An Analysis of Water Management Strategies in Drought Prone Areas

A comparison of water management techniques in California, Chile, and Australia

by
Sarah Vogel

Dr. David E. Hinton, Adviser

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Signature

Executive Summary

There is an old adage in the West: "whiskey is for drinking; water is for fighting". In the American West, as well as locales all over the globe, water scarcity is a subject rife with conflicts and emotion. Human beings approach drought in reactionary ways. Rather than plan for the eventuality of drought, societies enact drought policy or regulations well into, and not before experiencing drought conditions. Researchers have predicted that more than half of humanity will live in water-stressed areas in the near future. Understanding the significant role drought plays in water management and the costs of reactionary decision making can help stakeholders create proactive approaches to water allocation. This paper seeks to understand how drought affects water management strategies; how regulation is affected by drought conditions; how local agencies and state authorities interact to manage water resources in California; and how California water management compares to water management strategies employed in other drought prone areas of the globe.

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CHAPTER 1. INTRODUCTION

Drought is generally defined as an interval of time during which moisture supply is lower than expected in a given place (Palmer, 1965). Studies have shown that drought prone areas can be attributed to persistent cooler than normal sea surface temperatures in the Pacific Ocean. These cooler temperatures “force anomalous atmospheric circulations that produce multiyear droughts not only in the Great Plains and the Southwest, but also in the Mediterranean region of Europe, the Pampas region of South America, the steppes of Central Asia, and the outback of Western Australia” (Goodrich, 2007).

Human beings approach drought in reactionary ways. Rather than plan for the eventuality of drought, societies enact drought policy or regulations well into, but not before experiencing drought conditions. Governments provide emergency relief and attempt to limit water demand through enacting mandatory water conservation measures; however, this approach “has not reduced the economic losses or the level of inconvenience and suffering of the Nation's citizens” (Willaim R. Walker, 1991). As climate change continues, scientists predict that many parts of the world are likely to experience more severe droughts (Intergovernmental Panel on Climate Change, 200714).

Local governments frequently overlook drought-induced ecological issues (i.e. water for wildlife, contamination due to low flows) because these issues are not within the local governmental jurisdiction even though they are just as important as issues that have the attention of local government. Low stream lows caused by water shortages can lead to warming of water, low levels of dissolved oxygen, and increased concentrations of toxins affecting fish and wildlife. These impacts on fish and wildlife in turn affect overall water quality. For example, low oxygen in water leads to a hypoxic system which could lead to a hypoxic event in which aquatic organisms die due to depleted oxygen levels and the chemicals released from organic material can make water bodies more alkaline or acidic, thereby diminishing water quality (Australia Commonwealth Environmental Water Office, 2017).

Managing water in drought prone areas poses unique challenges. The public perception of policy makers’ actions is paramount. According to recent survey, “if the public is not on board, it is very difficult for elected officials to find the will to act even if they know it is in the best interest of their country, state, or town” (Stoutenborough & Vedlitz, 2014). Results of the Stoutenborough and Vedlitz survey indicated that “the public is willing to support government efforts to manage water, but not if they negatively affect the environment or agriculture”. In California, political pressures are quite often applied to policy makers from the agricultural sector in times of drought when farmers do not get the quantity of water necessary for adequate agricultural production. According to the Intergovernmental Panel on Climate Change (IPCC), availability and quality of water will present the main issues and pressures for societies and the environment.

Information on the cost of drought is lacking, which is a reason that only marginal interest in planning has been seen. Because the economic impact of drought varies by region, planners tend not to focus on drought as a major concern. This could be attributed to a lack of clarity about what constitutes drought and how it affects planning (American Planning Association, 2013). According to the United States Geological Survey (USGS), “the magnitude of drought costs is assumed to be less than that of other natural hazards because the losses associated with other natural hazards are more evident and generally are incurred during short periods of time. In contrast, drought losses generally are distributed over longer time periods. However, when the true costs of drought are known, drought losses can dwarf the losses from other natural hazards. For example, Australia determined that, for the period 1945-75, the costs of droughts were four times the costs of other natural hazards" (Walker, Hrezo, & Haley, 1991).

According to an article published in the Economist Magazine on November 5, 2016, "researchers from MIT predict that by the middle of the century, more than half of humanity will live in water-stressed areas, where people are extracting unsustainable amounts from available freshwater sources" (Water - The dry facts, 2016). Understanding the significant role drought plays in water management and the costs of reactionary decision making can help stakeholders create proactive regulation approaches to water allocation.

CHAPTER 2. OBJECTIVES OF ANALYSIS

This project seeks to understand how drought conditions affect water management strategies; how regulation is affected by drought conditions; how local agencies and state authorities interact to manage water resources in California; and how California water management compares to water management strategies employed in other drought prone areas of the globe. Using this information, future alternatives to current water management strategies in California will be explored.

CHAPTER 3. METHOD

To achieve the objectives of this project, observational evidence was gathered through literature review of available published research papers pertaining to drought, water management techniques, managing water in drought prone areas, water management systems in California, Chile, and Australia, and new technologies and methods of water management. In addition, the California water management system was studied through attendance at a Metropolitan Water Department (MWD) tour of facilities at the Colorado River and Hoover Dam and a tour of the Bay Delta. Attendance on these tours provided data including white papers provided by MWD, which include invaluable information with regard to the current system in place in California, as well as current and proposed infrastructure development and management strategies.

CHAPTER 4. DROUGHT

Drought is a natural hazard that occurs as a consequence of climate, geography, and hydrology resulting in a deficiency of precipitation that, if extended over a period of time, results in water supplies that do not meet the needs of humans or the environment. While a precise and universally accepted definition of drought does not exist, Kallis postulates that "droughts are socioenvironmental phenomena, produced by admixtures of climatic, hydrological, environmental, socioeconomic, and cultural forces" (Kallis, 2008). The lack of a precise definition means that the onset and longevity of drought can be unclear, making management decisions difficult. Droughts differ from other natural hazards in that their effects are typically varied and are experienced gradually, and the onset and end of a drought are difficult to precisely define.

Droughts can be more difficult to define, and more complicated to measure, than other natural hazards. Because drought is dependent on numerous factors that are not necessarily connected, the concept of drought is relative. Factors such as deviations from a historical record for a specific area, the slow pace of development, and extended time frame (as compared to other natural hazards) make it difficult to define the onset and/or end of drought. In addition, the lack of catastrophic damage as seen in other natural disasters (i.e. infrastructure destruction caused by tornados, hurricanes, or earthquakes) lends to difficulty in defining drought. Difficulty in defining drought leads to difficulty in identification and cost assessment of drought damages (Maybank, et al., 2010).

Droughts are dependent on broad, and often unconnected factors. These may include at least: intensity, number, timing, spatial distribution of rainfall events, geological conditions, hydrological conditions, and planned water uses. Taken together, one or more of the above typically play significant roles in both the onset and lifecycle (duration) of drought (Kallis, 2008). In the United States, drought severity is measured by the Palmer Drought Severity Index (PDSI). The PDSI measures moisture in the environment through a combination of precipitation and temperature where moisture evaporation in soil is determined based on temperature and plant use (California Academy of Sciences, 2012). While other methods for measuring drought have been proposed, the PSDI has been the standard since the 1960s. Climatic factors, timing, and effectiveness of rain can all aggravate drought severity. In a warming world, temperature is an important variable because of its impact on atmospheric demand (Wihite, 2016). A recent study by researchers at Princeton University suggests that the PDSI is too simplistic a model to accurately measure drought in relation to climate change. According to the study, paleoclimate drought reconstructions based on data from tree rings diverges from the PDSI-based drought record (Sheffield et al., 2012). Use of the paleoclimate record has been gaining traction in recent years. A study of the 2012-2014 California drought used paleoclimate reconstructions to show that the drought experienced in California between 2012 and 2014 was the most severe drought in the last 1,200 years (Griffin & Anchukaitis, 2014).

Drought usually requires two to three months or longer to become established, and then can last for months, or even years. Measuring the magnitude of drought involves identifying the impacts associated with precipitation shortage, timing, intensity, and duration of the drought event. At times, quick onset, or "flash" droughts occur when precipitation deficiencies are paired with temperature stress and atmospheric variability. “Flash” droughts were observed during drought events in the United States in 2012, including California (Wilhite & Pulwarty, 2017).

According to the World Resources Institute (WRI), global water stress is expected to increase through 2040 (Maddocks, Young, & Reig, 2015). Despite increases in frequency and severity of droughts worldwide, “responses to droughts in most parts of the world remain generally reactive in terms of crisis management and are known to be untimely, poorly coordinated and disintegrated” (World Meteorological Organization, 2017). The World Economic Forum anticipates that at a global level, water demand is expected to exceed supply by 40% by 2030 (Contreras & Nelson, 2018). The UN Convention to Combat Desertification and other agencies have recognized that “desertification, agricultural demands, land degradation, and drought are contributing to a global water crisis” (Wilhite & Pulwarty, 2017).

TYPES OF DROUGHT

There are different types of drought that are dependent on onset factors and the effect of impacts. Meteorological drought for example is marked by a deficiency of precipitation, and the resultant degree of dryness. A lack of rainfall coupled with dry periods of prolonged duration are hallmarks of meteorological drought. This type of drought is highly regionally-specific since average precipitation may vary considerably spatially. Abnormal precipitation deficits lead to diminished soil moisture conditions, which can occur over relatively short timescales (Kallis, 2008; Seasonal Drought Outlook Discussion, 2018).

Hydrological drought is characterized by deficits of rainfall causing reduced streamflow, lower reservoir and lake levels, decreased snowpack, and reduced groundwater levels. Hydrological drought typically results in significant impacts on hydroelectric power production, recreation and tourism, irrigated agriculture, ecosystems, and other sectors; however, because the effects of hydrological drought are typically felt much later, this type of drought is not typically at the forefront for stakeholders. “The characterization of hydrological drought is less associated with precipitation deficiency and more likely to follow the departure of surface and subsurface water supplies from so called average condition at various points in time” (Wilhite & Pulwarty, 2017).

Agricultural drought is evident when available water supplies are not able to meet crop water demand. An agricultural drought can occur in times of low precipitation and is dependent on timing of water availability. Abnormal soil moisture deficits are typically experienced during an agricultural drought (Kallis, 2008; Seasonal Drought Outlook Discussion, 2018).

“Although all droughts originate from a deficiency of precipitation, the magnitude of impacts associated with these types of drought, as well as with socioeconomic and political drought, is largely the result of water and land management practices and policies” (Kallis, 2008). No direct relationship exists between precipitation amounts and the status of surface and subsurface water supplies in lakes, reservoirs, aquifers, and streams because these components of the hydrological system are used for multiple and competing purposes such as recreation, irrigation, or hydroelectric power. Decreased precipitation affects streamflow, soil moisture, reservoir and lake levels and groundwater recharge; however, these affects are felt after a significant time lag. When these deficiencies eventually become evident, the harm has already been done. Abnormal streamflow, groundwater, reservoir, or lake deficits typically are slow to recover because of long recharge periods, and continued mis-management (Wilhite & Pulwarty, 2017).

Where snowpack represents the primary source of water (such as the American West, the Middle East, Central Asia, and southern Europe), infrastructure, regulatory bodies, and legal constraints determine drought severity. As an example, although snowpack in the Sierra Nevada Mountains, as of January 30, 2018, was only 30% of normal levels, California government (Rogers, 2018) suggested that the recent drought had ended. Determining drought severity “is also complicated by infrastructures, institutional arrangements, and legal constraints. For example, reservoirs increase this region’s resilience to drought because of their potential for storing large amounts of water as a buffer during dry years. However, the operating plans for these reservoirs try to accommodate the multiple, often conflicting and competing, uses of the water (e.g., protection of fisheries, hydroelectric power production, recreation and tourism, irrigation) and the priorities set by governments when the funds were appropriated to construct the reservoir” (Wilhite & Pulwarty, 2017). Allocation of water between various stakeholders can be difficult to manage for a drought of unforeseen duration, and this often leads to political and/or legal struggles. Conflicts usually heighten during drought because multiple values are advocated for a limited resource, and “poor water and land management practices exacerbate the problem” (Wilhite & Pulwarty, 2017).

Socioeconomic drought is caused by human activities with regard to water supply. “The interplay between drought and human activities raises a serious question with regard to attempts to define it in a meaningful way. The concept of socioeconomic drought is thus of primary concern to policymakers” (Wilhite & Pulwarty, 2017). When increased development and/or population growth demands exceed available supply, and when government planners fail to take into account future water demand, a socioeconomic drought may result.

CLIMATE CHANGE

Significant changes in measures of climate (i.e. global temperature, precipitation, wind patterns) that occur over several decades, or longer, are referred to as climate change. According to researchers at NASA’s Jet Propulsion Laboratory (JPL), the modern climate era began around 7,000 years ago with the end of an ice age (NASA's Jet Propulsion Laboratory, 2018). The IPCC Fifth Assessment Report indicates that the warming trend that the earth is currently experiencing is likely attributed to human influence, and anthropogenic emissions of greenhouse gases (Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]., 2014). As temperatures warm over time, drought increases in severity and frequency. According to the Intergovernmental Panel of Climate Changes (IPCC), there is high confidence that increased temperatures will lead to more precipitation falling as rain, rather than snow, which will have disastrous long-term effects on areas where snowpack is a major source of water. In addition, warmer temperatures will result in earlier snow melt, and increased evaporation, which will increase instances of hydrological and agricultural drought. As climate change continues, scientists predict that many parts of the world are likely to experience more severe drought conditions. The threat of climate change can increase the frequency, severity, duration, and spatial extent of drought events in the future (Intergovernmental Panel on Climate Change, 2014). Climate change is often blamed for persistent and recurring drought; however, population demands, government conflicts, and other socio-economic factors applying added pressure on finite water supplies cannot be ignored.

According to the WRI, there are numerous areas throughout the world currently experiencing water stress, making these areas vulnerable to episodic droughts. In Northern India, for example, groundwater is significantly depleted, as evidenced by changes in the Earth's gravity field observed by NASA's Gravity Recovery and Climate Experiment (GRACE) dual satellite system. GRACE generates precise observations of Earth's time variable gravity field, which provides integrated estimates of variation of terrestrial water storage (van Dijk A. I., et al., 2013). According to an article published by the WRI, "Nowhere on Earth are groundwater declines greater than in northern India; NASA found that large-scale irrigation caused 108 cubic kilometers of groundwater loss in Haryana, Punjab, Rajasthan, and Delhi between 2002 and 2008" (Iceland, 2015). Northern India's dependence on groundwater sources for agricultural production could result in collapse of agricultural output for the 114 million residents of the region if sustainable practices are not implemented. These examples highlight the prevalent reactive management style of water resources managers around the globe.

ECOLOGICAL RECOVERY

As drought takes hold and persists, the ecosystem changes. Ecosystem recovery time is the length of time an ecosystem needs to return to its pre-drought functional state. For example, when recurrence of forest or shrub land occurs following large-scale dieback events that killed trees and shrubs over large areas as a result of drought, or pest and pathogen outbreaks on drought-weakened trees. In general, when water is removed from an ecosystem plant life dies or goes dormant. As food sources disappear, herbivores either leave or perish. As the herbivores leave, predators follow. Eventually, as precipitation evaporates, and is not replaced, the ecosystem becomes uninhabitable to most of the organisms that contribute to its proper function. The ecosystem recovers as water returns, and vegetation and other organisms are replenished, bringing the ecosystem back to pre-drought function. A 2017 study indicates that as frequency of drought increases globally, ecological recovery time may exceed the interval between consecutive drought events, which could lead to "permanently damaged ecosystems and widespread degradation of the land carbon sink" (Schwalm, et al., 2017). The environmental costs associated with drought and increased development can be difficult to separate. For example, increased salinity resulting from agricultural activities is indirectly influenced by increased population; therefore, a municipality planning increased development and agricultural output to keep up with a growing number of residents, will have to factor drought conditions into planning efforts to avoid a negative impact on the ecological resources needed to sustain its existence.

HOW SOCIETY DEALS WITH DROUGHT

Drought is dissimilarly felt among regions and groups. Socioeconomic factors such as poverty and demography produce differential vulnerabilities. "Human agency, policies, and socioeconomic factors are part of the causal structure of hydrological, agricultural, and supply droughts" (Kallis, 2008). While the conditions and effects of drought are relatively constant (i.e. decreased precipitation), droughts differ in intensity, duration, and spatial coverage. These differences cause stakeholders to react in varying ways (Wilhite & Pulwarty, 2017).

According to the WRI, in recent years regions in Spain, China, Syria, and Brazil have suffered significant water stress due to drought mixed with poor management decisions. WRI's Aqueduct project has predicted that in the years 2020, 2030, and 2040, the global water picture will likely get worse. "Larger populations and growing economies demand more water, and in some places, climate change will likely reduce available water supply. While our vulnerability to drought grows, the incidence of extreme weather events, including drought, will grow as well, according to most climate change experts" (Iceland, 2015).

An early warning system, the drought early warning and information system (DEWIS), was designed to predict occurrence and potential impact of drought. The DEWIS detects trends of key meteorological, hydrological, and social indicators, and triggers appropriate mitigation and response measures (Pulwarty & Sivakumar, 2014). According to Wilhite & Pulwarty, "the continuum from drought forecasting to early warning is still a linear process based on a "sender–receiver" model of risk communication" (Wilhite & Pulwarty, 2017), which limits risk management capabilities to be reactive. The sender-receiver model of communication is limiting because both the sender and receiver of information are required to be engaged and information on both ends must be verified, which only allows risk managers time to react, rather than time to prepare. The DEWIS can provide information that can anticipate potential crisis and can provide data to support strategic responses. This enables risk assessments that are problem-specific, allows communication for effective decision-making, and provides information for preparedness and mitigation plans so that regions might deal with drought in a proactive manner (Pulwarty & Verdin, 2013).

The World Meteorological Organization (WMO) sponsored a group meeting, as part of the Conference of the Parties of the UN Convention to Combat Desertification (UNCCD), on early warning systems for drought preparedness. At the meeting, experts examined the current status of early warning systems and identified areas where DEWISs need change to achieve a greater level of drought preparedness (Wilhite & Pulwarty, 2017). Various international groups, including the UN International Drought Management Program, the US National Integrated Drought Information System, and PRONACOSE in Mexico, rely on DEWIS to combat global water stress. Development and implementation of a comprehensive DEWIS is a critical step in mitigating the damage caused by drought (Wilhite & Pulwarty, 2017). If the areas identified by the group at the UNCCD in need of change can be addressed, region-specific DEWIS' can be adopted in areas such as California, where drought is an ever-present threat. Mitigation of known potential drought impacts is an essential component to developing sustainable water resources.

SOLUTIONS

Adaptive management strategies enacted before drought events occur will likely reduce the need for emergency response by reducing vulnerability. Improving water use efficiency is one of such adaptations. DEWIS in conjunction with other adaptive solutions "are needed not only for event onset, at which a threshold above some socially acceptable or safe level is exceeded, but also for intensification and duration, ranging temporally from a season to decades and spatially from a few hundred to hundreds of thousands of square kilometers" (Pulwarty & Verdin, 2013). An enhanced understanding of the natural and social dimensions of drought assists in more effective management, and might include arrangements that allow or hinder proactive responses. Integrated drought and water scarcity management approaches are increasingly recognizing the urgent need for multi-stakeholder platforms, at the country, community, and transboundary levels, for the implementation of joint strategies and the coordinated response and prevention of crises" (Wilhite & Pulwarty, 2017).

Drought policies and activities around the world are tracked by the Integrated Drought Management Programme (IDMP) and partners. In a 2010-2012 survey the National Meteorological and Hydrological Services (NMSH) provided information as to their countries drought indices and individual policies. According to survey results, out "of the 52 countries that responded, 17 indicated some sort of national drought policy or plan" (Wilhite & Pulwarty, 2017). Surveys, such as the NMSH are important because they help the IDMP to review global drought policies and align plans and track what, if any, actions have been implemented and whether plan objectives are fulfilled.

In survey approaches related to drought and water crises it is proposed that a solution to finding financial resources to tackle drought may be found through diversion of resources from ineffective reactive response programs to a more proactive risk-based management approach. Agencies "divert resources from reactive response programs that do little, if anything, to reduce vulnerability to drought (and, as has been demonstrated, may increase vulnerability) to a more proactive, risk-based management approach" (Wilhite & Pulwarty, 2017). These diverted funds can then be invested in DEWIS', monitoring networks, or other data gathering systems that can be utilized as decision-making tools that may save millions of dollars in disaster relief assistance (Wilhite & Pulwarty, 2017).

CHAPTER 4. WATER MANAGEMENT STRATEGIES

MANAGEMENT STRATEGIES

There are a variety of influences that come in to play when developing water management strategies. Stakeholders need to consider geography, weather/meteorological data, culture, economic variability, and resource availability. Some of these factors may remain static, while others are constantly changing. Different water management strategies may be used to address the unique challenges of a particular system. According to a report from the UN Development Programme, UNDP Bureau of Crisis Prevention and Recovery (2004), "annual losses associated with natural disasters increased from US$75.5 billion in the 1960s to nearly US$660 billion in the 1990s. Losses resulting from drought likely follow a similar trend, but actual impacts, including economic loss numbers, are at the current time not well known" (Wilhite & Pulwarty, 2017). It is assumed that costs for natural disasters are underestimated due to inexact reporting and poor data collection. For example, indirect losses (such as ecosystem services, quality of live, psychological impacts) are not typically included in those works reviewed by Pulwarty and Verdin (2013) concerning estimates of drought related losses (Pulwarty & Verdin, 2013; Wilhite & Pulwarty, 2017).

INTEGRATED WATER RESOURCES MANAGEMENT

Since the 1990s, there has been an international debate about water policy. It has been recognized that when it comes to water allocation and distribution, there are often multiple, contradictory, pressures on water managers. These pressures lead to decision-making that is not sustainable in the face of competition across varying sectors. When water managers treat different aspects of the water cycle as separate entities, the inherent interdependency of each is ignored; whereas in an integrated approach, each part holds unique importance to the function of the whole interdependent system. In 1992, at the International Conference on Water and the Environment held in Dublin, Ireland, the following four main principles to an Integrated Water Resources Management (IWRM) strategy were developed:

1. Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment

2. Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels

3. Women play a central part in the provision, management and safeguarding of water

4. Water has an economic value in all its competing uses and should be recognized as an economic good

IWRM is a long-term and forward-moving process where the coordinated development and management of natural resources is promoted by through policy and resource managers. According to the Global Water Partnership, "IWRM helps to protect the world's environment, foster economic growth and sustainable agricultural development, promote democratic participation in governance, and improve human health" (Global Water Partnership Central and Eastern Europe, 2011). Rather than a sector-by-sector, or top-down approach, managers have begun to understand the interconnected nature of hydrological resources, and the necessity for ecological balance in order to preserve these resources. One of the fundamental principles of IWRM is viewing water as an economic good, rather than simply a finite resource (Global Water Partnership Central and Eastern Europe, 2011; Bauer, 2004). By treating water as a commodity and focusing on all parts of the water cycle as an integrated system, a need to strive for sustainability is created.

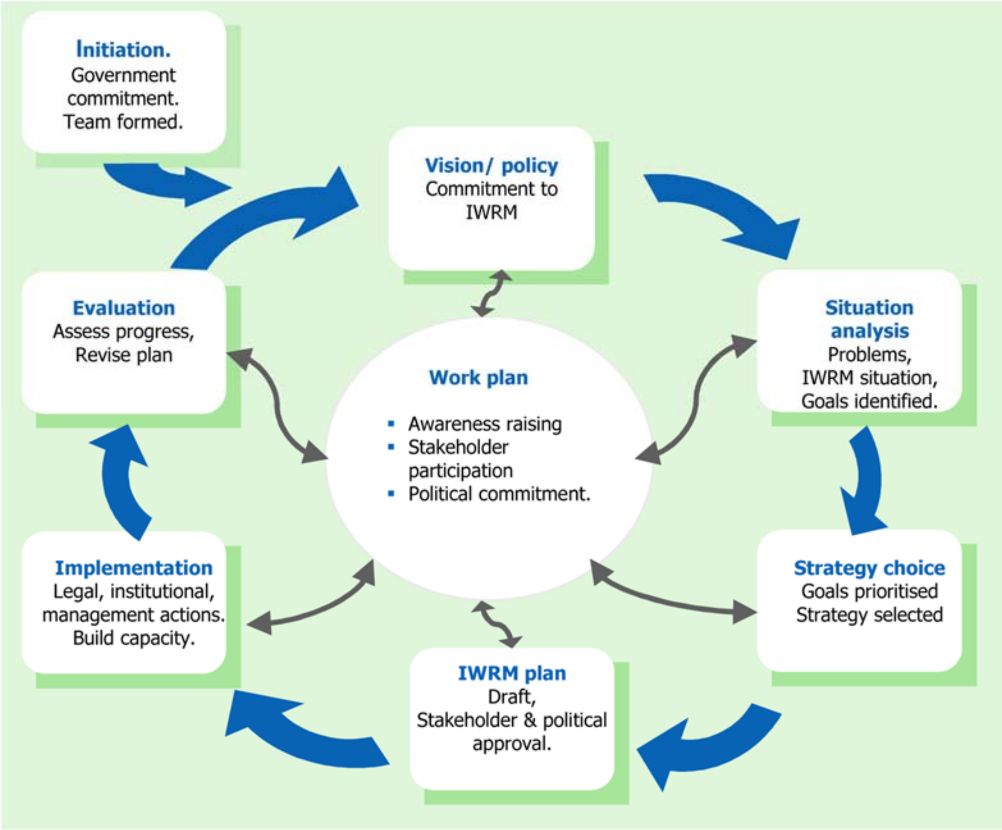

Figure 1 – An example of IWRM. An action is initiated and input into the cycle as checks and balances circulate a central work plan.
(Source: The Water Channel, Adaptation to Climate Change in Water Management, Figure 6.1 Integrated Water Resources Management Plans, Cap-Net, 2005).

As illustrated above, IWRM considers the system as a whole, and takes into account the impacts that changes in use or distribution of water will have on other aspects of the system. Rather than starting with the presumption that infrastructure is the first place to start in scarcity conditions, water resource managers are able to find alternative solutions by focusing in on the objectives of management. "IWRM should be advocated as the encompassing paradigm for adaptation to contemporary climate variability, and it is the prerequisite for coping with the consequences of global warming, climate changes associated with it and their repercussions on the water cycle" (Cap-Net/UNDP, WMO/APFM, UNESO-IHE, 2005).

ADAPTIVE MANAGEMENT

Adaptive management, in this context, is a structured approach to water resources management that incorporates uncertainty into the process, with an aim to reducing uncertainty over time. This approach allows water managers to make decisions and adjustments in response to changes in information. This type of management strategy has been employed in water resources management since the 1970s. It has been successful in that it allows management actions to be treated as experiments, creating a wealth of data as to actions and policy that work, and those that do not. The experimental nature of adaptive management has led to the promotion of monitoring and early warning, vulnerability and impact assessment and mitigation, preparedness, and response techniques, which in turn support the fundamental goal of adaptive management, which is to improve management. A key component to adaptive management is developing a method to work with environmental variability, rather than fighting against it. Pitfalls of adaptive management include the ability to recognize and measure success, institutional resistance, risk aversion, and lack of stakeholder engagement (Williams & Brown, 2012). The figure below illustrates a general framework for adaptive resource management. The first step is to define the problem and then create a plan by establishing goals and objectives, and gathering data to support proposed actions. These planning phase actions will prepare the manager for the design and implementation phase. An evaluation and response phase at the end of the cycle encourages analysis of gathered data and communication of understanding so that the management strategy can be adapted for success.

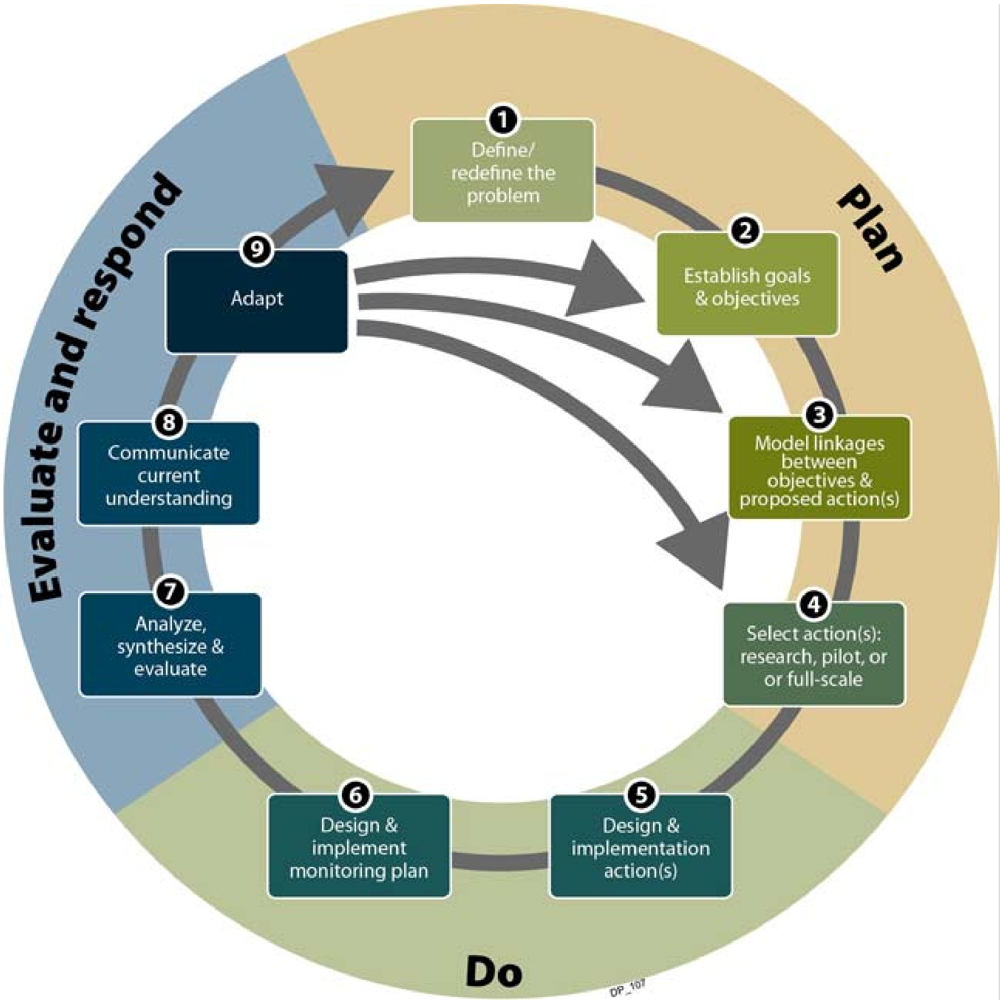

Figure 2 – The plan for California EcoRestore and Management. The plan (steps 1-5) shown here are followed by actions "DO" and then by evaluate and respond. Adaptations are incorporated as indicated by setp 9. (Source: California EcoRestore Adaptive Management Program White Paper, Figure 1. The 3-phase, 9-step adaptive management cycle (Delta Stewardship Council 2013a)).

WATER MARKETS

Market-driven risk management strategies can address variability and uncertainty in water supplies. This is achieved through trading of entitlements, or water rights. As water rights are bought and sold, water can be transferred from one use to another, eliminating under- and over-utilization of the resource, and creating longer-term shifts in demand (Hanak, et al., 2011). Globally, "more than 30 percent of all rivers, lakes and aquifers are being heavily tapped" (Richter, 2016). As global populations grow, so does dependency on these resources, and the impacts on the environment. High water stress creates a system in which water users are vulnerable to even small changes in supply. Participation in water markets provides flexibility in meeting withdrawal or use limitations and can create an otherwise non-existing source of revenue.

The basic idea behind water markets stems from the ‘cap and trade’ system which involves:

- The cap as the total pool of resource (i.e. water) available for consumption, as consistent with sustainable levels of use;
- Individual and group users are provided with rights/entitlements;
- Ownership can change over time since rights/entitlements are tradeable; and,
- Price is determined by demand (Fargher, 2012).

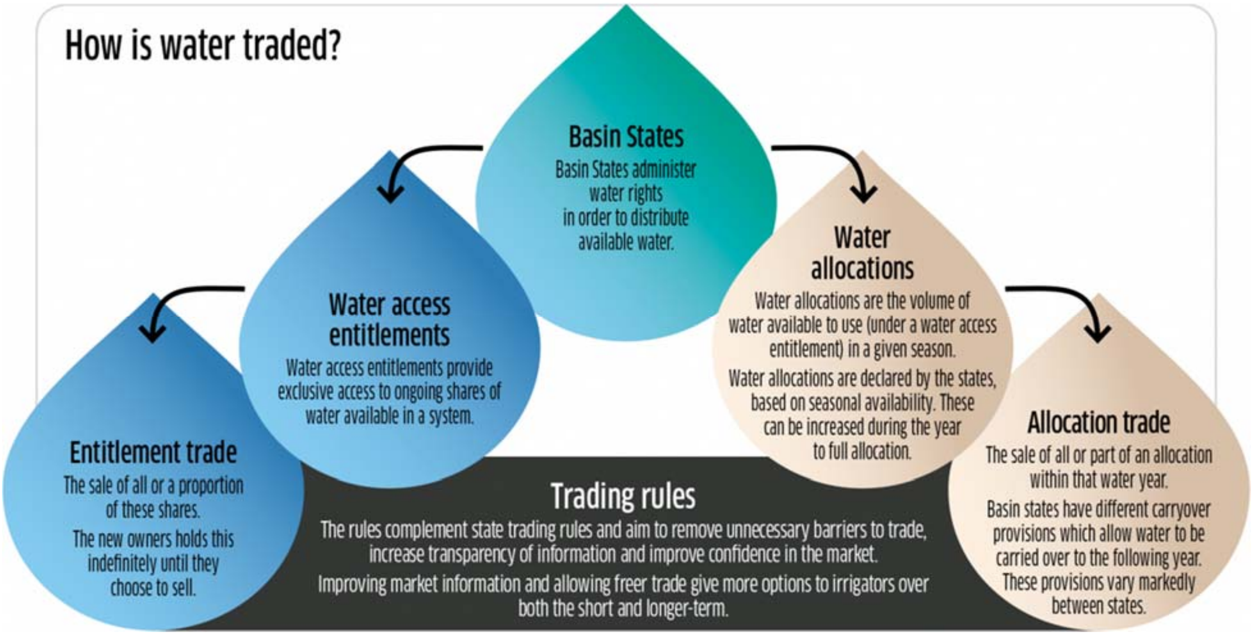

Figure 3 – Illustration of how water is traded.
(Source: Murray-Darling Authority: Basin Plan annual report 2015-16).

In order for water markets to be effective transaction costs (i.e. the cost associated with making a trade) must be low (Nikolakis & Grafton, 2011). Environmental impacts are mitigated in a market-based approach through impact investment. For example, Water Sharing Investment Partnerships (WSIPs) use investors’ money to acquire water rights/entitlements. The entitlements can then be either reallocated to ecosystems that have been depleted, or sold to end users in need of additional supply. This type of transaction generates financial returns for investors that are interested in having their money work for environmentally and socially positive outcomes (Richter, 2016).

According to Nikolakis and Grafton (Nikolakis & Grafton, 2011), an effective water market must meet with the following conditions:

- As stated above, transaction costs must remain low. While increasing transaction costs in a successful market climate may be tempting, operators must strive to keep transaction costs at a minimum. Drivers such as socio-political uncertainty and environmental issues can cause an upswing in transaction costs, constraining water markets.

- For a water market to be successful, it must also be economically efficient. Water markets are typically developed with a focus only on consumptive use. Economic efficiency is achieved when all of the benefits from trade have been realized and costs to stakeholders have been included in decision making of water users.

- Equity in water rights is key to developing a water market with long-term potential. Understanding the function of ecological resources (i.e. groundwater and surface water connectivity), and respecting stakeholder values (i.e. fair access for minority groups) are two examples of equitable parameters that need to be reflected in trading rules if a water market is going to enjoy extended success.

An established water rights system is also key to developing a water market since without ownership/rights, there is nothing to trade. There are several countries that successfully utilize water markets (i.e. Australia and Chile, as discussed in Chapter 6); however, societies approach to water scarcity is typically to invest in large storage projects or infrastructure to increase supply. High costs of new infrastructure can be out of reach for many communities, and global water supplies may be limited. A water market approach to water resource management may stimulate water conservation by shifting focus to water as a tradeable commodity that should be saved and made available for other users, which will garner reward. According to Brian Richter, Chief Scientist with The Nature Conservancy, "[i]f all regions with existing water rights systems could establish water markets functioning on par with the Australian market, they could collectively generate total annual water sales of US$13.4 billion per year, equating to market assets of US$331 billion" (Richter, 2016).

DROUGHT MANAGEMENT STRATEGIES

Stakeholders have employed a variety of drought management strategies including monitoring water supply, water conservation strategies, new technologies, and behavioral changes. For example, farmers may plant different crops to improve drought resilience, enroll in crop insurance schemes, or invest in soil health or water storage technologies (Wallander, Marshall, & Aillery, 2017). Commercial and residential end users might choose drought-tolerant landscape designs, install grey water systems, or develop behavioral change (i.e. limiting time in shower, turning off running water while brushing teeth, running washing machines at non-peak hours). Municipalities could invest in drought resilience improvements including impermeable pavements, additional capture and storage, or identification of alternative sources. Regulators may implement policy that limits water availability or punishes certain behavior as observed during the 2012-2014 drought in California. Due to diminishing resources, the State Water Project and Central Valley Project dramatically reduced water deliveries to achieve conservation goals set by the state. Citizens were encouraged to conserve electricity as well as water since only half of the hydropower generation that usually provided approximately 15% of California's electric supply had been cut in half. While these strategies may be specific to individual stakeholders, when enacted together they may reduce the economic, social, and environmental impacts of drought and enhance community resilience (Mount J. , et al., 2015).

CLIMATE CHANGE

While government response to drought has typically been through crisis management, “there is growing evidence that the frequency and extent of drought has increased as a result of global warming”, indicating that in future, government response will need to make a proactive or preventative shift (Wihite, 2016). “The crisis management approach has been mainly ineffective, leading to untimely and poorly coordinated responses. Hence, the HMNDP was organized by WMO, UNCCD, and FAO, in collaboration with a number of UN agencies, international and regional organizations, and key national agencies. HMNDP provided practical insight into useful science-based actions to address the key drought issues being considered by governments and the various strategies to cope with drought. The HMNDP declaration, adopted unanimously by the participants in the meeting, encourages all governments around the world to develop and implement national drought management policies, consistent with their national development laws, conditions, capabilities, and objectives” (Wilhite & Pulwarty, 2017).

CHAPTER 5. HISTORY OF WATER MANAGEMENT IN CALIFORNIA

Spanish author Garci Rodríguez de Montalvo wrote Las Sergas de Esplandián (The Adventures of Esplandián) in the early 16th century. In the romance novel, a mythical island populated by beautiful Amazon warriors was named California. Later, thinking that the Baja California peninsula was an island, Spanish explorers named the land after the mythical island described in Montalvo's novel, and the area was labeled "California" as the unexplored territory on the North American west coast on maps (Chapman, 1923). Separated into distinct regions by the Sierra Nevada mountain ranges, portions of the state experience drastically different ecological, meteorological, hydrological, and geological occurrences. The northern portion of the state consists of extensive forests and deserts, the eastern portions contain the high Sierra Nevada Mountains located behind the Great Basin Desert, the southern portions contain the Sonoran Desert and Mojave Desert, and the Pacific Ocean and coastal range are in the west. These geographical variances make California an unusual state with regards to both water management strategies and history of drought (Wikipedia, 2018).

California was occupied by several tribes of Native Americans for at least 10,000 years before European explorers and settlers arrived. These early inhabitants practiced some land management techniques to preserve watersheds, ease drought, and create barriers to natural wildfires; however, because irrigation is required during long dry seasons, agricultural techniques were not in use. Native Americans sustained by use of subsistence hunter-gatherer economy. Even without agriculture, the "natural abundance of California, and the environmental management techniques developed by California tribes over millennia, allowed for the highest population density in the Americas north of Mexico" (Lightfoot & Parrish, 2009).

In 1565 the Spanish established a nautical trading route between the Americas and Asia to move silver from Mexico to trade for goods and spices from China. Trade with Mexico involved an annual passage of galleons which sailed from the Philippines easterly using the westerly trade winds and currents, arriving off the California coast near Cape Mendocino (approximately 300 miles north of San Francisco). The south flowing California Current would then take the vessels south along the California coast until they reached port in Mexico. The use of this trading route lead numerous sailors to explore the California coast through the 16th and 17th centuries; however, European settlements were not established in California until the late 18th century during the Spanish colonial period. By 1763, due to the fear that Britain would attempt to claim the California territory, King Charles III of Spain began to establish missions and other outposts throughout California. "The remoteness and isolation of California, the lack of large organized tribes, the lack of agricultural traditions, the absence of any domesticated animals larger than a dog, and a food supply consisting primarily of acorns (unpalatable to most Europeans) meant the missions in California would be very difficult to establish and sustain and made the area unattractive to most potential colonists". Eventually, 21 missions would be established along the California coast. With the establishment of the missions, irrigation and agricultural practices were taught to Native Americans; however, missions were typically located along rivers or small streams, negating the need for extensive irrigation techniques.

To encourage settlement, the Spanish monarchy began giving out large land grants which eventually formed ranchos (cattle ranches) and pueblos (small towns/villages). At that time, the first system of water rights in the state were established by Spanish law, but those water rights were not conferred on the more than 800 ranchos throughout the state because Spanish and Mexican land grants were usually large enough to support cattle grazing on arid land. Because most stream or river diversions were limited to application to adjacent land, and only utilized relatively small quantities of water, the advent of ranchos and pueblos did not have a significant impact on California's native waterscapes (Hanak, et al., 2011).

In 1821 Mexico gained its independence from Spain. California was a territory of Mexico until 1846 when the United States began capture of coastal ports and towns. By 1847, the United States Navy had captured the largest town in the Mexican territory, Pueblo de Los Angeles (present day Los Angeles), and California became a territory of the United States. The Mexican-American War ended in 1848 and the United States acquired the California territory from Mexico. Following the war, the Treaty of Guadalupe Hidalgo documented and upheld property rights established under Spanish and Mexican law.

The history of water management in the state of California is complex and fraught with conflict. The novel Water and Power (Kahrl, 1982) states that the history of California in the 20th century is the story of a state inventing itself with water. There was very little federal or state input in the infancy of water management in California, as most water management schemes were taken on by individuals, corporations, or local actions. In 1848, a gold nugget was discovered in the American River, and the Gold Rush ensued. Prospectors and fortune-seekers from all over the globe flocked to California by the thousands. Cities like San Francisco burst with new arrivals by the day. The population in San Francisco grew from 1,000 in 1848 to over 20,000 by the time California was admitted to the Union as the 31st state in 1850 (Immigration to the US, 2018).

The Gold Rush led to the advent of a new rule of law for allocating water. Mining introduced the first large-scale water uses in California, and with the use of water came conflict. Miners had developed a practice of resolving disputes via the "first-in-time, first-in-right" rule. The California Supreme Court upheld the miners rule in 1855 when the court, recognizing that the rule worked in practice and was "commonly accepted as the most fair and efficient means of apportioning water in times of shortage and therefore adopted the rule of prior appropriation as the law of state" (Hanak et al. 2011).

In 1862, with the flooding of Northern and Southern California, and the Central Valley, it became apparent that flooding presented a major water management issue. Landowner built small embankments between their land and nearby rivers, but the small levees failed regularly flooding homes and fields. In 1868 local reclamation districts were formed. The districts allowed landowners to join together and raise funding for construction of flood control projects and land reclamation activities. Unfortunately, a system of separate districts proved to be problematic. As funds were raised, levees were constructed to be taller and stronger, which would interfere with the natural attenuation of flood waves, causing overflow or breach of smaller, weaker levees. This caused flooded landowners to increase the size of their levees to force the floodwaters onto their neighbors (Hanak, et al., 2011).

The early 1880s brought numerous environmental and economic problems caused by gold mining. Lawsuits resulted in declaring hydraulic mining to be a public nuisance, and continued mining was prohibited. Courts declared that mining "must give way to the paramount public interest in navigation and commerce and to the burgeoning commercial and agricultural development in the Sacramento Valley" (Hanak et al 2011). By the mid- to late-1880s, conflict was growing over riparian and appropriative rights. One of the most famous legal cases in California's history, Lux v. Haggin (1886) pitted wealthy and powerful riparian landowners against equally wealthy and powerful appropriators. The Supreme Court ruled in favor of riparian landowners resulting in a system where priority was given to riparians. "This meant that downstream riparians—including those farming the lower reaches of the Sacramento and San Joaquin Rivers and in the Delta itself—could claim the full, unencumbered flow of the rivers despite the burdens such claims would place on upstream appropriators. Moreover, riparian rights would become an obstacle to developing water supplies for California's growing cities, which sought to acquire supplemental water sources. These conflicts would play out over the next four decades".

The law of prior appropriation is suitable for the American West where there are few rivers and streams, and adequate water supply may not be adjacent to arable land. Not surprisingly, most western states adopted the prior appropriation system and rejected the riparian rights system where owners of riparian land have the right to use water that flows along the boundaries of their property, but share with all other riparian land owners, and may only use water on riparian land and within the watershed from which it is diverted. Under the riparian system in times of shortage, water is allocated based on reasonable use. In California, both forms of water rights are recognized.

As the population grew and food demands increased, California's farmers sought ways to increase production. Some farmers pooled resources to acquire water rights and construct water projects (i.e. dams, canals, irrigation ditches); however, adequate investment capital was lacking. The Wright Act in 1887 authorized the formation of irrigation districts that could acquire water rights, construct water projects, sell bonds, and assess property in support of water development and distribution (Pisani, 1984; Hanak et al., 2011). Irrigation districts formed by farmers in the Central Valley were among the first to build dams and canal systems for water storage and distribution. Other agencies were formed as real estate and businesses in the area began using water companies to develop and distribute domestic water supplies. At the same time, farmers and cities in Southern California began relying on groundwater. With the increasing population of the state, and the formation of regulatory bodies, conflicts between surface water and groundwater users began to arise. "In the 1880s, Los Angeles sued neighboring cities and private groundwater users and persuaded the California Supreme Court that its pueblo rights in the upper Los Angeles River also gave it superior rights to all groundwater in the basin hydrologically connected to the river. This was the first case to recognize surface and groundwater as an integrated resource" (Hanak et al., 2011).

As drilling technology improved, landowners were able to install wells at greater depths. Unfortunately, deeper wells meant that neighbors were in competition to drill deeper. As groundwater table were depleted, a 'race to the bottom' was fired up. By 1900, California's economy and population were the fastest growing in the nation. The fast-paced economic and population growth meant that large cities were exhausting their local water supplies. Leadership in San Francisco and Los Angeles began to search for ways to secure water supplies that would enable growth and prosperity for the next 100 years. San Francisco's mayor, James Phelan, and the city's chief engineer, Michael Mauricee O'Shaughnessy, turned toward the Tuolumne River and began designs for a dam at the mouth of the Hetch Hetchy Valley. John Muir and the Sierra Club delayed the project for more than a decade because Congress had included Hetch Hetchy Valley in the boundary of the Yosemite National Park in 1890; however, in 1913, Congress passed the Raker Act authorizing San Francisco's use of Hetch Hetchy Valley as a reservoir. Construction on the dam began following passage of the Raker Act; however, Tuolumne River water did not reach San Francisco until 1934.

The Mayor of the City of Los Angeles, Fred Eaton, appointed William Mulholland to be the chief engineer of the newly formed Los Angeles Department of Water and Power and the designing of the Owens Valley water project began. Eaton and Mulholland began acquiring riparian land and water rights in the Owens Valley and transferring them to the city. After the federal government granted the city a right-of-way across federal lands, in 1908 construction of the Owens Valley Aqueduct began. Five years later water from Owens River flowed into the San Fernando Valley for storage in the local aquifer. As Los Angeles' population increased, demand for water grew, and a new diversion works was constructed higher up in the Owens River Valley. Tension between valley residents and the city grew. Between 1929 and 1934 California experienced a drought that contributed to the start of the Central Valley Project (CVP). In 1928, the Metropolitan Water District of Southern California was established; the California Legislature passed an act to build the Colorado River Aqueduct; and the California constitution was amended to make "all water rights subject to the requirement of reasonable use – including the rights of riparians in competition with appropriative rights". "The enactment of the 1928 constitutional amendment would facilitate the dramatic expansion of the hydraulic society that would take place during the middle of the 20th century. By removing the obstacle of riparian claims to the full flow of the state's rivers—and by declaring a state policy to prevent waste and to promote the reasonably efficient use and allocation of California's water resources—the constitutional amendment laid the legal foundation for the statewide water projects that were on the drawing boards " (Hanak et al. 2011). In 1930 Los Angeles began to extend the aqueduct north into Mono Basin, and by 1933 the city had acquired most of the remaining private land in the Owens Valley. Los Angeles began pumping and exporting groundwater from the Owens Valley at that time. Diversions of the tributaries that fed into Mono Lake were completed in 1940. "Over the next four decades, the city's diversions would diminish the lake, imperil its wildlife, and ultimately set the stage for the California Supreme Court's recognition of the public trust as a fundamental limit on the exercise of water rights" (Hanak et al., 2011).

Numerous water projects (Colorado River Compact, Hoover Dam, Colorado River facilities, All-American Canal, Parker Dam, CVP, State Water Plan) were constructed through the 1920s, 1930s, and 1940s. An increasing population that followed World War II, and dry spells in the 1950s prompted an expansion of the MWD service area. In 1951 the state authorized the Feather River Project Act, which later became the State Water Project (SWP). In 1960, 30 public agencies and MWD signed a long-term contract for construction of reservoirs, pumping plants, and the 444-mile long California Aqueduct that make up the SWP. In the 1960 election California voters approved the SWP; however, the project approval was passed by a margin of less than three-tenths of one percent of votes. With the exception of Yuba and Butte Counties (which had recently flooded), all of the counties in the north voted no. The Southern California voters provided the margin of victory. "The SWP vote highlighted the north-south divide that would dominate California water politics for the next quarter century" (Hanak et al., 2011).

The following regulatory measures enacted between the late-1960s and early-1980s had a profound effect on water management in California:

- The National Environmental Policy Act (NEPA) of 1969 and California Environmental Quality Act (CEQA) of 1970 required an analysis of potential environmental effects, suggested alternatives, and consideration of mitigation actions, prior to beginning new water management and flood control projects.

- The modern Clean Water Act (CWA) was born of the California's Porter-Cologne Act of 1969 and the Federal Water Pollution Control Act Amendments of 1972. This legislation granted the State Water Resource Control Board (SWRCB) the power to set standards for water quality, and other beneficial uses of California's waters.

- The National Wild and Scenic Rivers Act of 1968 and the California Wild and Scenic Rivers Act of 1972 applied protections to numerous rivers that had been identified for dam projects to support the CVP and SWP.

- The Federal Endangered Species Act of 1973 and the California Endangered Species Act of 1984, listed a variety of native fish for protection, which altered the administration of California's water resources systems.

According to Hanak, et al., the environmental laws highlighted the environment as a stakeholder and indicated that the "era of large-scale water development projects was coming to an end" (Hanak, et al., 2011).

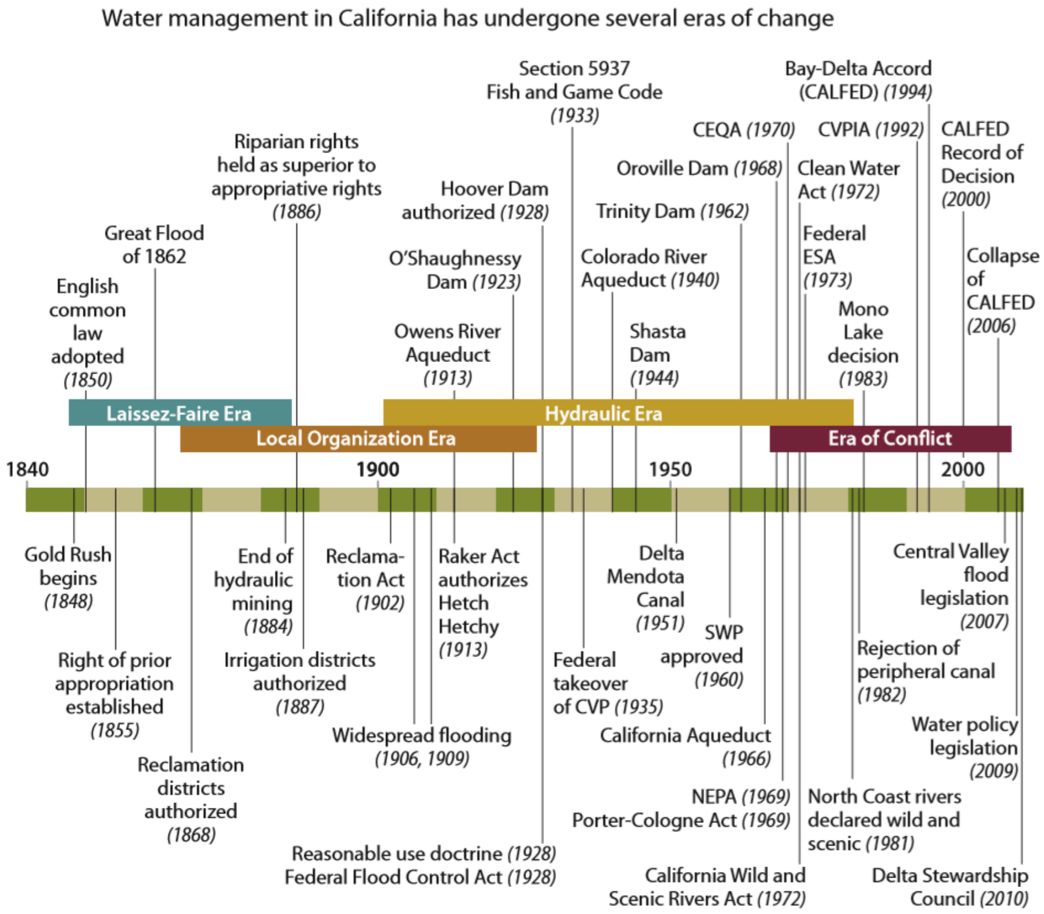

Figure 4 – A timeline showing the history of water management and regulation in California. (Source: Managing California's Water, From Conflict to Reconciliation, PPIC. Figure 1.1, page 26).

CHAPTER 6. CASE STUDIES

The main objective of the case studies are to develop an understanding of water resources management in select drought prone areas (California, Chile, and Australia). With this end, the water resources management structures are explored through evaluation of lessons learned, applicability to other regions, and identification of changes in the market design to insure a socially efficient water allocation. A comparison of these areas to the California system is provided in Chapter 7.

CALIFORNIA

With nearly 40 million people, the state of California is the most populated State in the United States. Approximately 19 million people live in Southern California, 10 million of which live in Los Angeles County. California is the third largest state in the United States, after Alaska and Texas, and yet, according to census data provided by the U.S. Census Bureau, in 2017 there were nearly twice as many citizens living in California than in Alaska and Texas, combined (US Census Bureau).

California is one of the most hydrologically altered landmasses on the planet and boasts more irrigated acreage than any other state. While 75 percent of California's available water is located in the northern third of the state, 80 percent of the urban and agricultural demand is in the southern two-thirds of the state. The vast state experiences a variety of climate types and a strong precipitation gradient (higher annual precipitation in the north, lower precipitation in the south). California's climate is identified as a Mediterranean climate which exhibits warm, dry summers, and mild, wet winters. "Significant precipitation occurs only during the winter, with more than half of the state's annual precipitation delivered in a handful of large storms from December through March. Year-to-year variations in streamflow are also large, with annual totals ranging from less than 25 percent of average to more than 200 percent of average over the past century." (Hanak et al., 2011).

Water in California is shared across three main sectors: Agriculture (40%), Environmental (50%), and Urban (10%) (Escriva-Bou, McCann, Hanak, Lund, & Gray, 2016). The Environmental sector includes "wild and scenic" protected rivers, water designated to habitat and to maintain stream flow, preserve areas (i.e. wetlands), and water needed to maintain water quality. The agricultural sector in California incorporates approximately nine million acres or irrigated farmland. According to the Public Policy Institute of California (PPIC), although farm production generated 60% more gross state product in 2014 than observed in 1980, the agricultural economy represents only 2% of California's gross state product (Mount & Hanak, 2016).

Urban water use includes residential, commercial, and industrial end-users. Information provided by the PPIC indicates that urban water use has reduced in recent years, even as the population has grown. For example, residential water use declined from 232 gallons per day per capita in 1995 to 178 gallons per day in 2010. Water use continued to decline at the onset of the 2012-2014 drought, and by 2015 water use was 130 gallons per day per capita. The reduction in use was likely spurred by various conservation campaigns and excessive use penalty schemes put in place by municipalities in order to comply with water use limitations set by the State. Municipalities achieved these declines through use of pricing incentives and initiating mandatory installation of water-saving technologies like low-flow toilets and shower heads (Mount & Hanak, 2016).

A significant challenge to water management on a large scale is the potential for unintended consequences. For example, during the 2012-2014 California drought water conservation was encouraged and deliveries were limited which resulted in changes in behavior on the part of stakeholders. In some areas of the state the agricultural sector and municipalities turned to groundwater sources to supplement state-operated surface water deliveries. This resulted in the depletion of groundwater aquifers, which caused other environmental issues such as land subsidence and increased salinity in freshwater sources. This also created a competitive "race to the bottom" attitude in the agricultural sector, in which large-scale farming industry was able to outcompete smaller family farms by installing wells deeper than small-scale farming could afford. The State addressed the domino effect by considering regulating groundwater; something that has never been attempted in California's history (Carlton, 2014).

In another example of unintended consequences, the construction of extensive water infrastructure "transformed the state into one of the world's leading agricultural producers, the most populated state in the country, and the eighth largest economy in the world" (Austin, 2015); however, that transformation allowed California to take larger quantities of water from the source. The Colorado River is one of the main sources of water in California. At one time, the Colorado River flowed from the Rockies to the Sea of Cortez in Mexico. This vast river supports people and agriculture in seven states and Mexico. By the time the Colorado River water has reached Mexico, 90% of the water has been captured. The Morelos dam is the final diversion on the Colorado River, at the United States-Mexico border. The delta where the Colorado River met the Sea of Cortez was once a vibrant wetland that hosted a variety of plant, bird, and marine life, and one of the largest estuaries in North America. Between the late-1990s and 2014, the river did not reach the sea. As the Colorado River reaches towards the Sea of Cortez, the river narrows, becomes increasingly shallow, and ends more than 100 miles from the sea (Postel, 2014).

The degradation observed in the Colorado River Delta was an example of unintended consequences. However, with every problem comes a unique challenge. In 2014, The Nature Conservancy, along with a variety of other organizations, the United States government, and Mexico, rose to the challenge. The group forged a binational agreement to restore Colorado river water to the delta. Water managers in the United States began releasing a pulse of water from the upriver Glen Canyon Dam to mimic natural floods in the spring. The sudden surge of water began to flush out sediment resulting in the return of a variety of river habitat that had not been seen since the dam was constructed (Postel, 2014). By 2015, the delta had been saturated with water from the Colorado River. The annual pulse of water flowing from the Morenos dam to the Colorado River allowed the Colorado River to connect to the sea (Gaynor, 2015).

Although drought is part of the natural ecosystem in California, drought conditions in California have been increasing in severity over the past few decades. In an article published in Geophysical Research Letters, An AGU Journal titled How unusual is the 2012-2014 California drought?, published December 28, 2014, the authors used paleoclimate reconstructions of drought and precipitation in California to identify if the severity of the recent drought was an unusual event. According to the article, the drought experienced in California between 2012 and 2014 was "exceptionally severe in the context of at least the last millennium and [was] driven by reduced though not unprecedented precipitation and record high temperatures" (Griffin & Anchukaitis, 2014).

According to the National Oceanic and Atmospheric Administration (NOAA) Climate Division data, November through April winter precipitation season in 2013/2014 was the sixth driest for the state of California as a whole that has occurred since records begin in 1895. It has been theorized that water management activities in California have resulted in intensifying drought conditions. A recent study found that "there is more than 50% chance that the probability of occurrence of an extreme 2014 magnitude drought event was at least doubled under the influence of human activities compared to natural variability" (He, et al., 2017). If this theory is accurate, it is vital that water managers employ a method of water management that encourages water conservation and provides flexibility during times of limited availability, such as water markets.

Currently, water rights trading in California has been limited. Participants in the market can buy and trade water through short-term leases and permanent sales of their water rights. Unfortunately, participation in the California water market is low as the process can be slow and inefficient. Various legislation create obstacles to transferring water making completion of a water transaction too slow for farmers to participate. However, a well-functioning market could "make better use of existing storage, provide an alternative to additional storage construction, and reduce the supply risks inherent in the California water system" (Hansen, Howitt, & WIlliams, 2008). A recent report published by PPIC has proposed reforms including California streamline the water rights administration, establish environmental water budgets, and facilitate regional water sharing programs (Gray, et al., 2015).

Several municipalities have begun to develop their own water policy in the face of climate change. The Los Angeles metropolitan area, for example, includes over 400 drinking water systems that serve approximately 19 million people. The severity of the recent drought has highlighted the fact that Los Angeles does not have access to a local water source, instead relying on imported water. The City of Los Angeles has developed a plan (One Water LA) intended to manage limited water resources, stave off the impacts of climate change, and slash the city's purchases of imported water by 50% by 2024. The One Water LA Plan encourages integration among several different water agencies and other stakeholders, thereby diminishing fragmentation that so typically plagues water management structure (The Planning Report, 2017).

At the State level, the need to secure enough water is a never-ending struggle. In the early 1980s, when Jerry Brown was Governor of California, he supported a water infrastructure tunnel project (Peripheral Canal) which ultimately did not gain voter support. Today, Governor Brown has championed a similar project, the Bay Delta Conservation Plan, now called the Water Fix and Eco Restore project, or Water Fix. The Water Fix project involves building two 35-mile long tunnels that will transport water from the Sacramento River to the California Aqueduct to provide water to the Southern California region. The following six agencies would be responsible for funding the project: Santa Clara Valley Water District, San Joaquin River Exchange Contractors Water Authority, San Luis & Delta-Mendota Water Authority, Kern County Water Agency, Westlands Water District, and the Metropolitan Water District of Southern

California. On April 10, 2018 the Metropolitan Water District voted to provide billions of dollars in additional financing necessary to allow for the construction of the Water Fix project. The project still faces opposition, and will likely see protests and lawsuits before it gets off the ground; however, according to Lisa Lien-Mager of the California Natural Resources Agency, Californians "understand the need to upgrade water infrastructure in the Delta, and they are right to make the connection between water supply reliability and the state's economy and quality of life" (Kukulich, 2018).

CHILE

In 2015, WRI ranked Chile number 24 in the top 33 water stressed countries by 2040 (Luo, et al., 2015). Chile is a long and narrow country with climatic landscapes that vary significantly. The northern portion of Chile is occupied by a portion of the Atacama Desert, the driest desert in the world. The central region contains the Andes mountain range and experiences a mainly Mediterranean climate. The southern portion of the country exhibits both temperate and wet weather punctuated by cool arctic air coming from the Tierra del Fuego and Patagonia region to the south. Rainfall is the main source of water in Chile. The central and southern regions experience the majority of rain events.

Since 2010, Chile has experienced one of the most severe droughts on record, which became known throughout the Country as a mega-drought. According to a recent study, the mega-drought has proven to be one of the warmest six year periods on record, has caused a substantial decrease in vegetation productivity in parts of the Country, and contributed to complex changes in vegetation (Garreaud, et al., 2017). Intense drought lasting one or two years are common; however, the longevity of the current drought has prompted regulators to adopt new water conservation policies. The Chilean government has introduced a variety of measures for water conservation, fire prevention, and education. In addition, investment in renewable sources such as solar and wind power are expected to generate at least 80 percent of the Country's energy by 2050 (Reeves, 2017).

The agricultural industry receives the majority of water resources in Chile (AQUASTAT, 2018), indicating that managing water in this country is strongly dependent on cooperation from one main sector. According to the World Bank, water withdrawals in Chile average approximately 4,000 cubic meters per second per year (Donoso, 2015).

The first documented water use regulations in Chile took place in 1855 when the State Civil Code granted licenses to private parties for exclusive use. In 1931 the General Director of Drinking Water and Sewage within the Ministry of Interior was created (Ferro, 2016). The 1951 Water Code was developed to provide a system of water rights administration where the government grants provisional water rights that become protected property rights after use. To continue the planning and repair of waterways throughout Chile, the Director of Waterworks was established in 1953. In 1967, the 1951 Water Code was amended with the intention of empowering private landowners to receive water. The 1967 Water Code attempted to redistribute water to reform the previous agrarian policy. Government control of water was strengthened through the 1967 amendments and land and water rights were reallocated without compensation to previous holders.

In 1973, the Chilean president, Salvador Allende and his government was overthrown in a military coup d'état and General Agusto Pinochet assumed power as President. Pinochet's government created a new constitution for the country and began adopting free-market economic policies which led to the development of the 1981 Water Code. “It was a period charged with strongly ideological viewpoints, when the military junta and their civilian advisers sought to lock in and institutionalize the dramatic social, economic, and political changes that the government had imposed (Bauer, 1998a)” (Bauer, Water Conflicts and Entrenched Governance Problems in Chile's Market Model, 2015).

Water supply and sanitation services in Chile's urban areas is provided by 53 entities. To prevent monopolization, the providers were classified into three categories according to the percentage of the population served by them, as illustrated in Table 1 below. No person or society is allowed to possess more than 49% of the companies within one category; however, there are only two companies that are categorized as bigger companies that serve half of the total population. (WIkipedia, 2018).

Table 1: Categories of Water Companies in Chile

Category	Criterion	Number of companies	Total category share of population
Bigger companies	Serve more than 15% of total population	2	50.5%
Medium-sized companies	Serve between 4 and 15% of total population	6	34.3%
Smaller companies	Serve less than 4% of total population	45	15.2%

The three largest companies, which serve 63% of urban water customers in Chile are:

- Aguas Andinas – serves the city of Santiago. Aguas Andinas is majority-owned by the Spanish company Aguas de Barcelona;

- Empresa de Servicios Sanitarios del Bio-Bío (ESSBIO) – serves regions around the city of Concepción. ESSBIO is majority-owned by the Latin American Investment Fund Southern Cross; and

- The Empresa Sanitaria de Valparaíso (ESVAL) – serves the Valparaíso Region and is owned by various institutional investors.

The 1981 Water Code (or the Code) established a framework of power sharing and divided responsibility for the allocation and management of water resources. The Code became known internationally as the 'Chilean Model' where free-market forces and water markets are used to reallocate water creating high-value usage. Before 1980, command and control methods of water management had failed to effectively allocate resources and capture economic gain. By securing private property rights, the 1981 Water Code encouraged private investment in water use and infrastructure, as evidenced by the above outlined ownership structure of the country's water service provider. These changes opened up other investment opportunities such as new mining in Northern Chile and planting of high-value agricultural products for export. The ability to trade water rights allowed the reallocation of water resources from low- to high-value use where transaction costs are low and water is scarce.

Trading water rights in Chile is implemented where plans, regulation, and promotion for the appropriate use of all water are directed through the government, and private stakeholders have the power to invest in both domestic and agricultural water uses and water system maintenance. The private sector may also play a role in management of water supply and sanitation. The Water Directorate, under the Ministry of Public Works, carries out all monitoring and research with respect to water supply, and is authorized to grant water use rights. The Water Cadastre, under the Water Directorate, records all water rights and transactions. In 1988 the Chilean government reorganized the water sector under 13 state-owned regional water companies. Privatization of these companies began in 1998 (Bitrán & Valenzuela, 2003) and resulted in an increase in private participation in the provision of water rights from 5% in 1999 to 95.5% in 2013 (Donoso, 2015).

The Chilean water market has received wide attention globally, even though market reallocation of water has not been common throughout the entire country. Active trading occurs mainly in areas where water is scarce and therefore has a high economic value, and the most active traders are mainly real estate developers and water companies. Pricing of water varies depending on availability. For example, water prices in the arid north are greater than in the south. The use of water markets in Chile has led to significant increases in the adoption of water conservation technologies and increased efficiency levels throughout the hydrological system (Donoso, 2015).

AUSTRALIA

One of the most arid countries in the world, Australia occupies 5.6% of the world's landmass, and receives just over 1% of the world's available fresh water sources. Australia experiences tropical climate with hot and humid summers and warm, dry winters in the northern portion; and cooler mild summers with cool, rainy winters in the southern portions. The majority of the population, agriculture and industry are in the south, while more the half of water run-off occurs in the north. Approximately 10% of annual rainfall reaches surface water bodies and groundwater aquifers. The Murray-Darling Basin is the largest system of rivers in Australia, serves half of the country's agricultural production, and provides water for most of the country's extractions (Lehane, 2014).

European settlement in Australia in the late 1700s ushered in the first water resource policies, which were focused on exploitation of water resources for economic and population growth. In 1886, legislature established State ownership of streams which were administered through State controlled water agencies, and a system of administrative allocation of water rights was instituted. What followed was years of development of supply infrastructure by government agencies. It was not until the 1980s when Australian water managers began to look towards alternatives to large infrastructure projects to solve water issues.

In the 1980s, water trading was introduced in Australia. Since that time, water markets have been expanded and developed based on the premise that trading provides economic and environmental benefits through reallocation of water in times of scarcity to higher valued uses. Utilizing water markets is especially prevalent in the southern Murray-Darling Basin (MDB). In the 1990s, the cost of water was steadily increasing as water resources were exploited and water infrastructure was aging, leading to numerous conflicts. Water authorities needed to find a way to quell the conflicts and meet the demands of the various environmental, economic, or social stakeholders (Tisdalle, Ward, & Grudzinski, 2002).

Through the 1990s, as water trading became more prevalent, it became a key instrument in managing water in the MDB. Over time, region by region, Australia has developed and implemented “the world’s only large-scale system of water trading” (Maddocks, Circle of Blue Water News, 2013).

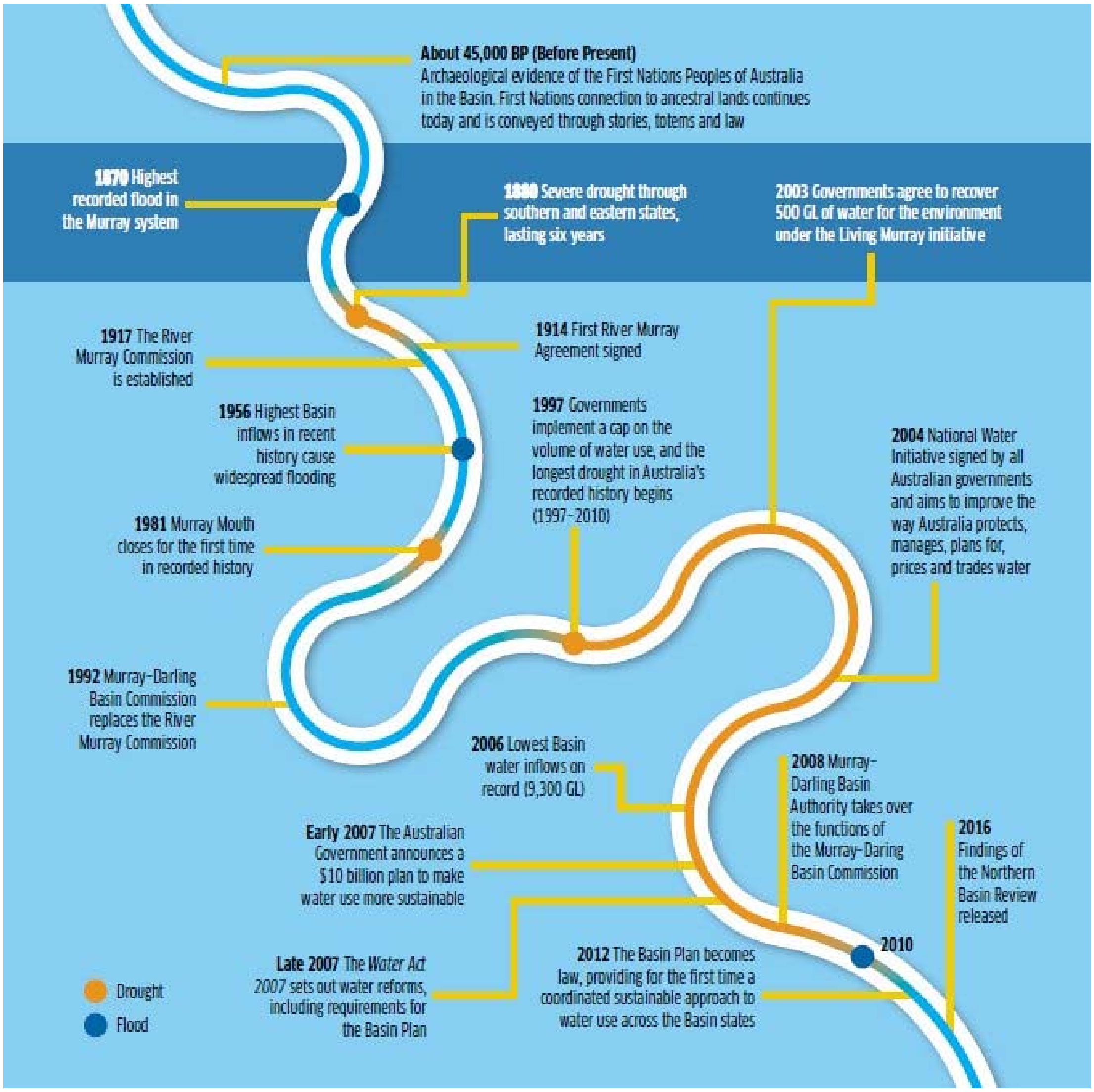

Figure 5 - The MDB has undergone extensive water management changes between the late 1800s and present day.

(Source: Murray-Darling Basin Authority: Basin Plan annual report 2015-16 (Murray-Darling Basin Authority, 2016).

Between 1997 and 2009 Australia experienced a significant drought, which was dubbed the Millennium Drought, and has been described as the worst drought on record for southeast Australia (van Dijk A. I., et al., 2013). This drought had significant impacts on the Country's environment and economy. Areas that suffered the most significant impacts included "river ecosystems and irrigated and dryland agriculture in Victoria and the Murray-Darling Basin (MDB), Australia's largest river system" (van Dijk A. I., et al., 2013). Small farms went out of business while midsized farms suffered significant losses. In addition to the direct costs associated with the drought (i.e. increased water prices, loss of agricultural product), the drought had indirect costs such as an increase in electricity prices and wildfire events in 2003 and 2009.

Following the end of drought, agricultural production returned to pre-drought trends fairly quickly. This quick recovery has been attributed to several reforms that regulators had put in place. Most notably, "(i) well-developed water market that allowed water trade to farmers in the greatest need; (ii) modernization of irrigation infrastructure that increased the efficiency of water delivery; and (iii) establishment of clear water entitlements for the environment that protected critical refuge habitats and populations as water availability declined" (Aghakouchak, et al., Australia's Drought: Lessons for California, 2014). Australia invested in infrastructure projects such as desalination and water recycling plants. Regulators also instigated a number of water conservation use restrictions including bans of certain activities (i.e. daytime car washing or landacape sprinkler use) and required installation of shutoff valves on hoses (Aghakouchak, et al., Australia's Drought: Lessons for California, 2014).

According to Aghakouchak et al., "The use of water markets was particularly critical. More than 40% of annual water allocations were traded at the height of the drought in 2007. For example, increased water prices allowed dairy farmers to sell their allocation and purchase fodder with the proceeds rather than irrigate pasture. Fruit growers and other producers who needed to maintain irrigation throughout the drought could purchase the dairy farmers' water to keep their operations viable" (Aghakouchak, et al., Australia's Drought: Lessons for California, 2014).

Water rights need to be established before water can be priced. The Australian system of tradeable water rights has been a leading example water market. When the market was established, old rights (typically belonging to landowners) were replaced with shares. The shares granted a portion of annual allocations, which meant that the source was considered finite and the only way to increase quantity of water was to purchase shares. This market structure resulted in emergence of two markets: "one in which seasonal allocations of available water can be traded, and another in which shares themselves can be" (Water - The dry facts, 2016). The Australian water market was estimated to be worth approximately USD$26 billion in 2013 (Maddocks, Circle of Blue Water News, 2013) with an average allocation price of around AUS$25 per megaliter between 2012-13 and 2013-14 (Murray-Darling Basin Authority, 2016).

Several trading platforms currently exist in Australia. One notable platform, Waterfind, provides online, up to date, accurate opportunities for temporary and permanent water trades. Trading platforms such as Waterfind allow a user to access the market at any time, 24 hours a day/seven days a week. The sale and purchase of parcels of water can be made through online orders in Waterfind’s system, and all trades can be tracked at each stage of the transfer process (Waterfind, 2018).

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

The Chilean and Australian models are examples of how development of an urban water market can be an innovative way to encourage more sustainable and equitable water management. In contrast, the California model is poorly administered and inefficient. California experiences climatic variations, water scarcity, and population demographics that are similar to Chile and Australia, indicating that a water market structured similarly as these countries might be successful in California. Further, California has the necessary infrastructure already in place and enjoys a stable socio-political structure, with citizens who value the environment, and regulators with an understanding of the connectivity and function of the California waterscape. As has been seen in Australia, sustainable use of water resources provides the foundation for quick recovery following drought. In addition, a water market could stabilize water pricing, which is currently wildly geographically variable. It is estimated that in the face of climate change, drought events in California will be longer and drier than previously experienced. An overhaul of the current California water market, and development of a trading platform similar to those used in Australia and Chile, would promote sustainable use of the state's water resources, encourage balanced water rates to end uses, and incentivize investment in both the environment and infrastructure.

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