The Trillion- Gallon Question

Extreme weather is threatening California's dams. What happens if they fail?

By Christopher Cox
Photographs by Spencer Lowell

Read online. Published June 22, 2023, Updated June 25, 2023

On the morning of Feb. 7, 2017, two electricians were working on a warning siren near the spillway of Oroville Dam, 60 miles north of Sacramento, when they heard an explosion. As they watched, a giant plume of water rose over their heads, and chunks of concrete began flying down the hillside toward the Feather River. The dam's spillway, a concrete channel capable of moving millions of gallons of water out of the reservoir in seconds, was disintegrating in front of them. If it had to be taken out of service, a serious rainstorm, like the one that had been falling on Northern California for days, could cause the dam — the tallest in the United States — to fail.

Kory Honea, the sheriff of Butte County, which includes the dam and the town it is named for, first heard that something was wrong from Dino Corbin, a local radio personality, who called him at his office: "Are you aware there's a hole in the spillway?" Around the same time, one of the sheriff's dispatchers received a confusing message from California's Department of Water Resources, which owns the dam, saying it was conducting a "routine inspection" after reports of an incident. "I don't believe anyone at D.W.R. was intentionally keeping information from me," Honea told me. "They were a siloed organization, steeped in bureaucracy. They weren't good at communicating externally." Honea sent his undersheriff up to the dam headquarters to figure out what was going on.

At the dam, D.W.R. officials closed the gates at the top of the spillway to prevent any more of its concrete slabs from being lost in what an independent forensic report prepared after the incident described as “a sudden, explosive failure.” The flow of water stopped. The rain, however, didn’t.

On Feb. 8, Honea drove up to the dam from Oroville, a gold-rush town that was set out on a grid along the Feather. Nearly 20,000 people live there, all of them downstream of the dam. At certain points during the drive, Honea would have been able to glimpse it: 770 feet high and nearly 7,000 feet wide at its crest, a gray wedge jammed between two hills.

Oroville is an earth-fill embankment dam with a clay core and a surface of loosely placed rocks. These structures can be incredibly resilient, especially to earthquakes — concrete dams like Hoover Dam are rare in seismically active California — but they are also more vulnerable if overtopped. Once water overwhelms the spillway and starts flowing over an embankment dam, its layers can melt away at an astonishing speed. If Oroville failed in this way, it would send a wave more than 185 feet tall sweeping into the valley below.

At the dam’s operations and maintenance center, D.W.R. had set up a command post in the main conference room. The room was about the size of a squash court, with a giant table in the middle, but still they needed a tent in the parking lot to accommodate everyone: engineers, geologists, D.W.R. executives, federal officials, fire and rescue. “They were all in the conference room plotting erosion patterns, not thinking the sheriff’s office might like to know what they’re up to,” Honea says. Scott Turnquist, an engineer at the dam, describes a situation so chaotic they didn’t even know if the site of the command center was safe from flooding if the dam failed. “We didn’t have good inundation maps,” he says, “and so we are real-time trying to generate those to understand whether we are at risk.”

For days, the group in the conference room tried to figure out how to stop Lake Oroville from rising despite the steady rain. They put the hobbled spillway back in service, but the stream dove into the hole and threw even more concrete into the air. Eventually, nearly half the spillway was gone, and the erosion started creeping toward the top of the dam.

Oroville had a kind of safety valve to prevent overtopping: an emergency spillway next to the main spillway that could release vast quantities of water. There wasn’t much to this spillway. It was an unimproved slope covered with dirt and trees, with a concrete lip, called an ogee weir, at the top. The weir was there to prevent the same kind of runaway erosion that would happen if water flowed over the dam itself. In the 50 years since the dam was completed, the emergency spillway had never been used.

Oroville Dam’s spillways. Credit...Spencer Lowell for The New York Times

On the evening of Feb. 10, D.W.R. decided to reduce the outflow on the main spillway, effectively ensuring the emergency spillway would be used.

One representative from the Federal Energy Regulatory Commission had asked whether it was “really the end of the world” if they went “an inch over the emergency spillway.” They would soon find out.

At around 7 the next morning, water started flowing down the emergency spillway. The geologists in the room had warned that the rock below the weir was unstable. After a large section of it eroded suddenly, they started talking about the dangers of headcutting: the possibility that the erosion would travel up the hill and undermine the concrete weir. By 3:25 p.m. on Feb. 12, the judgment in the command center was that within two to four hours, the weir could topple over, sending a wall of water as high as 50 feet rushing toward town.

At 4:27 p.m., Honea issued a mandatory evacuation order. To establish the size of the evacuation zone, he pulled out a map and called over Bill Croyle, the acting director of D.W.R. “Should it be this big?” he asked, dropping his hands down on the map about two feet apart.

“Maybe not that big,” Croyle said.

“How about this?” Honea asked, this time keeping his hands about 10 inches apart. Croyle had him move his hands a little bit wider. As many as 180,000 people ended up having to leave their homes.

Honea called in law enforcement from throughout the region to help with the evacuation. He recognized the gravity of calling all these officers into the inundation path. I may not have a department tomorrow, he thought.

As the citizens of Oroville jammed the roads out of town, the Sheriff’s Department started to evacuate the jail. They had 578 inmates in custody, far more than could fit in Butte County’s prison buses and vans, so they commandeered anything that had wheels. They saved their limited stockpile of handcuffs and waist chains for the most violent prisoners; even so, on one of the high-security buses, the inmates tried to kick the door open. The lower-risk evacuees were put, unshackled, in regular school buses. Eventually, the prisoners wound up in Alameda County, in the Santa Rita Jail, where they stayed for days.

Image: Kory Honea, the sheriff of Butte County, home to Oroville Dam
Credit…Spencer Lowell for The New York Times

After the evacuation, the situation at the dam stabilized. The rain let up, and the main spillway, although badly damaged, was able to channel enough water out of the reservoir to drop the level below the top of the emergency spillway. Slowly, the townspeople returned to their homes.

Today the dam has two new spillways, each of which survived major rains this spring with no problems. According to Honea, though, the people of Oroville remain traumatized. During a meeting with D.W.R. officials in 2019, one resident worried about the next incident. “I think about a little baby — they can’t save themselves,” she said. “We can’t save ourselves if that dam breaks or if we have another one of these catastrophic events, which I’m not sure we won’t in my lifetime.”

The independent forensic report faulted an “immature,” “significantly overconfident and complacent” culture at D.W.R. Officials ignored reports about the flawed rock below the emergency spillway, made repairs in a haphazard way and failed to find flaws in the spillway design — most notably drains that made the concrete more susceptible to cracking.

The report also noted that this attitude is typical among large dam owners: “The fact that this incident happened to the owner of the tallest dam in the United States, under regulation of a federal agency, with repeated evaluation by reputable outside consultants, in a state with a leading dam-safety regulatory program, is a wake-up call for everyone involved in dam safety.”

In the six years since Oroville, dam operators across the country have begun to reassess the structures under their control, looking for hidden weaknesses: the cracks in the spillway, the hillside that crumbles at the first sign of water. That work is necessary, but it may not be enough to prevent the next disaster. Bigger storms are on the way.

“We still haven’t severely tested California’s primary flood-control structures,” says Daniel Swain, a climate scientist at the University of California, Los Angeles. The emergency spillway at Oroville, for example, was operating at about 3 percent of its capacity when Honea ordered the evacuation. “If we had an even marginally bigger event on the weather front that year,” Swain says, “it would have been significantly worse.”

Dale Cox, a former project manager at the United States Geological Survey who has worked extensively with Swain, told me that California’s dams are unprepared for extreme weather because state water authorities have a false sense of how bad flooding can get. “The peak of record is driving a lot of engineering decisions in the state,” he says, and that peak is an underestimate, maybe a gross one. “Already, we are seeing several 100-year floods every 10 years.”

Some of this miscalculation arises from our failure to account for climate change, a problem that will only get worse as the atmosphere heats up and the amount of water vapor it can carry increases. “All of this infrastructure,” Swain says, “is designed for a climate that no longer exists.” But the error also lies in our understanding of the past. Most of the flood data that form the basis for the design of California’s dams come from the past century, which was an unusually placid period in the state’s weather.

Around three decades ago, meteorologists’ mental map of the state was given a jolt when satellites became sophisticated enough to pick up what came to be called atmospheric rivers. These storms, which resemble a lasso of rain thrown across the Pacific Ocean to the West Coast, deliver what Swain described to me as “almost incomprehensible volumes of water.”

In the mid-2000s, Cox assembled a group at the U.S.G.S. to study what would happen if the atmospheric rivers from two notable California flood years, 1969 and 1986, occurred back to back. They named the resulting scenario the Arkstorm: flooding throughout the state, water depths of up to 20 feet in the Central Valley and economic losses of $725 billion. When the report on this research was done, the authors presented it to emergency managers, municipal authorities and dam owners, including D.W.R. The response was demoralizing. "They said, 'That's too big, that's ridiculous,'" says Lucy Jones, the chief scientist for the project.

The authors of the Arkstorm report had a response ready, however. Their imaginary storm was modeled on the Great Flood of 1862, which also made a lake of the Central Valley and destroyed, by one account, a quarter of all the buildings in the state. "The minute that you say this is too big, this couldn't happen, this is unrealistic," says Michael Dettinger, a hydrologist who worked on the report, "I can just point at 1862 and say, '1862 was far worse than this.'"

In April 2021, Cox took me on a walk along the American River, about 30 minutes northeast of Sacramento. Somewhere downstream of Folsom Prison, he said, was a reliable high-water mark for the 1862 flood. Because it was so long ago, water authorities didn't count it as an official peak of record, but it showed what the river was capable of.

It was a hot and sunny day, but Cox wore blue jeans, black Vans and a black T-shirt with a paisley shirt over it. He looked like an aging session bassist, with a gray goatee and sunglasses. (We established, after a thorough discussion of our respective genealogies, that we aren't related.)

Cox was not a scientist; he had studied to be a journalist. "My role is going out and getting the ball rolling, starting the project, recruiting people," he said. His training proved useful because it taught him how to cut across disciplines — and how to ask a lot of annoying questions. I could see his mind at work when he talked about a project to restore the natural banks of the Los Angeles River. Experts had all sorts of stolid objections or arguments in favor of it. He was the one to ask: Once these habitats reunite, will we have to worry about mountain lions coming down and eating people's pets?

About a mile up the American River canyon, we reached a gate that read FOLSOM STATE PRISON NO TRESPASSING. Cox pressed up against the fence and pointed just upriver, to a flat spot on the bank across from us, where there was a pile of boulders. That, he said, is where Stockton and Coover flour mill once stood. Contemporary accounts noted that the water reached the mill's stone stable, which survived into the 20th century.

Image: Dale Cox, project manager for the Arkstorm scenario, at the American River. Credit...Spencer Lowell for The New York Times

By using the stable as a high-water mark for the American River, researchers were able to set the [peak discharge]() of the river during the flood at more than 300,000 cubic feet per second — greater than the median flow of the Mississippi River at St. Louis and far above the peak of record. On the day I was there, the American River was rolling along steadily at 1,000 c.f.s.

Did presenting state officials with these numbers make a difference? I asked. No, he said. So many of the officials he talked to about Arkstorm were like the mayor in “Jaws” — unwilling to see a problem they couldn’t fix. Most officials wanted to do nothing if possible, or if they had to do something, they wanted it to be the cheapest thing they could get away with.

Cox thought part of the reason he faced resistance was that a flood is not a “charismatic disaster,” like an earthquake. It is less sudden, less dramatic, the wreckage uglier. “Whereas an earthquake is more like an act of God,” he said, “flooding points out the flaws of man.”

The original plan for the Arkstorm scenario was to have D.W.R. and other agencies translate the storms they had created into water on the ground: turning meteorology into hydrology. But according to Cox, “D.W.R. ghosted the Arkstorm project about three-quarters of the way through.” He never got a straight answer about why, but one of his contacts there told him it was “political.” (“Is that a capital P or a small p?” Cox asked.) My own reporting would eventually reveal another possible answer: The numbers were scary enough to shut down any discussion.

The best the Arkstorm team could manage for the final report was this line, buried on Page 59, which read like a statement from a hostage negotiation: “Because of the extremely sensitive nature of a dam-damage scenario, the selection of a particular dam to imagine as hypothetically damaged in such a way is left to emergency planners.”

After 2017, Dettinger and Cox made a list of what they would do differently if they could start over from scratch: “What are the things that we assumed wouldn’t happen or that we just misjudged where they might happen,” Dettinger says. “And top of that list was, ‘Man, we shouldn’t have taken dam safety off the table.’”

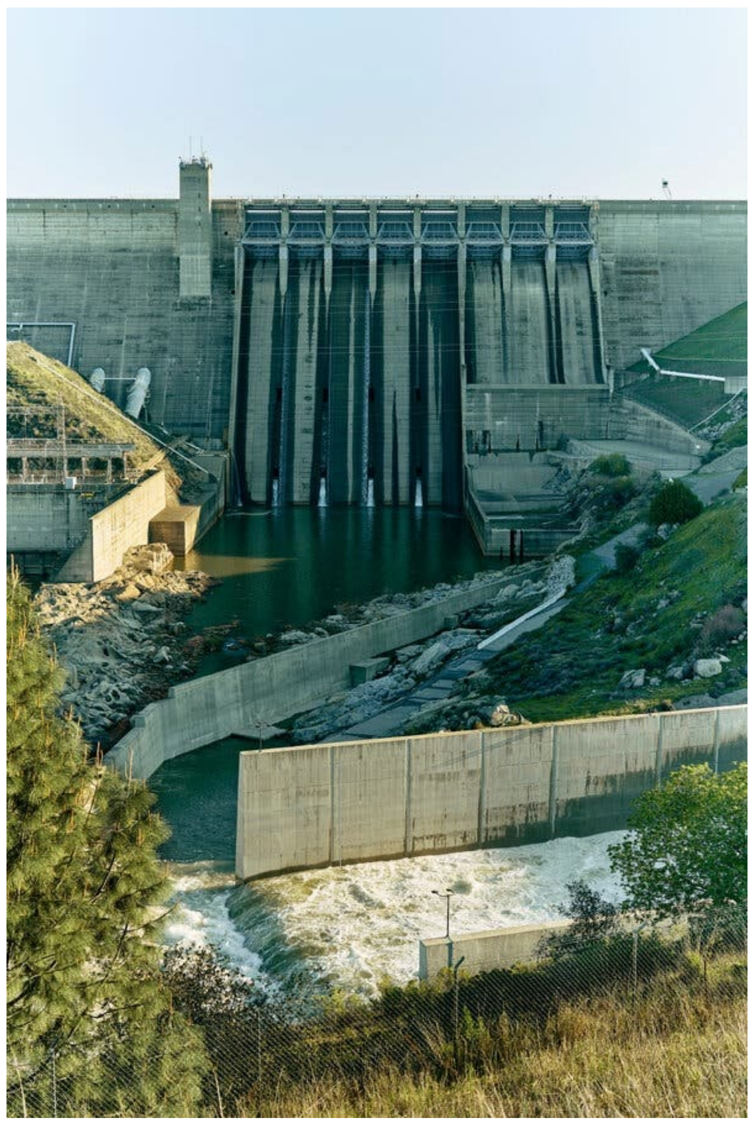


Image: Folsom Dam, whose recently built — and expensive — auxiliary spillway permits the release of excess water at a lower level. Credit...Spencer Lowell for The New York Times

Dam failures are rare, but when they happen, they can be deadly. Nearly as many lives were lost following the 1889 collapse of the South Fork Dam near Johnstown, Pa., as in the attack on Pearl Harbor. When St. Francis Dam near Los Angeles breached in 1928, it unleashed a wall of water that was initially 140 feet tall, carrying off people and houses and animals before emptying into the Pacific Ocean some 50 miles away.

And yet, as I discovered in examining the fallout from Oroville, dam safety is an orphaned problem. Meteorologists tend to talk only about the weather; hydrologists will tell you only about stream flows; engineers know about concrete but can't comment on climate; climatologists look at systems but rarely want to make specific predictions. Everyone is stuck in the mesoscale: the realm between macro and micro climate concerns, where everything is just fine-grained enough to appear blurry.

Ultimately, responsibility lies with state and federal authorities, but it's not clear that any single entity is capable of seeing the whole picture. "So much water is moved around California by so many different agencies," Joan Didion wrote in 1977, "that maybe only the movers themselves know on any given day whose water is where." Little has changed since then. D.W.R. has regulatory authority over more than 1,200 dams; the Bureau of Reclamation owns and operates 45, including some of the largest in the state, and hundreds more belong to private utilities and local water authorities from Yreka to Chula Vista.

For any dam receiving federal funding, the Army Corps of Engineers also plays a role. The corps usually had at least a hand in — if not total responsibility for — the building of these dams, and it helped write the water-control manual for each of them. The manual dictates when a dam should hold on to water during a flood and when it should release it. It is the bible for dam operations, with one unbreakable commandment: A dam shall not be overtopped.

Dettinger was the first person to tip me off that dam owners may have a bigger problem than they've publicly acknowledged. He began by telling me about a meeting he and the Arkstorm team had in La Jolla with Maurice Roos, the former chief hydrologist for D.W.R., who had been with the department since 1957. In that meeting, Roos claimed that Folsom Dam, which is owned by the Bureau of Reclamation, had come within six hours of overtopping in 1986 — six more hours of rain, and the dam might have been lost.

Dettinger said that something similar had happened in 2017, even while everyone was watching Oroville: "I am told by people who know these things pretty well at D.W.R. that there were some significant risks elsewhere, where they really were in danger of having the water go over the top of some of these dams." He called the overall situation "spooky."

Without a detailed model of how the Arkstorm would translate into water levels within the state's reservoirs, though, the authors of the report were left gesturing at a general calamity. "That was the outstanding missing piece," says Christine Albano, a researcher at the Desert Research Institute in Reno, Nev., who worked with the Arkstorm team.

To remedy that, shortly before his retirement, Cox began assembling a new group of collaborators, including Albano and Swain, for a project he called Arkstorm 2.0. Specifically, the group wanted to examine how a warmer climate would strengthen atmospheric rivers, and they wanted to finally plug that weather data into a hydrological model to see what it would do to the state's flood-control infrastructure.

The first half of that work is done: In August, Swain and Xingying Huang of the National Center for Atmospheric Research published a paper that predicted a storm, called ArkFuture, that would be a supercharged version of 1862: 30 days of unrelenting rain across the whole state. "It would be a transformational event for California, without any doubt, if and when it recurs," Swain says. In the next 40 years, he and Huang determined, the odds of such a storm sequence occurring were as high as 50 percent.

The detailed hydrology for Arkstorm 2.0 is still being worked out, but Albano told me that the Army Corps had already done a preliminary analysis. At her suggestion, Mike Bartles, an engineer at the Army Corps's Hydrologic Engineering Center, had run the sequence through a model he developed. The results were astounding — but she wasn't sure she could send them to me directly.

Armed with Albano's information, I went to the Army Corps to request a copy of Bartles's analysis. It took time to receive approval — "We have a completed draft response that is undergoing internal review" — but eventually the document arrived in my inbox: a series of charts detailing what would happen to six of the largest reservoirs in California during the 30-day storm sequence predicted by Swain and Huang.

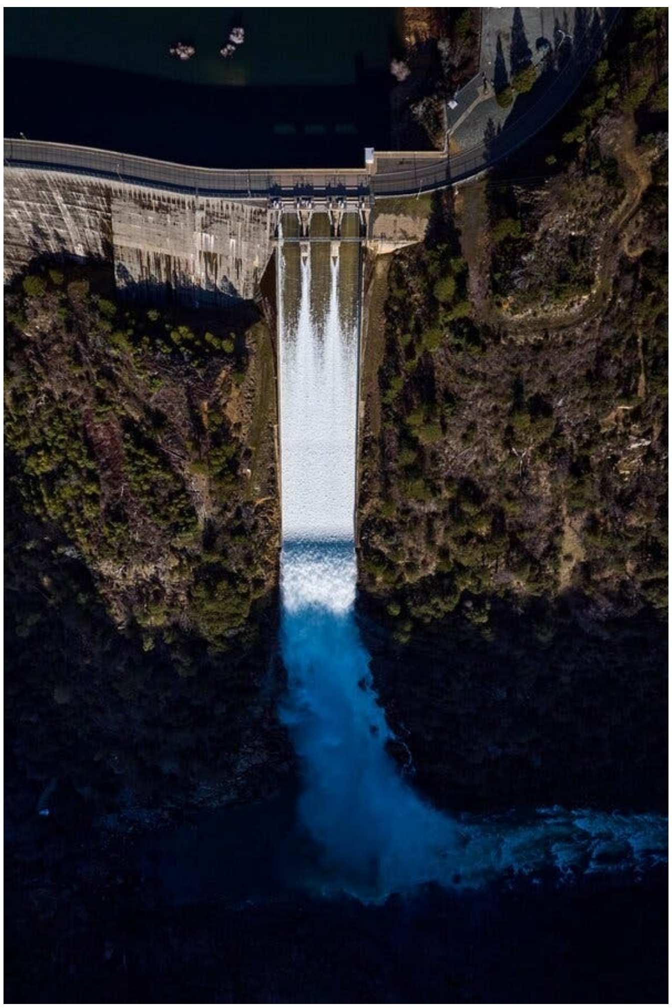


Image: New Bullards Bar Dam, which has become part of a pilot program to pre-emptively adjust reservoir levels in response to weather forecasts. Credit...Spencer Lowell for The New York Times

Some of the information was merely alarming. By matching up Bartles's data with public information about the reservoirs' outlet capacities, I could imagine the floods playing out in real time. It was apparent that Oroville Dam's emergency spillway would be tested again: as much as two whole days of water running down the dirt slope, at levels far beyond those seen in 2017. The same went for Don Pedro dam, which would need to push huge volumes of water over its never-before-used emergency spillway. Even if the dam survived, the expected outflow from Don Pedro would be multiple times the capacity of the levees downstream.

Other parts of the document were terrifying. Two large dams owned by the Bureau of Reclamation — Friant and New Melones — looked likely to overtop: Each would have periods when they would be taking on water faster than they could spill it, and they would reach those moments when the reservoirs were nearly full. Friant Dam, which is situated in the hills above Fresno, population 544,500, would take on an incredible six times its total volume in the course of the month. New Melones would have a peak inflow that was more than twice what it could release, and its spillway couldn't be used until the water was near the crest of the dam. In the probable inundation zone for New Melones were most of the 218,800 people of Modesto.

If these projections were correct, it would create an unprecedented amount of destruction. The Army Corps studied what would happen to six dams in California, and the results suggested that two of them would probably be overtopped. It seemed unlikely that a third of all the dams in the state would fail, but would none of them? When reached for comment, the Army Corps stressed that the model was "largely theoretical" and not meant to demonstrate the "hydrologic, hydraulic and economic consequences that would be likely to occur during this hypothetical event." The Bureau of Reclamation did not reply to a request for comment on the models prepared by Bartles, but the Army Corps confirmed that the organization had been briefed on them.

Cox described the "weird 'Chinatown' vibe" he encountered whenever the conversation turned to dams. I knew what he was talking about. In the course of my reporting this article, sources would stutter and shut down whenever dams came up. Public documents that might have been easily emailed to me instead had to be extracted via Freedom of Information Act or Public Records Act requests. (In one memorable moment, the California Governor's Office of Emergency Services sent me a copy of the "Northern California Catastrophic Flood Response Plan" that was markedly different from a draft version I had found. The changes all played down the risks involved.)

I thought of Cox's comment after I sent the flooding models for Arkstorm 2.0 to Dettinger. Where he had once been voluble ("I'll talk your arm off," he told me during our first conversation), now he shut down the discussion quickly. "I have nothing to say about the inflows, because they're not my numbers," he wrote to me in an email. "Please. Just lose my email address, OK?" I never heard from him again.

In March, I drove to Oroville to see what had changed since 2017. Even dams that should be able to handle the flows from Swain and Huang's storm would still need to perform perfectly — the water would find any weaknesses. On the way up from Sacramento, the signs of the wet winter were everywhere: flooded fields glinting like mica on the horizon, brown hills turned green, a waterway called Dry Creek overflowing its banks.

Originally, Dale Cox was meant to accompany me for the meeting, but D.W.R. pulled permission for him to go at the last minute. "My boss approved, but it was nixed by higher-ups," the public information officer at the dam wrote. When I relayed this message to Cox, he smiled ruefully. "The fact they didn't want me there is wonderful," he said.

I was surprised. Recently, D.W.R. agreed to fund hydrological studies based on Arkstorm 2.0 similar to the ones done by Bartles. And when I spoke with Karla Nemeth, who has been D.W.R.'s director since 2018, she was refreshingly candid about the challenges ahead. She called the Arkstorm 2.0 storm sequence plausible, even though "it's a tough scenario to put on the table because it's overwhelming."

Nemeth also admitted that some of the state's dams were "not up to snuff." Under her leadership, D.W.R. had begun to plan for major disruptions caused by flooding, not least the prospect of moving hundreds of thousands of people out of harm's way on short notice. (Do *you* ever feel overwhelmed? I asked. "I do," she said.)

Image: Oroville Dam's new emergency spillway, built to replace the one that was destroyed during an incident in February 2017. Credit...Spencer Lowell for The New York Times

Which D.W.R. was I meeting in Oroville? The political one that Cox knew, or the plain-speaking one that Nemeth represented? In a conference room at the dam's operations center — the same room that served as command center in 2017 — I sat down with Turnquist, who was now an engineering manager at the dam, and John Yarbrough, an assistant deputy director of D.W.R., who had come up from headquarters in Sacramento.

Yarbrough pointed out that after 2017, there were checks on complacency at D.W.R.: independent audits, extensive risk assessments, decennial reviews of each dam's design assumptions. All that supervision had pushed D.W.R. to make internal changes as well — Yarbrough walked me through a 16-point plan for reform. "We feel like we're more mature now," he said.

Yarbrough and Turnquist agreed to give me a tour of Oroville's new spillways, which required a 10-minute drive up a road that wound its way along the Feather River. At the top of the dam, we walked over to the main spillway, where the water seemed to be slipping under our feet, like a treadmill set to the highest speed. Far below, it hit a row of blocks known as dentates, creating a giant plume of water and mist that jumped into the air.

Eventually we reached the emergency spillway. Since 2017, the ground has been covered in roller-compacted concrete, which forms a 1,200-foot-wide staircase that drops down the hill. I was surprised to see it stopped well before it reached the river.

Although ArkFuture would in theory require extensive use of the emergency spillway, both Yarbrough and Turnquist deflected the question of what would happen when it was used for the first time. Yarbrough said they were still studying how much erosion would occur, though they expected some where the emergency spillway ended. Turnquist pointed out that if the main spillway was running at full capacity, it would already be a catastrophe: "If we have 270,000 c.f.s. going out of the spillway, most of the downstream levees are going to be failed."

That species of fatalism crops up frequently in discussions of extreme flooding. During an event like ArkFuture, perfect operation of a dam would take the total inflow, which comes in peaks and troughs, and parcel it out evenly. But most dams can't even release large amounts of water until they are nearly full, and even the best forecasts won't allow a dam operator to know what's coming much more than five days in advance. As flood control, dams are good at capturing single storms. Send California 30 days of rain, and there's not much they can do.

Still, there are efforts to chip away at both problems. The day after I went to Oroville, I drove into the Sierra foothills near Marysville, where I met John James, the director of resource planning for Yuba Water, which operates New Bullards Bar Dam. Our first stop was a spot just opposite the dam's spillway, which was thundering down the sides of a steep canyon. Upriver, we could see the broad concrete arch of the dam. Down below, the North Yuba River was cold, clear aquamarine.

James said that New Bullards Bar had recently become part of a pilot program known as Forecast-Informed Reservoir Operations. Under standard procedures, Yuba Water was allowed to schedule releases only in response to actual reservoir levels. With FIRO, though, more water could be spilled in advance if the forecast called for a big storm, and more water could be held back if meteorologists predicted a dry spell.

That forecast wasn't terribly useful, however, without the second part of Yuba's plan: a new spillway, which they wanted to install to the right of the current one. Crucially, its intake would be lower, allowing it to release water even when the reservoir was nowhere near the crest. If they spotted a dangerous-looking amount of rain coming their way, they could spill water early, when the river was low, and then hold back more when the rain was falling and the Yuba was running high. They called it the ARC spillway, for "atmospheric river control."

We drove to the spot at the top of the dam where construction would begin. The reservoir stretched out in front of us, looking blue and inviting. More so than an embankment dam, the sweep of a concrete-arch dam looks impossible, somehow: a flimsy curtain holding back an unimaginably large amount of water. On one side, an ocean; on the other, thin air. It was like a magic trick.

One study commissioned by Yuba suggested that if the ARC spillway had been available to use during the floods of 1997, the water in the Yuba River would have been two to three feet lower. That year, levees throughout the region failed, and 23,000 homes were destroyed. Had the new spillway been in place, the levees might have held. Yuba hopes to complete the project in the next 10 years.

I wondered why more dam operators weren't looking into retrofits like the ARC spillway. At a meeting with D.W.R. officials about Oroville, one county supervisor asked the same question: "If truly we are in global warming, global climate change, and all the experts say we'll have bigger storms quicker, then maybe we need to have a way to let out water sooner."

There was an important precedent: In 2017, Folsom Dam opened an auxiliary spillway that sits 50 feet lower than the main one, allowing the Bureau of Reclamation to release water earlier and increasing the total capacity for releases during extreme floods. The answer to the supervisor's question, though, might be found in Folsom's price tag. The project allowed the dam to gain 200-year-flood protection, but it cost $900 million.

The Bartles projections, for all their ingenuity, are a forecast built upon a forecast — not the kind of evidence that seems to generate all that many $900 million checks. They also don't cover any dam south of Fresno. To consider the risks to that area, we have to return to the historic record.

In arguing for the plausibility of their storm scenarios, both the Arkstorm and Arkstorm 2.0 teams cited the work of Arndt Schimmelmann, a senior scientist in the department of earth and atmospheric sciences at Indiana University Bloomington, and Ingrid Hendy, a professor in the earth and environmental sciences department at the University of Michigan, who have been conducting an ingenious series of experiments examining what's known as the paleoflood history of California. The largest floods push sediment into the Pacific, where it settles on the ocean floor; one stretch of coastline near Santa Barbara has proved to be particularly pristine when it comes to preserving this sediment record.

By extracting core samples from this site, Hendy and Schimmelmann were able to see evidence of the 1862 floods, visible as a gray layer. There were no significant gray layers in the 160 years that followed, but by looking deeper into the seabed, they found evidence of major floods that recurred on average every 120 years. They also found a gray layer that was 10 times thicker than the one from 1862.

Hendy and Schimmelmann's research is sounding the same warning as Swain and Huang's. Whether you believe the computer models or the sediment cores, it's hard to escape the conclusion that the next gray layer is going to arrive soon. So, what would a repeat of 1862, which Hendy called a "relatively small" event, do to Southern California's dams?

We can get a hint of what would happen, because, as it turns out, there's another high-water mark from 1862 there. Along the Santa Ana River, in a city called Colton, there's a patch of land fenced off from the industrial zone that surrounds it. This is the Agua Mansa Pioneer Cemetery, the last remnant of what was once the biggest town in the region.

The first adobe houses at Agua Mansa — the name means "gentle water" — were built in the 1840s. In 1853, the settlers there, most of whom came from New Mexico, built a sturdy church several hundred feet uphill of the Santa Ana. The river, as the town name suggests, spends most of its days as little more than a trickle. In drought years, it barely even reaches the Pacific.

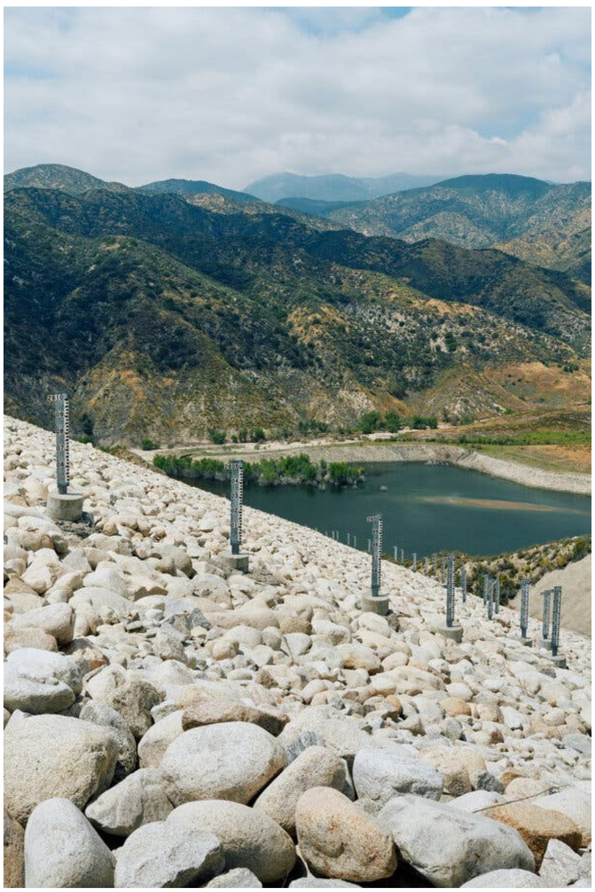
Image: The Seven Oaks Dam, one of the largest earth-fill dams in the world, in the San Bernardino Mountains. Credit...Spencer Lowell for The New York Times

In 1862, however, the rain started falling and did not stop. Edward Everett Ayer, a Union soldier stationed in San Bernardino, wrote in his diary of a storm that "absolutely tore Southern California to pieces," leaving "water, water everywhere, and little above." Hundreds of miles north, the flood even caught up with Mark Twain, who found himself stranded for eight days at a boardinghouse near Carson City, Nev., while he was out west prospecting for gold and silver. “Our inn was on an island in midocean,” he wrote. “As far as the eye could reach, in the moonlight, there was no desert visible, but only a level waste of shining water.”

Twain’s testimony, unfortunately, is exactly what the hydrologists say we can’t rely on when planning for the present. It’s imprecise, anecdotal and emotionally tinged — helpful fodder for a novel but useless for an engineer.

Agua Mansa, however, holds the secret to the flood on the Santa Ana in the same way that the Stockton and Coover mill can unlock the one on the American. Because although most of the town was swept away in 1862, the church survived. Indeed, the priest saved multiple lives by calling the townspeople there on Jan. 22. As they watched, the water climbed closer and closer, until it reached the stone steps of the church — but it went no farther. From those steps, the U.S.G.S. was able to determine, more than 100 years later, the flow of the Santa Ana on Jan. 22: 320,000 c.f.s.

Twenty miles upriver from the Agua Mansa cemetery is Seven Oaks Dam, completed by the Army Corps in 2002 and one of the largest earth-fill dams in the world. Unlike Oroville, Seven Oaks is meant for one thing: to take a surging river and throttle it, protecting the cities of San Bernardino, Riverside and, farther downstream, Anaheim and Huntington Beach. During a storm, no matter how much water is rolling down the mountains into the Santa Ana, the same maximum flow should emerge from an outlet at the bottom of the dam: 7,000 c.f.s.



During the design phase for a dam, engineers calculate what’s known as the probable maximum flood, which the Army Corps defined as “the flood that can be expected from the most severe combination of meteorologic and hydrologic conditions to be reasonably possible in the region.” According to the design memorandum for Seven Oaks, the inflow during the probable maximum flood would be 180,000 c.f.s.

When I visited Seven Oaks in May 2021, there was barely any water in the reservoir. Since construction, the Army Corps had turned over day-to-day operations at the dam to San Bernardino County, which sent a technician named Dan Worthington to give me a tour. We drove up switchbacks on the face of the dam itself, which was covered in pillow-size rounded rocks.

Image: Water-level markers at the Seven Oaks Dam reservoir. Credit...Spencer Lowell for The New York Times

I saw striations on the hills around us, the work of the San Andreas Fault, which runs right through the dam. The fault is one reason Seven Oaks, which was built to withstand a magnitude-8.0 earthquake, had to be an earth-fill dam; a concrete dam would crack.

Worthington said it had been a quiet 20 years at Seven Oaks. Droughts had tested operations more often than floods. In 2005, though, enough rain fell that the reservoir rose 120 feet overnight. The staff took bets on how high it would reach.

We arrived at the spillway, a wide bench cut into the bedrock next to the dam. The high-water mark from 2005 was 188 feet below us. Later, I asked the lead engineer for the dam, Robert Kwan, whether he thought the spillway would be used in his lifetime. “Personally, I don’t think so,” he said. “Maybe our kids, grandkids, great-grandkids.” The water hasn’t come close to it in any storm since the dam was built.

There is room for an aircraft carrier inside the spillway channel, but was it wide enough to safely pass the flow predicted by the U.S.G.S. at Agua Mansa? Because Seven Oaks is upstream of Agua Mansa, the full 320,000 c.f.s. wouldn’t flow into the dam, so I asked Kwan what would happen if 300,000 c.f.s. drained into the reservoir. He repeated the number back to me: “OK, so for 300,000 c.f.s. at the dam, yeah.” He was silent for a while, doing the math in his head. “Then you’re looking at probably not only spilling over the spillway but over the top of the dam,” he said. In fact, it would take only 162 minutes to fill the six feet of freeboard between the spillway and the top of the dam.

(The Army Corps denied that such a sustained and extreme flow at Seven Oaks was possible. I ran the math again using more conservative numbers, chosen to accord with the different flows at the two sites during the 1938 flood on the Santa Ana, but the result was still more than 20 percent above the probable maximum flood. If the storms were more in line with the thicker gray layers seen by Schimmelmann and Hendy, of course, the numbers would go even higher.)

Kwan said that Seven Oaks was one of his first assignments after he joined the Army Corps: He got to see it go from a sketch to a fully operating dam. But he didn’t register any emotion when confronted with the probability that it would fail in a repeat of 1862. Instead, he shifted to talking about the dam-break analysis that the Army Corps had done and the inundation map it prepared. He’s an engineer, after all.

From the top of Seven Oaks, you can see the crowded valley below, home to more than four million people. If you keep following the Santa Ana, you’ll reach the hills above Anaheim and Orange County, home to millions more. The wave running down the river following a dam breach would remain high all the way to those hills. Nearly a mile from the dam, it would still be 69 feet from top to bottom. By the time it got to the San Bernardino airport, an hour later, it would have spread out and slowed down, at merely 30 feet tall.

The inundation map shows all that would be caught in its path. Red dots for fire stations, purple dots for police stations, green squares for schools: Highland Grove Elementary, Cypress Elementary, Lankershim Elementary, Warm Springs Elementary, Bing Wong Elementary, Monterey Elementary, H. Frank Dominguez Elementary, Urbita Elementary, Woodrow Wilson Elementary, Patricia Beatty Elementary, Fremont Elementary, Ina Arbuckle Elementary, West Riverside Elementary.

Houses would be knocked off their foundations, warehouses would crumple, commercial jets would be tossed about. Much of the infrastructure along the river, bridges, highways and railroads, would be washed away. Thousands of people would have minutes to evacuate. The death toll would be far higher than that of an ordinary flood. If the surge found a flaw in Prado Dam, which sits above Orange County, all of Anaheim would be added to the inundation zone, Disneyland included, before the water met the sea.

In 1986, during one of the worst floods Northern California experienced in the 20th century, Mike Dettinger was stranded on Point Reyes with a colleague and both their families, including Dettinger's 9-month-old daughter. "We were a bunch of groundwater hydrologists, and we knew there was a storm coming in but really had no sense of how bad it was going to be," he told me. They ended up driving their Cadillac across a flooded road and losing control of it. The two families spent the next night sleeping in a fire station and the one after that in the manager's office of a local motel.

Getting people to believe the evidence in front them is the first step toward a solution, but it's only the first step. The threat to California's dams is no longer akin to Twain's being surprised by a flash flood. It's Dettinger in the Cadillac, heading into the torrent. The siren is blaring, but still we don't change course.

Image: The Oroville Dam spillway releases water into the Feather River.
Credit...Spencer Lowell for The New York Times

Engineers could keep raising the levees, holding back the water as best they can. Dam owners could build more spillways like the one at Folsom or the ARC spillway planned for New Bullards Bar. And state authorities could get better at evacuations, start drilling for dam failures as we do for earthquakes.

Probably California will have to do all three. But climate change requires a different kind of adaptation. What if, rather than trying to out-engineer the weather, or evacuate and return in an endless cycle, we changed where and how we live? It would be not an administrative feat but a psychological one, an attempt to check, in John McPhee's words, "the powerful fabric of ambition that impelled people to build towns and cities where almost any camper would be loath to pitch a tent."

Americans aren't good at retreating, and the ones who wound up in California, the cliché goes, are the people who didn't stop pushing forward until they ran out of continent. The Indigenous population, though, knew a floodplain when they saw one. Is it unimaginable that we might learn that lesson as we unlearn the ones of the 20th century.

Maybe this could be California: It's a drought year. The streams dry up. There's barely enough water for the people and the crops and the animals, but because there aren't too many of them, they survive. The next year it floods. The snow builds in the Sierra, storm after incredible storm, until the spring arrives and it all goes rushing out to the ocean. The people, though, live well above the rising water. The storms are intense, but after each one passes, the land around them, dun and brittle and dusty for years now, blooms with a million newborn flowers and endless gold-green grasses.

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