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The D+ Dilemma: Structural Fatigue, Aging Dams, and the Race to Fortify US Waterways

Environment * Climate Change * Ethics

Introduction

The terrestrial landscape of the United States is defined not only by its natural geography but by a century-long project of hydrological engineering. Across the fifty states, more than 91,000 dams serve as silent sentinels, regulating the flow of rivers to provide water for irrigation, municipal supply, flood control, and recreation.[1] However, this massive network of infrastructure is reaching a critical inflection point. The average age of dams in the national inventory is now approximately 57 years, and many were constructed during an era when the scientific understanding of seismic risk and the hydrologic impacts of climate change was in its infancy.[1] As these structures exceed their intended design lives, they face a convergence of threats: physical deterioration of materials, increased frequency of extreme weather events, and a phenomenon known as hazard creep, where downstream development places thousands of lives in the path of potential inundation.[4]

The current condition of this infrastructure is assessed periodically by the American Society of Civil Engineers, which has consistently assigned dams a grade in the D range, signifying a state of poor repair.[4] While the 2025 Report Card for America's Infrastructure showed a marginal improvement to a D+ grade -- largely due to initial infusions of federal funding from the Infrastructure Investment and Jobs Act -- the underlying structural deficit remains staggering.[6] To bring the nation's dams to a state of good repair, experts estimate a total investment need of approximately 93.6 billion dollars over the next decade, yet current funding levels address only a fraction of this requirement.[4]

The National Inventory of Aging Dams: Ownership and Hazard Classification

The primary repository for data regarding these structures is the National Inventory of Dams, which is maintained by the U.S. Army Corps of Engineers in collaboration with state regulatory offices and the Federal Emergency Management Agency.[2] The inventory tracks dams that meet specific criteria, such as a height of at least 25 feet with more than 15 acre-feet of storage, or a height of 6 feet with at least 50 acre-feet of storage.[8] This database is vital because it reveals a highly fragmented ownership landscape that complicates uniform safety standards.

Unlike many other forms of critical infrastructure, the majority of U.S. dams are not owned by the federal government. Approximately 56.4 percent are under private ownership, while only 4.7 percent are owned by federal agencies like the Bureau of Reclamation or the U.S. Army Corps of Engineers.[1] Local governments own about 20 percent, and state governments own less than 5 percent.[1] This distribution means that the financial burden of maintenance and safety compliance often falls on small

homeowner associations, private utilities, or rural municipalities with limited technical expertise and capital.[1]

Ownership Category	Percentage of Total Dams	Typical Primary Purpose
Private	56.4%	Irrigation, Fire Protection, Stock Ponds
Local Government	20.0%	Municipal Water Supply, Recreation
Federal Government	4.7%	Hydropower, Large-scale Flood Control
State Government	4.8%	State Parks, Small Water Reservoirs
Other/Utility	14.1%	Hydroelectric Power, Industrial Cooling

A critical distinction in dam management is the hazard potential classification, which is based solely on the anticipated consequences of a failure rather than the condition of the dam itself.[4] A high-hazard-potential rating signifies that a failure would likely result in the loss of human life.[1]

Significant-hazard-potential structures are those where failure would cause significant economic loss or environmental damage but is unlikely to cause fatalities.[1] Over the last twenty years, the number of high-hazard dams has more than doubled, largely because of development in the downstream floodplains.[1] This phenomenon, often called hazard creep, turns a low-risk agricultural dam into a high-risk structural liability as new subdivisions are built in its shadow.[4]

The Mechanics of Structural Failure: Embankment Integrity

The vast majority of dams in the United States are embankment dams, constructed from compacted soil or rock.[9] While these structures are resilient, they are uniquely susceptible to failures related to seepage and hydraulic forces. Internal erosion, often referred to by engineers as piping, is the leading cause of embankment dam failure.[9] This process begins when water seeping through the dam or its foundation starts to carry away soil particles.[10] As these particles are removed, a small void or "pipe" begins to form, typically starting at the downstream face and working its way backward toward the reservoir.[10]

The scientific mechanism of piping is often a result of suffusion or scour. Suffusion occurs when smaller particles are washed through the pores of a coarser soil skeleton, leaving behind a weakened and more permeable structure.[9] Scour refers to the erosion of material along a concentrated seepage path, such as along the outside of a buried conduit or at the contact point between the soil and the bedrock foundation.[9] Because these processes occur deep within the structure, they are often difficult to detect during routine visual inspections until the pipe reaches the reservoir, at which point a catastrophic breach can occur within hours.[10]

Seepage Indicator	Potential Failure Mechanism	Visual Signs for Inspectors
Muddy Discharge	Active Internal Erosion	Silt or sand deposits at the toe of the dam
Sinkholes	Internal Void Formation	Depressions on the crest or upstream slope

| Sand Boils || High Uplift Pressure || Small "volcanoes" of sand in the downstream area |

| Wet Spots/Green Grass || Sustained Seepage || Unseasonal vegetation growth or soft ground |

Another primary threat to embankments is overtopping, which occurs when the reservoir level exceeds the height of the dam crest.[11] For earthen dams, overtopping is nearly always fatal to the structure. As water cascades over the crest, it gains velocity and begins to rapidly erode the downstream slope.[12] This erosion can lead to a headcut -- a vertical drop in the soil that moves backward through the dam -- eventually lowering the crest and allowing the entire reservoir to empty in a sudden surge.[11]

The Chemistry of Decay: Concrete Degradation and ASR

While concrete dams may appear more permanent than their earthen counterparts, they are subject to a slow chemical deterioration known as Alkali-Silica Reaction, or ASR.[14] ASR is frequently termed "concrete cancer" because it is an internal, progressive, and effectively incurable disease of the material.[15] The reaction occurs between the highly alkaline hydroxides in the cement paste and certain forms of reactive silica found in the aggregate.[14] In the presence of moisture, this reaction produces a gel that has a powerful affinity for water.[15]

As the gel absorbs water, it expands, exerting internal tensile pressures that exceed the strength of the concrete matrix.[14] This leads to the formation of micro-cracks throughout the structure and macro-cracks on the surface, typically in a distinctive "map-cracking" pattern.[16] Beyond the structural weakening, ASR-induced expansion can physically shift large sections of a dam, leading to the binding of spillway gates, the misalignment of hydroelectric turbines, and the crushing of expansion joints.[16] Because dams are constantly in contact with water, providing a perpetual supply of moisture to the expansive gel, ASR is a particularly daunting challenge for hydraulic infrastructure.[15]

The history of concrete engineering shows that while some structures, like those of the ancient Romans, used volcanic ash to prevent such reactions, modern portland cement based structures are often more vulnerable.[16] Contemporary mitigation involves the use of supplementary cementitious materials like pumice or fly ash, but for the thousands of dams built between the 1920s and 1970s, the reaction may already be well underway, requiring sophisticated monitoring to determine the remaining service life of the structure.[16]

The Hydraulic Margin: Climate Change and the Probable Maximum Flood

The safety of a dam is fundamentally tied to its ability to pass extreme floods safely through its spillway. Engineers design these safety valves based on the Probable Maximum Flood (PMF), which is the most severe flood reasonably possible at a specific location.[19] The PMF is derived from the Probable Maximum Precipitation (PMP), a theoretical upper bound on the amount of rainfall that can occur over a given area in a specific timeframe.[21]

For much of the twentieth century, PMP values were treated as static figures based

on historical storm records.[20] However, as the global climate warms, the atmosphere can hold more moisture -- approximately 7 percent more for every degree Celsius of warming.[20] This shift has rendered many historical PMP estimates obsolete. Recent studies across North America and Australia suggest that PMP estimates may need to be increased by 14 to 38 percent to reflect modern atmospheric conditions.[20]

| Design Parameter | | Historical Definition | | Climate-Adaptive Definition |

| PMP (Precipitation) | | Physical upper bound on rainfall | | Extremely low exceedance probability |

| PMF (Flood) | | Maximum flood from PMP | | Risk-informed flood for specific climate period |

| Spillway Capacity | | Fixed for historical maximum | | Flexible/upgradable for shifting hydrology |

This "end of stationarity" poses a profound risk to existing dams. If a spillway was designed to handle a 1950s-era PMP, it may be undersized for a twenty-first-century storm.[3] When a spillway's capacity is exceeded, the dam is at risk of overtopping, which can lead to catastrophic failure.[12] To address this, many dam owners are exploring overtopping protection, such as armoring the downstream face with roller-compacted concrete or articulated concrete blocks, which allows the dam to safely withstand a moderate amount of overtopping without eroding.[13]

Forensic Analysis: The Oroville and Michigan Failures

The risks inherent in aging infrastructure were starkly demonstrated by two significant incidents in recent years. In 2017, the Oroville Dam in California, the tallest in the United States, suffered a failure of its main service spillway chute during a period of heavy rainfall.[23] The forensic investigation revealed a long-term systemic failure to recognize design and construction weaknesses.[23] The spillway slab was relatively thin and lacked modern waterstops, allowing high-velocity water to be injected into the underlying weathered bedrock through cracks and joints.[24]

The resulting "stagnation pressure" beneath the slab eventually exceeded its structural strength, causing a massive section of the concrete to lift and wash away.[23] This forced the use of the emergency spillway -- an unlined hillside -- which began to erode so rapidly that officials feared the entire crest structure would collapse, triggering an evacuation of nearly 200,000 people.[3] The Oroville incident highlighted the danger of "normalization of deviance," where observed cracks and seepage are accepted as normal behavior rather than investigated as symptoms of underlying decay.[24]

Similarly, in 2020, the failure of the Edenville and Sanford dams in Michigan provided a case study in geotechnical and regulatory failure.[26] The Edenville Dam failed due to static liquefaction of its downstream slope after a record rise in the reservoir level.[26] Static liquefaction occurs when loose, saturated soils suddenly lose their strength and behave like a liquid, often without any prior warning like overtopping.[26] The investigation found that the dam had not been built according to its original plans, with a slope that was too steep and materials that were

poorly compacted.[26] When Edenville failed, the resulting wall of water overtopped the Sanford Dam downstream, leading to its cascading failure.[26]

Regional Challenges: Oregon's Seismic and Ecological Conflict

In the Pacific Northwest, dam safety is further complicated by the threat of the Cascadia Subduction Zone, a 600-mile fault capable of producing a magnitude 9.0 earthquake.[29] Scientists estimate a 37 percent chance of a major Cascadia event within the next 50 years.[30] Such an earthquake would subject dams to intense shaking for five to seven minutes, potentially triggering slope failures or foundation damage.[29]

The Scoggins Dam in Washington County, Oregon, is a primary focus for seismic resilience.[32] Built in the 1970s, the dam provides water to 600,000 residents, but modern analysis shows it is at risk of breaching during a Cascadia earthquake.[32] The Bureau of Reclamation has proposed a massive retrofit project involving the construction of a downstream "shear key" to stabilize the foundation and adding additional berm material to the dam crest.[33] This project illustrates the economic trade-offs of modern dam safety: while the safety upgrades are essential, they are costly and can impact recreation and local ecology.[32]

Simultaneously, the U.S. Army Corps of Engineers is managing 13 dams in the Willamette Valley under a different set of pressures.[37] A 2021 court injunction requires the Corps to modify operations to improve passage for endangered salmon and steelhead.[37] This has led to "deep drawdowns," where reservoir levels are lowered significantly in the fall to allow juvenile fish to pass through the dams.[38] While these operations are critical for ecological recovery, they create operational conflicts by reducing hydropower generation and increasing downstream turbidity, which can stress municipal water treatment systems.[37]

The Future of Monitoring: InSAR and Fiber-Optic Sensing

To manage this aging portfolio, engineers are increasingly turning to space-based and subsurface technologies. Interferometric Synthetic Aperture Radar (InSAR) is a satellite-based technique that can detect ground deformation with millimeter-scale accuracy.[40] By comparing radar signals from multiple satellite passes, InSAR can track the subtle sinking or bulging of a dam crest that might be invisible to the naked eye.[40] A recent study from Virginia Tech used InSAR to reveal that several major U.S. dams are actively sinking, likely due to internal degradation that has gone undetected by traditional ground-based surveys.[43]

| Monitoring Technology | | Measured Parameter | | Primary Advantage |

| InSAR (Satellite) | | Surface Deformation | | Wide-area coverage, millimeter precision |

| Fiber-Optic (DTS) | | Internal Temperature | | Detects localized seepage/leaks |

| Fiber-Optic (DAS) | | Internal Vibration | | Monitors structural health in real-time |

| AIoT Sensors | | Real-time Pressure/Flow | | Autonomous alerting during extreme weather |

Inside the structure, Distributed Fiber-Optic Sensors (DFOS) are providing an unprecedented look at internal conditions.[44] By deploying fiber-optic cables along the length of a dam, engineers can use Distributed Temperature Sensing (DTS) to identify anomalies in heat patterns that indicate water is seeping through the embankment.[45] Furthermore, Distributed Acoustic Sensing (DAS) can turn a fiber cable into a continuous array of vibration sensors, allowing for the detection of the minute sounds of internal erosion.[45] When combined with Artificial Intelligence and the Internet of Things (AIoT), these sensors can provide autonomous, real-time alerting to dam managers during typhoons or earthquakes, significantly reducing the response time to potential failures.[46]

The Policy of Removal: The Klamath Case Study

For some dams, the cost of safety upgrades and environmental mitigation is simply too high, leading to a decision for removal.[48] The decommissioning of four hydroelectric dams on the Klamath River in 2024 is the largest such project in history.[50] Driven by a four-decade effort led by the Klamath, Hoopa Valley, Karuk, and Yurok Tribes, the removal has reunited 400 miles of salmon habitat.[50]

The economic logic of removal is often stark. For the Klamath dams, the cost of installing modern fish passage and water quality systems would have far exceeded the economic return from the hydroelectric power generated.[51] Dam removal is not without its socio-economic impacts, however. It can lead to the loss of reservoir-based recreation and changes in the local water table, but for many communities, the restoration of a free-flowing river provides significant non-market values, such as cultural identity and biodiversity.[48]

Conclusion: A Strategy for Resilience

The crisis of aging dams in the United States is a multifaceted challenge that requires a fundamental shift in how we value and manage water resources. The transition from a "D" to a "D+" grade reflects progress, but it is merely the first step in a multi-decade journey toward resilience.[4] High-hazard dams must be prioritized for technical upgrades, and every high-hazard structure should have a functional and regularly tested Emergency Action Plan by 2025.[1]

The integration of advanced technologies like InSAR and fiber-optic sensing will be essential to provide the data necessary for proactive management.[43] Simultaneously, we must embrace a more dynamic understanding of climate risk, ensuring that our dams are designed not just for the floods of the past, but for the extreme weather of the future.[20] Whether through the reinforcement of structures like Scoggins Dam or the removal of obsolete barriers like those on the Klamath, the goal remains the same: ensuring that our hydrological legacy does not become a catastrophic liability for future generations. The silence of these massive structures belies the urgent work required to maintain the hydraulic stability upon which modern society depends.

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