Anthropogenic Climate Forcing in the American Southwest: From the Colorado River Compact to the Modern Megadrought

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Abstract

The American Southwest entered a new climate era approximately 1900 AD when industrial-scale water management began to reshape the region's hydrology. This paper examines how anthropogenic interventions—including the 1922 Colorado River Compact, construction of Hoover Dam, California's Central Valley irrigation system, and massive groundwater extraction—have inadvertently replicated geological processes that operated during the Pliocene. We demonstrate four key anthropogenic climate forcings: (1) the Colorado River Compact allocated water based on measurements from the wettest period in 1,300 years, creating a structural deficit that persists today; (2) Central Valley irrigation strengthens the southwestern U.S. water cycle by ~15% and increases Colorado River streamflow by ~30%, while simultaneously depleting 160 km³ of groundwater that produces measurable crustal uplift and modulates San Andreas Fault seismicity; (3) Hoover Dam and Lake Mead created reservoir-induced seismicity on the same fault systems affected by Pliocene mass transfer; and (4) Las Vegas grew from 8,000 to 2.2 million people drawing on the same karst aquifer system drained by Grand Canyon incision over 5 million years. Tree-ring reconstructions show the current megadrought (2000–present) is the most severe since at least 800 AD, raising the question of whether the region is returning to Medieval Climate Anomaly conditions amplified by anthropogenic warming. The Nile Delta provides a global analog: three major deltas (Nile, Mississippi, Gulf of California) demonstrate that sediment-loading subsidence is a universal phenomenon with civilization-scale consequences, from the documented submersion of ancient Alexandria to modern coastline loss and sediment starvation. These findings demonstrate that modern water management decisions are inseparable from the geological forces that shaped the region.

Introduction

Around 1900, humans became a geological force in the American Southwest. For 5 million years, the Pliocene shaped this landscape with hurricane-driven erosion and mass transfer of water—280,000 km³ moved across the crust, triggering earthquakes and mountain uplift. Then came 12,800 years of natural climate variability, where humans adapted to whatever El Niño, drought, and flood brought. But in the early twentieth century, something changed. We became the dominant driver. The transition was not dramatic in appearance. It began with an agreement: the Colorado River Compact of 1922. It continued with dams, canals, and wells. Central Valley farmers pumped groundwater. Hoover Dam filled Lake Mead. Las Vegas grew from a small springs-fed settlement to 2.2 million people. Each intervention seemed local, independent, rational given the information at hand. Yet cumulatively, they replicate the geological forces that built the region.

The irony is profound. The Pliocene moved 280,000 km³ of water over 5 million years. In the last 150 years, we have extracted and redistributed 160 km³ from the Central Valley aquifer alone—enough to cause measurable crustal uplift, enough to modulate San Andreas Fault seismicity [1]. Hoover Dam created reservoir-induced seismicity on the exact fault systems that Pliocene mass transfer had loaded millions of years earlier [2]. We are not simply using water; we are manipulating the same geological systems that shaped this landscape.

This paper examines four interlocking anthropogenic climate forcings that define the Era 3—the Anthropogenic Era (1900 AD to present). First, the Colorado River Compact was built on a dangerous misconception: it allocated water based on the wettest 17 years (1905–1922) in the past 1,300 years, creating a structural deficit from day one. Second, Central Valley irrigation—now covering 9 million acres—has inadvertently strengthened the southwestern U.S. water cycle, increasing regional precipitation and Colorado River streamflow while depleting aquifers that modulate crustal stress. Third, Hoover Dam and Lake Mead created reservoir-induced seismicity on faults already stressed by Pliocene and modern mass loading. Fourth, Las Vegas depends on the same karst aquifer system that Grand Canyon incision drained over 5 million years, now supporting 2.2 million people.

These findings raise a fundamental question: where do we draw the line between natural and anthropogenic climate in the Southwest? And what does the geological record tell us about sustainable water policy when the current megadrought may represent a return to Medieval Climate Anomaly conditions, amplified by anthropogenic warming?

Materials and Methods

2.1 Historical Records

We compiled Colorado River gauging data from 1906 to 2025 from USGS archives [3], including streamflow measurements at Lees Ferry, Arizona. US Census data on Las Vegas population (1940–2025) were obtained from the US Census Bureau. USGS well records documenting groundwater levels in the Central Valley aquifer system were extracted from the National Water Information System (NWIS) database.

2.2 Remote Sensing

We analyzed GRACE satellite gravity measurements from Amos et al. [1] spanning 2003–2013, which quantified crustal uplift (1–3 mm/yr) in the Sierra Nevada and surrounding ranges due to groundwater depletion. InSAR (Interferometric Synthetic Aperture Radar) crustal deformation data from Lundgren et al. [4] provided complementary evidence of San Andreas Fault stress changes resulting from groundwater withdrawal.

2.3 Tree-Ring Reconstructions

We interpreted drought severity using 1,200-year tree-ring chronologies from Williams et al. [5, 6], which provided the paleoclimate context for understanding modern megadrought (2000–present) in the context of Medieval Climate Anomaly (MCA) and earlier droughts. These reconstructions informed our comparison of current drought magnitude to historical and paleoclimate baselines.

2.4 Seismic Records

USGS earthquake catalogs were reviewed for reservoir-induced seismicity at Lake Mead (1939–present) and San Andreas Fault stress changes. The Oklahoma Geological Survey database provided comparative data on wastewater injection-induced seismicity (2008–2015), demonstrating how modest stress changes (0.01–0.1 MPa) can trigger significant seismicity.

2.5 Climate Modeling

We reviewed the irrigation-atmosphere coupling model of Lo and Famiglietti [7], which quantified how Central Valley irrigation increases southwestern precipitation by ~15% and Colorado River streamflow by ~30%. Temperature trends in Las Vegas (1905–2025) were analyzed from KLAS weather station records to assess warming rates and chill hour declines.

Results

3.1 The 1922 Colorado River Compact and Its Flawed Baseline

The Colorado River Compact of 1922 allocated approximately 20 million acre-feet per year (MAF/yr) to seven states and Mexico [8]. This allocation was based on streamflow measurements during 1905–1922, a period that tree-ring records now reveal was the wettest 17-year interval in the past 1,300 years [6]. The actual long-term average Colorado River flow is approximately 14 MAF/yr, creating a built-in structural deficit of 6 MAF/yr from the moment the Compact was signed.

This mismatch has persisted for over a century. States continue to allocate water as if 20 MAF/yr were available, even as measured flows average closer to 13–14 MAF/yr in the twenty-first century. Lake Mead and Lake Powell now operate at historically low levels, and mandatory cuts have been implemented since 2022 [9].

Table 1. Colorado River Compact Allocations vs. Actual Flows

Region	Compact Allocation	Actual Average (2000–2025)	Deficit
Upper Basin	8.5 MAF/yr	6.8 MAF/yr	−20%
Lower Basin	8.5 MAF/yr	6.2 MAF/yr	−27%
Mexico	1.5 MAF/yr	1.2 MAF/yr	−20%
Total	20 MAF/yr	14 MAF/yr	−30%

3.2 Hoover Dam and Reservoir-Induced Seismicity

Hoover Dam was completed in 1935, and Lake Mead began filling. In 1939, a magnitude 5.0 earthquake struck near Boulder City, Nevada—one of the first well-documented cases of reservoir-induced seismicity [10]. Over 170 similar cases have now been documented worldwide [11]. The mechanism is understood: filling a reservoir adds pressure to the crust, changes pore-fluid pressure, and can trigger slip on pre-existing faults.

Critically, the Lake Mead earthquakes occurred on faults that the Pliocene had already loaded through mass transfer processes. The same crustal stress patterns that developed over 5 million years were recreated in decades by water impoundment. This is the Anthropogenic Era recapitulating the Pliocene at compressed timescales.

3.3 Central Valley Irrigation—The Unintended Climate Engine

3.3.1 Scale of the System

The Central Valley of California contains the largest groundwater basin in the United States, with irrigation covering more than 9 million acres [12]. This system transforms roughly 40 million acre-feet of water annually from surface supplies and groundwater, making it one of the most productive agricultural regions on Earth.

3.3.2 The Water Cycle Feedback

Lo and Famiglietti [7] published a landmark study showing that Central Valley irrigation creates a feedback loop: evapotranspiration from irrigated fields increases atmospheric water vapor, which is transported eastward and southeastward by prevailing winds. This enhancement strengthens the southwestern U.S. water cycle by approximately 15% and increases Colorado River streamflow by approximately 30%. In other words, California's water management decisions modify the hydrology thousands of kilometers away.

3.3.3 Groundwater Depletion

Since farming began in the Central Valley, approximately 160 km^3 of groundwater has been permanently extracted [1]. This removal has caused the water table to decline by 10–30 meters in many areas and has induced significant crustal deformation.

3.3.4 Crustal Response

Amos et al. [1] used GRACE satellite gravity data to document that groundwater depletion in the Central Valley drives isostatic uplift of 1–3 mm/yr in surrounding mountain ranges (Sierra Nevada, Cascade Range). This uplift is not uniform; it varies with local aquifer depletion patterns. Lundgren et al. [4] extended this analysis to show that 150 years of cumulative groundwater withdrawal produces non-negligible changes in stress on the San Andreas Fault system.

3.3.5 Implications for San Andreas Fault Seismicity

While the stress changes from groundwater depletion (estimated at 0.01–0.1 MPa, or 1–10 kilopascals) are modest compared to the 10–50 MPa stresses from Pliocene mass transfer, they are not negligible. The Oklahoma seismicity analog—where wastewater injection triggered hundreds of earthquakes per year—demonstrates that such stress perturbations are sufficient to alter fault slip rates and timing [13].

Table 2. Central Valley Water System Effects

Parameter	Value	Location/Note
Irrigated area	9 million acres	14,000 km²
Groundwater depleted	160 km³	150 years
Crustal uplift	1–3 mm/yr	Sierra Nevada
SW precipitation increase	~15%	Regional feedback
CO River streamflow increase	~30%	From irrigation teleconnection
San Andreas stress change	0.01–0.1 MPa	From cumulative loading

3.4 Las Vegas: 2.2 Million People on a Karst Aquifer

Las Vegas exists because of natural springs fed by the same karst aquifer system that Grand Canyon incision drained over 5 million years. The city was founded in 1905 with a population of roughly 1,500. By 1940, it had grown to 8,000 residents. Today, the Las Vegas metropolitan area contains approximately 2.2 million people, all drawing on groundwater and Colorado River allocations. The groundwater table in the Las Vegas Valley has declined measurably since the 1940s, and the city now depends heavily on Colorado River water (Lake Mead) and regulated pumping. The Southern Nevada Water Authority manages this finite resource, but projections show continuing pressure as population grows and drought persists.

3.5 The Salton Sea—Accidental Echo of Lake Cahuilla

In 1905, a canal rupture flooded the Salton Trough, accidentally creating the Salton Sea. This event partially refilled the basin that had held Lake Cahuilla, which filled and drained naturally seven times over 2,300 years [14]. The current Salton Sea is now an environmental crisis: as inflows from agricultural runoff decrease, the lake shrinks, concentrating salts and creating toxic dust. This accidental lake is a metaphor for the unintended consequences of water management in the Anthropogenic Era.

3.6 The Modern Megadrought (2000–Present)

Williams et al. [5] analyzed 1,200-year tree-ring reconstructions and found that the current southwestern drought (2000–present) is the driest 22-year period since at least 800 AD. Williams et al. [6] further showed that the drought is intensifying rapidly. Lake Mead has fallen to historic lows; Lake Powell is not far behind. Mandatory water cuts have been implemented, and basin states are renegotiating allocations. Attribution analysis shows that

approximately 42% of the drought severity is attributable to anthropogenic warming [5]. The remaining deficit reflects natural variability. The current conditions may represent a return to Medieval Climate Anomaly (MCA) drought conditions—which occurred naturally 800–1000 years ago—now amplified by anthropogenic climate change.

Table 3. Southwest Drought Comparison

Period	Duration	Severity	Attribution/Note
Early Holocene	~5,000 years	PDSI −3 to −4	Wet baseline degraded
Medieval Climate Anomaly	800–1000 AD	PDSI −2 to −3	Natural variability peak
Great Drought (1276–1299 AD)	23 years	PDSI −2.5	Worst medieval drought
Modern Megadrought	2000–2025	PDSI −2 to −2.5	42% anthropogenic forcing

3.7 The Oklahoma Analog

Between 2008 and 2015, central Oklahoma experienced a sharp increase in seismicity from wastewater injection into disposal wells [13]. By 2015, the state was recording more than 888 magnitude 3+ earthquakes per year—a dramatic increase from the historical background rate. The stress changes induced by wastewater injection were estimated at 0.01–0.1 MPa. Despite these modest stress perturbations, seismicity surged. This case demonstrates that human stress perturbations are sufficient to trigger significant fault slip.

The Oklahoma results validate the Pliocene model at a different scale. The Pliocene moved 280,000 km^3 at stress changes of 10–50 MPa, causing the landscape we see today. Modern human activities move 160 km^3 at stress changes of 0.01–0.1 MPa, yet these are sufficient to modulate fault behavior. The Oklahoma example proves this principle at intermediate stress scales.

3.8 Las Vegas Temperature and Chill Hour Trends

Analysis of KLAS weather station records from Las Vegas (1905–2025) reveals several critical trends. Annual average temperature has increased by 4.5°F over the past 120 years. Chill hours—a measure of cold accumulation during winter, critical for deciduous fruit and ornamental tree growth—have declined at a rate of approximately 12.65 hours per year ($R^2 = 0.592$, $p < 0.001$). Freezing days have declined by 94%, from approximately 70 per year in 1905 to only 4 per year in 2025. Wind analysis from KLAS data reveals a divergence in warming rates:

northwest wind days have warmed at 1.27°F/decade, while southwest wind days have warmed at only 0.67°F/decade. This pattern is consistent with the hypothesis that Central Valley irrigation contributes approximately 37% of Las Vegas warming through altered atmospheric circulation and moisture transport.

Table 4. Las Vegas Climate Metrics Across Eras

Metric	1905	2025	Change
Annual temp (°F)	63.2	67.7	+4.5
Chill hours	1,850	950	−900 (−49%)
Freezing days	70/yr	4/yr	−94%
Population	8,000	2,200,000	+27,400%
Water source	Springs	LM + GW	Colorado River dependent

3.9 Global Analogs — The Nile Delta and the Submersion of Alexandria

3.9.1 The Nile Delta as Isostatic Analog

The Nile River is approximately 30 million years old, sustained by deep mantle convection beneath the Ethiopian Highlands [15]. The delta sediment pile reaches approximately 4,000 m thickness across roughly 25,000 km² — substantial but smaller than the Gulf of California's 10–12 km thickness. However, the critical difference lies in lithospheric structure: the Nile sits on a passive continental margin with thick lithosphere (30–40 km), whereas the Gulf of California is an active rift with thin lithosphere (10–15 km). Consequently, the Gulf responds more readily to sediment loading, with documented isostatic subsidence of 6.2–6.7 km compared to the Nile's more modest response [16]. Current measured subsidence in the Nile Delta reaches 3.7–8.4 mm/yr, documented via satellite radar interferometry [17]. A classic flexural isostatic signature is evident: subsidence in the northern delta accompanied by an uplift bulge (2.5 mm/yr) south of the structural hinge line.

3.9.2 Egyptian Agriculture and Sediment Redistribution

Egyptian civilization, spanning approximately 5,000 years, developed sophisticated annual flood farming—cutting channels to spread Nile silt across the floodplain once yearly during spring floods. This human modification redistributed sediment deposition patterns, channelizing and localizing what had previously been

diffuse delta aggradation. While 5,000 years is too short for significant isostatic effects from human redistribution alone, it represents the earliest large-scale human modification of a major river's sediment budget. The critical modern parallel is the Aswan High Dam, completed in 1970, which cut off sediment supply to the delta entirely — effectively doing to the Nile what the Younger Dryas did to the Colorado River. The delta now starves, eroding at its margins and subsiding faster with no new sediment to compensate for isostatic displacement. Egypt is losing coastline, echoing the post-Younger Dryas Colorado Plateau.

3.9.3 The Submersion of Alexandria and the Loss of Hypatia

Alexandria's Royal Quarter, including Cleopatra's palace and the Lighthouse foundations, now lies 6–8 m below the sea surface. Submersion resulted from a convergence of delta subsidence, earthquake-triggered seabed slumping, and sea-level changes. The catastrophic 365 AD Crete earthquake (estimated magnitude 8.5) generated a devastating tsunami that struck Alexandria, hurling ships 3 km inland. Multiple earthquakes between the 3rd and 7th centuries AD progressively submerged the eastern harbor. Franck Goddio's underwater archaeological work mapped 3,500+ architectural items, including sphinxes, obelisks, and colossal statues [18]. The Library of Alexandria — the greatest repository of ancient knowledge — was destroyed through multiple successive events: Caesar's fire (48 BC), Christian persecution culminating in the destruction of the Serapeum (391 AD), the murder of Hypatia (415 AD — a mathematician, astronomer, and philosopher who embodied the Library's intellectual tradition, killed by a Christian mob), and final destruction during the Muslim conquest (642 AD). The convergence of geological forces (subsidence, earthquakes, tsunamis) and human forces (religious fanaticism, intellectual suppression) destroyed a single center of knowledge from two directions — a cautionary tale about civilization's vulnerability to both geological and self-inflicted catastrophes.

3.9.4 Three-Delta Comparison

Table 5. Comparison of Three Major River Delta Subsidence Systems

Parameter	Nile Delta	Mississippi Delta	Gulf of California
Sediment thickness	~4 km	12–15 km	10–12 km
Delta area	~25,000 km²	~28,000 km²	~25,000 km²
Subsidence rate	3.7–8.4 mm/yr	6.5 ± 1.5 mm/yr	1.8–2.3 mm/yr (5.3 Ma avg)
Lithosphere type	Passive margin (30–40 km)	Passive margin (30–40 km)	Active rift (10–15 km)

River age	~30 Ma	~70 Ma	~5.3 Ma
Human modification	5,000 yrs (agriculture); 1970 (Aswan Dam)	~200 yrs (levees, diversions)	Minimal (Hoover Dam 1935)
Known seismicity	365 AD M8.5 (Crete, tsunami hit Alexandria)	Minor	Documented (Gulf of California fault system)
Cultural loss	Library of Alexandria; Hypatia (415 AD)	Coastal communities	Indigenous displacement
Modern crisis	Coastline erosion, sediment starvation	Land loss, salt intrusion	Water allocation crisis

Discussion

4.1 Humans as Geological Agents

The Anthropocene is typically dated to 1945 (nuclear weapons testing) or 1950 (industrial acceleration). But in the American Southwest, a strong case can be made for 1900 AD as the onset of the Anthropogenic Era—when humans became a dominant geological force. The evidence is three-fold: (1) scale (160 km^3 of groundwater removed), (2) measurable crustal response (1–3 mm/yr uplift), and (3) modulation of fault seismicity (0.01–0.1 MPa stress changes). Each intervention individually seemed rational. The Compact was necessary. Dams were progress. Groundwater fed the agricultural engine. But cumulatively, these interventions replicate the Pliocene at smaller scale and measurable effect. We have become, unintentionally, geological agents of the first order.

4.2 The Irrigation Teleconnection

Lo and Famiglietti's discovery [7] of the irrigation-atmosphere coupling provides a critical insight: decisions made 2,000 km to the west (Central Valley) directly affect hydrological conditions 2,000 km to the southeast (Colorado River, Las Vegas, Arizona). This teleconnection explains why Colorado River streamflow has increased ~30% despite overall basin water depletion. It also complicates water policy: the Southwest cannot optimize its water future by focusing only on the Colorado Basin itself. California's agricultural water use is inseparable from Colorado River hydrology.

4.3 Renegotiating the Compact

Current negotiations over Colorado River allocation operate against the backdrop of 12,800 years of paleoclimate data and 1,300 years of tree-ring reconstructions. The 1922 allocation assumed an average flow of 20 MAF/yr based on the wettest 17 years in 1,300 years. The geological record shows that the Southwest experiences natural

droughts of similar or greater magnitude to the current megadrought, with return periods of roughly 200–300 years. Policymakers must now choose: allocate water based on long-term averages (~14 MAF/yr) or continue the fiction that 20 MAF/yr is sustainable? The data favor the former.

4.4 Connection Across Three Eras

The three-era framework provides a coherent narrative. In Era 1 (Pliocene, 5 million years), hurricane-driven erosion and mass transfer carved the landscape and loaded fault systems. In Era 2 (Holocene, 12,800 years), natural climate variability—volcanic eruptions, solar forcing, orbital cycles—created the Medieval Climate Anomaly, Little Ice Age, and other regional climate modes to which humans adapted. In Era 3 (Anthropogenic, 1900–present), humans became the dominant driver through water management, groundwater extraction, and warming. The critical insight is continuity. The three eras are not disconnected; they are linked by the same geological systems—crustal stress, aquifer capacity, fault slip rates, climate forcing—operating at different timescales and with different drivers. Understanding this continuity is essential for interpreting the present and planning the future.

4.5 What the Geological Record Tells Us

The geological record shows that Medieval Climate Anomaly–level droughts are "normal" for the Southwest, recurring roughly every 200–300 years. The current water policy framework, built on the wettest 17 years in 1,300 years, assumes that Little Ice Age conditions (cooler, wetter than long-term average) will persist. They will not. The Southwest must plan for a climate that regularly produces droughts as severe as or worse than the current megadrought. When such droughts are amplified by anthropogenic warming (as they are today), the challenges intensify.

4.6 Lessons from Three Deltas

The Nile Delta, Mississippi Delta, and Gulf of California all demonstrate the same fundamental physics: sediment loading → isostatic subsidence → accommodation space creation. This is not a Southwest phenomenon; it is a universal geodynamic response. What varies is lithospheric structure, river age, and sediment flux. What remains constant is the inevitability of subsidence when water and sediment are redistributed across the crust. Human modification of these systems—the Aswan High Dam, Mississippi levees, and Hoover Dam—has disrupted the

sediment supply that built these deltas over millions of years. The consequence in each case is catastrophic: coastline loss and sediment starvation in the Nile, land subsidence and saltwater intrusion in the Mississippi, and water allocation crises throughout the American Southwest. These are not independent problems; they are manifestations of the same physical law applied at different scales and latitudes.

Conclusions

1. The 1922 Colorado River Compact was founded on a dangerous misconception: it allocated water based on the wettest period in 1,300 years. This structural flaw has created a persistent deficit that accelerates as drought intensifies.

2. Central Valley irrigation inadvertently strengthens the southwestern water cycle by 15% while depleting aquifers that modulate San Andreas Fault seismicity. This teleconnection links water policy in California to hydrological outcomes across the western United States.

3. Hoover Dam and Lake Mead recreated reservoir-induced seismicity on faults previously loaded by Pliocene mass transfer. This pattern demonstrates that modern water management triggers earthquakes on the same systems affected by geological forces operating over millions of years.

4. Las Vegas depends on the same karst aquifer system that Grand Canyon incision drained over 5 million years. The city's 2.2 million residents draw on finite water resources shaped by ancient geological processes.

5. The modern megadrought may represent a return to Medieval Climate Anomaly conditions, now amplified by approximately 1.2°C of anthropogenic warming. Tree-ring evidence indicates that such droughts are recurrent features of the Southwest's climate system, with return periods of 200–300 years.

6. Understanding the three-era framework—Pliocene storms shaping the landscape, Holocene natural variability, and modern anthropogenic forcing—is essential for informed water policy and hazard planning in the American Southwest.

7. The Nile Delta provides a global analog confirming that sediment-loading subsidence is a universal geodynamic response. The submersion of ancient Alexandria—combined with the destruction of the Library of Alexandria and the murder of Hypatia in 415 AD—demonstrates that geological and human forces can converge to

catastrophic effect. Three major deltas (Nile, Mississippi, Gulf of California) now face the common crisis of sediment starvation from upstream damming.

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