## *Contents*

ONE

# At the Headwaters

> Crossing the summit of an elevated and continuous range of rolling hills, on the afternoon of the 30th of June we found ourselves overlooking a broad and misty valley, where, about ten miles distant, and 1,000 feet below us, the South fork of the Platte was rolling magnificently along, swollen with the waters of the melting snows. It was in strong and refreshing contrast with the parched country from which we had just issued; and when, at night, the broad expanse of water grew indistinct, it almost seemed that we had pitched our tents on the shore of the sea.
>
> *—John Charles Frémont, on reaching the base of the Colorado Rockies after traveling westward across the Great Plains, June 1843*

## SNOWFALL

In much of the world, a flowing river represents the excess water that cannot be held by the plants and soil along the river's course. The adjacent landscape overflows into the river, each tributary swelling the flow of the mainstem. In contrast, the stream flow that sustains the largest rivers of the western prairie begins far from the dry lowlands, and tributaries heading on the prairie

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contribute little to the mainstem. This is one of the paradoxes of rivers of the western prairie: flowing for hundreds of kilometers across some of the continent's driest and most open country, the rivers begin in, and are sustained by, abundant winter snows falling in deep, narrow valleys of the topographic exclamation point that is the Rocky Mountains.

Snow starts to fall on the Rockies west of the prairie during September. In most years, the early snowfalls barely persist. A warm air mass moves eastward from the Pacific Ocean, and the thin skin of new snow melts into the soil or sublimates into the cold, dry air of 4,000 meters elevation. Air temperature in the drier central and southern parts of the Rockies can resemble a yo-yo, fluctuating rapidly up and down by 20°C or more from day to day. Within a month, however, at least a portion of each new snowfall remains on the ground. Great rivers and oceans of moist air flowing steadily inland from the Pacific collide with cold, dry Arctic air flowing down the spine of the Rockies. The tumultuous collisions create wind-driven snow granules and feathery powder snowflakes. What began as a light dusting of snow in September quickly deepens to a continuous covering of white as each new storm gradually builds the snowpack. The prairie remains a desiccated landscape of cured tan grasses, but in the mountains the snow can reach depths of 5 meters.

A year of abundant snowfall in the Colorado Rockies reflects the transfer of immense amounts of energy across half the planet. Equatorial and tropical latitudes receive the bulk of the solar radiation reaching Earth. Much of this intense low-latitude sunlight falls upon the broad expanse of the Pacific Ocean, creating a wide band of warm surface waters about the equator. The sun in a sense cooks the tropical oceans, warming the surface water and creating much higher rates of evaporation than occur over colder portions of the oceans. As water vaporizes and crosses the boundary from sea to air, warm, moist air billows up toward the sky. Some of this moisture cools, condenses, and falls back to the sea as torrential rains. Some of the moisture remains aloft and flows out from the equator toward each pole. Below these massive currents of air, warm water floats on the cooler, denser water beneath, flowing across the ocean surface toward higher latitudes until the water gradually cools and sinks to greater depths. These surface currents transfer heat to the atmosphere before sinking into the cold darkness of the deep ocean and returning at depth toward the equator. This is part of the aptly named Great Ocean Conveyor Belt, an endless cycling between the Pacific and the Atlantic that carries heat up into the North Atlantic. Only because of this pattern is northwestern Europe warmer and more suited for agriculture and habitation than equivalent latitudes in Canada and Siberia.[1]

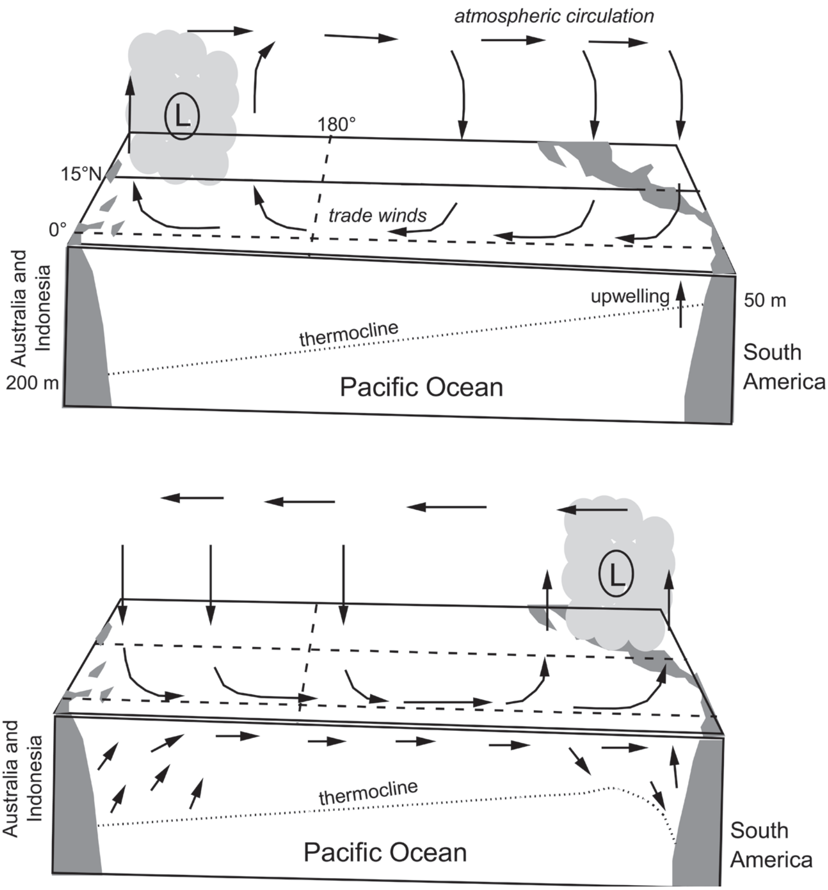
*By late January the upper elevations of the South Platte River drainage basin already have a thick snowpack that completely buries headwater creeks, as here in the Poudre River drainage tributary to the South Platte River. Melt water from the snowpack is vital to the ecological health of the rivers in the basin and to the existence of human communities.*

Most of the water vapor carried by air moving toward the poles from the equatorial oceans falls as precipitation before the air reaches 30° North and South. This is where the spent, dry air descends back toward Earth's surface before continuing at low elevations within the atmosphere back to the equator. The complete cycle is known as the Hadley Cell after the eighteenth-century gentleman who first described it. Unless another moisture source such as an ocean with warm surface water is nearby, drylands—prairie, pampas, veld, steppe, savanna, and desert—occupy continental interiors at 30°–40° latitude.[2]

This latitudinal belt accounts for a big chunk of the Southern Rocky Mountains within the United States. Every other mountain range between the Pacific and the Rockies only exacerbates the dryness. The ocean of moist air flowing eastward from the Pacific rides a topographic roller coaster, rising and cooling over each mountain range and dropping more of its precious moisture with each rise. By the time the air reaches the eastern half of the Rockies, there often isn't much water vapor left. These mountains receive snowfall each year only because of their great height. Most winds that flow eastward down the mountain front in winter come as warm, dry chinooks that rearrange anything portable in the landscape but do nothing to increase precipitation on the plains. This is a second paradox of the rivers of the western prairie. The Rockies make the prairie drier than it might otherwise be, but they also supply the major rivers of the prairie. These rivers are able to flow through much, if not all, of the year only because of the snow that falls and then gradually melts off the Rockies.

Air does not flow through the Hadley Cell as regularly as the hands of a clock making a circuit, however, and blips in the circulation pattern can create years of heavy snowfall in the Colorado Rockies. While warm surface waters flow toward the poles and cold water flows back toward the equator at depth, water also moves across the Pacific in east-west currents. Cold water wells up from the great depths off the west coast of South America and then flows west across the surface of the tropical and equatorial Pacific, warming as it moves and creating a persistent pool of warm water around Indonesia and northern Australia. Warm water means evaporation and heavy rainfall. Monsoon rains fall on the lands around the western Pacific from December to February during most years, supporting lush rainforests, while the Atacama and Sechin Deserts lie at the other end of the Pacific.

Every few years, for reasons still unknown, the entire pattern reverses. Sea level pressure, which is normally low over the western Pacific and high over the eastern Pacific, flips in a pattern known as the Southern Oscillation. Warm surface waters slosh back toward the eastern Pacific. Indonesia goes into drought, and western South America receives torrential El Niño rains during the Christmas season. The effects of the combined El Niño–Southern Oscillation (ENSO) spread from the




*Schematic diagrams of atmospheric circulation patterns over the Pacific Ocean during normal conditions (top) and El Nino–Southern Oscillation (bottom). Under normal conditions, the difference in atmospheric pressure between a high-pressure center in the southeastern Pacific and a low-pressure center (L in diagrams) over Indonesia and northern Australia drives easterly trade winds along the equator. This circulation depresses the thermocline, the boundary between warm surface water and underlying cool layers, to a depth of almost 200 meters in the western Pacific Ocean. Because the trade winds drive surface water offshore along the western coast of South America, the thermocline is shallow, and cool water wells up to the ocean's surface. The trade winds converge with westerly winds near Indonesia, and the moist, rising air brings heavy rain. The air flows eastward at high altitudes before sinking over the central and eastern Pacific, where the weather is dry. During El Niño, the east-west pressure difference decreases, and the trade winds cease or weaken in the western Pacific. Warm surface water flows back toward the east, and the thermocline is depressed off South America, so that upwelling water is warm. The warming of the sea surface leads to convective activity and heavy rains over the eastern Pacific and adjacent land masses. After Ramage (1986, 76).*

tropical Pacific like a rock thrown into a still pond. Normal rainfall and snow patterns change from southern Australia to India, and more abundant winter and spring precipitation delights skiers and water managers in the Colorado Rockies.[3]

Year-to-year variations in snowfall across the Rockies also reflect the Pacific Decadal Oscillation (PDO). The northern Pacific Ocean oscillates between warmer and cooler conditions at time spans of twenty to thirty years. Cool phases of the oscillation correspond to drought in Colorado as the surface of the Pacific cools off western North America. The cooling ocean reduces evaporation and inland transport of moisture. The jet stream is the express freight bringing much of this moisture inland, and changes in sea level pressure occurring during the PDO act like a giant switch, sending the jet stream further north. The last warm phase of the PDO persisted from 1977 to 1999, but during the past decade the PDO has alternated at shorter intervals between warm and cool phases.

Between the ENSO, the PDO, and other, less regular fluctuations, snowfall in the Rockies can bury the mountain meadows so deep that not a slight dimple reveals the little headwater creeks, or it can be so miserly that in midwinter the creeks still flow freely between whitened banks. These fluctuations in snowfall translate all the way downstream to the dry plains.

## SNOWMELT

A lot happens between a winter storm over the Rockies and stream flow in the rivers of the western prairie. First there is the snow itself, a much more complex entity than delicate little six-pointed flakes drifting quietly down. As a result of variations in the moisture content of the cloud in which the snowflake formed, air temperature when the snow fell, and wind speed at the surface on which the snow landed, not all snowflakes are created equal. Snow falling during the first part of the winter in the Rockies tends to be the light, fluffy "powder" snow that delights skiers. This is the low-density snow that seems bottomless when you fall into it and punch your ski pole down looking for support to get back up. As air temperatures grow warmer during March and April and strong winds buffeting the mountains break snowflakes into fragments that can pack together tightly, falling snow compacts into a dense, wet mass detested by homeowners shoveling their driveways.

The density of the snowpack exerts a vital control on how much water will actually melt out of the pack, as does the depth of snow. Depth is easy to measure, except that it varies quite a lot across the steep, wind-blasted topography of the Rockies. Density is more difficult to measure because it continues to alter once the snow has fallen. As the snow keeps coming—1 meter, 2 meters, 3 meters, 4 meters—the overlying weight compacts the snow at the base of the pack. In the dark, cold depths, a subtle alchemy occurs as delicate flakes with projecting points melt slightly under pressure and then re-freeze as larger, more spherical particles of greater density. Some of the re-freezing snow-water creates bridges between adjacent particles, further reducing the air spaces within the snowpack. Density of the snowpack progressively increases as snow accumulates, but the rate and degree of this increase vary. Sometimes layers of solid ice form within the pack through the combined effect of settling, melting, and re-freezing. Then again, extremely cold temperatures and relatively shallow snow depths can result in relatively little change in snowpack density.[4]

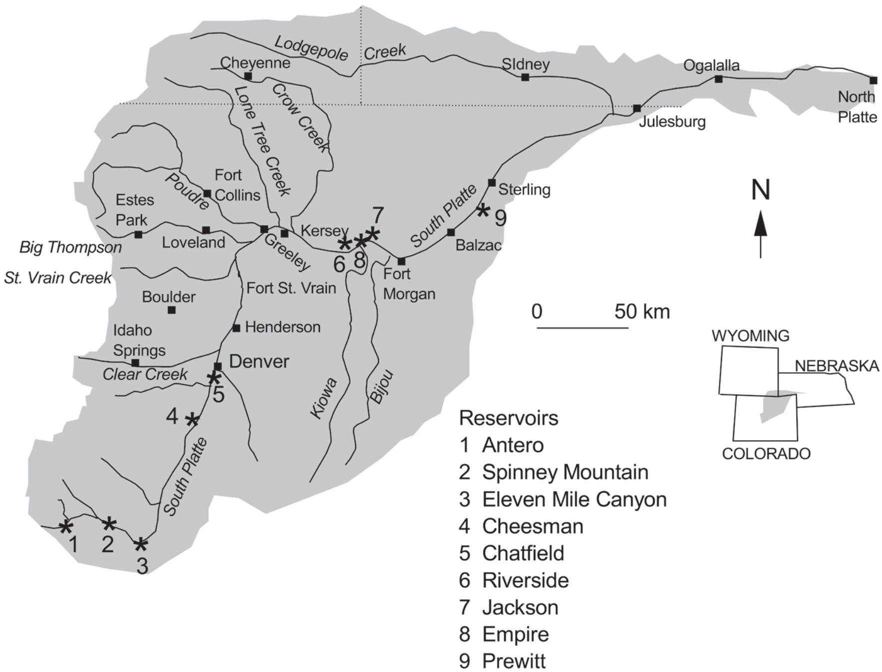
Snow has historically fallen during every month of the year in the Colorado Rockies. Spring typically begins with a series of "false starts" when snowstorms follow periods of warmth. Eventually, even the densest snowpack warms under the influence of increasing air temperatures and lengthening hours of sunlight. Feathery snow crystals and dense ice lenses vanish during the next few weeks as the snowpack disintegrates. Snow sublimates directly into water vapor as dry winds slip across the surface. Given the gusts that can blast across the Rockies and plains in springtime, it is surprising that any snow remains to melt into water. Yet some of the snow does melt at the surface before filtering down into the porous snow beneath or flowing across the surface crust of ice. Meanwhile, snow at depth melts and seeps downward. As melting increases, the snowpack behaves like a sponge, storing the melt water until it finally becomes saturated and water begins to percolate downward. Arriving at the base of the snowpack, some of the melt water infiltrates into the soil. Some of it accumulates to form a saturated zone that moves downslope toward a stream channel. All across the highlands the ground becomes mushy with water moving down toward the valleys.[5]

This is one of those recurrent miracles we take for granted: water filtering drop by drop into layers of sand and gravel in the soil through which it can seep or finding minute cracks in the seemingly impenetrable bedrock, forced onward by the pressure of the water behind it. Water following shallower underground paths reaches the stream channels in days to weeks, but some of the snowmelt filters down to the saturated zone below the water table, moving so slowly that it reaches the nearest stream channels months or years later. All of these millions of tiny, hidden pathways gradually fill up with water as spring continues into early summer, until the stream banks cut into mountain meadows dribble water like a leaky faucet.

Melting of the snowpack is largely invisible on the slopes while the snow is present. Early hikers may "posthole" at every step as they break through the icy surface crust and sink into the mushy snow beneath, but the only real indication of the progressive melting is the gradual rise in stream flow and the slow reemergence of snow-buried rocks and fallen logs. The most intriguing signs of all the action occurring in the snowpack appear once the melting is largely complete. Small, linear mounds of soil lie scattered across the slopes, discontinuous hieroglyphics written by rodents tunneling between their burrow entrances at the base of the snowpack. Melt water flowing downslope carries the sand and gravel dug up by the little animals, and the tunnels fill with sediment that remains briefly after the snow is gone. A few summer rains or the heavy tread of a passing elk and the perfect casts of tunnels smear into loose heaps of sediment.

Even without the mounds of pocket gophers, a mountain hill slope is not a smooth, regular surface. Snowmelt flowing across the recently thawed ground finds every little hollow and trough, concentrating into small rivulets in which water a few centimeters deep starts to erode exposed sediment grains. Occasionally, the soggy hill slopes give way abruptly in debris flows or landslides that move masses of sediment downslope. The winter streams of clear water flowing quietly patterned in green and black against the white ice give way to churning masses of milky brown color. Emily Dickinson described this transformation: "When the snows come hurrying from the hills, and the bridges often go." For most of the year, streams in the Colorado Rockies carry only a few milligrams of sediment in suspension per liter of water. During snowmelt this level can rise to more than a thousand milligrams per liter, although mostly remaining below a hundred milligrams.

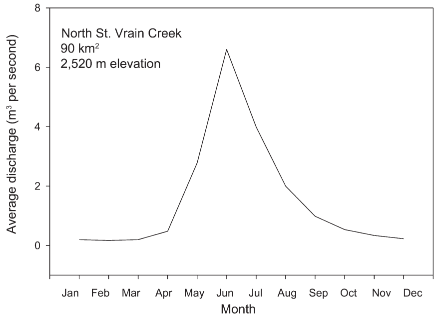
The mountain tributaries of the South Platte River spread widely from north to south along the spine of the Rockies, collecting melting snow like an enormous rake. Up near the Wyoming border, the Cache la Poudre River starts in a modest lake in Rocky Mountain National Park and flows northeast before curving eastward to join the South Platte near the city of Greeley. Named by French fur trappers for a cache of gunpowder left near the channel, the Poudre was Colorado's first federally designated wild and scenic river. Only a few kilometers from Poudre Lake, the headwaters of the Big Thompson River flow southeast through Forest Canyon, one of the most rugged backcountry areas in the national park, collecting water from cirque lakes named Azure, Inkwell, Lonesome, Rainbow, and Highest Lakes before funneling into the narrow gorge of Big Thompson Canyon and joining the South Platte on the plains. North, Middle, and South St. Vrain Creeks drain the mountains south of Longs Peak. Like the Poudre, the names of these rivers reflect the history of beaver trapping. Both David Thompson and Ceran St. Vrain trapped beaver in the region during the early decades of the nineteenth century. South of the St. Vrain drainage lie Boulder Creek, Clear Creek, Tarryall Creek, and the forks of the South Platte itself. The South Fork of the

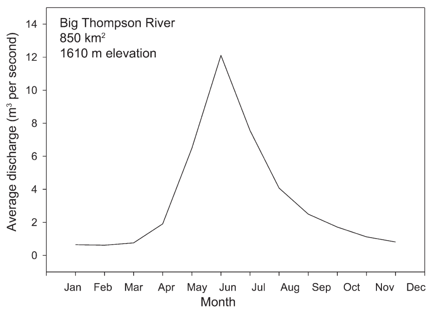


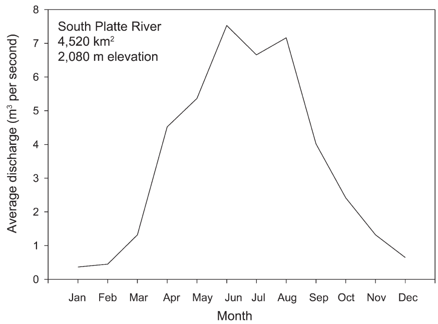

*Schematic map of the South Platte River drainage basin (shaded), showing selected tributary rivers (names italicized), some of the communities and historical sites (e.g., Fort St. Vrain) mentioned in the text, and nine of the major reservoirs on or near the South Platte mainstem (many other off-channel and tributary reservoirs exist).*

South Platte lies close to the northern headwaters of the Arkansas River, the next major river of the western prairie, just as the northern tributaries of the Poudre River lie close to the southern headwaters of the North Platte River. The abundance of melting snow flowing down steep slopes has carved the landscape into a dense network of streams, where only relatively narrow topographic high points separate adjacent drainages.

Spring snowmelt across the broad upper basin of the South Platte is a flush that spreads upward with time. As the nearby snow melts, stream flow at the lower elevations rises and then remains high while tributaries farther up the drainage basin swell with melting snow at the higher elevations. The result is a remarkable synchronicity in the timing of peak flow throughout the mountains. From streams near the top of the mountains at elevations of nearly 3,000 meters down to streams flowing beyond the mountain front at 1,400 meters elevation, peak flow commonly occurs between June 8 and 16 each year.




*Sample hydrographs from stream sites at various elevations throughout the mountainous portion of the South Platte River basin. These curves show average monthly flow for each site. The drainage area and elevation of the river at that site are also listed. The hydrographs clearly show the strong annual peak in June and the relatively low flows during October to April.*

Measurements of stream flow taken since the last decade of the nineteenth century record the consistent timing of peak flow, but changes now occurring in the mountains are altering this regular seasonal pulse. Global climate change is not simply an increase in mean air temperature. Storm tracks, extremes of temperature and precipitation, and timing of seasonal shifts also change. One of the most important alterations in regions such as the Colorado Rocky Mountains, where the gradual melting of the winter snowpack drives stream flow far beyond the mountains, is the possibility of less snowfall or faster snowpack melting. Less snowfall simply means less water, which has far from simple implications for survival in the western prairie. Faster melting can cause storage reservoirs to overflow early in the season but then be unable to store sufficient water for consumptive uses later in the summer and autumn. Global change might push the already boom-and-bust nature of seasonal fluctuations in stream flow on the western prairie to an extreme to which human and non-human communities will struggle to adjust.

Snow can also melt faster when it gets dirty. The Rocky Mountains, rearing up 4,000 meters, form a magnet to the world's winds, and the highlands catch other things besides snow. Increased dust results from changes in land use as diverse as replacing camels with four-wheel–drive vehicles in the Middle East and increasing drought and overgrazing in China. Once airborne, the dust becomes a globetrotter. Dust from the Middle East creates "blood rains" in England and settles as far away as Greenland and Caribbean coral reefs. Dust storms from China cross the Pacific Ocean and help drive air pollution levels close to federal health standards in Denver, Colorado. It is a small world after all.[6]

Ocean-crossing dust storms began to make national news during the first years of the twenty-first century. In 2006, National Public Radio reported that six dust storms hit the Colorado Rockies between December 2005 and May 2006. This resulted in more dust settling onto mountain snowpacks than scientists had recorded in at least two decades. Dust sounds vaguely benign, like something the mountain winds would just blow away. But dust settling onto an uneven snow surface acts like a dark blanket spread across the snow, increasing the rate of snowmelt much more significantly than the steadily increasing temperatures do. The combined effects of all the dust and anomalously warm temperatures during spring and summer 2006 showed up in stream flow that year. Peak flows were just over half to three-quarters of average values, even though the snowpack had been at or slightly above the thirty-year average at the end of March. The problem was that the snowpack was gone about a month early, by the end of May. Scientists predict that such changes in timing and volume of snowmelt will continue to grow more pronounced as climate warms.[7]

## LIFE IN THE FAST LANE

The tributaries of the mountain tributaries—tiny, unnamed creeklets that rise from a spring in an alpine meadow or a seep at the base of a talus slope—coalesce into small lakes perched on the steep slopes near the Continental Divide. Glacier ice coalesced here in the past, and the bouldery rampart of a glacial moraine forms the downslope margin of each lake. Water overflowing from the lake cuts a channel through the moraine and leaps downslope in waterfalls and cascades. Tannic acids released by the pines stain the cold water a light, clear brown, like weakly steeped tea. Vertical drops and big rocks beat the brown water to a white froth. Any plant or animal living in these mountain creeks adapts to cold water with plenty of oxygen, fast currents, and limited sunlight where the creeks flow through forests.

Most of the animals that live in the creeks, at least on the creek bottoms, are insects. Ecologists refer to the streambed as the benthic environment from the Greek *benthos*, for depths of the sea, and the turbulent world of the creek bed creates challenges as great as those in the deep, dark sea. Where sunlight reaches the channel, algae and aquatic macrophytes can grow. In the mountain streams of the South Platte catchment, macrophytes are limited to mosses, lichens, and liverworts. Much of the photosynthesis occurs in the periphyton (from the Greek *peri* for "around" and *phyton* for "plant"), an assemblage of diatoms, green algae, blue-green algae, bacteria, and other microorganisms attached to submerged rocks and logs. This is the greenish or brownish slime a fisherman slipping on a rock may curse, but it provides a banquet for the benthic insects. Bits of fine organic detritus trapped among the living cells, like food crumbs in a shag carpet, further increase the nutritional value for insects that can digest such material. Ecologists refer to the benthic insects that feed on periphyton as scrapers or grazers. Using mouthparts structurally suited for rasping, tiny mayfly nymphs move among the creekbed rocks as steadily as mountain goats on land. Similar to goats that scramble on muscular legs up steep, rocky slopes to reach succulent plants, the benthic grazers can move through the rushing water thanks to bodily adaptations such as flattening, streamlining, claws or hooks, and friction pads. Where the plants are too big to simply rasp off the rocks or logs, herbivore shredders mash up the green tissues into ingestible chunks.[8]

In portions of the creek where shade limits photosynthesis, plant parts dropped from the riverside forest or carried downstream on the current provide the food for aquatic insects. Detrivore shredders such as stonefly nymphs are the little street sweepers of the creek bed, converting shed plant parts into living insect tissue. Gougers help the shredders by boring into submerged logs, riddling the wood with tiny tunnels that promote decay and eventual breakage and dissolution of the wood. Collectors take care of the finest leftovers, the nearly microscopic bits carried along suspended in the water. Some filter-feeding collectors construct tiny silk nets that they drape across a crevice between rocks; others simply expose hair fringes along their bodies that trap moving particles. Net-spinning caddisfly nymphs fish from a cave, projecting their fine silk nets from a snugly fitting tube of sand grains cemented together and attached to the creek bed. It's good to have a cave to retreat into when predatory insects come around.[9]

Stoneflies, mayflies, caddisflies, dipterans, and elmid beetles together make up the benthic fauna of the mountain streams. For most, the stream is the world of their youth, from which they move to a terrestrial adult life. If insects possessed consciousness, the loss of youth would be particularly poignant: the mayflies, aptly named Ephemeroptera from the Greek "for a day," live as adults for at most a few days. Some live only an hour. Their juvenile phases last longer: aquatic insects can live in juvenile stage for more than two years. Juvenile insects are known as larvae, from the Latin for "ghost" or "mask," because they bear so little resemblance to an adult or as nymphs from the Greek for "bride," derived from the nymphs who resided in streams in classical mythology.[10]

Spring and early summer can be a lean time at the benthic insect banquet table. The snowmelt flood carries pulses of sand and fine gravel along the creek bed, scouring the periphyton. If the collectors can hang on, a lot of food is moving by in the current, but it's traveling fast. Partly because of seasonal fluctuations in water temperature and food supply, most aquatic insects living in the mountain streams take at least a year to complete the juvenile, aquatic phase of their lives. Benthic insects down on the prairie are more likely to rush through more than one generation in a year.[11]

As the little creeks join together, they form streams large enough to support fish. Much of the energy in the steepest streams is expended simply getting around the big obstacles in the creek bed. Water plunges off vertical drops and breaks into standing waves, gushing over and around boulders and logs as wide as the flow is deep. Where the water has sufficient energy to rearrange the boulders dropping in from rockfall or left by retreating glaciers, alternating drops and shallow pools form a flight of stairs in the steeper channel sections. As the creek grows larger and gentler, these steps and pools give way to pools and riffles. Rocks exposed in the creek bed become smaller, and the current is better able to rearrange them. Where a giant boulder or a logjam constricts the channel, the faster current through the constriction scours a pool into the creek bed. Backwaters upstream from the constriction and eddies along its margin trap finer sediment and organic materials, and here the fish wait for food to drift by or rest from the exertions of moving against the swift current. Benthic insects such as burrowing mayflies like eddies, too: here, they can burrow into the sand and fine gravel in search of organic detritus. The rule of thumb—or tarsus, for insects—is that the more diverse the streambed, the greater the variety of benthic insects present. Likewise, the more diverse the habitats, the greater the variety of fish present.

Beavers (*Castor canadensis*) create an important source of habitat diversity by building low dams across channels. These dams pond water and trap sediment and nutrients moving downstream. As sediment gradually fills the channel upstream from the beaver dam, floods are more likely to spill over the channel banks and submerge the adjacent low-lying valley bottom. Water filters down into the floodplain sediment, raising the water table and creating wetlands and habitat suitable for dense thickets of willows, a preferred food source for beavers. Beavers in effect keep their larders well stocked with tasty plants by maintaining the wet soils that sustain willows.

Having stated that fish diversity correlates with habitat diversity, I must admit that the mountain tributaries of the South Platte are not world record holders for fish diversity. Winter is the annual bottleneck here, with only those species that can withstand extremely cold water temperatures able to survive. Not much water is required. Fish biologists have cored down through thick winter ice to find native trout hunkered down in crevices among the boulders, surviving in only a few centimeters of water, their metabolism slowed nearly to a stop until the returning warmth of spring brings flowing water and food. Greenback cutthroat trout (*Oncorhynchus clarki stomias*) was the only fish historically abundant in the mountain streams. In addition to the physiological adaptations required to live in perennially cold water, mountain streams provide relatively few choices of neighborhood. Although they have deep pools scooped around logjams and gravel-bedded eddies above riffles, mountain streams flow through narrow valleys that lack the diversity of lowland streams, where floodwaters spread periodically into secondary channels and through floodplain wetlands.

Fishermen took it upon themselves to increase fish diversity in the mountain tributaries of the South Platte. Even as native trout grew scarce during the late nineteenth and early twentieth centuries from the combined effects of over-fishing and habitat degradation resulting from timber harvest, placer mining, and flow regulation, streams in the region became famous as a scenic fishing destination. Seeking to enhance their sport, fishermen introduced game fish that fought hard for their lives when hooked. Now, exotic brook trout (*Salvelinus fontinalis*) dominate lower reaches of the mountain tributaries, rainbow trout (*Oncorhynchus mykiss*) occupy the larger channels down to the mountain front, and brown trout (*Salmo trutta*) swim in the waters just downstream from the mountains. Native greenback cutthroats remain only in the highest-elevation tributaries, where a physical barrier such as a waterfall limits upstream migration by the introduced species.[12]

## HIDDEN WATERS

The great swelling of stream flows produced by melting snow across the mountains continues hundreds of kilometers beyond the mountain front, creating higher flows all across the arid western prairie. Yet the rivers continue to flow beyond the mountain front once the snow of the high country has completely melted. This base flow fed by groundwater integrates the melting snow and falling rain of centuries that filtered deep into the subsurface and moved downslope into stream channels much more slowly. Here again the distant Rockies are like the wizard behind the curtain, invisibly controlling the dynamics of rivers on the plains. Base flow that keeps the rivers vital throughout the year comes from an aquifer—an underground storage reservoir—diffused through thick, porous layers of sand and gravel. The sand and gravel are the erosional debris of the ancestral Rockies spread in a mantle about the base of the contemporary mountains.

If a drought parches the region for years at a time, the peak flows fed by surface runoff decrease noticeably, but the base flows remain relatively constant thanks to that underground reservoir.

Pumping of subsurface water for irrigated agriculture and municipal and industrial consumption has increased so much within the past few decades, however, that underground water levels, and the base flow they feed, can drop. Groundwater levels in the mountains rise with snowmelt and seasonal infiltration, peaking between March and June. Groundwater is pumped at these high elevations mainly for individual household supplies, which does not affect water levels except during extreme droughts. Groundwater levels further downstream, on the plains, rise naturally in response to recharge from stream flow soaking into the ground. Groundwater levels on the plains also rise as irrigation water is spread across farm fields or drop as water is pumped for irrigation or municipal use. Where irrigation water infiltrates, plains groundwater tables reach their highest levels between July and September. Where subsurface water is extracted, groundwater tables have been steadily falling for decades.[13]

## STREAM FLOW AND SEDIMENT

The Rocky Mountains are the great, slow-beating heart for rivers of the western prairie, pumping out snowmelt that pulses eastward across the plains each year. But this annual pulse varies in strength. An El Niño–Southern Oscillation episode strengthens the pulse; a drought weakens it. At smaller scales, a wildfire that burns the protective vegetation off the slopes and reduces the ability of the soil to absorb rainfall and snow melt dramatically increases the flow of water and sediment for a year or two in a portion of the mountains. A widespread die-off in conifers attacked by insects reduces interception of snowfall and slightly increases stream flow.

Human uses of the mountain landscape can also alter the pulse of melt water that nourishes the rivers of the western prairie. We might like to think of ourselves as doctors regulating the pulse for better health, but our effects are not usually that disciplined. Widespread timber harvest is even more effective than wildfire in reducing the stability of hill slopes and the infiltration of precipitation. This can increase stream flow, but the effect is usually offset by much greater sediment movement, producing debris flows and streams filling with sediment instead of more clear water.

Urbanization and the building of roads that accompany timber harvest can cause more persistent alterations of the pathways by which water and sediment move downstream. Snow and rain do not soak into ground covered by pavement.

Instead, the water funnels into storm sewers that rapidly dump it into streams, causing larger, quicker floods. Perhaps more important, mountain communities need dependable water supplies, and they draw from the flow of adjacent streams or dam the streams to create reservoirs. Ski resorts pull water from one stream in autumn to make snow, and the manufactured snow melts into another stream the next spring. Roads interrupt the subsurface flow paths of water moving toward stream channels. Roads also increase the movement of sediment into streams by creating unstable points on the slope that give way in landslides or by leaking sediment from erosion of unpaved roads and sand applied to paved roads to improve traction during winter. Pure mountain spring water became an advertising slogan because we think of mountains as remote and pure, but urban areas in the mountains introduce the same contaminants to mountain streams that plague urban areas in the lowlands. All of the nasty things that come out of our vehicle tailpipes and our houses and yards—heavy metals, pharmaceuticals, phthalates from plastics and endocrine disrupters from personal-care products, pesticides and other synthetic chemicals—flow with the waters coming from urban areas and roads.[14]

Each of these variations in the quantity and quality of water and sediment flowing down from mountain sources affects the rivers of the western prairie. Time-lapse photography of the past 2 million years would show the pulses of water and sediment waxing and waning as valley glaciers in the upper portions of the Rocky Mountains advanced and retreated. The contemporary landscape at the base of the mountains records each glacial change in terraces that rise like flights of steps beside the river courses. Warmer, drier intervals between glacial advances left wind-blown dunes between the rivers, although a thin veneer of grasses and cacti now covers these dunes. The largest mountain glaciers melted about 10,000 years ago, but little cirque glaciers grew and shrank back enough during the intervening time to cause periods of sediment accumulation along the rivers of the western prairie, followed by periods of erosion when the stream channels cut down through the older sediments. Fluctuating water and sediment pulses from the mountains alternately created narrow, sinuous rivers bordered by stands of deciduous trees and floodplain wetlands down on the plains or wide, shallow rivers divided among a thousand shifting sand bars and stream banks largely bare of trees.

The most recent great shift in river conditions on the western prairie occurred within the past century in response to human land uses. Changes so swift that they are clearly recorded in maps and photographs spanning only a few decades of time have left many of the native plants and animals of the plains rivers struggling to survive in the early twenty-first century.

## NOTES

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