CONTENTS

Introduction

Oroville is the tallest dam in the United States, which means it impounds a lot of water. Unlike the stunning concrete colossus that is Hoover Dam, Oroville is an earthen dam that straddles the Feather River like a mountain. Constructing this super-sized dam required transporting 80 million cubic yards of material excavated from enormous piles of hydraulic mining debris—a legacy of the California Gold Rush.[1]

Oroville Dam is just one piece of California's State Water Project. Considered one of the engineering Wonders of the World, the project involved more than 700 miles of canals, tunnels, and pipelines to move a river of water to Southern California and other areas of need.[2]

The biggest challenge was how to get all that water over the Tehachapi Mountains lying between the Central Valley and Southern California. The easiest and obvious solution was to tunnel it in, but that was too risky because of earthquake hazards. The only other solution was to go up and over, resulting in five water lifts. The last one, the highest single water lift in the world, vertically lifts water almost 2,000 feet. *All this* to correct, as Governor Pat Brown put it, "an accident of people and geography."[3]

The linchpin of the entire State Water Project depends on Oroville Dam delivering the goods. In his 1968 dedication speech, Governor Ronald Reagan concluded, "I dedicate Oroville Dam and Lake Oroville to the people of California's future, who will benefit for the generations from this giant structure and the water that it impounds."[4] There was a tremendous sense of accomplishment on that sunny day in May so long ago. California finally had water security.

It worked. For a while.

For the first quarter century everything went according to plan. Except for a few years, the State Water Project (SWP) met 100 percent of the contractual allocations for municipal use.[5] But in the early 1990s, recurring problems began. And it happened fast. Only twice in the past 25 years did the SWP meet 100 percent of their allocations—with about half of these years coming in at less than 50 percent. The past quarter century has been a wild ride from better, to worse, to a lot worse, to a little better. In 2021–22, water deliveries almost went belly-up at 5 percent two years in a row.[6]

In the early 2000s, state water managers talked about getting back to "normal" precipitation patterns. This was the transitional period when many hydrologists and climate scientists believed that significant impacts of climate change were out a half century or more. Scary, but at least comfortably in the future. It took them by surprise to realize that this was possibly more than just normal swings of regular old drought. It was suspiciously looking like all those climate change predictions.

Scientists weigh their words carefully. There have always been droughts, particularly in California with its drought-prone Mediterranean climate. Therefore, to jump to the conclusion that this was driven by climate change was not an easy call to make. Then came the Hot Drought.

In the summer of 2011, Lake Oroville was relatively flush with water. By August 2014, the reservoir was experiencing historic lows, with 82 percent of the state in *extreme* or *exceptional* drought conditions. Soil moisture was so low that 100 million trees died.[7] Governor Jerry Brown declared a state of emergency that didn't let up for another two years. As the name implies, the Hot Drought was unusually hot. This dual punch of soaring evaporation rates on reservoirs and significantly less mountain snowpack nearly brought the state to its knees.

Sierra snowpack is California's water lifeline. It is often referred to as the state's "frozen reservoir" due to its ability to store water and release it gradually throughout the spring and into summer, keeping reservoirs topped-up for the hot, dry, high-water-use months ahead. During the Hot Drought, the snowpack had not only sharply declined, but what there was of it was melting earlier and faster. This meant that reservoirs were filling up in a much more concentrated flood of meltwater, leaving dam operators with no choice but to release a significant amount of all that precious water. The term "snow drought" has entered the water management lexicon to refer to the increasingly common meager snowpacks in the American West. Both the amount of snow and the timing of snowmelt are of considerable concern in the face of climate change.

The drought finally broke in 2016. Then came the *weather whiplash*—also predicted in climate-change models. Over a period of six days in

February 2017, back-to-back atmospheric rivers pummeled the Feather River basin. Oroville Dam came close to failing, requiring the emergency evacuation of 180,000 people living downstream. The rain stopped just in time. Then during the summer of 2021, extreme drought once again gripped the state. Lake Oroville fell to a record 24 percent capacity.

California is not alone. Since 2000, the southwestern US has been experiencing an historic, extended drought, made more severe by the influence of human-caused climate change.[8] We've all seen the pictures of the bathtub ring around Lake Mead. This gives you a picture of what's happening to the most critical reservoir for the Lower Colorado Basin states, but it doesn't convey the full scale of the problem like the story of St. Thomas does.

On a June morning in 1938, Hugh Lord was the last to leave. The other 500 or so residents of St. Thomas had accepted the fate of their town, along with the government buy-out, and moved on. But Hugh was a stubborn old codger. There was no way the federal government was going to push him out of the place where he'd lived his entire life. And on top of that, those government agents obviously didn't know what they were talking about. Hoover Dam was over *60 miles* away! There was no way on God's green earth the water would ever back up all the way to St. Thomas. And so, on a June morning in 1938, with water lapping over the top steps of his front porch, Hugh set fire to his house as a final act of defiance, then got in his boat and rowed away.[9]

The water kept rising until Lake Mead was 110 miles (180 kilometers) long and St. Thomas was submerged under 60 feet (18 meters) of water. Water levels fluctuated over the following years, several times declining enough to reveal the remains of the town, but the reservoir always recovered. In 2000, Lake Mead was near full capacity, and St. Thomas was once again deep under water.[10]

Then everything changed. The town began to reemerge steadily in 2002. Six years later, Las Vegas was so concerned about declining water levels in Lake Mead that the city began constructing its *third straw*—a 3-mile- (5-kilometer) long tunnel through solid rock tapping into the deepest part of the reservoir.[11] As the third straw became operational in 2015, St. Thomas was sitting on dry desert floor and has remained that way. If you didn't know better, you would never guess that just 15 years earlier this entire region was deep under water.

The glory days of surface water storage are behind us. Periods of unusually low storage in reservoirs are becoming longer and more severe in the face of climate change.[12] On a global level, communities and governments are increasingly turning to intentionally recharging aquifers as an alternative approach—a practice known as managed aquifer recharge or MAR.[13]

Managed aquifer recharge captures available water during wet periods, times of low demand, or water that would otherwise be lost, and moves this water underground for later recovery or other benefits. MAR is part of the solution to a host of issues—water shortages, emergency supply, groundwater depletion, land subsidence, seawater intrusion, water quality degradation, streamflow depletion, and endangered groundwater-dependent ecosystems, among others.

Managed aquifer recharge has several advantages compared with dams. Among these are lower capital costs, reduced evaporation losses, and location in proximity to areas with high water demands. A key advantage is that MAR projects are scalable, allowing for staged implementation—often starting as smaller pilot or demonstration projects.[14]

Approaches to MAR can be grouped into five categories:

Water spreading uses spreading basins, ponds, and constructed or natural wetlands to recharge an unconfined aquifer.

Recharge wells are commonly used in situations where the target aquifer is deep, confined, or overlain by low permeability layers. It is also practical where economy of space is an important consideration, such as in urban areas.

Bank filtration involves pumping groundwater from aquifers that are hydraulically connected to rivers or lakes. The pumping induces seepage from the surface water body into the aquifer and provides filtration of the water as it flows to the water supply well.

Streambed channel modifications use low technology surface and subsurface impoundments to capture or slow down runoff, which infiltrates through the bed and is extracted down-valley.

Small-scale options recharge aquifers through collection tanks, drywells, or sand filters. A common approach is rainwater harvesting from roof drainage.

A successful MAR project requires several features. Foremost is sufficient demand for recovered water at a cost that can support the project. Other requirements are a source of water for recharge of adequate quality and quantity, a suitable aquifer in which to store and recover the water, sufficient land to harvest and treat water, and the capability to effectively manage the project.[15]

These basic requirements seem simple in concept, but in practice they can be challenging and raise key questions. What are the effects of harvesting water for MAR on downstream flows and environmental conditions? Are we simply robbing Peter to pay Paul? How will climate change affect the sources of water for MAR? Will the enhanced recharge introduce contaminants into groundwater? What are the effects of mixing the recharged water with the ambient groundwater? Who has rights to the water once underground? Can these rights be transferred? How can those who recharge the water be assured of the ability to recover it? What are the possible unintended consequences? We explore these and other questions in a wide variety of settings to enhance understanding of the various approaches to managed aquifer recharge. As a recent review noted, applications of MAR face both growing prospects and growing pains.[16] We examine both.

There's nothing new about intentionally recharging aquifers. As far back as the Warring States period (circa 475–221 BCE), the Chinese dug channels to facilitate the infiltration of surface water into the ground.[17] What is different today is the increasing use, scale, and variety of it.[18]

The growth potential for water storage now lies largely underground.

Index

Note: Figures are indicated by an italic *f* following the page number.