CHAPTER ONE

Tapping into a Planetary Cycle

See how every raindrop and snowflake, every skyborne molecule of H_2O that falls…is also a child of Ocean and Sun.… See how those streams and rivers, as Aldo Leopold pointed out, are "round," running past our feet and out to sea, then rising up in great tapestries of gravity-defying vapor to blow and flow back over us in oceans of cloud, fall once more upon the slopes as rain and snow, then congeal and start seaward, forming the perpetual prayer wheels we call watersheds.

—David Duncan, *My Story as told by Water*

Especially as I drink the last of my water, I believe that we are subjects of the planet's hydrologic process, too proud to write ourselves into textbooks along with clouds, rivers, and morning dew.

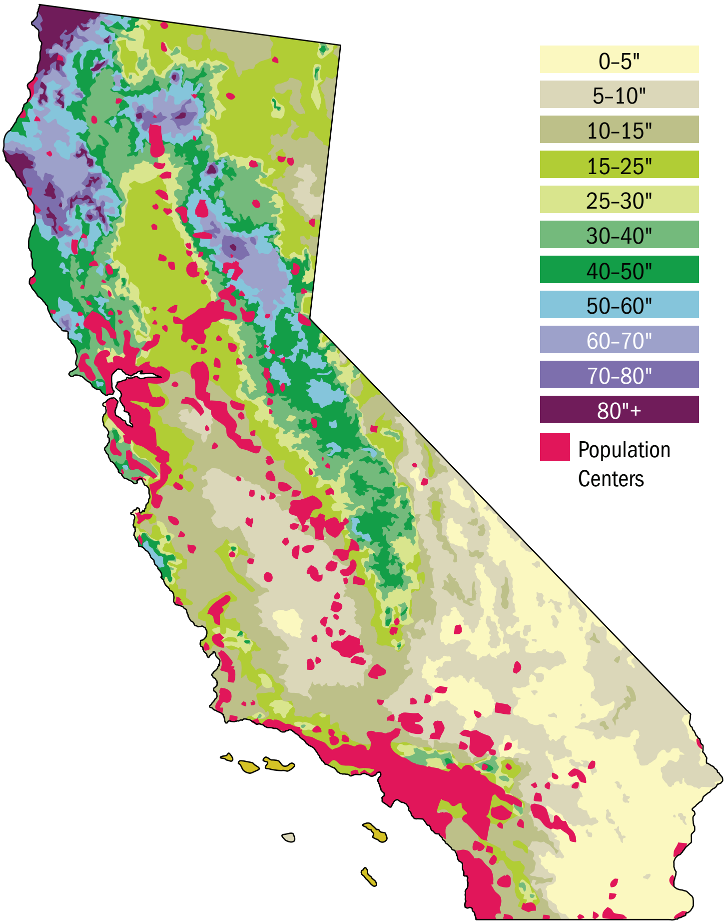
—Craig Childs, *The Secret Knowledge of Water*

A GREAT WATER WHEEL

A partnership between land and a planetary water cycle produces the California climate and shapes the natural landscape of the state. California's weather is generated primarily by westerly winds off the Pacific Ocean. In the winter, low pressure in the northern Pacific sends cold, wet storms to the state. California receives 75 percent of its annual precipitation between November and March, the majority from December through February. The dry weather of summer is associated with a high-pressure "dome" over the Pacific. Such "Mediterranean" climates, with wet winters and summer droughts, occur on the west coasts of continents in the middle latitudes due to global patterns of atmospheric pressure circulating over the oceans.

California's rainfall is heaviest in the north and decreases toward the south (map 1). Eureka, surrounded by redwood rain forests, usually receives more than 50 inches of rain each winter. That North Coast town has as much claim to a "California climate" as Los Angeles does, with only 15 inches on average. It *does* rain in Southern California, contrary to the myth popularized by real estate promoters and Hollywood, and Los Angeles does experience seasons. Winter rains activate the southern California growing season, as dormant plants awake and seeds of annual plants germinate. Summer brings a seasonal drought, and the autumn transition includes hot, dry Santa Ana winds and wildfires. Mountain communities such as Lake Tahoe and Mammoth Lakes experience yet another version of California weather, with six months of winter snow and the brief summer growing season characteristic of alpine landscapes (fig. 1).

California's diverse landscape is responsible for this wide range of precipitation patterns. The state's coastline stretches 800 miles from Oregon to Mexico. A map of California, superimposed over the east coast of the United States, would extend from southern Maine all the way to South Carolina, crossing more than nine degrees of latitude. But California has more diverse weather and climate than the East, because its 100 million acres contain the tallest mountain ranges in the 48 contiguous states and desert basins that lie hundreds of feet below sea level (map 2).



Map 1. Average annual precipitation, in inches, in California (redrawn from Hundley Jr. 2001).

Figure 1. Mammoth Creek. Six months of winter snow and a brief summer growing season are one version of the California climate.

Rainfall and snowfall result when humid air masses blow in from the ocean and interact with the state's mountain ranges. Moist air, moved inland by the prevailing westerlies, pushes up against California's mountain backbones, which wring vapor out of air as it rises, cools, and condenses (fig. 2). Precipitation generally increases two to four inches for each 300-foot rise. Seasonal snowfall totals about two feet at the 3,000-foot elevation in the Sierra Nevada foothills, but increases to 34 feet on Donner Summit, the famous 7,000-foot pass where the Donner party spent a tragic winter. The Sierra Nevada occupies one-fifth of the land area of California and has a major influence on the climate, weather, and water supply of much of the state. Its crest extends 430 miles; 8,000-foot summits in the north rise to over 14,000 feet in the south, intercepting the westerly jet stream at higher and higher elevations. Most of the precipitation in the Sierra

Map 2. Landform provinces in California (redrawn from Schoenherr 1992).

Figure 2. Air cooling and condensing as it rises over mountains.

Nevada falls as winter snow (fig. 3). In Plumas County, north of Lake Tahoe, an average of 90 inches of precipitation falls at 5,000 feet. The same elevation in the southern Sierra receives as little as 30 inches.

As air descends the east side of California's mountain ranges, the process is reversed. Air becomes warmer and holds more of its water vapor. Relatively dry "rain shadows" are the result. The Sierra Nevada rain shadow creates the Great Basin desert. The Coast Ranges produce a rain-shadow effect for the Central Valley too, although a major gap at San Francisco Bay lets more moisture directly strike the northern Sierra Nevada. The Mojave and Colorado Deserts lie in the rain shadow of the southern Sierra Nevada but are primarily influenced by the Transverse and Peninsular Ranges. The Mojave Desert town of Barstow averages only four inches of rain per year; Imperial, farther south in the Colorado Desert, is even drier (fig. 4).

Figure 3. Sierra Nevada precipitation builds the winter snow pack.

Figure 4. The Mojave Desert in the rain shadow of the Sierra Nevada.

A broad cross section through the state, beginning near San Luis Obispo and extending roughly northeastward, intersecting the mountain ranges at right angles, would pass through the Central Valley near Visalia, cross Sequoia National Park, and take in the Owens Valley town of Independence. San Luis Obispo, at the base of low mountains in the Coast Ranges, averages 22 inches of rain; Coalinga, in the Coast Ranges' rain shadow and down on the floor of the Central Valley, receives only seven inches. Farther east, just below the Sierra Nevada foothills, Visalia picks up 11 inches. Giant Forest, in Sequoia National Park, is at 7,000 feet; snow and rain there total 46 inches of precipitation (fig. 5). Independence is in a desert created by the Sierra's rain shadow and averages only five inches of rain. East of the White Mountains, in Death Valley, 178 feet below sea level, annual precipitation is a mere two inches at Greenland Ranch (fig. 6).

California receives almost 200 million acre-feet (MAF) of precipitation in an average year. One acre-foot (AF) equals 325,851 gallons, which would cover a football field one foot deep. Planners commonly figure that an AF serves the annual domestic needs of one to two families, or five to eight people, depending on how wisely it is used and conserved. Water that falls on the state may evaporate back into the atmosphere, be used by plants that then return vapor to the air, or soak deep into groundwater basins. What remains is about 71 MAF of "runoff" water, which moves across the landscape and is the water most accessible to people. Streams draining the sodden North Coast contain about 40 percent of this runoff. The Sacramento River basin generates another 31 percent, mostly originating with the Sierra Nevada snowpack. Snowmelt from the southern Sierra drains into the San Joaquin and Tulare Valleys, producing much of the balance (map 3). The Colorado River receives almost no runoff

Figure 5. Snow at 7,000 feet in Sequoia National Park.

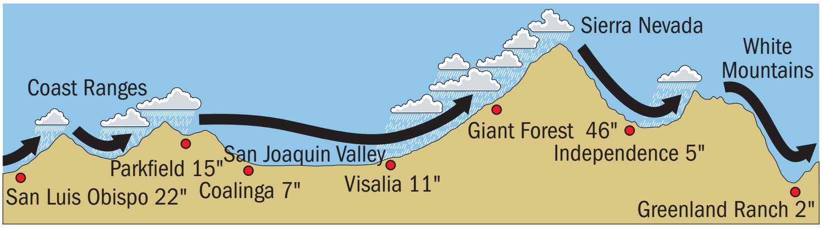


Figure 6. Influence of topography on precipitation; a southwest–northeast cross section of California (redrawn from Durrenberger 1968).

Map 3. Average annual streamflow in California (redrawn from Durrenberger 1968).

originating inside California, but because the river serves as the state's southeastern border, California receives 4.4 MAF from it. This apportionment, along with Klamath River water out of Oregon, allows water planners to figure on a statewide supply of 78 MAF of annual runoff.

The Sierra Nevada snowpack has historically peaked by April 1 and then begun melting. By midsummer it is gone, except for a few small glaciers and snowfields on north-facing exposures that are shaded from direct sunlight. The delayed release of snowpack water overlaps only partly with the optimum growing season for plants in California. Moisture is most available in the winter, when temperatures are low, and is scarce during the long, warm days that optimize growth. Urban and agricultural water demands are out of sync with the natural runoff pattern, peaking during summer and at their low point during winter. California's natural vegetation evolved adaptations to the local patterns. Many annual plants flower quickly in spring and produce seeds that sleep through the long drought of summer and early autumn. Winter rains break that dormancy. Some perennial shrubs and trees rely on deep root systems to tap water even during the long seasonal droughts. Others go dormant, simply shutting down their metabolisms. Riparian vegetation found along riverbanks and in wetlands benefits from year-round water availability. The New England pattern of four seasons—lush, green springs; hot, wet summers that encourage plant growth; autumn color before leaves are dropped; and freezing winter weather—is found in California only in mountain and foothill river canyons. There plants can keep their roots wet and local hydrologic conditions mimic the New England pattern (fig. 7).

Water moving within California is part of a greater planetary water cycle that includes many circular movements, wheels

Figure 7. Plants watered year-round by a mountain creek.

within wheels (fig. 8). Water is continuously shifting among three "reservoirs": the ocean, the atmosphere, and the land. These are connected by precipitation, evaporation, and plant absorption and transpiration (evaporation through leaf pores). Water is perpetually changing form and traveling the globe. It has been said that we drink the same water the dinosaurs drank. That is not accurate for specific water molecules. During photosynthesis, for

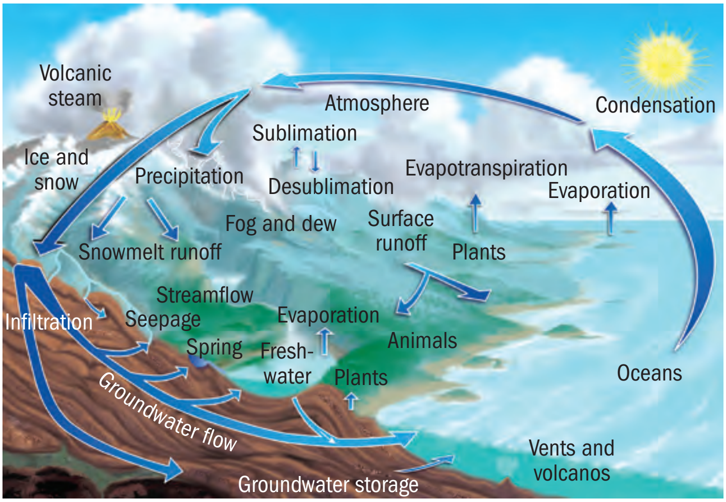


Figure 8. The water cycle: wheels within wheels. From U.S. Department of the Interior, U.S. Geological Survey (John Evans, Howard Perlman). http://ga.water.usgs.gov/edu/watercycle.html.

example, these molecules split into oxygen and hydrogen atoms. Yet it is true that no water is lost in the overall planetary balance; water returns. The respiration of plants and animals recycles it, reversing the photosynthesis equation by consuming oxygen while breaking complex molecules into water and carbon dioxide. Fire, an important decomposition agent in the natural California landscape, produces the same chemical results. And when organisms die and decompose, water is reconstituted.

This planetary recycling is powered by the sun, which evaporates water from the ocean and the land. In photosynthesis, the sun's energy is also what splits the bonds holding water molecules together. Of the water vapor returned to the atmosphere, 16 percent comes from transpiration by land plants (fig. 9); most of the rest comes from the ocean. At any given moment, only a

Figure 9. Evapotranspiration returning water to the atmosphere.

thousandth of one percent (0.00001) of the planet's total water is in the air. Yet that small percentage produces thick coastal fogs, dramatic thunderheads, and drenching downpours. In a journal entry written during a January storm, John Muir marveled "that so much rain can be stored in the sky" ([1938] 1979, 335). The recycling that replenishes atmospheric vapor is so constant and

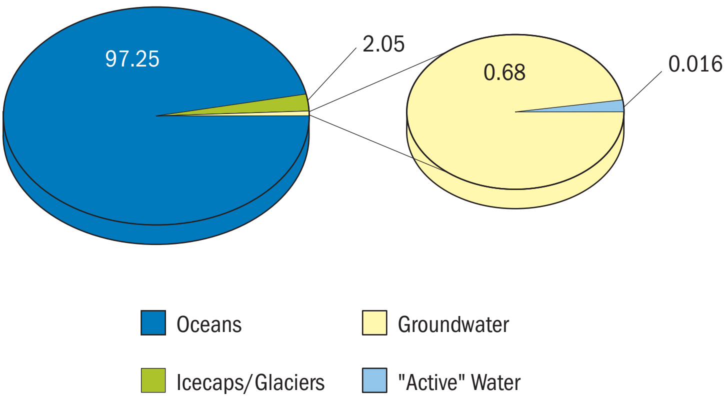


Figure 10. Planetary water reservoirs (percent of planetary water).

voluminous that this water is completely replaced every eight days and the equivalent of all the oceans' water passes through the atmosphere every 3,100 years.

Two-thirds of the Earth's surface is covered by liquid water. Philip Ball wrote, in *Life's Matrix: A Biography of Water* (2001, 22), "We call our home Earth – but Water would be more apt." Over 97 percent is salt water, though, and over two-thirds of the freshwater is locked up in ice caps and glaciers. Less than one percent of the total is available freshwater, with most of that below ground, in aquifers that are never fully accessible. On this watery planet, just 0.016 percent (0.00016) of the precious fluid is "active" freshwater, moving through lakes, rivers, the atmosphere, and living creatures (fig. 10).

The cogs in the water-recycling wheel revolve at different speeds, like different-sized gears meshing inside an enormously complex clock. Vapor evaporated from the surface of the sea may circulate for only a few hours or for days. Deep ocean water may take thousands of years to complete a circuit of evaporation, condensation, and return. Some of the water in the polar ice caps may remain solid for millions of years. The ice in some small Sierra Nevada glaciers has been there for nearly a thousand years. Under certain conditions, groundwater can be trapped in deep, confined aquifers, held back from the water cycle for thousands of years. At its own speed, however, groundwater does participate in the cycle. It feeds springs, rivers, or lakes, and it is replenished when surface water percolates into the ground.

Water may travel for weeks through California's river arteries before finally returning to the sea or terminating its journey in inland waters such as Mono Lake. Almost anywhere along these routes it may be shunted aside, pulled in by the roots of a plant, or drunk by an animal.

Water is essential for life on Earth and is the critical habitat factor that shapes California's ecosystems. As the leaf and root designs of plants adapt to climate, elevation, soil, and topography, both the gathering and the conservation of water are of supreme importance. Bands of different flowers lining a vernal pool sort themselves out by their particular relationships with water. The spiny leaves of a Joshua tree *(Yucca brevifolia)*, like the extremely efficient kidneys of a kangaroo rat, are water-conservation adaptations to life in the desert (fig. 11). Indeed, everywhere in the state—in the wetland marshes rimming San Francisco Bay, the grassy prairies of the Central Valley, the north coast rain forests, the chaparral shrublands of southern California, the foothill oak woodlands, and the pine forests of the Sierra Nevada—all forms of life accommodate to the local availability of water. Photosynthesis requires water, often in enormous amounts. Plants combine water with carbon dioxide to manufacture food for themselves and the herbivores that feed on them; in the process, they replenish the atmosphere with oxygen gas.

Figure 11. Needles and leaves designed to conserve water.

Various mechanisms and behaviors foster "best management practices" for water conservation by living things. At the boundaries between multicellular bodies and the rest of the world, barriers of skin, bark, scales, or mucous membranes regulate water passage in and out. Every living cell has a membrane that encloses and regulates its internal concoction of water and essential chemicals. Multicellular organisms bathe their cells in watery environments. Water management is critical to homeostasis, the maintenance of the internal conditions necessary for life.

We are bodies of water. Humans can live without food for weeks, but die within days when deprived of water. Our bodies are 65 percent water (our brains more than 95 percent); a 150-pound human body contains over 12 gallons of water. We need to replenish about two and a half quarts a day, one-third from drinking and the rest in foods, as we lose water in breath, sweat, and urine. Water is the primary medium for biochemical reactions and a participant in many of the essential processes of life. It helps break down our food, then carries the digestion products to our cells. It regulates temperature and transports dissolved oxygen and carbon dioxide through our circulatory systems. Proteins that rely partly on their shapes to fulfill their jobs as enzymes are folded into those shapes by bonds with water in the fluid of our cells. As cellular metabolism generates wastes, water dissolves them and moves them across filtration membranes in our kidneys, returning them (and the water itself) to the environment.

Water is so essential to us that it is amazing we ever take it for granted. If it is our most precious resource, that is not simply because the supply sometimes grows scarce. H_2O is the vital essence of life on Earth, an almost magical molecule. A full appreciation of our relationship with California water begins at the molecular level.

THE VITAL MOLECULE

Water is so familiar that we seldom give any thought to what sets this particular molecule apart from other substances commonly found in our lives. Unusual characteristics are behind water's critical importance. "Water is life's true and unique medium," Philip Ball has written. "That the only solvent with the refinement needed for nature's most intimate machinations happens to be the one that covers two-thirds of our planet is surely something to take away and marvel at" (2001, 268).

Most solids, liquids, or gases that we encounter naturally are found in just one phase. Minerals, such as silica or calcium carbonate, that form rocks and soils remain solid (unless heated to extremes by volcanic action or movement of the plates that form the Earth's crust). Other elements and compounds, too, stay in a single phase under normal circumstances. "Silicon vapor" is not part of our daily experience or vocabulary. Neither is "liquid wood" or, for that matter, "solid air." Decomposition or digestion breaks molecules apart to build something new, but this is not simply a matter of phase changes. The water molecule, however, is widely abundant on this planet in all three phases: as solid ice, liquid water, and gaseous water vapor (fig. 12). When most other molecules *are* transformed, those changes regularly involve water because it is so nearly ubiquitous, dissolves most anything, and is good at carrying other materials along with it.

The explanation for water's unusual phase character also helps explain why water contains "an invisible flame...that creates not heat but life," as described by David Duncan in *My Story as Told by Water* (2001, 190). Water is a "community molecule." That is, water molecules constantly form, break, and re-form bonds with one another. Those bonds produce a cohesive tendency that is behind most of water's special attributes. Working together, H_2O molecules pick up the colors of the sky, create the pleasing sounds of water and gravity working together, and shape our most beautiful landscapes.

The cohesiveness is explained by the relationship between two hydrogen atoms and one oxygen atom. H-O-H is a polar

Figure 12. Ice crystals, one widely abundant form of water.

molecule, more positively charged at the hydrogen ends and more negatively charged toward the oxygen atom. Because opposite charges attract, hydrogen atoms within a water molecule will orient toward the oxygen in another, nearby. Each H_2O molecule can form such "hydrogen bonds" with up to four others (fig. 13).

This bonding explains many unique properties. H_2O's polarity makes it the "universal solvent" because its charged ends

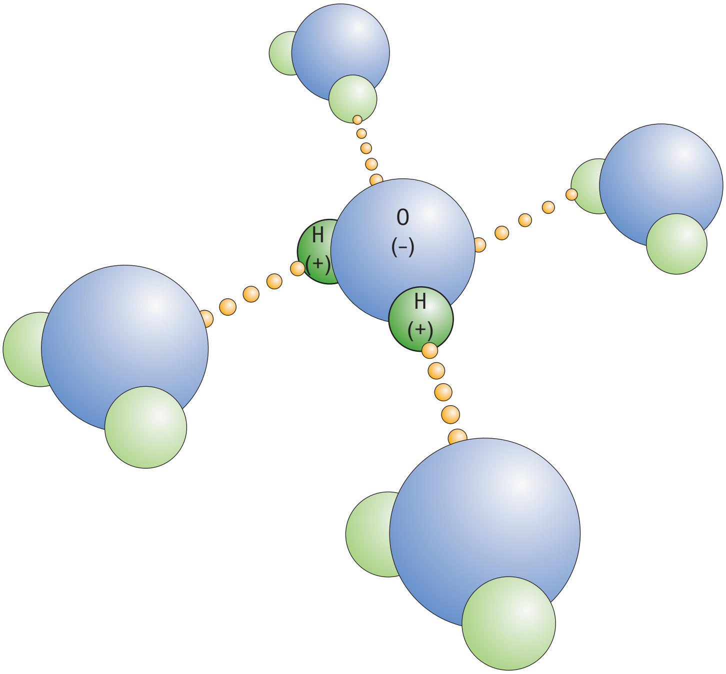


Figure 13. Hydrogen bonds between water molecules.

seek out opposite charges on many other kinds of molecules as well. Water weasels its way between such molecules, separating them and carrying them into solution. It dissolves so many things that truly pure water is rarely, if ever, found in nature. The chemistry of your local water supply reflects whatever rock and soil it has touched. Even atmospheric vapor, distilled to purity by evaporation, soon finds substances to react with in the air. Acid rain is one familiar and unpleasant result.

Bonded cohesiveness also accounts for the ability of California's 300-foot-tall redwood trees to lift water from the ground up to their topmost branches inside cellular tubes—water ropes

Figure 14. A water strider on the surface of a pond, skating on the surface tension created by water molecules.

that move against gravity because tension is applied from the top, where leaves pass water out to the atmosphere. It also explains the surface tension that allows a water strider to skate across the surface of a pond (fig. 14).

Unlike almost every other liquid naturally found on Earth, water expands when it freezes. The expansion begins, oddly, *before* the freezing point is reached. As cooling water drops below 40 degrees F, it suddenly becomes less dense—the opposite of its behavior above that temperature. It takes on a regular crystalline shape with empty space between the oppositely charged hydrogen and oxygen portions of neighboring molecules. Because of this strange behavior, solid water—ice—is less dense than liquid water, and ice floats (fig. 15). If the water in mountain lakes behaved like most liquids, cooling at the surface would cause denser ice to settle to the bottom and, gradually, the lake would freeze solid right up to the surface. Because ice floats, fish

Figure 15. Ice floating on a mountain lake.

and other aquatic creatures can carry on through the winter beneath insulating ice layers that eventually arrest further cooling of the depths. Because water expands when it freezes, mountain residents have to protect pipes from bursting in the winter. The internal liquid environment in all living things must also be protected from freeze-expansion that could destroy cellular membranes and tissues. Freezing water even shapes the California landscape wherever water in cracks expands as ice, causing rock to peel and break.

The cohesiveness of hydrogen bonds means that it requires an unusual amount of energy for water to change phases. Water has high melting and boiling points because bonded molecules resist being pulled apart. Thus, for example, when sweat evaporates, a great deal of heat is carried off, efficiently cooling our bodies. Water also resists too-rapid heating. It takes more heat to raise the temperature of water than to raise that of most other liquid or solid substances by the same amount. Though a sandy beach in the sun gets very hot, the nearby seawater or a lawn bordering the beach remains cool. Both the ocean and the grass heat up slowly and are constantly losing energy through evaporation.

The cohesive attraction between molecules of water also means that there is a direct connection between you and your watershed, through hundreds of miles of pipes, treatment plants, aqueducts, reservoirs, and rivers. Continuous "ropes" of water may extend from a San Diego faucet all the way to the northern Sierra Nevada and the Colorado Rockies. "Pull" from your end and water molecules transmit that tiny force, reacting all the way up the line.

"NORMAL" WEATHER: ANYTHING BUT "AVERAGE"

> *And it never failed that during the dry years the people forgot about the rich years, and during the wet years they lost all memory of the dry years. It was always that way.*
>
> —John Steinbeck, *East of Eden*

The normal climate of California includes droughts and years that are particularly wet (fig. 16). Very rarely does California weather actually match long-term averages. The state's average annual runoff totals 71 MAF, but the range is tremendous—as little as 15 MAF during the severe drought year of 1977, but up to 135 MAF in the exceptionally wet winter of 1983. The annual volume in Sierra Nevada rivers can be 20 times as great in very wet years as in very dry years (fig. 17).

Such year-to-year variations are partially tied to variable Pacific Ocean temperatures known as the El Niño Southern Oscillation. When warmer ocean currents shift eastward in the Pacific, toward the coasts of North and South America, jet streams

Figure 16. A sign of drought, part of the normal weather cycle in California.

and storm tracks overhead shift accordingly. Results vary, but strong El Niño winters often lead to wetter than normal winters for northern California, with a smaller effect in the southern part of the state. El Niño events are interspersed with La Niña events, with colder-than-normal ocean temperatures and, usually, below-normal precipitation for California. This cycling between El Niño and La Niña, every three to seven years, is a natural phenomenon that can be traced back thousands of years (figs. 18a, 18b).

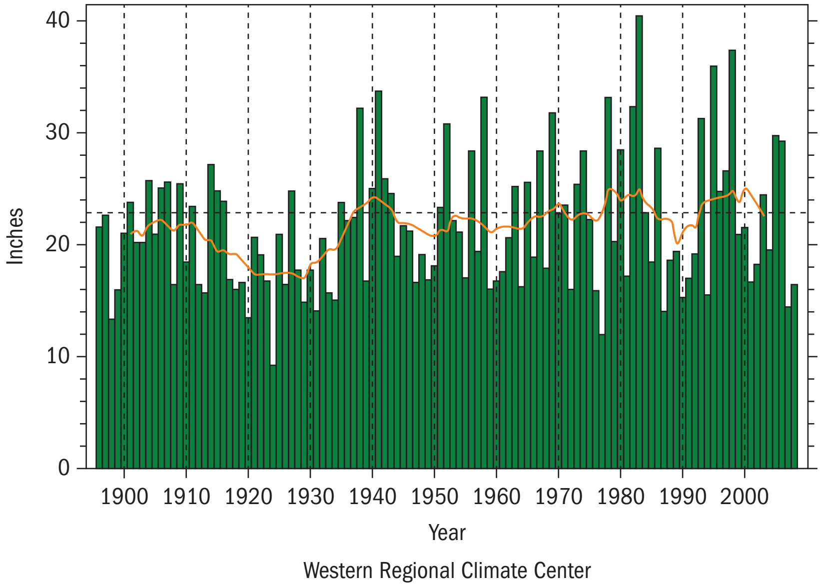
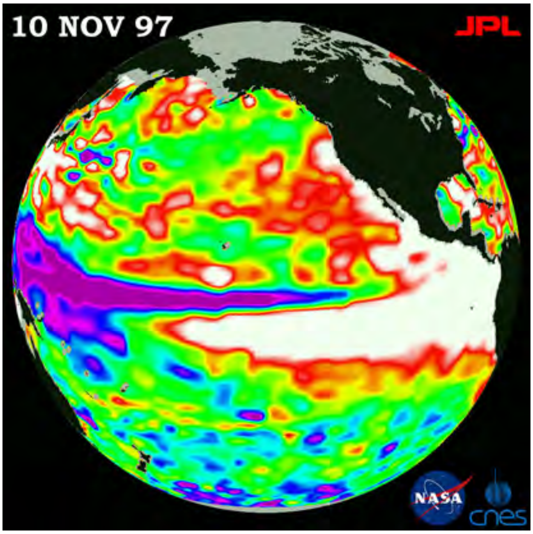


Figure 17. California statewide precipitation variability, 1896 to 2009 water years, October–September (redrawn from California Department of Water Resources 2013b).
NOTE: Orange line denotes 11-year running mean.

The Pacific Decadal Oscillation (PDO) is a separate 10- to 20-year ocean-atmosphere cycle producing less spectacular effects than El Niño, but with a longer duration. During positive phases of the PDO, an El Niño event can be amplified, while negative phases of the decades-long cycle may accentuate La Niña effects and lead to droughts.

Droughts

No simple criteria define a drought. Water providers in California may announce a drought emergency whenever there is too



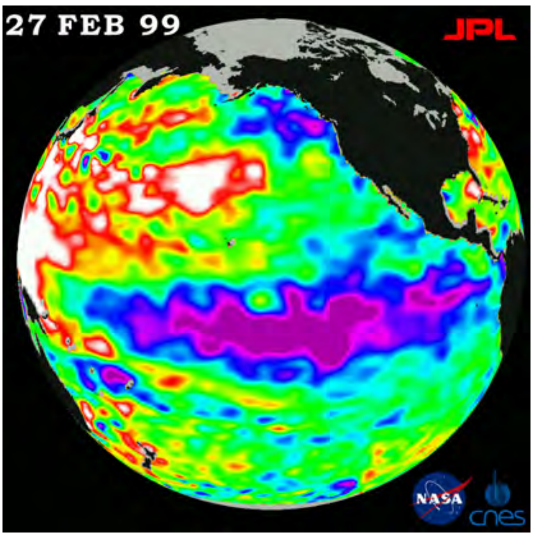


Figure 18a. El Niño conditions in the Pacific Ocean, November 10, 1997. Red and white colors indicate warmer water.

Figure 18b. La Niña conditions in the Pacific, February 27, 1999. Blue and purple indicate cooler water. NOTE: Images and captions of figs. 18a and 18b were combined as fig. 6 in *Introduction to Air in California* (2006, 25).

TABLE 1

Severity of extreme droughts in the Sacramento and San Joaquin Valleys

	Sacramento Valley runoff (avg 18.26 MAF/year)*		San Joaquin Valley runoff (avg 5.95 MAF/year)*	
	MAF/year	*% of Avg*	*MAF/year*	*% of Avg*
1929–34	9.78	54	3.33	56
1976–77	6.66	36	1.51	25
1987–92	9.98	55	2.73	46
2012–14	10.50	58	2.51	42

*50-year average in million acre-feet (MAF), from 1961 to 2010.

SOURCE: California Department of Water Resources (2014b).

little supply to meet demand. Different regions may perceive a given year's rainfall totals differently, depending on their local storage capacities, alternative supply sources, and regional populations. The most severe recorded California droughts occurred from 1929 to 1934 and from 2012 to 2014 (extending into 2015 as this book went to print) (table 1). The drought of the early 1930s set the standard that has been applied ever since for developing needed reservoir storage capacity in the state's water system, but the climate is changing and past records may no longer serve as relevant models. The single driest calendar year recorded came in 2014. The 2012 to 2014 drought was the most severe in the last 1,200 years (based on analysis of annual tree-ring growth records). The 2015 snowpack was only 5 percent of the average, the lowest ever measured. In the twenty-first century, climate change appears to be contributing to longer and more intense droughts, not just by reducing precipitation, but also by generating record high temperatures. The year 2014 was the warmest year in California since record keeping began (see fig. 74 in the "Climate Change and the Water Cycle" section, Chapter 4).

Since it is the mismatch between demand and supply that defines "drought," population growth is another key element. By the extreme drought year of 2014, California had 16 million more people than during the 1976–77 drought.

With such variability between seasons and between years, water storage systems, particularly reservoirs created by dams, have become important tools in moderating the swings in water supply. The Sierra Nevada snowpack is our largest and most effective "reservoir" (fig. 19), slowly releasing its water in spring and summer. A storm that drops one inch of rain in the lowlands may leave 10 inches of snow around the 5,000-foot elevation. The amount of water in the snowpack is not simply a product of snow depth. Snow that falls when it is cold often has less water content: one cubic foot of the powdery snow that falls at 14 degrees F may only produce 0.05 cubic foot of water, but at 32 degrees F, a cubic foot of snow may contain four times as much.

In 1929, the state legislature established a statewide California Cooperative Snow Surveys Program, coordinated by the Department of Water Resources (DWR). State, national, and private agencies pool data from about 300 snow survey sites sampled each winter (fig. 20). The snowpack data, along with precipitation records, help DWR water planners forecast the water supply that will be available each spring and summer.

Though accurate rainfall and snowpack records only go back a century, dendrochronologists studying the thickness of annual tree rings can identify major historic weather patterns. Near San Diego, 560 years of tree rings were studied in bigcone spruce

Figure 19. The Sierra Nevada snowpack on May 23, 2002.

(Pseudotsuga macrocarpa). Dry cycles averaging 15 years were found to be interspersed with wet cycles about 12 years long. A 420-year reconstruction of Sacramento River runoff data, also based upon tree rings, was used to establish the drought of 1929 to 1934 as the most severe in those four centuries.

Age dating of tree stumps that are now submerged in lakes and rivers has identified two epic drought periods in California during the Middle Ages. Stumps at Mono Lake, Lake Tenaya, and Walker River show two medieval droughts, one lasting 140 years and the other at least 100 years. The twentieth century

Figure 20. A snow survey site in the Sierra Nevada.

was not "normal" when compared to this longer record; it was, in fact, California's third or fourth wettest century of the past 4,000 years. Scott Stine, in his report on this research, noted, "Since statehood, Californians have been living in the best of climatic times. And we've taken advantage of these best of times by building the most colossal urban and agricultural infrastructure in the entire world, all dependent on huge amounts of water, and all based on the assumption that runoff from the Sierra Nevada will continue as it has during the past 150 years" (1994, 548).

Floods

At the other extreme, floods are equally normal products of the California climate. The Central Valley used to flood annually, becoming a great inland sea when the Sacramento and San Joaquin Rivers, carrying snowmelt from the Sierra Nevada, left their banks to reinhabit the floodplain of the valley floor. Fertile sediments deposited on that flat land were attractive to farmers. Once modern human settlements were established, attempts began to straitjacket the rivers with levees and dikes. Riparian forests were cut down so crops could be planted right up to the edges of the rivers. Towns also were planted, and some grew into major cities. Sacramento, the state's capital, is at the confluence of the American and Sacramento Rivers. Called "River City," it has a long history of floods. Concern about levees and upstream dams remains an issue today. For cities located on floodplains around the state, dams and levees built to prevent floods have often only postponed them.

When warm winter rain events, triggered by "atmospheric rivers," sometimes dubbed the "Pineapple Express," fall onto snow deposited earlier in the winter, rivers suddenly swell. About 40 percent of California's annual snowpack arrives suddenly in just a few atmospheric river events. Water planners and engineers established the "100-year flood" concept not to indicate the actual frequency, but to predict the likelihood of serious floods. Unfortunately, such predictions were based only on the records of flooding available since statehood, in 1850.

California experienced major floods in 1850, 1862, 1955, 1964, 1995, and 1997. The January 1997 event was the largest flood disaster in the state's history (defined by damage to human structures, rather than quantity of runoff water flowing over floodplains). That year 120,000 people were forced from homes and 300 square miles of agricultural land were flooded (fig. 21). Ironically, that flood was followed by a record-setting dry period

Figure 21. Trailer park flooded by the San Joaquin River in 1997.

from February through June 1997. Flooding in 1986 had also marked the beginning of a severe multiyear drought. Those kinds of events make managing for flood protection a challenging trick, one that often conflicts with the maximum storage of water for later use. If water is released during the winter to make room for spring floodwater, the result can be less summer storage.

Since the 1990s, extreme precipitation events in California increased by 20 percent. That may be a consequence of global warming, which is expected to produce wetter and warmer winter storms.

Despite our efforts at controlling them, floods have played an important role in natural water cycling in California, fertilizing floodplains and helping shape the landscape. Water in motion, whether liquid or frozen, also has the power to transform landforms. Glaciers carved broad, U-shaped valleys, such as

Figure 22. U-shaped granite basins scoured by glaciers where the Merced River drops over Nevada and Vernal Falls in Yosemite National Park.

Hetch Hetchy and Yosemite (fig. 22). Rivers have incised narrower, V-shaped canyons, such as the American River canyon in the Sierra Nevada foothills. They also carried debris sediments on down to the Central Valley, building its rich alluvial soils.

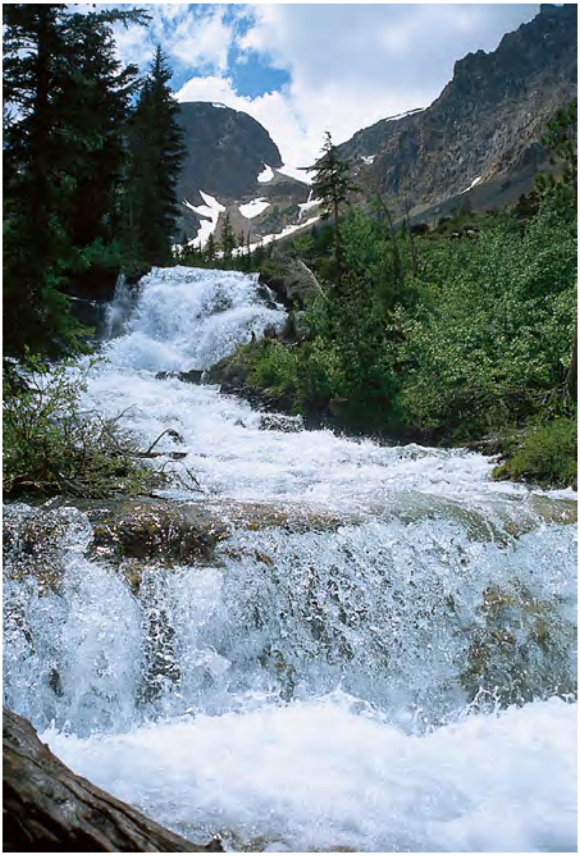


Figure 23. Mill Creek in Lundy Canyon.

John Muir listened to the voices of water as it did such work, and wrote of "silvery branches interlacing on a thousand mountains, singing their way home to the sea," or "booming in falls, gliding, glancing with cool soothing, murmuring" (1901, 181, 182) (fig. 23). Mountain streams, Muir said, sang "the history of every avalanche or earthquake and of snow, all easily recognized by the human ear. . .beside a thousand other facts so small and spoken by the stream in so low a voice the human ear cannot hear them" ([1938] 1979, 95).

Wherever rain falls from the sky over California and rivers sing of their interactions with the land, water speaks in eloquent voices across this state's water landscape.