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The California water model: Resilience through failure

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1 | CALIFORNIA'S WATER MANAGEMENT: SUCCESS OR FAILURE

No earth resource is more abundant than water, but no other resource is more oversubscribed or a source of greater controversy. California, for example, generates an average run-off of 100 km^3/year, but the state's ecosystems and parts of its economy have been water limited for decades, with drought punctuated by years of exceptional rain or snowmelt and flooding. California has nonetheless managed to thrive, with 40 million people, agricultural production exceeding $45 billion/year, and the world's sixth largest economy. Through droughts, floods, and constant tension between environmental protection and economic growth, California has evolved a diverse toolkit for managing its water. But … *is California's model of water management one of the world's great successes or instead a history dismal failures?*

We argue that the answer to the question above is both: that the success of California's water model rests on its past failures—often crisis after crisis—from which local, regional, and state agencies and water users have learned and adapted. As the semiarid to arid world looks for solutions to looming water challenges, the failures and lessons from California's turbulent history provide guidance for future global water resilience.

2 | WATER MODELS AND MANAGEMENT TOOLKITS VARY AROUND THE WORLD

Successful management of water, particularly in drier regions, requires a collective system of infrastructure, laws, regulatory policies, institutions, and economic tools. These integrated water management systems, or "water models," vary globally, depending on local hydrology, politics and economic context, and history ("path-dependent technologies"). Water management in humid northern Europe differs broadly from models in generally arid Australia. Water management in Israel is known for technological innovations in irrigation, desalinization, and water reclamation. The water model for the Colorado River pioneered large-scale reservoir storage and interstate and international compacts to allocate a water supply that originally was grossly overestimated. Today in contrast, more science and investment in the United States goes into removing old dams than constructing new ones (East et al., 2015; Poff & Hart, 2002). However, China continues to build large new dams both domestically and internationally. Other national water models present intermediate and nuanced alternatives. The Dutch model of using dikes (levees) and storm barriers has been developed continuously for centuries, evolving from thousands of local water boards supervising local dike construction and maintenance to a national system of highly engineered and instrumented dikes, lakes, and storm surge barriers. Elsewhere in Europe, the United Kingdom is looking to natural flood management (NFM) solutions, including the possibility of broad watershed reforestation (e.g., Soulsby, Dick, Scheliga, & Tetzlaff, 2017). Water management in 21st century Europe is broadly harmonizing under the EU's Water Framework Directive, which emphasizes protection of water quality and the environment and integration of diverse economic interests (Grantham, Figueroa, & Prat, 2013).

Within the U.S., California's water model shares common elements with other arid western states but remains distinct, shaped by the state's tumultuous history of water use. Water management in California has evolved from early settlement, through the gold mining era, the ascendancy of agriculture, the rise of cities, and the recent maturing mix of objectives that includes strong environmental objectives. California has prospered and steadily adapted its management of water by making mistakes and haltingly, often grudgingly, learning from those mistakes. In 2017, for example, Central California sidestepped major flooding despite one of the wettest winters on record. This was partly a matter of luck, with reservoirs emptied by earlier drought and widely spaced storms, but most infrastructure, particularly the state's flood bypasses, functioned well. Looking forward, California's successes and failures in water management offer broad lessons, particularly for the growing populations of the earth's arid regions. And in general, diverse water models and management toolkits from around the world should be studied in order to select optimum solutions from broad ranges of past experience.

3 | ADAPTIVE WATER POLICY AND MANAGEMENT

Water in California is framed by the state's Mediterranean climate. Summers are dry, with most annual precipitation falling as rain or snow during the winter. Historically, dry-season water supply in California has been provided by mountain snowmelt (the "water tower" for the state), reservoirs, and groundwater. In addition to seasonality, interannual precipitation variability is far greater in California than elsewhere in the United States (Dettinger, Ralph, Das, Neiman, & Cayan, 2011). Flood years often follow on the heels of droughts, and vice versa, and this volatility is accentuated by climate change (Swain, Langenbrunner, Neelin, & Hall, 2018). We argue that this near-perpetual state of water crisis has forced California to find solutions. Whereas other U.S. states and other countries may have decades to settle into a false sense of security, California's schizophrenic hydrologic extremes accelerate innovation (Lund, 2016; Pisani, 1984).

California emerged in 2017 from a severe 5-year drought (and in 2019, or any year, may be heading into another). Agriculture was impacted, but these impacts were limited because past California droughts led to development of flexible water markets. Although the state lost as much as 33% of its water supply, agricultural revenue losses were only 3%. This was in part because producers of lower value crops sold or transferred their water to producers of higher value crops like fruit, nuts, and vegetables and to urban water users. During the last drought, about 6% of California's irrigated land was fallowed, but in a perfectly flexible market, water from up to 50% of the state's irrigated land could theoretically be transferred to high-value crops, with net loss of only ~10–15% of revenue and jobs (Figure 1). California has been forced to develop hydroeconomic tools for drought management. Side-by-side comparisons with the California drought toolkit with, for example, European toolkits show some areas of overlap but also broad differences. During the 2015 European drought, limitations on irrigation were imposed locally, while water continued to be provided for some high-value crops, as in California. At the same time, water transfers, including even trucking of water in extreme cases, and a range of distinctly European tools were also used to navigate the drought (Van Lanen et al., 2016). Looking broadly across our globalizing world, where the location of water use may sometimes be continents away from the location of product consumption (Konar et al., 2016), effective models and technologies for water supply become a shared global concern.

Flood control in California also illustrates the mixed blessings of climate variability. California has an ugly history of flooding and persistent and pervasive flood risk today. Storms carrying "atmospheric rivers" of precipitation in the winter of 1861–1862 turned much of the Central Valley into an inland sea (Kelley, 1989), and a single levee breach in 1986 resulted in a legal judgment of liability against the state of $464 million. In less variable regions, the decades between major floods lead to a "hydro-illogical cycle" (Smith, 2000) in which policy changes or meaningful steps towards reliance are forgotten in the intervals between disasters. In California, repeated flooding since the 1800s led to construction of Yolo and Sutter Bypasses, which remain world models for basin-scale flood management (James & Singer, 2008). The 1986 levee failure sparked new legislation and investment that has upgraded many California levees from some of the worst in the nation to some of the best. Repeated flood disasters have kicked the state in the right direction, although much work remains. The near disaster at Oroville Dam in February of 2017, where the emergency spillway came within hours of a major failure, sparked scrutiny and investment at Oroville Dam and for aging water infrastructure across California (Bea & Johnson, 2017;

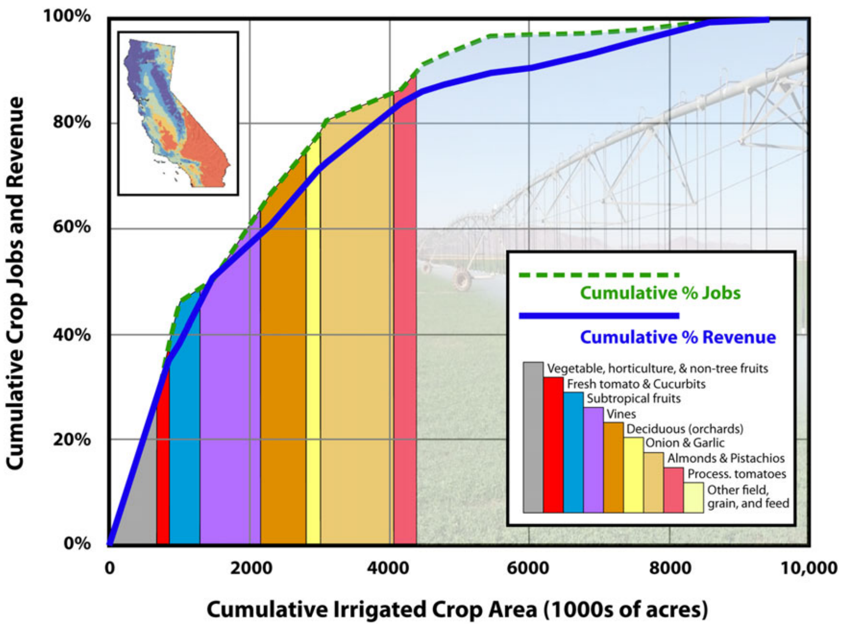

FIGURE 1 Cumulative agricultural revenue and jobs in California relative to irrigated acreage, with high-value crops on the left and lower value crops on the right. With enough management flexibility, large reductions in water use theoretically can result in much smaller economic impacts. Water markets are one reason why California's severe drought of 2013–2017 had disproportionately less severe impacts on the state's agricultural economy. Curcurbits include watermelons, cucumbers, pumpkins, and squash (after Lund, 2016; analysis by J. Medellin-Azuara)

Independent Forensic Team, 2018; Vahedifard, AghaKouchak, Ragno, Shahrokhabadi, & Mallakpour, 2017). Other areas of the world with large dams, or contemplating new dams, should make Oroville a chapter in their textbook (sample lessons: fully understand a dam's geological substrate and invest in routine structural maintenance).

California is also learning from past mistakes in groundwater management. Groundwater pumping is a common response to drought and economic expansion globally. California's aquifers have substantially buffered drought impacts since the early 1900s. But this reliance on groundwater has decreased summer flows in streams, dried up shallow wells, and driven subsidence that exceeds 9 m in some spots and continues today (Faunt & Sneed, 2015). However, many aquifers overdrafted during dry years can be recharged during wet years. This practice has expanded across irrigated and urban areas with each drought, but improvements in recharge have been counterbalanced in recent decades by increased irrigation efficiency – which has counterintuitive, but significant negative impacts. Drip irrigation is great for maximizing crop yields from a property owner's limited water allocation but leaves much less to replenish the underlying aquifer. And without legal mandates for metres on wells or, until recently, for basin-scale accounting of groundwater supplies, wet-year recharge in parts of California has not nearly counterbalanced drought-year withdrawals. As a result, in 2014, the state passed SGMA, the Sustainable Groundwater Management Act, which requires the delineation of groundwater basins and requires water users and jurisdictions within those basins to implement binding groundwater sustainability plans. SGMA should lead to much tighter, more explicit, and better integrated groundwater management at local and state levels.

The benefits of looking at water management paradigms outside one's own borders are emphatically two-way. Despite some successes, California's water management faces persistent challenges, including lingering geographical tensions (e.g., between California's water-rich north and its thirstier south), rural water supply, groundwater sustainability, and ecosystem management. The last point in particular—balancing California's consumptive uses of water with protection of its aquatic species and ecosystems—continues to be a vexing challenge. Despite legal protections under the U.S. Endangered Species Act and a welter of state regulations, California's native fishes are undergoing rapid decline, with 80% of species on paths towards extinction (Moyle, Lusardi, Samuel, & Katz, 2017). A major cause of these declines has been competition between people and fish for water, with the fish generally losing. Facing seemingly intractable problems, California too must look outside of its own local toolkit—perhaps to Europe, where past errors have pushed river ecologists and policymakers to accept "reconciliation ecology" as a new model for maintaining natural diversity in the face of human pressures and a changing climate (Grantham et al., 2013; Schoukens, 2017; Tockner & Stanford, 2002).

4 | FAR-SIGHTED INCREMENTALISM

Without argument, the past 170 years of water management in California show many mistakes, as well as improvements, new solutions, and continued challenges. Episodic droughts and floods, we argue, accelerate new solutions. However, the cultural, political, and economic context of every region is unique. Each of California's water successes is connected to its broader context, and each of the state's persistent water challenges reflects its particular cultural, political, and economic headwinds. Cross-cutting these contextual details, however, the key to snatching resilience from the jaws of disaster may be what we call "far-sighted incrementalism."

California has several distinctive characteristics that must be recognized before exporting solutions to other parts of the world. First, water management in California is multi-layered, with local, regional, state, and federal management and policies reporting to different geographical constituencies. Despite their distributed authorities, California system managers are more integrated than in most other regions. But integration does not mean centralization, and conflicts among California water users are frequent and often litigious. A second characteristic of California is the growing and now widespread recognition that water management must serve multiple, overlapping purposes: domestic and agricultural water supply, flood management, water quality, ecosystems, and others. Finally, the broad geographic scale of California's water systems provides economies of scale and scope for developing ideas, understanding problems, and developing technical and political solutions. Some California solutions may never be fully exportable to the poorest areas of the world. But California itself has evolved economically over time, from mining, to agriculture, to industry and technology and urban services. Today's global economic engagement and diversified economic structure have greatly lessened California's dependence on abundant water supplies.

We argue that a prerequisite for providing adequate supplies of clean water and maintaining healthy aquatic ecosystems is "far-sighted incrementalism" among water managers and political leaders. "Incrementalism" involves addressing seemingly intractable problems by small steps. "Far-sighted," at least in California, has involved cool-headed and forward-thinking planning among scientists, managers, and leaders during and immediately after the state's many water-related crises. The too-common response after a crisis like a damaging flood is reactive—repair the levee breach and rebuild floodplain neighbourhoods. Far-sighted leaders see opportunities in a crisis to move the system forward, usually incrementally, in a longer term strategic direction (which may be too controversial or difficult to achieve in one step). Across much of the United States, flood-damaged levees have been repeatedly rebuilt in the same location, sometimes a dozen or more times over many years (Pinter, Damptz, Huthoff, Remo, & Dierauer, 2016). In the eastern ~two thirds of the United States, levee setbacks to reduce hydraulic constrictions and meaningfully reduce regional flood hazard (Opperman et al., 2009; Phelps, Tripp, Herzog, & Garvey, 2015; Ward, Tockner, & Schiemer, 1999) have been limited to a handful of projects. In California and the similarly forward-looking states of Oregon and Washington, several dozen levee-setback projects have been completed, are in progress, or are now in advanced planning (Floodplains by Design, 2018; Multi-Benefit Flood Protection Project, 2017).

5 | LESSONS FOR MANAGING WATER IN A THIRSTY WORLD

By 2050, an additional 2.3 billion people worldwide will face severe water stress, especially in Africa and southern and central Asia (OECD, 2012). Already, 2.1 billion people worldwide lack access to safe drinking water (WHO & UNICEF, 2017). Three out of four jobs worldwide depend upon access to water and water-related services (WWAP, 2016). Water-limited regions and populations must prepare for changes in water management, addressing existing and emerging weaknesses and learning from mistakes, if possible from other areas, without repeating those errors.

A review of 170 years of water-related missteps and hard-earned successes in California suggests that most of those successes can be traced directly to past mistakes. California's highly variable climate has made it—unhappily and unwillingly—a crucible for innovations in water technology and policy. Similar water imperatives have led to advances in water management in other areas of the world, such as Israel and Australia. A close look at California's history and water model suggests that "far-sighted incrementalism" is a path to progress for the most persistent challenges. Given the complexity of water management systems, scientific information and policy tools must be developed coherently and collaboratively, both despite and because of the systems' many competing interests. A history of making improvements from previous weaknesses and failures can guide future global progress towards the goal of stable, secure, and resilient water systems. The one option clearly superior to innovating from your own mistakes is learning from the mistakes of others.

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