The Colorado River

Introduction

The mean annual precipitation for much of the western United States is less than 20 inches and it is far from evenly distributed (Figure 1). John Wesley Powell placed the boundary for dry-land agriculture, that is, agriculture that does not require irrigation water, at 20 inches of precipitation per year and noted that much of the US "beyond the 100th meridian" was poorly suited for agriculture without irrigation projects that tap the streamflow resources of the region ([44] and [37]). The principal tributaries of the Colorado River have their headwaters in the mountainous regions of Wyoming, Colorado, and New Mexico (Figure 2), but much of the Colorado River basin lies in the arid region of the southwestern US.

By volume the Colorado River (Figure 2) is far from the largest river in the United States, or even in the West. But as one of the only sources of water in the region, the Colorado River has played a prominent role in development of the arid West over the last century and a half. Efforts to control, divide, and transport the waters of the Colorado River have provoked political conflict and provided an arena for debate about contentious economic, political, and environmental issues ([43]). Over the last century the primary result of these efforts has been to transform the Colorado River into one of the most intensively controlled rivers in the world. The transformation of the Colorado River has paralleled the development of the arid southwest, most strikingly seen in the urban landscapes of Los Angeles, Phoenix and Las Vegas, cities that could not exist in their current form without the Colorado River.

John Wesley Powell and the Surveys of the Colorado River

On May 24, 1869 John Wesley Powell and nine fellow explorers set off from Green River, Wyoming on an expedition down the Colorado River, one of the country's last unmapped regions (Figure 2). The landscape Powell and his crew encountered was unique and inhospitable. An array of canyons, gorges, and mesas surrounds the river on both sides. Although they faced considerable difficulties, the Powell expedition eventually reached the junction of the Colorado and Virgin Rivers, after the arduous journey through the Grand Canyon (Figure 2). Aside from being a remarkable feat of exploration, the 1869 expedition laid the groundwork for a series of comprehensive surveys that finally charted the unknown regions of the West. Powell completed a second expedition down the Colorado River in 1871 - 1872 and continued survey work through 1879. Along with Powell, the Colorado surveys included two of the preeminent geologists of the 19th and early 20th centuries, Clarence Dutton and Grove Karl Gilbert ([31], [33] and [44]).

Powell's scientific interests centered on rivers and their relationship to the landscape. The most striking scientific questions concerning the Colorado River focused on the physical processes that created the spectacular landscapes of gorges and canyons (Figures 3). The artist Thomas Moran accompanied Powell to the Grand Canyon in 1873 and this trip provided the material for his painting "Chasm of the Colorado" (Figure 4). Moran would paint the Grand Canyon many times, but never again with the alienating effect of his initial work. Artists of the Rocky Mountain school of painting, like Moran and Albert Bierstadt, presented images of the West that celebrated nature following Ruskin's view that "every painting should speak without ambiguity about the divine order of the universe" ([44]).

Powell's conception of nature was different and reflected emerging scientific ideas of the late 19th century. Scientific orthodoxy of the early 19th century held that landscapes like the Grand Canyon were the product of a great flood - the Genesis Flood. This viewpoint is associated with *catastrophism*, the doctrine in geology that the features of Earth's surface, such as mountains, valleys and rivers, were formed by cataclysms - rare and short-lived events. In the late 18th century, James Hutton developed a competing theory for interpreting geological features, *uniformitarianism*, which centers on the notion that processes now at work on and within the Earth have operated with general uniformity through long periods of time and are sufficient to account for all geologic change. Hutton's work was influential in shaping Charles Darwin's ideas on evolutionary biology. One of John Wesley Powell's most important scientific contributions was establishing a firm foundation for uniformitarian interpretations of the landscape of the Colorado River.

Tectonic processes linked to mountain building, especially folding, faulting and volcanic activity, contributed to the distinctive features of the Colorado River. Powell observed that in certain courses of the Colorado River, the channel had developed across highly resistant strata, while in others the pattern of the river followed weaknesses imposed by the geologic strata. In some reaches, which Powell termed *consequent* reaches, the course of the river is a direct consequence of the original slope of the surface upon which it developed. An *antecedent* reach is older than the uplift that it crosses; the stream has been able to maintain its course by eroding downward as the land surface rises; the Grand Canyon is the most dramatic example. A river reach is *superimposed* if it was established on a preexisting surface, now eroded; the course is unrelated to the present underlying geological structure. The processes that Powell and his colleagues put forward for explaining the structure of the Colorado River require long periods of time, millions of years; within decades, scientific orthodoxy in geology had shifted to a uniformitarian perspective.

The Colorado Plateau province is a physiographic unit that contains much of the central portion of the Colorado River (Figure 5). It centers on the Four Corners region, marked by the intersecting boundaries of the states of Colorado, Utah, New Mexico and Arizona. Clarence Dutton conceptualized the terrain of the region in terms of a series of elevation breaks which he termed the *Grand Staircase*. The tectonic processes which shaped the Colorado River are vividly expressed though the topographic features of the Grand Staircase (Figure 6).

Powell used the notion of *base level* to characterize the elevation below which a stream cannot erode its bed. The ultimate base level of a river is the elevation of the ocean, or interior lake, into which it flows. Fisk's study of base level changes in the Gulf of Mexico on Mississippi River structure and evolution illustrates one area in which the notion has played a central role ([10] and Chapter 1). Powell's conception was broader and includes the role of *local base level* in controlling the processes of erosion and transport of sediment through a river system. The *longitudinal profile* of a river, i.e. the relationship between bed elevation and downstream flow distance, provides a compact summary of the variation of local base level along a river (Figure 7).

In Powell's journal entries from the 1869 Colorado River expedition prior to entering the Grand Canyon, he described the rapids they had already encountered and speculated on what was yet to come - "may be, we shall come to a fall in these canyons we cannot pass, where the walls rise from the water's edge ... and where the water is so swift that we cannot return"([31]). Luna Leopold took Powell's concerns as the point of departure to examine how the end-member example of the canyons of the Colorado River shed light on general questions about river structure ([23]). For hundreds of miles the Colorado River alternates between flat pools and steep rapids, but there are no waterfalls. A characteristic feature of rivers is to maintain a uniform profile of water surface elevation in a downstream direction, modulated by an alternation of low-gradient pools and higher gradient riffle or rapid reaches (see also [21]). Even in the exceptional case of the Colorado River gorges, this pattern holds. Leopold wrote: "the river seems encased in a vise so confining and limiting that any freedom of action or movement seems to be foreclosed. In fact, however, the river has nearly all of the characteristics of an unconfined channel, save one, the tendency to move laterally. The Colorado adjusts its depth and velocity by scour and fill of the bed in response to changes in debris load. It formed and maintains bed alternations of deep pool and shallow rapid by the construction of gravel bars. The river profile, except for the alternation of pool and rapid, is smooth and nearly straight" ([23]).

The exchange of ideas between biology and geology went both ways. The diffusion of Darwinian ideas into geology promoted the thinking that rivers and other landforms exhibit a characteristic sequence of evolutionary steps, with the most notable examples being William Morris Davis's *cycle of erosion* theory of landscape evolution and J. Hoover Mackin's notion of the *graded stream* ([26]). Although the views of Mackin and Davis were influential, modern thinking has followed G. K. Gilbert's notions of dynamic equilibrium developed from his Colorado River studies of the Henry Mountains ([12]). Gilbert's ideas of river and landform development have more in common with punctuated equilibrium models of evolution ([7]) than with the 19th and early 20th century ideas that motivated Davis's cycle of erosion.

“The Paroxysmal Precipitation of the Desert”

“Sooner or later the cloudburst visits every tract, and when it comes the local drainageway discharges in a few hours more water than is yielded to it by the ordinary precipitation of many years... So far as may be judged from the size of the channels draining small catchment basins, the rare, brief, paroxysmal precipitation of the desert is at least equal while it lasts to the rainfall of the fertile plain.” G. K. Gilbert [1890]

Gilbert used the term paroxysmal in its dictionary formulation, “marked by bursts of destructive force or intense activity” (Merriam-Webster Dictionary), to describe the storms that shape the channels of Southwestern US drainage basins. Gilbert’s insights were grounded in observations made during field investigations with the Powell Survey, especially those leading to his landmark studies of the Henry Mountains ([12]) and Lake Bonneville ([13]). Gilbert’s vivid description highlights a central issue concerning rivers in the arid lands of the Colorado River - variability of rainfall in time and space is exceptionally large.

Cloudburst floods in the Southwestern US are typically produced by thunderstorms during the *North American Monsoon* season, which peaks during July and August and extends into September (Figure 8). A *monsoon* is a seasonal reversal of the winds and the most prominent is the East Asian Monsoon which transports moist air from the Indian Ocean to the continental region of East Asia. Thermal contrasts between land and ocean drive all of Earth's monsoon circulations; their seasonal cycle is controlled by heating of high-elevation mountain regions. The North American Monsoon is weaker than the East Asian Monsoon, largely because the Tibetan Plateau is larger and higher than the Mexican Plateau.

The increase in thunderstorm frequency during late June and early July in the Southwestern US (Figure 8) is directly tied to the sharp increase in water vapor transport from the Pacific Ocean by way of the Gulf of California ([1] and [16]). The North American Monsoon is characterized by "burst" periods of particularly strong flow of moist air from the Pacific Ocean into the Southwestern US. Thunderstorms that form during burst periods typically move from southwest to northeast; in Figure 9, the mean motion of storms that produced flash floods in the Colorado Plateau during the period 1998 - 2015 is shown for a sub-region that contains Fort Pearce Wash and the Virgin River basin. Wind direction from the southwest not only signals the transport of water vapor from the Pacific but also determines the direction that storms will be "steered".

There are striking spatial contrasts in thunderstorm frequency over the Colorado Plateau and these features are strongly linked to terrain (Figure 10). Thunderstorms are most common in high elevation plateau regions. Thunderstorm frequency varies by more than a factor of 5 from the high elevation regions to low elevation regions including Lake Mead and Glen Canyon (see Figure 10 for locations).

A "cloudburst" in southern Utah on September 14, 2015 resulted in 20 flash flood fatalities, making it the most deadly natural disaster in Utah history. It is the quintessential example of the storms Gilbert described as the "paroxysmal precipitation of the desert". Of the 20 fatalities, 13 occurred in Hildale, Utah and resulted from flooding in Short Creek (Figure 11). The Short Creek Community was settled in 1913 by a polygamous offshoot of the Mormon Church, the Fundamental Church of the Latter-Day Saints, or FLDS Church. The remote location was selected so that the group could practice plural marriage without interference from state or federal officials. The 13 fatalities from the September 2015 Short Creek flood were women and children from the FLDS Church community.

The duration of heavy rainfall over Short Creek was short, more than 10 minutes but less than 20, and catastrophic rainfall was focused on the 5 km^2 Maxwell Canyon tributary of Short Creek (Figure 11). The wave of water that carried three cars and 13 people into Short Creek came down the Maxwell Canyon tributary. Rainfall intensity decreased rapidly after the storm passed Maxwell Canyon, but extreme rainfall redeveloped as the storm approached the East Fork Virgin River. An additional 7 fatalities occurred 20 km north of Hildale when hikers were trapped by floodwaters in Keyhole Canyon in Zion National Park.

Keyhole Canyon has an upstream drainage area of 1 km^2 and is located along the lower margin of the East Fork Virgin River drainage basin (Figures 11 and 12). The storm that resulted in 7 flash flood fatalities in Keyhole Canyon at 1 km^2 scale also produced the largest flood peak in ihe 26 year stream gaging record of the East

Fork Virgin River at 890 km^2 (Figure 12). Extreme rainfall in the East Fork Virgin River lasted no more than 20 minutes and was restricted to a small portion of the watershed (Figure 12).

Flooding on September 14, 2015 was produced by one of the most intense thunderstorms in Utah history; the storm produced copious lightning and hail, especially as it passed over the Vermillion Cliffs, which mark the western boundary of Maxwell Canyon (Figures 13 and 14). The storm developed during a monsoon burst period, with strong atmospheric flow from the southwest producing near-record water vapor in southern Utah. Like most monsoon thunderstorms, the storm moved from southwest to northeast, but its storm speed, greater than 50 $km\ h^{-1}$, was exceptional.

During the critical period of heavy rainfall over Maxwell Canyon (Figure 14), a hail core was located in the northwest portion of the storm, with lines of convective rainfall extending to the east and south of the storm core. The line of convective rain extending south of the storm core was located upwind of Maxwell Canyon. Polarimetric radar measurements point to this portion of the storm as the agent of extreme rainfall rates over Maxwell Canyon, with melting hail and liquid water shed from hail the source of rainfall at the surface. Strong downdrafts associated with negative buoyancy in the north-south oriented convective line contributed to extreme rainfall rates over Maxwell Canyon.

The period of extreme rainfall indicated by polarimetric radar measurements was short-lived, forming shortly after 2200 UTC and diminishing after 2216 UTC (Figure 14). Although extreme rainfall decayed rapidly after the storm passed Maxwell Canyon, it redeveloped as the storm approached the East Fork Virgin River and Keyhole Canyon (Figure 15). Like flash flooding in Maxwell Canyon, extreme rainfall over Keyhole Canyon and the East Fork Virgin River was linked to a small region of extreme rainfall rates in close proximity to the hail core of the storm . Multiple pulses of extreme rainfall rates, with weaker rainfall occurring between the rain pulses, characterized the storm producing catastrophic flooding in southern Utah on September 14, 2015.

Peak discharge measurements made by the USGS for the 14 September 2015 flood in Short Creek at a drainage area of 58 km^2 and for the Maxwell Canyon tributary at a drainage area of 5.3 km^2 are both 270 m^3 s^{-1}. The Maxwell Canyon flood peak is on the envelope curve of flood peaks for the Colorado Plateau (Figure 16), illustrating the exceptional nature of the September 14, 2015 storm. Envelope curves provide representations of maximum observed discharge as a function of drainage area ([6]) and have provided a framework for examining upper bounds on flood peak distributions, most notably for the Colorado River ([8]).

Short Creek is a tributary to Fort Pearce Wash, which joins the Virgin River above Lake Mead (Figure 17). More than 11 hours elapsed before the flood wave from Short Creek reached the outlet of Fort Pearce Wash. During that time the peak discharge decreased from 270 m^3 s^{-1} to less than 50 m^3 s^{-1} (Figure 18). The decrease in discharge from Short Creek to the Fort Pearce Wash gaging station resulted from flood peak attenuation and channel infiltration losses. Decrease in peak discharge from attenuation results principally from expansion of the flood wave onto a broad floodplain. The downstream variation in channel and floodplain size determines the downstream pattern of flood peak attenuation. In arid regions of the Colorado River, many stream channels are dry for much of the year. In these settings infiltration into the channel bed can greatly diminish flood peaks.

The record flood peak in Fort Pearce Wash at a drainage area of 3400 km^2 has the same magnitude as the 14 September 2015 storm in Maxwell Canyon at 5 km^2. The hydrograph for the July 2012 flood (Figure 18) illustrates the common usage of "flash" as a verb for Colorado Plateau rivers. From a dry channel, discharge increased to the 270 $m^3\ s^{-1}$ peak in 40 minutes, with a similarly rapid falling limb of the hydrograph. Fort Pearce Wash flashed in response to extreme rainfall rates from a severe thunderstorm that tracked from southwest to northeast through the region from 2200 to 2400 UTC (Figure 18). Like the record flood for the East Fork Virgin River on 14 September 2015, the rapid rise and fall of the Fort Pearce Wash hydrograph for the 16 July 2012 storm was produced by extreme rainfall rates from a monsoon thunderstorm during a short period as it passed over the basin outlet (Figure 18).

The flood hydrology of Colorado Plateau watersheds over a wide range of basin scales is dependent on hydrologic response to small areas of intense rainfall and channel infiltration losses over downstream channel segments. There is relatively weak dependence of flood peaks on drainage area. For drainage areas smaller than 10,000 km^2, monsoon thunderstorms are often responsible for record flood peaks, as in Fort Pearce Wash and the East Fork Virgin River.

The picture of extreme floods changes in the lower Colorado River. At the Lee's Ferry stream gaging station, which has a drainage area of 290,000 km^2, the flood of record is 6230 $m^3\ s^{-1}$ and it occurred on June 18, 1921. Like all major lower Colorado River floods, the June 1921 flood peak was due to rapid snowmelt. The most extreme floods result from a combination of exceptionally large snowpack in mountainous portions of the watershed and rapid warming, typically due to warm air surges associated with extratropical cyclones. Rainfall from Fall - Winter extratropical cyclones have produced the extreme flood peaks for watersheds with drainage area ranging from 1,000 to 100,000. km^2. Elements of the climate system that control the occurrence of extreme floods in the Colorado River cover physical processes ranging from the dynamics of monsoon thunderstorms to the tracks of Pacific extratropical cyclones.

Gilbert's observations on the "size of channels" in Southwestern US watersheds presaged the *Arroyo Problem*, which developed into one of the great geological puzzles of the 20th century ([14] and [15]). In 1925, Kirk Bryan summarized evidence from the Surveys of the 19th century and early 20th century field studies, concluding that channels throughout the arid Southwest had deepened and widened dramatically in the second half of the 19th century ([19]). Channel elevation of Kanab Creek dropped more than 50 feet near Kanab, Utah - decreases of 60 feet in the Virgin River and

50 feet in the Escalante River occurred (see Figure 17 for locations), all during a period of several decades. Explanations for the Arroyo Problem have followed three different paths: 1) land use change, especially the impacts of cattle grazing, 2) internal adjustments of the river system and 3) climate variability.

Livestock grazing in the late 19th century severely degraded rangeland, resulting in enhanced soil erosion, runoff and sediment yield. Erosion expanded the drainage network by channelizing flow on hillslopes; elaboration of the drainage network concentrates and amplifies flood peaks, providing a mechanism for altering channels. The effects of grazing provides, at best, however, only a partial explanation for arroyo cutting. Time mismatches between introduction of cattle and arroyo cutting limit the settings in which it could play a role ([15]). An additional problem with cattle grazing arguments is that enhanced erosion should increase floodplain sedimentation, rather than lead to trenching of floodplain sediment.

Arguments based on internal adjustments of the river system, which mirror one line of thinking used to examine meander formation and cutoff in the Mississippi River (Chapter 1), explain arroyo cutting as a response to the unique processes involved in sediment transport and erosional processes in the arid lands. High sediment yields oversteepen longitudinal profiles locally, leading to cycles of arroyo cutting and filling. In this view, arroyo systems are characterized by erosional reaches in which *knickpoint* retreat results in channel incision progressing upstream. A knickpoint is a sharp gradient in the longitudinal profile of the river. Downstream aggradation reaches are locations where sediment is deposited. Although geomorphic processes, including knickpoint migration, play a role in arid region rivers, this theory does not address the observation that many channel systems developed arroyos through their entire alluvial valleys, nor does it address the near-synchronous periods of arroyo formation in adjacent, but disjoint watersheds.

Explanations based on climatic variability, include the effects of both drought and flood, with the latter playing the more prominent role. Drought weakens vegetation and can make the river system more susceptible to erosion during floods. Drought has been invoked as a contributor to arroyo cutting, but not as a direct agent.

Arroyo formation has been directly linked to sequences of floods ([14] and [38]). Kanab Creek provides a striking example - "On August 30, 1882, a terrific flood swept down Kanab Creek Canyon and literally swamped the town. This was followed by similar cloudburst floods each summer until 1886. In that period of 5 years the channel was changed almost beyond the comprehension of even those who saw it. Its depth was increased by 50 feet or more and its width by about 200 feet in places" ([42]). The recent history of flooding in Kanab Creek near Kanab, Utah (drainage area of 503 km^2) has been quiet, with the largest flood peak during the past 40 years not even reaching 100 m^3 s^{-1}.

Arroyo cutting in the late 19th and early 20th century reversed by the middle of the 20th century and most channels in the Colorado Plateau began to fill with sediment ([24]). The *arroyo cycle* pairs trenching of channels with a subsequent period of fill.

Climate variability at decadal time scales provides the most consistent explanations for the arroyo cycle; alternating periods of high frequency of extreme floods and low flood frequency, as illustrated by Kanab Creek, are the key climate ingredients.

The arroyo cycle was not a unique episode restricted to historical times. Stratigraphic studies of floodplain sediments have uncovered multiple arroyo cycles during the past 10,000 years ([15]). From approximately 1000 years before present to 800 years ago, Colorado Plateau channels were filled with sediment. The following 200 years included a period of major arroyo cutting, followed by rapid fill. Channels remained filled with sediment until the historical period of arroyo formation commenced in the second half of the 19th century.

Periods of arroyo cutting are associated with elevated frequency of extreme floods ([14], [39]). These conclusions are based on *paleohydrology* studies in which elements of the hydrologic cycle have been reconstructed from proxy measurements. Tree ring observations have provided tools for reconstructing rainfall variation over multiple centuries. Paleoflood measurements have been based on hydraulic analyses of the sedimentary record of flood deposits ([3]). The broad conclusion of paleohydrology studies is that cycles of drought and flood have characterized climate variability in the Colorado Plateau for millennia.

Rain Follows the Plow: Developing the Colorado River

In 1881, Charles Dana Wilber formulated an experiment on the intentional modification of Earth's climate: "Suppose an army of frontier farmers 50 miles in width, from Manitoba to Texas, could, acting in concert, turn over the prairie sod, and after deep plowing and receiving the rain and moisture, present a new surface of green growing crops instead of dry, hard baked earth covered with sparse buffalo grass" ([40]). What would be the effect on climate? Without resorting to experimentation, Wilber reasoned that "No one can question or doubt the inevitable effect of this cooling condensing surface upon the moisture in the atmosphere as it moves over by the western winds. A reduction of temperature must at once occur, accompanied by the usual phenomena of showers. The chief agency in this transformation is agriculture. To be more concise, rain follows the plow" ([40]). Wilber, who was more land speculator than climatologist, based his claims largely on climatological analyses made by the Survey of Frederick Hayden. G. K. Gilbert looked skeptically on these claims ([32]) and it was ultimately shown that Hayden's theory was based on faulty evidence arising from brief climatological fluctuations in rainfall that happened to coincide with settlement.

After the Powell expedition of the Colorado River, the question for policymakers and settlers was what could be done with this newly explored land. How could humans make productive use of the inhospitable lands drained by the Colorado?

These questions sparked intense national debate in the two decades that followed the Civil War. The gravity of this debate imparted political expectations on the explorers and surveyors, Powell included, whose expert knowledge and experience were called upon to support different visions of the future of the West.

Most people involved in the debate over the West in the late nineteenth century accepted the premise that the West should be made habitable for American settlers. In its early stages the struggle to tame the West was fought primarily not on the ground but in the forum of public opinion. Advertising campaigns and enthusiastic promoters promised that Western lands, even the high plateau regions of the Colorado River basin, were incredibly fertile, merely waiting for habitation and cultivation. William Gilpin, a land speculator and onetime governor of the Colorado territory, was one of the chief prophets of this westward expansion. He expounded a vision of the West as the core of a territorial American empire whose natural bounty promised unprecedented power, productivity, prosperity, and unity ([44]). For Gilpin and his colleagues this was not just empty rhetoric: behind their grand vision for the West lay scientific rationales, including Alexander Von Humboldt's theories on geographic determinism in state development ([43]) and the climatological theory that "rain follows the plow".

There was little agreement as to how the barren dry lands of the West could be made to support settlement, or what form future development would take. John Wesley Powell laid out his vision of the West in his 1878 "Report on the Lands of the Arid Region of the United States" ([32]). The report was the result of more than a decade's worth of exploration and surveying of the arid West, a region comprising roughly two-fifths of the contiguous United States whose remarkable environmental diversity was surpassed only by its shared dryness. The Arid Lands Report demonstrated that lands lying to the west of the rough boundary formed by the 20 inch rainfall isohyet (Figure 1) were too dry to permit agriculture without irrigation works. Moreover the available water resources in the West were sufficient to irrigate only a tiny fraction of the available land; in Utah, Powell calculated this irrigable area as only 2.8% of total land.

These observations served as the basis for Powell to propose a reform of land law for the West ([32]). Faced with a new type of frontier, Powell maintained that the Homestead Acts and the Jeffersonian ideal of the independent yeoman farmer ([11]) that underlay it were unsuitable models for expansion into the West. In his proposed reforms, Powell emphasized (1) dividing available land into three categories of use: arable, pasturage, and timberlands, (2) using irrigation districts, with boundaries delineated by drainage basins, as the characteristic political unit of the West, and (3) fostering a communitarian ethos among settlers. While Powell's vision of the West was predominantly agricultural, he recognized that high elevation and aridity made large areas of western land unsuitable for farming. Mid-elevation but non-irrigable lands would be cleared, according to Powell's plan, for use as pasturage, while higher land would be left for timber. Lower elevation river valleys would be home to small communities of farmers working irrigated fields.

For Powell, careful management of water resources was the most important issue facing policymakers and settlers due to the aridity of the Western climate. Political, social, and economic structures would have to be adapted to the unique constraints imposed by scarcity of water. They would also have to mesh seamlessly with institutions dedicated to managing water resources. Powell's solution to these challenges, inspired in part by his observation of Mormon communities, centered on communal management of water resources. For communities to function in this way, they would have to foster a strong sense of civic duty rooted in their particular community. These small towns, predominantly agrarian and pastoralist, would work together, with minimal government intervention, to build necessary water resource infrastructure. For Powell's plan to succeed, careful topographic studies were required. Water resources throughout the West would have to be carefully studied in order to assess the irrigation potential for different plots of land; only these lands would be open to agrarian settlement.

Powell's vision generated intense criticism from settlers and speculators who wanted to see the West developed immediately and had little interest in Powell's "pure science" ([44]). Many disagreed with Powell on more substantive grounds as well, finding his sociopolitical vision of the West too populist and communal, and therefore restrictive of large-scale free enterprise. These politicians and businessmen understood, like Powell, that settling the arid West required an unprecedented degree of social and political organization. Like Powell, too, they argued that the federal government should be kept at arm's length. Instead of small, self-sufficient communities, however, these politicians and businessmen put forth a vision of the West in which social, economic, and political life was organized around elite industrialists and their capital. This elite sought to exploit the massive natural resources of the West, especially its mineral reserves, using their economic and political capital to establish monopolies, and they did not want to wait for Powell's exhaustive survey work to tell them where to go.

Senator William Morris Stewart of Nevada fell squarely into this latter camp, and by opposing Powell's political efforts in Washington the two became bitter enemies. Stewart had become wealthy defending (and investing in) mining interests in the West. In 1864 he parlayed his success in the mines and the courtroom into election to the Senate, where he was instrumental in the passage of an 1872 law that removed obstacles preventing mining operations from developing public lands. Stewart was instrumental in defeating Powell's proposals for development in the arid West. In Congressional hearings and in the press he sought to portray Powell as overly scientific and an "un-American" enemy of free enterprise. Powell replied that his fight was against the speculators who wanted to monopolize the irrigable land and water resources of the West in order to establish a "sort of hydraulic feudal system, to which American farmers would be hopelessly subject." ([44]). Ultimately, Stewart and his allies were able to derail Powell's Arid Lands proposals, in part by appealing to lofty ideas of national progress and invoking America's manifest destiny to settle the continent all the way to the Pacific. This rhetoric swept away Powell's scientific concern with adapting Western development to the environment and replaced it with "courage" and "enterprise."

Despite industrialist's opposition to Powell's land reform plans, there was broad agreement that continued surveys of the resources of the West were necessary. The United States Geological Survey (USGS) was founded in 1879 by act of Congress. Its stated mission was formulated by Congress as: "classification of the public lands, and examination of the geological structure, mineral resources, and products of the national domain". In effect, the USGS brought under federal control the task of mapping and categorizing the lands of the US, a task that had previously fallen to an ad hoc collection of surveys.

Powell had played a central role in creation of the the USGS and served as its second Director; he viewed water as one of the central resources that should be assessed by the USGS. Under his leadership, and spurred by drought in the mid 1880's that sharply affected Midwestern agriculturalists, the USGS began to play a greater role in studying water resources in the West. Powell ordered expansive programs to measure streamflow and map drainage basins with an eye towards irrigation. In 1889 the USGS began constructing a network of stream gages that remains in place today.

Powell was an ardent supporter of dams as a means of "conserving" the waters of the West. Although the broad vision expressed in Powell's Arid Lands Report was not embraced as a model for development of the western US, his views of "reclaiming" the lands of the western US through water projects were. The Reclamation Act of 1902 created the Reclamation Service within the USGS; its mission was to create irrigation projects within the arid regions of the West. President Theodore Roosevelt aggressively championed the reclamation movement and provided necessary political support. Roosevelt, a staunch "conservationist" in contemporary usage, believed that the country's natural resources should be carefully managed, or conserved, in such a way that they could be sustainably exploited for the benefit of society. The Reclamation Service promised to do this by building dams and irrigation works that would make the arid lands of the West habitable and cultivable.

In 1907 the Reclamation Service was reorganized as an independent bureau under the authority of the Department of the Interior. The Reclamation Service's small-scale projects in the first quarter of the twentieth century were largely unsuccessful, tending to run over cost and behind schedule. It was not until the Boulder Canyon Project in the mid 1920's that the Reclamation Service, renamed the Bureau of Reclamation in 1924, came into its own. Previously restricted to relatively small-scale construction projects, Boulder Dam - soon to be renamed Hoover Dam - helped inaugurate a period in which the Bureau of Reclamation, supported by extensive public funding, built massive dams in the West ([4]).

Hoover Dam and the Law of the River

"California's a garden of Eden, a paradise to live in or see."

Do Re Mi, ***Woody Guthrie, 1940***

Behind the Bureau of Reclamation's rise in the 1920s was a history of changing attitudes towards water management in the first two decades of the twentieth century. Both private investors and the Bureau of Reclamation widened their focus beyond irrigation projects for small farmers to larger projects that sought to manage water resources over larger regions and use them in new ways. Greater ambitions on the part of engineers corresponded to perceptions of growing development opportunities in the arid West - especially in California.

Two groups provided critical support for Hoover Dam. The first were agriculturalists looking to cultivate California's Imperial Valley; developers had long recognized the agricultural potential of the fertile valleys drained by the lower Colorado River, but a reliable supply of water was needed to create a Garden of Eden in southern California. The second group, Los Angeles developers and politicians, sought to meet the city's growing water and power needs.

In 1896 the privately owned California Development Company began an irrigation project in the Imperial Valley. Engineers with the Company began clearing a silted-up former riverbed of the Colorado River, known as the Alamo River, that ran directly through the valley. Within a short time they had cleared the channel and cut an irrigation canal connecting this riverbed to the main stem of the Colorado River. With an irrigation system in place, development in the Imperial Valley proceeded swiftly and profitably, until 1905, when a large flood swept away the control structures at the mouth of the newly created Alamo River. A tremendous volume of water was diverted from the main stem of the Colorado River down the new channel, resulting in severe flooding in the valley, most of which lay below sea level. Although the California Development Company eventually managed to close the channel, the landscape of the Imperial Valley had been profoundly altered. The Salton Sea, California's largest lake, was created by the Colorado's floodwaters and continues to cover roughly five hundred square miles of the Imperial Valley (Figure 19). The California Development Company's failure drove home the point that controlling the flow of the Colorado, especially during times of extreme flooding, was an essential precondition to development.

The city of Los Angeles had profited from effective water management in the late nineteenth and early twentieth centuries, particularly under the direction of William Mulholland ([29]), chief of the Los Angeles Department of Water and Power. Under Mulholland's controversial leadership, an extensive network of aqueducts and canals was constructed that supplied the growing city with water ([29]). Chief among these was the Owens Valley Aqueduct that imported water from the Owens River in the Sierra Nevada Mountains down to the city. Mulholland planned to expand the water supply from the Owens River through a water supply reservoir on the San Francisquito River. The St. Francis Dam was designed by Mulholland and built by the Los Angeles Water Department (completed in 1926). Its failure on March 12, 1928 resulted in more than 400 fatalities and was one of the worst civil engineering disasters of the 20th century ([29])

Even prior to the St. Francis Dam failure, the need for Colorado River water (and power) to support growth of Los Angeles was apparent. During the first two decades of the 20th century, Mulholland and the Los Angeles Water Department aggressively pursued strategies to draw water from the Colorado River. Imperial Valley developers and Los Angeles interests provided the critical mass necessary to gain approval for the construction of a large hydroelectric storage dam on the lower Colorado. Passed by Congress in December 1928, the Boulder Canyon Project Act provided $177 million for the construction of the dam. Major political hurdles had to be overcome prior to Congressional authorization of the Boulder Canyon Project in 1928. As Powell's 1869 expedition clearly demonstrated, the Colorado River was a navigable waterway and it passed through portions of Wyoming, Colorado, Utah, New Mexico, Arizona and Nevada before a short stretch in California. In the early 1920s, legal barriers stood between southern California and large quantities of Colorado River water.

Water law in the West developed separately, and differently, from that of the East. Courts and lawmakers in the East, drawing from English common law, had long recognized *riparian* rights, in other words, the rights of landowners to make reasonable use of water from bodies of water adjoining their property. In the West, by contrast, the *prior appropriation* doctrine held sway. It holds that rights to a quantity of water go to whoever can first demonstrate continuing beneficial use of that water.

In 1882 the Colorado Supreme Court heard a dispute over water rights between George Coffin, a farmer from Longmont, Colorado in the St. Vrain River valley, and the farmers of the nearby Left Hand Creek watershed. The Left Hand Creek farmers dug an irrigation ditch and diverted water from St. Vrain Creek across the basin divide to their farms. During an extended drought in 1877, St. Vrain Creek ran dry and Coffin filed suit against his neighbors in Left Hand Creek. What was at stake in this particular case was not simply a dispute between neighbors: it was a fundamental difference between legal principles for establishing water rights. The Left Hand Creek farmers, who appealed to the prior appropriation doctrine, won out over Coffin, whose argument rested on the riparian principle.. By ruling in favor of the Left Hand Creek farmers, the Colorado Supreme Court established a precedent that water law in Colorado, and soon, the West, would rest on the principle of prior appropriation.

There are several reasons why prior appropriation has been thought better suited to the West than riparian rights. This can be attributed in part to the comparative scarcity of water in the West, as prior appropriation rights establish more precise water allocations than riparian rights. More importantly, prior appropriation rights facilitate larger and more complex irrigation systems to be built, increasing the potential for large-scale agricultural development in arid lands ([43]). The political and economic character of westward expansion also influenced the forms of water law adopted in the West. Through most of the nineteenth century the federal government retained ownership of large areas of Western land; in order to give settlers badly needed access to water on federal lands an alternative to riparian rights had to be adopted. Moreover, by supporting the water rights of development projects undertaken by settlers themselves the prior appropriation doctrine also checked the influence of wealthy land speculators from the East who did not develop the land themselves.

Seven states came together in 1922 to work out how the Colorado Rivers waters were to be divided among themselves. The agreement they reached, known as the Colorado River Compact, began by dividing the states in question into two groups corresponding to the Upper and Lower reaches of the river (Figure 2). The Upper Basin states included Wyoming, Colorado, Utah, and New Mexico, while the Lower Basin was composed of Nevada, Arizona, and California.

The key point of contention was that the prosperous Lower Basin states, especially California, were using more water than the relatively undeveloped Upper Basin states and were planning additional water development projects, like Hoover Dam, that would further increase their claim on Colorado River water. Under the prior appropriation doctrine in force everywhere in the West, the Upper Basin states worried that they might be prevented access to the water because of prior downstream claims in the Lower Basin. The Colorado Compact addressed these concerns in 1922 by establishing roughly equal water allocations for the Upper and Lower Basins in a hypothetical average year of rainfall. Surplus water beyond the standard allotments was to go to the Lower Basin, but the Compact did not specify how water was to be allocated within each basin, leaving that decision to the involved states themselves.

Unsatisfied with the scale of California's claims, Arizona ultimately refused to sign the Colorado Compact. Arizona continued to protest California's water appropriations (at one point attempting a naval blockade to prevent the construction of Parker Dam, which would permit further water diversion into California). The issue was resolved before the Supreme Court in 1963, at which time Arizona began its own extensive program of hydrologic infrastructure improvement known as the Central Arizona Project.

The Colorado Compact helped to resolve gridlock in Washington that had impeded the construction of large water resource projects in the Lower Basin of the Colorado, Hoover Dam in particular. More broadly, by precisely defining water rights and by opening the river and its basins to further development of hydrologic infrastructure the Compact was an important step in the transformation of the Colorado River into one of the most tightly controlled rivers in the world.

Aside from privileging Lower Basin states over the Upper Basin, the Colorado Compact and the series of agreements that have followed it have been criticized for excluding Native Americans from all plans to divide water resources. The Colorado Compact reads: "Nothing in this compact shall be construed as affecting the obligations of the United States of America to Indian tribes." Implicit in this statement was the understanding that Native American tribes, especially the Navajo, had reserved water rights dating back to the late nineteenth century (which therefore have relatively high priority according to the prior appropriation doctrine), but that no claims had been formally filed on their behalf. In this manner the Law of the River managed to skirt the question of Native American water rights. Based on the extent of irrigable territory they possess and the decision rendered in Winters v. United States (1908), Navajo water entitlement could amount to as much as 2 million acre-feet per year. All parties have long recognized that claims by Native American groups, whether they can be incorporated into the Colorado Compact framework or not, could break apart the water allocation framework ([2]).

Construction began on Hoover Dam in 1931 and Lake Mead began to fill on February 1, 1935 (Figure 20). Despite a series of labor and workplace safety controversies ([4]), Hoover Dam came to occupy a significant place in the national consciousness as a symbol of American ingenuity in the face of Depression-era adversity. Until 1987, the operations center of Hoover Dam, near Las Vegas, Nevada, was managed by the Los Angeles Department of Water and Power.

Glen Canyon Dam and the Environmental Movement

Hoover and Glen Canyon are book-end dams. They lie at opposite ends of the Grand Canyon, Hoover downstream, impounding Lake Mead, and Glen Canyon above, impounding Lake Powell (Figure 2). The completion of Hoover Dam in 1935 occurred at the beginning of the era of big federal dams; the completion of Glen Canyon in 1963 marks its final phase. Hoover is the iconic structure symbolizing the legacy of the *Conservation Movement* introduced by Theodore Roosevelt. Opposition to Glen Canyon galvanized the environmental movement.

While Hoover Dam provided water and power for the Lower Basin states since the mid 1930s - especially for Los Angeles and southern California - the Upper Basin states were relatively underserved by Colorado River water. In the decade following the end of the Second World War, the Bureau of Reclamation turned its attention to the Upper Basin states and ultimately settled on a site in Glen Canyon to construct a large concrete storage dam. Located in northeast Arizona just a few miles south of the border with Utah, it was an extremely remote site (Figure 21). Before construction began, the nearest paved road was thirty miles away. According to the Bureau of Reclamation, the new dam at Glen Canyon would play a number of important roles: it would provide flood control in Arizona, it would create a large reservoir from which irrigation waters would flow, and thanks to a large generating plant it would also produce tremendous amounts of hydropower for the Southwest.

Construction began on Glen Canyon Dam in 1956 and in 1963 the concrete structure was finished (Figure 22). Like Hoover Dam, Glen Canyon is a composite arch -gravity dam made of concrete, although Glen Canyon is less thick. Hoover Dam was designed so that dead weight of the dam alone would support the load from a fully filled dam. Glen Canyon relies somewhat on arch action transferring load from the impounded water to the canyon walls; dead weight alone would not provide structural stability for a fully filled reservoir ([4]). It was only a modest innovation. The era of big dam building in the US was marked by conservative engineering design, with deep-seated resistance to innovation in structure and form ([18]). Multiple factors contributed, but the 20th century view of dams as hazards to society was an important one, initially created by the 1889 South Fork Dam failure; the resulting Johnstown Flood on the Conemaugh River in western Pennsylvania killed more than 2000 ([27]). The failure of William Mulholland's St. Francis Dam in southern California on March 12, 1928, resulting in more the 600 fatalities, reinforced the image of big dams as hazards ([17]).

The naming of Lake Powell honored the contributions of John Wesley Powell and he was indeed an ardent champion of dams as important elements of water conservation in the west. From its earliest days, the Conservation Movement included two distinct strands - utilitarian and preservationist. Powell's proposals for managing resources of the arid lands and Gifford Pinchot's promotion of forest reserves provide guiding principles for the utilitarian branch of the Conservation Movement. Pinchot's justification for environmental protection was purely utilitarian, "conservation means the greatest good to the greatest number for the longest time." ([30]).

John Muir, founder of the Sierra Club and the philosophical leader of the preservationist branch of the Conservation Movement ([45]), agreed with Powell and Pinchot that natural resources should be protected, but he took the argument for stewardship of the environment further. Muir argued that natural resources should be preserved for their own sake and kept in pristine condition, not exploited. For Muir, heavily influenced by the writings of Ralph Waldo Emerson and Henry David Thoreau, pristine nature offered transcendental spiritual experiences. Muir's last environmental battle, the preservation of Hetch Hetchy Valley in Yosemite National Park, ended in failure. O'Shaughnessy Dam on the Tuolumne River was completed in 1923, inundating Hetch Hetchy. Albert Bierstadt's paintings provide the most vivid images of Hetch Hetchy (see, for example Figure 23). A central issue that the Preservationists and Utilitarians would wrestle with is the use of federal lands, like the portions of Yosemite that are inundated by O'Shaughnessy Dam.

Between completion of Hoover and Glen Canyon Dams two manifestos, Aldo Leopold's ASand County Almanac ([20]) and Rachel Carson's Silent Spring ([34]) shaped the foundations of the environmental movement. Aldo Leopold promoted an environmental land ethic through the simple prescription - "a thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise" ([20]). A Sand County Almanac, which was published in 1949 a year after Aldo Leopold's death, was completed by his son Luna Leopold and informed the younger Leopold's views of rivers. Luna Leopold expanded the notion of "biotic community" to "hydrologic continuum" and used his father's prescription to assess the role of dams - including Glen Canyon Dam - on the environment of rivers ([25]).

John Muir's mantle as head of the Sierra Club and environmental movement, fell to David Brower in the 1950s ([28]). Brower's formulation of conservation goals was absolute - "if you are against a dam, you are for a river" ([28]). Like Muir, he would leave an imprint on the environmental movement, especially through the successful campaign to halt construction of Echo Park Dam in the upper Colorado River basin. The dam would have inundated portions of Dinosaur National Park; dams in national parks had been a line in the sand for environmentalists since Hetch Hetchy. Brower would point to one great failure in his career - Glen Canyon Dam ([28]).

Glen Canyon has been termed a "cash register dam", that is, a dam whose primary purpose is to generate revenue to support the broader dam building activities of the Bureau of Reclamation ([28]). Glen Canyon produces revenue by generating hydropower for sale. The generating capacity of Glen Canyon, 1,320 megawatts, is large, but its utility to the regional power grid is not fully reflected in its capacity. Electricity generation from hydropower plants can be rapidly varied simply by changing the releases from the dam through the turbines. Glen Canyon's role within the regional power grid is to meet the peak loading in the system, following the fluctuating electrical demand. Larger, less-flexible coal and nuclear power plant provide baseload power.

Brower deeply regretted the loss of spectacular canyon landscapes in the area inundated by Lake Powell, a perspective embraced by the preservationist strand of the Conservation Movement. Utilitarian conservationists point to the fact that Lake Powell has become one of the most popular boating and outdoor recreation areas in the country, attracting roughly three million visitors annually. Prior to construction of Glen Canyon Dam, the number of people who had seen Glen Canyon had not increased markedly since Powell's expeditions down the river in the 19th century. Glen Canyon Dam brought the contrasting views of utilitarian and preservationists into sharp relief.

Lake Powell began to fill with completion of the dam in 1963 and it took more than 7 years to reach capacity. The mismatch between flow of the Colorado River and storage in Lake Mead and Lake Powell were at the heart of Luna Leopold's critique of Glen Canyon Dam ([22]). He argued that the added storage capacity of Lake Powell did little to augment water supply from Lake Mead, a feature borne out by experiences of the 21st century (as discussed in the following section). Moreover, there was little impact of Glen Canyon on flooding in the lower Colorado below Hoover and irrigation was simply not an option due to the remote and inhospitable terrain.

Leopold also asserted that Glen Canyon, and other dams in the Colorado River, had severely disrupted the "hydrologic continuum" of the river. As Worster suggests in Rivers of Empire, "the Colorado of the 21st century has more in common with a concrete irrigation ditch than with the free-flowing river it was a century ago." ([43]). The river no longer reaches the Gulf of California in any but the wettest of years. More than forty dams control the flow of the Colorado and its tributaries. As a result, the river, which once ran warm and full of sediment, now discharges cold sediment-free water from its reservoirs, which has led to the extinction of most species of native wildlife. Dam control structures allow engineers to precisely set the volume of discharge in the river to maximize power production, effectively turning the river on and off like a faucet. Indeed, below Glen Canyon dam, the flow of the Colorado River is most closely tied to time-of-day electricity demand in Los Angeles (Figure 24).

Climate and Water Sustainability for the Arid Southwest

On 16 August 2013, the Bureau of Reclamation announced that for the first time since Lake Powell filled, releases from Glen Canyon Dam to Lake Mead would be reduced; releases would decrease from 8.2 million acre-feet (MAF) in 2013 to 7.5 MAF in 2014. Water storage in Lake Mead and Lake Powell in August 2013 had reached historically low values (Figures 25 - 27). In September 2018, the combined storage of Lake Mead (38% of capacity) and Lake Powell (48% of capacity) remained near record low levels.

In a world in which irrigation is a driving force for water management, it is natural to think of water in terms of the requirements for agriculture. In Arizona, where precipitation is extremely low (Figure 1) and the potential for evapotranspiration is particularly high, approximately 60 inches, or 5 feet, per year of irrigation water are needed to grow crops ([5]). Under the Homestead Acts, land was granted in 160 acre units (1 acre equals 0.00156 square miles), so a reasonable representation of the irrigation water required for agriculture in Arizona is 5 feet for each acre of land under cultivation, or 5 acre-feet. Water agreements, like the Colorado River Compact, express water rights in units of acre-feet; moreover water managers conceptualize the water system through the lens of water quantity expressed in acre-feet.

Time series of annual streamflow of the Colorado River at Lees Ferry from 1895 - 2002 show that flow in the Colorado below the site of the Glen Canyon Dam has decreased over the 20th century, principally due to increasing *consumptive use* in the Upper Colorado River basin (Figure 28). The Bureau of Reclamation has computed "naturalized" flows for the Colorado River at Lees Ferry, accounting for the consumptive withdrawals of water from the river system. The average naturalized flow of the Colorado River at Lees Ferry from 1905 to 2013 is 15.0 MAF annually. During the period from 1905 to 1922, which was used to allocate water under the Colorado River Compact, the mean annual flow of the Colorado River at Lees Ferry was 16.1 MAF.

The ratio of the total storage capacity in the Colorado River basin, 60 MAF, to the mean annual streamflow of 15 MAF per year, is 4 years - an exceptionally large value compared with other drainage basin in the US. The Columbia River basin, which has an extensive network of dams (Chapter 4), has a ratio of 0.3 years. The large ratio of storage to inflow generally implies that Colorado River water supply depends on streamflow variability at time scales longer than 1 year; decadal-scale variability in streamflow dictates broad features of water availability. More painfully, recovery from severely depleted reservoir storage generally requires years of elevated streamflow.

On the demand side of the ledger, the average annual *consumptive use* for the Colorado River system for the period from 2001 - 2005 was 15.3 MAF. Consumptive use of water refers to water that is removed from the river and not returned - some uses of water, like hydropower production, do not remove water from the system. Irrigation, municipal water supply and industrial processes are the principal components of consumptive use, but under the Colorado Compact definitions it also includes water that evaporates from reservoirs in the Colorado River system. The consumptive use by the 7 states party to the Colorado Compact totaled 13.7 MAF from 2001 - 2005, with California and Arizona the peak users at 4.7 MAF each. An additional 1.6 MAF in consumptive use is evaporation from the reservoirs in the Colorado River system. During the drought years of 2001 - 2004 a consumptive use in the vicinity of 15.3 MAF results in a net depletion of storage in Lake Mead and Lake Powell, as illustrated in Figure 26.

Estimates of annual evaporation losses from water supply reservoirs total 0.5 MAF in the upper basin, almost exclusively Lake Powell, and 1.1 MAF from the lower basin, mainly Lake Mead. Evaporation estimates were based on regional estimates of mean annual evaporation from a free water surface (in feet) and the surface area of the lake in acres. Evaporation is one of the most difficult elements of the water cycle to measure and controversy has surrounded assessments of evaporative losses from the Colorado River basin reservoirs.

"Beneficial use" of Colorado River water, under the Colorado Compact accounting rules, is divided into the following classes: irrigated agriculture, municipal and industrial uses, export of water and reservoir evaporation. In a typical year, approximately 60% of beneficial use is for irrigation, 15% is for municipal and industrial uses, 10% is for export to Mexico (in the Colorado River) and 15% is for reservoir evaporation. Approximately 30% of Colorado River water is exported outside of the Colorado River basin, with the bulk going to California for irrigation and municipal water supply. By international treaty, 1.8 MAF of Colorado River water is “exported” to Mexico in the Colorado River.

The reductions in 2014 releases from Glen Canyon Dam were attributed by the Bureau of Reclamation to the consequences of 14 years of drought in the Colorado River basin. Rainfall during 2012 in the upper Colorado River basin was the lowest in the past 120 years and the previous 12 years experienced below normal rainfall. A sequence of 4 consecutive years beginning in 2000 initiated the period of water shortages in the Colorado basin (Figure 30). The water level at Lake Powell was at near-record low water levels in October 2004 (Figure 31). By August of 2013, storage in Lake Powell was at 45% of capacity and the lake level was below the 2004 minima.

In addition to extreme drought, the 120 year period of direct rainfall observations also includes extended periods of elevated precipitation. Perversely, the most extreme period of elevated precipitation occurred during the 10-year period preceding the 1922 Colorado Compact agreements. This period was used as the baseline to establish water allocations from the Colorado River. *Paleohydrology* techniques have been developed to estimate precipitation over multiple centuries using tree-ring observations. Rainfall reconstruction using tree ring methods indicate that the 1910 - 1920 decade used to allocate water user the Colorado Compact agreements was the wettest during at least the last 500 years ([9] and [41]).

Global climate models (GCMs) used for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) predict that the Colorado River basin will become warmer and drier through the 21st century. Predictions of streamflow change in the Colorado River to the middle of the 21st century, in response to changing climate, exhibit large variability but almost uniformly show decreasing streamflow. Climate model projections of decreased precipitation in the Colorado River basin are part of a global-scale change in the hydrological cycle, with the tropics becoming wetter, the subtropics becoming drier, and the higher latitudes trending to wetter conditions ([36]).

What is the current mean annual flow of the Colorado River? The 16.1 MAF used for the Colorado River Compact is almost certainly too large. The long-term average of 15 MAF may be too large. Does the "mean" vary over decadal time scales in response to natural variations in climate, such that we are currently operating in a regime with a mean flow that is significantly less that 15 MAF? Is there a systematic shift in climate to a drier state for the Colorado River basin? These questions are central to water management in the southwestern US.

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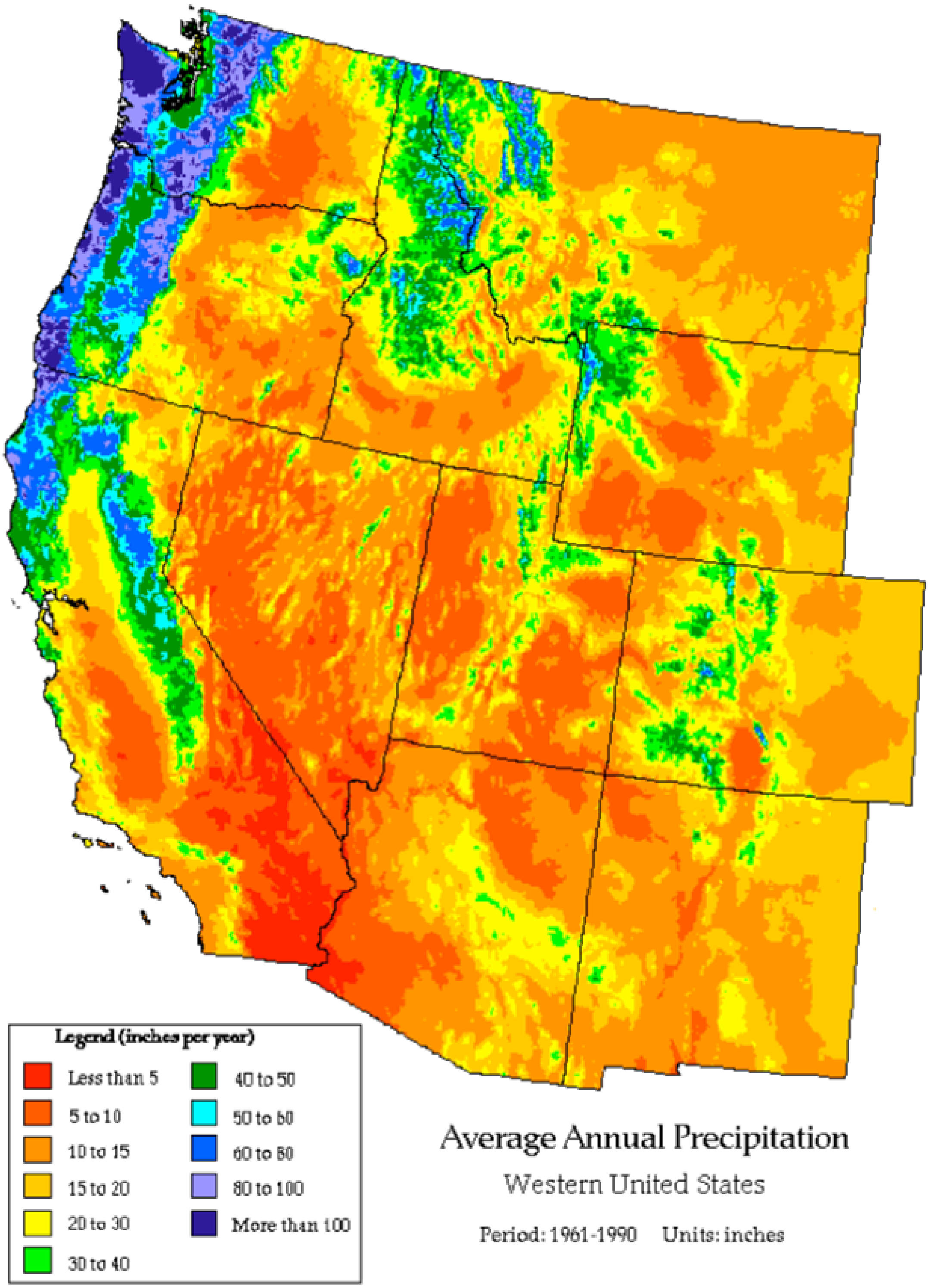


Figure 1: Mean annual precipitation (inches) in the western US based on rain gage observations for the period 1961 - 1990.

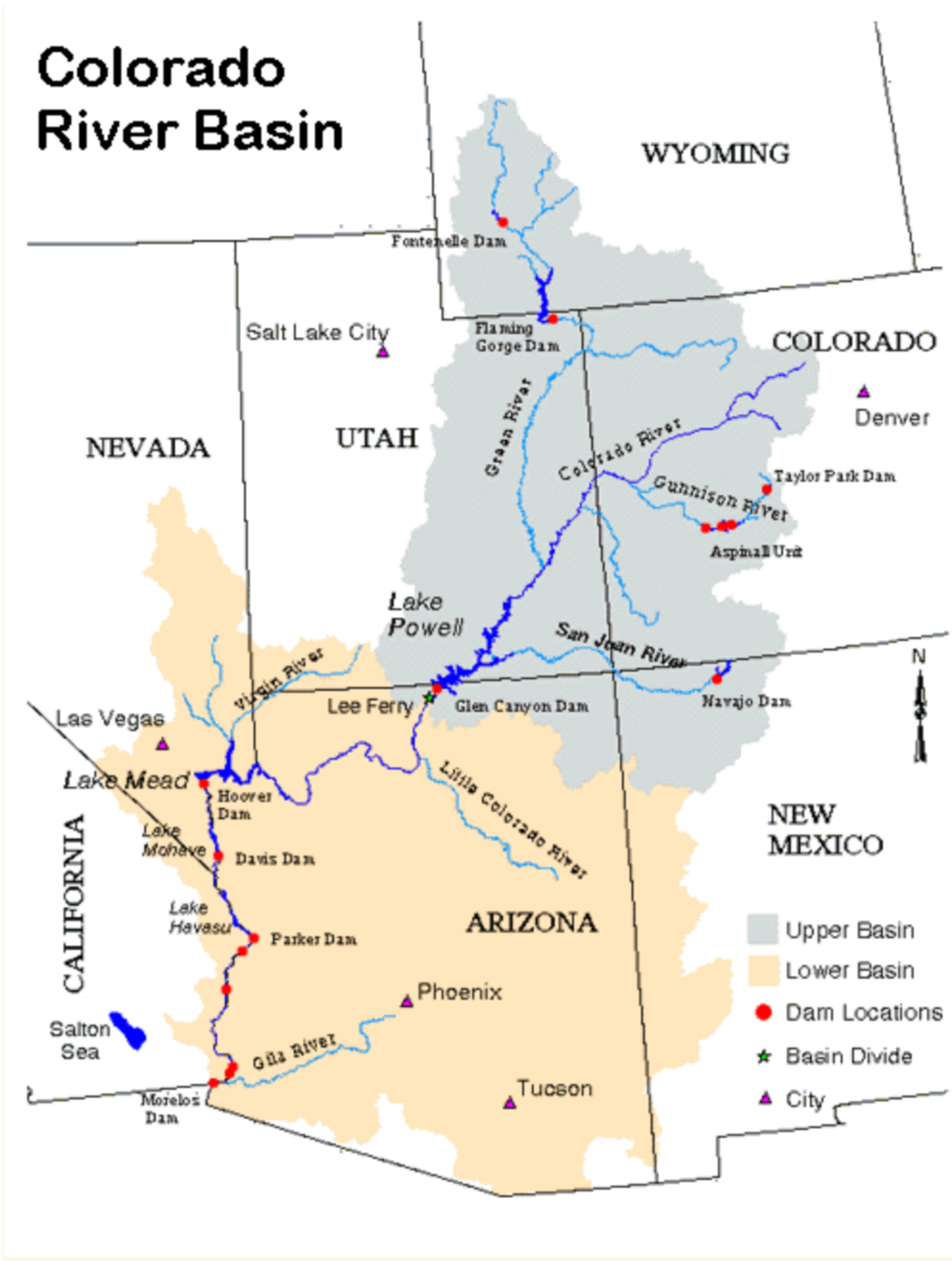
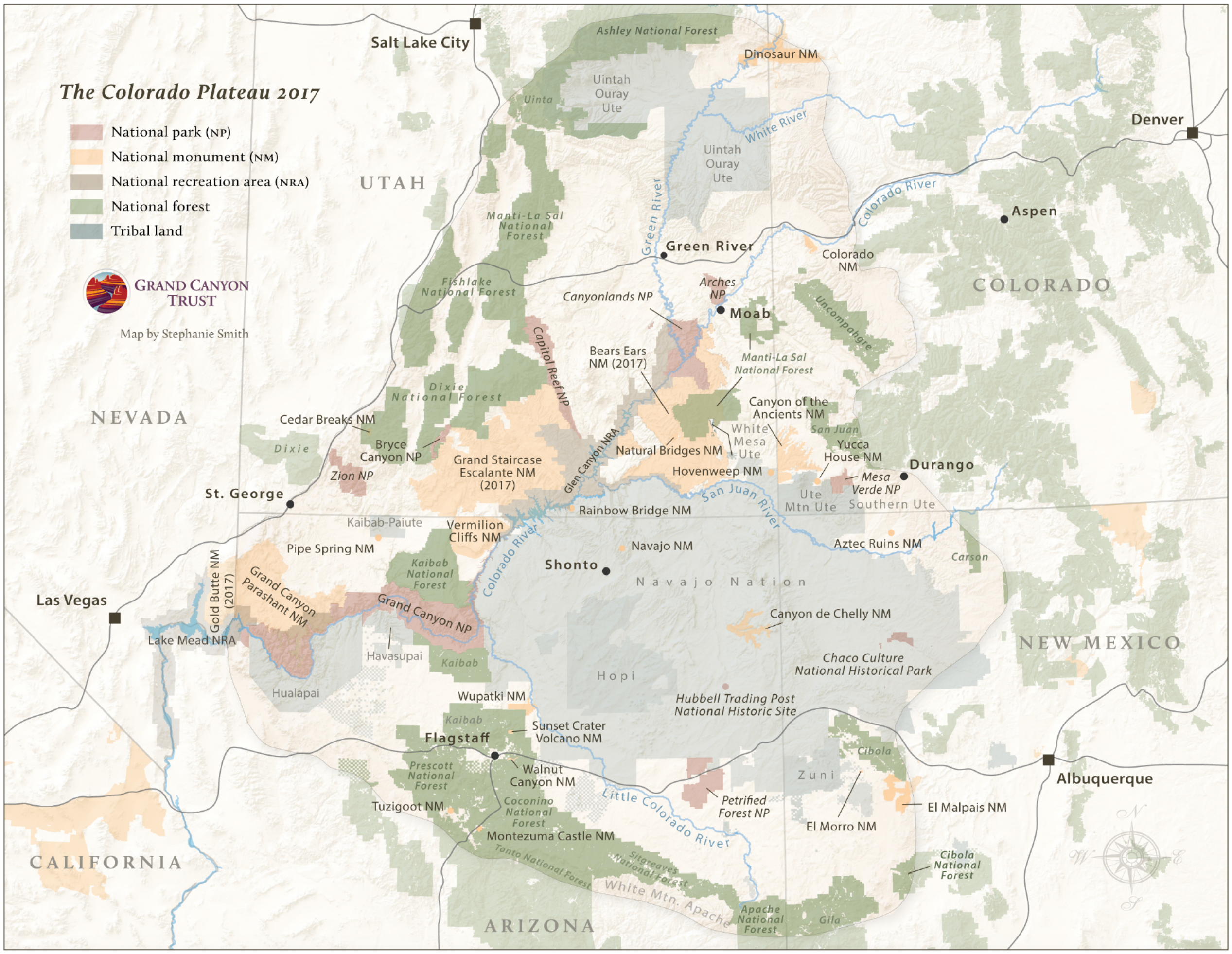


Figure 2: The Colorado River basin, the Colorado River basin and its main tributaries; the Green River, Gunnison River, San Juan River, Little Colorado River, Gila River and Virgin River. The Colorado River basin is divided into the Upper Basin (gray) and Lower Basin (beige). Major dams are shown, including Fontenelle and Flaming Gorge on the Green River, Taylor Park and Aspinall on the Gunnison, Navajo Dam on the San Juan, Glen Canyon, Hoover, Davis and Parker Dams on the mainstem Colorado River.

Figure 3: The Colorado River near Lees Ferry. Glen Canyon Dam and Lake Powell are located upstream (upper right portion of the image; the Grand Canyon, Lake Mead and Hoover Dam are located downstream.

Thomas Moran, *Chasm of the Colorado*, 1873-1874, Department of the Interior Museum, Washington, D.C.

Figure 4: Chasm of the Colorado by Thomas Moran



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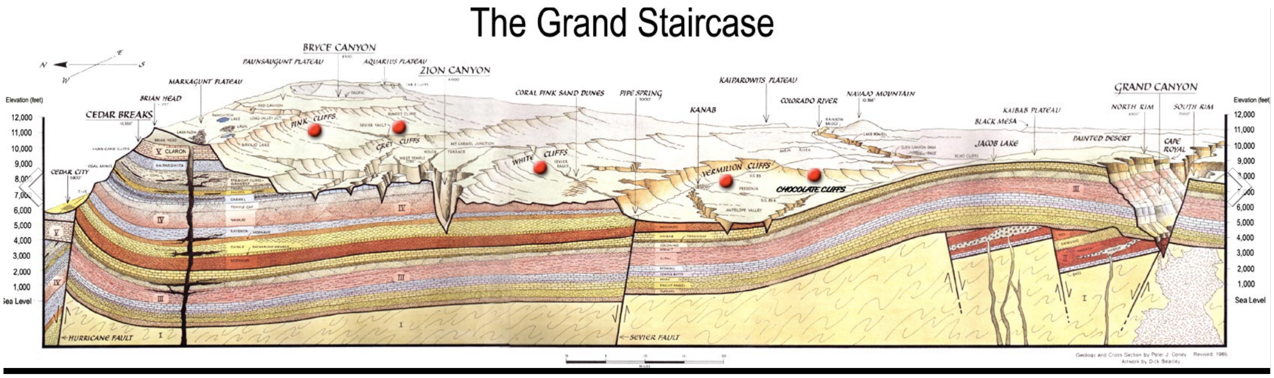

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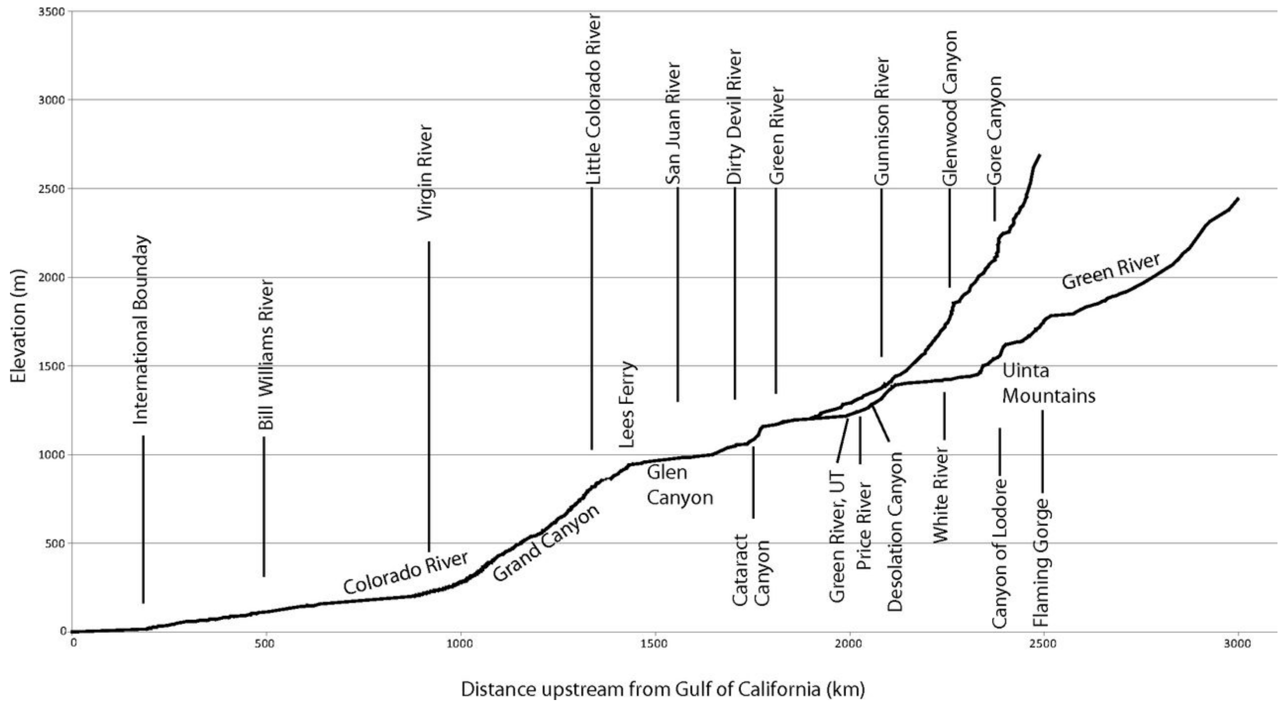

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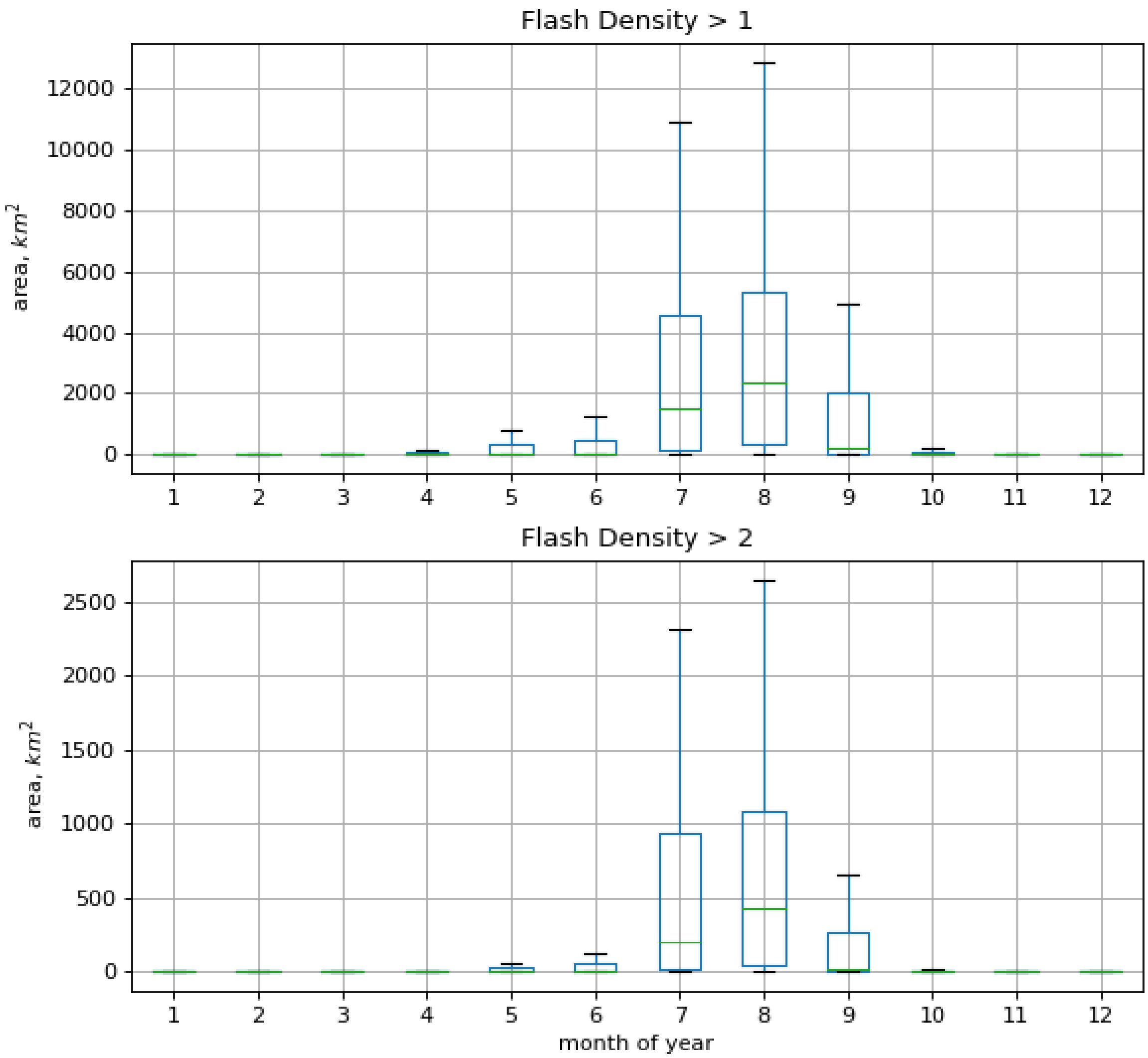

Figure 8: Boxplots of daily area with CG flash density exceeding 1 km^{-2} (top) and 2 km^{-2} for the Colorado Plateau.

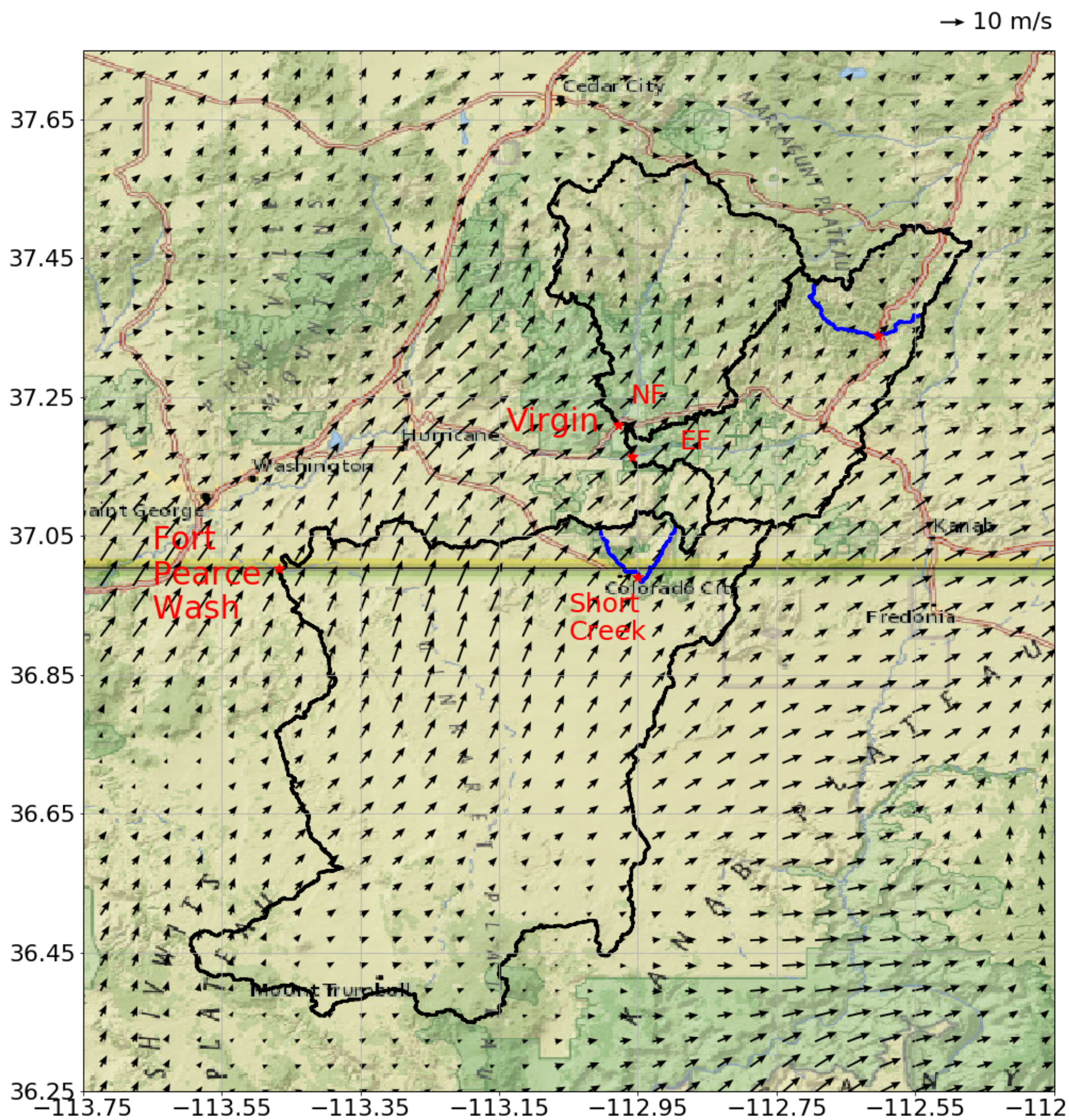

Figure 9: Storm motion vectors for flash-flood producing storms, 1998 - 2015 for a sub-region of the Colorado Plateau, that includes Fort Pearce Wash (and Short Creek), the East Fork Virgin River and North Fork Virgin River (basin boundaries are shown). The location of Short Creek is shown in Figure 10 as a red star.

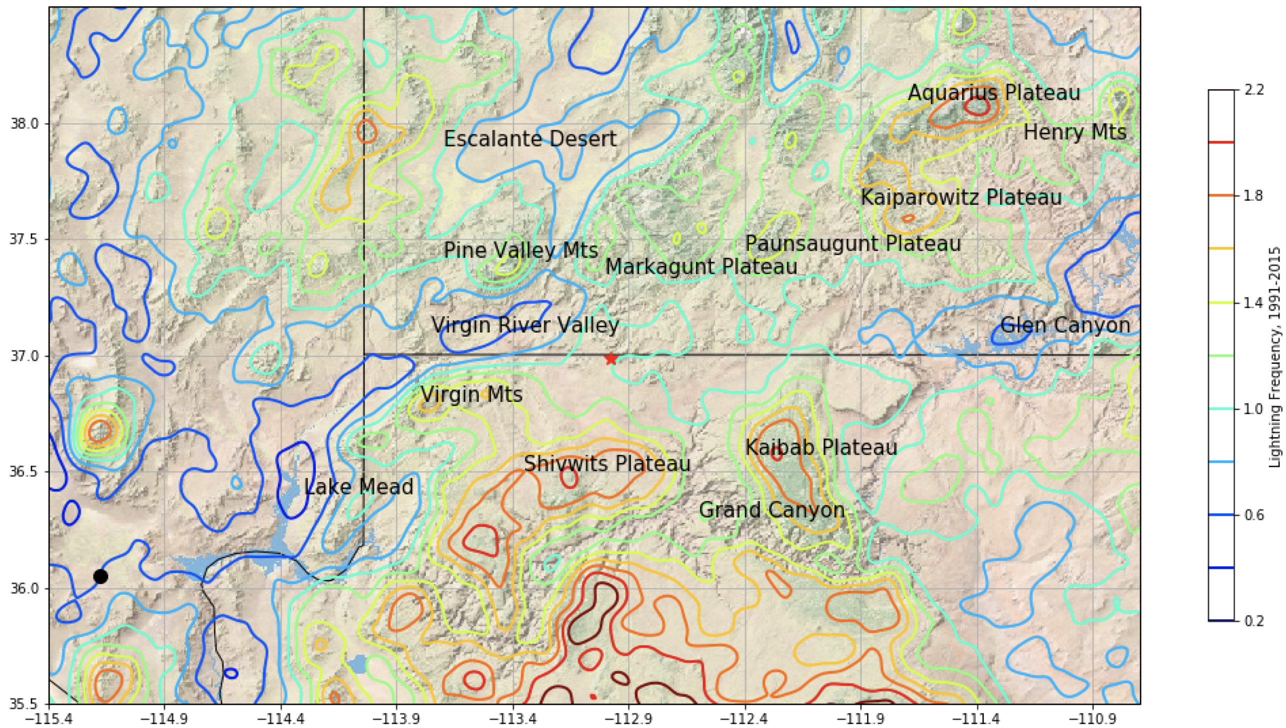

Figure 10: Mean CG flash density (strikes km^{-2}) for southern Utah, northern Arizona and eastern Nevada. Geographic features are labeled. The red square shows the location of the Short Creek stream gaging station.

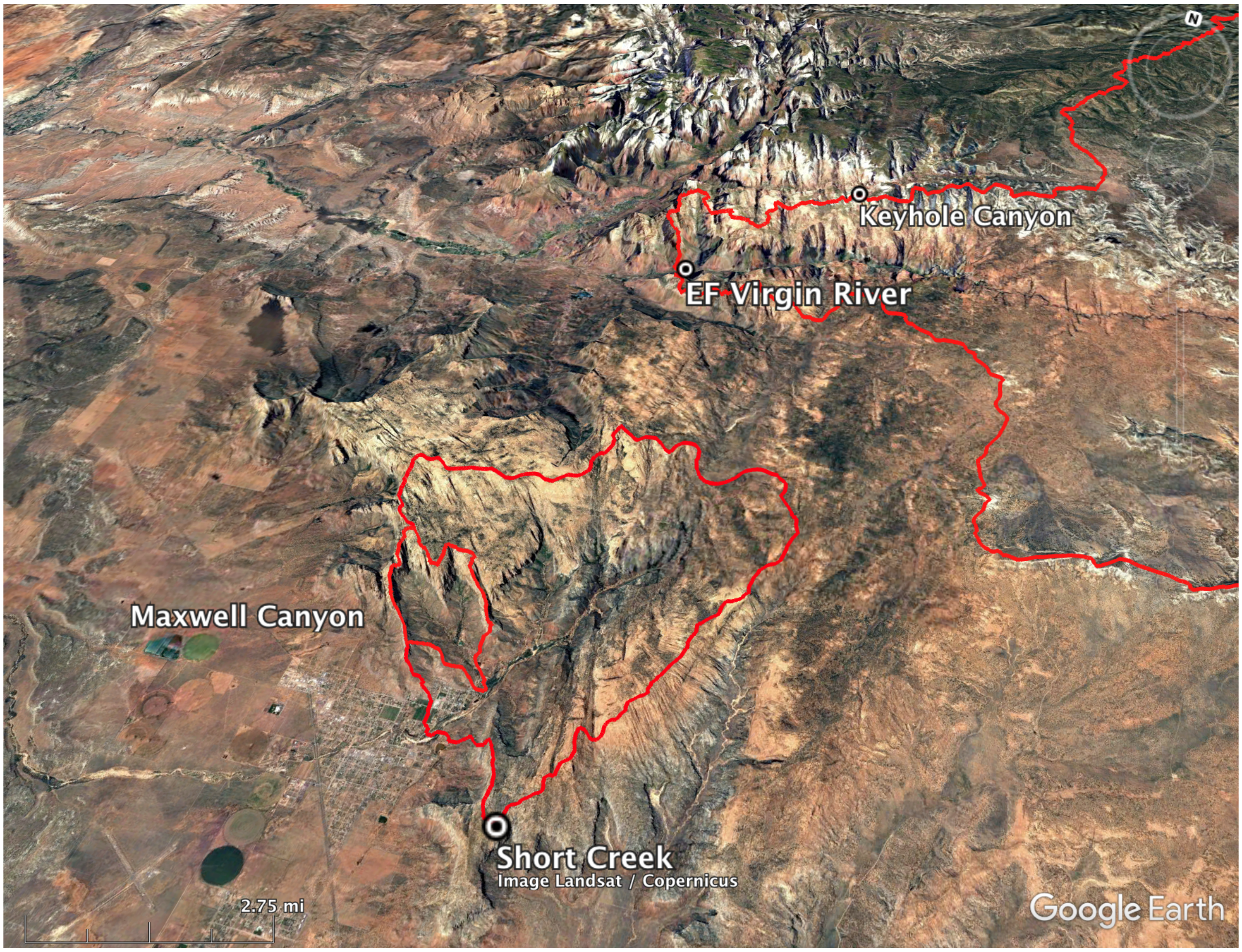

Figure 11: Short Creek, Maxwell Canyon and Virgin River study region. Basin boundaries of Maxwell Canyon and Short Creek are shown, along with a partial basin boundary for the East Fork Virgin River (outline is marked by black circle). Keyhole Canyon is also marked by a black circle.

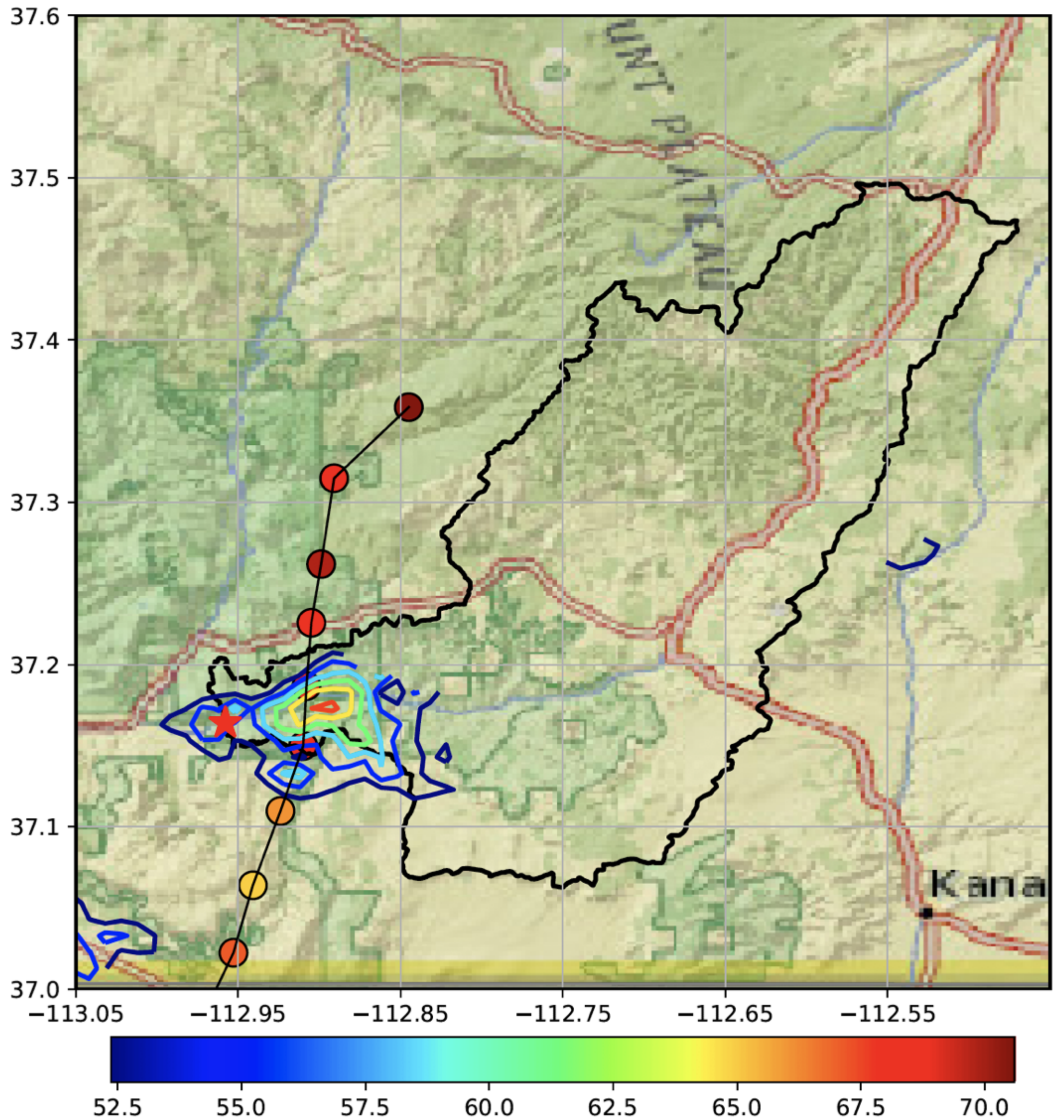

Figure 12: Rainfall rate field at 2245 UTC with basin boundary for East Fork Virgin River and storm tracks of the Hildale storm from 2232 UTC to 2306 UTC . Outlet of the basin is denoted by a red star.

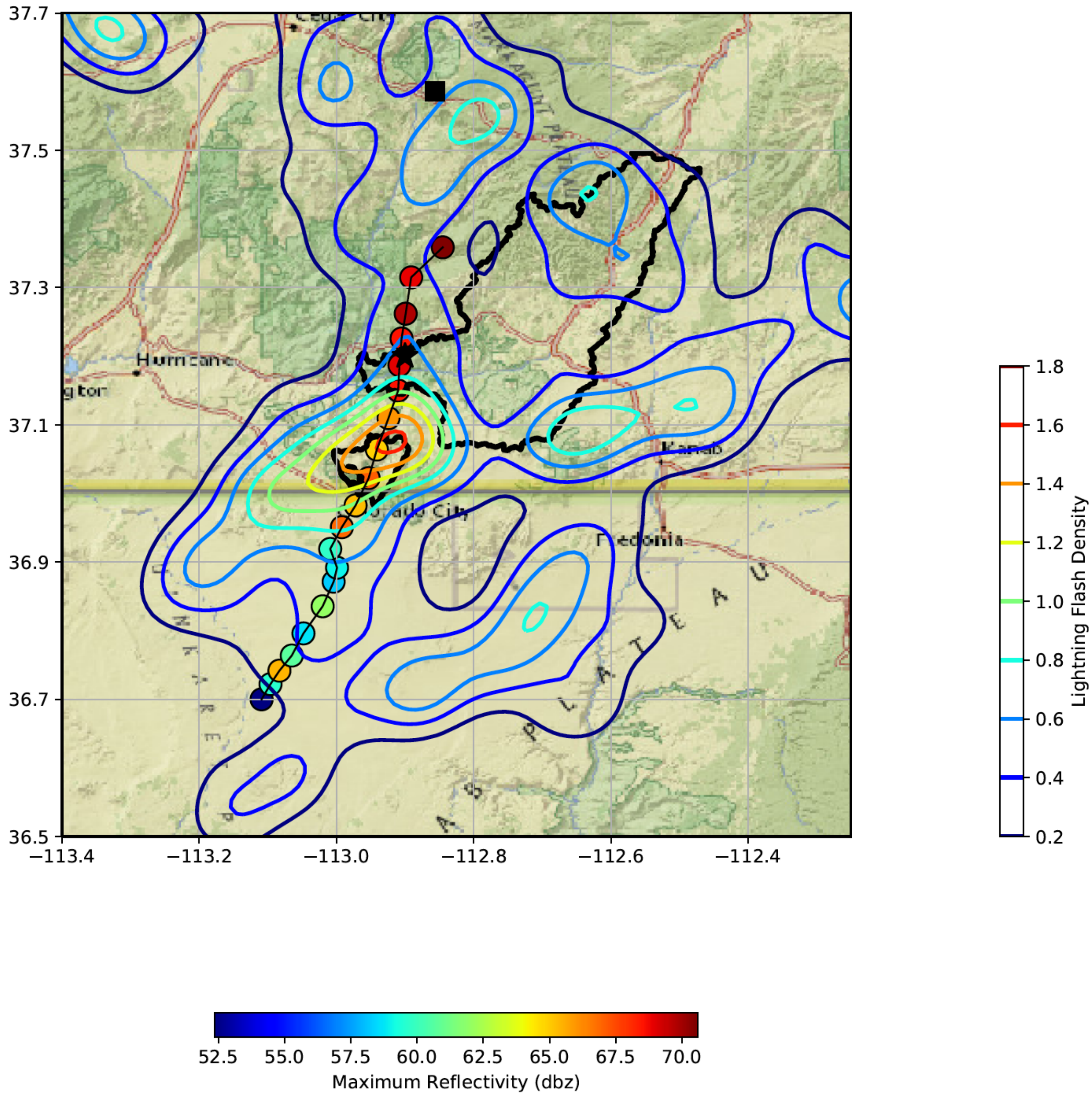

Figure 13: CG lightning flash density contours (CG strikes km^{-2}) on 14 September 2015 storm, with storm .storm tracks (filled circles) from 21:30 to 23:30 UTC. The time interval between track locations are 5 - 6 minutes. Color scale for storm track provides storm intensity in maximum reflectivity. The Maxwell Canyon, Short Creek and E. Fork Virgin River basin boundaries are outlined. KICX radar location is denoted by a black square.

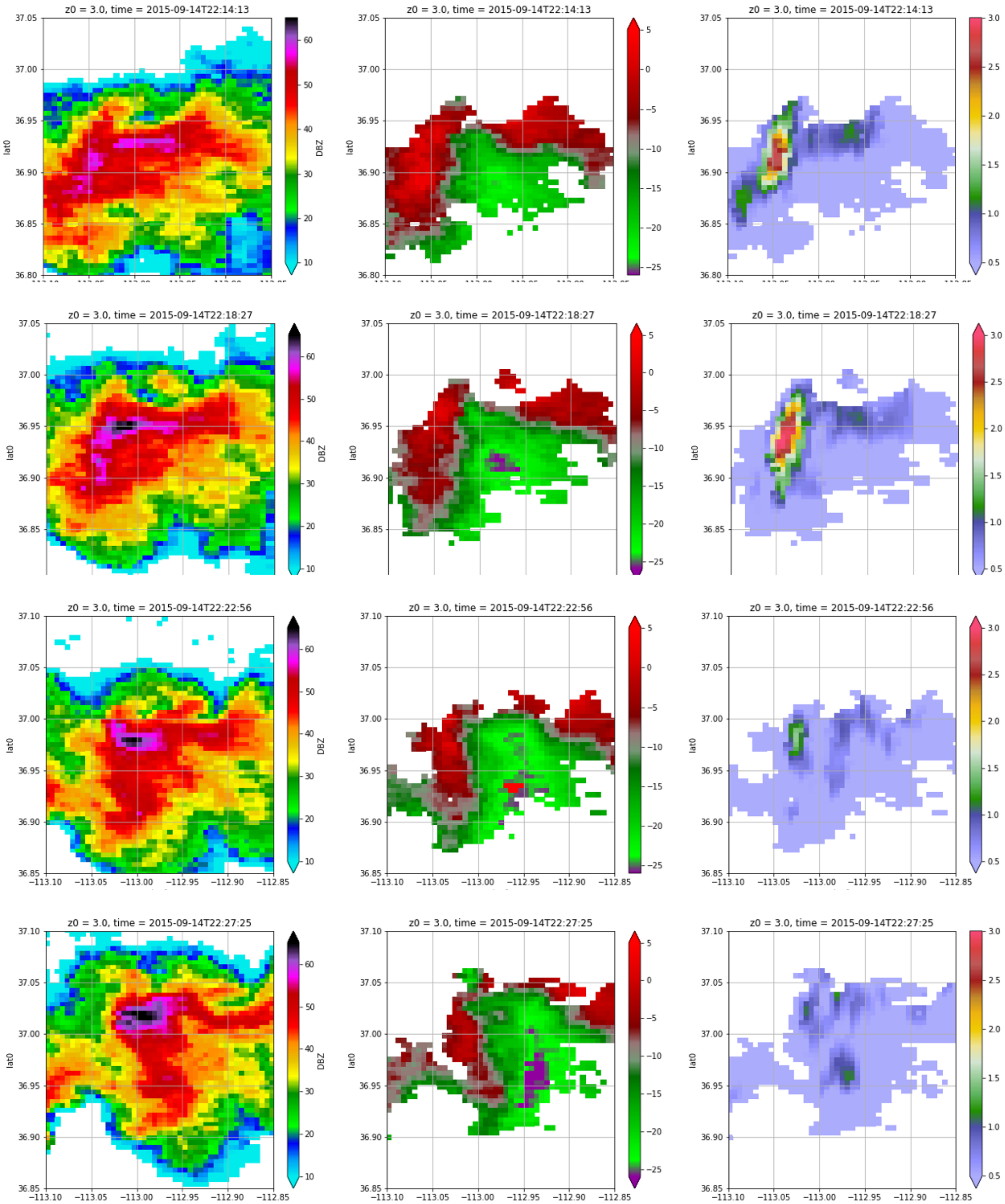

Figure 14: Reflectivity (left), Doppler velocity (middle) and specific differential phase shift (K_{DP}; right) at 2214, 2218, 2222 and 2227 UTC (from top to bottom) on 14 September 2015 from the Cedar City WSR-88D. Extreme rainfall is tied to regions of elevated K_{DP}.

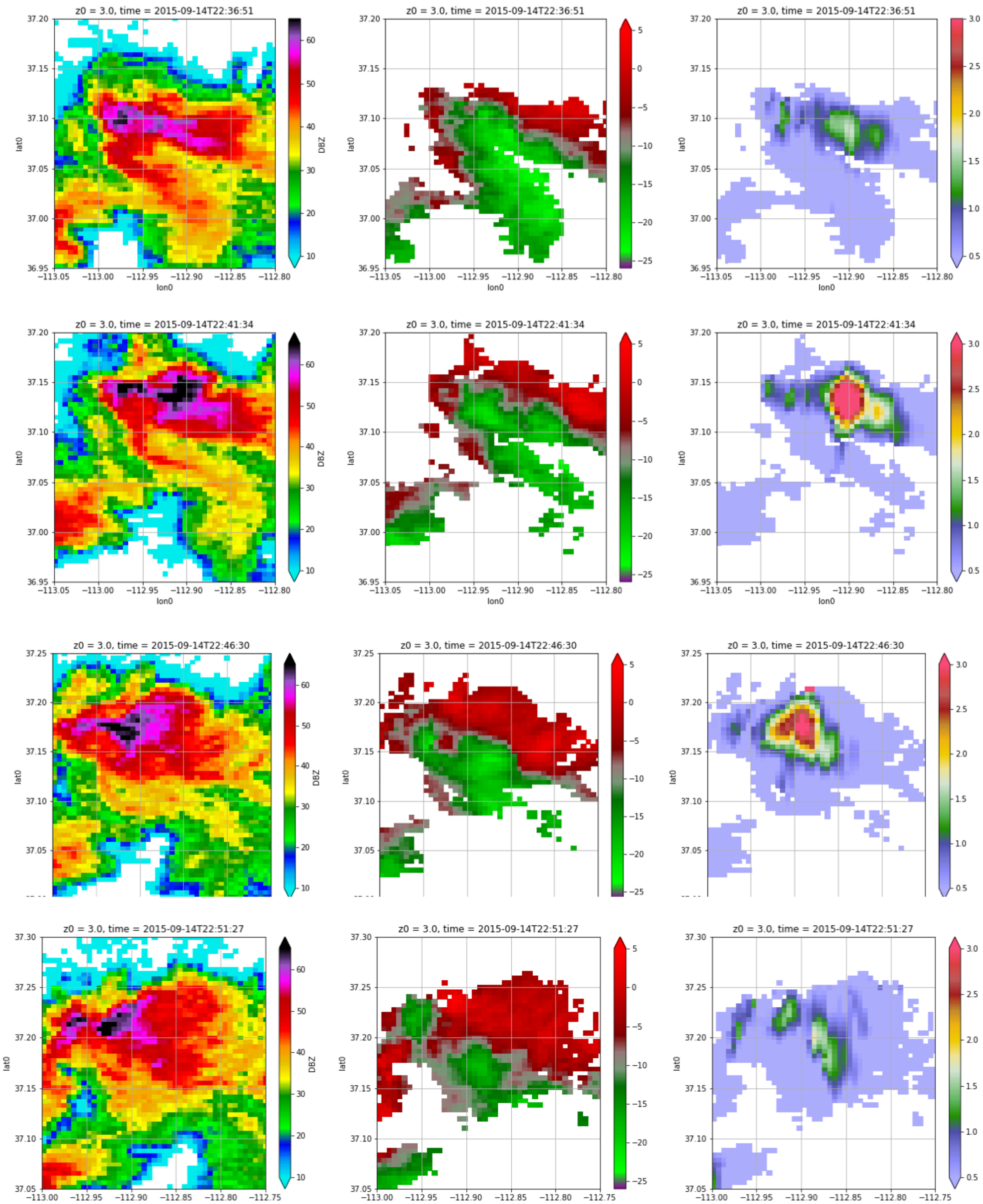

Figure 15: Reflectivity (left), Doppler velocity (middle) and specific differential phase shift (right) at 2236, 2241, 2246 and 2251 UTC (top to bottom) on 14 September 2015 from the Cedar City WSR-88D.

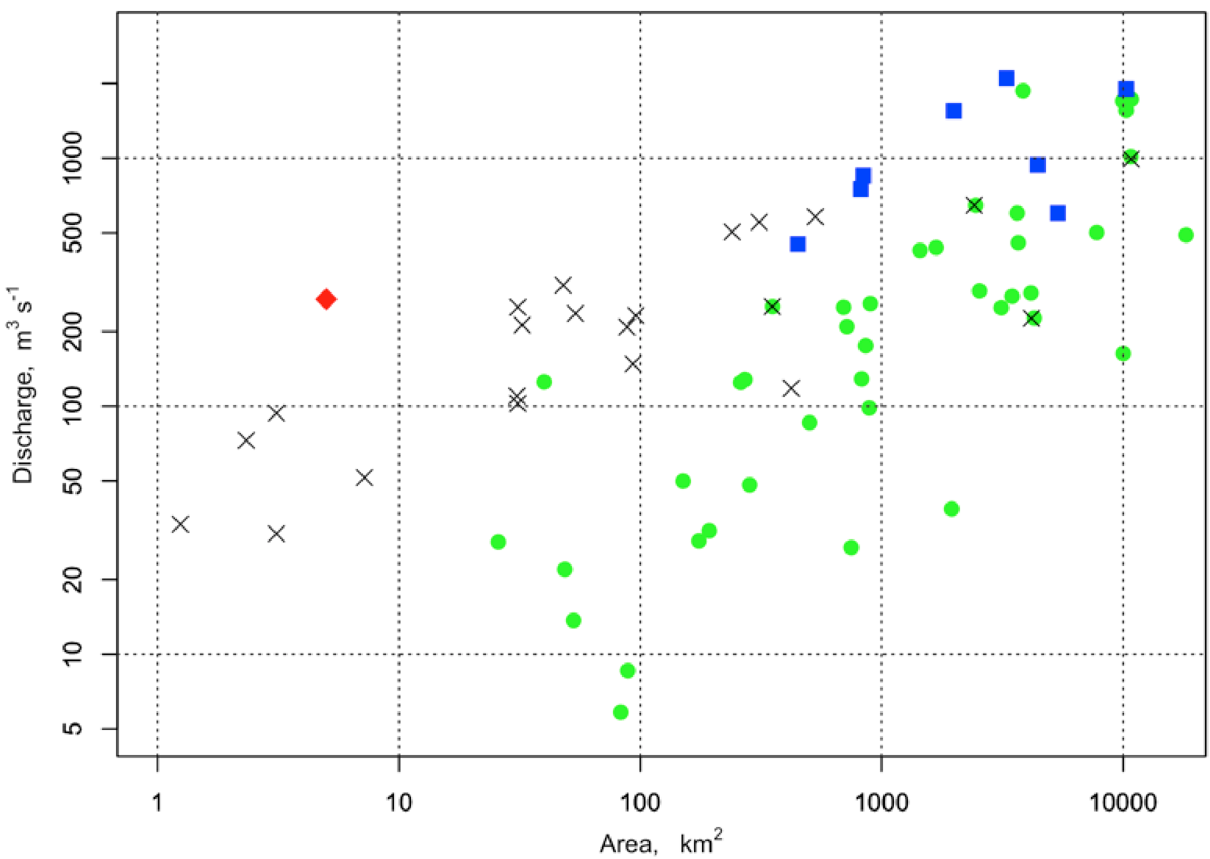

Figure 16: Record flood peaks in the Colorado Plateau of Utah, with the 14 September 2015 peak from Maxwell Canyon shown as a red diamond. The green circles are record flood peaks from USGS stream gaging stations. Flood peaks denoted by black "x" are record flood peaks from Utah, including "miscellaneous" peaks (from [6]). The flood peaks in blue are paleoflood peaks from [8].

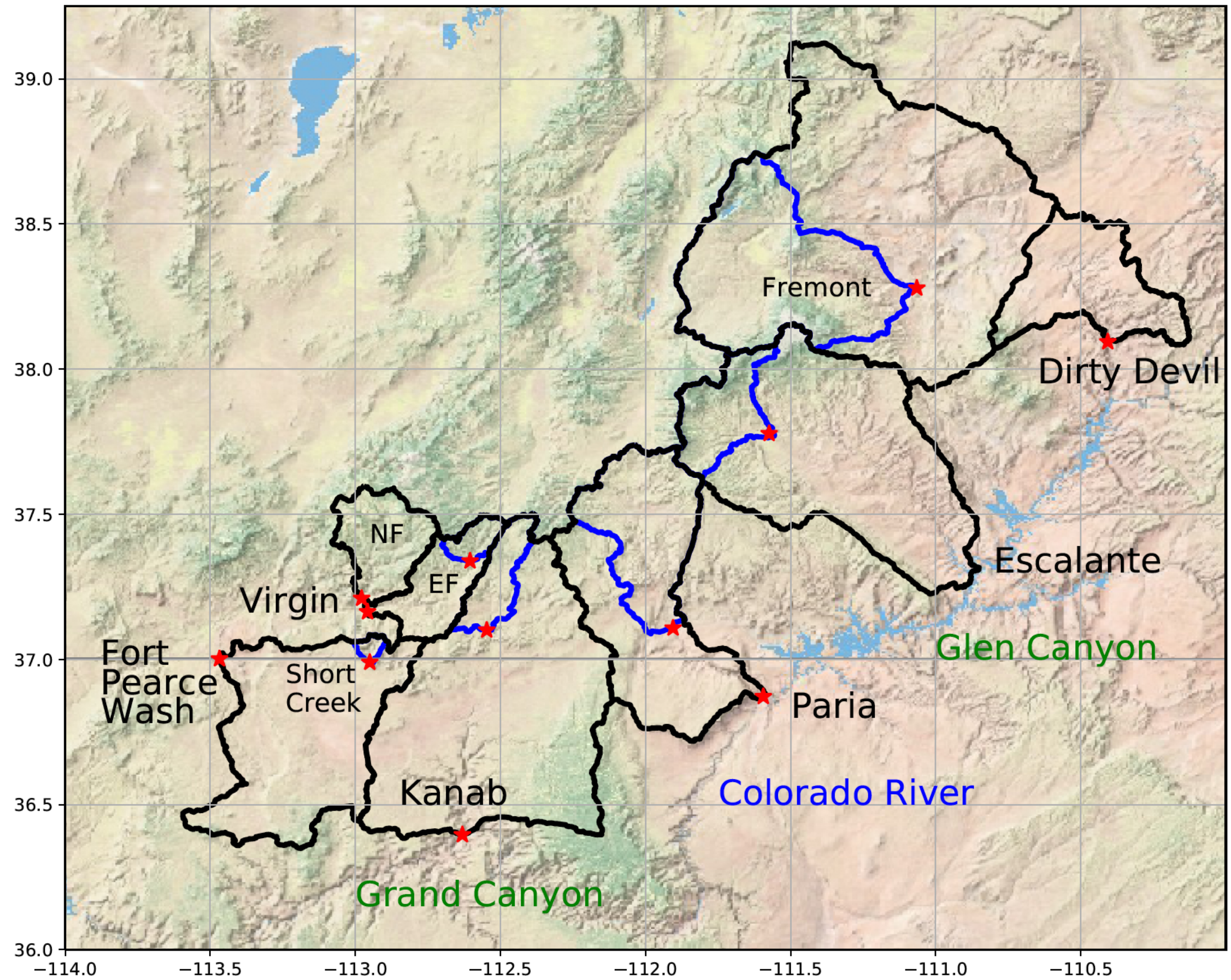

Figure 17: Basin boundaries for the Kanab Creek, Paria River, Escalante River, Dirty Devil River and Virgin Rivers basins (outer basins are all outlined in black). Blue Boundaries are for gaged sub-basins. Short Creek, the setting of the 14 September 2015 flood, is a sub-basin of Fort Pearce Wash. Locations of stream gaging stations are denoted by red stars.

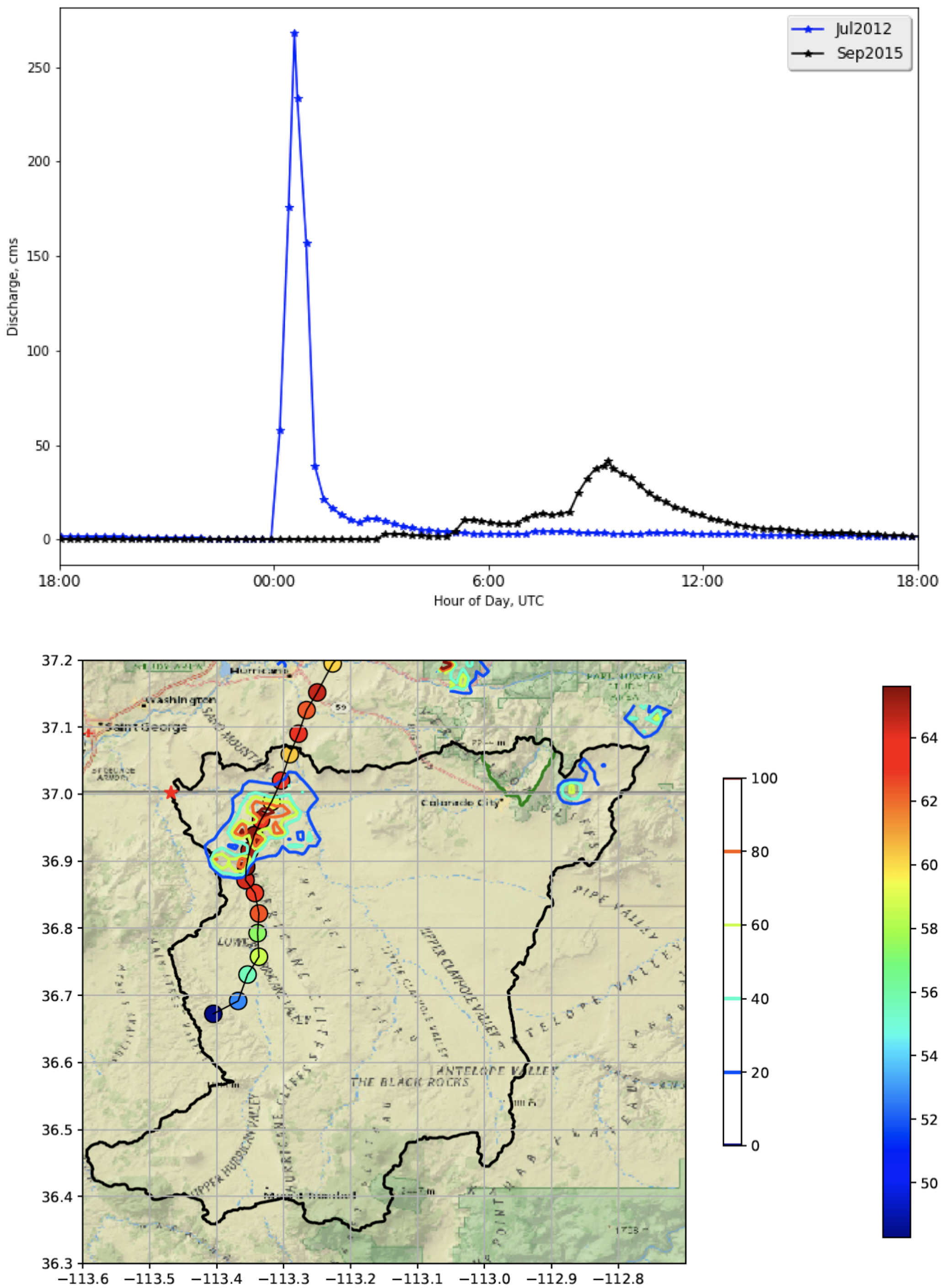

Figure 18: Discharge hydrographs (top) for Fort Pearce Wash on 16-17 July 2012 (blue) and 14-15 September 2015 (black; the storm moved through Short Creek around 22:45 UTC). Rainfall rate field at 2245 UTC on 16 July 2012 (bottom), with the Fort Pearce Wash basin boundary outlined in black; the outlet is denoted by a red star. The Short Creek boundary is outlined in green.

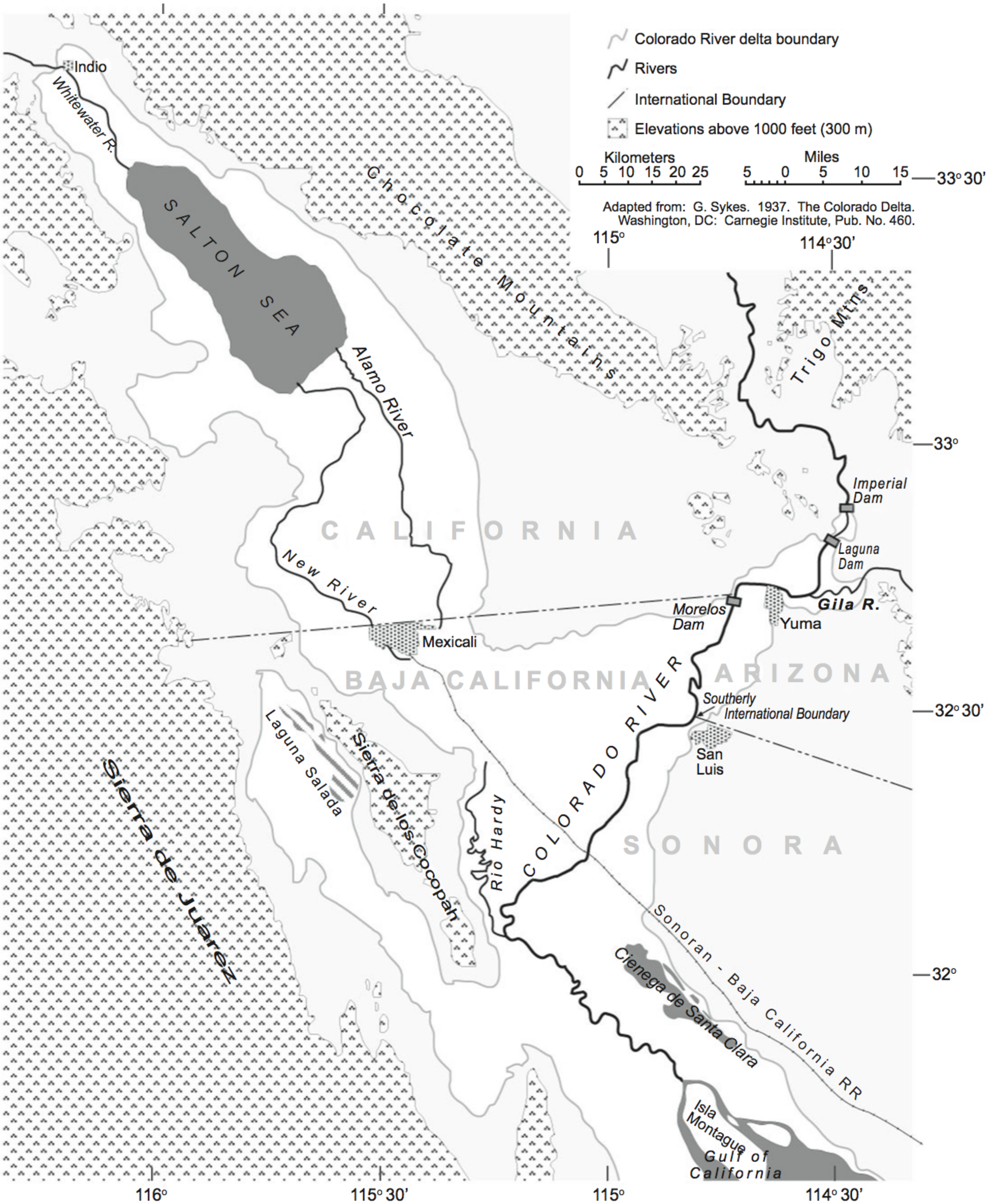

Figure 19: The lower Colorado River, Alamo River and the Salton Sea.

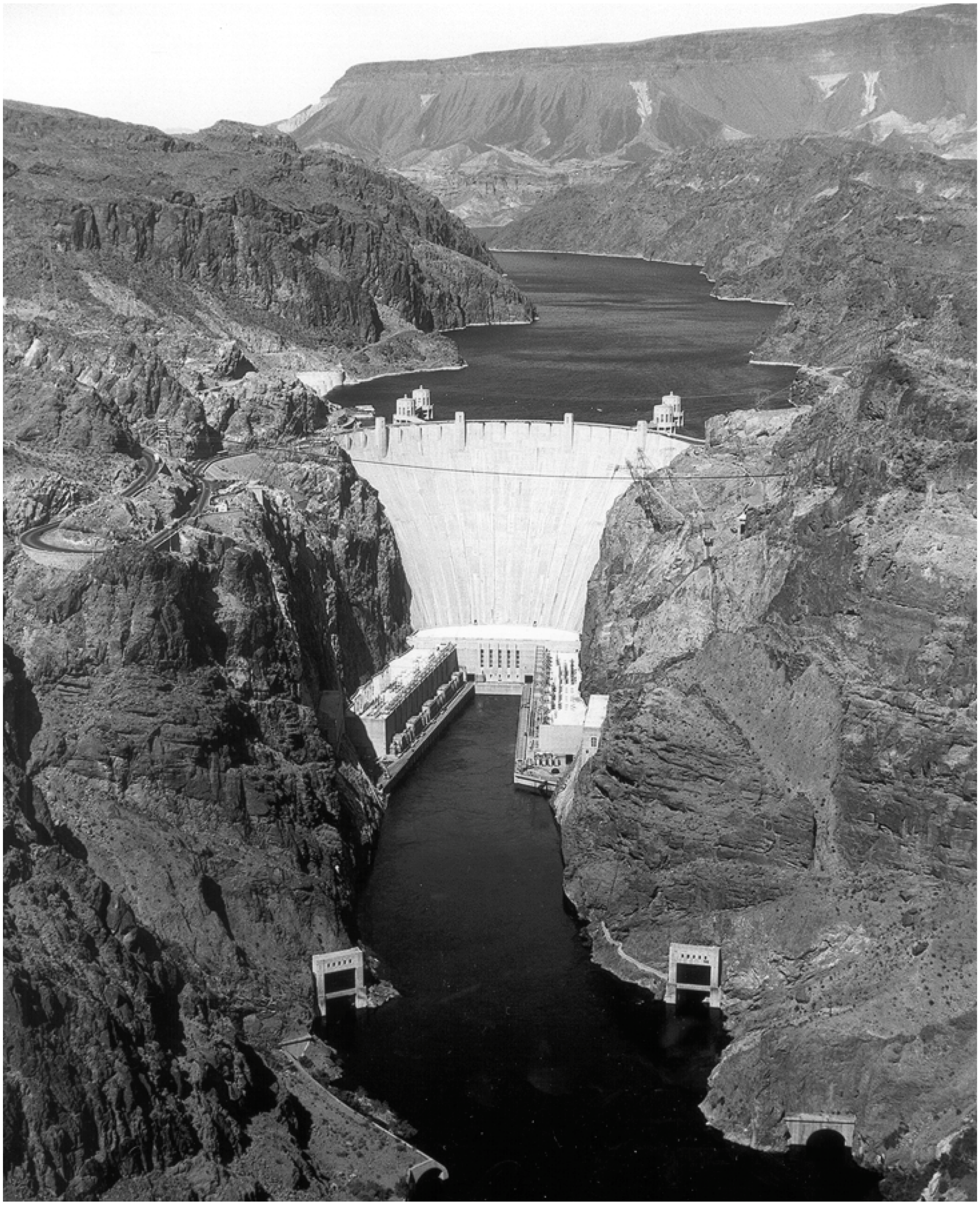

Figure 20: Hoover Dam (see Figure 2 for location).

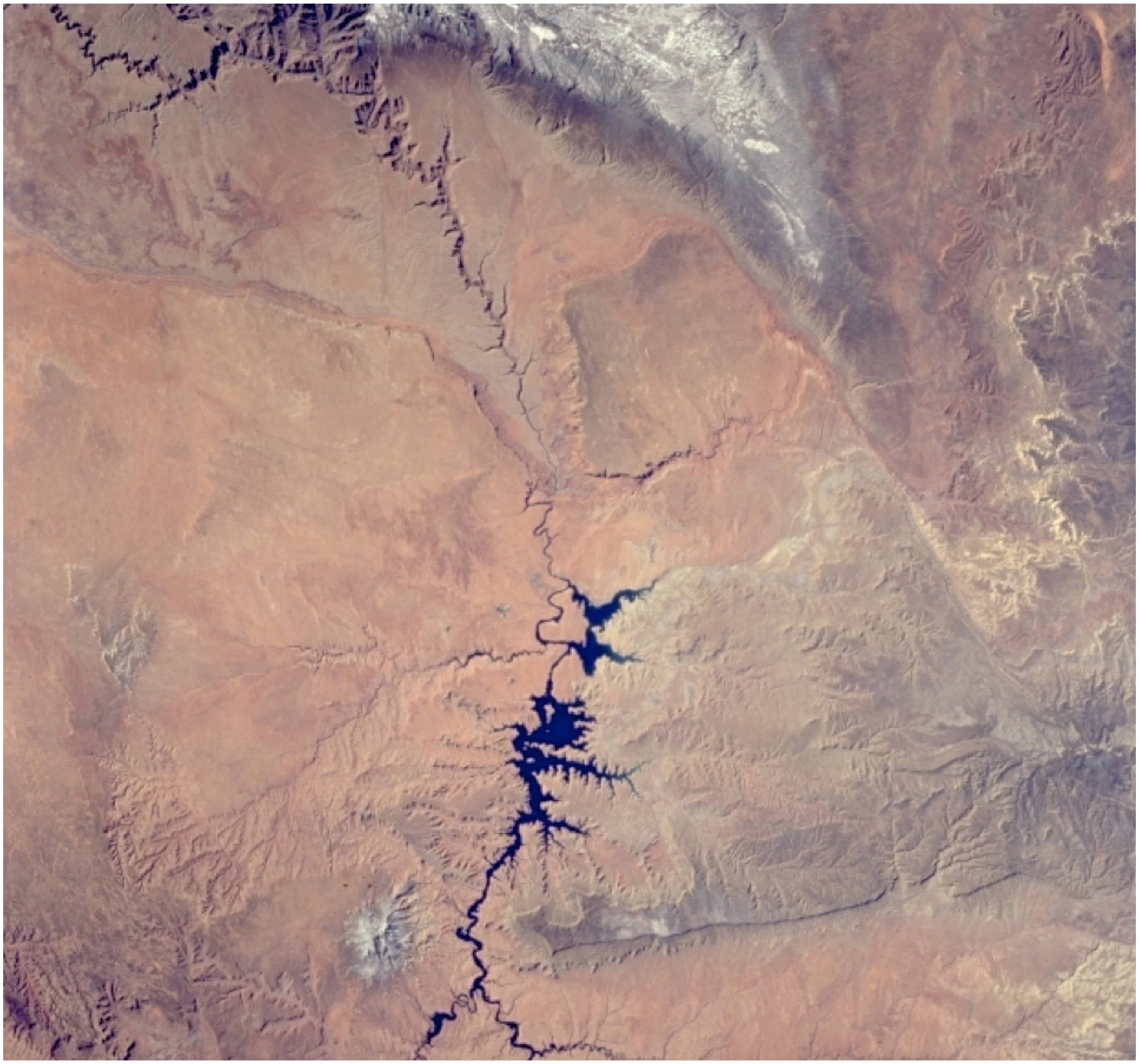

Figure 21: Lake Powell from space. Entrance to the Grand Canyon is in the upper left corner of the image.

Figure 22: Glen Canyon Dam (see Figure 2 for location).

Figure 23: Hetch Hetchy Valley by Albert Bierstadt (late 19th century; Springfield Museum of Fine Art, Massachusetts)

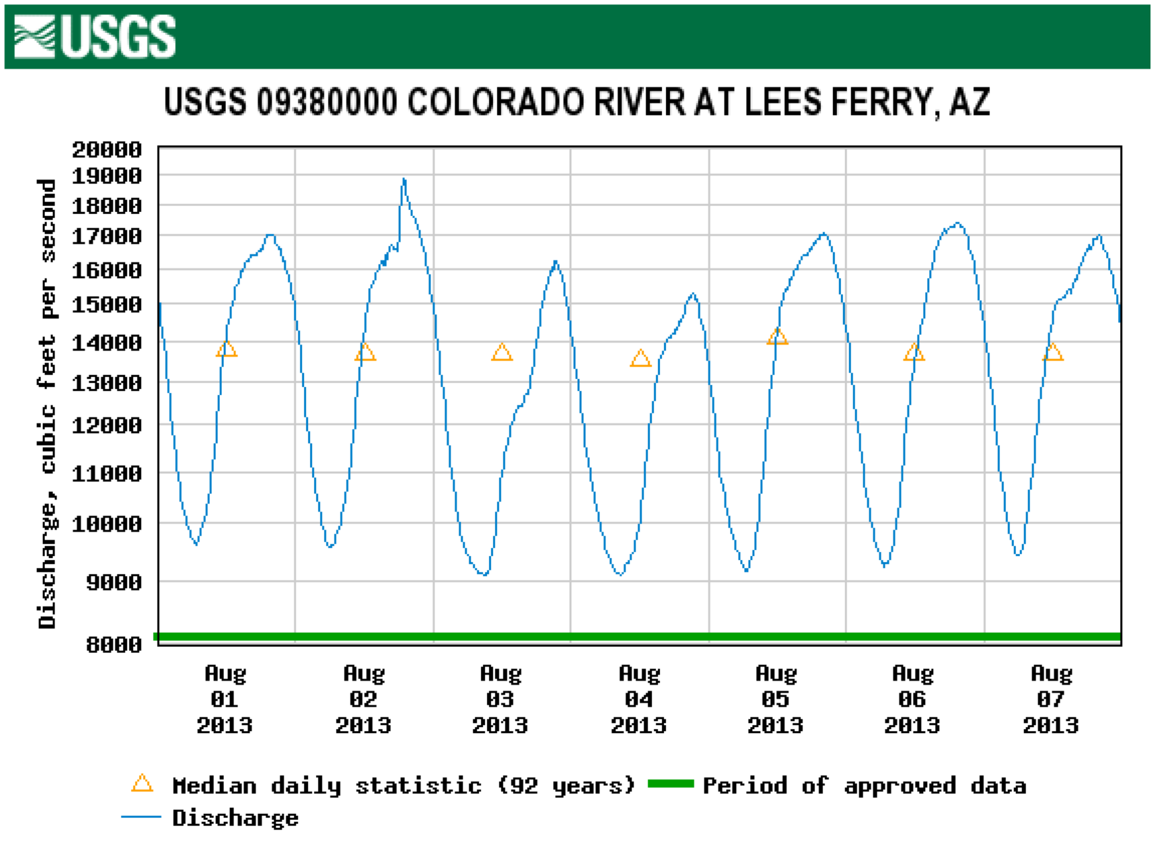

Figure 24: Time series of discharge in the Colorado below Glen Canyon Dam (Lee's Ferry, Arizona) from 1 - 7 August 2013. Note the pronounced diurnal cycle of discharge with minima during the early morning (minimum power demand in the urban areas of the southwest during the summer) and peaks in the early evening (during the time of peak power demand).

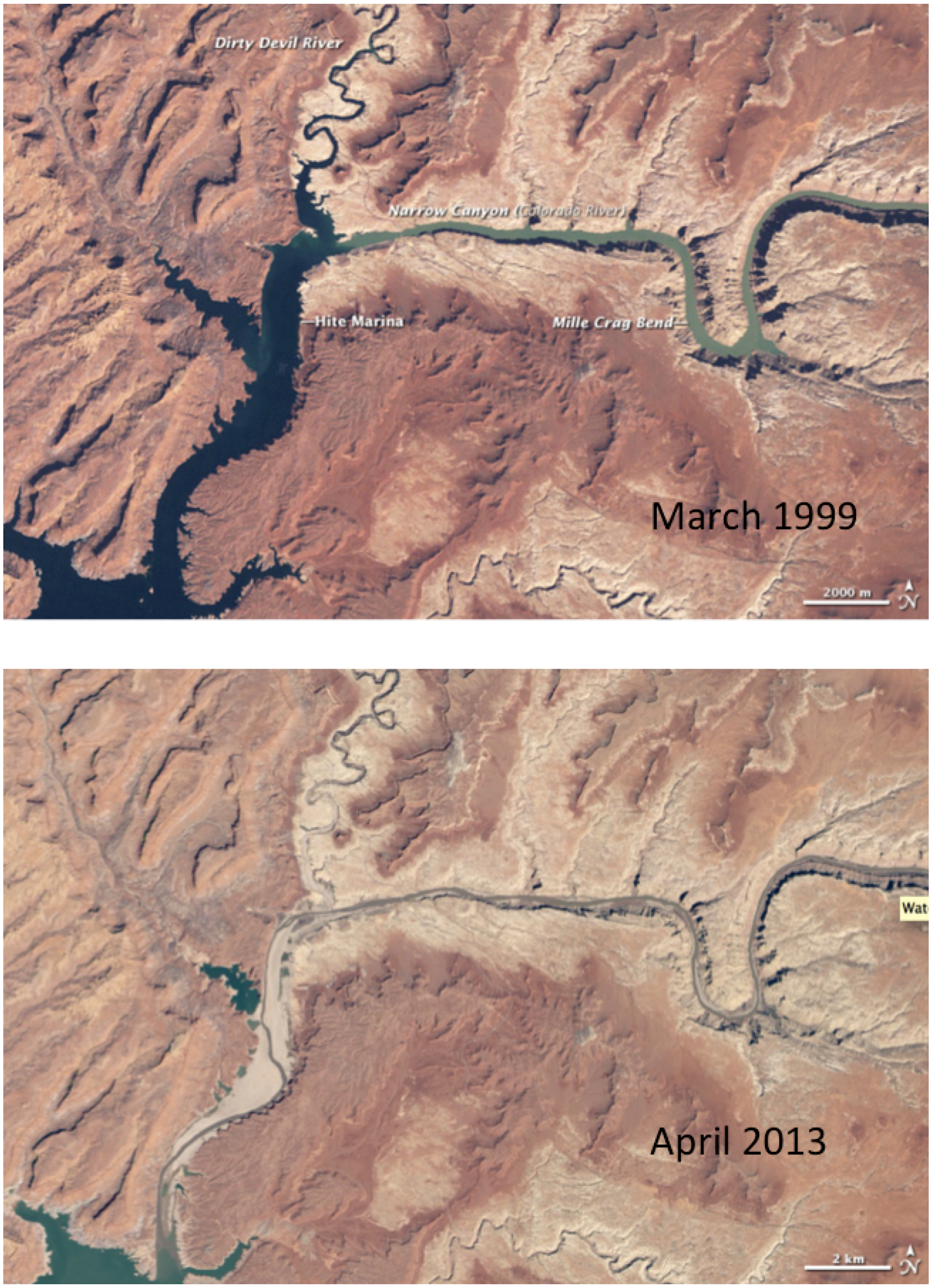

Figure 25: Changes in the northeastern reaches of Lake Powell are documented in this series of natural-color images taken by the Landsat satellites for 1999 and 2013. The Colorado River flows in from the east around Mille Crag Bend. At the west end of Narrow Canyon, the Dirty Devil River joins the lake from the north. At the beginning of the series in 1999, water levels in Lake Powell were relatively high and the water was a clear, dark blue. The sediment-filled Colorado River appeared green-brown. ln 2013 large expanses of dry canyon floor were visible.

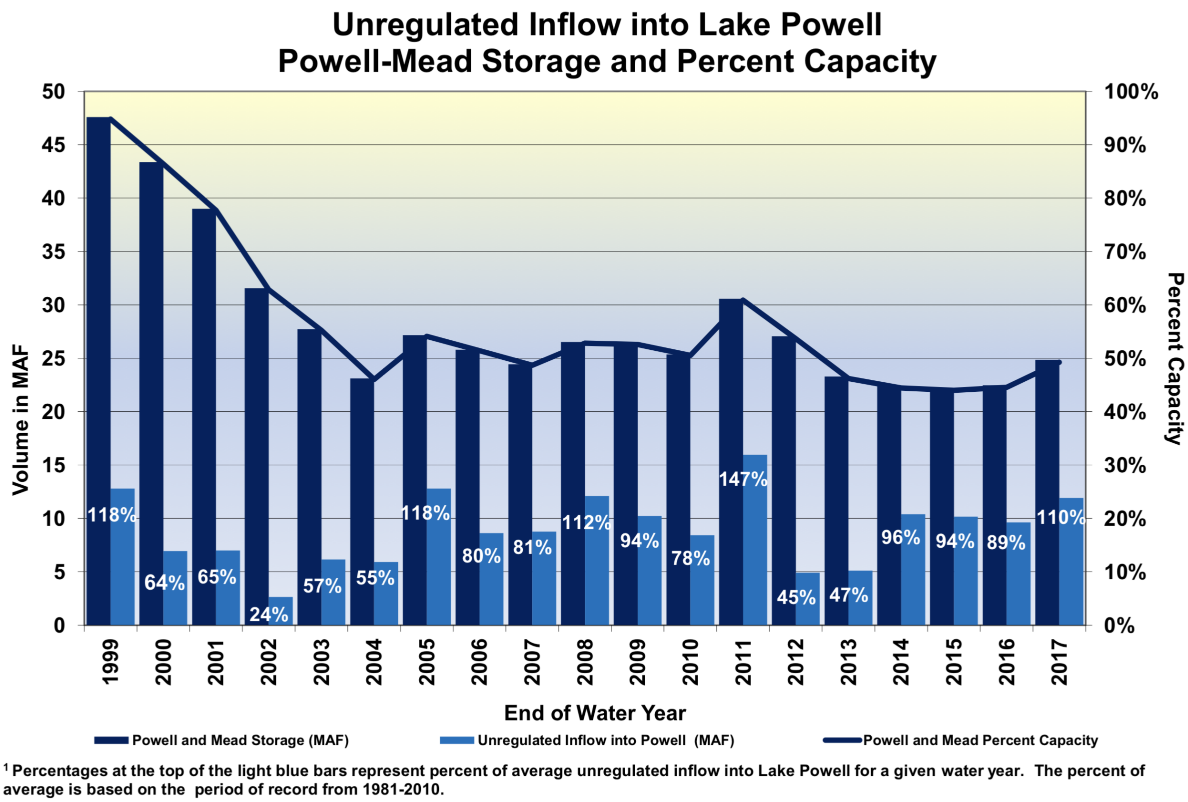

Figure 26: Combined storage volume (MAF; Million acre-feet for Lake Mead and Lake Powell (left axis) in purple bars; the right axis gives the combined storage volume as a per cent of the total capacity. The blue bars give unregulated Lake Powell inflow (MAF).

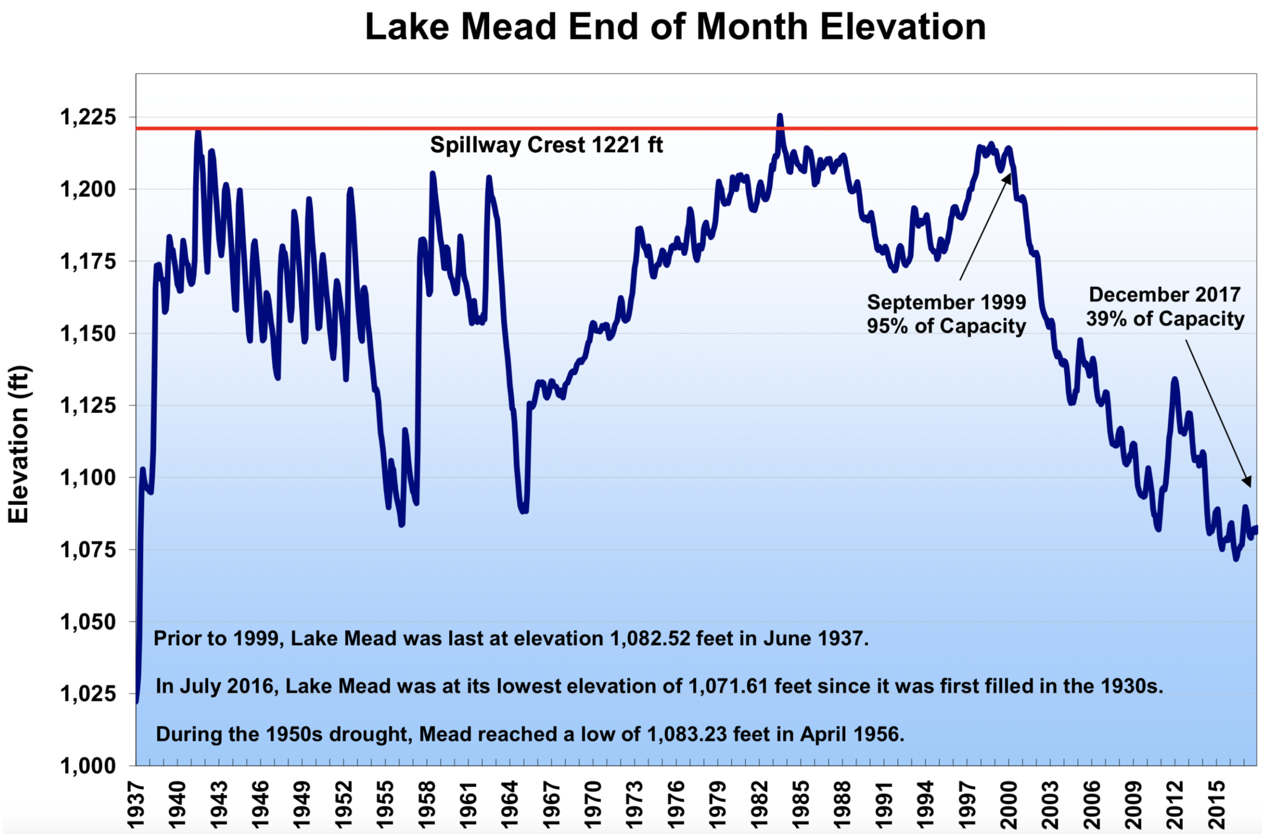

Figure 27: Monthly time series of Lake Mead pool elevation from 1937 - 2017.

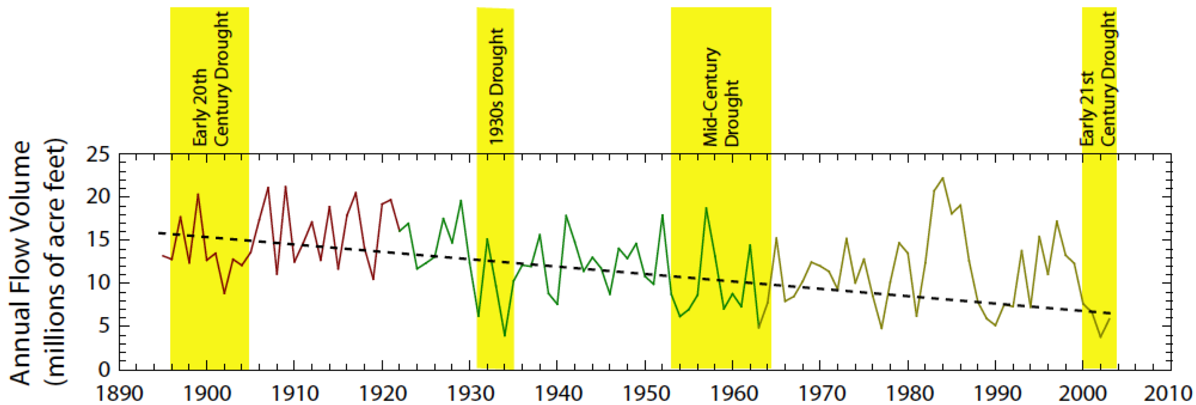

Figure 28: Annual time series of flow volume (in acre-feet) for the Colorado River at Lee's Ferry. Dashed line is the linear trend for the period. Vertical bars and shading delineate drought periods as defined using the Palmer Drought Severity Index for the climate divisions encompassing the upper Colorado River basin.

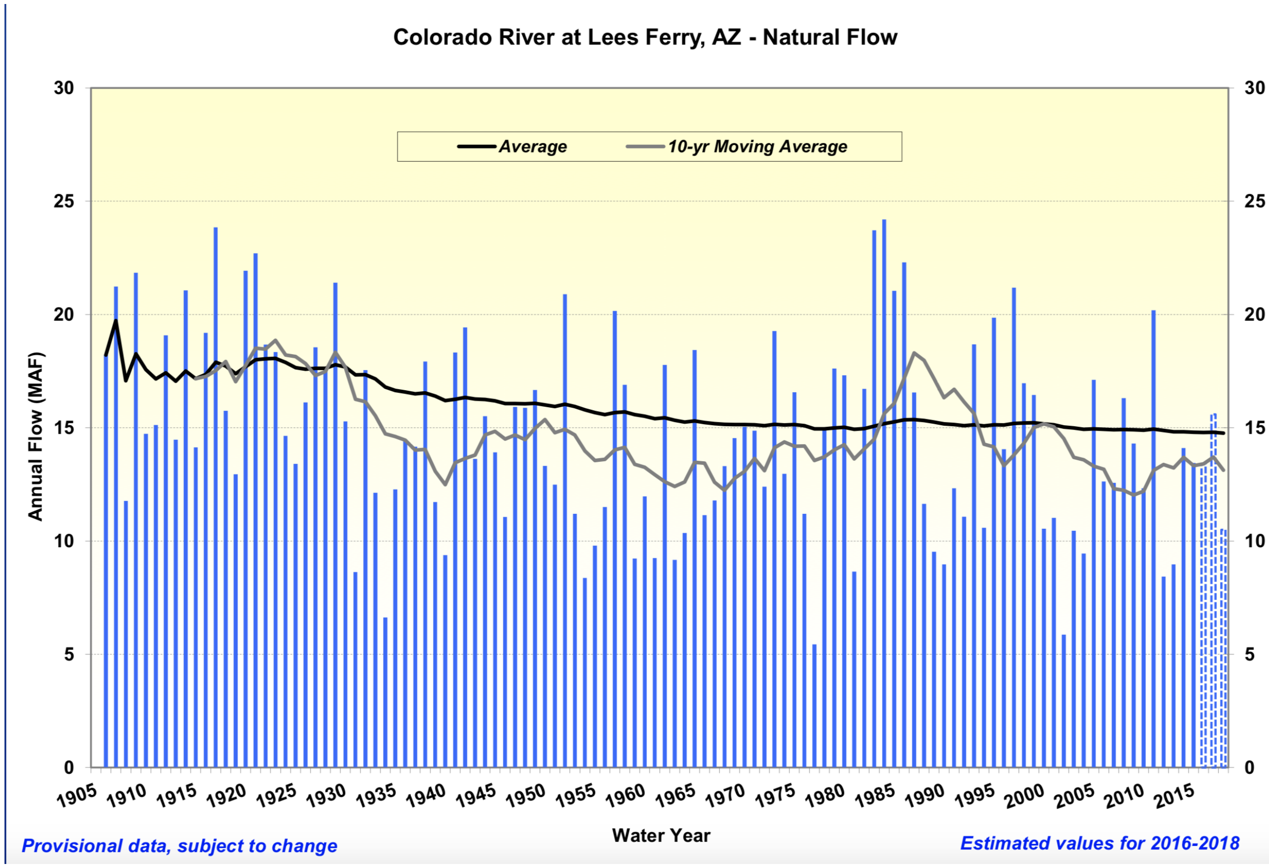

Figure 29: Annual time series of "naturalized" flow volume (MAF; million acre-feet) for the Colorado River at Lee's Ferry (source Bureau of Reclamation). Naturalized flow removes the effects of upstream consumptive use. The green line shows the period of record mean annual flow volume. The red line shows a 10-year running average flow volume.

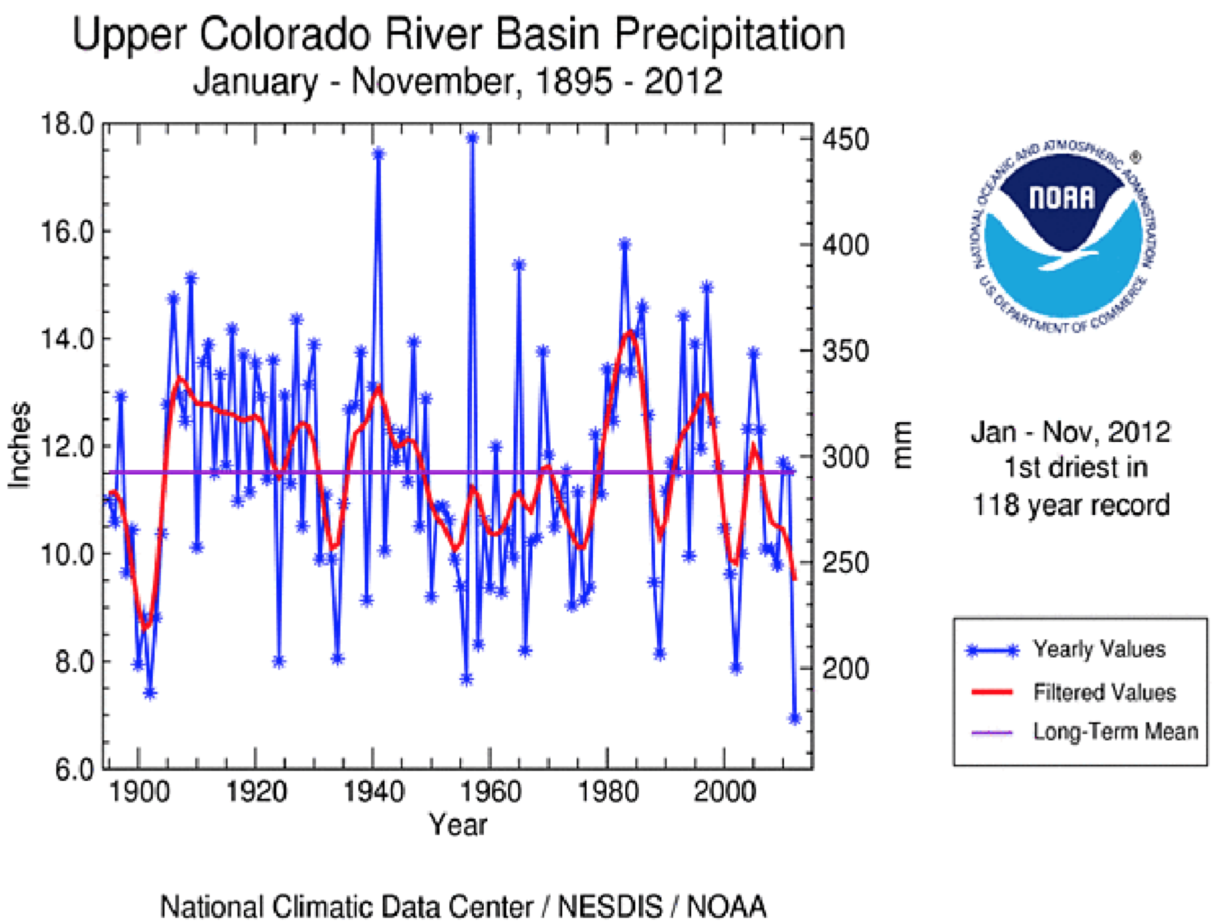

Figure 30: Annual time series of January - November rainfall for the Upper Colorado River basin (blue); time series in red show "smoothed" time series of annual rainfall.

Figure 31: Lake Powell in October 2004. Precipitates along the margin of the reservoir create a white "bathtub ring" illustrating the high water level of Lake Powell (boat on the lake provides scale).