Kurt Schwabe · José Albiac
Jeffery D. Connor · Rashid M. Hassan
Liliana Meza González *Editors*

Drought in Arid and Semi-Arid Regions

A Multi-Disciplinary and Cross-Country Perspective

Springer

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Foreword

Drought is often, for a variety of reasons, largely disregarded among the wide range of natural disasters that routinely affect societies in substantive ways. Because of its creeping or slow onset nature, its impacts accumulate over a long period of time; consequently, it is difficult to recognize both the onset and end of the event. In addition to being difficult to recognize, it also appears difficult to define as there is no universal definition of drought. Drought is best defined by region and impact sector. Literally, hundreds of definitions exist, often resulting in confusion as to whether or not a drought exists and its severity. This feature of drought sometimes leads to inaction on the part of government authorities, managers, and others. To complicate matters further, each drought episode also differs from all previous events in its intensity, duration, and spatial extent, and because of its long duration, droughts usually have multiple and migrating epicenters.

Impacts associated with drought are non-structural and, therefore, do not catch the imagination of the media and policy makers until those impacts reach devastating proportions, as we have seen in recent years in many countries throughout the world, including recent droughts in the Greater Horn of Africa, China, Southern Africa, and the United States. This is one reason why drought is referred to by many as an invisible natural hazard. Yet, drought affects more people globally than any other natural hazard and results in far-reaching and massive economic, social, and environmental impacts. Societal vulnerability to drought is constantly changing in response to increasing population, regional shifts of population, changes in land use, urbanization, applications of new technology, and many other factors. The projected increase in the frequency and severity of extreme climatic events, such as drought, will also exacerbate impacts. Because drought is a slow onset phenomenon with cumulative impacts, any increase in the duration of drought episodes will also affect the ability of society to recover since the time between events will be shortened.

The impacts of drought differ markedly between countries and even within countries because of the differing physical characteristics of drought and the societal context in which these events occur. People most closely associate the impacts of drought with the agricultural sector because of its direct effects on water availability and food production. Certainly, the agricultural sector remains one of the most vulnerable to an extended period of precipitation deficiency.

However, the impact of droughts today is more complex and often affects many other sectors. Most notable are impacts on transportation, energy production, tourism and recreation, ecosystem services, and health, as well as broader environmental and social impacts. Since the mid-1980s, the losses associated with drought in the United States have exceeded all other natural hazards, with the exception of hurricanes, whose primary impacts have occurred outside the agriculture sector.

The stated goal of this book, *Drought in Arid and Semi-Arid Environments: A Multi-Disciplinary and Cross-Country Perspective*, is to provide a synthesis of how scientists, water managers, and policy makers have managed drought and water scarcity, with particular reference to arid and semi-arid regions. The countries chosen for this comparative approach are Spain, Mexico, Australia, South Africa, and the United States. In my opinion, each of these countries present a clear opportunity to characterize the diverse array of approaches to drought management that illuminate the wide range of monitoring, early warning, impact assessment, mitigation, planning, and policy choices available to decision makers at all levels. The book provides a new and multidimensional assessment of drought and water scarcity and explores the many faces of drought in these diverse geographical settings. These case studies were initially captured at an International Drought Symposium held at the University of California, Riverside in 2010. Each of the chapters included in the book provides readers with a case study from which to extract valuable lessons that can be applied by many countries and adapted to their unique physical, social, institutional, and political settings. The book's editors are to be commended for their effort to assemble such a broad and rich perspective on such a timely and highly relevant topic.

Donald A. Wilhite, Director
School of Natural Resources
University of Nebraska-Lincoln

Preface

The goal of this book is to provide a synthesis of how scientists, water managers, and policy makers have considered drought and water scarcity in Spain, Mexico, Australia, South Africa, and the United States with attention to these countries arid and semiarid regions. A cross-country exposé for understanding the various elements of drought and drought management is a much more expedient approach to understanding the relative merits of various approaches to address drought and water scarcity than waiting for each country to explore such options over an extended and uncertain time horizon and drawing conclusions from those experiences. In addition to providing a cross-country description and comparison of drought awareness and experience, this book will also provide an assessment of drought from the perspective of multiple disciplines. To wit, efforts to efficiently mitigate and/or cope with the effects of drought requires an understanding of the biophysical aspects of drought, including the hydrologic and ecologic elements, as well as the technical, economic, and policy aspects. Hence, researchers from multiple disciplines within these countries, including disciplines such as agronomy, ecology, economics, hydrology, and irrigation technology, provided an assessment of drought experiences from their particular disciplinary perspective. Additionally, water manager and policy makers from each of these countries provided background and the current status of drought policy within their own country.

Each of the main sections in the book is discipline specific and provides the reader with an in-depth understanding of particular drought experiences, knowledge bases, and approaches to modeling drought from multiple countries. Together, these separate sections offer the reader with a better understanding of how to approach drought from a multidisciplinary perspective. The final chapter provides an in-depth comparison of drought experiences, descriptions, and approaches within each discipline by experts within each discipline. As such, after reading this book an interested reader should be able to identify both the successful and problematic approaches used to cope with various aspects of the droughts. Such an outcome should prove useful to researchers, practitioners, water managers, and policy makers who are looking to improve their baseline understanding of drought from different disciplines and levels of management. Furthermore, highlighting and identifying the different approaches and experiences from various integral disciplines across a multitude of countries should go a long way at improving our fundamental understanding of the interactions between physical impacts of drought and the effectiveness of mitigation policies on the economic consequences of droughts. Finally, a comparison of alternative policy outcomes and the evaluation of particular policy approaches from one country to another will enhance our understanding of how physical, institutional, and economic factors impact the effectiveness of one policy instrument relative to another.

The genesis of this book was developed on the heels of a symposium titled, "International Drought Symposium: Integrating Science and Policy" that took place on March 24–26, 2010 in Riverside, California (http://cnas.ucr.edu/drought-symposium/). The symposium, which was organized by the Water Science and Policy Center at the University of California, Riverside, brought together senior disciplinary experts from Spain, Australia, South Africa, Mexico, and California—all drought-prone areas—to sit together and share scientific and policy aspects related to drought and its mitigation in each of these areas. Most, but not all, of the initial drafts of these chapters were submitted to, and presented at, this symposium.

While there are many people and organizations that provided support in one way or another for this book and for which we are thankful, we want to begin by thanking Springer Press, and in particular the editors we interacted with directly—Fritz Schmuhl and Takeesha Moerland-Torpey—for their support and patience. We are especially grateful to Dr. Ariel Dinar, Professor and Director of the Water Science and Policy Center at the University of California, Riverside for bringing this group of scholars, water managers, and policy makers together and providing the platform and encouragement for this book. Without Ariel's support, this book would have never materialized. We have benefited greatly from numerous reviewers who provided critical and constructive comments during the review process in which all of the chapters were sent out to independent scholars. Special thanks go to these scholars, including Ken Baerenklau, Khaled Bali, Richard Clark, David Cresswell, Randy Dahlgren, Edwin Fagin, Theodor Geisel, Steve Grattan, Jonathon D. Kaplan, Nelson Lourenco, Siwa Msangi, Alfredo Ollero, Manuel Omedas, Andres Sahuquillo, Donald Suarez, Frank Ward, John Ward, and Santhi Wicks. Additionally, we are thankful to Marti Childs (EditPros LLC) for her extremely adept copy editing skills that allowed her to take chapters from five different countries and umpteen different formats and make sense of them all. The completion of this book was greatly facilitated by input and editing from Carol O'Brien, administrative assistant at the Water Science and Policy Center, University of California, Riverside.

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Jeffery D. Connor is a Senior Research Scientist in environmental economics with the CSIRO Ecosystem Sciences research group where he has previously held several research group management positions. Jeffery received Master's and Ph.D. degrees in Environmental and Resource Economics from Oregon State University. His research interests are in the areas of integrated biophysical—economics modeling for basin and catchment scale water policy analysis; the economics of water allocation, water quality, and salinity; the economics of land use change, the economics of land-based carbon sequestration; and evaluation and design of market-based policy for natural resource management. He has extensive experience advising international, Australian Commonwealth, state, and local water management agencies on water resource policy and economics. Jeffery is the author of more than 30 peer reviewed journal articles and book chapters.

Rashid Hassan is Professor and Director of the Centre for Environmental Economics and Policy in Africa (CEEPA), Faculty of Natural and Agricultural Sciences, University of Pretoria. He has wide international experience through his past and present involvement in international research organizations such as CIMMYT, Rockefeller Foundation, CGIAR Climate Change Challenge Program (CCCP), External Academic Advisory Panel for the World Development Report 2009 on Climate Change, World Bank, Steering Committee of the African Centre for Climate and Earth Stewardship Science-ACCESS, Stockholm Resilience Centre Board of Directors, GEF Science and Technical Advisory Panel-STAP IV, Science Panel of the Millennium Ecosystem Assessment; Member of the Science Council for the Consultative Group on International Agricultural Research

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Liliana Meza-González is a Research Fellow at the Program of Migration Issues at the Universidad Iberoamericana in Mexico City. She graduated with honors with a B.S. and an M.Sc. in Economics from the Instituto Tecnológico Autónomo de México (ITAM). She received an M.A and Ph.D. in Labor Economics from the University of Houston. Dr. Meza has published over 20 articles in specialized journals and has authored two books and coauthored five more on the subject of migration and labor economics. She has been invited as a speaker to several academic events in Mexico and other Latin American countries, as well as in the U.S. and Europe. She has been an invited scholar at American University and at Georgetown University, and has been a consultant to the World Bank and the Interamerican Development Bank. In 2005, she was appointed as Coordinator of the Program of Migration Issues at the Universidad Iberoamericana, and in 2007 was invited to collaborate with President Felipe Calderón as Technical Secretary of the Social Cabinet.

Kurt A. Schwabe serves as Associate Professor of Environmental Economics and Policy and Associate Director of the Water Science and Policy Center at the University of California, Riverside. His research specialization includes water economics, alternative policy instruments for pollution control, salinity and drainage management and policy, wildlife and fisheries management, and valuing ecosystem and forest services. His honors and awards include: the Flagship Fellowship (Australia's Commonwealth Scientific and Industrial Research Organization) to help address the salinity and drainage issues related to Australia's irrigated agricultural production; the Outstanding Journal Article Award of 2002 (*Journal of Agricultural and Resource Economics*); Editor's Citation for Excellence in Manuscript Review 2002 (*Journal of Environmental Quality*); Best Teaching Practices Award Recipient (Center for Teaching Excellence, Ohio University, 1998); and the Kenneth R. Keller Research Award for Excellence in Doctoral Research (North Carolina State University, 1996). He received a B.A. in Mathematics/Economics from Macalester College, M.S. in Economics from Duke University, and a Ph.D. in Economics from North Carolina State University.

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Chapter 1
Introduction

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Abstract Semi-arid and arid regions worldwide regularly confront drought. Some of the potentially significant and far reaching consequences of drought include impacts on: poverty rates, health, ecosystem services, land sustainability, and economic development. Unfortunately, recent climate change models predict that over the next 40 years, semi-arid and arid regions worldwide will experience an increase in the severity and intensity of drought as these regions encounter more aridity and less precipitation. The objective of this chapter is to introduce the issues that drought present in semi-arid and arid environments. We summarize our understanding of drought and its significant costs, as well as experience from managing and/or responding to drought from scientists, water managers, and policy makers across five countries—Australia, the United States, Mexico, South Africa, and Spain. The chapter provides a synopsis of arguments detailed in later

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chapters that explain how better understanding of drought indicators and experiences in management can reduce the cost of mitigation and adaptation.

1.1 Drought

Most populated regions, especially in arid and semi-arid environments, are experiencing substantial conflicts over freshwater resources as governments try to meet agricultural and urban water demands and leave flows for the environment (UNEP 1999). And while the global supply of freshwater resources has been nearly constant for the last 2,000 years (Hinrichsen et al. 1998), recent predictions from climate change models suggest less precipitation and hence further reductions in freshwater supplies in many of the already water-stressed semi-arid and arid regions worldwide, including parts of the Europe, Africa, Australia, and western United States (Shindell et al. 2006; Seager et al. 2007). These losses in freshwater supplies, coupled with increases in demand due to increased population growth that averages nearly one billion people per decade, portends unprecedented levels of water scarcity; consequently, how to allocate water among agricultural, urban, and environmental interests will be a challenging problem with global implications.

Historically, popular responses to water scarcity and drought have included conveying water from less-populated yet water-rich areas to more-populated yet water-poor regions, and storing water during non-drought periods in dams to be used during drought years. As Fig. 1.1 shows, the number of dams commissioned throughout the 20th century increased dramatically up until the 1980s. The

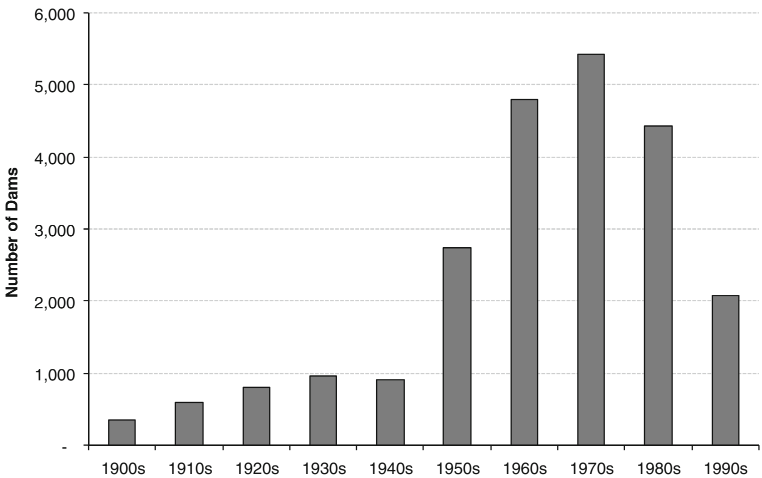

Fig. 1.1 Commissioning of large dams globally from 1900 to 2000. (adapted from Table 15, World's Water 2002–2003 data, Gleick 2011)

precipitous decrease in the number of new dams commissioned since the 1980s, though, is likely due to a number of factors, including, possibly, a public that is both more aware of the impacts of dams on the environment and better at communicating such awareness to its public officials, and fewer opportunities for low-cost river diversions to develop such storage. Another response has been to utilize available groundwater. This often unregulated open-access resource has been exploited to the point where most large aquifers worldwide are confronting extraction rates in excess of their recharge rates. For example, the Ogallala Aquifer in the central US, an aquifer that supports 1/5th of the irrigated acreage in the US, has an average area-weighted recharge rate of approximately 22 mm/year while the drawdown due to pumping for urban and agricultural uses is approximately 55 mm/year (McGuire 2007).

Reliance on large-scale engineering solutions or groundwater extraction, then, would seem to provide at best a partial fix to mitigating and coping with future drought events, especially if freshwater consumption rates continue to outpace population at growth rates similar to those experienced in the 1990s.[1] While there have been significant gains in water use efficiency from the largest demander of water supplies, irrigated agriculture, further gain in this direction is at best a partial fix given that overall consumption continues to rise and outpace supplies. Hence, continued water scarcity, and in particular drought, continually linger as a potentially severe stressor on economic development, agricultural production, and ecological sustainability. Such stress is compounded in arid and semi-arid regions where precipitation is often trumped by evapotranspiration. Spain, Australia, South Africa, Mexico, and the United States, for example, all contain regions experiencing periodic drought stress, which is not surprising given their similar climatic and physical conditions. Unfortunately, current and future availability of surface and groundwater resources in these regions are threatened not only by water scarcity arising from excess demand, but also by pollution and salinization, which are partly a consequence of the excess demand. With the looming threat of climate change and its expected impacts on water supplies, the frequency and severity of water shortages in these regions will likely increase in the future; impacts will be pervasive across natural, economic, cultural, and political systems.

The goal of this book is to provide insight and examples of how scientists, water managers, and policy have considered drought and water scarcity in arid and semi-arid regions of Spain, Mexico, Australia, South Africa, and the United States. These five countries, which contain nearly one-quarter of the irrigated land outside of India, Pakistan, and China (CIA 2008), each deal with their own complicated water issues and recurring droughts using a variety of mechanisms. The effectiveness of each country's approach to drought is likely a function of the bio-physical characteristics of the region, the characteristics of the urban, agricultural,

[1] Global freshwater consumption rose more than six-fold in the 1990 s, twice the rate of population growth, resulting in 1/3rd of the world's population living in countries with moderate to high water stress (UNEP 1999).

and environmental demand for water, as well as the particular array of technical, economic, institutional, and policy-related measures adopted to address not only water scarcity, but also poverty, energy, and land use reform. Formalized cross-country descriptions and experiences with drought from a research, management, and policy perspective are limited, and there is little organized narrative of their successes, failures, and challenges. Our hope is that this cross-country comparison and formalized treatise may help these and other countries with arid and semi-arid regions more expediently identify a larger array of feasible options for addressing drought and their potential consequences. We also aim to highlight and characterize how natural system attributes influence the effectiveness of such options.

In addition to providing a cross-country description of drought experience, this book provides an assessment of drought from multiple disciplines. Researchers from multiple disciplines, including agronomy, ecology, economics, hydrology, and irrigation technology, provide assessments of drought experiences from their own disciplinary perspectives. Additionally, water manager and policy makers from each of the countries represented in the book describe the backdrop and the current status of drought policy within their country or a particular region in their country. The final chapter summarizes the disciplinary-specific lessons to be taken from each section. The book is organized in sections of chapters by disciplinary focus; together, these separate sections provide the reader with a better understanding of how to approach drought from a multidisciplinary perspective. The goal is to allow researchers, practitioners, water managers, and policy makers to identify successful and problematic coping mechanisms for addressing the multifaceted aspects of drought.

The remaining sections of this chapter provide a general summary of drought conditions associated with each of the five countries targeted in this book; country-specific summaries of the chapters also are provided. Table 1.1 lists chapter contributions by discipline and country. As shown, there are seven chapters from Australia, six chapters from the United States, three chapters each from Mexico and South Africa, and six chapters from Spain. Included in Table 1.1 is the particular geographic focus within each country for each chapter. For instance, for the chapters associated with the United States, the geographic focus is primarily California except for Chap. 10 by Jenerette, which addresses ecological issues spanning the southwestern USA. We emphasize that even if the research is focused on a particular geographic area, the lessons, approaches, and issues can be extended to other semi-arid and arid regions suffering drought.

1.2 Australia

Australia is a continent of climatic extremes: it is the driest of all continents excluding the Antarctic, though the north is tropical and experiences extreme floods. Inter annual variation in inflows to Australian rivers is much greater than on any other continent. Droughts in southern Australia are also extreme. South-eastern

Table 1.1 Chapter Contributions by Country and Discipline[a]

Country	Section I agronomy, irrigation technology, and water supply	Section II ecological impacts of drought	Section III hydrology and drought	Section IV economic considerations and drought	Section V water management and policy
Australia	3, 5	12	16	20	24, 26
Geographic focus	Adelaide, Australia; South Australian Riverland	Murray-Darling Basin	Murray-Darling Basin	Murray-Darling Basin	Murray Darling Basin; Australia
United States	2, 7	10	17	19	25
Geographic focus	California	Southwestern USA	California	California	Southern California
Mexico	–	11	15	–	22
Geographic focus	–	Chihuahuan Desert of Northeastern Mexico	San Luis Potosí Basin	–	Mexico
South Africa	8	–	14	21	–
Geographic focus	Free State and Northwest provinces	–	Steenkoppies Dolomitic Aquifer	South Africa	–
Spain	4, 6	9	13	18	23
Geographic focus	Ebro Basin; Valencia Region	Iberian Peninsula	Júcar River Basin	Ebro Basin, Júcar River Basin, Spain	Ebro Basin

[a] Geographic areas in italics indicate specific areas focused on in a chapter; a general focus on the country as a whole is indicated by country name

Australia, especially in Australia's largest river basin the Murray Darling Basin, can experience very protracted droughts (seven to ten or more years in duration). Three such extreme droughts have occurred in the past 120 years. The most recent of these droughts, now known as "the Millennium Drought" (1997–2009) included the three consecutive years of lowest in-flows in the recorded hydrologic history to the Murray Darling Basin. Extreme protracted droughts have historically and continue to challenge Australia to evolve new and innovative ways to manage water resources. There are seven Australian chapters in this volume; all share a unified theme: drought induces innovation in water resource management.

Chapter 16 (Kirby et al.) sets the hydrologic scene for the other Australian chapters by suggesting, based on empirical results, that the severity of this recent drought is not only a result of another period of low rainfall, which has been the driver of previous droughts (e.g., the Federation Drought from 1895 to 1902), but also the result of higher temperatures. These higher temperatures lead to more soil moisture evaporation than in past droughts, thereby exacerbating the reduced runoff impacts from lower rainfall. Kirby et al. also provide insight into the nature of future droughts that could occur in the Murray Darling Basin under climate change, including the possibility of more protracted and frequent droughts. The authors conclude that the severity of the Millennium drought was beyond previous expectations used in river operations and water allocation planning, but that such drought and even more severe drought should be explicitly considered in future water planning.

A theme from Chap. 16—that droughts beyond previous experience are likely in the future and should be planned for—resonates through many of the remaining Australian chapters. Chapter 24 (Dreverman) provides perspective on how the operational managers of the system realized at the peak of the recent drought that existing contingency plans to ensure water for the most critical human needs, based on historically experienced dry periods, were not adequate to deal with the level of drought beyond historical precedent that were experienced in 2006–2009. Dreverman describes ad hoc adaptation, in the short term, at the height of the drought and then describes the challenges in developing a longer term plan that adequately deals with possible future droughts similar to or even more severe than the recent Millennium Drought.

Kendall (Chap. 26) offers a big picture perspective on how major droughts have spurred significant water management policy reforms in Australia. Prior to the Federation Drought (1895–1902), management of the River was a disparate matter of individual States initiatives. The severe Federation drought lead to failures, especially in being able to ship commodities downstream on what was then one of the primary modes of transport for commodities such as wheat and sheep produced in the interior of the Murray Darling Basin. This resulted in the first major agreement between States on River management with provisions to develop and share water for storages and to regulate and operate the river to ensure uninterrupted shipping. The chapter then outlines how nearly a century later the Millennium Drought sparked further major policy reform including a 1994 cap on diversion, the National Water Initiative with incentive money for states to implement wide ranging water policy reforms such as full adjudication of volumetric and monitored water rights, and even more recently the Water Act (2007) giving the Commonwealth authority to set limits on diversion that reduce current taking of water for consumptive purposes such as irrigation in order to enhance environmental flows.

Chapter 5 (Hayman and McCarthy) outlines the ways that irrigation adapted to more severe than anticipated drought and the challenges ahead in further adjustment. A theme in this chapter is the progress toward and further need for development of irrigation management strategies that are resilient in a future with more severe droughts. The chapter focuses on the South Australian Riverland, a region that grows predominantly high value wine and horticultural crops with a historically very reliable water supply for irrigation. Hayman and McCarthy coin the phrase "irrigation drought" in reference to the fact that the recent drought was the first one in history that significantly disrupted irrigation water supply. Indeed, allocations from 2007 to 2009 were in the range of 20–40 % of historic "normal levels." Previously steady irrigation supplies were secured even in the face of varying annual inflows by a system of large dams.

Hayman and McCarthy document greater than expected improvements in irrigation efficiency in response to drought including a doubling of wine yields per mega litre in some cases. The chapter ends with a caution that there may be limits to efficiency as an adaptation strategy for irrigation and that there are trade-offs between efficiency and resilience. This potential is illustrated for the case of wine crops grown with reduced canopy cover. While such production systems can produce high quality crops with significantly less water, in the extreme heat that accompanied the drought such an approach offered little protection against heat damage with some crops faring poorly. Conversely, less efficiently grown crops, with more canopy, proved more resilient.

Chapter 3 (Maier et al.) provides a civil engineering, water resource planning perspective on water supply provision for Adelaide, the largest city in Australia dependent on the River Murray for water supply. The authors outline the historic evolution of water supply infrastructure. They describe how new dams in the local catchment and pipelines from the Murray were built from the beginning of the 20th century through the 1960s each time that growing demand coincided with a dry period. They then describe how in more recent time the cap on withdrawals from the Murray, a lack of well suited local dam sites and increasing scrutiny of dam environmental impacts have led to increasingly energy intensive and expensive infrastructure (e.g., desalinization) as the main engineering options to secure future supply.

Maier et al. conclude with a focus on challenges of future water supply planning with growing demand, possibilities of protracted droughts, and increasing emphasis on energy and greenhouse gas intensive supply options. They demonstrate concepts of risk-based planning, including stochastic shortfall probability and magnitude assessment for decisions to mix multiple supply options to meet supply reliability and greenhouse gas objectives. They present a case study of how risk-based assessment can be used when mixing newer less rain fall dependent sources with more variable traditional rainfed supply sources. Their main conclusion is that increased use of risk-based assessment is both feasible and necessary in municipal industrial water supply drought planning as it provides a systematic understanding of the trade-off in costs, reliability and environmental externalities such as greenhouse gas emissions.

Connor and Kaczan (Chap. 20) outline how water policy reforms through the 1990s established secure, monitored and enforced volumetric water property rights in the Murray Darling Basin. Economists have long argued for such property rights as a prerequisite for flexible and low transaction cost water trading. Yet such clearly defined volumetric water property rights remain an unrealized aspiration in many parts of the world, including countries often seen internationally as advocates of market based resource allocation such as the United States. The Australian experience shows that active water markets can be expected to arise once an adequate property right regime is in place. The chapter reviews the experience with water trade during the recent Millennium Drought documenting how the water market reallocated large volumes of water from lower value irrigation uses such as pasture and grain production to higher value perennial horticulture and wine production. A number of studies assessing the economic benefits of water trading are reviewed with the conclusion that the value of irrigated agricultural production was enhanced as a result of water trade on the order of hundreds of millions of dollars a year during the peak years of the drought. The chapter concludes with a discussion of some remaining challenges in property rights definitions that can both encourage low transactions costs water re-allocation and avoid adverse third party impacts that can arise from water trade.

Overton and Doody (Chap. 12) describe how a trend of growing extractions and very low inflows experienced during the Millennium drought significantly degraded Murray Darling Basin ecosystems. Floodplain forest ecosystems that had survived for centuries, including previous protracted droughts, died off on a scale of hundreds of thousands of hectares. The authors explain the threshold impacts reached through the combined effects of increased extraction and reduced flows resulting in intervals between inundations longer than these unique and highly valued ecosystems could endure. The authors echo the theme in other Australian chapters that new planning paradigms for water resource management will be required to deal with future droughts. They make the point that changes in ecosystem characteristics have already occurred and that return to pre-development ecological conditions, often the benchmark in current environmental flow management thinking, is simply not possible. They conclude that it would be advisable that future environmental flow management strategies begin with a realistic sense of where active floodplains (those likely to receive inundation on frequent enough intervals to ensure ecological functioning) can be maintained in the presence of drought and to identify constraints on the amount of water that we are willing to re-allocate from extractive uses.

One unifying theme of the Australian chapters is that the recent, 12 year long, low inflow period that ran from 1997 to 2009 was beyond previous precedent. This, and the growth in extractions in the decades leading up this dry period, resulted in unexpectedly severe disruptions to consumptive water supply and environmental degradation. All of the Australian chapters discuss aspects of how this has created a need to re-calibrate thinking about drought in water resource planning. Many of the Australian contributions to this book draw attention to the need to plan for future droughts based on assumptions outside of the historical hydrologic experience and the benefit of using systematic risk based approaches. Overall, the Australian contributions to this volume give the impression of a country that recognizes drought as an integral feature of their natural environment which will continue to pose large challenges for environment, food production and municipal industrial water supply. The chapters also demonstrate an ongoing legacy of successfully adapting to drought that many other countries can learn from including a history of substantial policy reforms to limit extractions, to reallocate water to environmental uses, and to create well defined and tradable water property rights.

1.3 California and the Southwestern United States

The southwestern United States consisting of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming continue to experience some the greatest population growth rates in the country.[2] This region also is the most arid within the US, with forecasts that overwhelmingly suggest increased aridity and more intense and frequent drought (Seager et al. 2007). Climate predictions suggest that the region will suffer an average decline in runoff of 15 % between 2021 and 2040 relative to average surface moisture between 1950 and 2000 due to warmer air and less rain (Seager et al. 2007). Consequently, the region is likely to experience greater water scarcity and an increased susceptibility to drought. Water scarcity challenges are likely to be particularly acute in California, a focus for all but one US chapter in this book, as a result of a large and fast growing population and water demand already well in excess of supply in the arid south of the State.

There are six chapters in this volume that focus on drought in the southwestern part of the United States from multiple disciplines, including chapters in the sections *Agronomy, Irrigation Technology, and Water Supply* (Ayres; Hutmacher), *Ecological Impacts of Drought* (Jenerette), *Hydrology and Drought* (Mirchi et al.), *Economic Considerations and Drought* (Medellin et al.), and *Water Management and Policy* (Rossi et al.).

Mirchi et al. (Chap. 17) underscore why a better understanding of drought is crucial. As the authors emphasize, extensive observations and research demonstrate that California's climate is changing, with consequent impacts on

[2] While the average growth rate for the US in the mid 2000s was around 0.9%, the rates of these particular states place them in the top fifteen states in terms of growth rates (with rates at or above 1.1%; US Census Bureau 2011).

California's water resources. For instance, several components of California's hydrologic cycle are likely to be influenced by climate change in ways that lead to scarcer and more variable water supply including (1) reduced snow accumulation and changed melt patterns, (2) reduced precipitation, (3) changed seasonal runoff, (4) increased evapotranspiration, (5) reduced stream flow, and (6) increased stress on groundwater and receiving water bodies. The implications of climate change, as the authors stress, are that California's water management plans need to be revised and updated to better deal with a higher level of water scarcity. One strategy that the authors highlight to better deal with drought is infrastructure improvement, including an obvious need for more water storage and more conveyance to balance supply and demand between the northern and southern regions in California. In the event that the large price tags turn the public sour to the idea of large infrastructure projects, the authors identify potential water saving opportunities that are likely less costly and more flexible, including the conjunctive use of surface and groundwater resources, increased conservation and reuse, ecosystem rehabilitation, and water quality protection, any or all of which might help mitigate the impacts of climate change in California.

One way California and the arid and semi-arid southwest U.S. may respond to drought is to consider how agriculture may be able to get by with less water. The issue and practicality of one strategy to use less water—deficit irrigation—is taken up in detail in Chap. 7. Hutmacher focuses on identifying crop and water management issues that may arise when such a strategy is considered. One conclusion that emerges from Hutmacher's insight and experience is that for deficit irrigation to be a cost-effective response to water shortages, knowledge of the various growth stages of the plant and their relative sensitivities to reduced water applications must be known. Hutmacher discusses experiences with using deficit irrigation on both annual crops and perennial crops, yet emphasizes that there is sparse information on the effects of deficit irrigation on crop production and quality if practiced over many years. Understanding the impacts of deficit irrigation on crop productivity and quality is just one piece of the puzzle, though, as other issues are important, including (1) designing irrigation scheduling to match the temporal sensitivities of the plant while controlling for other factors, (2) considering the physical and chemical properties of soils and how they may respond to deficit irrigation over time, and (3) how to monitor all these factors so growers can make timely decisions based on the characteristics of the plant, soil, climate, and market conditions. Much of this real-time information currently is available to aid growers, i.e., there is easy access to CIMIS reference evapotranspiration (ET_0) and weather data as well as soil and plant-based water status evaluation tools. Yet USDA surveys typically indicate that less than 15 % of growers utilize these tools to make irrigation scheduling decisions (USDA 2003).

In addition to deficit irrigation, there are a number of other on-farm strategies growers may employ to respond to drought. As Ayres identifies in Chap. 2, irrigation efficiency improvements can save water, similar to deficit irrigation, yet the long run sustainability of such practices will depend on how the soil conditions evolve. For example, replacing furrow irrigation with drip irrigation may result in