snow

As the West Goes Dry

Mount Bachelor, Oregon—Under the dome of a concrete-gray sky, Stan Fox assembles four pieces of aluminum tubing into a 3-meter-long hollow pipe. After standing it on end, he plunges it through more than 2 meters of snow at Dutchman Flat, an alpine meadow perched on the shoulder of this 3000-meter mountain. Fox, who heads the Oregon snow-survey program for the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS), removes the tube and reads the snowpack depth, a measurement that has been tracked at nearby sites monthly since the 1930s. Today the snow is 250 centimeters deep, and by comparing the weights of the tube both filled and empty, Fox and a colleague determine that the snow contains about 30% liquid water. If all the snow were instantly liquefied, the water would be nearly 1 meter deep. Not too bad. In a region prone to spikes in precipitation, Dutchman Flat is more than 15% above its 30-year average. "The snow in these mountains is a virtual reservoir," Fox says. As the snow melts in the spring and summer, it will slowly release that water, filling streams and reservoirs, which provide lifeblood to the region during the normally bone-dry summer months.

But indications are that this age-old cycle is beginning to change. New assessments of decades' worth of snowpack measurements show that snowpack levels have dropped considerably throughout the American West in response to a 0.8°C warming since the 1950s. Even more sobering, new studies reveal that if even the most moderate regional warming predictions over the next 50 years come true, this will reduce western snowpacks by up to 60% in some regions, such as the Cascade Mountains of Oregon and Washington. That in turn is expected to reduce summertime stream flows by 20% to 50%. "Snow is our water storage in the West," says Philip Mote, a climatologist at the University of Washington (UW), Seattle, who leads a team that has produced much of the new work. "When you remove that much storage, there is simply no way to make up for it."

The impacts could be profound. In the parched summer months, less water will likely be available for everything from agriculture and hydropower production to sustaining fish habitats. Combined with rising temperatures, the dwindling summertime water could also spell a sharp increase in catastrophic fires in forests throughout the West. With much of the current precipitation headed downstream earlier in the winter and spring, the change is also likely to exacerbate the risk of floods.

For resource managers already struggling to apportion limited water supplies throughout the West, the predictions are grave. "If that's true, it would have a huge impact," says Christopher Furey, a policy analyst with the Bonneville Power Administration in Portland, Oregon, which markets electricity from over a dozen power-generating dams in the Columbia River Basin that provide power to millions of people. In a region where farmers, fishers, recreationalists, and municipalities already compete for water, climate change may be setting the stage for an entirely new round of conflicts. "We think of the water wars in the past," says Fox, referring to the epic battles over rerouting western waters in the early 20th century. "In the future they will probably be more peaceful but much more prevalent."

Too wet, too soon

The root of the problem is easy to state: The semiarid West has too little water, spread too unevenly throughout the year. Most of Montana sees less than 46 centimeters of precipitation a year. Even rainy Portland receives only about one-tenth of its annual 91 centimeters of precipitation during the summer. For most of California the fraction is even smaller. Philadelphia, by contrast, typically receives 102 centimeters of annual precipitation, 30% of which comes in the summer.

Thanks to massive dam-building in the first half of the 20th century, more than 60 million people—roughly one-fifth of the U.S. population—now live in the Pacific and Intermountain West. Those tens of millions of people are dependent not just on water, but on snow. Snowmelt makes up 75% of all water in streams throughout the West. If that snow falls as rain or melts too early, there will be little water left in the virtual reservoir come late summer and fall. Unfortunately, that is just what appears to be happening.

Back down the mountain in a conference

CREDIT: CRAIG TUTTLE/CORBIS

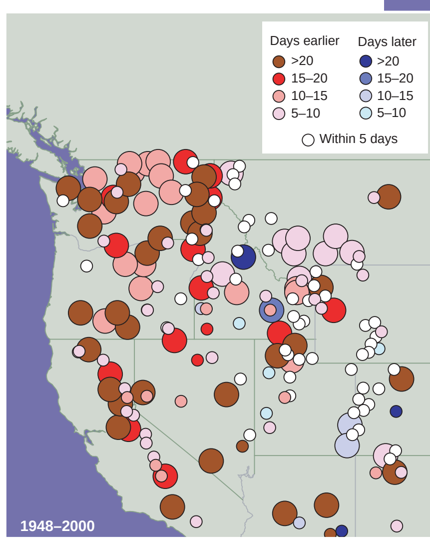
room at a small ski resort outside Bend, Fox and a collection of about 50 water experts from the Northwest settle in to listen to Mote describe some of his group's latest data on western snowpacks. Perhaps fittingly, outside the temperature has warmed up on this mid-January day to about 5°C. Icicles encircling the roof drip steadily.

Mote describes work published last year in *Geophysical Research Letters*, in which he took a detailed look at the trend in snowpack accumulations throughout the Pacific Northwest over the last half of the 20th century. Mote reviewed federal records of snow water equivalents (SWE)—the amount of water in a given depth of snow—on 1 April, typically the peak of the season's snowpack. Of the 230 sites where SWEs were measured back to the 1950s, Mote found that nearly all showed negative trends, even as precipitation increased in most places. The hardest hit: areas in the Cascade Mountains in Oregon and Washington, which saw as much as 60% declines in total snow accumulation. The most likely explanation, Mote says, was the region's temperature rise. When he plotted the snowpack declines against the elevation of the snow-tracking sites, he found that the biggest decreases occurred at the lowest elevations, suggesting that the moderate warming throughout the region was raising the freezing level.

That's just the beginning. In work presented last month at the American Meteorological Society meeting in Seattle, Washington, Mote teamed up with UW Seattle colleague Alan Hamlet and University of Colorado, Boulder, hydroclimatologist Martyn Clark to expand his initial analysis to look at historical snowpack levels throughout the West (see righthand figure). The news was better, but not much. Snowpacks decreased at 85% of the nearly 600 snow-measurement sites throughout the West. The biggest decreases hit the Northwest, where the mountains are smaller and the temperatures warmer, thanks to their proximity to the Pacific Ocean. Declines in the northern Rockies were mostly in the range of 15% to 30%. In these inland areas, Clark points out, winter temperatures are typically far lower than in the Pacific Northwest, so a rise of a few degrees still does not push the mercury above freezing. "In the interior regions all the winter precipitation falls as snow," Clark says. And some regions in the Southwest even witnessed large SWE increases, thanks primarily to a rise in precipitation.

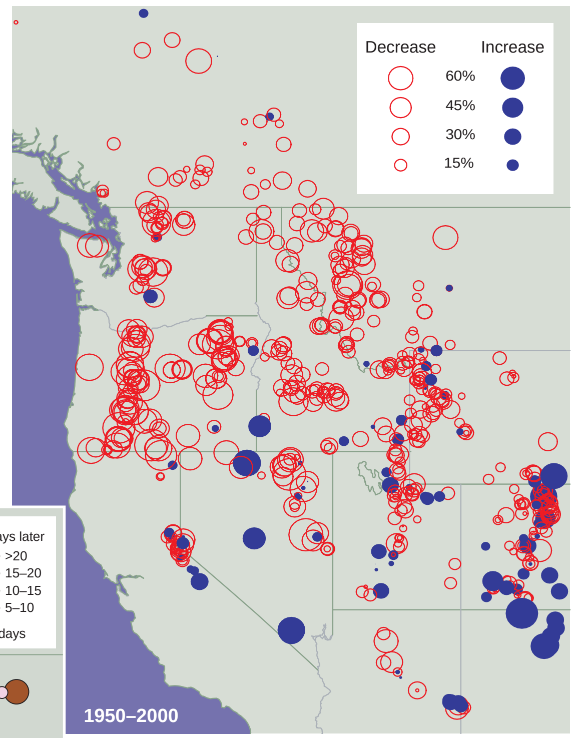
Other clues also suggest that the West's snowpack is changing. The biggest: Snow is melting earlier in the spring. "There has been a fairly broad tendency in snowmelt basins to exhibit advances in runoff timing," says Daniel Cayan, a climate researcher at the Scripps Institution of Oceanography in La Jolla, California. Last month, Cayan, postdoctoral assistant Iris Stewart, and Michael Dettinger, a hydroclimatologist with the U.S. Geological Survey (USGS) in San Diego, reported in *Climatic Change* that the peak of the annual spring runoff in streams throughout California's Sierra Nevada now comes as much as 3 weeks earlier than it did in 1948 (see lower figure). Again, the effect was most pronounced in streams adjacent to lower elevation snow that is more sensitive to temperature increases. "This is very consistent with the evidence Phil [Mote] and company have seen with the snowpack," Cayan says. In a paper now under review at the *Journal of Climate*, Clark and colleagues at the University of Colorado recently found much the same shift for streams in the Northwest. "There is definitely something happening," Clark says.

That evidence is further bolstered, Cayan points out, by records that track the first springtime blooms of flowers such as honeysuckle and lilac, which show a similar 1- to 2-week advance. "This is a totally independent measure and one that is quite strongly related to temperatures in the springtime," Cayan says.



Not everyone is yet ready to believe that these trends will continue. George Taylor, the state of Oregon climatologist and a climate researcher at Oregon State University in Corvallis, for example, argues that broad trends in temperature and snow accumulation over the past century are most likely due to natural multidecade swings as the climate oscillates between periods of relative warm and cold temperatures. "There was significant warming in the 1920s, '30s, and '40s, cooling in the '50s and '60s, and warming again from the 1970s through '90s," Taylor says. "In my opinion, the effects of human-induced global warming are small compared to the multidecadal cycles."

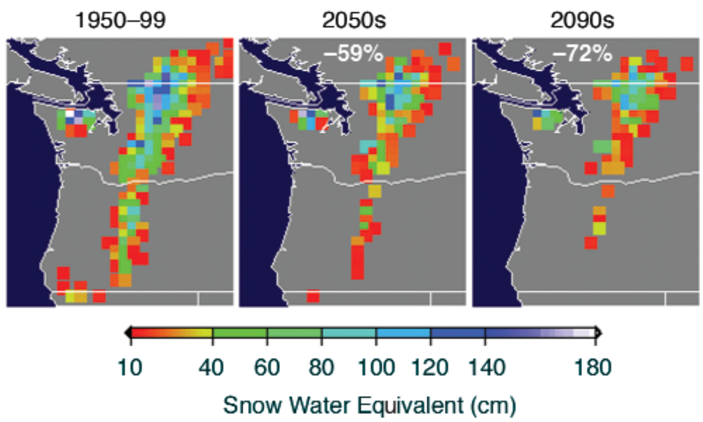
Greg Johnson, a climatologist with NRCS in Portland, also points out that Mote typically starts his analysis of snowpack trends at the beginning of the 1950s, which saw some of the largest snow accumulations over the past century. "If you use those numbers, you will show large decreases," he says. Decadal swings in climate caused by El Niño and the Pacific Decadal Oscillation, he adds, further muddy the numbers.



In retreat. A modest temperature rise since the 1950s has reduced spring snowpacks throughout the West (*top*) and shifted the peak snowmelt earlier in the year (*left*).

"I'm not saying it's a nonissue, just that we need to keep watching it closely," Johnson says. "The point is, if you look at the historical record, we've seen some warming and drops in low-elevation snowpack. The question is what can we tie it to. But from a planning standpoint, I think people have to be concerned about this."

Mote agrees that the trend data may be skewed to some degree by the high-snow years of the early 1950s. However, he says, before the 1950s there were so few snow measurement sites that earlier data are suspect. Furthermore, he says, the snow loss is still best explained by the region's modest warming. "The thing that really stands out is that the largest losses are at the lowest elevations, which can only be explained by warming," Mote says. As for whether this warming is best explained by the decade-long climate swings, Mote defers to the latest work by the Intergovernmental Panel on Climate Change (IPCC), the global body of hundreds of scientists that has assembled the "standard model" of climate change. Although IPCC's latest report does show that both natural and human-induced factors explain portions of the last century's global temperature record, climate models that take both into account do the best job at reproducing the complete temperature record.



Virtually gone. Computer models suggest that even moderate warming will drastically reduce the spring (peak) snowpack in the Oregon and Washington Cascades.

Dry times ahead?

No matter what the historical picture, Mote, Cayan, and others argue that the picture for western snowpacks looks far more bleak when the anticipated future warming is taken into account. Here, too, several teams have been working to understand how events are likely to unfold. All agree there is considerable uncertainty. Precipitation trends, for example, "are all over the map" in different climate models, because precipitation can vary drastically over a short distance, Mote says. However, Mote, Cayan, and others agree that climate models generally do a far better job of estimating temperature, because temperature differences drive winds that tend to reduce those differences. Regional climate models suggest that over the next 100 years, western temperatures are likely to rise between 2° and 7°C, depending on—among other factors—the rate of increase of greenhouse gases in the atmosphere. And unlike the precipitation forecasts, the models all show an increase in temperature.

Modelers then feed these temperature data and other variables into another set of computer programs called hydrology models that compute the effects of changing climate on snowpack and stream runoff. And these hydrology models consistently show that even low-end temperature changes produce big effects. As part of a study described in last month's issue of *Climatic Change*, for example, UW Seattle hydrologist Dennis Lettenmaier and colleagues used a global climate model to compute how the western snowpack would respond to modest temperature increases. They found that a temperature rise of 1.5°C by 2050 resulted in a loss of nearly 60% of the 1 April snowpack in the Oregon and Washington Cascades, and a 3° rise by 2090 reduced those snowpacks by 72% (see figure). "That's the best-case scenario," Mote says. "By the 2090s with a warm scenario, you would have essentially no snow left in Oregon by April 1st." When the Pacific Northwest is taken as a whole, the picture is only a bit better, showing a 35% loss in 1 April snowpack by the 2050s and 47% loss by the 2090s.

In a *Geophysical Research Letters* paper last year, Cayan and former postdoc Noah Knowles—now with USGS in Menlo Park, California—computed a similar analysis for the watersheds that make up the western drainage of California's Sierra Nevada Mountains. They found that a predicted temperature rise of about 2.1°C over the next century would reduce the Sierra snowpack by one-third by 2060, primarily at mid to low elevations, and would halve it by 2090. A separate analysis by L. Ruby Leung and colleagues at the Pacific Northwest National Laboratory in Richland, Washington, together with researchers from the National Center for Atmospheric Research in Boulder, Colorado, and Scripps reached similar conclusions when they looked at the effect of climate throughout the West. The one notable difference: In the Rockies, the colder wintertime temperatures are expected to limit the losses to 30%. Without putting too much faith in the exact amount of losses, Mote says, "it's nearly inescapable that we're going to continue losing snowpack."

"Enormous impacts"

"It doesn't mean we've lost water," Cayan hastens to point out. "It means the water is coming off earlier." Rather than sticking around as snow into the late spring and summer, western snowpacks will wash down mountainsides in the winter and spring. Simply stated, the upshot is wetter winters and drier summers.

In the Sierras, for example, Knowles and Cayan's models predict that the portion of water that flows through the watershed's rivers from April through July each year will decline from 36% today to 26% by 2030. "This represents over 3 km^3 [3 billion cubic meters] of runoff shifting from post–April 1 to pre–April 1 flows," the authors write. That figure nearly doubles by 2090. Other studies show that parts of the Columbia River Basin are likely to fare worse, whereas the Colorado River watershed, with smaller anticipated declines in snowpack and generally colder temperatures, is likely to emerge comparatively unscathed. Overall, however, a steady temperature climb will likely affect tens of millions of people. "There are enormous impacts from this potential change," Cayan says. "Water management in the West has been to use the snowpack as a natural reservoir. This reservoir is really important. It's water that will come later when a lot of the water demand is heaviest." Without that water "people will need to make some difficult choices," adds Todd Reeve, who directs watershed restoration programs for the Bonneville Environmental Foundation in Portland.

That's particularly true in the Pacific Northwest and California. Reservoirs in the Columbia River Basin capture only about 30% of the region's annual runoff, whereas California's reservoirs hold slightly more. The typical pattern is to fill these reservoirs with late spring runoff and use that water throughout the summer and fall for irrigation and then in the early winter for power generation. An earlier snowmelt means that the water must be spread over a longer dry season when irrigation, recreation, and municipal demand peaks. "You're losing natural storage and taxing built storage. Something has to give," Lettenmaier says. (Here too, Lettenmaier says, the Colorado River Basin is unique, because reservoirs there can store four times the region's annual precipitation.)

With less summertime water, one of the hardest hit areas is likely to be agriculture. Today, farmers in California use about 75% of the state's water. Earlier this month, agricultural economists Wolfram Schlenker of the University of California, San Diego, and W. Michael Hanemann and Anthony Fisher of UC Berkeley presented a preliminary study at the American Economic Association meeting in San Diego of the likely impacts of climate change on California agriculture. Using a range of hypothetical climate and stream-flow scenarios in line with published modeling results, the researchers forecast that snowpack losses could lower farmland values by more than 15%. If that pattern holds for the state's 3.84 million hectares of irrigated farmland, the loss to the

CREDIT: D. LETTENMAIER/UNIVERSITY OF WASHINGTON state's agriculture economy would be measured in the billions of dollars.

What is more, Fisher says, because access to irrigation water in California depends on the historical system of first-come, first-served water rights, those losses will likely be absorbed primarily by the farmers lowest on the water-rights totem pole, driving many out of business. That same pattern is likely to hold true in the Northwest, particularly in the dry lands east of the Cascades. "It's not going to be feasible to have the irrigated acreage we have now," Mote says—fighting words in a region long wedded to an agricultural way of life.

Forests are also likely to suffer, according to Anthony Westerling, a climate researcher at Scripps. Westerling recently fed data from Cayan and Knowles's climate and hydrology models of the Sierras into a model of his own that attempts to forecast changes in wildfires. Westerling says his preliminary results show that fire danger will soar. "The mean area burned more than doubled by 2090" relative to the present, Westerling says.

Although less easily quantified, low summertime stream flows are also expected to exacerbate problems with declining fish runs, crimp water supplies for recreation and cities, and increase the likelihood of winter and springtime flooding throughout the Northwest and California. But not all the impacts are sure to be bad. Last year, John Fazio, a river flow analyst with the Northwest Power and Conservation Council in Portland, plugged some of the UW group's hydrology forecasts into his Columbia River flow models and found that a warmer Northwest may actually benefit Northwest electricity consumers. Warmer winters, Fazio says, will likely lower the need for electricity during the region's peak demand period, and an expected small increase in wintertime precipitation could churn generators to the tune of an extra 1900 megawatts of power—nearly enough to power two cities the size of Seattle. Of course, if precipitation swings toward the dry side, it could wind up costing rate payers hundreds of millions of dollars, he says.

No matter how the climate evolves, water managers will face uncomfortable tradeoffs between providing water for agriculture, hydropower, and recreation, and keeping it in streams to support fish runs. In their current *Climatic Change* paper, for example, Lettenmaier and colleagues show that to keep summertime flow levels in the Columbia River high enough to support endangered-fish recovery plans, water managers will likely have to sacrifice 10% to 20% of the river's wintertime hydropower generating capacity, because it will force water managers to draw down their reservoirs in the summer. "Even with these reductions in power, late-summer minimum flows would still be lower than at present," the authors write.

More big dams?

In a region prone to water shortages, talk of such tradeoffs doesn't go down easy. "We already have a problem with shortages," says Maury Roos, chief hydrologist for the state of California. And coming up with the water to deal with population growth throughout the region is already an acute problem, he adds. "This will certainly make the problem worse."

In hopes of heading off some of those problems, Roos and other water officials are beginning to incorporate climate change into their regional water plans. California's latest draft water plan, for example, discusses climate change, although it doesn't yet recommend changing California's infrastructure. Portland, Seattle, and other cities have begun studying the issue in detail to see whether they need to change their water-management plans.

Initial rumblings are also being heard among advocates for building new dams throughout the West. That comes as something of a surprise to many, because during the Clinton Administration, then–Secretary of the Interior Bruce Babbitt claimed that the era of big dam building was over, due to their adverse impacts on fish and wildlife. Already, for example, California is considering building several new dams as part of a joint state and federal effort to provide water for threatened ecosystems while keeping water available for farmers. Washington too is flirting with building a dam at a cost of more than $1 billion in the eastern part of the state to provide irrigation water for farmers near Yakima. And Idaho water managers say that climate change may force them to build new reservoirs to prevent winter floods along the Boise River, where one-third of the state's inhabitants currently live.

But due to their high dollar and environmental costs, many water experts doubt whether such projects will go forward. "Dams are tough fights and so expensive," says Hal Anderson, planning chief for the Idaho Department of Water Resources. And even if built, they will only soften the blow.

Dangerous consequences. Over the next century, larger winter and spring runoffs from melting snow are expected to increase flooding and catastrophic wildfires.

CREDITS: (LEFT TO RIGHT) RICH PEDRONCELLI/AP; JONATHAN YOUNG/EPA/AP

With the amount of spring snow expected to be lost due to climate change, "there is no way we're going to build that many dams to capture it all," Mote says.

Other strategies may help. Most water officials agree that there is much that can be done to conserve water, particularly by lining irrigation canals and making other improvements to irrigation. As well, a handful of new programs have sprung up recently to buy or lease water rights from farmers and then keep the water in stream during the low-flow months to improve habitat for fish. Last year, for example, one umbrella effort called the Columbia Basin Water Transactions Program sponsored 32 such deals to keep 28.4 million cubic meters of water in tributaries where it's needed most. That amount of water pales in comparison to what stands to be lost. But for now, water planners still have some time to act before climate change alters the American West in a way humans have never witnessed.

–ROBERT F. SERVICE