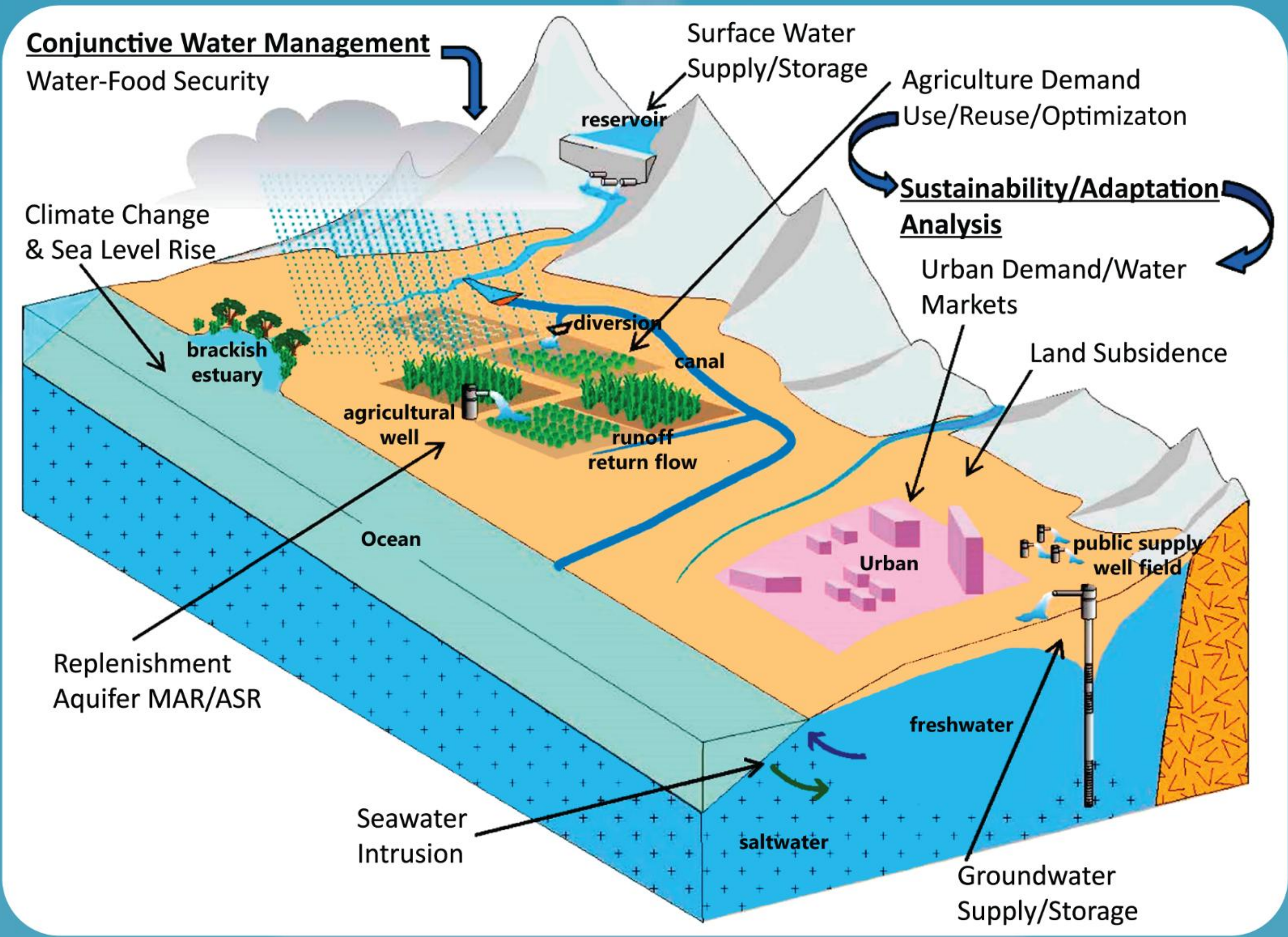

Conjunctive Water Management

Richard S. Evans and Randall T. Hanson

THE GROUNDWATER PROJECT

Conjunctive Water Management

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Thank you.

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Dedication

Richard Evans dedicates this book to his wife, Gillian, for all her support during the development of this book, and his thoughtful colleagues who have inspired him over many years.

Randall Hanson dedicates his contributions in this book to his family (Anne, Tyler, Erika, Lia, Corey, and Cassius), Dr. Scott Boyce (US Geological Survey), the many US Geological Survey and California partners that have forged this path with him, and his Mexico colleagues who have also joined his journey over many years.

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The Groundwater Project Foreword

The United Nations (UN)-Water Summit on Groundwater, held from 7 to 8 December 2022, at the UNESCO headquarters in Paris, France, concluded with a call for governments and other stakeholders to scale up their efforts to better manage groundwater. The intent of the call to action was to inform relevant discussions at the UN 2023 Water Conference held from 22 to 24 March 2023 at the UN headquarters in New York City. One of the required actions is *strengthening human and institutional capacity*, for which groundwater education is fundamental.

The UN-Water website↗ states that *more than three billion people worldwide depend on water that crosses national borders*. There are 592 transboundary aquifers, yet most do not have an intergovernmental cooperation agreement in place for sharing and managing the aquifers. Moreover, while groundwater plays a key role in global stability and prosperity, it also makes up 99 percent of all liquid freshwater—accordingly, groundwater is at the heart of the freshwater crisis. *Groundwater is an invaluable resource*.

The Groundwater Project (GW-Project), a registered Canadian charity founded in 2018, pioneers in advancing understanding of groundwater and, thus, enables *building the human capacity for the development and management of groundwater.* The GW-Project is not government funded and relies on donations from individuals, organizations, and companies. The GW-Project creates and publishes high-quality books about *all-things-groundwater* that are scientifically significant and/or relevant to societal and ecological needs. Our books synthesize knowledge, are rigorously peer reviewed and translated into many languages. Groundwater is 'hidden' and, therefore, our books have a strong emphasis on visualizations essential to support the spatial thinking and conceptualization in space and time of processes, problems, and solutions. Based on *our philosophy that high quality groundwater knowledge should be accessible to everyone*, The GW-Project provides all publications for free.

The GW-Project embodies a new type of global educational endeavor made possible by the contributions of a dedicated international group of over 1000 volunteer professionals from a broad range of disciplines, and from 70 countries on six continents. Academics, practitioners, and retirees contribute by writing and/or reviewing books aimed at diverse levels of readers including children, youth, undergraduate and graduate students, groundwater professionals, and the general public.

The GW-Project started publishing books in August 2020; by the end of 2024, we have published 55 original books and 77 translations (55 languages). Revised editions of the books are published from time to time. In 2024, interactive groundwater education tools and groundwater videos were added to our website, gw-project.org↗.

We thank our individual and corporate sponsors for their ongoing financial support. Please consider sponsoring the GW-Project so we can continue to publish books free of charge.

The Groundwater Project *Board of Directors*, January 2025

Foreword

Conjunctive water management (CWM), is at the heart of what is most limiting to the effective use of freshwater resources for societal and environmental good. CWM refers to the planned, coordinated use of surface water, groundwater, and any other water sources within the management area, along with the management of demand for water, land use, and energy, to optimize use of the water resources and sustain ecological systems. The better-known term, conjunctive use (CU), excludes the well-being of ecosystems as an objective and may also exclude some sources of water. CWM and CU represent the movement and use of all the water everywhere and all the time within the area of interest, and as such, the water is considered to be in compartments of a single system with water continually moving within and exchanging between these compartments.

In practice, this integrated approach to purposeful management rarely occurs primarily because the main water sources (groundwater and surface water) are not clearly understood to be part of a single hydrologic system with continual exchanges. Typically, laws and regulations consider groundwater and surface water separately which results in conflicting policies and ineffective management. In practice, groundwater is commonly ignored or discounted because it is unseen while the visible surface water gets the attention even though groundwater constitutes nearly all of the water in most watersheds. Documented examples of CWM being fully accomplished in a purposeful manner are largely unknown and even CU is rarely accomplished according to a prescribed plan, nevertheless in some places efforts to conjunctively manage water have been successful.

The authors of this book, Dr. Richard Evans, based in Australia as a principal hydrologist with the multinational consulting firm Jacobs, and Randall Hanson, an emeritus research hydrologist with the US Geological Survey, have produced a book with a balanced perspective on water management that encompasses both groundwater and surface water. Their deep insights arise from their exceptional diversity of experience, each having spent more than 40 years engaged in projects involving a combination of groundwater and surface water management, policy issues, environmental assessments, and integrated hydrologic numerical modeling.

John Cherry, The Groundwater Project Leader

Guelph, Ontario, Canada, June 2025

Preface

Conjunctive use of groundwater and surface water is the process of using water from multiple sources for consumptive purposes for humanity and the environment in a broader sustainability framework. In this book, this process is called Conjunctive Water Management (CWM), and this refers to the use and movement of "all the water, everywhere, all the time". CWM also includes the more widely known term of Conjunctive Use that traditionally has referred just to human uses.

The planned conjunctive use of all water, including groundwater and surface water, has the potential to offer major benefits in terms of economic, social, and environmental outcomes through significantly improved efficiencies in water management and use that will support sustainability of water resources. Conjunctive use can be planned (where it is practiced as a direct result of management intention in formal water-resource frameworks) or spontaneous (where it occurs at a grass root level in informal water-resource frameworks).

Adopting a planned approach results in an operational framework that provides the greatest potential for the optimal capture, storage, abstraction, and reuse systems for agricultural irrigation, urban delivery, and ecosystem maintenance of all water sources, plus the management of surface and sub-surface drainage. Collectively, these attributes contribute significantly to achieving sustainable economic, social, and environmental outcomes when combined in a sustainability framework with land-use and energy management to foster food–water–energy security for humanity and the surrounding natural environment.

Conjunctive use is common in many parts of world; however, integration with land-use and energy management is generally incidental, arising from informal or independent actions rather than being an outcome of a robust integrated planning process within a resource management framework for sustainability. Consequently, despite being heralded as a major new advance in water management over the last 30 years, *planned* CWM is rarely practiced. This lack of practice has contributed to overexploitation of resources as well as conflicts over use and sharing of resources.

In most cases, surface water and groundwater are considered by both managers and users as separate resources with policy and management, as well as institutional and governance arrangements also evolving separately. The effect has been the establishment of boundaries within the existing policy, statutory, and regulatory framework that apply to surface-water and groundwater resources by adjacent or overlapping management groups. These boundaries and isolated frameworks are problematic as adoption of a full CWM model is dependent upon a single holistic and integrated institutional framework and a robust governance structure that incorporates authority, accountability, transparency, stakeholder participation in planning, and regulatory/compliance arrangements.

A poor understanding of the technical aspects of CWM may be an impediment to its adoption; however, it is the absence of integrated institutional and governance arrangements that is likely a greater barrier to the development of a sustainable and holistic framework for resource management. Potentially significant benefits would be achieved by adoption of a holistic planning approach to groundwater and surface-water management when combined with land-use, climate, and energy contingencies. The potential for benefits within most urban and irrigation systems around the world is yet to be realized. Achieving the benefits requires reform of institutional structures, policy objectives, funding mechanisms, monitoring networks, data and analysis sharing, and regulatory arrangements.

This CWM book is intended to not only inform and educate on the current aspects of CWM, but to also provide a roadmap and pathway forward for those who endeavor to develop, modify, or expand current resource-management systems that include CWM. The coordinated use of all water sources, including groundwater and surface water, to maximize the total available water resource for consumptive and environmental purposes requires a broader and more holistic approach than is presented in this book. CWM needs to be considered within a framework of sustainability that includes land-use management, consideration of climate change and variability, and alignment of governance that will provide a management mechanism over multiple timeframes. This broader objective can be facilitated through understanding of the ongoing and past barriers to CWM that need to be overcome to successfully move forward with humankind and the environment in better harmony. Ultimately, this book provides a new, more holistic way of thinking of water, land, and energy resources and their many linkages within the hydrosphere and to other supply-and-demand drivers.

A list of cross-referenced acronyms and abbreviations is included in this book to help the reader with their use throughout the text and in related references. By using the Navigation Pane, readers can easily jump to an acronym or abbreviation in the list and back to their place in the text.

Acknowledgments

Some of this book is based on a report by Evans and Dillon (2017) titled *Linking Groundwater and Surface water: Conjunctive Water Management*↗. Additional parts are based on the continued research, development, and applied studies of the US Geological Survey.

We also appreciate the reviews of this book by the following individuals:

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- Bill Alley, Director of Science and Technology, National Ground Water Association & Scientist & Retired, US Geological Survey;
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Sources of figures and tables are cited when adapted from other published works. Where a source is not cited, the figures or tables are original to this book.

1 What is Conjunctive Water Management?

Immense resource-sustainability issues face the entire world over the next decades to centuries owing to the combined influences of climate change and variability, population growth, water pollution, land development, and environmental degradation. To mitigate the impact of these factors, breakthrough water-management technologies combined with changed practices and governance are urgently required.

Conjunctive Water Management (CWM) can be a vital component of these new approaches. The ultimate goal of a CWM framework is to develop monitoring, analytical, operational, and governance systems that are regionally integrated in a sustainability framework. This book describes the considerable advantages of CWM over conventional water management approaches and explains how it can be an integral part of a larger resource-management framework that includes land use, energy use, and climate for more complete and more flexible sustainability.

CWM is the planned and coordinated use of all water resources, including groundwater and surface water, to optimize their combined use and minimize any undesirable physical and environmental effects that may result from the use of one or the other. Thus, a new *holistic* definition is required to encompass the broader components of supply and demand that are connected within CWM. Various authors have used slightly different terms, such as Conjunctive Use, Conjunctive Use Management, or Conjunctive Management. This book has adopted the term Conjunctive Water Management (CWM) purely to emphasize that this book focuses on water planning and management as a contribution to achieving sustainability goals (van der Gun, 2020), as distinct but not independent from other natural resource management issues.

While this management approach is intended to be proactive, it is not independent of the other aspects of resources management that include the environment, land and energy use, and climate. Other organizations have used slightly different definitions. For example:

- US Bureau of Reclamation (USBR) defines the approach as *"the coordinated use of surface water and groundwater"* (US Bureau of Reclamation, 2022),
- United Nations Educational, Scientific and Cultural Organization (UNESCO) defines it as *"combined use of surface water and groundwater to optimize the use of water resources"* (UNESCO-WHO, 2012), and
- California Department of Water Resources (CA-DWR) defines it as "*the planned use of both surface water and groundwater resources to maximize total water availability in a region long-term*" (California Department of Water Resources, 2016a).

The Food and Agriculture Organization of the United States (FAO, 1995,) describes the concept as, "*Conjunctive use of surface water and groundwater consists of harmoniously combining the use of both sources of water in order to minimize the undesirable physical, environmental and economic effects of each solution and to optimize the water demand/supply balance.*" The

Groundwater Project's book *Glossary of Hydrogeology* (Sharp, 2023) also defines these terms, although in a less descriptive form. Additional differences between conjunctive use (CU) and conjunctive water management (CWM) are also briefly summarized by Dudley and Fulton (2006) (Conceptual Exercise 1↴).

Imported water can represent any form of water that is brought into a watershed from outside of the watershed. This can represent surface water sources as, for example, for Los Angeles, USA, by the Water Replenishment District from the Owens River and by Metropolitan Water from the Colorado River, or from the Sierra Nevada mountains where water from Hetch Hetchy reservoir is imported to the City of San Francisco and the Santa Clara Valley. However, imported water can also represent groundwater sources from *planetary* basins as from Avra Valley to Tucson Basin in Arizona, USA, basins north of Las Vegas Valley in Nevada, USA, and from the Conejos-Medanos to adjacent Ciudad Juarez, in Chihuahua, Mexico. In contrast, many locations export large volumes of wastewater as discharge to the ocean or as irrigation supply as in the Tule Valley adjacent to Mexico Valley in central Mexico.

Our updated definition of CU encompasses all water sources and uses:

> C*U is the c*ombined use of precipitation, surface water, recycled, imported, saline water, and groundwater to optimize the use and quality of all water resources throughout the watershed and connected aquifer systems for human and environmental uses that promote sustainability.

Our related updated definition of CWM presents this more holistic view in the broader supply-and-demand paradigm of all the water everywhere all the time:

> *CWM is the integral resource management of consumptive use from all water sources for all uses providing a diverse portfolio that facilitates reliable mechanisms for adaptation, mitigation, replenishment, and sustainability within a supply-and-demand framework for human and environmental needs and is connected to other potential drivers of supply and demand including land use, population, industry, climate, and transboundary governance.*

The concepts presented in these definitions are illustrated on the cover of this book.

Thus, the aim of CWM is to maximize the benefits arising from the innate characteristics of surface water and groundwater use; characteristics that, through planned integration of both water sources, provide complementary and optimal productivity and water-use efficiency outcomes. It is recognized that the *optimal* situation is dynamic and frequently depends on stakeholder perspectives; hence the necessity of good stakeholder engagement where different interests are balanced. For example, this balance may include honoring treaties or other transboundary agreements, such as river compacts, as well as reducing the potential for water conflicts to develop with neighbors who share these resources (Conceptual Exercise 2↴).

Most recently, the World Bank Group (2023a, 2023b) summarized groundwater as the hidden wealth of nations with examples of aquifers from Europe, Africa, and South America. It also reemphasized not only access to water resources, but also the management and development of water resources are subject to different economic theories in these settings, as well as consideration of multi-risk insurance of groundwater, and the policy and management instruments implemented through different governmental frameworks. This summary of groundwater in times of climate change also revisits other important aspects of CWM including its interrelation with: groundwater dependent ecosystems (GDEs), urban supply to cities, and the exponential threat of groundwater-quality degradation, which are illustrated on the cover of this book.

The concept of planned CWM is not new but must now be viewed in the context of supply and demand as well as sustainability; however, this view is not frequently applied globally due to technical, institutional, monetary, and policy impediments, as described in this book. The primary focus of this book is on the coordinated use of groundwater and surface water to maximize the total available water resource for consumptive purposes. However, it also discusses the use of other resources such as land, minerals, and habitat in the context of this management framework. Considering other resources in CWM has major economic, social, and environmental benefits—while minimizing adverse impacts to human and environmental sustainability. For example, a recent workshop by the United Nations Economic Commission for Europe (UNECE) on Conjunctive Water Management↗ reviewed selected aspects of considering other non-water resources in CWM with examples from Europe, Africa, and South America.

In this context, we provide new definitions of both CU and CWM so as not to conflate the two concepts. In addition, the outdated paradigm of simply stewarding resource development has been superseded by modern concepts of sustainability as originally discussed in a sequence of papers: Bredehoeft and others (1982) and Bredehoeft (1997, 2002). The modern emphasis on sustainability started with Bredehoeft's seminal editorial paper on the "Safe Yield and the Water Budget Myth" (Bredehoeft, 1997). This was further explored by others in the context of sustainability (Alley & Leake, 2004) and conjunctive use (Hanson et al., 2010).

In other settings (such as India), the Green Revolution that promoted the installation of millions of wells has ended, as it severely diminished groundwater resources and resulted in substantial groundwater depletion and reduced stream flows (Uttar Pradesh: India - Box 1). Similarly, Vorosmarty and others (2010) showed how the additional stresses of population growth (and, indirectly, land-use growth) and climate change are the two major stressors on the sustainability of water resources in a supply-and-demand framework (Figure 1). In Figure 1, Q is accumulated runoff as river discharge from the mean annual surface and subsurface (shallow aquifer). It is assumed to constitute the sustainable water supply to which local human populations have access. *DIA* is the combined domestic, industrial, and agricultural demand on a mean annual basis.

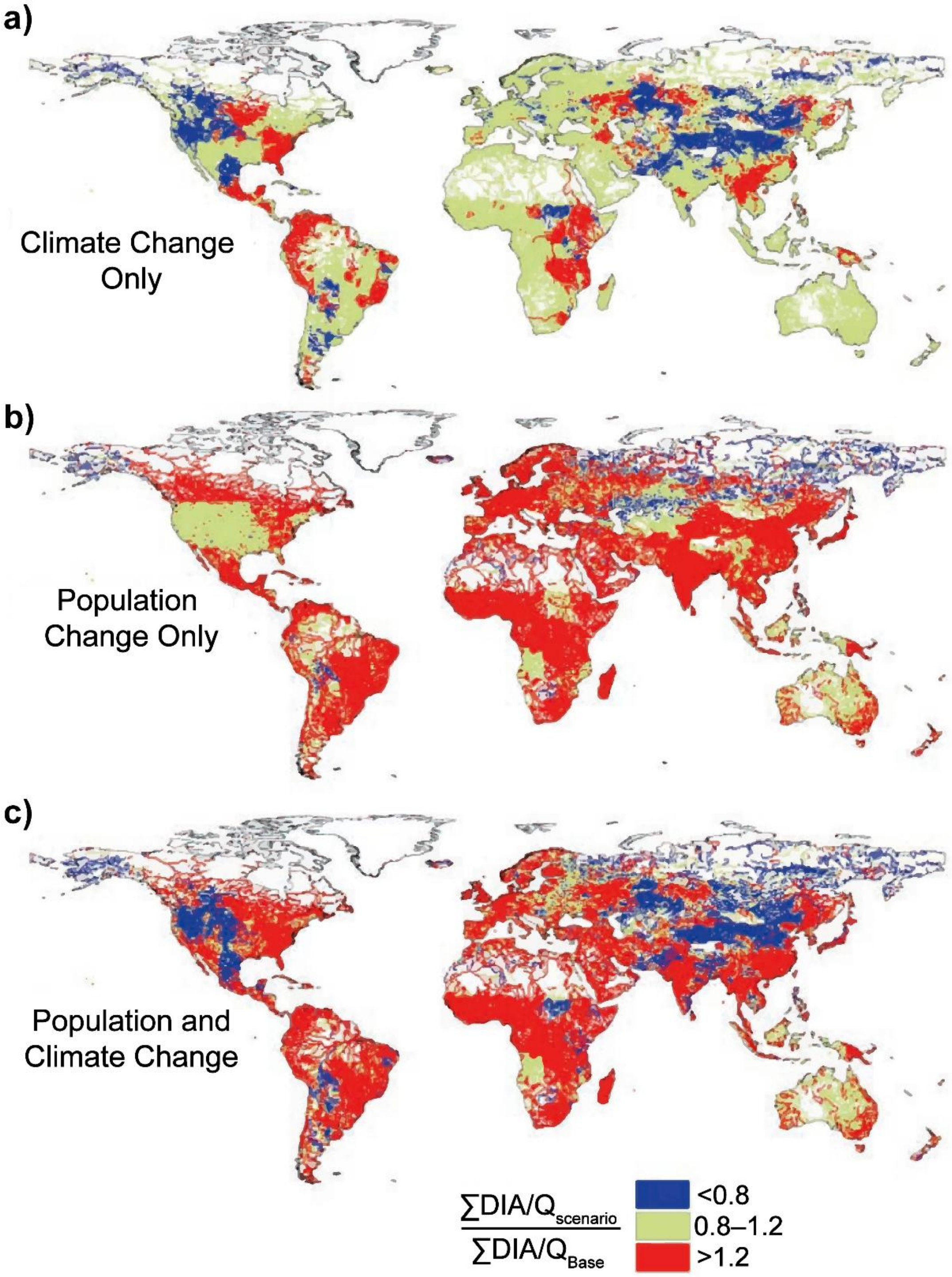


Figure 1 - Maps of the change in water reuse index (Σ*DIA*/*Q*) predicted by the CGCM1/WBM model configuration under a) Scenario 1 (climate change alone), b) Scenario 2 (population and economic development only), and c) Scenario 3 (both effects). Changes in the ratio of scenario specific *DIA*/*Q* ($\Sigma DIA/Q_{scenario}$) relative to contemporary ($\Sigma DIA/Q_{base}$) conditions are shown. A threshold of 120 percent is used to highlight areas of substantial change (Vorosmarty et al., 2010). Areas that are not blue indicate extreme stress. Q is accumulated runoff as river discharge (i.e., the sustainable, accessible, water supply for local human populations. DIA is mean annual combined domestic, industrial, and agricultural demand.

The summation of DIA in Figure 1 represents the aggregate upstream water use relative to discharge (*Q*); this ratio represents the relative degree of human interaction with the sustainable water supply. Values ranging from <0.8 to 1.2 represent medium to high sustainability stress and values above 1.2 represent severe water limitations (Vorosmarty et al., 2010). So, conjunctive use and conjunctive water management must be developed in formal systems in the context of sustainability that manages and acknowledges the limits and variability of the resources and other related stresses.

Other water sources—such as urban storm water, treated sewage, desalinated water, and irrigation runoff—should be considered in the context of CWM. These other water sources tend to have specific quantity, quality, temporal, and spatial characteristics that require different types of assessment for each source. These other sources are increasingly important to developing a diversified portfolio of sources within CWM that provide redundancy, reliability, and resilience from the increasing and variable stressors of water demand, as illustrated on the cover of this book.

Managing water demand spans a wide spectrum of uses. It is necessary to consider the temporal and spatial disparities between supply and demand and indirect drivers that may grow or sustain demand as well as provide additional supply. These are collectively assessed in the context of a dynamic water budget, which represents estimates of all the inflows and outflows. The budget also includes changes in storage such as changes in groundwater, reservoir, or soil moisture storage. Compiling and understanding all the demands of a hydrologic system is key to developing a suite of water-flow budgets that includes defining all types of demands: urban, agricultural, and environmental. The budget might need to include transboundary demands, for example, upstream or downstream demands on a river or groundwater underflow between watersheds or jurisdictions. Estimating projected future demands of these categories is critical for determining potential future surpluses or deficits and managing sustainability over longer time periods.

Quantifying peak seasonal demands is also important in many (probably most) areas as well as measuring the disparity between peak demands and peak supply periods. Indirect drivers of demand can include urbanization, industrial growth, planting permanent crops (hardening demand), and potential water exports as well as changes of land use, climate cycles, and climate.

2 Fundamental Concepts of Conjunctive Water Management

Conjunctive use of groundwater and surface water in an irrigation or urban setting is the process of using water from multiple sources for consumptive purposes that collectively mitigates the potential disparity between the timing and magnitude of supply and demand for water resources. It can refer to the practice of spontaneously extracting water from both a well and an irrigation delivery canal or river that is commonly referred to as an *informal system*. Alternatively, it can point to a strategic approach to irrigation demands at the aquifer, river basin, watershed, or city level where surface water and groundwater inputs are centrally managed as an input to irrigation or water-supply systems, commonly referred to as a *formal system*. The latter approach is a planned or *formal systems* of CWM.

Accordingly, CWM can be characterized as being either planned (where it is practiced as a direct result of management intention, generally with a top-down and orchestrated approach referred to here as a formal system) or spontaneous (where it occurs at a grass roots level, generally from the bottom-up without consideration of resource sustainability and referred to here as an informal, or unplanned, system). The significant difference between unplanned and planned CWM is explored in Section 4 of this book. Informal (unplanned) and highly planned (formal) water systems represent the two ends of the spectrum, with most cases falling somewhere in between and more toward informal systems. The informal systems commonly evolve into more formal frameworks with increased demands and limited supplies.

Both informal and formal systems may occur at different levels of size (local versus regional) and sophistication. There are examples of successful sustainable sophisticated local systems and examples of the opposite on a large regional scale. The important factors of CWM are planning; coordination; understanding and incorporation of physical, economic, and institutional frameworks; monitoring; flexibility; and community participation. These factors can occur at different scales, and may be driven by and evolve from a developing recognition of all of the factors as informal systems—or groups of informal systems—evolve into formal systems.

Where both surface water and groundwater sources are directly available to the end user without overarching CWM resource management, monitoring, or limitations, spontaneous (informal) conjunctive use generally proliferates, with individuals opportunistically making decisions about water sources at the local scale. This tendency—combined with outside drivers like expansion of land use, population, or climate drivers such as drought or flooding—generally results in resource overexploitation.

The classic example of this exploitation is in the Punjab state in northwest India (noted earlier), where the Green Revolution resulted in the installation of millions of wells, diversion of rivers, storage depletion, and degradation of water quality from salinity and other chemicals. In contrast, the state of California's (USA) Sustainable Groundwater Management Act (SGMA), enacted in 2014 (SGMA, 2014; University of California at Davis [UC-DAVIS], 2023), sets limits on conjunctive use and includes six criteria as deleterious effects that must be prevented, managed, and mitigated to insure sustainability over five-year periods of recurring assessment (Pavely, 2014a; Pavely, 2014b; Dickinson, 2014; California State Assembly Bill [CA-AB], 1739). The six criteria are:

1. groundwater-level declines,
2. groundwater-storage reductions,
3. seawater intrusion,
4. water-quality degradation,
5. land subsidence, and
6. depletions of interconnected surface water and groundwater.

Additional physical and regulatory issues may also need to be considered, including:

- climate change/variability including drought contingencies;
- changing/expanding land use and agricultural demands (including hardening of demand);
- US National Marine Fisheries Service (NMFS) fish passage streamflow and stage requirements;
- habitat maintenance including Groundwater-Dependent Ecosystems (GDEs);
- alternate water sources (runoff, reuse/recycle, imported, and desalination);
- supply management (Water Reuse and Aquifer-Storage-and-Recovery, ASRs);
- demand management such as land-use, crop-type, and saline-water irrigation restrictions;
- US Environmental Protection Agency (US-EPA) and California Environmental Protection Agency (Cal-EPA) water-quality requirements; and
- transboundary impairment of groundwater or surface water resources.

This legislation resulted in the recognition that too much land-use development and related agriculture was allowed in areas such as California's Central Valley, Borrego Valley, and Cuyama Valley. Like the Punjab situation in India, semi-arid regions in North America—such as Baja California, Mexico (Mireya, 2023) and the Yuma and West Salt River Valley, Arizona, USA—have seen salinity as another emerging issue that will require additional supply-and-demand management within a CWM sustainability framework.

The absence of both sustainability planning and a strategic agenda within governments to capitalize on the potential for planned CWM is a significant impediment to meeting national goals as they pertain to water supply, food and energy, security. There is an urgent need to maximize production within the context of sustainable management of all water sources, including groundwater and surface water.

Many existing irrigation systems obtain their water supply from both catchment runoff and aquifers. Typically, water has been sourced from either surface water or groundwater supplies, with the primary supply supplemented by the alternative source over time. In less arid regimes, this is also done in the agricultural context of "dry-land farming" where the primary source can be precipitation that is then supplemented with other sources when needed. Accordingly, governance settings, infrastructure provisions, and water management arrangements have emphasized primary sources of supply needs; this inevitably requires the retrofitting of management approaches onto existing irrigation or urban supply systems to incorporate supplementary water sources over time. Optimizing the management and use of such resources, which have been developed separately, will in some situations require substantial investment in capital infrastructure and reform of institutional structures and financial support for CWM.

Put simply, planned CWM is relatively simple with greenfield (i.e., new development) sites but harder to achieve within existing (i.e., brownfield) physical and institutional/social systems. However, the Distrito De Riego Del Rio Yaqui, Sonora, Mexico (http://www.drryaqui.org.mx/↗ this link may not be accessible in all regions), provides an excellent example of a retrofitted system transformed into a *smart valley*, combining the centralized control of over 530 wells and several reservoirs, plus hydrologic, climate, land-use monitoring, and conveyance canals from a centralized server complex (Figure 2).

Figure 2 - Rio Yaqui Server command room for control of the entire water, climate, security, and demand system for agriculture.

While these challenges and the associated benefits of a strategically planned approach are well understood and the subject of numerous studies, papers, and reports on CWM (Kemira, 2023; Lautze, 2018; CD-DWR, 2016b; Jakeman et al., 2016; Ziaja et al., 2016; Thompson, 2011; Cosens, 2010; Roberts, 2010; Valdez & Maddock, 2010; Peltier, 2006; World Business Council for Sustainable Development [WBCSD], 2006; SWRCB, 2005), the current status of water management and planning around the world suggests that widespread implementation is just beginning. This book explores some successes and failures as well as some of the reasons underpinning the apparent lack of full integration in the management and use of all water sources, and the absence of more coordinated monitoring, analysis, and planning. There remain significant gaps in water managers' understanding of what aspects of the contemporary management regime need to be overhauled to achieve integrated management and the improved outcomes that could be expected, compared to separate management arrangements for the different sources of water supply and water demand.

To compound this problem, conservation in many settings is not an option as it leads to revenue shortfalls that will not cover operational and maintenance (O&M) costs. Such lack of understanding and lack of appropriate business models to provide funding are serious impediments to governance, and institutional and physical infrastructure reforms required to facilitate planned CWM, an approach that could improve existing management and regulatory arrangements. While many locations do not charge for groundwater and supply surface water for agriculture at reduced costs, typically the revenues do not cover O&M costs.

Reforms may also be impeded by different ownership models of groundwater and surface water delivery infrastructure and the associated entitlement regime (i.e., private and/or public) as well as transboundary competition for these resources. This situation has implications for social and institutional behavior where transboundary conflicts may ultimately lead to the adoption of a CWM approach. An example of this was summarized for the International Shared Aquifer Resources Management (ISARM) of the Americas by UNESCO (Rivera, 2015).

Even though the primary focus of this book is surface water and groundwater, additional important aspects of CWM involve other components of the hydrologic cycle as well as supply-and-demand drivers. Conjunctive water management includes large-scale areas of the world where artificial drainage intentionally lowers the groundwater level to combat water logging as well as salinization. In these situations, groundwater is usually (but not always) an environmental factor rather than a usable resource.

However, shallow groundwater levels indirectly support and sustain habitat related to groundwater-dependent ecosystems (GDEs) adjacent to surface water networks. Such successful groundwater-level management can only exist in conjunction with surface water management. Where groundwater levels are in decline, intermittent surface water sources may be used to augment recharge to sustain supplies and prevent saline intrusion provided the groundwater depletions are not impeding conveyance of surface-water deliveries to areas where it is needed.

Groundwater-level management in agricultural settings includes dewatering to prevent waterlogging of agricultural areas with shallow groundwater levels within the root or soil zone without damaging any adjacent habitat that relies on shallow groundwater known as groundwater dependent ecosystems (GDE's). This type of drainage control can be achieved using French or tile drains buried beneath the fields, groundwater drainage-capture canals peripheral to the fields, or by pumping groundwater. Unfortunately, the groundwater captured from inefficient irrigation or natural shallow conditions is not always reused, and is commonly high in nitrates, salinity, trace elements, and other agricultural byproducts.

Drain water captured beneath agricultural fields was demonstrated to be an unused resource in the analysis of future CWM within the Pajaro Valley, California, USA, where French drains are used (Hanson et al., 2014c). In contrast, the use of peripheral drain canals in the Lower Rio Grande (spanning the border of Mexico and the USA states of Texas and New Mexico) helped with the reuse of inefficient irrigation water for downstream deliveries (Hanson et al., 2020). The active pumpage of shallow groundwater from the Gila and Yuma Valleys, USA, in the Lower Colorado River Basin reduces soil-zone waterlogging and is used to supplant treaty deliveries of the Colorado River from the USA to Mexico (Hanson et al. 2015). The Andrate Drain was constructed to help mitigate shallow groundwater in the Mexicali Valley, Mexico, just south of the USA–Mexico border, but this is now less useful following the lining of the All-American Canal, which stopped water leakage from the All-American Canal. This transboundary example demonstrates how CWM and related infrastructure change and evolve through time and can result in some sources no longer being a problem or new sources becoming available for reuse.

CWM includes water quality management. Though there are many different mechanisms for water quality management, a common one is where surface water–groundwater interaction directly influences water quality; this is primarily in terms of salt levels but also in terms of pollution management in both agricultural and urban environments. Salinity and nutrient degradation of groundwater and surface water resources is a common problem affecting supply-and-demand aspects of conjunctive use that includes water quality. Mitigation is possible, such as the program being implemented in Central Valley, California (CVSALTS, 2023), to minimize the effects of salinity and nutrient depletion on supply and demand. In conjunction with California's Sustainable Groundwater Management Act (SGMA) of 2014, this approach provides comprehensive sustainability innovations combined with conjunctive use (Quinn & Oster, 2021).

In other regions, emerging anthropogenic contaminants—such as antibiotics and other urban contaminants, plus agricultural contaminants from fertilizers, soil amendments, insecticides and herbicides, and geogenic contaminants like trace metals and radionuclides—are being mobilized from water resource development. This action may impact the sustainability of CWM and related urban and agricultural water supplies. Groundwater quality may be improved by recharging aquifers with fresh water, thereby restoring otherwise unproductive aquifers, but salinity flushing can dramatically increase the demand for irrigation water and further contaminate the aquifers. CWM strongly influences environmental water requirements for ecosystem maintenance and protection, like the items described above.

Another aspect of CWM that needs to be considered relates to surface water–groundwater interaction where avoidance of double counting is fundamental to total water management. Double accounting refers to the inclusion of either groundwater or surface water that moves from one system to the other and is accounted for in both systems.

At a practical level, planned CWM considers water supply options in both a spatial and temporal context. With respect to the spatial sense, Figure 3 (Foster et al., 2010) shows typical schemes for both urban and irrigation supply where the contrast between spontaneous (informal/unplanned) and planned (formal) CWM is depicted at the local and watershed scale, which is the fundamental unit of supply and demand in most settings. Figure 3a shows the typical unplanned (informal) urban supply case where intensive local groundwater use is often added later, causing local interference and hence reducing the available water resources from surface water capture and groundwater storage. Figure 3b (planned/formal) incorporates an external wellfield and therefore increases the total available water resource, but to provide a sustainability framework, the resource cannot exceed the rate of groundwater replenishment (Mendoza - Argentina - Box 2↴).

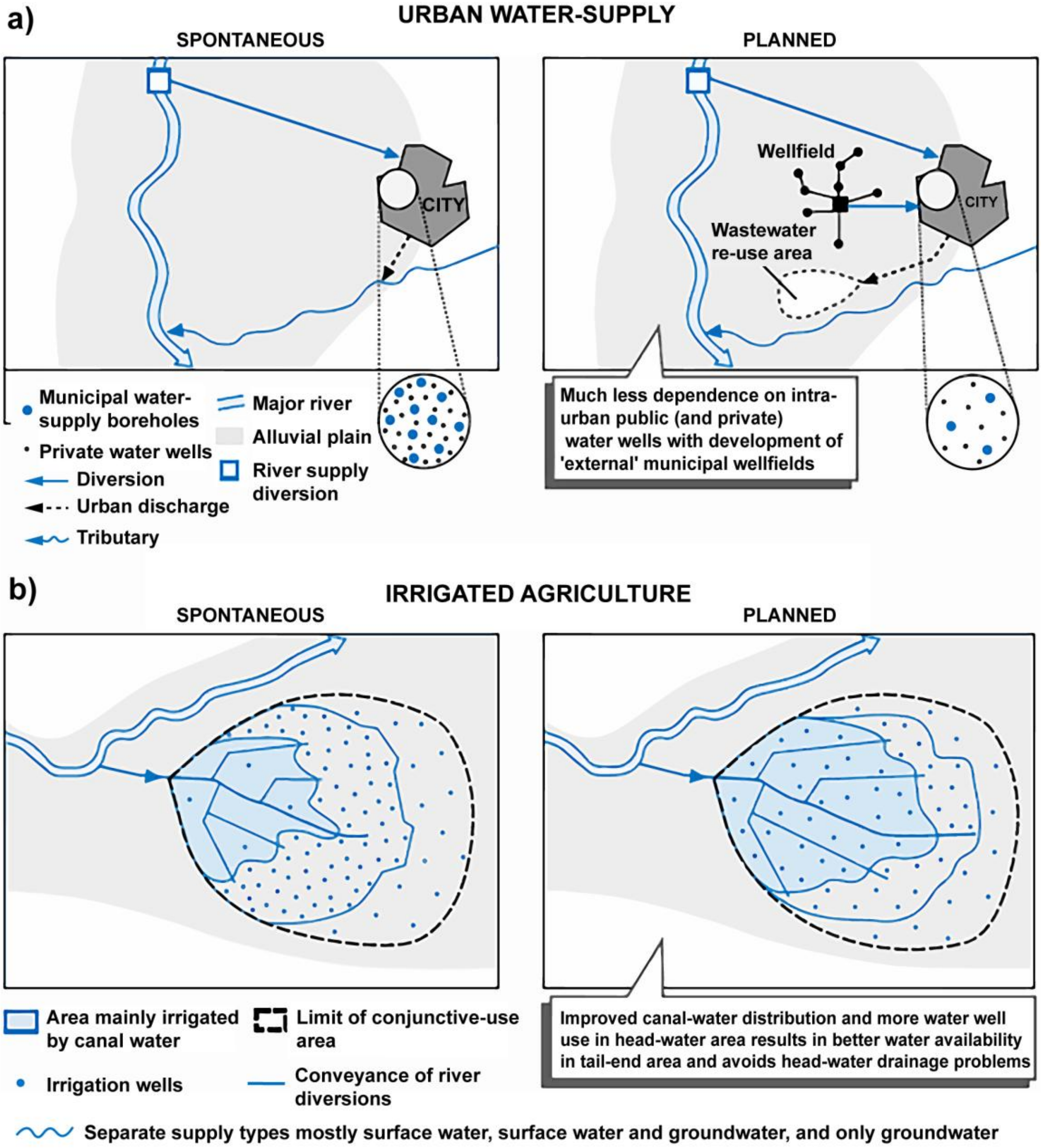


Figure 3 - Typical schemes of conjunctive use of groundwater and surface water resources for a) urban water supply and b) irrigated agriculture, evolving from spontaneous (informal) occurrence to planned (formal) development. Blue outlines in (b) separate regions by type of supply: mostly surface water, surface water and groundwater, and only groundwater (Foster et al., 2010).

Similarly, for Figure 3b (the irrigated agriculture situation), the planned CWM case involves an improved canal water distribution network and more widely spaced groundwater use, resulting in greater water availability and flexibility and less environmental impact (Queensland - Australia - Box 3↓). The effectiveness of this approach is contingent on whether land use increases without limit or if conversion to permanent crops such as orchards, nuts, and vineyards are hardening demand over decades that may also be subject to climate variability and drought-related restrictions of supply. The spatial considerations of a formal CWM framework may also require supply-and-demand considerations at the regional scale downstream from the formal system, including various levels of transboundary obligations.

Considering the temporal sense, in practice CWM involves relying more on surface water when it is available during wetter years or months (including recharge groundwater) and relying more on groundwater during drier years or months and droughts. Retrofitting existing water supply systems for CWM practices is much easier with respect to the temporal than spatial aspect. Deciding when, and to what extent, groundwater use is preferred over surface water use and vice versa requires considerable monitoring, forecasting skill, analysis, and judgment (Indus Basin - Pakistan - Box 4⤵). Some of the advantages of CWM infrastructure were initially summarized for watersheds of Australia and the USA by Ross (2012) (Conceptual Exercise 3⤵) and for Spain (Other CWM Management Examples - Box 5⤵).

For example, many more arid regions (e.g., the southern parts of the Central Valley, California, USA) shift sources seasonally, using surface water from snowmelt runoff in the early months of the growing season followed by groundwater irrigation in the later summer and fall months (Faunt et al., 2009). The magnitude and timing of the combined use of these two water supplies is also affected by climate variability and changing land use. In addition, the other element of SGMA within regional and local hydrologic systems within California is to develop indicators and thresholds that are monitored, assessed, and potentially acted upon regularly as a measure of sustainability for all the components plus the secondary effects related to water resource use, quality, and development (Shilling et al., 2013; Central Valley - California, USA - Box 6⤵).

Thus, monitoring networks connected to hydrologic budget assessments—with related indicators and thresholds—help to create a framework for assessment and decision making within CWM (CA-DWR, 2020). Analysis through a combination of monitoring and modeling is one of the available decision tools that are discussed in Section 8 of this book. Several examples of approved a Groundwater Sustainability Plan (GSP) in California include the Pajaro Valley which is used to provide examples in this book and the Napa Valley Subbasin (NAPA, 2022). Pajaro Valley was classified as a critically over-drafted basin, but because of decades of monitoring, modeling, analysis, and management, the Pajaro Valley Water Management Agency (PVWMA, 2024) was granted a GSP. Alternative assessment was granted under SGMA (CA-DWR, 2024a).

A further example is the Napa Valley Subbasin, California, USA, which is categorized by the CA-DWR as one of 46 high-priority groundwater basins statewide. Medium- and high-priority basins are subject to the SGMA requirements (Napa County Groundwater Agency, n.d.), along with participation in the statewide groundwater monitoring program: California State Groundwater Monitoring (CASGEM; CA-DWR, 2024b). With the initiation of the SGMA law in 2014 in California, Napa County was required to form a Groundwater Sustainability Agency (GSA) that would steward CWM activities. These activities include the development of a GSP and provide continuous monitoring, reevaluation of sustainability every five years, and help initiate needed mitigation activities to help achieve sustainability by 2040.

3 Technical and Management Differences Between Surface Water and Groundwater

The characteristics of the two primary water sources associated with CWM (i.e., groundwater and surface water) are inherently different and those differences must be appreciated to optimize their combined use. Table 1 summarizes the typical characteristics associated with each of these water resources. There are considerable disparities between the timing and magnitude of supply and demand of groundwater and surface water, and these differences can be advantageous in CWM (Conceptual Exercise 4↴).

Table 1 - Typical characteristics of relative response of groundwater and surface water supply systems.

Characteristic	**Groundwater**	**Surface water**
Response time to flow events	Slow	Quick
Time lag between supply-and-demand components	Long	Short
Size of storage	Large	Small
Security of supply	High	Low
Spatial management scale	Diffuse	Generally linear
Flexibility of supply	Very flexible in localized regions	Not flexible without more infrastructure
Adaptability to progressive increase in demand or sources of supply	Usually very adaptable	Not usually adaptable
Time to recover from a depleted resource	Years to decades	Months to years
Time to recover from seawater Intrusion	Decades to never	Years to never
Time to recover from land subsidence	Never	Never
Time to recover from quality degradation	Decades to never	Months to years
Response to drought, climate cycles, and climate change	Years to centuries	Months to decades

Given the extent and diversity of irrigation and urban supply systems covering a vast range of physical environments throughout the world, in many situations the surface/groundwater components of local water do not reflect the typical characteristics presented above. Areas with informal water supply and localized demands can rely on direct use of rainfall for "dry-land" agriculture, rely on numerous small lakes for localized supply, or have annual access to snowmelt; in these situations, formal groundwater and surface water systems may be less important or even unnecessary, depending on other external drivers such as land use and climate.

Nonetheless, physical differences as well as differences in the history and growth of formal system development of the two resource types provide both challenges and benefits to CWM. They also reveal how enhancing groundwater with occasionally available surface water can help to replenish the groundwater resource and improve its quality and sustainability. Also, irrigation return flows from groundwater sources can supplement the reuse of surface water for downstream users potentially helping with the conjunctive reuse of commingled groundwater and surface water supplies.

To make progress on CWM, the specific characteristics of groundwater and surface water in the target region must be assessed. Such an assessment includes the social (and cultural), economic, and environmental aspects (the so-called triple bottom line) plus governance frameworks so as to evaluate how the particular characteristics of the hydrologic environment can be integrated to achieve optimum and flexible outcomes that help promote sustainability through organized adaptation and mitigation. Such an assessment also needs to include the types of uses (industrial, agricultural, and public and private supply), land use, and existing infrastructure such as surface water storage capacity, delivery and return-flow networks, wastewater-treatment operations, as well as other reclamation operations such as recycling or desalination facilities. The distribution, depth, and types of wells must also be assessed and managed under a complete CWM framework (Conceptual Exercise 5↴).

4 Informal and Formal Systems

UNESCO categorizes water agreements, water use, and related human settlements and agriculture into informal and formal systems (UNESCO, 2023). These categories also span related activities of water use and sharing, including water markets, governance, and related developments (Marston & Cai, 2016; Hadjigeorgalis, 2009; Conceptual Exercise 6↴).

Sections 1 through 3 of this book highlight the two fundamentally different approaches to conjunctive use; however, CWM evolves from informal (spontaneous/incidental/unplanned) to formal (planned) use along a continuum. For example, at one end of the CWM planning spectrum, an informal system typically starts with one water source such as streamflow diversion for local or single use that is potentially neither reliable nor sustainable owing to increased demand and variable supply. This may transition into more management of runoff such as improved catchment management to reduce erosion and flooding; increased soil moisture also has the effect of enhancing recharge. Finally multiple sources and multiple users can evolve an initial informal system into conjunctive use with the goal of more reliability and sustainability (as discussed for Mendoza, Argentina in Box 2). At the other end of the planning spectrum is an intentional recharge enhancement called managed aquifer recharge (MAR), designed to increase groundwater supplies, improve their quality, or sustain groundwater-dependent ecosystems (Dillon et al., 2009a). This concept also includes the use of aquifer-storage-and-recovery systems (ASR) as well as capture and recharge runoff during wetter periods called FloodMAR.

Commonly not included in these examples and related assessments of CWM and related MAR, is the role and importance of multi-aquifer wells. These wells have been documented to provide direct recharge conduits to deeper aquifers with groundwater that can be thousands to tens of thousands of years old and commonly impaired from receiving modern recharge. As such, these wells contribute to enhanced streamflow infiltration, deep aquifer recharge, enhanced water quality, reduced storage depletion, reduced groundwater-level declines, and reduced land subsidence. The wells depicted in the spontaneous (informal) and planned (formal) settings (Figure 3) would both benefit from conjunctive use through the movement of water as vertical wellbore flow down multi-aquifer wells.

Analysis of municipal wellfields from San Jose, California, USA, was present by Hanson (2015).

Figure 4 and Figure 5 show how clusters of multi-aquifer wells provide modern water at depths of 1,000 ft (305 m) while multi-level monitoring wells a mile (1.6 km) away show that these deeper aquifers contain water that is over 10,000 years old and lack modern recharge. Similarly, taking multi-aquifer wells out of production in coastal regions with the irrigation water supply replaced with municipal recycled water can help reduce groundwater depletion and related seawater intrusion (Hanson et al., 2014b, 2014c). Finally, multi-aquifer wells can provide recharge conduits as part of conjunctive use throughout entire regional aquifer systems as demonstrated for a variety of regions in California, such as the Santa Clara (Hanson, 2015), Pajaro (Hanson et al., 2014b, 2014c; Hanson et al., 2010), Cuyama (Hanson et al., 2014d), and the Central Valley with wellbore inflow contributing as much as 20 percent of the inter-aquifer vertical flow. For example, in the Central Valley it was determined from the initial Central Valley Hydrologic Model (CVHM1; Faunt et al., 2009) that, over the entire period of simulation, wellbore inflow represents 17 percent of wellbore outflow with variation from seven percent during the end of the growing/irrigation season to more than 20 percent during the end of the non-growing season. The percentage of vertical flow as wellbore flow in CVHM1 ranged from a few percent to more than 35%, (Figure 5a) suggesting that this is an important component of vertical flow. With the addition of all farm wells simulated by the Multi-Node-Well package (MNW2) in CVHM2 (Faunt et al., 2024), the percentages for some regions increased to as much as 70% of total vertical flow (wellbore flow plus interlayer flow) (Figure 5b).

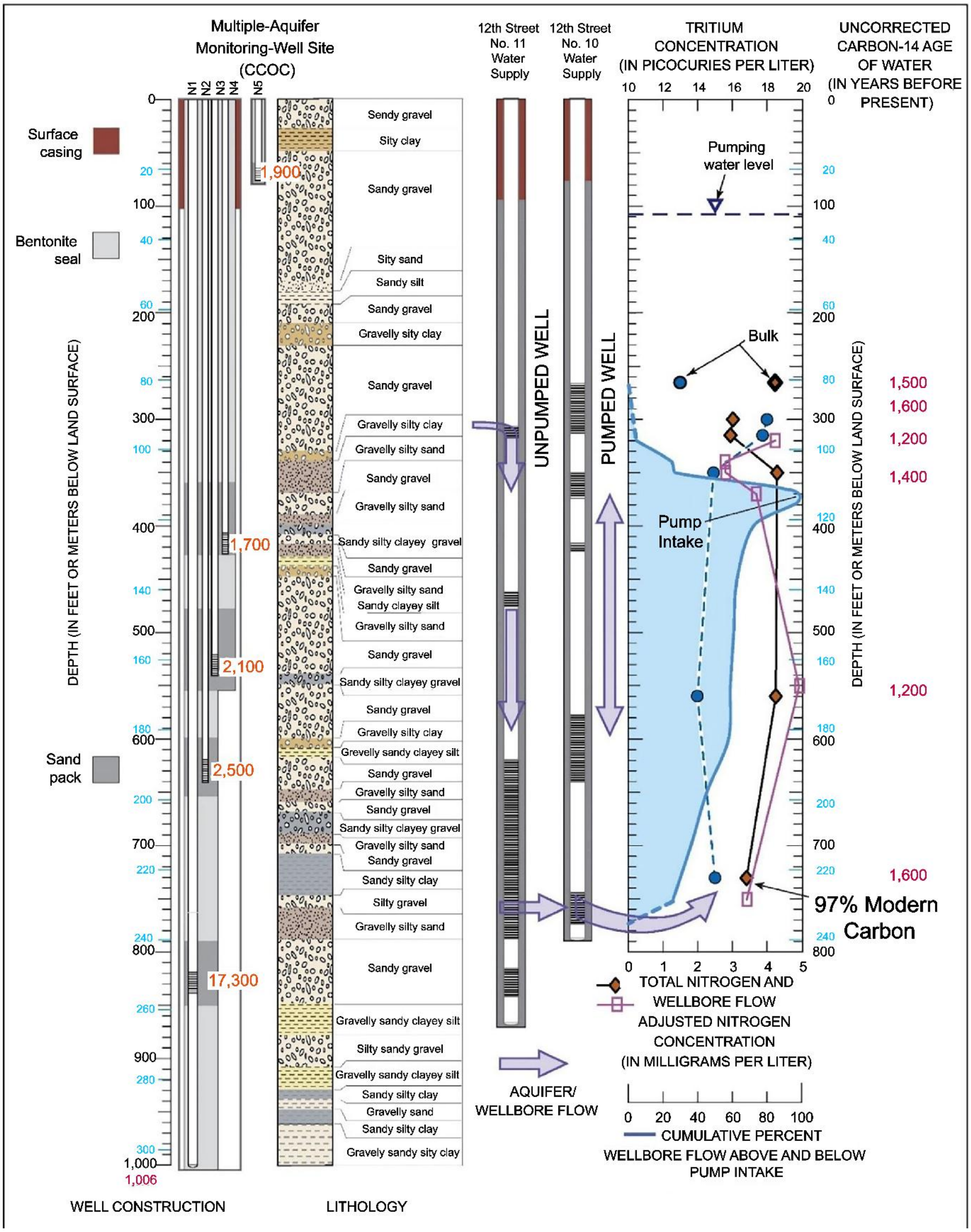


Figure 4 - Wellbore flow examples with a diagram showing distribution of wellbore flow in the 12th Street No. 10 water supply well, and its relation with adjacent water-supply wells in the well field known as the CCOC multiple-well monitoring site in the small, coastal Santa Clara Valley, California, USA (Figure 10 within Hanson, 2015). The numbers in red represent uncorrected carbon-14 ages-before-present for water at that depth and the lavender arrows represent the directions of wellbore flow.

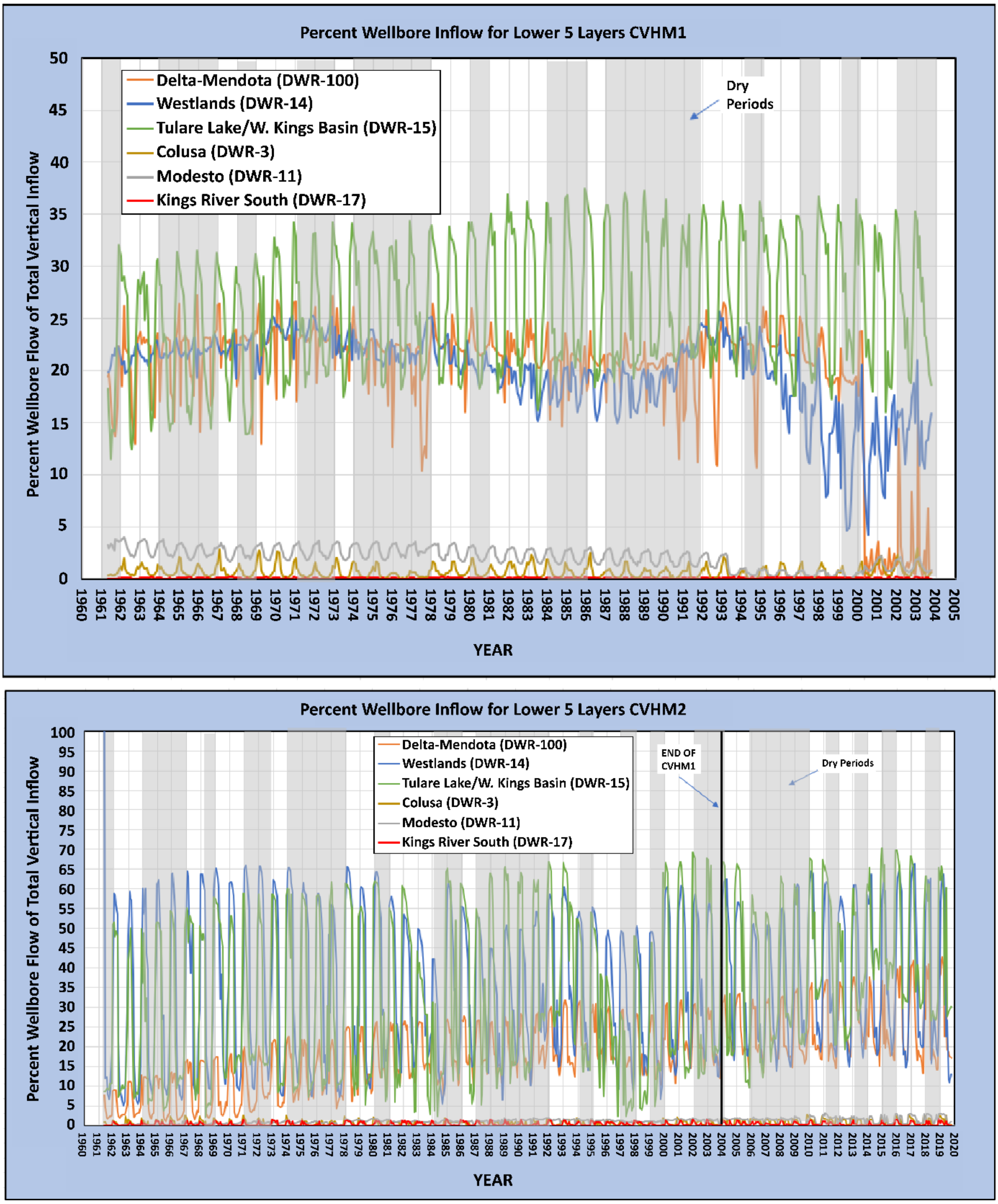


Figure 5 - a) Selected time series of the percentage of downward flow from simulated wellbore flow for the CVHM1 model of the inland Central Valley, California, USA (Faunt et al., 2009). b) Selected time series of the percentage of downward flow from simulated wellbore flow for the CVHM2 model of the inland Central Valley, California, USA (Faunt et al., 2024).

Foster and others (2010) report that informal conjunctive use of surface water and groundwater resources most commonly occurs where canal-based irrigation systems are:

- inadequately maintained and unable to sustain design flows throughout the system;

- poorly administered, allowing unauthorized or excessive diversions;
- overstretched with respect to surface water availability for dry season diversion; and
- tied to rigid canal water delivery schedules and unable to respond to crop needs or drought conditions.

Yet, the biggest driver of conjunctive use is fueled by a *growth* business model that fundamentally conflicts with sustainability of natural resources given the related continued development of land use for agriculture, industry, and urban growth. Demand also may exceed supply or timing of supply from canal systems due to increases in land use development or intensification of crop-water demand, such as hardening of demand from the need to irrigate permanent crops over decades. Additionally, informal conjunctive use is also driven to a large degree by poor reliability of water quality in surface water supply channels. While wells have become viewed as an insurance against this unreliability, doing so has resulted in overexploitation with groundwater mining and additional agricultural development and urbanization, as well as capture through increased infiltration of surface water supplies that were previously assumed to arrive downstream for use.

Poor water quality is a common factor at the tail of most irrigation canal systems and beneath agricultural areas. It usually reflects concentration of salinity owing to irrigation evaporation as well as salt flushing from runoff and deep percolation return flows. These factors lead to inadequate irrigation services because of the increased demand for irrigation for salt flushing. For example, the degradation of groundwater below the agricultural lands in the Oxnard Plain (coastal region of the Santa Clara–Calleguas Basin, California, USA, is due to accumulation from inefficient irrigation that resulted in perched groundwater that is saltier than seawater (Izbicki, 1996). Consequently, drilling of private water wells usually proliferates, often followed by a growing reliance on groundwater (Foster et al., 2010).

Foster and van Steenbergen (2011) report informal (spontaneous) conjunctive groundwater and surface water use in Indian, Pakistani, Moroccan, and Argentinean irrigation-canal surface water systems (aka *commands*), which have largely arisen due to inadequate surface water supply to meet irrigation demand. This situation does not only occur in developing countries—it is also an inherent problem wherever canal-based irrigation is practiced and where there are challenges in terms of the reliability and quality of the water supply. These examples also exemplify the unplanned expansion of demand that, combined with climate variability, commonly drives the supply shortages from related additional land-use development in agricultural regions (Uttar Pradesh - India - Box 1).

In summary, the spontaneous (informal) approach to the conjunctive use of surface water and groundwater sources reflects a *legacy of history*. However, many Indigenous cultures have administered these water distribution systems for centuries, with some still in use today. Yet some of the most elaborate systems, such as Mayan ones, were also prone to supply-and-demand failures, owing to overexploitation combined with climate variability

(Fagan, 2008); there are other examples of the decline of Indigenous groups related to multi-century climate variability (Renteria et al., 2022).

The focus for greenfield irrigation developments is primarily access to water, rather than the efficient and optimal use of that water; a consideration that does not gain attention until competition for water resources intensifies. Advancing beyond the farm-scale informal (spontaneous) access to each water source to a formal (planned) CWM approach entails significant technical, economic, institutional, and social challenges that can only be overcome with an effective governance and funding model combined with comprehensive scientific monitoring and analysis.

5 Highly Versus Poorly Connected Systems

When groundwater and surface water are hydraulically connected, the interchange of the resource and the drivers that affect it must be considered during the monitoring, analysis, and governance of the sustainability framework management process. Accordingly, their degree of connectivity with one another must be considered within a CWM framework. The degree of connection can shape the available options and hence define the optimal approach and potential contingencies needed for adaptation and mitigation in order to achieve a sustainable CWM framework that minimizes disparities between supply and demand, promotes sustainability, and reduces potential conflict between transboundary neighbors (Conceptual Exercise 7↴).

The different time scales that apply to groundwater and surface water typically lead to groundwater buffering fluctuations in surface water availability. The World Bank Group (2023a, 2023b) summarized the economic accessibility, resource availability, and buffering capacity of groundwater systems for four general types of aquifer systems:

1. local shallow,
2. major alluvial,
3. complex, and
4. karstic.

Local shallow aquifers typically are highly connected to surface water, while major alluvial aquifers may be well connected their magnitude relative to the surface water system renders the connection less dynamic. Complex aquifer systems are typically not as well connected to surface water, while karstic aquifers are often an integral part of surface water flow. Because the dynamics of connectivity may affect supply and demand disparities and ecological health, all of these systems potentially require some degree of institutional involvement relative to CWM sustainability.

Other factors that influence the connectivity groundwater and surface water systems include the layering of alluvial systems and the nature of openings in complex aquifers (e.g., fractured bedrock aquifers with secondary permeability and karst aquifers with tertiary permeability). The key message from the World Bank analysis underlines the utility of groundwater systems as buffers for human and environmental uses in the context of climate change as nature’s insurance, helping to protect food security, reduce poverty, and boost resilient economic growth. Yet the connectivity between surface water and groundwater systems and the related vertical distribution of well screens relative to layering or other forms of permeability will largely control the extent of interchanging flow between groundwater and surface-water systems.

Hydraulic connectivity between these types of aquifers and their watershed comprises two important components: the degree of connection between the two resources (Figure 6) and the time lag for extraction from one resource to affect the other. A highly connected system has a relatively short time lag for transmission of impacts: on the order of days or weeks. A fundamental tenet of connectivity is that, essentially, all surface water and groundwater systems are connected and that it is just a matter of time for impacts to be felt across the connection (Technical Question 1⮧).

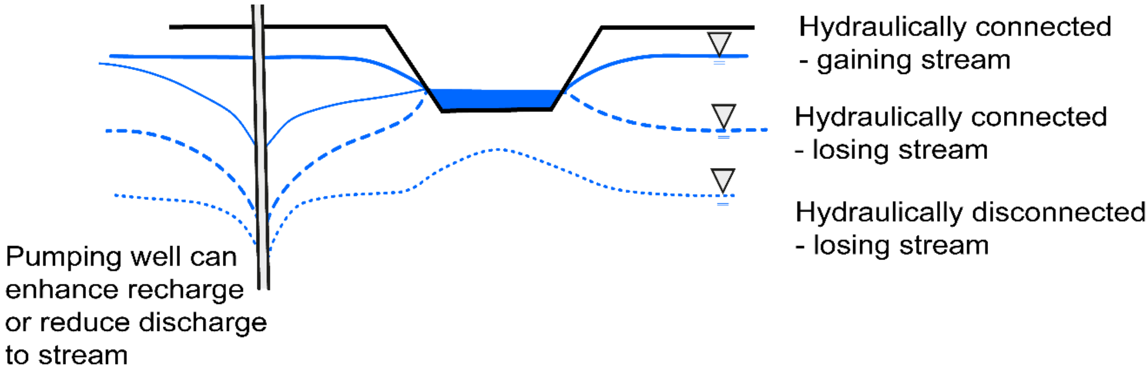


Figure 6 - Stream–aquifer interaction connections (Evans & Dillon, 2017). Pumping can increase recharge to the aquifer by lowering the water table and thus both reducing evapotranspiration and increasing seepage from streams, which in turn reduces streamflow and evapotranspiration.

An important exception to this analogy is the use of lined canal-dominated irrigation that is now automated and monitored across the entire distribution system. Where the water table is below the water level in an unlined canal system or where the water table is shallow, groundwater extraction may also capture groundwater that previously outflowed as evapotranspiration (ET) or groundwater outflow.

In other systems, either tile drainage systems a few meters below the land surface and below the typical root depth of the crops or unlined peripheral canals are commonly used as drain networks to capture groundwater from inefficient irrigation and rainfall. This use helps reduce groundwater levels that potentially waterlog the interval of root zone for non-phreatophyte crop types causing anoxia and reduced crop production as, for example, in the Lower Rio Grande Valley of the southern USA and northern Mexico (Hanson et al., 2020). In such areas, artificial recharge may also be dominated by the inefficient irrigation-induced root zone drainage, and hence vertical unsaturated-zone flow and shallow lateral groundwater flow may control the interaction/connectivity process.

In these latter areas, the canal distribution systems may provide a significantly reduced contribution to groundwater extraction. When these canal systems are used for drainage control, they can also substantially contribute to the reuse of precipitation and irrigation return flow from runoff and inefficient irrigation recharge. For example, in the Lower Rio Grande of New Mexico and Texas, USA, about 20 to 30 percent of this water is captured and reused downstream (Hanson et al., 2020; Lower Rio Grande, New Mexico, Texas, USA, and Conejos-Medanos, Chihuahua, Mexico - Box 7⮧).

The salient issue for CWM, especially in a planned environment, is to understand the nature of connectivity as a factor in resource use optimization and to ensure that connectivity is understood when considering water resource accounting in a conjunctively managed water system. This water resource accounting now commonly requires automated data collection and very well managed irrigation scheduling (down to minutes to days duration) with the help of soil-moisture or plant-stomatic pressure sensor networks to guide irrigation and even drive deficit irrigation. So, conjunctive use now includes the agricultural demand referred to as the total farm delivery requirement combined with the ephemeral storage and drainage of the soil and root zones.

Impact timing is also very important. Bredehoeft (2011) showed that timing is important to water-resource managers whether the impacts from groundwater pumping on a stream occur within an irrigation season or over a longer period. Connectivity will control the timing and the lag for groundwater recharge and the timing of changes in discharge from groundwater to the streams due to groundwater abstraction and climate variability. This timing can result in capture of groundwater discharge as well as additional capture of streamflow that can exacerbate secondary impairment issues noted above, for example, fish passage flows, GDEs, and floodplain habitat.

In connected systems, a serious issue of double accounting often arises. Double accounting occurs where the same volume of water is potentially attributed to both the surface water and groundwater resources. It is a common occurrence throughout the world due to the evolution of water resource development and associated regulatory arrangements, and it may reflect an absence of a proper water resource assessment, poor understanding of the water balance, or the undertaking of independent resource assessments for surface water and groundwater.

There are two common double accounting situations, the first being when surface water-based irrigation canals cause recharge to the groundwater system. This groundwater recharge is seen as a loss from a surface water point of view. A typical water resource management response may be to invest in improved sealing canals or constructing pipelines; however, doing so may not be the most efficient way to save water and energy. In some regions, canals are being used for groundwater recharge, such as in the Lower Rio Grande Valley, New Mexico, USA, and the Central Valley, California, USA. Combined now with complete automation of headgates and diversion gates, these more modern surface water networks save water and labor.

When unlined canals result in conveyance losses, this is an additional form of groundwater recharge, and the water may infiltrate as artificial recharge to the depths being pumped. But in settings with fine-grained layers, such infiltration is often prevented or retarded, so groundwater is not recharged and waterlogging occurs from perching of conveyance losses. This may also require other forms of capture such as tile or French drains below the fields, adjacent peripheral drain canals to capture the excess water, or even dewatering wells.

In situations where groundwater recovery is financially viable, it may be more efficient to utilize aquifer storage capacity and diffuse distribution of the resource provided by the groundwater system. However, aquifer storage and recovery systems also require infrastructure and maintenance and have an energy footprint. If in such situations, canal leakage (carriage losses) has already been allocated to surface water users, then it should not also be allocated to groundwater users or a combined surface water and groundwater allocation or water rights may impose additional limits within a conjunctive-use governance framework. Instead, mechanisms such as trade should be used to transfer entitlements from one user to another and, hence, maintain the integrity of the water accounting framework.

These water transfers can occur as leases or sales and may also require government review and approval as well as restrictions that may prevent or control basin exports. Furthermore, any decision to reduce leakage and recharge through canal lining would require revision to the water-resource assessment and may require appropriate adjustments to entitlements, particularly if such recharge had been allocated to groundwater users. However, some linings have deleterious effects in transboundary settings, such as the lining of the All-American Canal, California, USA, which terminated on the order of 60,000 ac-ft/yr (74 Mm^3/yr) of groundwater recharge that benefited the replenishment of groundwater in the Imperial Valley, USA, and adjacent Mexicali Valley, Mexico (Hanson et al., 2015).

The second double accounting situation relates to the classic surface water–groundwater interaction where groundwater is recharged through streamflow infiltration and also discharges as stream base flow. Both captured surface water as groundwater recharge and captured groundwater discharge as surface water base flow are part of the safe yield myth and have an impact on sustainability (Bredehoeft, 1997, 2002; Bredehoeft et al., 1982). Considered in isolation, this situation may be deemed as a loss from a groundwater management perspective and a basis for allowing groundwater pumping to substantially reduce stream flow. However, in other settings such as the Lower Rio Grande Valley, New Mexico, USA, the effects of surface water capture from groundwater pumpage interferes with surface water conveyance and related surface water allotments of downstream users (Hanson et al., 2013, 2020).

Similarly, from a surface water management perspective, the significance of groundwater discharge in maintaining stream flow during the dry season may be poorly recognized. There are many examples from around the world where not recognizing such interaction has contributed to the depletion of rivers, as well as infringement on water supply, GDEs, riparian habitat, and fish passage flows. The interaction requires an integrated resource assessment, with the water balance considering all extraction regimes and the consequential impacts on both groundwater and surface water resources.

Eliminating double accounting requires integrating water entitlements with a water balance that reflects the full hydrological cycle, and hence fully appreciating the amount and timing of the interaction between groundwater and surface water. It is also critical to appreciate the temporal variability of the process. In this case, it is important that the conjunctive planning time frame be long term and aligned with common climate cycles, for example 60 years or more could represent a positive plus negative Pacific Decadal Oscillation (PDO) that drives winter recharge in North America. However, some variable planning horizons over different time periods may be needed with other climate cycles, expansion of conjunctive use frameworks and water components, and other demand drivers, such as land use development and population growth. As shown for the transboundary regions of the USA and Mexico in the Rio Conchos, Mexico, watershed (Renteria et al., 2022), aligning a management/governance framework with climate cycles for these planning horizons can fall into four categories that are subject to different cycles of climate variability, land use, and governance:

1. annual-interannual, operations;
2. interannual-decadal, operations/governance in climate variability/change;
3. multi-decadal, infrastructure for bi-national climate change; and
4. multi-century, bi-national sustainability and adaptation.

Short-term planning to meet political or social objectives will not achieve effective CWM and related sustainability. There are some relatively rare situations where there is effectively no interaction between groundwater and surface water such as the largest known fossil-water aquifer system in the Nubian Sandstone Aquifer System of northeastern Africa. In such situations, CWM is relatively less complicated but nonetheless important in terms of achieving optimal water management outcomes. Planning, management, and governance may also need to account for the potential adverse effects of climate change and land use (Mendieta-Mendoza et al., 2021).

In cases where the two water resources are highly connected with short time lags, CWM may be supported by a transparent water accounting framework that can be reported on for both surface water and groundwater on a monthly to annual basis. The Rio Yaqui Irrigation District in Sonora, Mexico, USA, is a potential example of a formal CWM system with this operational framework that is connected to a Supervisory Control and Data Acquisition (SCADA) system and centralized control of all resources supplied. This framework may provide flexibility in the way surface and groundwater is allocated on an annual basis and could facilitate the development of a robust two-way water-trading regime between the groundwater and surface water systems—provided that third-party and environmental impacts are understood and effectively managed and monitored.

CWM in an environment where surface water and groundwater systems are poorly connected is unlikely to provide such a degree of integration. While there are opportunities for integration (such as the application of MAR, recycled, direct reuse, seawater desalination, and stormwater runoff capture) and for taking advantage of the unique attributes of groundwater and surface water (such as storage, distribution, and reliability in dry periods), the opportunities and benefits that have the potential to arise from CWM will be different, reflecting differences in the hydrological environment. In other words, within poorly connected systems, CWM will be framed around the task of complementary and integrated management of water use. However, even in poorly connected systems, both sources of water are commonly affected by the same demand drivers and may still require integration to consider natural hydrological linkages of the water sources within a supply-and-demand framework. Engineered solutions enable better (anthropogenic) connection between the two parts of the water system, and the climate, land use, industry, and public supply drivers are part of the capacity and flexibility of the engineered solutions. Additional governance, transboundary agreements, or treaties to facilitate management and sharing of resources may also be needed.

6 Benefits of CWM

Planned conjunctive management of surface water and groundwater is usually practiced at the state or regional level and can optimize water allocation with respect to surface water availability and distribution. While reducing evaporative losses in surface water storages and minimizing energy costs of irrigation in terms of kW/hr/ha (Foster et al., 2010) are some of the ancillary benefits of CWM, the overall distribution and management of water is fundamentally based on availability and related rights and indirectly by land use and climate variability. More modern integrated CWM also includes other sources of water and combined water management with climate assessments and monitoring. It also includes land-use management such as limiting additional land-use development (e.g., the *smart valley* developed by the Rio Yaqui Irrigation District in Sonora, Mexico; Distrito de Riego del Rio Yaqui, 2023) for agricultural CWM (Conceptual Exercise 8↴).

CWM systems for municipal supply can include combinations of surface water, groundwater, imported water, desalination, and recycled water sources as is the case for coastal urban centers such as Los Angeles, Orange, and San Diego Counties in coastal southern California, USA. While planned CWM is best implemented at the commencement of a development, optimal outcomes may be more difficult to achieve when attempts are made to redesign and retrofit the approach once water-resource and land use development is well advanced. However, new technology is making retrofitting more possible and more affordable.

Where groundwater and surface water are used conjunctively in various parts of the world, informal (spontaneous) use still commonly prevails. Foster and van Steenbergen (2011) emphasize that informal (spontaneous) conjunctive use of shallow aquifers in irrigation systems is driven by the capacity for groundwater to buffer growth in land use combined with variability of surface water availability enabling:

- greater water-supply security;
- securing existing crops and permitting new crop types to be established;
- better timing for irrigation, including extension of the cropping season;
- larger water yield than would generally be possible using only one source;
- reduced environmental impact; and
- avoidance of excessive surface water or groundwater depletion.

Another benefit of CWM in many settings where supply and demand of conjunctive use requires the active management of GDEs is globally summarized by Rohde and others (2017), who demonstrated how many locations have included management of GDEs as part of their sustainable groundwater policies. Managing and protecting GDEs has been highly developed in Australia and includes risk assessment. Similarly, protection of GDEs in California, USA, is also tied to protection of endangered species and maintaining fish passage and habitat, as well as sediment transport, flood protection, and river/runoff recharge infrastructure (as discussed for Queensland, Australia in Box 3).

Informal systems in some cultural and social settings may not include consideration of environmental impacts or degradation of water quality. This has become part of the framework for CWM of many formal systems such as SGMA in California, USA, but issues remain in other formal CWM systems such as the Murray–Darling Basin of Australia (Pittock et al., 2023).

The planned conjunctive management of groundwater and surface water has the potential to offer benefits in terms of economic and social outcomes through significantly increased water-use efficiency, but sustainability and reliability of resources cannot occur within an unlimited growth business model. This type of management must be linked to the other potential drivers of development and climate variability and require limits that facilitate managed growth within the capacity of the resources. Combined with these other sustainability and development constraints, CWM can help support greater food and fiber yield per unit of water use, an important consideration within the international policy arena given the critical concerns for food security that prevail in many parts of the world.

At the resource level, groundwater pumping for irrigation used in conjunction with surface water provides benefits that increase the water supply or mitigate undesirable fluctuations in it (Tsur, 1990). This also controls shallow water table levels with related water logging—and, consequently, soil salinity—and improves fairness of access to water across a catchment or basin. Various requirements, such as improved access, can be a defined objective if it is stipulated. These requirements within a CWM sustainability framework also need to consider environmental benefits and requirements.

7 Role of Managed Aquifer Recharge

An increasingly important tool used in CWM is managed aquifer recharge (MAR) (Dillon et al., 2016, 2019). This approach to artificial groundwater recharge is becoming more popular and is spanning the world from California, USA (Hanson et al. 2008. 2010, 2014b,c; Faunt et al., 2024) to South Africa (Braune and Israel, 2022) and Australia (Dillon et al., 2009a,b, 2012). MAR is the intentional recharge of water to aquifers for subsequent human use or environmental benefit. In many cases the primary water source is excess wet season surface water that can be stored in aquifers to secure or supplement dry season supplies and improve groundwater quality. It can be used by individual farmers to refresh their wells when there is flow in nearby ephemeral streams or perennial rivers but is increasingly used in planned approaches to aquifer replenishment.

MAR has emerged as an important linking technique that can often be used to encourage conjunctive management (Figure 7) particularly where aquifers and surface water systems are poorly connected. As a supply-side measure, MAR can increase the available total water resource and help mitigate the disparity between the timing of supply and demand, but it is not a substitute for effective demand-side management as well as direct use or reuse. While many CWM settings have not formally included MAR, the practice of inefficient irrigation is commonly the largest form of artificial recharge and is implicitly a historical form of MAR in irrigated agricultural settings. CWM has not historically included formal MAR operations but doing so is now becoming a widespread practice that can also include incentives such as a recharge credit or permission to capture runoff for recharge. For example, the California State Water Resource Control Board (CA-SWRCB) has formally implemented Flood-MAR in Executive Order N-4-23 (CA-SWRCB, 2023a) that includes permitting along with specific regulations and restrictions (CA-SWRCB, 2023a, 2023b). In other regions of the southwestern United States where the USBR operates reservoirs, the capture of runoff (“wild water”) on rivers such as the Colorado and Rio Grande is another institutional mechanism for locals to use runoff before it enters the formal river–reservoir management system.

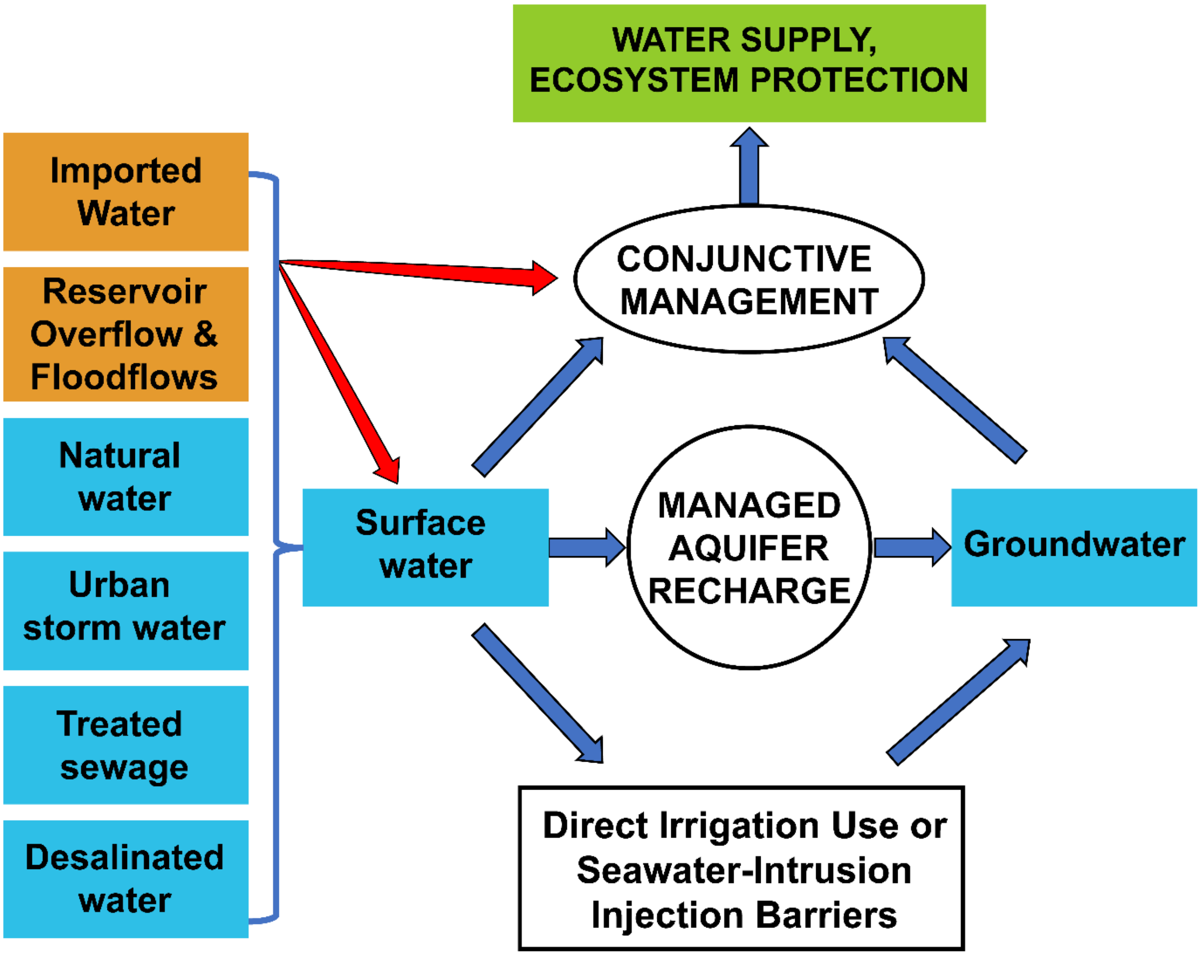


Figure 7 - The role of MAR in conjunctive water management (modified from Dillon & Arshad, 2016).

In areas with seasonal surface water excesses, supply-side measures such as MAR can protect, prolong, sustain, or augment groundwater supplies through recharge or direct use of this water. As one of a suite of integrated water resources management strategies, this approach expands local water resources, reduces evaporation losses, and assists with replenishing of depleted aquifers. The amount of recharge that is economically or technically achievable is generally less than the annual groundwater deficit, and a combination of demand management and recharge enhancement is essential to restore a groundwater system to equilibrium (Dillon et al., 2009b). The most effective mechanism is direct use of these captured, recycled, or imported water. When this water is used in a way that results in infiltration to shallow aquifers, it has the additional indirect benefits that a) multi-aquifer wells may deliver some of the water to deeper aquifers through wellbore flow and b) the passive nature of this activity reduces power consumption.

There are many methods for recharging aquifers (e.g., Dillon et al., 2009a) and these are selected based on local hydrogeological characteristics, sources, and the quality of water available to be harvested or captured. Importantly, cost per unit volume needs to be competitive with the foregone net benefits of demand reduction, considering the costs of managing supply and demand. The history of MAR is more recently summarized by Dillion and others (2019) and UNESCO (Zheng et al., 2021). The relative costs of MAR for some examples across the world were summarized by Ross (2022).

As an alternative to recharging the aquifer, groundwater supplies can be augmented or replaced by surface water supplies such as canals and pipelines. Doing so has the effect of reducing demand on the aquifer but is commonly perceived by groundwater users as supply augmentation.

The complementary roles of demand management and expanding supplies and types of supplies, either via MAR or by providing alternative supplies, are graphically depicted in Figure 7 for an over-allocated aquifer and for systems where demand exceeds all sources of local supply. Where surface water is in public ownership and groundwater in private ownership, MAR effectively privatizes public good, so MAR is best implemented where water entitlements are divorced from land ownership.

Some exceptions to this paradigm are occurring. For example, in the Pajaro Valley, California, USA, monetary credit can now be provided for recharge based on a recharge net metering program (novel-effort-aid-groundwater-California's-central-coast↗). The synergistic effect of MAR on demand management has much potential and is just beginning to be used systematically as shown for Pajaro Valley, California, USA, (CA-DWR, Water Users Handbook Revised 2020↗) (Pajaro Valley, Conjunctive-Use Modeling – Box 8).

Combining MAR with conjunctive use is growing in the face of increasing water demands and climate variability. For example, in a 445-km^2 groundwater irrigation area of Central Valley, California, a combination of MAR and conjunctive use over a period of 46 years (1968 to 2013) has helped to stabilize falling groundwater levels. Six of the ten water-banking operations recovered 4.1 km^3 of recharged groundwater during this period so the net replenishment was 9.4 km^3 of the total 13.5 km^3 replenishment (US Geological Survey, 2022).

The relationship between climate variability, water banking replenishment, and withdrawals for the Central Valley provides a good example of banking in wet periods and withdrawals in drier periods as part of CWM (Figure 8). This distribution of water banking and groundwater recovery from water banks along with climate variability indicates that these activities are closely linked and need to be part of an integrated CWM framework. Both measures are undertaken in the states of California and Arizona, USA, and contribute substantially to security of supply and sustaining groundwater levels (Scanlon et al., 2016) and at a cost substantially less than for constructing surface water storages (Perrone & Rohde, 2016). However, the latest mega drought (2000 to 2021) and overexploitation of land use—combined with overallocation of surface water—have resulted in continued water shortages. This has been accompanied by over-pumping of groundwater and has had secondary effects in the Central Valley with continued groundwater declines and related land subsidence, reduced stream flows, and increased salinity.

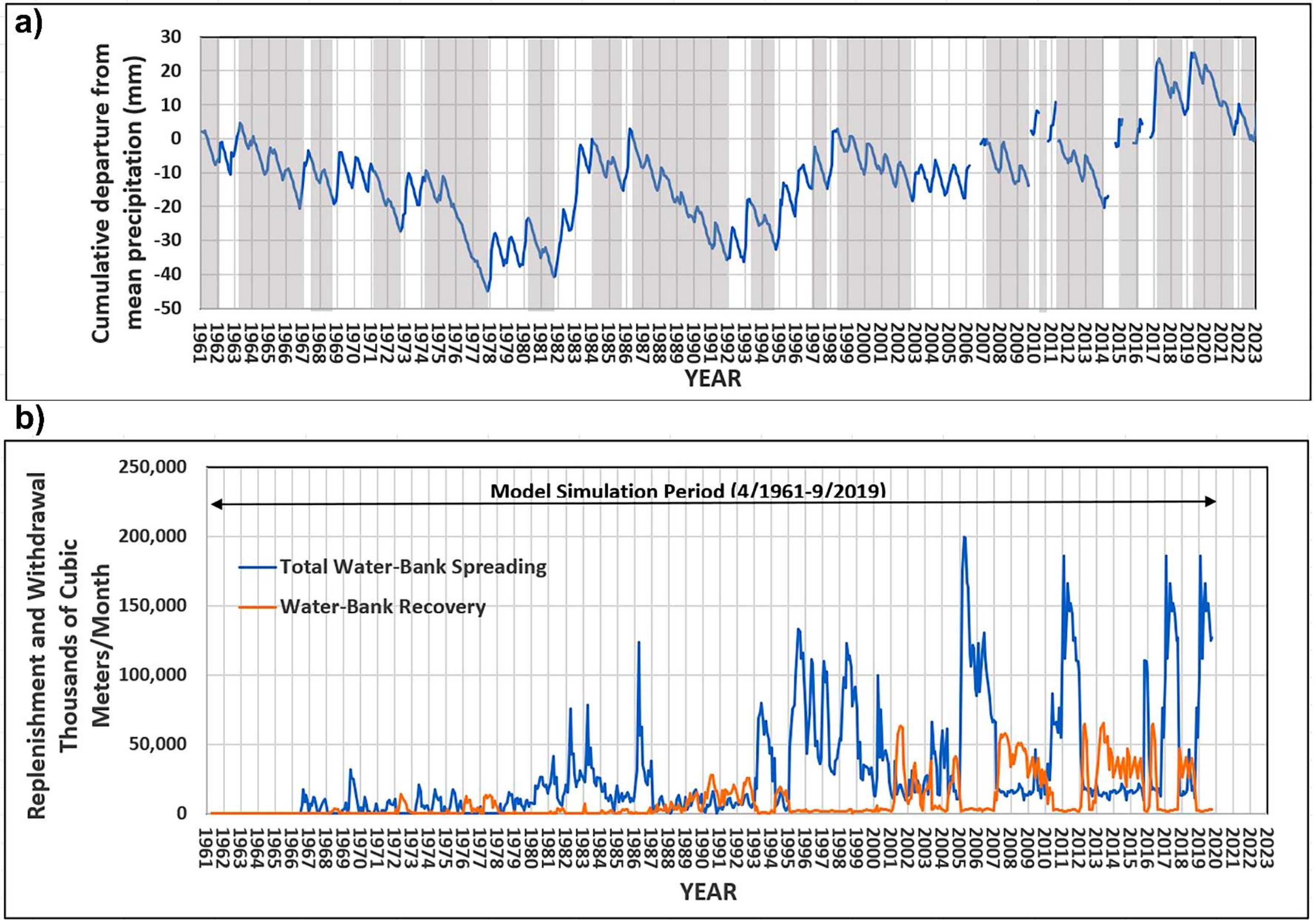


Figure 8 - Comparison of climate variability with water-banking spreading and recovery for the Central Valley, California, USA. a) Cumulative departure of precipitation from conditions starting in 1961 with positive slopes indicating increased precipitation. Gray regions with a negative slope generally indicate drier periods (USGS, 2022; CDEC, 2023). b) Time series of total water banking and recovery of groundwater from water banks (modified from Faunt et al., 2024).

In arid climates, the lack of availability of a water source constrains the opportunities for aquifer replenishment. Runoff is so infrequent in arid areas that investment in runoff collection and recharge facilities needs to be cost efficient as runoff is rarely available, and MAR is primarily for inter-year storage to increase long-term yield. However, alternative supplies such as treated wastewater and desalinated water as a byproduct of energy production are increasingly being adopted as sources for MAR and these are relatively constant sources of supply.

In semi-arid and Mediterranean climates, water availability is a smaller constraint and seasonal demand for water can be high, meaning that inter-season storage has high value in addition to inter-year storage. In both climates, factors other than climate are driving increases in water demand, including land-use development, and hardening of demand by switching to perennial higher-profit crops like orchards and vineyards. Also, many arid areas are now being developed to grow seasonal crops during the wintertime, thus creating a new mechanism for overexploitation of resources with year-round farming.

Inter-season storage can have immediate commercial benefits, whereas water banking for buffering against drought and climate change can have higher value but its benefits are not realized quickly, thus it requires institutional support for governance and costs of operation and maintenance, as well as additional infrastructure (Rodella, 2023a; 2023b). In humid climates, opportunities for natural recharge are greater and the demand for storage is less, so MAR is expected to have a minor or niche role. Yet capture and use of runoff does supplant most needs for development of groundwater resources in humid climates, too.

Van Steenbergen and Tuinhof (2009) and van Steenbergen and others (2011) have reported a wide range of watershed interventions that enhance groundwater recharge, retain soil moisture, and reuse water, which they term the 3R concept for climate change adaption, food security, and environmental enhancement. These interventions have also been applied in relatively small-scale projects in arid and semi-arid areas of Africa, Asia, and South America with startling results for improvement of the capability of land and farm income. Applications range from the individual landholder scale up to sub-catchment and catchment scale, typically at very low cost and with active stakeholder participation and community ownership (e.g., in Rajasthan and Gujarat, India; Maheshwari et al., 2014). However, the largest concern of many farmers is the intensification of climate variability within climate change resulting in more severe wet and dry periods, a trend that has led to the widespread development of canopied agriculture and large industrial-scale growing warehouses to help offset these extreme events and reduce water consumption. For example, canopied agriculture is already widespread in several arid, Mediterranean, and tropical desert climate settings in Spain, Mexico, and the state of California, USA. With longer-term cycles from both the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and multi-century cycles—along with millennial solar oscillation (Renteria et al., 2022)—mitigation and adaptation within agriculture will continue to look for more *closed loop* solutions that maximize productivity and minimize the effects of climate and water scarcity.

MAR can increase the value of water resources by transferring surface water in times of abundance to add to groundwater storage and thereby conserve water, the technique of capturing runoff and excess reservoir storage water is commonly referred to as Flood-MAR. It replenishes depleted groundwater and avoids evaporative losses, salinity increase, and possibilities for blue green algal blooms if the water had been retained in surface reservoirs.

The surface water used for MAR can be excess water from reservoirs that have exceeded their capacity but also may include natural water from catchments, urban stormwater, water recycled from treated sewage effluent, desalinated water from brackish aquifers or the sea, and suitably treated industrial effluents. Since treated effluent and desalination processes have a relatively constant production stream, it is critical to have a combination of recipients and additional surface or groundwater storage to accommodate the through put. This challenge became apparent in the Pajaro Valley (Figure 9a) where treated wastewater and MAR water was used to supplant groundwater pumpage to reduce groundwater overdraft and related seawater intrusion (Hanson et al., 2014b). In this example, most irrigation was scheduled at night and delivery targets were problematic until above-ground storage tanks provided a buffer between supply and demand. This approach allows analysis of the use of this scheme within an integrated hydrologic model (Figure 9b) to further assess its efficacy—subject to sustained operations over decades into the future coupled with climate change and variability (Hanson et al., 2014e; Pajaro Valley, Conjunctive - Use Modeling - Box 8).

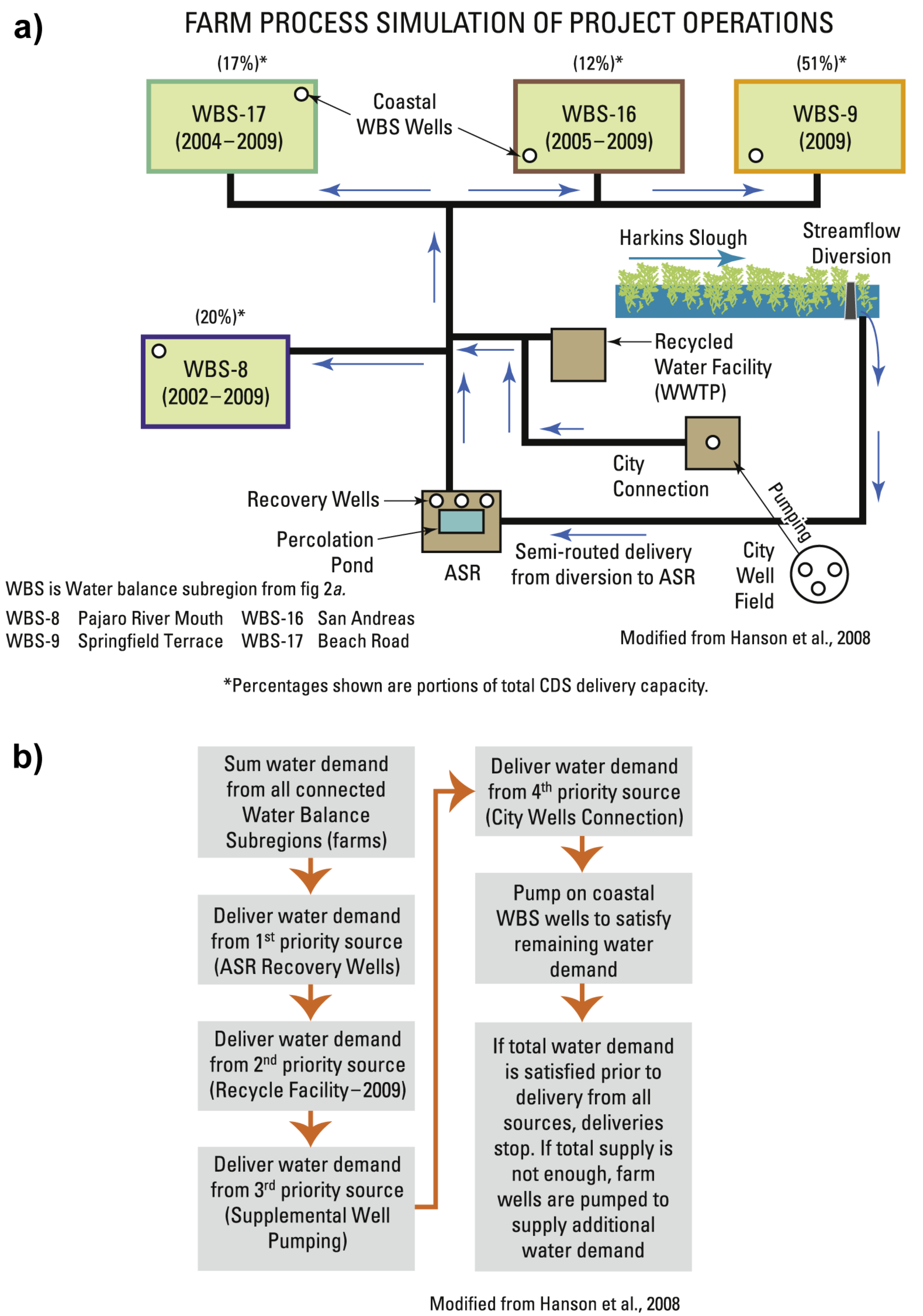


Figure 9 - a) Structure of local water deliveries, and b) hierarchy of simulated operation of water deliveries from the aquifer-storage-and-recovery (ASR) system and the Coastal Distribution System (CDS) to regions serviced by the CDS, Pajaro Valley, California, USA (modified from Hanson et al., 2014b).

For any aquifer, a range of recharge options can be ranked in order of increasing unit cost of supply. Similarly, foregoing extraction for each use of groundwater will have a range of unit costs that can be ranked in increasing order. Each element of the water uses is associated with a list of ranked extractions that has an associated volume and unit cost. The two lists can be merged to a) identify the cheapest option and b) determine the volume of demand reduction or supply enhancement expected if that option was implemented. Depending on the degree of over-exploitation, a series of options may be required to reduce groundwater storage depletion and help promote the sustainability of groundwater resources subject to the forces of supply and demand (Figure 10; Conceptual Exercise 9↴).

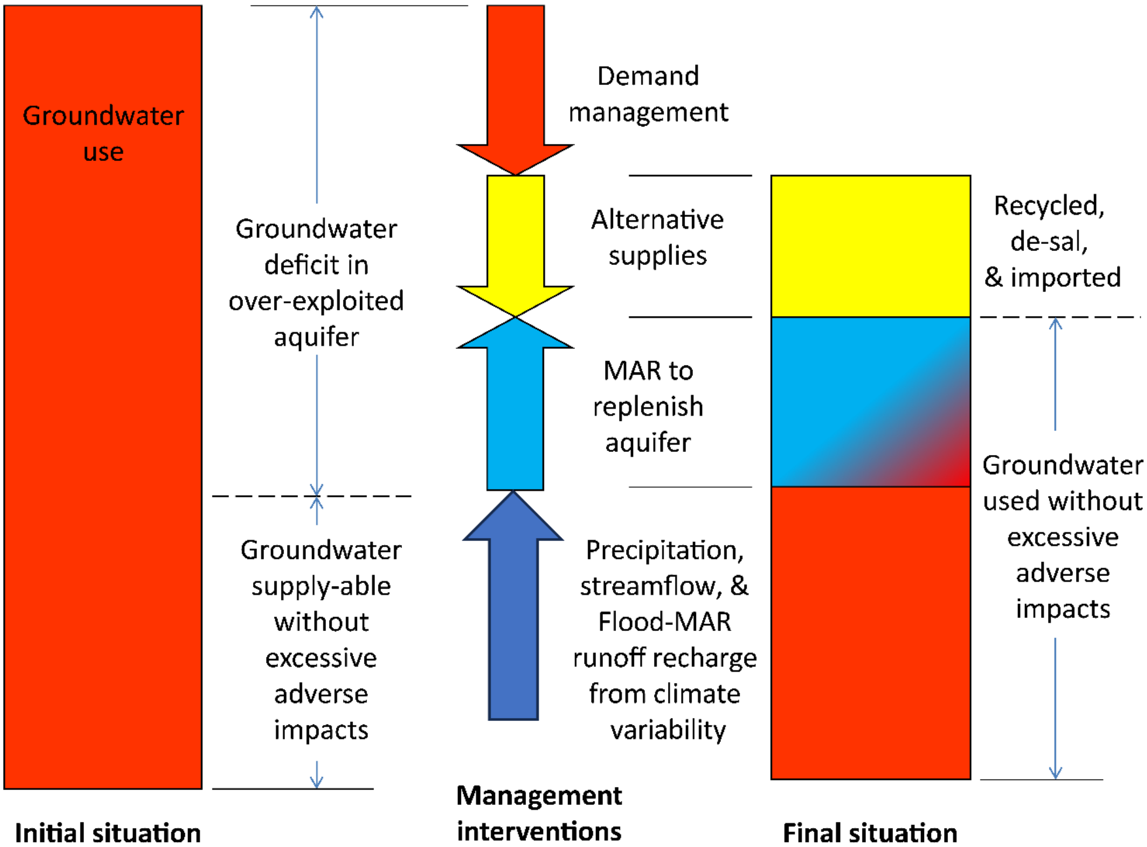
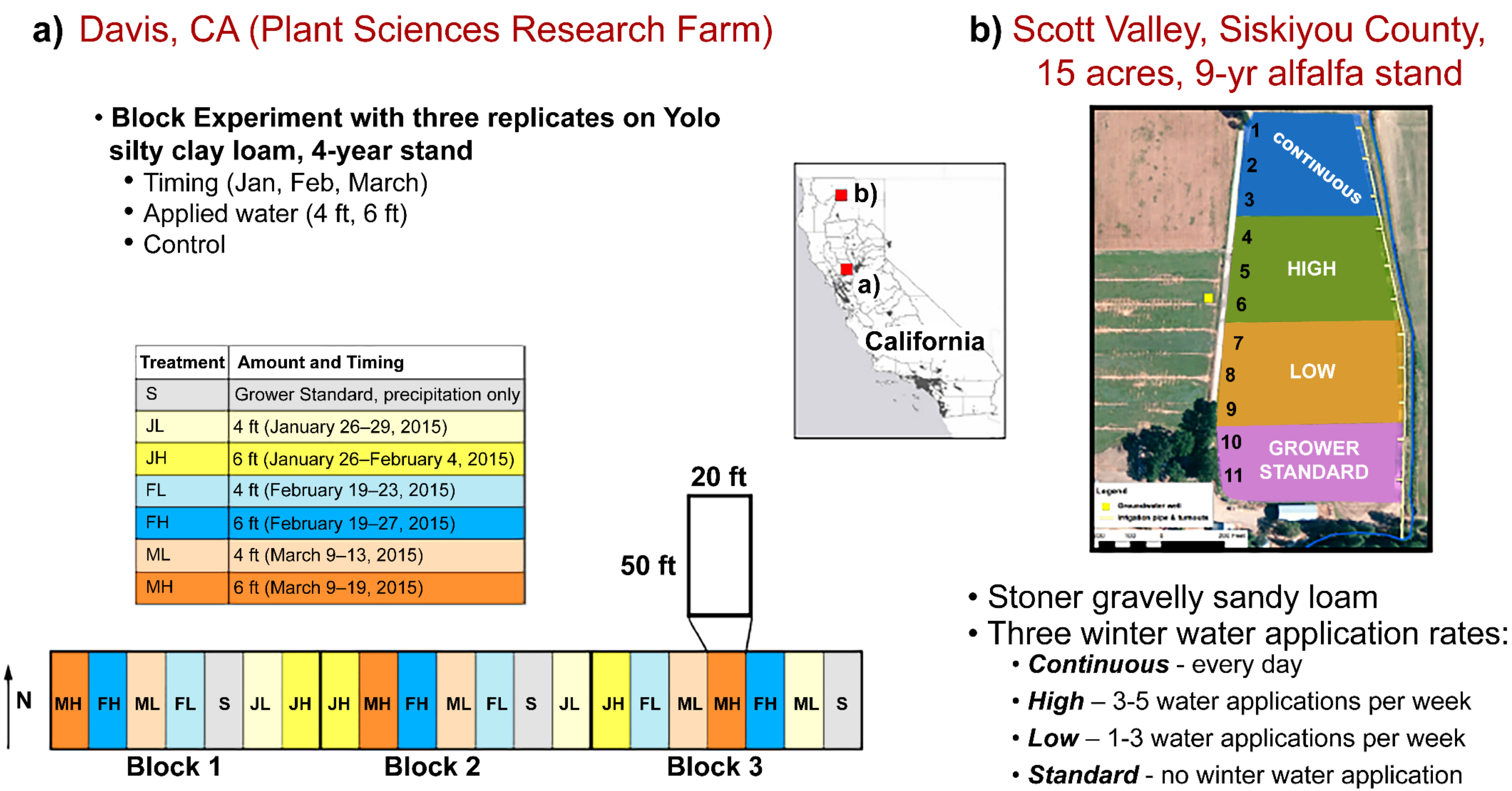


Figure 10 - The severity of the disparity between supply and demand within the dynamic nonequilibrium of an aquifer can be reduced by reducing extractions (demand), augmenting supplies, or both. Options for achieving this include groundwater replenishment, providing alternative sources of supply (conjunctive use), reducing land uses that have high water demand, and/or reducing other water demand drivers (modified from Dillon et al., 2012).

While water may be one of the lower production costs in most agricultural and economic settings, improving water use efficiency and water productivity is generally the cheapest option, followed by MAR replacing high-consumption low-profit crops (such as forage crops like alfalfa) with high-value and lower-consumption nut, orchard, grape, and seasonal fruit/vegetable crops. Integrated management of surface water and groundwater helps ensure that the benefits of recharge upstream outweigh decline in surface water availability for downstream delivery commitments. Flood mitigation may, in fact, be a recharge benefit, as currently explored in the wetter climates of Thailand and India (Pavelic et al., 2012, 2015; Reddy, 2020).

Flood management as a source of recharge in the USA is exemplified by the new Flood-MAR program implemented in Pajaro, California, USA, as well as being implemented in the Central Valley, USA (CA-SWRCB, 2023a), and its feasibility investigated in selected agricultural regions of California (Dahlke et al., 2018; Kocis & Dahlke, 2017). For example, the availability of high-magnitude streamflow for groundwater banking was evaluated (Kocis & Dahlke, 2017). High-magnitude flows (HMF) are river discharges that exceed a specified threshold, typically the 90th or 95th percentile of historical streamflow. HMF in the Sacramento River and San Joaquin-Tulare Basins of the Central Valley, USA, were estimated using data from 93 streamflow gaging stations. HMF occurred in about 7 and 4.7 of 10 years, respectively, resulting in five to seven one-day peak events within flood flows lasting 25 to 30 days between November and April (Kocis & Dahlke, 2017).

However, this recurrence-probability estimate ignores the temporal cycles of climate variability that also need to be considered for complete management strategies. Nonetheless, this analysis indicates sufficiently unmanaged surface water is available to potentially mitigate long-term groundwater overdraft in the Central Valley of California, USA (Kocis & Dahlke, 2017). In addition, the efficacy of Flood-MAR on various types of land use was evaluated for potential use (Dahlke et al., 2017, 2018) taking into consideration the combined application of precipitation and flood water for alfalfa fields and almond orchards with different soils (Figure 11). These study examples confirm that groundwater recharge from infiltration through the soil zone typically occurs within weeks to a month of the flood event.



Treatment	Amount and Timing
S	Grower Standard, precipitation only
JL	4 ft (January 26–29, 2015)
JH	6 ft (January 26–February 4, 2015)
FL	4 ft (February 19–23, 2015)
FH	6 ft (February 19–27, 2015)
ML	4 ft (March 9–13, 2015)
MH	6 ft (March 9–19, 2015)

Figure 11 - Field layout of the experimental sites for on-farm experiments at a) Plant Sciences Field Facility (Plant Sciences Research Farm), Davis, CA (California). For the Davis site, a randomized complete block design consisting of seven treatments with three replicates was implemented. The table in (a) summarizes the treatments for the Davis site. S is the control, and is the Grower Standard with precipitation only applied. The letters L and H stand for low and high applied diverted water amounts of 4 ft and 6 ft, respectively, which are combined with letters J, F, and M to indicate the month in which the winter recharge was performed (i.e., January, February, March); and b) Scott Valley, in Siskiyou County, California (Dahlke et al., 2017, 2018).

Additional Flood-MAR infrastructure includes the use of inflatable dams on a footwall dam or gabions to enhance infiltration, provide intermittent diversions to recharge ponds such as on the Santa Ana River, California, USA, or to facilitate intermittent diversion of surface water from larger stream flows such as the Salinas River, California, USA. This type of infrastructure also allows for fish migration, sediment transport, and can be used as needed, based on streamflow and other environmental factors. For example, a footwall dam is also used to enhance diversions of reservoirs such as to Lake Casitas from the Ventura River, California, USA.

Another significant consideration in water banking and CWM is water quality and salinity. Many previous strategies have advocated leaching for salinity management (Cahn & Bali, 2015; Ayers and Wescot, 1985; Rhoades; 1972, 1977, 2012; Rhoades & Merril, 1976). However, this approach generates additional demand for water to flush salinity from soils and can result in additional degradation of groundwater quality due to artificial recharge of saline water and saline runoff to surface water networks. More recently, management programs such as CVSALTS (2023) have also focused on source control to help minimize the accumulation of salinity in soils, increase groundwater recharge, and reduce surface water runoff from agricultural return flows through additional management of conjunctive use. The increased demand related to salinity flushing was exemplified by modeling that results in the potential for a 22 to 38 percent increase in irrigation water demands (Figure 12a), with a 20 to 80 percent increase in groundwater pumpage to facilitate salt flushing (Figure 12b), a 22 to 43 percent increase in irrigation of vegetable row crops, and a 24 to 34 percent increase in irrigation of orchard crops (Figure 12c; Boyce et al., 2020).

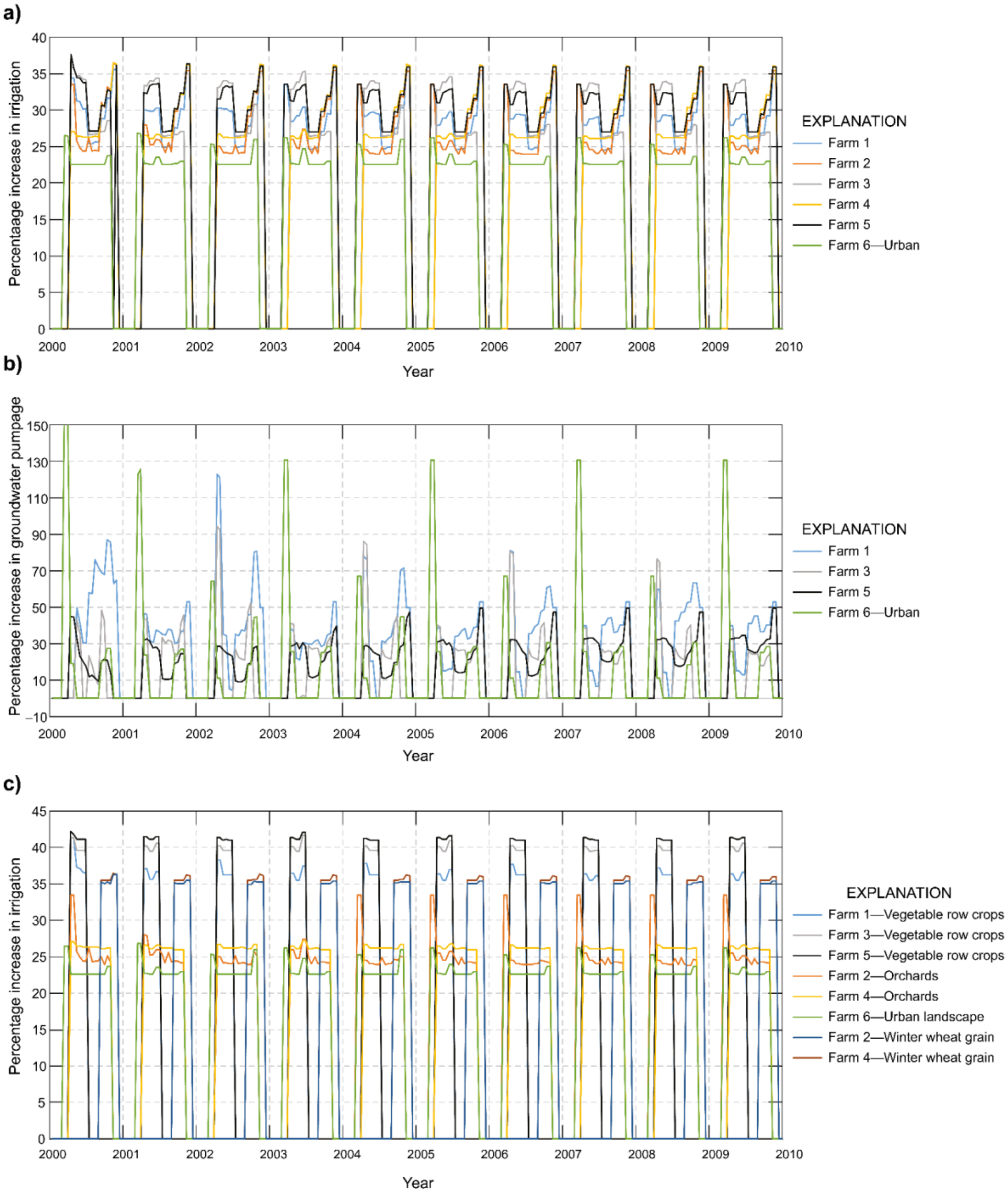


Figure 12 - Relative increase of water use when leaching is used to flush salinity based on simulations using an example model both with and without flushing to control salinity: a) irrigation, b) groundwater pumpage, and c) additional irrigation for selected crops and farms (Boyce et al., 2020).

8 Analysis and Modeling Approaches for CWM

8.1 Integrated Surface water and Groundwater Models

CWM involves the optimum use of all water sources, including surface water and groundwater While in some settings CWM may not necessarily involve surface water–groundwater interaction, many systems that only have groundwater may have water sources that can be incorporated into the CWM framework such as precipitation, runoff, FloodMAR, recycled, MAR, imported, and desalinated. For example, locations like the Pajaro Valley, California, only provided groundwater but more recently have included MAR from captured runoff and recycled water sources (Hanson et al., 2014b, 2014c). CWM may only involve how and when to use any and all independent resources and could involve a preference of some sources over others relative to the timing of demand and the potential disparity between supply and demand. Understanding the spatial and temporal aspects of demand and availability (supply) of all water resources is a key part of CWM and may include changes in sources with continued development of a sustainability framework within CWM beyond groundwater and surface water sources (Conceptual Exercise 10↴).

One way to understand how surface water and groundwater sources can be used together and in concert with other natural and anthropogenic sources, and to define the amount and timing of the interaction (if any) is through analysis of the output from an integrated hydrologic model that includes the simulation of climate, land use, as well as groundwater and surface water use and movement. Analysis in this context can also refer to the use of relatively simple analytical tools to initially understand the amount and timing of interactions before using more complete model-analysis tools (Other Modeling Examples - Box 9↴).

Use of data analysis and analytic tools is commonly an initial step to determine the most appropriate numerical modeling approach. However, many hydrologic settings violate the simplifying assumptions of analytical tools. Modeling is often used to determine the amount of interaction between surface water and groundwater as well as to simulate scenarios of different management approaches so as to optimize use of the total water resource in the context of defined objectives and constraints.

A very broad range of tools is available to analyze the integrated use and movement of all water everywhere all the time in various settings and especially interactions between surface water and groundwater supplies. This discussion divides the different approaches into two broad groups (Hanson & Schmid, 2013; Hanson et al., 2010; Nathan & Evans, 2011):

1. analytical and other methods and
2. numerical.

Water balance approaches, the use of tracers, and hydrological (surface water) models are typically used to quantify surface water and groundwater interactions at a single point in time and may be site-specific, synoptic events, such as at a well or streamflow gaging site, whereas analytical and integrated hydrologic (numerical) models are usually used to understand and predict how the interactions change over time (Conceptual Exercise 11↴).

8.2 Analytical and Field Methods

Many analytical solutions are available to estimate the interaction of groundwater with streamflow, which is often a major component of CWM. These solutions are based on the original work by Glover and Balmer (1954), which were refined and modified by many authors, especially Hantush (1965), Neuman (1974), Neuman (1975), Hunt (1999), and Reeves (2008). Sophocleous and others (1995) provided some indication of the likely errors associated with using analytic solutions, which are based on idealized assumptions.

The water balance approach is a quantification of a conceptual hydrogeological model. In many cases, this basic approach should be undertaken before any numerical modeling is carried out. Various flows between different components of the hydrologic cycle would—ideally—need to be quantified to better understand their interaction (Figure 13). However, every flow between the different components of the hydrologic cycle within such a water balance is subject to uncertainty associated with both measurements and model assumptions that can be many times greater than the magnitude of the interaction flows of interest. Although a water balance approach coupled with an integrated hydrological model (IHM), may not be helpful in meaningfully quantifying the volume of the interaction, it can help evaluate uncertainty in the magnitude of these fluxes relative to other flow components, to field measurements, and to related flux controlling properties within the model. Thus, a combination of analytical and IHM methods may be warranted for some settings and CWM evaluations of some events.

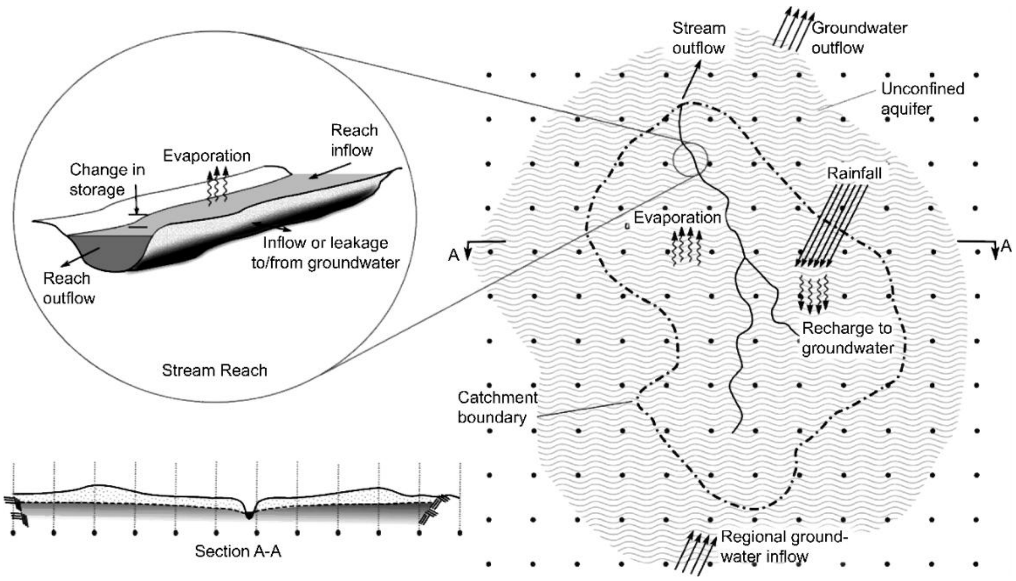


Figure 13 - Schematic illustration using a hypothetical catchment for evaluation of surface water–groundwater interaction (from Nathan & Evans, 2011) with dots indicating nodes of a groundwater flow model. Other sources of water can include runoff from adjacent catchments, mountain-block recharge (peripheral groundwater underflow), and losses from evapotranspiration.

A range of field-based methods have been applied to measure the flux between surface water systems and groundwater. These techniques are generally local-scale and, although useful, the results are very locale-specific. Three major field techniques commonly used are:

1. temperature studies,
2. seepage meter measurements, and
3. tracer studies.

Additional indirect estimates on a more subregional to regional scale include the streamflow differences between upstream/downstream gaging stations as an estimate of gains and losses to groundwater between gaging stations and the measurement of surface water diversions and return flows. These estimates indicate the level of loss to groundwater infiltration and related conveyance to the point of diversion as well as any net returns from diverted water, respectively.

Temperature studies can include vertical analysis of temperature profiles at specific points as was completed by the USGS at the Rillito River in Tucson, Arizona, USA (Hoffmann et al., 2007). Additional studies were performed along the Pajaro River and Corralitos Creek in Pajaro Valley, California, USA, to estimate flows and transmission properties (Hatch et al., 2006) that could be used in integrated hydrologic models (Hanson et al., 2014b, 2014c). The USGS also provides extensive examples and guidance on how to design these measurements and measurement sites (Stonestrom & Constantz, 2003) with case studies provided by Stonestrom and others (2007). More recently the use of fiber optic cables buried across stream channels and towed thermal sensor arrays can yield estimates of wetted perimeters as well as the timing and duration of groundwater infiltration or exfiltration events (Mohamed et al., 2021).

Examining changes in tracer concentrations in stream flow is useful in quantifying groundwater contributions to streamflow but requires tracers that potentially have a wide range of detection including very low concentrations. In addition, repeated synoptic seepage studies can be useful to monitor the gains and losses between groundwater and surface water flows as was done on the Lower Rio Grande for decades of annual winter seepage measurements (Hanson et al., 2020; Briody et al., 2016; Crilley et al., 2013; Byrd et al., 2002; Borland & Beal, 1988; Ortiz & Lange, 1996; Miller & Stiles, 2006).

The seepage in this context is calculated as the difference in streamflow from nearby and sequential in-stream channel profile flow measurements. These types of gain and loss estimates not only provide estimates of surface water and groundwater interaction and changes in conditions but also provide an additional set of *higher-order* observations needed for integrated hydrologic modeling (Hanson et al., 2020). The gains and losses to streamflow for the Lower Rio Grande in New Mexico for selected years of winter streamflow when the reservoir is not releasing water is an example of how these observations were used to help calibrate the surface water–groundwater interaction components of an IHM model with field and model observations of groundwater seepage gains/losses (Figure 14).

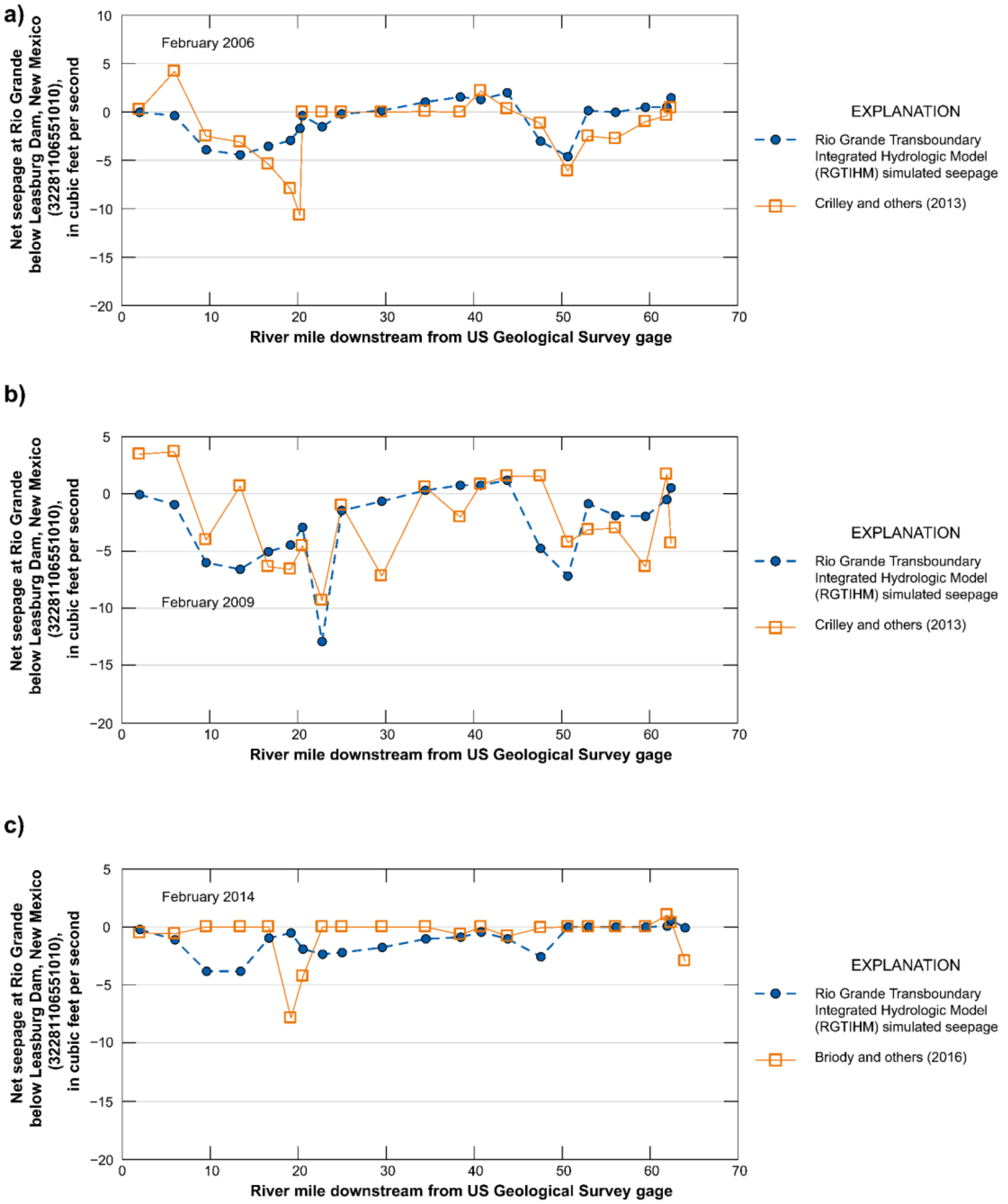


Figure 14 - Simulated and observed streamflow hydrographs for selected Rio Grande winter-seepage estimates, where positive values represent seepage gains, and negative values represent seepage losses, Lower Rio Grande, New Mexico, USA: a) February 2006; b) February 2009; and c) February 2014 (Hanson et al., 2020).

8.3 Numerical Models

Many numerical modeling codes can simulate the exchange of water between groundwater and surface water bodies. They all have their advantages and disadvantages when considering different aspects of the hydrologic cycle, climate, and land use. Multiple levels of hydrologic models can represent and estimate different features and different degrees of coupling between features. They can be placed in three categories.

- Models that simulate only one or the other of groundwater or surface water and treats the other type of flow as one of three types of user-specified boundary conditions (i.e., specified flow, head-dependent flow, or a spatial or temporal mixture of specified flow and head-dependent flow).

- Passively coupled groundwater and surface water models that use output from the companion model as input and do not receive feedback from the flow of the companion model.
- Fully coupled hydrologic models that are either iteratively or fully integrated solutions of surface water and groundwater flow.

Some of the integrated hydrologic models calculate and simulate additional flow features that cover all components of the use and movement of water—such as climate, land use, MAR, and ASRs—as well as secondary effects such as land subsidence, unsaturated flow, conduit flow, salinity, transport, and seawater intrusion. These additional features and couplings are essential for meaningful CWM analysis in systems where such features have a large effect on water movement in the context of CWM.

Most groundwater models typically simulate the presence of a surface water body through the implementation of a specified flow, head-dependent flow, or combination of them at the interface with the surface water body where the specified head is equivalent to the surface elevation of the water feature (i.e., its stage). Since the stage is a specified head, there is no coupling where the groundwater inflows or outflows would alter the stage. This is commonly called a one-way coupling. This kind of modeling can be useful in settings with perennial-flow conditions, but are problematic in settings of intermittent or ephemeral flow conditions or where there are human or natural changes to the surface water level and/or changes in channel form (geometry, location, elevation, and hydraulic properties), changes in augmentation and diversion of streamflow, or changes in flow related to climate variability and/or runoff.

While running separate surface water and groundwater models may initially appear to be the most efficient modeling approach, most systems are coupled and require a coupled and integrated modeling approach so that as one portion of the system changes the other portion responds. Integrated hydrologic flow models simulate the use and movement of water related to changing climate, land use, surface water, and groundwater with feedback between the systems, and internal estimation of all flows.

When simulating coupled processes such as climate, land use, and groundwater–surface water interactions, one of the first things to consider is how these processes may interact, affect the supply and demand of water, and contribute to the use and movement of water within a sustainability framework. For example, if the groundwater exchange flux is likely to cause a measurable difference in the flow or stage of a surface water body, that may affect the conveyance or delivery of the surface water, that, in turn, may be driven by variable climate and/or land use, then simulation of these processes and related couplings may be needed.

Conversely, if perennial, ephemeral, or intermittent surface water flows affect the delivery of water for agriculture, water supply, or environmental uses such as habitat or fish passage, then these processes need to be included in the model to fully simulate the interactions and related outcomes that will affect the sustainability framework. If a water body is perennial and holds or conveys a significant volume of water, then groundwater interactions are unlikely to cause the stage to change appreciably or affect the conveyance or delivery of water to downstream uses. However, many reservoirs only contain a few years of water at typical use rates without additional replenishment, so climate and droughts can be a major consideration of how these features contribute over longer periods of time (e.g., decades to centuries; Renteria et al., 2022). Changes in climate and drought can increase groundwater interactions by streamflow capture reducing streamflow conveyance as was exemplified on the Lower Rio Grande (Hanson et al., 2020).

Passively-coupled models use a watershed (precipitation-runoff) model to provide recharge as lateral runoff and mountain-block recharge as groundwater underflow from surrounding sub-watersheds that is computed first and then used as input to an IHM. Some examples include the:

- Basin Characterization Model (BCM; Flint et al., 2021);
- Variable Infiltration Capacity model (VIC; Liang et al., 1994, 1996; Nijssen et al., 1997);
- Hydrological Simulation Program-Fortran (HSPF; Donigian et al., 1995; Donigian, 2002);
- Soil-Water Balance model (SWB; Westenbroek et al., 2018); and
- Precipitation Runoff Modelling System (PRMS; Markstrom et al., 2015).

For example, the framework used for a Groundwater Sustainability Plan shows how the watershed model and basin model are connected to inflows from surrounding sub-watersheds (e.g., CA-DWR, 2020), as well as providing climate, land use, supply-and-demand subregions, and climate change models (Figure 15). This approach involves running the two models in a series. Thus, the watershed–climate BCM model is run, then data are extracted and transferred to the IHM as user-specified input. Alternate or future scenarios of climate or land use can be linked from global climate model data or land-use models. The approach can be referred to as a loose (or passive) coupling or non-dynamic coupling of the two models, which is typically defensible because the watershed model only simulates the mountain-block (groundwater underflow) recharge and runoff from surrounding and higher elevation sub-watersheds surrounding the basin-wide IHM model. Thus, conditions in the IHM have little influence on mountain block recharge and higher elevation sub-watershed runoff so there is little to no need for feedback from the IHM to the rainfall-runoff model. The IHM simulates all coupled processes within the basin such as land use as well as surface water and groundwater flow in a supply-and-demand framework.

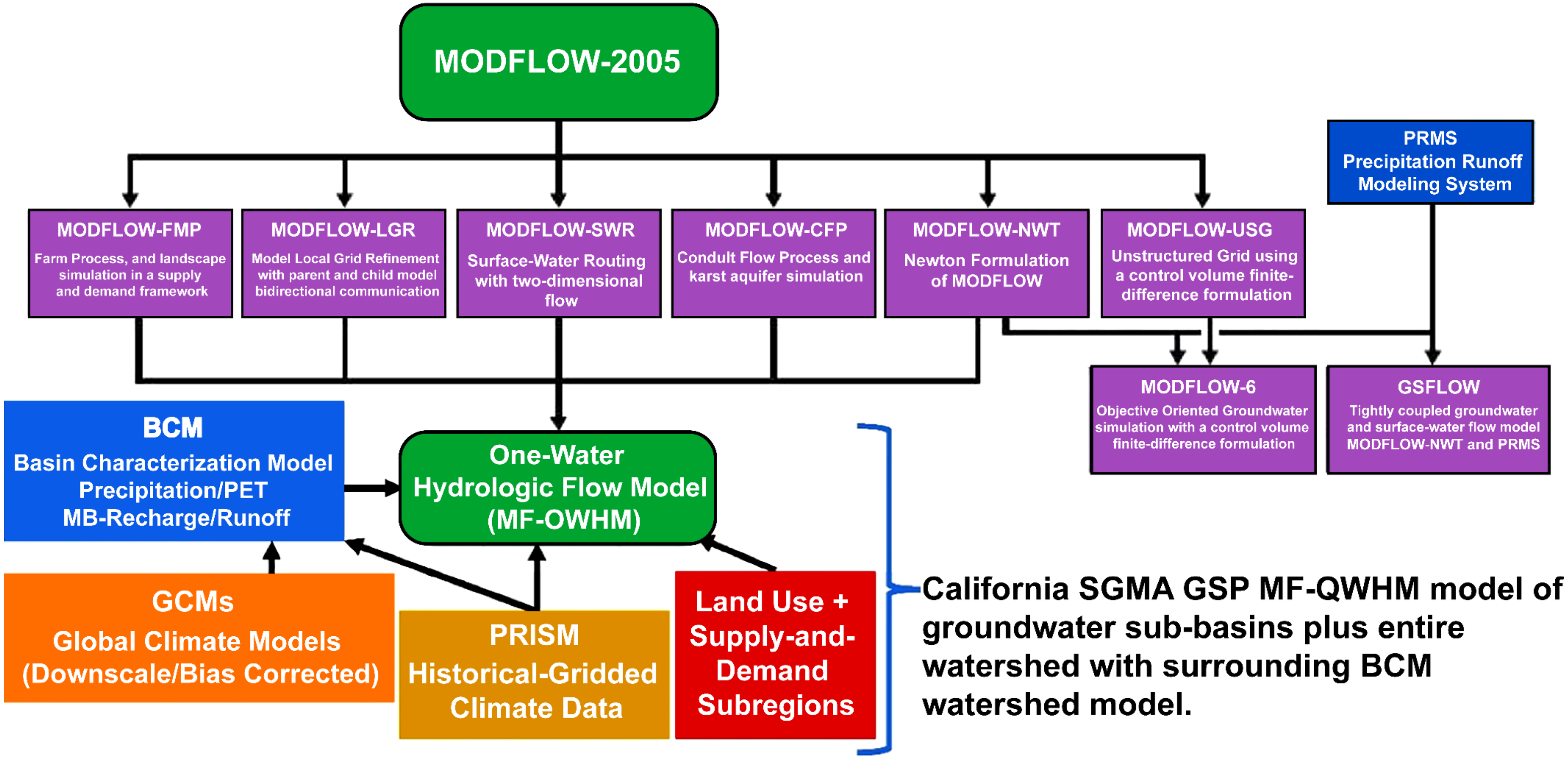


Figure 15 - MF-OWHM2 conjunctive-use modeling framework is a fusion/update/upgrade of the MF-2005 code family that incorporates land use, supply-and-demand subregions, and global climate model (GCM) data into a two-model watershed (BCM) and basin (IHM) framework (modified from Boyce et al., 2020).

The coupling of the processes within the IHM is essential to CWM development and for analyzing the effects and interaction between surface water and groundwater flows as demonstrated for the Lower Rio Grande (Hanson & Schmid, 2013; Knight, 2015; Figure 16). This model example demonstrates that streamflow capture occurs with increased groundwater pumpage within conjunctive use. This type of groundwater–surface water interaction—also subject to potential climate change and variability—was further investigated by the US Bureau of Reclamation (USBR) in their Environmental Impact Statement that reviewed project operations, including conjunctive use that may affect reservoir operations, treaty obligations, and other transboundary deliveries (USBR, 2016, 2017; Ferguson & Llewellyn, 2015). The water crisis is growing across numerous transboundary aquifers and watersheds with previous litigation in many such aquifers and ongoing US Supreme Court litigation in the Lower Rio Grande example of Texas v. New Mexico and Colorado↗ (Rivera & Hanson, 2022). Although the IHM approach is very involved, it is the most holistic approach for modeling and analyzing hydrologic budgets and sustainability that includes all the possible uses and movements of water needed for CWM analysis and development.

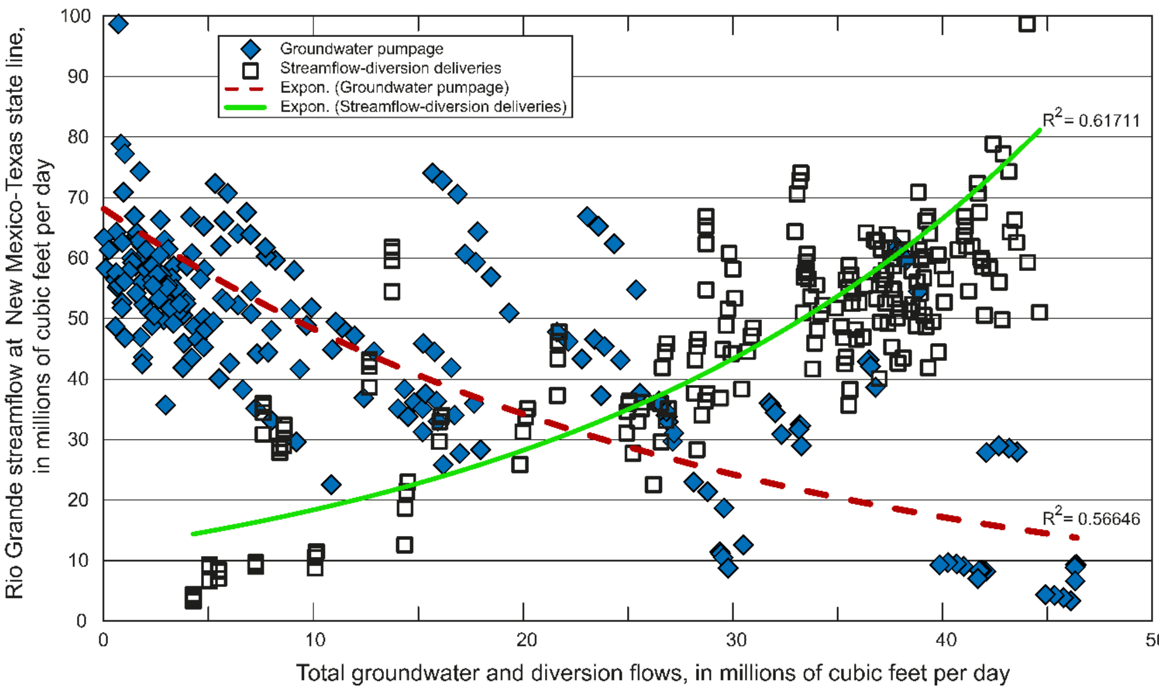


Figure 16 - Lower Rio Grande Model Analysis showing impact of upstream agricultural use and pumpage on downstream streamflow and agricultural diversion deliveries. The nonlinear relation between streamflow, diversions, and pumpage demonstrates that conjunctive use requires analysis of all water use and movement with an IHM model where these processes are internally simulated and coupled. The R^2 indicates the goodness of exponential (Expon.) model fit to the data. (Hanson & Schmid, 2013).

A further example of this sustainability-assessment framework for setting multi-level hydrologic budgets for groundwater, surface water, land system, and climate was developed by the CA-DWR. In support of California's Sustainable Groundwater Management Act (SGMA, 2014), CA-DWR produced a hydrologic budget guidance document (CA-DWR, 2020) that sets out the goals of good groundwater management and, in effect, directly and indirectly governs conjunctive use including limiting the adverse indirect effects listed previously. CA-DWR considers sustainability through subregional water budgets of the connected hydrosphere, related land use, surface water, and climate systems (Figure 17) as subject to the six previously-listed criteria (Section 2) that are deleterious effects on the sustainable conjunctive use of water resources. To comply with the California SGMA, all of these items need to be monitored, modeled, evaluated, and mitigated.

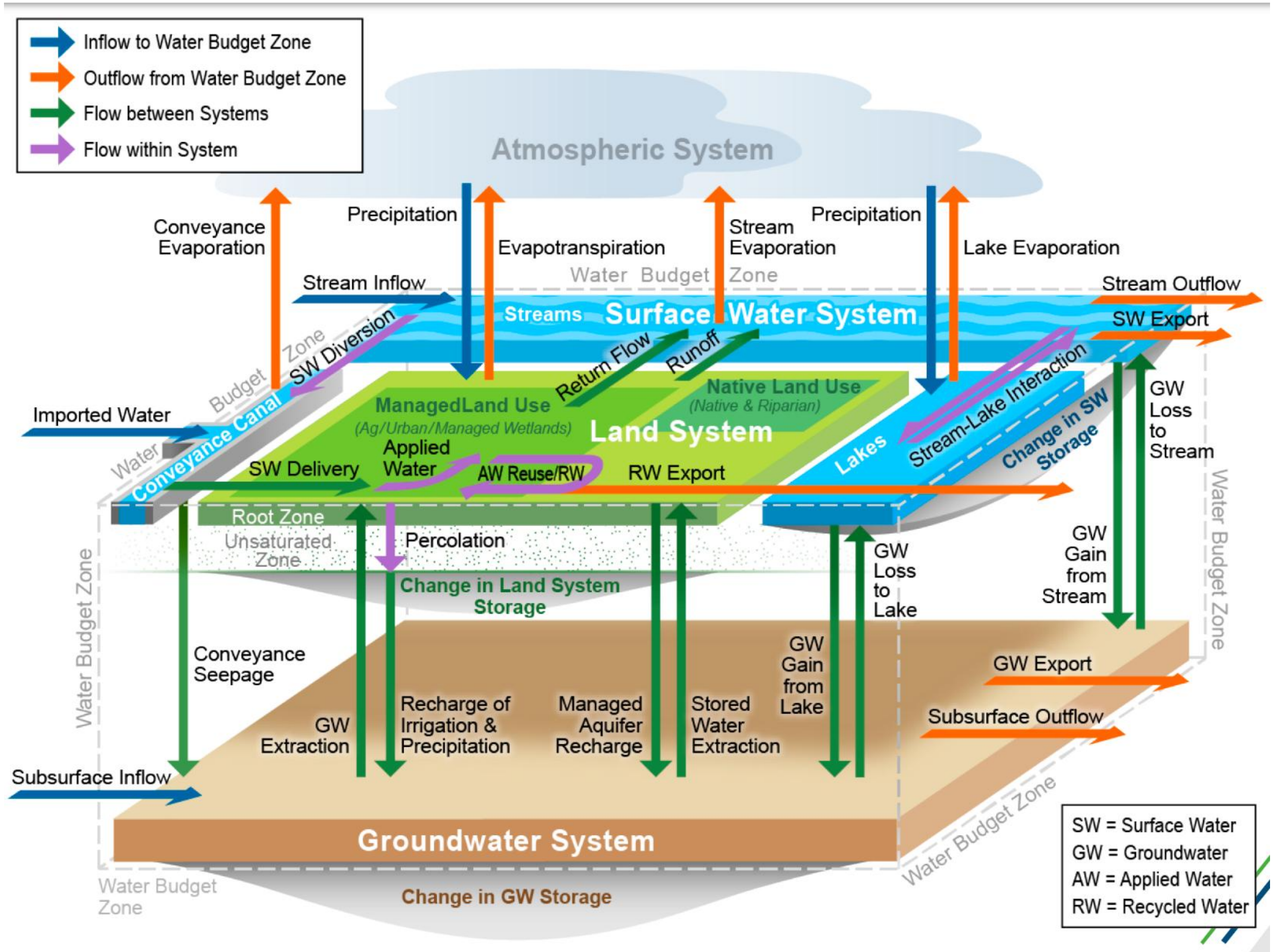


Figure 17 - Factors considered in the Hydrologic Budget for groundwater sustainability analysis using an IHM modeling framework (modified from CA-DWR, 2020).The hydrologic budgets estimated for any Groundwater Sustainability Agency subregion includes hydrologic budgets for the climate, land system, surface water, and groundwater flows within the subregion, as well as additional flows among these four systems within each water-budget subregion (WBS).

MODFLOW (MF; Harbaugh, 2005; McDonald & Harbaugh, 1988) is a commonly used groundwater model developed by the US Geological Survey with multiple current variants. MF has been coupled with the Precipitation Runoff and Modeling System (PRMS; Markstrom et al., 2015) to produce the GSFLOW model (Markstrom et al., 2008). GSFLOW simulates iteratively coupled groundwater–surface water flow and climate interactions. MF has also been more completely coupled as an IHM within MF-OWHM (Boyce et al., 2020), which includes enhanced coupling to land systems and reservoir operations.

MF also has been iteratively or passively coupled with many other watershed models, such as the Soil and Water Assessment Tool (SWAT; Kim et al., 2008), which is agriculturally focused, and the Hydrologic Engineering Center's River Analysis System (HEC-RAS; Rodriguez et al., 2008), which has a hydrodynamic surface water model component to enable conjunctive water planning. These coupled models vary in features, types of couplings and level of couplings, as well as varying limitations with respect to suitability for simulating all aspects of CWM. For example, SWAT does not include a viable and current connection to one of the modern versions of MF, and HEC-RAS is limited in its ability to simulate a wide range of conditions and does not include a connection to groundwater inflows and outflows. Some of these limitations and comparisons were originally summarized by Hanson and others (2010).

MF has been used as the base software for several model variants, including a comprehensive integrated hydrologic flow model designed for the analysis of a broad range of conjunctive use issues (Figure 15). A recent variant of the USGS MF software family that simulates integrated hydrologic flows (Figure 15), is the MF One-Water Hydrologic Flow Model (MF-OWHM↗; Boyce et al., 2020; Hanson et al., 2014a), currently being used worldwide for CWM projects. Twenty years of use includes applications from the Contiguous United States (CONUS) scale of the USA (Alattar et al., 2020) to agricultural analysis in Mexico (Mohammed, 2019; Bushira et al., 2017), Ethiopia (Azeref & Bushira, 2020), South Africa (Ebrahim et al., 2019), Argentina (Puricelli, 2019), Australia (Turnadge & Lamontagne, 2015), and across Europe (De Filippis et al., 2019).

MF-OWHM↗ facilitates the simulation, analysis, and management of human and natural water movement within a physically-based supply-and-demand framework. Multiple budget and observation types are provided that are specifically tailored to analysis of CWM. Fundamentally, this type of integrated hydrologic model can be selectively coupled between the flow and use processes and creates a simulation that is demand-driven and supply-constrained. Thus, many of the inputs from traditional surface water and groundwater models are derived from simulations and are not pre-specified as fixed or time-varying inputs.

The World Bank rated MF-OWHM↗ as one of the top three codes for analyzing conjunctive use (Borden et al., 2016) in addition to MIKE SHE↗ and GSSHA↗. MF-OWHM↗

also is recommended for sustainability analysis by the CA-DWR (California Department of Water Resources, 2020).

With MF-OWHM↗ simulating the groundwater, surface water, and landscape systems together, it is suited for analysis of agricultural supply and demand and coupled processes that control the use and movement of water. Recent enhancements allow for more realistic land use and reservoir operations. Examples of using MF-OWHM↗ for various CWM objectives are included in the discussion of Uttar Pradesh, India in Box 1. The framework used for many of the California sustainability assessments is illustrated in Figure 15. Some view this approach as containing too many parameters, however the initial model construction can be simple with MF-OWHM↗ features added to the model framework incrementally as needed. It is important to not confuse or conflate complex with complete. A model without the salient features will not allow the analysis needed to address the CWM issues.

Using of a model that simulates and analyzes the management of human and natural water movement within a physically-based supply-and-demand framework allows for more types of observations that help to constrain the calibration of a conjunctive-use model than can be used for conventional groundwater models. These observations include more first-order observations such as pumpage and ET as well as higher-order observations that are commonly unavailable for many groundwater or surface water models that lack the coupling of multiple hydrologic flow processes across the groundwater, surface water, land, and climate systems (Figure 17). This approach also allows the model to be trained using historical simulations to facilitate use on a broader spectrum of alternate scenarios and future projections that facilitate conjunctive use and sustainability analysis within the context of development, adaptation, and mitigation of changing water demands related to changing climate, population, land use, and water supplies. MF-OWHM↗ can be used with codes such as UCODE↗ (Poeter & Hill, 1998, 1999; Poeter et al., 2014) and PEST↗ (Doherty, 2004, 2010a, 2010b, 2010c; Doherty & Hunt, 2010) for parameter estimation and sensitivity and uncertainty analysis. Application of these methods is further summarized by Hill and Tiedeman (2007) and Doherty and Hunt (2010).

The USGS MF-OWHM↗ code and supporting analysis software are constantly maintained and upgraded and are connected to several Graphical User Interfaces (GUIs), such as the European Union's FREEWAT↗ (Rossetto et al., 2019; De Filippis et al., 2019; Borsi et al., 2016) and the USGS's ModelMuse↗ (Winston, 2009) that facilitate use of MF-OWHM↗. MF-OWHM↗ and all these support programs and GUIs are also freeware with complete documentation and user guides. Upgraded by USGS and USBR, MF-OWHM↗ is also able to simulate coupled reservoir operations with the surface water operations (SWO) process that is being used for a variety of conjunctive use models.

Other proprietary numerical models have been developed from a surface water modeling base and include a groundwater component. A well-known example of this approach is the proprietary DHI code MIKE+Rivers↗, a commonly used program for surface water routing and river modeling that can be connected to the FEFLOW↗ groundwater model. This one-dimensional river modeling package also has been linked with the Systeme Hydrologique European (MIKE-SHE↗), developed by Abbott and others (1986) to represent hydrological processes with a greater level of physical defensibility, and in a spatially explicit manner. MIKE-SHE↗ is extensively used to analyze conjunctive use options and can also be used with FEFLOW↗. Additional comparison of various model features and capabilities was included in the review by the World Bank (Borden et al., 2016).

A common application of IHMs is to use river operation models that more completely incorporate surface water and groundwater processes resulting in more effective CWM, as demonstrated by the indirect passive coupling of GSFLOW↗ with the proprietary reservoir operations model MOD-SIM↗ (Morway et al., 2016). Similarly the proprietary model called the Water Evaluation and Planning Model (WEAP↗; Stockholm Environmental Institute, 2023) and associated GUI can also be used for simulation water allocation and reservoir operations along with limited linkages to some older versions of MODFLOW (MF-2000, MF-2005) and has been used for some evaluations of drought and climate change.

An option for simulating reservoir operations linked for deliveries to streamflow routing (SFR) and to water demands (FMP) within MF-OWHM↗ is the Surface Water Operations Process (SWO↗; Ferguson et al., 2016; Boyce & Ferguson, 2023), an open source, freeware alternative directly coupled within the code for dynamic feedback from other flow and use processes within the CWM supply-and-demand framework. It is important to note that surface water-groundwater interaction processes may take many years, owing to large climate cycles and changes in demand related to changes in population and land use as well as physical retardation of flow between the two flow systems. Annual or seasonal operational models usually do not allow for these long-term effects; many decades of simulation time may be required to capture these protracted and delayed effects driven by longer term forcings such as land-use development and climate variability.

In contrast, SWO↗ allows for simulations on these longer time periods as was initially demonstrated for the EIS analysis of the USBR operations of the Lower Rio Grande Project (US Bureau of Reclamation, 2016, 2017; Ferguson & Llewellyn, 2015). Also, the use of daily time intervals can be physically and conceptually incorrect as many of these model codes have no surface water storage and the relationship between surface water inflows (e.g., reservoir releases) and downstream diversions (as observations) can be a week or more of transit time after the initial inflow or reservoir release.

Fully integrated hydrologic model codes such as PARFLOW↗ and HydroGeoSphere↗ are three-dimensional finite element simulators, which have gained popularity for certain applications. They are designed to model the whole terrestrial portion of the hydrologic cycle. It solves the two-dimensional diffusive wave equation for overland and surface water flow, and the three-dimensional form of the Richards equation for groundwater flow. They integrate all the key components of the hydrologic cycle including evaporation from bare soil, vegetation transpiration, unsaturated zone flow, flow in porous and fractured media, and reactive transport. Tile drains as well as snow accumulation and melting can be discretely incorporated. While PARFLOW↗ and HydroGeoSphere↗ have been used effectively to simulate and analyze synoptic events such as the effects of specific runoff events, flooding, and reservoir releases, the protracted simulation times may make it more prohibitive for some applications at the regional scale and longer time periods such as the Central Valley, California (Harter & Morel-Seytoux, 2013).

Another advancement in MF is MODFLOW 6 (MF-6↗; Hughes et al., 2017; Langevin et al., 2017) linked to an Application Programming Interface (API) (MF6-API↗; Hughes et al., 2022), which gives model users the flexibility to readily adjust the modeling approach to include relevant processes and features not included in MF-6↗. However, MF-6↗ has limitations related to sustainability analysis, such as not providing features for simulating land-use change, climate change, a more complete suite of surface water geometries, and reservoir operations. MF-6↗ allows for structured or unstructured grids, which is beneficial when properly utilized, but can add to simulation runtime. The trade-off between the additional computational effort required by an unstructured grid often needs to be balanced by a sufficient reduction in the number nodes.

Most modelers performing conjunctive-use analysis for CWM consider the discretization of time and separation and coupling of supply-and-demand components as the most significant features with respect to sustainability analysis. The use of MF6-API↗ with MODFLOW (Hughes et al., 2022) facilitates automatic creation of model input files and post-processing of results but, like any model-code application, does not preclude the effort needed to develop the data used for those inputs and any related observation types as well as linking models as initially summarized for model integration processes (Belete et al., 2017). With MF6-API↗, modelers can program site-specific management into their model, and call MF-6↗ on a time step-by-time step basis. For instance, a regional-scale groundwater model may be coupled with multiple local-scale groundwater models, or a surface water flow model could be coupled to multiple groundwater flow models. Though not currently available, the software is being upgraded to allow integration of a surface water stream network with subsurface hydrogeology. Because it does not include simulation of land use or integration of climate data, as do MF-OWHM↗ and the integrated hydrologic model code of CA-DWR called the Integrated Water Flow Model (IWFM↗; Dogrul, 2012), it is not used throughout most areas of California for sustainability analysis under California's SGMA. Ultimately, the application of model codes or suites of codes will be setting- and problem-specific but will need to consider the answers and related analysis needed to address the CWM and related sustainability issues.

With such a broad range of modeling options available it is suggested that the approach shown in Figure 18 be used in determining which model is the most appropriate for each situation when using separate surface water and/or groundwater models.

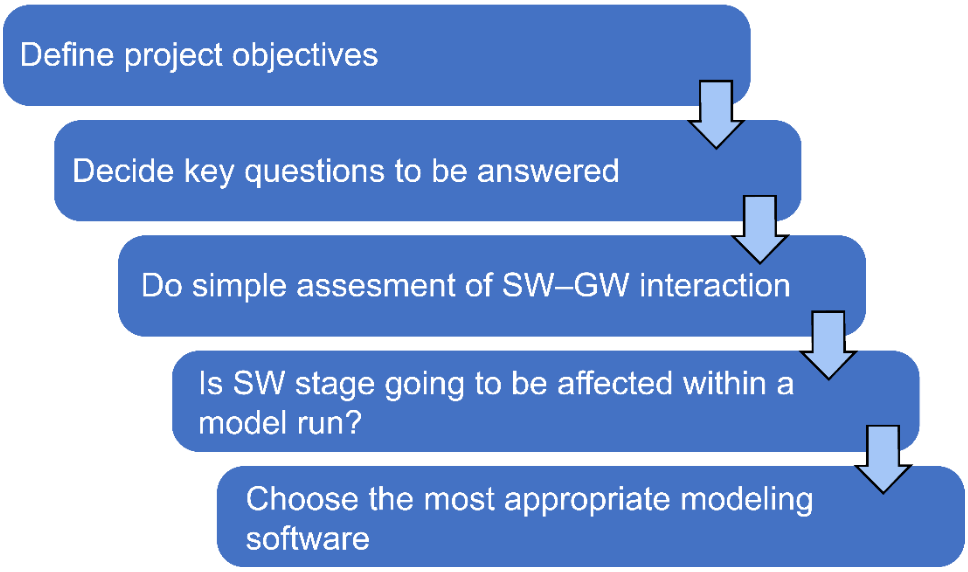


Figure 18 - Suggested logic tree to be used to determine the most appropriate modeling platform for CWM with respect to the use of simple and separate groundwater models (SW: surface water; GW: groundwater).

Designing and building a model using IHM codes like MF-OWHM↗ or IWFM↗ may be required for more complex CWM and sustainability analysis issues. This will require additional model capabilities that link the flows across climate, land use, surface water, and groundwater systems, as well as additional information for input and observations (Figure 19). This approach may also require linkage to a precipitation–runoff model such as the Basin Characteristic Model (BCM, Flint et al., 2021) PRMS, VIC, HSPF, or SWB as well as linkage to multiple climate models (Figure 15).

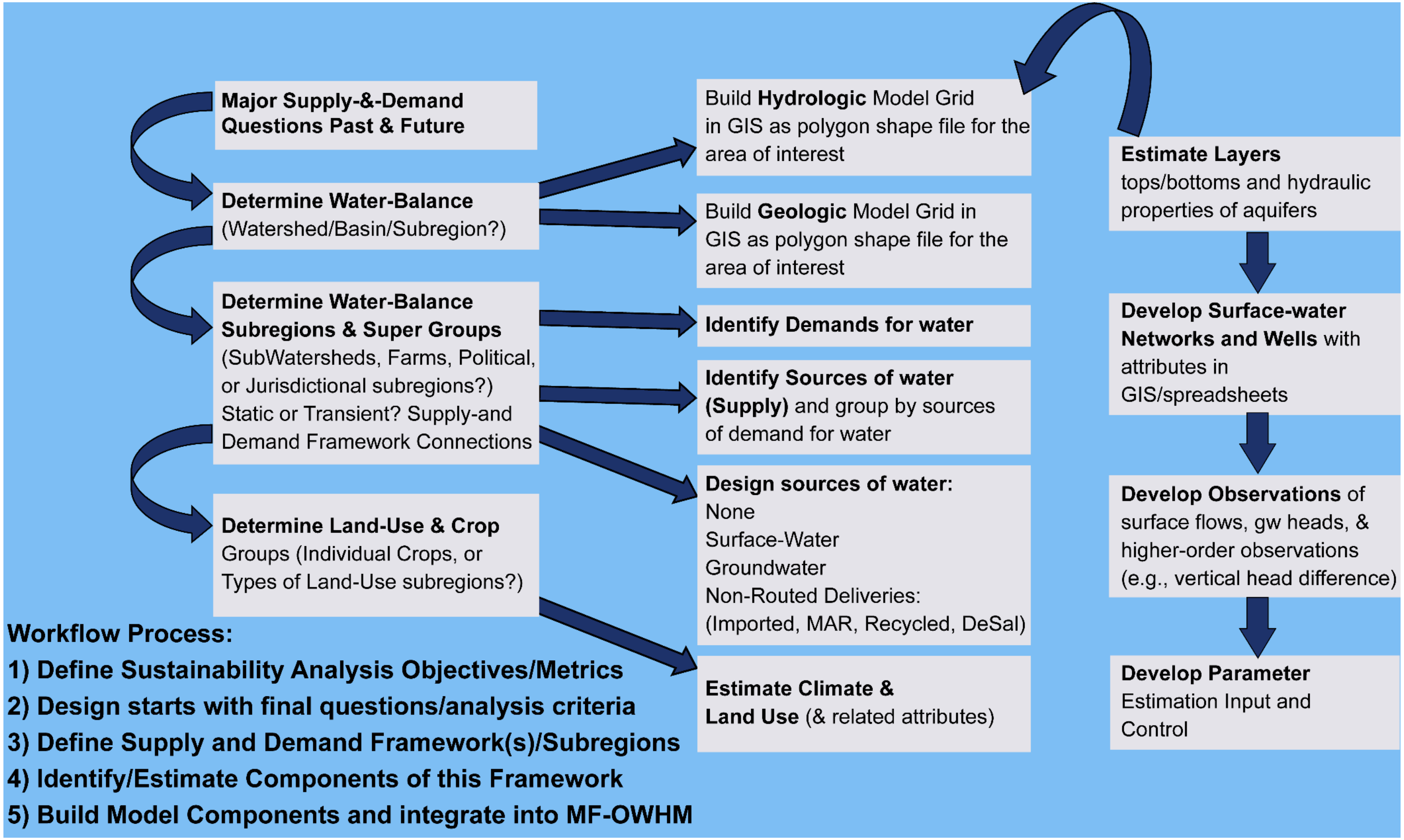


Figure 19 - Workflow for IHM development with MF-OWHM for CWM sustainability analysis.

8.4 Economic Optimization Models

Another type of CWM modeling features economic optimization. In these models, using an economic objective function—for example, maximizing the net economic value of water use—provides solutions that optimize economic efficiency in water resource management (Pulido-Velazques et al., 2006). This approach includes modeling of stream aquifer interaction with embedded multiple reservoirs.

The objective function minimizes the total cost of the system, which includes a summation of scarcity costs and variable operating costs. This function can be applied to both irrigation demands and urban demands and can identify the relative cost of using surface water and groundwater at different times. A monthly time step is often used. The nonlinear relationship between economic losses and water shortage is well known, therefore, the benefits of CWM can be identified. However, an ideal water market is assumed to have perfect institutional and operational flexibility, which is obviously often not the case.

One of the biggest issues in the optimization of agricultural profit is that the cost of water (including the cost of power to pump groundwater) is a relatively insignificant cost relative to those for labor, fertilizers, farm equipment, and even packaging. So, optimization is more useful for irrigation scheduling or picking the types of crops to grow than water conservation itself, as per some examples of crop selection optimization (Colón et al., 2016; Fowler et al., 2015, 2016). In addition, soil-moisture or stomatic-pressure monitoring networks that guide irrigation scheduling and are used by some modern agricultural companies, can be used to perform deficit irrigation to increase sugar content of vineyards and fruit orchards. Some are advocating for the use of Artificial Intelligence (AI) applications for this task, but process-based decision making is still more viable. Because AI is only trained on the past in a statistical framework and not a process-based framework, once the environment changes, it may be difficult to make new and different choices via AI that would be based on mimicking a limited past history (Conceptual Exercise 12↴).

9 Institutional Structures for Effective CWM

CWM is constrained more by lack of effective funding combined with ineffective and incompatible institutional structures and related governance than by lack of technical understanding. The governing structures have separate management arrangements that are almost always established and operated by different institutions, and with few transboundary agreements. This problem is compounded by the fact that, at the sovereign level, water resources are often managed by a dedicated water resource agency, while irrigation demands are often managed by agricultural agencies or dedicated irrigation-command authorities as discussed in Box 4 for the Indus Basin, Pakistan.

The types and distribution of water rights can also provide a challenge when applying CWM. Water rights may be administered at different levels (nationally or by state/province) or be non-existent in adjacent jurisdictions within a watershed and they may include different types of water rights (e.g., separate surface water and groundwater rights). Further, they may be derived from a variety of social structures such as the English riparian, the Spanish prior-appropriation, or the Indian matriarchal systems of water allocation and rights.

Overall water resource policy is sometimes set at a jurisdictional scale that requires the irrigation sector to operate under the authority of a regulatory agency. There is typically little to no data sharing nor coordinated monitoring by the different levels of transboundary use and management. Different sets of laws and ownership of surface water and groundwater in adjacent transboundary regions may occur within the same groundwater basin or watershed. Such a situation can result in a complex mosaic of use, planning, and decision pathways that are not easily overcome. Close coordination is needed to plan and undertake the extensive monitoring and modeling needed to support conjunctive water management and sustainability analysis (Central Valley - California, USA – Box 6). Given these obstacles, a treaty or operating agreement that supports CWM may never be developed. There are some notable exceptions that include governance combined with related monitoring and modeling in support of a planned conjunctive management model and sustainability analysis (Central Valley - California, USA – Box 6).

It is commonly understood that coordination is rare in water management as acknowledged by Foster and van Steenbergen (2011, p. 962).

> *In many alluvial systems, the authority and capacity for water-resources management are mainly retained in surface-water-oriented agencies, because of the historical relationship with the development of irrigated agriculture (from impounded reservoirs or river intakes and major irrigation canals). This has led to little interest in complementary and conjunctive groundwater management as may be the case in larger regional watersheds that are charged to look after groundwater but are largely focused on surface water management. Some significant reform of this situation is essential—*

such as strengthening the groundwater-resource management function and/or creating an overarching and authoritative "apex" agency.

Similarly, Shah and others (2006, p. 3) recognize that *"A major obstacle to conjunctive management is the fragmented structure of governmental institutions entrusted with various water management roles,"* while Foster and others (2010, p. 24) emphasize that:

The promotion of improved conjunctive use and management of groundwater and surface water resources will often require significant strengthening (or some reform) of the institutional arrangements for water resource administration, enhanced coordination among the usually split irrigation, surface water and groundwater management agencies, and gradual institutional reform learning from carefully monitored pilot projects.

In a USA case study, Bredehoeft (2011, p. 474) found that effective management of conjunctive use *"requires integrated institutions that can plan and sustain the management of the system for long periods"* because it typically "*takes more than a decade for significant changes in groundwater pumping…to have their full impact on the river."* Bredehoeft (2011, p. 474) also stresses that, in the western states of the USA, the legal system for water management is based on prior appropriation which fundamentally works against CWM:

Effective conjunctive management can probably only be accomplished by an approach that integrates the groundwater and surface water into a single institutional framework; they must be managed together to be efficient. Current institutions based upon the present application of the rules of prior appropriation make conjunctive management not practical.

CWM requires major organizational changes in water agencies. Furthermore, reformed institutions need structures that can operate at the multiple scales that groundwater, especially, requires. One example of these changes was the study of groundwater–surface water interactions (Miller et al., 2007; Colorado Water Institute, 2014), and the related development of CWM (Blomquist et al., 2001) on the Lower Platte River in Colorado (Interim Water Resource Review Committee, 2017) that also spans three western states in the USA. Other examples of evaluations of benefit cost ratios for CWM implementations and frameworks were summarized for the Murray–Darling Basin, Australia (Ross, 2022), and for selected other regions by UNESCO (Zheng et al., 2021).

Ironically, this view of prior appropriation (i.e., first in time and first in right) does not preclude management in most modern settings of the western USA as many also include consideration of any potential impairment by neighboring users. These states control both granting of water rights (through a centralized authority such as a state engineer) and well permits. Less controlled is the growth of urban areas and development of additional land use for agriculture, both of which drive the demand for additional water beyond the limits of the resources within the bounds of variable climate. Recent assessments for the Central Valley of California have found that between 500,000 and one million agricultural acres may need to be retired to achieve sustainability within conjunctive use (Peterson et al., 2022). With about 40,000 acres per year being urbanized throughout California (Thompson, 2009), agricultural land is now almost completely absent throughout many coastal areas of the state. Thus, successful CWM must be connected to the demand drivers of land use as well as population and industrial growth.

This need is further exemplified by the recent (2023) decision in Phoenix, Arizona, to limit any further urban development because overexploitation of groundwater within the Arizona Department of Water Resources' Phoenix Active Management Area (AMA) can no longer sustain such growth. that is partly driven by the continued transition from agriculture to urban demand beyond supplies of surface water and groundwater. In the Mimbres Basin of southwestern New Mexico, the ability to appropriate additional water rights has been closed since 1975 (Hanson et al., 1994). Yet use of groundwater for mining is not deemed a beneficial use and thus is exempt from this limit and control. The alluvial aquifer of the Mimbres Basin also is a transboundary aquifer and is another example of a region without CWM and with disparities in water use in the adjacent countries that are not covered by treaties or other cooperative agreements of water management. As with the use of groundwater for mining, in many settings, groundwater used for hydrocarbon production has its own separate regulation and rights.

Garduño and others (2011, p. 45) emphasize that:

> *The promotion of more planned and integrated conjunctive use has to overcome significant socio-economic impediments through institutional reforms, public investments, and practical measures, including: (a) the introduction of a new overarching government agency for water resources, because existing agencies tended to rigidly follow historical sectoral boundaries and thus tend to perpetuate separation rather than the integration needed for conjunctive use; (b) gradual institutional reform learning from carefully monitored pilot projects; and (c) a long-term campaign to educate farmers through water-user associations on the benefits of conjunctive use of both canal water and groundwater, crop diversification, and land micro-management according to prevailing hydrogeologic conditions.*

In their view, institutional strengthening is probably the most important challenge to CWM, especially in already developed irrigation systems where a more optimized management approach needs to be retrofitted. Current examples of coordinated CWM management include regions in Mexico, such as the Rio Yaqui District (known as the "Breadbasket of Mexico": *Summary of area*↗), and in the USA, such as the Coachella and Imperial Valleys of California, where everything is automated, monitored, and coordinated over their entire irrigation district. These areas also have limits on other items that impact water demand such as extent of land-use development.

Evans and others (2012) describe several case examples of the social, environmental, and economic successes and failures of conjunctive water management. They point to institutional structures as being key to the successful implementation of CWM schemes. The approach must include either rights or monetary value for environmental flows and water storage and related habitat (including related to GDEs), and not just management of human use and movement of water. Successful institutional structures vary from the local to the sovereign level. In most cases, the local level controls the management arrangements.

An optimal approach to CWM may prove to be purely theoretical if implementation is inhibited by existing institutional or policy structures. Feasibility requires complete connections between technologies for monitoring as well as operational decision making and planning. Some regions, such as the state of New Mexico, USA (via the state engineer), are adjudicating combined surface water and groundwater rights throughout the state including the Lower Rio Grande River basin. Since 2009, New Mexico also has required monthly reporting of pumpage from most wells throughout the state. This situation specifically applies to the legal ownership of water rights as well as the ability to rent or transfer these rights, the ability of local regulatory bodies or water-user associations to make day-to-day decisions, and the ability to undertake effective and coordinated planning for CWM.

Clearly, economic incentives are needed to justify the adoption of CWM at both (or either of) the sovereign or individual level. These incentives need to be independent of market drivers. Examples provided by Evans and others (2012) indicate that economic gain is made—where it has been assessed and reported—because of CWM adoption. This gain has usually been at the head-gate (i.e., the diversion location) level in the form of reduced costs and increased income; however, economic returns may also be achieved at the sovereign level through more efficient use of the available water resource, lower subsidies to achieve the same production, and increased levels of production leading to regional development opportunities from post-head-gate multipliers. Further work to demonstrate sovereign-level economic gains is warranted as part of a program to encourage governments to commit to the institutional and policy reforms needed to adopt planned CWM. For effective management, regulatory arrangements are needed for both access entitlements and powers to place restrictions on the timing and volume of water abstraction, as well as some restrictions, or controls, on development of additional land use.

Several investigations and studies have assessed and confirmed the economic gains to be made from CWM (e.g., Shah et al., 2006). This evidence is being used to promote CWM implementation. However, the extent of published socio-economic benefit analysis is limited. Such analyses are mainly found in unpublished reports. It is rare to see detailed analyses of the benefits and costs of CWM; rather, the data show the incremental economic benefits when CWM is retrofitted to unplanned irrigation commands (districts). In particular, it is rare to see an analysis of benefit and cost associated with planned CWM and even rarer to see a discussion of the policy and institutional approaches that support planned CWM.

10 CWM Development Options

10.1 Governance Approaches

Effective CWM must involve governance for both surface water and groundwater as well as other sources—such as recycled, MAR, Flood-MAR, desalination, and imported water—that are part of CWM and any modern sustainability framework. Good governance principles associated with groundwater alone still apply, but they must be made to fit a broader governance paradigm—that is, Integrated Water Resource Management (IWRM).

General water governance principles include several main areas: authority, accountability, transparency, stakeholder participation, and integration.

- **Authority** relates to the policy and statutory powers vested in the government—or delegated to an agency to administer and regulate on behalf of the government. The authority becomes the decision maker who must be held accountable for operationalizing policy and legislative instruments.
- **Accountability** The authority must be accountable for its decisions, with appropriate mechanisms in place, and supportive of natural justice by enabling appeals against decisions to be independently reviewed. Such authorities typically operate at the basin scale, which raises issues with defining the boundary when, for example, river basin boundaries do not match the underlying aquifer system boundary.
- **Transparency** is required to demystify the decision-making process, support stakeholder confidence in the management process, and provide the grounds for appeal. Transparency also must include public outreach, monitoring, and data sharing.
- **Stakeholder participation** ensures there is ownership of the process by all, which goes a long way toward achieving planned outcomes.
- **Institutional and technical integration** is required to ensure that all aspects of water tenure are subject to a single basic water resource regime. Water is a single resource and should be managed accordingly and in concert with the other major stressors of supply and demand such as land use, population and industrial growth, and climate.

Optimum water-resource use, reuse, and replenishment will be significantly advanced through planned management of conjunctive use. The governance model is crucial to the adoption of this planned management approach in several ways; however, there is no single governance model that can be applied universally. Rather, elements of different approaches may be needed depending on specific circumstances

There are two fundamental approaches to the linkage between governance and management: either *top-down* or *bottom-up* structures. For example, top-down management and governance is used by Mexico at the federal level through the Mexican National Water

Commission (Comision Nacional del Agua: CONAGUA), the country's national water system where the people who are represented by the federal government own all water, but rights are then administered by the federal government to individuals and companies. In contrast many of the western states in the USA have a state engineer to administer well permits, data monitoring, water rights, and water transfers. Similarly, other nations such as India administer these water-resource attributes at the state (province) level (Conceptual Exercise 13⤵).

A recent example of bottom-up governance and management linkage is California's SGMA program (CA-DWR, 2014; SMGA, 2014). Another example, emerging from India, shows the power of participatory management of groundwater, based on water-level observations by farmers, to influence cooperative decision making on dry season cropping, water use efficiency measures, drilling restrictions, and development and maintenance of recharge structures in ephemeral streams (Maheshwari et al., 2014).

Establishing effective governance arrangements to underpin a CWM strategy is deemed to be the most significant challenge to CWM. Danton and Marr (2007, p. 63), when discussing the governance arrangements associated with conjunctive use in the state of Uttar Pradesh, India, point out that:

> *[M]ulti-faceted governance arrangements are necessary for successful management of smallholder surface water irrigation systems. In managing conjunctive use…these arrangements become more complex…. The greater complexity in management arises from the need for coordinated management of the two resources through greater participation and networking of stakeholders at each stage of water allocation, use and management.*

Further, Livingston (2005; as referenced in Danton & Marr, 2007) subdivides water governance models for water supply systems into three types: bureaucracy, community, and market. Governance approaches may favor one model but will ultimately include elements of all three. In the example of California's SGMA, the CWM metrics, monitoring, modeling, and sustainability analysis are updated every five years; this information is submitted, reviewed, and approved by the state, and communicated to all stakeholders. Improving California's CWM within SGMA may ultimately include water markets with trading and water banking as additional management elements (Ayres et al., 2021).

Garduño and Foster (2010, p. 36) listed some challenges when considering the CWM governance. They reported that:

> *Serious impediments have to be overcome to realize such water resource management policies. They are primarily institutional in character, given that the structure of provincial government organizations often simply mirrors current water-use realities and tends to perpetuate the status quo, rather than offering a platform for the promotion of conjunctive management.*

Corporate entities can pose problems when they launch legal challenges to sustainability frameworks and related CWM management strategies.

The Chilean example summarized by Fagan (2008) is perhaps the most problematic as it shows a combination of factors including climate variability and governance issues that are exacerbating CWM. Climate variability has been a significant driver in the rise and fall of many civilizations worldwide over the last 10,000 years. The recent mega-drought (2010 to 2020) in Chile and the related multi-year drought propagation prolongs the hydrological recovery times of groundwater and surface water resources of the Andes and has affected the limited water supply of central Chile (Alvarez-Garreton et al., 2021). The low social involvement in Chile's CWM is due to the market-based water governance with a "free market" framework of private tradable water rights since 1981 (Budds, 2020). Yet, this privatization of water rights coupled with little to no government control of watershed management, constraints, or oversights (Tinoco et al., 2022; Langrand, 2023)—combined with overexploitation and drought since 2010—is challenging water security with a supply-based response to drought that may be counterproductive (Budds, 2020).

In contrast, the Mexican and Brazilian CWM frameworks provide more citizen involvement in watershed organizations where ecosystems and aquifers are also part of water management; however, all three countries may still exhibit deficiencies in gender indicators, financing, monitoring for decision making, and mechanisms for social participation within governance (Tinoco et al., 2022).

CWM can be most successful in large watersheds such as the Murray–Darling Basin, Australia, when management includes the water users as well as governance and monitoring (Holley et al., 2016). In some settings, three tiers of governance—corresponding to constitutional, collective choice, and operational governance in systems for governing common property resources—have been developed to achieve some elements of a CWM framework (Schlager & Ostrom, 1992; Ostrom, 2009). Thus, a more successful and robust CWM framework would be a holistic mix of all these factors to achieve sustainability—subject to other forces driving supply-and-demand such as development and climate variability.

In the Americas, governance and its promotion were further developed by UNESCO and the Organization of American States (OAS; UNESCO & OAS, 2010) with an assessment of institutional framework and management of transboundary aquifers (dos Anjos et al., 2008). As well, these agencies developed an inventory of transboundary aquifers and their socio-economic, environmental, and climate-related aspects (UNESCO & OAS, 2010) including the assessment of governance and management issues in transboundary aquifers and watersheds (Rivera, 2015). For example, along the USA–Mexico border, two Treaties of the Rivers were developed to assist initially with the sharing and management of surface waters for the Rio Grande and Colorado and Tijuana Rivers (Convention between the United States and Mexico: Equitable distribution of the water of the Rio Grande, 1906; Water Treaty concerning the utilization of water of the Colorado and Tijuana Rivers and of the Rio Grande, 1944). These treaties are uniquely dynamic as they have the mechanism to have modifications (called minutes), that allow for inclusion of new management or structural activities that now include elements of transboundary groundwater management as well as water quality criteria (e.g., IBWC, 2010, 2017). Guidance on pathways to groundwater management of transboundary aquifers along the USA–Mexico border is further summarized by Sanchez and others (2021) and across the Americas by Rivera and others (Rivera, 2015). While similar agreements occur between other countries such as Chile and Peru and within the five countries that include the regional Guarani Aquifer in South America, this type of governance structure allows for changes and increased management of water resources in a transboundary setting that is subject to changes in water resources, industry, population, land use, and climate. This type of analysis is also combined with modeling of the Guarani transboundary aquifer which spans parts of five countries (Gonçalves, 2020).

In summary, the governance model needs to address four areas of endeavor: legislative, organizational, technical, and socio-political. In many countries, the organizational aspect may require the most significant changes.

10.1.1 Institutional Strengthening

Institutions that manage water, at the international, national, and regional scale, must not only remove impediments but also reinforce and facilitate cooperation through CWM. Doing so requires the adoption of frameworks that promote IWRM where surface water and groundwater functions operate collectively towards a single overarching objective and where the function of water and agriculture ministries are also aligned for this purpose. Institutions must be clear on who operates and manages both physical infrastructure and the different parts of the hydrologic cycle as well as the permitting of surface water and groundwater rights and related additional land-use development. These arrangements may be in either the public or private sphere, or a combination of both.

Resolving chain of command issues across various levels of government needs to be reviewed, including permitting, monitoring, and data sharing. That is, each level of government must understand its role in implementing national water resource policy and be effective in enacting that role at multiple levels of CWM. Any activities that undermine CWM must be confronted and remedied to promote conjunctive use within operations, monitoring, modeling, and sustainability analysis. Institutions must have a strong compliance culture to ensure CWM outcomes are achieved, and that limitations of resources, climate, and land use are part of the broader holistic sustainability framework.

10.1.2 Policy and Legislation

In many instances, there is a need to understand and review the current approaches to allocating rights in water and land use, as well as the form and attributes of those rights. For example, policies and regulations may be poorly formulated and hence not operating efficiently to achieve the intended outcomes. Effective water and land use allocation planning is paramount. It must be supported by strong national policy and occur within a framework that ensures sustainable levels of taking and using the resources.

For example, some jurisdictions, such as Santa Cruz County, California, USA, have implemented land-use zoning to help preserve regions that are more conducive to groundwater recharge. To do so requires significant technical input, especially considering the need to assess the available consumptive pool, land use, and climate cycles that are all part of the supply-and-demand sustainability framework. CWM relies on monitoring networks, water policies, and regulations that are efficient at promoting movement of water from diversified supplies or access between all water resources when required and appropriate. Legal and market powers and mechanisms must also be aligned, including some sustainability constraints, rather than depending on a completely free market as was attempted in Chile (Budds, 2020). Public policies that have encouraged overuse of water through subsidies and underpricing also need to be modified (Hadjigeorgalis, 2009).

10.1.3 Planning

By its very nature, planned CWM requires a strong management platform nested within a broader sustainability management framework that includes land use, population and industry dynamics, as well as climate variability. It needs to clearly define objectives, outcomes, activities, performance measurements, and compliance arrangements.

At the governmental level there must be monitoring, data sharing, modeling, and analysis combined with legal reporting requirements, as well as permitting fees to fund operations and fines for noncompliance. Such plans and related statutes and procedures need to be based around water allocation mechanisms and reflect a technical understanding of the total consumptive water available. This has been problematic to implement in many settings and overexploitation of resources a common problem in settings where the resources and rights are administered from the federal level, such as in Mexico (CONAGUA, 2023) and also in settings where they are administered at the state level such as in parts of India (Kaur, 2023).

Compliance and enforcement of water licensing has been problematic in other regions such as New South Wales, Australia (Sinclair &Holley, 2012). Changes in governance and management continues to present issues in the Murray–Darling Basin at many levels including political conflicts in implementation and adaptive management, and in development of clear management objectives that include all parties (Hart et al., 2023).

While a good example, the California SGMA program (CA-DWR, 2014; SGMA, 2014) can still result in issues and legal conflicts if the various water-use parties do not cooperate and comply with the local proposed sustainability plan. Implementation planning must define investment requirements and identify who will make those investments, and who will ultimately pay, including both capital investment in infrastructure and operating and maintenance (O&M) costs. Because of the financial structure of some water utilities, conservation can be problematic. For example, many utilities that are profit-based commonly must pay dividends to investors, and conservation can leave them with insufficient funds for covering O&M costs or any capital-equipment maintenance, improvement, or expansion.

Ideally, planning should incorporate the triple-bottom-line notion of achieving environmental, economic, and social objectives. CWM must also consider land use policy changes so that groundwater protection outcomes can be achieved within a sustainability framework. Such policy decisions are not usual in most countries and may require considerable input as well as political and corporate support (Conceptual Exercise 14↴).

10.1.4 Market and Pricing Approaches

Surface water and groundwater have differential cost structures. The frameworks, challenges, and opportunities of water markets and transfers were previously summarized in Section 4 of this book (Thompson, 2011; Hadjigeorgalis, 2009). One of the biggest obstacles to a common economic framework is the non-monetization of environmental flows or habitat consumption leaving the full monetary spectrum of uses and movement incomplete. In centralized government systems, these cost structures may be heavily subsidized because of related policy decisions (i.e., policy decisions for food and energy), resulting in unwanted outcomes usually related to inefficient water use or to a lack of constraint on land and water development.

In general, groundwater users either fully finance their associated infrastructure or are part of a distribution system that includes transmission and purchase fees, or sometimes a pump tax. On the other hand, surface water infrastructure has primarily been either wholly or partly subsidized by federal or state-based institutions, though some private reservoirs and surface water transmission systems exist. The different ownership models contribute to differential cost impacts for irrigators, leading to decisions that are inconsistent with optimized planning objectives. There is commonly a large disparity between charges for municipal and agricultural water use: by a factor of 10 to more than 20 for municipal water, even though agricultural water use is typically 80 to 90 percent of all water use in many regions outside of major cities. CWM must remove these impediments by combining the rights and fees into a common framework of various rates for public, agricultural, and environmental water.

Government-sponsored groundwater development is an area where investment may be required. Given differences in economic approaches at the macro and micro scale, any activity to enhance the water market needs to acknowledge the two different scales of benefits, which can also include import/export of real or virtual water and related types of land use or land development. This macro and micro distinction is also important where economic incentives are implemented, such as the recharge credits and pump augmentation fees implemented in the Pajaro Valley Water Management Area of California, USA (PVWMA, 2016; Miller et al., 2021). Similarly, in the Murray–Darling Basin, Australia, with risks to groundwater availability (Ross et al., 2023), water markets have been implemented and have evolved as an important policy tool to help address water scarcity with the evolution of the overarching water management plan with some issues and some successes (Wheeler, 2022). Examples from Australia, Spain, and the USA demonstrate that including some element of collective action is fundamental for effective CWM (Holley et al., 2016).

10.1.5 Actual Implementation

Planned CWM strongly benefits from, and possibly requires, strong ownership, especially by the irrigated farming sector. The Distrito De Riego Del Rio Yaqui↗ (this link may not be accessible in all regions), Sonora, Mexico, (as illustrated in Figure 2 of this book) is an excellent example of infrastructure and operations owned and run by the irrigation district that includes wells, reservoirs, climate monitoring, and transmission systems. This district states it has achieved sustainability because it does not allow any additional land-use development. It demonstrates how sustainability is possible by building strong local water user groups through targeted education and enabling actions, and through a limited membership of users and landowners.

This approach is simplest when drivers for change are inescapable, such as declining or erratic farm incomes or a declining resource base. In the past, many communities have focused on single resource–supply issues (either surface water or groundwater) and have been reluctant to address management issues associated with the other side of the resource picture or to engage in managing demand or developing additional sources beyond groundwater and surface water supplies. Doing so requires reorganization and diversification to better reflect the distribution of user demands and potential alternative supplies such as recycled, MAR, Flood-MAR, desalination, or even imported water sources.

This issue is exacerbated by several factors including the absence of a revenue base for cost recovery and the politicization of the user groups towards maintaining subsidized surface water supplies. There needs to be a participatory culture of education, demonstration, and capacity building between governments and the irrigation farming community or industry partners and its key stakeholders.

10.1.6 Building Knowledge and Communication

To facilitate CWM, knowledge is required in two key areas:

1. technical understanding through development and sharing of networks that monitor the spatial and temporal distribution of the total consumptive available water, replenishment of water, and other sources of supply; and
2. support for planning through the capability to provide future impact scenarios; the latter may be in the form of a complex numerical model of aquifer-river basin performance or, at times, simple analytical approaches.

This knowledge helps demonstrate the mitigation of overexploitation and enhanced sustainability through alternative CWM actions and components. CWM also requires the establishment or improvement of monitoring programs so that the quantity and quality impacts of the use of surface water on groundwater and vice versa can be demonstrated and evaluated for sustainability, and so that the beneficial impacts of water management actions can be seen by all stakeholders. Finally, these knowledge components must be communicated regularly to stakeholders and the public through websites, meetings, and summaries to connect and engage everyone who is affected by these policies and related CWM activities (Conceptual Exercise 15↴).

10.2 Use of Financial and Market-based Instruments to Develop Planned CWM

Financial and market-based instruments (FMBI) are a range of financial and economic measures that can be used to encourage specific actions and trends of water use. In the context of water resource planning, FMBI can consist of the following:

- direct financial incentives (e.g., taxation reduction, subsidies to lower electricity cost, resource grants, bonds, water markets, and replenishment incentives);
- disincentives (e.g., taxation increases, transmission fees, and litigation costs); or
- indirect trade-offs or offsets (e.g., pollution reduction schemes; watershed, climate or salt credits) and the introduction of inter-basin or regional import/export systems such as water trading.

Some countries have favored a regulatory approach to bring about various water resource outcomes, while others have tended to favor economic instruments or monetizing the resources, in the belief that clear financial signals are a strong lever to achieve policy objectives. These vehicles need limits and rate-based constraints to ensure sustainability subject to other supply-and-demand drivers such as land use, climate variability/change, population growth, and industrial development. With respect to CWM, countries have subsidies that distort the true cost of water delivery (surface water and groundwater) that bias water-user behavior, hence retarding the potential for planned CWM to contribute to optimal water use outcomes.

Conversely other FMBI (i.e., those not aligned with subsidies) are very powerful tools that encourage adoption of optimal CWM. The range of options tends to be very location- and culture-specific. Nonetheless, schemes that provide both financial incentives (e.g., through taxation decreases) when a defined minimum volume of water is used conjunctively, and indirect economic offsets (e.g., for salinity control) are considered the most effective. These schemes should generally be used to quickly initiate planned CWM and should not be viewed as permanent measures. Some incentives are indirect—such as *Beat-the-Peak* electricity production tiered rate charges—to minimize the use of electricity for groundwater pumpage during peak hours when electricity is at the highest demand, is most expensive, and when ET may also be greatest (Technical Question 2↴).

The introduction of clearly defined water rights, the application of well-defined caps (i.e., maximum limits of groundwater use and surface water allotments) and the introduction of a water trading regime can strongly facilitate more efficient, diverse, and flexible total water use and replenishment. Surface water trading regimes currently operate in many countries; however, groundwater trading regimes, such as the ones in the Central Valley of California, USA, are not as common. Although surface water to groundwater (and vice versa) trading regimes are common in California where imported water is commonly brought in and recharged in forebay regions or supplanted for direct use, such trading regimes are rare in developing countries. Nonetheless, water trading can be a strong market instrument to encourage conjunctive use if it is managed appropriately and has constraints on how the water is traded or water rights purchased. There are, however, few examples of this in the world—a couple of examples include, the Namoi Valley, Australia (described in Dillon et al., 2012) and the free-market water scheme in Chile (Budds, 2020). Overall, formal trading systems are rare in developing countries because the institutional mechanisms often do not exist. Government decrees/orders also often occur to move water from one user to another, yet in some instances these may also include financial transfers.

Not all market mechanisms are designed to account for environmental impacts (e.g., water-quality degradation such as salinity effects, seawater intrusion, land subsidence, environmental stream flows, and habitat maintenance). Nonetheless, FMBIs can still achieve measures of *national good*—for example, national gross production from irrigated agriculture or poverty alleviation. The issue is to apply the most appropriate reward and compliance signals to water/irrigated agriculture or industrial and public-supply sectors. FMBIs are not as recognizable where governments exercise regulation over monetization with centralized control as opposed to a market-based approach. However, in such centralized governance approaches, positive benefit–cost outcomes through similar initiatives can be developed along with constraints to support sustainability and limit other demand driving forces.

Water management policy—and its role in planned CWM—is part of a larger policy position by governments that involves national food policy, poverty alleviation, economic growth, sustainability, climate change, and energy considerations. Good governance is more likely to ensue once the impacts of these related areas on national water use policy decisions (including subsidies) are considered in a more holistic sustainability framework that does not embrace unlimited growth and related overexploitation of resources (Conceptual Exercise 16⤵).

11 CWM Wrap-up

CWM is a continuum that bridges the interfaces linking the supply-and-demand framework of water use and movement to the environment and society. These linkages result in a continuum of interactions between governance and treaties; development and maintenance of policy and institutional structures; transboundary conflicts and sharing; social and environmental needs; monitoring; analysis; integrated into a holistic operations framework (referred to as *smart valleys*, such as the Rio Yaqui); as well as adaptation and mitigation (Figure 20). CWM needs to include and link to drivers outside of the hydrosphere such as changes in population, industry, land use, and climate (Figure 20; Conceptual Exercise 17↴).

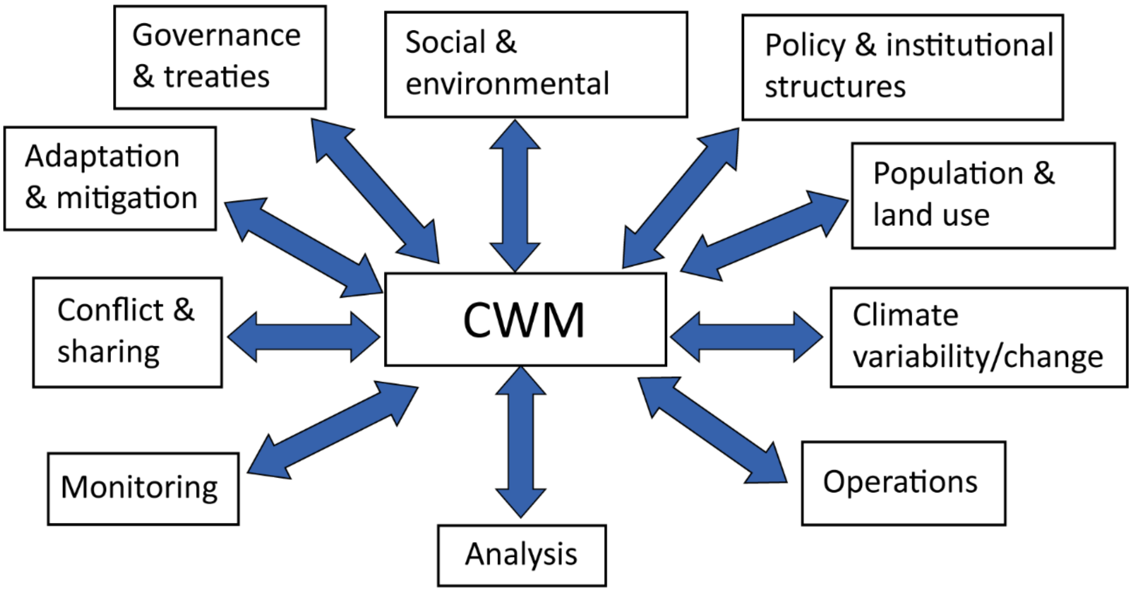


Figure 20 - Diagram showing the social and physical interfaces within a CWM supply-and-demand framework.

Examples of CWM throughout the world are presented in the Boxes section of this book (Section 14). These examples highlight a common history and common challenges. In nearly all cases where conjunctive use is being practiced (either spontaneously or in a planned manner), surface water is the dominant historical water source. Either through expansion of demand, technology uplift, new knowledge, or deteriorating water access/quality, the water management system moved toward incorporating groundwater along with other sources. This incorporation was done either within a regulatory environment (with varying degrees of compliance) or spontaneously by individuals.

The development of these water sources, combined with newer diverse sources, juxtaposes the inherent difference between surface water and groundwater ownership, development, and management. Surface water is predominantly a state-owned or managed commodity (a product that can be bought and sold) that in most cases is heavily subsidized via direct infrastructure investments as a part of national agricultural or food security policy or protection of urban and industrial supplies.

Groundwater, on the other hand, may or may not be state-owned, is typically managed locally, and does not usually attract the same level of subsidy or facilitate funding as a commodity. When groundwater is state-owned, such as in Mexico, the government administers the rights to individual users. In other words, the management of groundwater and surface water is commonly underpinned by different philosophies—differences that arguably are a significant impediment to progressing CWM. However, the development of additional alternative water sources combined with demand management is broadening the utility of CWM within a more holistic sustainability framework.

CWM offers significant benefits to all water users and the environment by helping to create a mechanism for supply-and-demand management within the entire hydrosphere of a watershed and related aquifer systems. It also offers major economic advantages in a world where improved water management is becoming much more important due to growth in land use, industry, and population combined with the pressures from climate change and climate variability. This will not only include growing and evolving adaptive management but also further study to continue to refine and update the methods used for monitoring, analysis, and decision making within a sustainable CWM strategy (Conceptual Exercise 18⤵, Follow-Up Conceptual Question 1⤵, Follow-Up Conceptual Question 2⤵, Follow-Up Conceptual Question 3⤵).

Exercises that provide both conceptual and technical questions and answers are provided to help further explore the concepts of CWM and related issues that arise in the application of various factors within CWM (Sections 12.1, 12.2, and 12.3).

Additional exercises that demonstrate how to analyze specific sustainability issues within CWM using an IHM model are included in a set of modeling exercises provided in a separate document titled "CWM Example-Model Scenario Exercises with MF-OWHM". The exercise manual is included in a zip file that can be downloaded from the book page https://gw-project.org/books/conjunctive-water-management/↗. These six exercises provide an opportunity to use an IHM model for simulating and analyzing the following six changes from a base-case situation.

(1) Addition of an Urban Well
(2) Changed Crop Type
(3) Addition of Salinity Flushing
(4) Adjustment of Water Demand to Equal Supply for Sustainability
(5) Changed Water Supply and Demand due to Climate Change
(6) Adjustment of Surface-Water Operations

12 Exercises

This section includes general and more technical exercises as well as a couple of selected modeling exercises that demonstrate how to use an IHM to analyze some CWM issues. Links to worked solutions are included.

12.1 Conceptual Exercises

Conceptual Exercise 1

What is the difference between Conjunctive Water Management (CWM) and Conjunctive Use (CU)?

Solution to Conceptual Exercise 1↓

Return to where text linked to Conceptual Exercise 1↑

Conceptual Exercise 2

What types of water can be considered in the supply-and-demand portfolio of Conjunctive Use?

Solution to Conceptual Exercise 2↓

Return to where text linked to Conceptual Exercise 2↑

Conceptual Exercise 3

Does CWM have to include MAR?

Solution to Conceptual Exercise 3↓

Return to where text linked to Conceptual Exercise 3↑

Conceptual Exercise 4

What are the differences between surface water management and groundwater management?

Solution to Conceptual Exercise 4↓

Return to where text linked to Conceptual Exercise 4↑

Conceptual Exercise 5

What are the drivers of supply and demand that need to be included or linked to CWM?

Solution to Conceptual Exercise 5↓

Return to where text linked to Conceptual Exercise 5↑

Conceptual Exercise 6

What are the differences between informal and formal systems?

Solution to Conceptual Exercise 6↓

Return to where text linked to Conceptual Exercise 6↑

Conceptual Exercise 7

What are some levels of connection in the hydrologic cycle that relate to CWM activities?

Solution to Conceptual Exercise 7↓

Return to where text linked to Conceptual Exercise 7↑

Conceptual Exercise 8

What are the benefits of CWM?

Solution to Conceptual Exercise 8↓

Return to where text linked to Conceptual Exercise 8↑

Conceptual Exercise 9

How can CWM implement replenishment for sustainability?

Solution to Conceptual Exercise 9↓

Return to where text linked to Conceptual Exercise 9↑

Conceptual Exercise 10

What are the main forms of analysis that can support CWM decision making?

Solution to Conceptual Exercise 10↓

Return to where text linked to Conceptual Exercise 10↑

Conceptual Exercise 11

What are the modelling approaches that can support CWM?

Solution to Conceptual Exercise 11↓

Return to where text linked to Conceptual Exercise 11↑

Conceptual Exercise 12

In what ways do allocation, optimization, and integrated hydrologic models (IHM) differ?

Solution to Conceptual Exercise 12↓

Return to where text linked to Conceptual Exercise 12↑

Conceptual Exercise 13

How can CWM be promoted and developed?

Solution to Conceptual Exercise 13↴

Return to where text linked to Conceptual Exercise 13↥

Conceptual Exercise 14

How can monitoring and analysis be linked to CWM governance and funding?

Solution to Conceptual Exercise 14↴

Return to where text linked to Conceptual Exercise 14↥

Conceptual Exercise 15

Are all numerical models able to address CWM?

Solution to Conceptual Exercise 15↴

Return to where text linked to Conceptual Exercise 15↥

Conceptual Exercise 16

What are the key institutional and governance barriers to implementing CWM?

Solution to Conceptual Exercise 16↴

Return to where text linked to Conceptual Exercise 16↥

Conceptual Exercise 17

How can integrated institutional and governance arrangements be enhanced to facilitate CWM?

Solution to Conceptual Exercise 17↴

Return to where text linked to Conceptual Exercise 17↥

Conceptual Exercise 18

What role can market- and finance-based mechanisms play in facilitating CWM?

Solution to Conceptual Exercise 18↴

Return to where text linked to Conceptual Exercise 18↥

12.2 Follow-Up Conceptual Questions

Follow-Up Conceptual Question 1

Which of the following are examples of water *operations*?

a) Installing gutters along the sides of paved streets.
b) Decision to release water from a dam.
c) Homeowner choosing to use a water filter.
d) All of the above.

Answer to Follow-up Conceptual Question 1⤵

Return to where text linked to Follow-up Conceptual Question 1⤴

Follow-Up Conceptual Question 2

Why are monitoring and analysis important?

Answer to Follow-up Conceptual Question 2⤵

Return to where text linked to Follow-up Conceptual Question 2⤴

Follow-Up Conceptual Question 3

Which of the following are examples of water *governance*?

a) Voter campaign literature saying that gutters are needed along paved streets, and that the water needs to be routed so that it is treated before it is allowed to flow to a natural water body.
b) Federal requirements that water levels behind dams not exceed given levels at different times of the year.
c) A news report about new water quality data in an area indicating high levels of lead in the water.
d) All of the above.

Answer to Follow-up Conceptual Question 3⤵

Return to where text linked to Follow-up Conceptual Question 3⤴

12.3 Technical Questions

Technical Question 1

What are the factors controlling the typical length of the time lag between groundwater pumping and the impact on streams? Why would a well close to a river not have 1:1 impact of groundwater pumping on the river flow?

Answer to Technical Question 1⤵

Return to where text linked to Technical Question 1⤴

Technical Question 2

In a typical water balance, what percentage of the total rainfall returns to the atmosphere as evapotranspiration (ET)?

Answer to Technical Question 2⤵

Return to where text linked to Technical Question 2⤴

12.4 Modeling Analysis Exercises

Exercises that demonstrate how to analyze specific sustainability issues within CWM using an IHM model are included in a set of modeling exercises provided in a separate document written by the authors and titled "CWM Example-Model Scenario Exercises with MF-OWHMv2". The exercise manual is included in a zip file that can be downloaded from the book page https://gw-project.org/books/conjunctive-water-management/↗. These six exercises provide an opportunity to use an IHM model for simulating and analyzing the following six changes from a base-case situation.

(1) Addition of an Urban Well
(2) Changed Crop Type
(3) Addition of Salinity Flushing
(4) Adjustment of Water Demand to Equal Supply for Sustainability
(5) Changed Water Supply and Demand due to Climate Change
(6) Adjustment of Surface-Water Operations

13 References

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., & Rasmussen, J. (1986). An introduction to the European Hydrologic System: Systeme Hydrologique European, SHE, 1: History and philosophy of a physically based, distributed modeling system. *Journal of Hydrology*, *87*, 45–59. https://doi.org/10.1016/0022-1694(86)90114-9↗.

Alattar, M., Troy, T., Russo, T., & Boyce, S. E. (2020). Modeling the surface water and groundwater budgets of the US using MODFLOW-OWHM. *Advances in Water Resources*, *143*, 103682. https://doi.org/10.1016/j.advwatres.2020.103682↗.

Alley, W. M., & Leake, S. A. (2004). The journey from safe yield to sustainability. *Groundwater*, *42*(1), 12–16. https://doi.org/10.1111/j.1745-6584.2004.tb02446.x↗.

Alvarez-Garreton, C., Boisier, J. P., Garreaud, R., Seibert, J., & Vis, M. (2021). Progressive water deficits during multiyear droughts in basins with long hydrological memory in Chile. *Hydrology and Earth System Sciences*, *25*(1), 429–446. https://doi.org/10.5194/hess-25-429-2021↗.

Ayers, R. S., & Westcot, D. W. (1985). *Water quality for agriculture* (FAO Irrigation and Drainage, Paper 29). Food and Agriculture Organization. https://www.waterboards.ca.gov/water_issues/programs/tmdl/records/state_board/1985/ref2648.pdf↗.

Ayres, A., Hanak, E., Gray, B., Sencan, G., Bruno, E., Escriva-Bou, A., Gartrell, G., & Collins, J. (2021). *Improving California's water market: How water trading and banking can support groundwater management* (Annual Report, 2021). Public Policy Institute of California. https://www.ppic.org/publication/improving-californias-water-market/↗.

Azeref, B. G., & Bushira, K. M. (2020). Numerical groundwater flow modeling of the Kombolcha catchment northern Ethiopia. *Modeling Earth Systems and Environment*, *6*(2), 1233–1244. https://link.springer.com/article/10.1007/s40808-020-00753-6↗.

Belete, G. F., Voinov, A., & Laniak, G. F. (2017). An overview of the model integration process: From pre-integration assessment to testing. *Environmental Modelling & Software*, *87*(January), 49–63. https://doi.org/10.1016/j.envsoft.2016.10.013↗.

Blomquist, W., Heikkila, T., & Schlager, E. (2001). Institutions and conjunctive water management among three western states. *Natural Resource Journal*, *41*(3), 653–683. https://digitalrepository.unm.edu/nrj/vol41/iss3/7↗.

Borden, C., Gaur, A., & Singh, C. (2016). *Water resource software - Application overview and review*. World Bank, South Asia Water Initiative. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/279391467995445292/water-resource-software-application-overview-and-review↗.

Borland, J. P., & Beal, L. V. (1988). *Water resources data, New Mexico, water year 1988* (Water Data Report NM-88-1). US Geological Survey.

https://www.usgs.gov/publications/water-resources-data-new-mexico-water-year-1988↗.

Borsi, I., Rossetto, R., Cannata, M., De Filippis, G., Ghetta, M. (2016, October 12–14). *Open source for water management: including capabilities of MODFLOW-OWHM in the FREEWAT GIS modelling environmen*t. IV Open Source Geospatial Research & Educational Symposium, Perugia, Italy. https://doi.org/10.7287/peerj.preprints.2209↗.

Boyce, S. E., Hanson, R. T., Ferguson, I., Schmid, W., Henson, W., Reimann, T., Mehl, S. M., & Earll, M. M. (2020). *One-water hydrological flow model: A MODFLOW based conjunctive-use simulation software* (Techniques and Methods 6-A60). US Geological Survey. https://pubs.usgs.gov/publication/tm6A60↗.

Boyce, S. E., & Ferguson, I. M.(2023). *MODFLOW One-water hydrologic flow model (MF-OWHM): Conjunctive use and integrated hydrologic flow modeling software with surface oater Operations* (Version 2.2.0) [Computer software]. U.S. Geological Survey. https://doi.org/10.5066/P9P8I8GS↗.

Braune, E. and Israel, S. (2022). Managed Aquifer Recharge: Southern Africa: The Groundwater Project, 96p., ISBN: 978-1-77470-006-8, https://doi.org/10.21083/978-1-77470-006-8↗.

Bredehoeft, J. D. (1997). Safe yield and the water budget myth. *Ground Water 35*(6), 929. https://doi.org/10.1111/j.1745-6584.1997.tb00162.x↗.

Bredehoeft, J. D. (2002). The water budget myth revisited: Why hydrogeologists model. *Groundwater 40*(4), 340–345. https://doi.org/10.1111/j.1745-6584.2002.tb02511.x↗.

Bredehoeft, J. D. (2011). Hydrologic trade-offs in conjunctive use management. *Groundwater, 49*(4), 468–475. https://doi.org/10.1111/j.1745-6584.2010.00762.x↗.

Bredehoeft, J. D., Papadopulos, S. S., & Cooper, H. H., Jr. (1982). Groundwater: The water-budget myth. In National Research Council Geophysics Study Committee, *Studies in geophysics: Scientific basis of water-resource management* (pp. 51–57). National Academy Press. https://nap.nationalacademies.org/read/19530/chapter/7↗.

Briody, A. C., Robertson, A. J., & Thomas, N. (2016). *Seepage investigation of the Rio Grande from below Leasburg Dam, Leasburg, New Mexico, to above American Dam, El Paso, Texas, 2014* (Scientific Investigations Report 2016-5010). US Geological Survey. https://doi.org/10.3133/ofr20131233↗.

Budds, J. (2020). Securing the market: Water security and the internal contradictions of Chile's Water Code. *Geoforum, 113*(July), 165–175. https://doi.org/10.1016/j.geoforum.2018.09.027↗.

Bushira, K. M., Hernandez, J. R., & Sheng, Z. (2017). Surface and groundwater flow modeling for calibrating steady state using MODFLOW in Colorado River Delta, Baja California, Mexico. *Modeling Earth Systems and Environment, 3*(2), 815-824. https://doi.org/10.1007/s40808-017-0337-5↗.

Byrd, D., Lange, K., & Beal, L. (2002). *Water resources data, New Mexico, water year 2001* (Water Data Report NM–01–1). US Geological Survey. https://doi.org/10.3133/wdrNM011↗.

Cahn, M., & Bali, K. (2015). *Managing salts by leaching* (Publication no. 8550). University of California Agriculture and Natural Resources. http://anrcatalog.ucanr.edu↗.

California Data Exchange Center. (2024). *Historical data selector* [Data set]. CA-DWR. http://cdec.water.ca.gov/dynamicapp/selectQuery?station_id=DVS&dur_code=M&sensor_num=2&start_date=01/01/1800&end_date=now↗.

California Department of Water Resources (CA-DWR). (2014). California Sustainable Groundwater Management Act. https://water.ca.gov/programs/groundwater-management/sgma-groundwater-management#main-content↗. (last accessed June 19, 2023).

California Department of Water Resources. (2016a). *Conjunctive use*. CA-DWR. https://groundwaterexchange.org/conjunctive-use↗.

California Department of Water Resources. (2016b). *Conjunctive management and groundwater storage*. CA-DWR. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/California-Water-Plan/Docs/RMS/2016/08_ConjMgt_GW_Storage_July2016.pdf↗.

California Department of Water Resources. (2020). *Draft handbook for water budget development: With or without models* (Water Budget Handbook). CA-DWR. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Data-and-Tools/Files/Water-Budget-Handbook.pdf↗.

California Department of Water Resources. (2024a). *Alternative to groundwater sustainability plans.* CA-DWR. https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Alternatives↗.

California Department of Water Resources. (2024b). *California state groundwater elevation monitoring (CASGEM).* CA-DWR. https://water.ca.gov/Programs/Groundwater-Management/Groundwater-Elevation-Monitoring--CASGEM↗.

California State Water Resource Control Board. (2005). *California water plan update 2005, Volume 2 - Resource management strategies, Chapter 4 - Conjunctive management and groundwater storage.* CA-DWR. https://www.cdfa.ca.gov/agvision/files/California/California_CaliforniaWaterPlanUpdate2005.pdf↗.

California State Water Resource Control Board. (2023a). *Executive Order N-4-23*. CA-DWR. https://www.gov.ca.gov/wp-content/uploads/2023/03/3.10.23-Ground-Water-Recharge.pdf?emrc=6418bc35810b4↗.

California State Water Resource Control Board. (2023b). *Governor's Executive Orders N-7-23 & N-4-23 for flood diversion*. CA-DWR.

https://www.waterboards.ca.gov/waterrights/water_issues/programs/groundwater-recharge/↗.

Colón, A. I., Hanson, R. T., Jenkins, E. W., & Kavanagh, K. R. (2016, October 15-16). Using simulation-based optimization to guide allocations of surface and ground water resources for agricultural water use. In *Proceedings of the 2016 South Carolina Water Resources Conference*, Columbia Metropolitan Convention Center, Columbia, South Carolina, USA. https://tigerprints.clemson.edu/cgi/viewcontent.cgi?article=1384&context=scwrc↗.

Colorado Water Institute. (2014). South Platte groundwater [Special Issue]. *Colorado Water, 31*(1), 1–44. https://watercenter.colostate.edu/wp-content/uploads/sites/91/gravity_forms/38-9ff4779ecc3d11bed26f3edfd095c739/2019/06/JanFeb31_1.pdf↗.

Convention between the United States and Mexico: Equitable distribution of the waters of the Rio Grande. May 21, 1906. https://www.ibwc.gov/wp-content/uploads/2022/11/1906Conv.pdf↗.

Cosens, B. (2010). *Evolution of the policies surrounding ground and surface water management in the west.* University of Idaho Law Digital Commons. https://digitalcommons.law.uidaho.edu/faculty_scholarship/179/↗.

Crilley, D. M., Matherne, A. M., Thomas, N., & Falk, S. E. (2013). *Seepage investigations of the Rio Grande from below Leasburg Dam, Leasburg, New Mexico, to above American Dam, El Paso, Texas, 2006–13* (Open-File Report 2013–1233). US Geological Survey. https://doi.org/10.3133/ofr20131233↗.

CVSALTS. (2023). *Salt and nutrient control program*. https://www.cvsalinity.org/↗

Dahlke, H. E., Kocis, T., Brown, A. G., O'Green, T., Orloff, S., Putnam, D., Volder, A., Shackel, K., Harter, T., & Sandoval-Solis, S. (2017, March 22). *Impact of agricultural groundwater recharge on soil water balance and crop productivity of alfalfa and almonds*. California Water and Environmental Modeling Forum, [Conference Session 21]: The Surface-Groundwater Continuum: A Modeling Challenge. https://cwemf.org/wp/wp-content/uploads/2017/05/meeting_program2017.pdf↗.

Dahlke, H. E., Brown, A. G., Orloff, S., Putnam, D., & O'Green, T. (2018) Managed winter flooding of alfalfa recharges groundwater with minimal crop damage. *California Agriculture, 72*(1), 65–75. https://doi.org/10.3733/ca.2018a0001↗.

Danton, D and Marr, A. J., 2007 Conjunctive use of surface water and groundwater in a water abundant river basin. Riversymposium, Australia, 2007.

De Filippis, G., Pouliaris, C., Kahud, D., Vasile, T. A., Manea, V. A., Zau, F., Panteleit, B., Dadaser-Celik, F., Positano, P., Nannucci, M. S., Grodzynskyi, M., Marandi, A., Sapiano, M., Kopač, I., Kallioras, A., Cannata, M., Filiali-Meknassi, Y., Foglia, L., Borsi, I., & Rossetto, R. (2019). Spatial data management and numerical modelling: Demonstrating the application of the QGIS-Integrated FREEWAT Platform at 13 case studies for tackling groundwater resource management: *Water, 12*(1), 41.

https://doi.org/10.3390/w12010041↗.

Dickinson, R. (2014). California Assembly Bill (CA-AB) 1739. *Legislative Counsel's Digest, chapter 347.* https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140AB1739↗.

Dillon, P., Pavelic, P., Page, D., Beringen, H., & Ward J. (2009a). *Managed aquifer recharge: An introduction* (Waterlines Report. No. 13). Australian National Water Commission. https://recharge.iah.org/files/2016/11/MAR_Intro-Waterlines-2009.pdf↗.

Dillon, P., Gale, I., Contreras, S., Pavelic, P., Evans, R., & Ward, J. (2009b). Managing aquifer recharge and discharge to sustain irrigation livelihoods under water scarcity and climate change. In *Improving integrated surface and groundwater resources management in a vulnerable and changing world. IAHS-AISH 330*, 1–12. https://www.semanticscholar.org/paper/Managing-aquifer-recharge-and-discharge-to-sustain-Dillon-Gale/19512455db993ad4cd98168a088017199d337edb↗.

Dillon, P., Fernandez, E. E., & Tuinhof, A. (2012). Management of aquifer recharge and discharge processes and aquifer storage equilibrium (Thematic paper No. 4). *IAH contribution to GEF-FAO Groundwater Governance.* https://publications.csiro.au/rpr/pub?list=BRO&pid=csiro:EP124969&sb=RECENT&n=8&rpp=25&page=4&tr=3785&dr=all&dc4.browseYear=2012↗.

Dillon, P., & Arshad, M. (2016). Managed aquifer recharge in integrated water resource management. In A. Jakeman, O. Barreteau, R. Hunt, J. D. Rinaudo, & A. Ross (Eds.), *Integrated groundwater management; Concepts, approaches and challenges* (pp. 435–452). Springer International. https://link.springer.com/book/10.1007/978-3-319-23576-9↗.

Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R. D. G., Jain, R. C., Bear, J., Schwarz, J., Wang, W., Fernandez, E., Stefan, C., Pettani, M., van der Gun, J., Sprenger, C., Massmann, G., Scanlon, B. R., Xanke, J., Jokela, P., Zheng, Y.,…& Sapiano, M. (2019). Sixty years of global progress in managed aquifer recharge. *Hydrogeology Journal, 27*(1), 1–30. https://link.springer.com/article/10.1007/s10040-018-1841-z↗.

District Rio Yaqui. (2023). *Distrito de Riego del Rio Yaqui, Sonora, Mexico* [Yaqui River Irrigation District, Sonora, Mexico]. http://www.drryaqui.org.mx/↗.

Dogrul, E. C. (2012). *Integrated Water Flow Model (IWFM Version 4.0): Theoretical documentation.* Sacramento (CA): Integrated Hydrological Models Development Unit, Modeling Support Branch, Bay-Delta Office, California Department of Water Resources. https://data.ca.gov/dataset/integrated-water-flow-model-iwfm-version-4-0-331↗.

Doherty, J. (2004). *PEST—Model-independent parameter estimation - User manual* (5th ed.). Watermark Numerical Computing. http://www.pesthomepage.org/About_Us.php↗.

Doherty, J. (2010a). *PEST—Model-independent parameter estimation - User manual* (5th ed., with slight additions). Watermark Numerical Computing. http://www.pesthomepage.org/About_Us.php↗.

Doherty, J. (2010b). *Addendum to the PEST manual*. Watermark Numerical Computing. http://www.pesthomepage.org/About_Us.php↗.

Doherty, J. (2010c). *BeoPEST for Windows*. Watermark Numerical Computing. http://www.pesthomepage.org/About_Us.php↗.

Doherty, J. E., & Hunt, R. J. (2010). *Approaches to highly parameterized inversion - A guide to using PEST for groundwater-model calibration* (Scientific Investigations Report 2010–5169). US Geological Survey. https://doi.org/10.3133/sir20105169↗.

Donigian, A. S. (2002). Watershed model calibration and validation: The HSPF experience. *Proceedings of the Water Environment Federation, 2002*(8), 44–73. http://dx.doi.org/10.2175/193864702785071796↗.

Donigian, A. S., Bicknell, B. R., Imhoff, J. C. (1995). Hydrological simulation program - FORTRAN (HSPF). In V. P. Singh (Ed.), *Computer models of watershed hydrology* (pp. 395–442). Water Resources Publications.

dos Anjos, N. F. R., Stephan, R. M., Donoso, M. C., González, A., del Castillo-Laborde, L., Miletto, M., Aureli, A., & Ugas, L. (Eds.).(2008). *Transboundary aquifers of the Americas: Legal and institutional framework in the management of the transboundary aquifer systems in the Americas*. UNESCO/OAS ISARM Americas Program. https://www.oas.org/dsd/waterresources/projects/ISARM/Publications/ISARMAmericasBook2(Eng).pdf↗.

Dudley, T., & Fulton, A. (2006). *Conjunctive water management: What is it? Why consider it? What are the challenges?* University of California Agricultural Extension, Tehema County Cooperative Extension. https://cetehama.ucanr.edu/files/20596.pdf↗.

Ebrahim, G. Y., Villholth, K. G., & Boulos, M. (2019). Integrated hydrogeological modelling of hard-rock semi-arid terrain: Supporting sustainable agricultural groundwater use in Hout catchment, Limpopo Province, South Africa. *Hydrogeology Journal, 27*, 965–981. https://doi.org/10.1007/s10040-019-01957-6↗.

Evans, W. R., Evans, R. S., & Holland, G. F. (2012). *Conjunctive use and management of groundwater and surface water within existing irrigation comments: The need for a new focus on an old paradigm. Thematic Paper 2*. Groundwater Governance - A Global Framework for Action. https://sswm.info/sites/default/files/reference_attachments/conjunctive%20use%20and%20mgmt.pdf↗.

Evans, R., & Dillon, P. (2017), Linking Groundwater and Surface Water: Conjunctive Water Management. In K. G., Vilholth, E. Lopez-Gunn, K. Conti, A. Garrido, & J. van der Gun (Eds.), *Advances in Groundwater Governance* (chapter 17). CRC Press. https://www.taylorfrancis.com/chapters/edit/10.1201/9781315210025-17/linking-groundwater-surface water-conjunctive-water-management-evans-richard-dillon-peter↗.

Fagan, B. (2008). *The great warming: Climate change and the rise and fall of civilizations*. Bloomsbury Press.

Faunt, C.C., ed., (2009), Groundwater Availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766, 225 p., https://pubs.usgs.gov/pp/1766/

Faunt, C. C., Hanson, R. T., Belitz, K., Schmid, W., Predmore, S., Rewis, D. L., & McPherson, K. (2009). Numerical model of the hydrologic landscape and groundwater flow in California's Central Valley. In C. C. Faunt (Ed.), *Groundwater availability of California's Central Valley* (Professional Paper 1766). US Geological Survey. http://pubs.er.usgs.gov/usgspubs/pp/pp1766↗.

Faunt, C.C., Traum, J.A., Boyce, S.E., Seymour, W.A., Jachens, E.R.; Brandt, J.; Sneed, M.; Bond, S., Marcelli, M.F., (2024). Groundwater Sustainability and Land Subsidence in California's Central Valley. Water, 16(1189):40p., https://doi.org/10.3390/w16081189↗.

Ferguson, I. A., & Llewellyn, D. (2015). *Simulation of Rio Grande project operations in the Rincon and Mesilla Basins: Summary of model configuration and results.* (Technical Memorandum 86-68210-2015-05). 56. US Department of the Interior, Bureau of Reclamation.

Ferguson, I. A., Llewellyn, D., Hanson, R. T., & Boyce S. E. (2016). *User guide to the surface water operations process - An integrated approach to simulating large-scale surface water management in MODFLOW-based hydrologic models* (Technical Memorandum 86-68210–2016-02). US Department of the Interior, Bureau of Reclamation.

Flint, L. E., Flint, A. L., & Stern, M. A. (2021). *The basin characterization model - A regional water balance software package* (Techniques and Methods 6-H1) [Computer software]. US Geological Survey. https://pubs.usgs.gov/publication/tm6H1↗.

Food and Agriculture Organization of the United Nations. (1995), January 31–February 02 1993). *Land and water integration and river basin management*: *Proceedings of a FAO informal workshop, Rome, Italy*. https://www.fao.org/3/v5400e/v5400e00.htm↗.

Foster, S. & Garduño, H. (2006). *Integrated approaches to groundwater resource conservation in the Mendozan Aquifers of Argentina* (GW-MATE Case Profile Collection, Number 6). The World Bank. www.worldbank.org/gwmate↗.

Foster, S. & van Steenbergen, F. (2011). Conjunctive groundwater use: A 'lost opportunity' for water management in the developing world? *Hydrogeology Journal, 19*, 959–962. https://doi.org/10.1007/s10040-011-0734-1↗.

Foster, S., van Steenbergen, F., Zuleta, J. & Garduño, H. (2010). *Conjunctive use of groundwater and surface water: from spontaneous coping strategy to adaptive resource management* (GW-MATE Strategic Overview Series 2). The World Bank. www.un-igrac.org/publications↗.

Fowler, K. R., Jenkins, E. W., Ostrove, C., Chrispell, J. C., Farthing, M. W., & Parno, M. (2015). A decision-making framework with MODFLOW-FMP2 via optimization: Determining trade-offs in crop selection. *Environmental Modeling and Software 69*, 280–291. https://doi.org/10.1016/j.envsoft.2014.11.031↗.

Fowler, K. R., Jenkins, E. W., Parno, M., Chrispell, J. C., Colón, A. I., & Hanson, R. T. (2016). Development and use of mathematical models and software frameworks for integrated analysis of agricultural systems and associated water use impacts. *AIMS Agriculture and Food, 1*(2), 208–226. http://www.aimspress.com/article/10.3934/agrfood.2016.2.208↗.

Garduño, H., Romani, S., Sengupta, B., Tuinhof, A. and Davis, R., 2011. *India Groundwater Governance: Case Study*. Water Papers, Water Partnership Program, The World Bank.

Glover, R. E. & Balmer, C. G. (1954). River depletion resulting from pumping a well near a river. *Eos, American Geophysical Union Transactions, 35*(3), 468–470. https://doi.org/10.1029/TR035i003p00468↗.

Gonçalves, R. D., Teramoto, E. H., & Chang, H. K. (2020). Regional groundwater modeling of the Guarani aquifer system. *Water, 12*(9), 2323. https://www.mdpi.com/2073-4441/12/9/2323↗.

Hadjigeorgalis, E. (2009). A place for water markets: Performance and challenges. *Applied Economic Perspectives and Policy, 31*(1), 50–67. https://doi.org/10.1111/j.1467-9353.2008.01425↗

Hafi, A. (2002). Conjunctive use of groundwater and surface water in the Burdekin delta area [Special Issue]. *Economic Record, 79*, S52–S62.

Hanson, R. T. (2015). Hydrologic framework of the Santa Clara Valley, California: *Geosphere 11*(3). https://ca.water.usgs.gov/pubs/2015/Hanson2015.pdf↗.

Hanson, R. T., McLean, J. S., & Miller, R. S. (1994). *Hydrogeologic framework and preliminary simulation of groundwater flow in the Mimbres Basin, southwestern New Mexico* (Water-Resources Investigation Report 94-4011). US Geological Survey. http://pubs.er.usgs.gov/usgspubs/wri/wri944011↗.

Hanson, R. T., Li, Z., & Faunt, C. (2004). *Documentation of the Santa Clara Valley regional groundwater/surface water flow model. Santa Clara County, California* (Scientific Investigations Report SIR2004-5231).US Geological Survey. http://pubs.usgs.gov/sir/2004/5231/↗.

Hanson, R.T. & Dettinger, M.D. (2005). Ground-water/surface Water responses to global climate simulations, Santa Clara-Calleguas Basin, Ventura County, California, 1950-93. Journal of the American Water Resources Association, 41(3), 517–536. https://doi.org/10.1111/j.1752-1688.2005.tb03752.x↗.

Hanson, R. T., Schmid, W., Lear, J., & Faunt, C. C. (2008, May 18–21). Simulation of an aquifer-storage-and-recovery (ASR) system using the farm process in MODFLOW for the Pajaro Valley, Monterey Bay, California. In *Proceedings, MODFLOW and more: Ground water and public policy* (pp. 501–505). Golden, CO, USA. https://www.pvwater.org/images/hydrology/assets/ASR_FMP_PVWMA_Hansonetal_FINAL.pdf↗.

Hanson, R. T., Schmid, W., Faunt, C. C., & Lockwood, B. (2010). Simulation and analysis of conjunctive use with MODFLOW's farm process. *Groundwater, 48*(5), 674–689. https://doi.org/10.1111/j.1745-6584.2010.00730.x↗.

Hanson, R. T., Flint L. E., Flint A. L., Dettinger M. D., Faunt C. C., Cayan D., & Schmid W. (2012). A method for physically based model analysis of conjunctive use in response to potential climate changes. *Water Resources Research, 48*, W00L08. https://doi.org/10.1029/2011WR01077↗.

Hanson, R. T., & Schmid, W. (2013). *Economic resilience through "one-water" management* (Open-File Report OFR 2013-1175). US Geological Survey. https://www.usgs.gov/publications/economic-resilience-through-one-water-management↗.

Hanson, R. T., Schmid, W., Knight, J., & Maddock, T., III. (2013, June 2–6) Integrated hydrologic modeling of a transboundary aquifer system, Lower Rio Grande. In *Proceedings, MODFLOW and more 2013. Translating science into practice*. Golden, CO.

Hanson, R. T., Boyce, S. E., Schmid, W., Hughes, J. D., Mehl, S. M., Leake, S. A., Maddock, T., III, & Niswonger, R. G. (2014a). *One-water hydrologic flow model (MODFLOW-OWHM)* (Techniques and methods 6–A51). US Geological Survey & US Bureau of Reclamation. https://pubs.usgs.gov/tm/06/a51/pdf/tm6-a51.pdf↗.

Hanson, R. T., Schmid, W., Faunt C. C., Lear, J. & Lockwood, B. (2014b). Integrated hydrologic model of Pajaro Valley, Santa Cruz and Monterey Counties, California (Scientific Investigations Report, 2014-5111). US Geological Survey. https://pubs.usgs.gov/publication/sir20145111↗.

Hanson, R. T., Lockwood, B., & Schmid, W. (2014c). Analysis of projected water availability with current basin management plan, Pajaro Valley, California. *Journal of Hydrology, 519*(A), 131–147. http://www.sciencedirect.com/science/article/pii/S0022169414005228↗.

Hanson, R. T., Flint, L. E., Faunt, C. C., Gibbs, D. R., & Schmid, W. (2014d). *Hydrologic models and analysis of water availability in Cuyama Valley, California* (Scientific Investigations Report 2014–5150). US Geological Survey. http://dx.doi.org/10.3133/sir20145150↗.

Hanson, R. T., Chávez-Guillen, R., Tujchneider, O., Alley, W. M., Rivera, A., Dausman, A., Batista, L., & Espinoza, M. (2015). Conocimiento básico científico y técnico necesario para la evaluación y gestion de los SAT [Basic scientific and technical knowledge required for the evaluation and management of SAT]. In A. Rivera (Ed.), *Estrategia regional para la gestión de los Sistemas de Acuíferos Transfronterizos (SAT) en las Americas* [Regional Strategy for the Management of Transboundary Aquifers Systems in the Americas] (pp. 79–124). UNESCO/OEA–ISARM AMERICAS. https://unesdoc.unesco.org/ark:/48223/pf0000235394?posInSet=7&queryId=32a47d34-c6c2-47d0-bc1c-6a9756cb7847↗.

Hanson, R. T., Ritchie, A. B., Boyce, S. E., Galanter, A. E., Ferguson, I. A., Flint, L. E., Flint, A., & Henson, W. R. (2020). *Rio Grande transboundary integrated hydrologic model and water availability analysis, New Mexico and Texas, United States, and northern Chihuahua, Mexico* (Scientific Investigations Report 2019–5120). US Geological Survey. https://doi.org/10.3133/sir20195120↗.

Hantush, M. S. (1965). Wells near streams with semipervious beds. *Journal of Geophysical Research, 70*(12), 2829–2838.

Harbaugh, A.W. (2005). *MODFLOW-2005, the U.S. Geological Survey modular ground-water model–The ground-water flow process* (Techniques and Methods 6-A16). US Geological Survey. https://doi.org/10.3133/tm6A16↗.

Hart, B., Nelson, R., & Marsh, R. (2023). Editorial. *Australasian Journal of Water Resources, 27*(2), 205–210. https://doi.org/10.1080/13241583.2023.2260581↗.

Harter, T., & Morel-Seytoux, H. (2013, August). *Peer review of the IWFM, MODFLOW and HGS model codes: Potential for water management applications in California's Central Valley and other irrigated groundwater basins. Final report*. California Water and Environmental Modeling Forum, Sacramento. https://www.cwemf.org/Pubs/GWModelsPeerReviewFinal.pdf↗.

Hatch, C. E., Fisher, A. T., Revenaugh, J. S., Constantz, J., & Ruehl, C. (2006). Quantifying surface water–groundwater interactions using time series analysis of streambed thermal records: Method development. *Water Resources Research, 42*, W10410. https://doi.org/10.1029/2005WR004787↗.

Hill, M. C., & Tiedeman, C. R. (2007). *Effective groundwater model calibration - With analysis of data, sensitivities, predictions, and uncertainty*. Wiley & Sons. https://doi.org/10.1002/9780470041086.index↗.

Hoffmann, J. P., Blasch, K. W., Pool, D. R., Bailey, M. A., & Callegary, J. B. (2007). *Estimated infiltration, percolation, and recharge rates at the Rillito Creek focused recharge investigation site, Pima County, Arizona* (Professional Paper 1703-H). US Geological Survey. https://pubs.usgs.gov/publication/pp1703H↗.

Holley, C., Sinclair, D., Lopez-Gunn, E., & Schlager, E. (2016). Conjunctive management through collective action. In A. J. Jakeman, O. Barreteau, R. J. Hunt, J. D. Rinaudo, & A. Ross (Eds), *Integrated groundwater management* (pp. 229–252). Springer. https://doi.org/10.1007/978-3-319-23576-9_9↗.

Hughes, J. D., Langevin, C. D., & Banta, E. R. (2017). *Documentation for the MODFLOW 6 framework* (Techniques and Methods, 6-A57). US Geological Survey. https://doi.org/10.3133/tm6A57↗.

Hughes, J. D., Martijn, J. R., Langevin, C. D., Morway, E.D. & McDonald, R. R. (2022). The MODFLOW application programming interface for simulation control and software interoperability. *Environmental Modeling and Software 148*, 104257. https://pubs.usgs.gov/publication/70227751↗.

Hunt, B. (1999). Unsteady stream depletion from ground water pumping. *Ground Water, 37*(1), 98–102. https://doi.org/10.1111/j.1745-6584.1999.tb00962.x↗.

Interim Water Resources Review Committee. (2017). *South Platte History*. Colorado General Assembly. https://leg.colorado.gov/sites/default/files/images/committees/2017/1005waterresourc espresentation_from_water_rights_association_of_the_south_platte_concerning_risin g_groundwater.pdf↗.

International Water Management Institute. (2002). *Innovations in groundwater recharge* (IWMI-Tata Water Policy Briefing No. 1). http://www.iwmi.cgiar.org/gwmate↗.

Izbicki, J. A. (1996). *Seawater intrusion in a coastal California aquifer* (Fact Sheet 125-96). US Geological Survey.

Jakeman, A. J., Barreteau, O., Hunt, R. J., Rinaudo, J. D., & Ross, A. (Eds.).(2016). *Integrated groundwater management - Concepts, approaches, and challenges*. Springer Open. https://doi.org/10.1007/978-3-319-23576-9↗.

Kaur, A. (2023, March 3). Punjab's water depletion crisis. *#SavingPunjab*. https://savingpunjab.org/2023/03/03/punjabs-water-depeletion-crisis/↗.

Khepar, S. D., Yadav, A. K., Sondhi, S. K., & Sherring, A. (2000). Modelling surplus canal water releases for artificial recharge of ground water through surface drainage systems. *Irrigation Science, 19*, 95–100. https://doi.org/10.1007/PL00006708↗.

Kim, N. W., Chung, I. M., Won, Y. S., & Arnold, J. G. (2008). Development and application of the integrated SWAT–MODFLOW model. *Journal of Hydrology, 356*(1–2), 1–16. https://www.sciencedirect.com/science/article/pii/S0022169408000991↗.

Kemira. (2023). *Water management 2040 - Future scenarios*. https://www.kemira.com/insights/report-water-management-2040↗.

Knight, J. (2015). Use of an integrated hydrologic model to assess the effects of pumping on streamflow in the Lower Rio Grande [Master of Science thesis, University of Arizona]. UA Campus Repository. http://hdl.handle.net/10150/556878↗.

Kocis, T., & Dahlke, H. E. (2017). Availability of high-magnitude streamflow for groundwater banking in the Central Valley, California. *Environmental Research Letters, 12*(8), 1–13. https://doi.org/10.1088/1748-9326/aa7b1b↗.

Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., & Provost, A. M. (2017). *Documentation for the MODFLOW 6 groundwater flow model* (Techniques and Methods, 6-A55). US Geological Survey. https://doi.org/10.3133/tm6A55↗.

Langrand, M. (2023). Part I: Chile's battle to reclaim its water. *Geneva Solutions: Explorations - The water we share, 1*. https://genevasolutions.news/explorations/the-water-we-share/chile-s-battle-to-reclaim-its-water↗.

Lautze, J. (2018, April 25). Conjunctive surface–groundwater management of shared waters: A new USAID Project. *Agrilinks*. https://agrilinks.org/post/conjunctive-surface-groundwater-management-shared-waters-new-usaid-project↗.

Liang, X., Lettenmaier, D., Wood, E., & Burges, S. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research, 99*(D7), 144115–14428. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/94jd00483↗.

Liang, X., Lettenmaier, D., & Wood, E. (1996). One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model. *Journal of Geophysical Research, 101*(D16), 21403–21422. https://doi.org/10.1029/96JD01448↗.

Maheshwari, B., Varua, M., Ward, J., Packham, R., Chinnasamy, P., Dashora, Y., Dave, S., Soni, P., Dillon, P., Purohit, R., Hakimuddin, Shah, T., Oza, S., Singh, P., Prathapar, S. Patel, A., Jadeja, Y., Thaker, B., Kookana, R., Rao, P. (2014). The role of transdisciplinary approach and community participation in village scale groundwater management: Insights from Gujarat and Rajasthan, India [Special Issue]. *Water Open Access Journal*, *6*(6), 3386–3408. http://www.mdpi.com/journal/water/special_issues/MAR↗.

Markstrom, S. L., Niswonger, R. G., Regan, R. S., Prudic, D. E., & Barlow, P. M. (2008). *GSFLOW - Coupled ground-water and surface water flow model based on the integration of the precipitation-runoff modeling system (PRMS) and the modular ground-water flow model (MODFLOW-2005)* (Techniques and Methods, 6-D). US Geological Survey. https://pubs.usgs.gov/tm/tm6d1/↗.

Markstrom, S. L., Regan, R. S., Hay, L. E., Viger, R. J., Webb, R. M. T., Payn, R. A., & LaFontaine, J. H. (2015). *PRMS-IV, The precipitation-runoff modeling system, Version 4* (Techniques and Methods, 6-B7). US Geological Survey. https://dx.doi.org/10.3133/tm6B7/↗.

Marston, L., & Cai, X. M. (2016). An overview of water reallocation and the barriers to its implementation. *Water 3*(5), 658–677. https://doi.org/10.1002/wat2.1159↗.

McDonald, M. G., & Harbaugh, A. W. (1988). *A modular three-dimensional finite-difference ground-water flow model* (Techniques of Water-Resources Investigations, 06-A1). US Geological Survey. https://doi.org/10.3133/twri06A1↗.

McMahon, G. A., Arunakumaren, N. J., & Bajracharya, K. (2002, May 12–17). *Estimation of the groundwater budget of the Burdekin River Delta aquifer, North Queensland, Australia* [Paper presentation]. International Association of Hydrogeologists Conference, Darwin, Australia.

Mendieta-Mendoza, A., Hanson, R. T., & Renteria-Villalobos, M. (2021). Potential adverse impacts on vulnerability and availability of groundwater from climate change and land use. *Journal of Hydrology*, *594*, 125978. https://doi.org/10.1016/j.jhydrol.2021.125978↗.

Miller, L. K., & Stiles, J. A. (2006). *Water resources data, New Mexico, water year 2005* (Water Data Report NM–05–1). US Geological Survey. https://doi.org/10.3133/wdrNM051↗.

Miller, C. D., Durnford, D., Halstead, M. R., Altenhofen, J., & Flory V. (2007). Stream depletion in alluvial valleys using the SDF semianalytical model. *Groundwater*, *45*(4), 506–514 https://doi.org/10.1111/j.1745-6584.2007.00311.x↗.

Miller, K., Fisher, A. T., & Kiparsky, M. (2021). Incentivizing groundwater recharge in the Pajaro Valley through recharge net metering (ReNeM). *Case Studies in the Environment*, *5*(1)1–10. https://doi.org/10.1525/cse.2021.1222393↗.

Mireya, I. (2023, October 9–13). *Gestión del agua en México* [Water management in Mexico]. [Paper presentation]. XIII Mexico Groundwater Congress, La Paz, Baja California Sur, Mexico. https://iah.org/events/xiii-mexico-groundwater-congress↗.

Mohamed, R. A. M., Gabreilli, C., Selker, J. S., Selker, F., Brooks, S. C., Ahmed, T., & Carroll, K. C. (2021). Comparison of fiber-optic distributed temperature sensing and high-sensitivity sensor spatial surveying of stream temperature. *Journal of Hydrology, 603*, Part B, 127015. https://doi.org/10.1016/j.jhydrol.2021.127015↗.

Mohammed, K. (2019). MODFLOW-farm process modeling for determining effects of agricultural activities on groundwater levels and groundwater recharge. *Journal of Soil and Groundwater Environment, 24*(5), 17–30. https://doi.org/10.7857/JSGE.2019.24.5.017↗.

Morway, E. D., Niswonger, R. G., & Triana, E. (2016). Toward improved simulation of river operations through integration with a hydrologic model. *Environmental Modeling and Software 82*, 255-274. https://doi.org/10.1016/j.envsoft.2016.04.018↗.

Murray-Rust, H. & Vander Velde, E. (1994). Conjunctive use of canal and groundwater in Punjab, Pakistan: Management and policy options. *Irrigation and Drainage Systems, 8*, 201–231. https://publications.iwmi.org/pdf/H013476.pdf↗.

Napa County Groundwater Agency. (n.d.). *About the subbasin*. https://www.countyofnapa.org/3077/About-the-Subbasin↗.

Napa County Groundwater Sustainability Agency. (2022). *Napa Valley subbasin groundwater sustainability plan, SGMA GSP*. https://www.countyofnapa.org/3084/Groundwater-Sustainability-Plan↗.

Nathan, R., & Evans, R. (2011). Groundwater and surface water connectivity. In Q. Grafton & K. Hussey (Eds), *Water resources planning and management* (pp. 46–67). Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511974304↗.

Neuman, S.P. (1974). Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response, Water Resources Research, vol. 10, no. 2, pp. 303-312. https://doi.org/10.1029/WR010i002p00303↗.

Neuman, S.P., 1975. Analysis of pumping test data from anisotropic unconfined aquifers considering delayed gravity response, Water Resources Research, vol. 11, no. 2, pp. 329-342.http://dx.doi.org/10.1029/WR011i002p00329↗.

Newhouse, M. W., & Hanson, R. T. (2000, October). Application of three-dimensional borehole flow measurements to the analysis of seawater intrusion and barrier injection systems, Los Angeles, California. In *Proceedings of the Minerals and Geotechnical Logging Society Annual Meeting* (pp. 281–292), Golden, Colorado.

Newhouse, M. W. & Hanson, R. T. (2004). *Evaluating seawater intrusion with three-dimensional flow measurements (A cooperative study with the Water Replenishment District of Southern*

California) [Poster presentation H21E-06]. American Geophysical Union Annual Meeting, San Francisco, CA.

Nijssen, B., Lettenmaier, D. P., Liang., X., Wetzel, S. W., & Wood, E. F. (1997). Streamflow simulation for continental-scale river basins. *Water Resources Research, 33*(4), 711–724. https://nro-dd.sagepub.com/lp/wiley/streamflow-simulation-for-continental-scale-river-basins-oojE5niv4o?↗.

Ortiz, D., & Lange, K. M. (1996). *Water resources data, New Mexico, water year 1995* (Water Data Report NM–95–1). US Geological Survey. https://doi.org/10.3133/wdrNM951↗.

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science, 325*(5939), 419–422. https://doi.org/10.1126/science.1172133↗.

Pajaro Valley Water Management Agency. (2016). *Recharge net metering recharge program* (PVWMA Memorandum, 8).

Pajaro Valley Water Management Agency. (2024). *Sustainable groundwater planning*. Pajaro Valley Water Management Agency.
https://www.pvwater.org/sgm#:~:text=Sustainable%20Groundwater%20Planning&text=Under%20SGMA%2C%20PV%20Water%20prepares,at%20least%20every%205%2Dyears↗.
https://www.pvwater.org/recharge-net-metering-program-information↗.

Pavelic, P., Srisuk, K., Saraphirom, P., Nadee, S., Pholkern, K., Chusanathas, S., Munyou, S., Tangsutthinon, T., Intarasut, T., & Smakhtin, V. (2012). Balancing-out floods and droughts: Opportunities to utilize floodwater harvesting and groundwater storage for agricultural development in Thailand. *Journal of Hydrology,* 470–471, 55–64. https://doi.org/10.1016/j.jhydrol.2012.08.007↗.

Pavelic, P., Karthikeyan, B., Amarnath, G., Eriyagama, N., Muthuwatta, L., Smakhtin, V., Gangopadhyay, P. K., Malik, R. P. S, Mishra, A., Sharma, B. R., Hanjra, M. A., Reddy, R. V., Mishra, V. K., Verma, C. L. & Kant, L. (2015). *Controlling floods and droughts through underground storage: From concept to pilot implementation in the Ganges River Basin* (Research Report No. 165). International Water Management Institute.
http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub165/rr165.pdf↗.

Pavely, F. (2014a). California Senate Bill (CA-SB) 1168. *Legislative Counsel's Digest, chapter 346*.
https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB1168↗.

Pavely, F. (2014b). California Senate Bill (CA-SB) 1319. *Legislative Counsel's Digest, chapter 348*.
https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB1319↗.

Peltier, J. (2006, April 5). *Testimony: Conjunctive water management - A solution to the West's growing water demand?* Office of Congressional and Legislative Affairs.
https://www.doi.gov/ocl/Conjunctive-Water-Management↗.

Perrone, D. & Rohde, M. M. (2016). Benefits and economic costs of managed aquifer recharge in California. *San Francisco Estuary and Watershed Science 14*(2), Article 4, 1–13. https://doi.org/10.15447/sfews.2016v14iss2art4↗.

Peterson, C., Pittelkow, C., Lundy, M., & Collins, J. (2022). *Exploring the potential for water-limited agriculture in the San Joaquin Valley*. Public Policy Institute of California. https://www.ppic.org/publication/exploring-the-potential-for-water-limited-agriculture-in-the-san-joaquin-valley/↗.

Pittock, J., Corbett, S., Colloff, M. J., Wyrwoll, P., Alexandra, J., Beavis, S., Chipperfield, K., Croke, B., Lane, P., Ross, A., & Williams, J. (2023). A review of the risks to shared water resources in the Murray–Darling Basin. *Australasian Journal of Water Resources, 27*(1), 1–17. https://doi.org/10.1080/13241583.2023.2190493↗.

Poeter, E. P., & Hill, M. C. (1998). *Documentation of UCODE, a computer code for universal inverse modeling* (Water-Resources Investigations Report 98-4080). US Geological Survey. https://doi.org/10.3133/wri984080↗.

Poeter, E. P., & Hill, M. C. (1999). UCODE, a computer code for universal inverse modeling. *Computers & Geosciences, 25*(4), 457–462. https://www.sciencedirect.com/science/article/abs/pii/S0098300498001496?via%3Dihub↗.

Poeter, Eileen P., Hill, M.C., Lu, D., Tiedeman, C.R., & Mehl, S. (2014). UCODE_2014 with new capabilities to define parameters unique to predictions, calculate weights using simulated values, estimate parameters with SVD, evaluate uncertainty with MCMC, and more. Integrated Groundwater Modeling Center Report Number GWMI 2014-02. https://geology.mines.edu/igwmc/ucode/↗.

Pulido-Velazquez, M., Jenkins, M. W., & Lund, J. R. (2004). Economics values for conjunctive use and water banking in Southern California. *Water Resources Research, 40*(3), W03401. https://doi.org/10.1029/2003WR002626↗.

Pulido-Velazquez, M., Andreu, J., & Sahuquillo, A. (2006). Economic optimization of conjunctive use of surface water and groundwater at the basin scale. *Journal of Water Resources Planning and Management, 132*(6). http://dx.doi.org/10.1061/(ASCE)0733-9496(2006)132:6(454)↗.

Puricelli, M. (2019). *Evaluación de un modelo hidrogeológico con aplicación en sististemas de alerta temprana–Aplicado a la Cuenca A1-Rio Salado* [Evaluation of a hydrogeological model with application in early warning systems–Applied to the A1-Rio Salado basin] [Unpublished master's thesis]. Universidad de Buenos Aires.

Quinn, N. W. T., & Oster, J. D. (2021). Innovations in sustainable groundwater and salinity management in California's San Joaquin Valley. *Sustainability, 13*(12), 6658. https://www.mdpi.com/2071-1050/13/12/6658/↗.

Qureshi, A. S., Turral, H., & Masih, I. (2004). *Strategies for the management of conjunctive use of surface water and groundwater resources in semi-arid areas: A case study from Pakistan* (Research Report 86). International Water Management Institute.

https://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub086/RR86.pdf↗.

Reddy, V. R., Rout, S. K., Shalsi, S., Pavelic, P., & Ross, A. (2020). Managing underground transfer of floods for irrigation: a case study from the Ramganga basin, India. *Journal of Hydrology, 583*(April), 124518. https://doi.org/10.1016/j.jhydrol.2019.124518↗.

Reeves, H. W. (2008). *STRMDEPL08—An extended version of STRMDEPL with additional analytical solutions to calculate streamflow depletion by nearby pumping wells* (Open-File Report 2008–1166). US Geological Survey. https://mi.water.usgs.gov/software/groundwater/strmdepl08/↗.

Renteria-Villalobos, M., Hanson, R. T., & Eastoe, C. (2022). Evaluation of climate variability on sustainability for transboundary water supply in Chihuahua, Mexico. *Journal of Hydrology, Regional Studies*, 44(December), 101207. https://doi.org/10.1016/j.ejrh.2022.101207↗.

Rhoades, J. D. (1972). Quality of water for irrigation. *Soil Science, 113*(4), 277–284. https://journals.lww.com/soilsci/citation/1972/04000/quality_of_water_for_irrigation.7.aspx↗.

Rhoades, J. D. (1977, July 20–22). Potential for using saline agricultural drainage waters for irrigation. *Proceedings of the American Society of Civil Engineers Irrigation and Drainage Division Specialty Conference on Water Management for Irrigation and Drainage* (pp. 85–116), Reno, Nevada, USA.

Rhoades, J. D. (2012). Evidence of the potential use of saline water for irrigation. *Options Méditerranéennes*, 133–145. https://halophyteskh.biosaline.org/sites/default/files/content/BestPractices_MWManagement/JDRhoades1.pdf↗.

Rhoades, J. D., & Merril, S. D. (1976). *Assessing the suitability of water for irrigation—Theoretical and empirical approaches. Prognosis of salinity and alkalinity* (Soils Bulletin 31, pp. 69–109). Food and Agriculture Organization (FAO). http://www.fao.org/3/a-ar112e.pdf↗.

Rivera, A. (Ed.).(2015). *Estrategia Regional para la gestión de los sistemas de acuíferos transfronterizos (SAT) en las Americas* [Regional strategy for the management of transboundary aquifers systems in the Americas]. PH1-VIII/Serie ISARM AMÉRICAS No. 4. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000235394?posInSet=7&queryId=32a47d34-c6c2-47d0-bc1c-6a9756cb7847↗.

Rivera, A., & Hanson, R. T. (2022). State of affairs of models and governance of transboundary aquifers along the Mexico–US border: In R. Sánchez (Ed.), *Transboundary aquifers: Challenges and the way forward* (pp. 124–133). UNESCO. Estrategia regional para la evaluación y gestión de los Sistemas Acuíferos Transfronterizos en las Américas - UNESCO Digital Library↗.

Roberts, S. V. (2010). *Conjunctive surface water and groundwater management: A new framework for strategic decision-making* [Doctoral dissertation, Texas State University-San Marcos].

Texas State University DSpace: Theses and dissertations, capstones, and directed research/RobertsSusan.pdf. https://digital.library.txstate.edu/handle/10877/3120↗.

Rodella, A. S., Zaveri, E., & Bertone, F. (Eds.).(2023a). *The hidden wealth of nations: Groundwater in times of climate change*. The World Bank. https://www.worldbank.org/en/topic/water/publication/the-hidden-wealth-of-nations-groundwater-in-times-of-climate-change↗.

Rodella A. S., Zaveri, E., & Bertone, F. (Eds.).(2023b). *The hidden wealth of nations: Groundwater in times of climate change – Annexes*. The World Bank. https://www.worldbank.org/en/topic/water/publication/the-hidden-wealth-of-nations-groundwater-in-times-of-climate-change↗.

Rodriguez, L. B., Cello, P. A., Vionnet, C. A., & Goodrich, D. (2008). Fully conservative coupling of HEC-RAS with MODFLOW to simulate stream–aquifer interactions in a drainage basin. *Journal of Hydrology, 353*(1–2), 129–142. https://doi.org/10.1016/j.jhydrol.2008.02.002↗.

Rodriguez, L., Vives, L., & Gomez, A. (2013). Conceptual and numerical modeling approach of the Guarani Aquifer System. *Hydrology and Earth System Sciences, 17*, 295–314. https://doi.org/10.5194/hess-17-295-2013↗.

Rohde, M. M., Froend, R., & Howard, J. (2017). A global synthesis of managing groundwater dependent ecosystems under sustainable groundwater policy. *Groundwater, 55*(3):293–301. https://ngwa.onlinelibrary.wiley.com/doi/10.1111/gwat.12511↗.

Ross, A. (2012). *Water connecting, people adapting: Integrated surface water and groundwater management in the Murray–Darling Basin, Colorado and Idaho* [Unpublished doctoral dissertation]. Australian National University. https://researchers.anu.edu.au/publications/77577↗.

Ross, A. (2022). Benefits and costs of managed aquifer recharge: Further evidence [Special Issue]. *Water, 14*(20), 3257. https://doi.org/10.3390/w14203257↗.

Ross, A., Evans, R., & Nelson, R. (2023). Risks related to groundwater in the Murray Darling Basin. *Australasian Journal of Water Resources, 27*(1), 31–46. https://doi.org/10.1080/13241583.2023.2260581↗.

Rossetto, R., De Fillipis, G., Triana, F., Ghetta, M., Borsi, I., & Schmid, W. (2019). Software tools for management of conjunctive use of surface and groundwater in the rural environment: Integration of the Farm Process and the Crop Growth Module in the FREEWAT platform. *Agricultural Water Management, 223(*August), 105717. https://www.sciencedirect.com/science/article/pii/S0378377418319978?via%3Dihub↗.

Sahuquillo, A. (2005). Conjunctive use of surface water and groundwater. *Encyclopaedia of Life Support Systems, Groundwater, 3*. https://www.eolss.net/sample-chapters/c07/E2-09-07-04.pdf↗.

Sanchez, R., Breña-Naranjo, J. A., Rivera, A., Hanson, R., Hernández-Espriú, A., Hogeboom, R. J., Milman, A., Benavides, J. A., Pedrozo-Acuña, A., Soriano-Monzalvo, J. C., Megdal, S. B., Eckstein, G., & Rodriguez, L. (2021) Binational reflections on pathways to groundwater security in the Mexico-United States borderlands. *Water International, 46*(7-8), 1017–1036. https://doi.org/10.1080/02508060.2021.1999594↗.

Scanlon, B. R., Reedy, R. C., Faunt, C. C., Pool, D., & Uhlman, K. (2016). Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. *Environmental Research Letters*, *11*(3), 035013. https://doi.org/10.1088/1748-9326/11/4/049501↗.

Schlager, E., & Ostrom, E. (1992). Property-rights regimes and natural resources: A conceptual analysis. *Land Economics, 68*(3), 249–262. https://doi.org/10.2307/3146375↗.

Schmid, Wolfgang, Hanson, R.T., Maddock, Thomas, III, Leake, S.A. (2006) User guide for the farm process (FMP1) for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, MODFLOW-2000: U.S. Geological Survey Techniques and Methods 6-A17, 127 p.

Shah, T., Dargouth, S., & Dinar, A. (2006) *Conjunctive use of groundwater and surface water* (Agricultural and Rural Development Notes, Issue No. 6). The World Bank.

Sharp, J. M., Jr. (2023). *A glossary of hydrogeology.* The Groundwater Project. https://gw-project.org/books/a-glossary-of-hydrogeology/↗.

Shilling, F., Khan, A., Juricich, R., & Fong, V. (2013, May 19–23). Using indicators to measure water resources sustainability in California. In C. L. Patterson, S. D. Struck, & D. J. Murray (Eds.), *Proceedings of the World Environmental and Water Resources Congress 2013: Showcasing the future* (pp. 2708–2715). American Society of Civil Engineers. https://doi.org/10.1061/9780784412947↗.

Sinclair, D., & Holley, C. (2012). Compliance and enforcement of water licences in NSW: Limitations in law, policy and institutions. *Australasian Journal of Natural Resources Law and Policy, 15*(2), 149–189. https://researchprofiles.anu.edu.au/en/publications/compliance-and-enforcement-of-water-licences-in-nsw-limitations-i↗.

Sophocleous, M., Koussis, A., Martin, J. L., & Perkins, S. P. (1995). Evaluation of simplified stream–aquifer depletion models for water rights administration. *Ground Water, 33*(4), 579–588. https://doi.org/10.1111/j.1745%2D6584.1995.tb00313.x↗.

Stockholm Environment Institute. (2023). *Water evaluation and planning* (WEAP) [Computer software]. https://weap.sei.org/index.asp?action=200↗.

Stonestrom, D. A., & Constantz, J. (Eds.).(2003). *Heat as a tool for studying the movement of ground water near streams* (Circular 1260). US Geological Survey. https://pubs.usgs.gov/circ/2003/circ1260/↗.

Stonestrom, D. A., Constantz, J., Ferré, T. P.A., & Leake, S. A. (Eds.).(2007). *Ground-water recharge in the arid and semiarid southwestern United States* (Professional Paper 1703). US Geological Survey. https://pubs.usgs.gov/pp/pp1703/↗.

Sustainable Groundwater Management Act, State of California 10608.50. (2014). Codes Display Text (ca.gov)↗.

Thompson, E., Jr. (2009). Agricultural land loss & conservation. In California Department of Food and Agriculture, *American Farmland Trust* (pp. 19–22). https://www.cdfa.ca.gov/agvision/docs/agricultural_loss_and_conservation.pdf↗.

Thompson, B. H. (2011). Beyond connections: Pursuing multidimensional conjunctive management. *Idaho Law Review*, *47*, 265–307. https://law.stanford.edu/publications/beyond-connections-pursuing-multidimensional-conjunctive-management/↗.

Tinoco, C., Julio, N., Meirelles, B., Pineda, R., Figueroa, R., Urrutia, R., & Parra, O. (2022). Water resources management in Mexico, Chile and Brazil: Comparative analysis of their progress on SDG 6.5.1 and the role of governance. *Sustainability*, *14*(10), 5814. https://doi.org/10.3390/su14105814↗.

Tsur, Y. (1990). The stabilisation role of groundwater when surface water supplies are uncertain: The implications for groundwater development. *Water Resources Research*, *26*(5), 811–818. https://doi.org/10.1029/WR026i005p00811↗.

Traylor, J. P., Guira, M., & Peterson, S. M. (2023). *An integrated hydrologic model to support the Central Platte Natural Resources District Groundwater Management Plan, central Nebraska* (Scientific Investigations Report 2023–5024). US Geological Survey. https://pubs.usgs.gov/publication/sir20235024↗.

Turnadge, C. J., & Lamontagne, S. (2015). *A MODFLOW-based approach to simulating wetland–groundwater interactions in the Lower Limestone Coast Prescribed Wells Area* (Technical Report Series No. 15/12). Goyder Institute for Water Research. https://goyderinstitute.org/reports/?tag=turnadge&pyear=2015&author=turnadge↗.

United Nations Educational, Scientific and Cultural Organization, &. Organization of American States (UNESCO). (2010). Aspectos Socioeconómicos, ambientales y climáticos de los sistemas acuíferos transfronterizos de las Americas [Socioeconomic, environmental and climatic aspects of transboundary aquifer systems in the Americas]. PHI-VII/ Serie ISARM Americas, Book 3. https://unesdoc.unesco.org/ark:/48223/pf0000215516↗.

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2012). *International Glossary of Hydrology*. UNESCO/WHO, WMO-No. 385, 469p. https://unesdoc.unesco.org/ark:/48223/pf0000221862/PDF/221862qaa.pdf.multi↗.

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2023). *Partnerships and Cooperation for Water. The United World Development Report, 2023.* UNESCO World Water Assessment Programme. https://unesdoc.unesco.org/ark:/48223/pf0000384655↗.

University of California at Davis. (2023). *Groundwater in working landscapes – Nora S. Gustavsson endowed professorship & cooperative extension: Sustainable Groundwater Management Act*. https://groundwater.ucdavis.edu/SGMA/↗.

US Bureau of Reclamation. (2016). *Continued implementation of the 2008 operating agreement for the Rio Grande Project, New Mexico and Texas: Final environmental impact statement*. US Bureau of Reclamation. https://www.usbr.gov/uc/envdocs/eis/pdf/RGOA_DEIS_20160313_508.pdf↗.

US Bureau of Reclamation. (2017). Record of decision: Continued implementation of the 2008 operating agreement for the Rio Grande Project, New Mexico and Texas. https://www.usbr.gov/uc/envdocs/rod/Jan2017_RioGrandeROD.pdf↗.

US Bureau of Reclamation. (2022). *Reclamation Library/Glossary/Conjunctive use*. US Bureau of Reclamation. Library | Bureau of Reclamation (usbr.gov)↗.

US Geological Survey. (2022). *CVHM2: Central Valley Hydrologic Model version 2, Data release* [Data set]. US Geological Survey. https://www.sciencebase.gov/catalog/item/62bf279cd34e82c548ced8d7↗.

Valdez, J., & Maddock, T., III. (2010). Conjunctive water management in the US southwest. In G. Schieier-Madanes & M. F. Courel (Eds). *Water and sustainability in arid regions: Bridging the gap between physical and social sciences.* SpringerLink. https://doi.org/10.1007/978-90-481-2776-4_14↗.

van der Gun, J. (2020). *Conjunctive water management: A powerful contribution to achieving the Sustainable Development Goals*. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000375026.locale=en↗.

van Steenbergen, F., & Tuinhof, A. (2009). *Managing the water buffer for development and climate change adaptation: Groundwater recharge, retention, reuse and rainwater storage*. MetaMeta Communications. http://www.bebuffered.com/3rbook.htm↗.

van Steenbergen, F., Tuinhof, A., & Knoop, L. (2011). *Transforming landscapes transforming Lives: The business of sustainable water buffer management.* 3R Water Secretariat. http://www.bebuffered.com/downloads/transforming_land_3108_LQ_total.pdf↗.

Vorosmarty, C. J., Green, P., Salisbury, J. , & Lammers, R. B. (2010). Global water resources: Vulnerability from climate change and population growth. *Science, 289*(5477), 284–288. https://doi.org/10.1126/science.289.5477.284↗.

Water Treaty concerning the utilization of waters of the Colorado and Tijuana rivers and of the Rio Grande. February 3, 1944. https://www.ibwc.gov/wp-content/uploads/2022/11/1944Treaty.pdf↗.

Westenbroek, S. M., Engott, J. A., Kelson, V. A., & Hunt, R. J. (2018). SWB Version 2.0 – A soil–water-balance code for estimating net infiltration and other water-budget components (Techniques and Methods 6-A59). US Geological Survey. https://doi.org/10.3133/tm6A59 (https://pubs.usgs.gov/publication/tm6A59)↗.

Wheeler, S. A. (2022). Debunking Murray–Darling basin water trade myths. *Australian Journal of Agricultural and Resource Economics, 66*(4), 797–821. https://doi.org/10.1111/1467-8489.12490↗.

Winston, R. (2009). *ModelMuse—A graphical user interface for MODFLOW-2005 and PHAST* (Techniques and Methods 6–A29). US Geological Survey. http://pubs.usgs.gov/tm/tm6A29↗.

World Bank Group. (2023a) *The hidden wealth of nations: The economics of groundwater in times of climate change.* World Bank Group. https://www.worldbank.org/en/topic/water/publication/the-hidden-wealth-of-nations.pdf↗.

World Bank Group. (2023b). *The hidden wealth of nations: The economics of groundwater in times of climate change: Annexes*. World Bank Group. https://documents1.worldbank.org/curated.pdf↗.

World Business (2012). Annex H: Possible breakthroughs - Conjunctive water use and drainage. In *Co-optimizing Solutions*. https://www.wbcsd.org/contentwbc/download/419/4442/1↗.

Zheng, Y., Ross, A., Villholth, K. G., & Dillon, P. (2021). *Managing aquifer recharge: A showcase for resilience and sustainability*. UNESCO. https://www.unesco.org/en/articles/managing-aquifer-recharge-showcase-resilience-and-sustainability↗.

Ziaja, S., Sugg, Z. P., & Schlager, E. C. (2016). Conjunctive groundwater management as a response to social ecological disturbances: A comparison of four western US states. *Texas Water Journal*, *7*(1), 1–24. https://scholarworks.law.ubalt.edu/all_fac/1120↗.

14 Boxes

Examples of CWM throughout the world tend to fall into two groups:

1) those where approaches to CWM focus on management structures and
2) those where a technical-focused approach usually involves surface water–groundwater modeling.

The management approach may include an allocation model and/or an economic model that is linked to local constraints and requirements for the use and movement of water. The modeling approach generally provides a physical-based supply-and-demand framework to simulate the use and movement of water as a basis for exploring management, governance, or future sustainability options.

Boxes Part A - Management focused CWM examples

The Boxes 1 through 5 describe examples of irrigation commands ('Districts') where conjunctive use of groundwater and surface water resources occur. This section draws heavily on the work of GW-MATE (Foster et al., 2010 and related references) to illustrate what has been done and how it was developed.

Box 1 - Uttar Pradesh - India

Foster and others (2010) have described the setting for conjunctive use in the state of Uttar Pradesh, India, which is categorized as a humid but drought-prone middle-alluvial-plain hydrogeological setting. The alluvial plains of the Ganges Valley (the Indo-Gangetic Plain) in Uttar Pradesh are underlain by an extensive aquifer system holding groundwater that represents as much as 70 percent of the overall irrigation water supply. It is one of the largest groundwater storage reserves in the world.

Its utilization as a water resource has primarily arisen in response to reduction in supply and unreliable operation of the irrigation canal systems. The aquifers are recharged directly from infiltrating monsoon rainfall and indirectly from canal leakage and inefficient irrigation (i.e., excess rates of field application)—a common scenario in such hydrogeological settings.

Increasing groundwater abstraction has resulted in a declining water table, particularly in high intensity *groundwater exploitation zones*, whereas in other areas (in some cases within 10 to 20 km of groundwater exploitation zones), flood irrigation and canal leakage have maintained shallow water tables. The decline in water tables in some areas is correlated with evidence of irrigation tube wells going dry, reduction in their yield, and pump failure, together with hand-pump failure in rural water-supply wells.

Conversely, threats arising from shallow water tables elsewhere are evident in about 20 percent of the land area. These areas are subject to shallow or rising groundwater levels, with soil waterlogging and salinization leading to crop losses and even land abandonment

(Foster et al., 2010). Protocols for the operation of the distributary canal system have not been strictly adhered to, contributing to an imbalance in surface water delivery throughout the system.

In light of the challenges posed by rising water tables in some areas and declines in the water resources elsewhere, a better planned and enforced conjunctive use approach is being implemented in the Jaunpur Branch canal-command area in Central Pradesh. The adopted approach uses extensive datasets and associated analysis to understand the hydrogeological, agronomic, and socioeconomic situation. Strategies include attempts to reduce leakage through maintenance of bank sealing in major irrigation canals, enforcement of current operational codes, promotion of tube well use in non-command and high-water table areas, and investment in research and specialist extension services in soil salinity mitigation and sodic land reclamation (Figure Box 1-1).

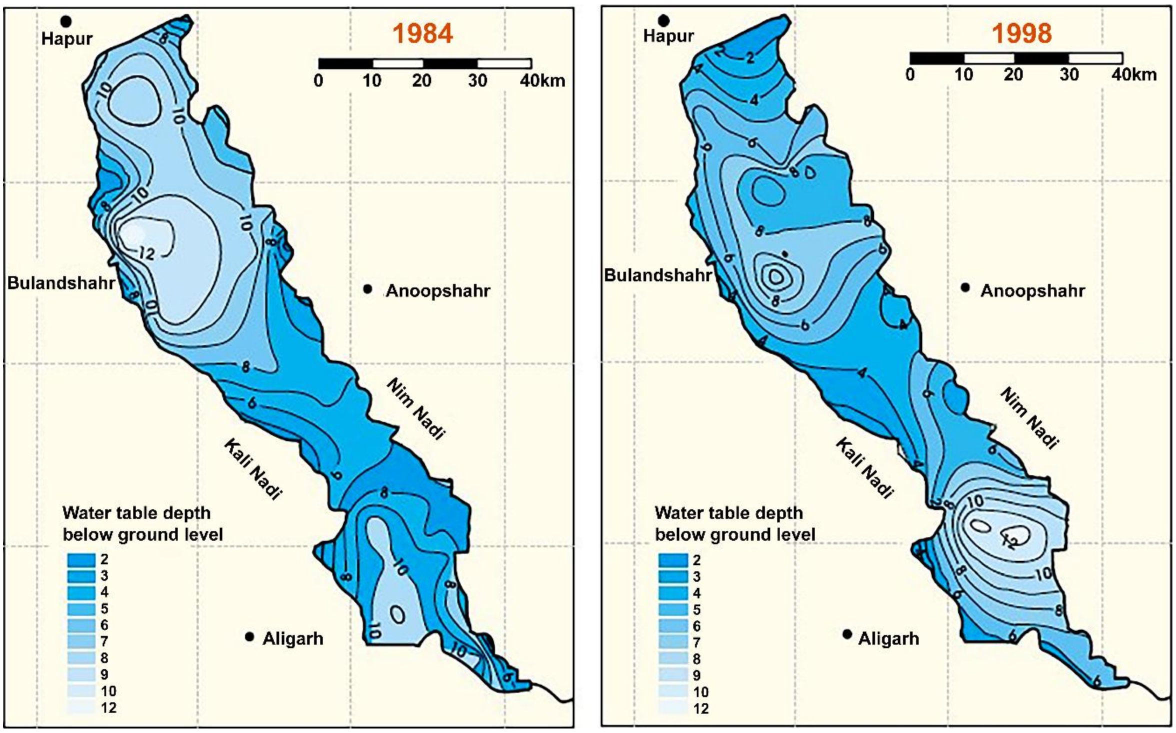


Figure Box 1-1 - Comparison of water-table depth before (1984) and after (1998) recharge, Uttar Pradesh Maps of the Lakhaoti Branch Canal, Utter Pradesh, India, showing post-monsoon depth to groundwater before (1984) and after (1998) recharge management began in about 1984. Dark blue areas show where groundwater levels are close to the surface (from International Water Management Institute, 2002)

These activities are being aligned with the pursuit of an appropriate management plan, for which the land surface has been subdivided based on hydrogeologic and agroeconomic criteria into micro-planning and management zones. For each zone, a canal reach (e.g., head, mid, or tail) is assigned with an indication of current irrigation canal flow and water table level. Then the irrigation water service situation, the groundwater resource status, and the groundwater management needs are identified.

This zoning approach allows targeted management actions that range from encouragement of groundwater use in the head end of the irrigation systems where shallow groundwater levels prevail, focusing upon higher value crops in some areas, and improving canal water availability for those at the lower ends of the system. Collectively, these mechanisms are intended to provide a more balanced approach across the canal command (and beyond) and contribute to a sustainable future for agriculture in the region (Foster et al., 2010). Figure Box 1-1 shows the beneficial changes in water table depth for one such targeted area.

The International Water Management Institute (IWMI, 2002) describes the situation for the western Indo-Gangetic plain where—although rainfall ranges between 650 and 1,000 mm annually—only 200 mm naturally percolate through soil layers to recharge underlying aquifers. In this area, like many others in India, groundwater pumping by farmers exceeds the combined recharge from rainfall, leakage from canals and rivers, and excess application of irrigation water. Farmers generally rely on irrigation from monsoon rains, which can fail to provide water when and where it is needed. The high concentration of rainfall over a three-month period means most of the water runs off the already saturated soil and is neither captured nor stored nor implemented in Flood-MAR programs. During the dry season, a lack of canal water means a reliance on pumping from groundwater stores that are not totally replenished from the previous year, hence there is further depletion (mining) of the aquifer system.

A 10-year pilot project (the Madhya Ganga Canal Project) undertaken in this area has demonstrated a low-cost way of using the excess surface water during monsoon season by conserving and rejuvenating falling groundwater reserves. The project involved diversion of 234 m^3/s of monsoon water in the River Ganga to the Madhya Ganga Canal, which feeds both the Upper Ganga Canal system and the Lakhaoti Branch Canal system. Through systems of unlined (unsealed) earthen canals, water is delivered to farmers for irrigation of water-intensive monsoon crops such as paddy rice and sugarcane. The unlined nature of the canal systems and infiltration of excess irrigated water facilitated the recharge of underlying aquifers, in which the water table was raised from an average 12 m bgl (below ground level) to an average 6.5 m bgl. Simulations showed that without such a conjunctive management approach, levels would have continued to decline to an average depth of 18.5 m bgl over the course of the study.

The conjunctive management of surface water and groundwater has proved productive with average net income increasing by 26 percent through reductions in pumping costs and improved cropping systems. It has demonstrated a more sustainable system through improved cropping patterns and through more reliable and sometimes new sources of water for irrigation and other uses, such as domestic/industrial supplies (e.g., providing water in previously existing dry pockets). During the dry season, drawdown from groundwater pumping prevents waterlogging and maximizes storage space for recharge during the following year's monsoon.

Unused (often lined) drainage canals constructed in the 1950s to control water logging and floods are also being targeted as a version of Flood-MAR for diverting monsoon water across India—either for irrigation, storage, and later use or for recharge to underlying aquifers. Modification of previously lined canals can aid their transformation into temporary reservoirs, where *check structures* at suitable intervals slow down water flow and increase the aquifer recharge capacity of the canals (Khepar et al., 2000). In combination with the use of earthen irrigation canals, the use of old drainage networks can maximize water use and storage for very low cost compared to building new infrastructure such as dams (Khepar et al., 2000).

Return to where text linked to Box 1⮥

Box 2 - Mendoza - Argentina

Foster and Garduño (2006) describe the situation in the Mendoza Aquifers located in the northern part of the Mendoza Province, Argentina, which are highly developed within and outside existing irrigation canal networks. The Mendoza Aquifers are characterized by an upstream arid-outwash peneplain hydrogeological setting and are shown diagrammatically in Figure Box 2-1. The aquifers are recharged directly from the Mendoza and Tununyan rivers as they emerge from the Andes mountains and indirectly from irrigation canals and irrigated fields. The DGI's initial approach to groundwater resource management involved:

- encouraging irrigation well drilling in areas outside and on the margins of existing irrigation-canal-commands networks and
- permitting well drilling within surface-water-irrigation-command networks if existing canal allocation did not provide a reliable supply at times of low river flow and/or maximum plant demand.

Although the strategy was generally a success, problems with high and increasing groundwater salinity in two areas of intensive groundwater irrigation started to emerge. This occurrence underscores the additional issue that water quality is an important component of conjunctive use within CWM. Salinity distribution during 2003 and 2004 suggested the current groundwater flow, irrigation use, and return flow were significant contributors to these problems in the Carrizal Valley. The expansion of high-intensity groundwater use for irrigation of export-quality viticulture and fruit production, while efficient due to application of modern irrigation practices, has put pressure on the groundwater system. Six to seven hundred active production wells were reported in the valley in 2006, with consistently elevated electricity consumption reflecting the high dependence on the wells for agricultural irrigation.

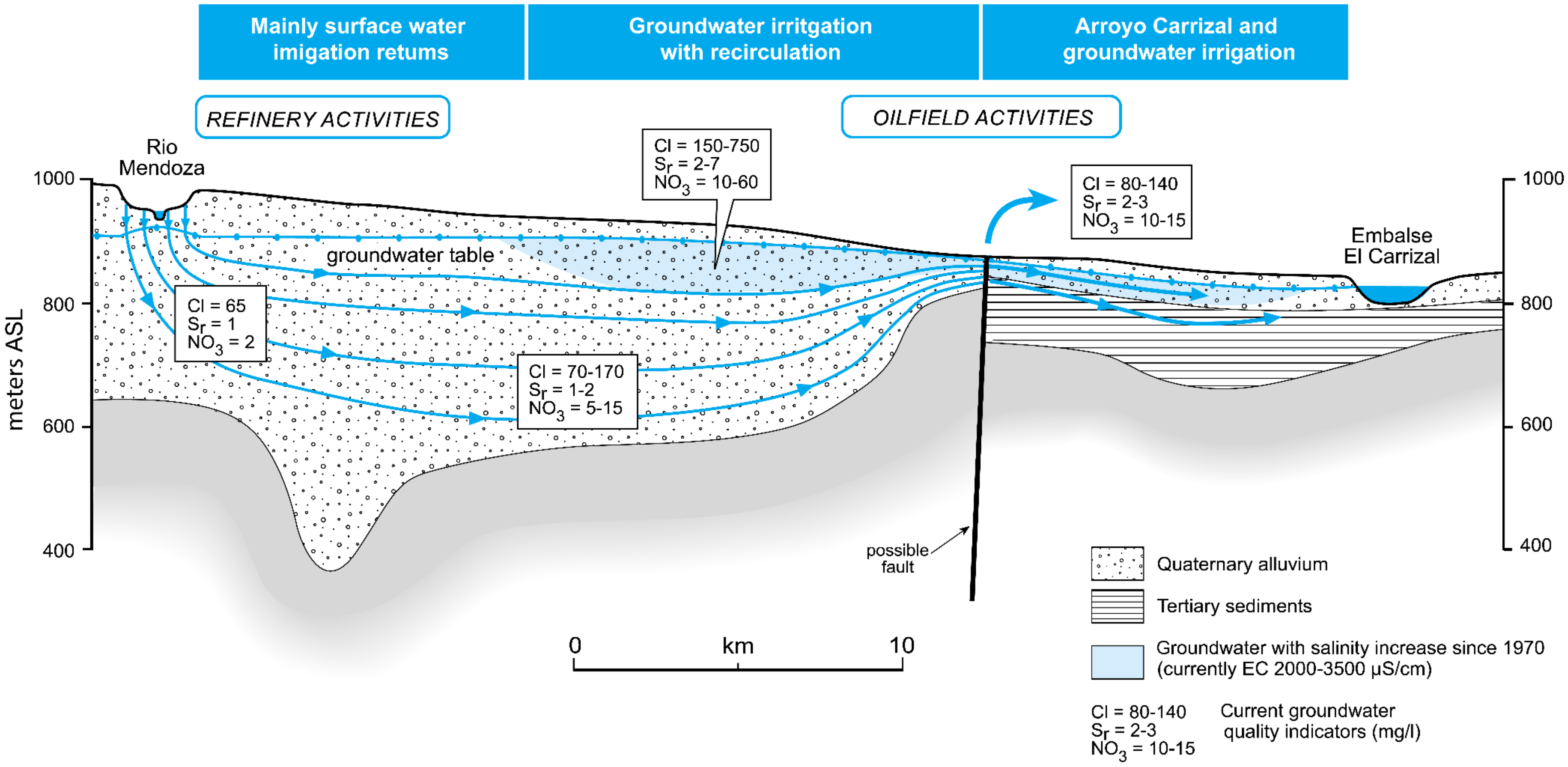


Figure Box 2-1 - Hydrogeological profile along the flow direction of the Carrizal aquifer system (from Foster & Garduño, 2006). The General Department for Irrigation [Departamento General de Irrigacion; DGI] is the autonomous water resource authority responsible for water management in the entire province, down to the primary canals and the delivery of water to the Water Users' Associations (WUAs). Groundwater abstraction is the main source of water for irrigation outside the command network of main canals and is used to supplement surface water during times of critical plant demand and in years of low flow.

In the Monte Caseros zone (the second problematic area), the aquifer system has marked layering into sub-aquifer units separated by aquitards. Groundwater salinity in the shallowest of these sub-aquifers increased substantially between the 1970s and 1995, instigating a shift to extraction targeting deeper sub-aquifers. However, there has been downward migration of saline groundwater—thought to be related to, among other things, pumping water from deeper sub-aquifers—that is potentially derived from overlying strata and less so from poorly constructed and/or highly corroded wells providing conduits for brackish water.

When estimated demand exceeded available resources—following continued below-average riverbed recharge amidst concerns around falling water tables, increasing groundwater salinity in some areas, competition amongst groundwater users, and between others dependent on downstream groundwater discharge—the Carrizal Valley and Monte Caseros zone were declared groundwater use restriction zones (GRZ) in 1997 and 1995, respectively.

GRZs have more rigorous well drilling controls aimed at reducing current, and preventing further growth of, groundwater abstraction. They do so while still allowing construction of more energy-efficient (replacement) wells and reallocation of groundwater resources to high-value uses by purchase and sealing of existing wells with construction of new wells at close-by locations within the same zone, even though water trading is not permitted under provincial water law. Sale of excess surface water is also permitted in GRZs but with the relatively high costs of irrigation modernization, this is unlikely to be a significant incentive to invest in water-saving measures.

The DGI is working towards a proactive groundwater management and protection program to widen the base of stakeholder participation and foster shared appreciation of problems. The initial step identified to this end was to improve scientific understanding of aquifer behavior. This step has involved significant field work (e.g., intensification of groundwater level and salinity monitoring) to enhance understanding of the hydrogeological structure and irrigation well abstraction/use patterns that will inform numerical modeling. Simulating various scenarios should allow evaluation of potential impacts, thus providing an improved basis for future conjunctive water use management.

Other land and water management measures to improve water-use efficiency and minimize the further mobilization of salinity instigated by DGI include:

- delivering surface water by lined canals/pipeline to increase efficiency, and reduce infiltration to the uppermost saline aquifer to avoid water table rise and increased downward leakage (Monte Caseros zone);
- providing additional water from the surface water supply to salinity affected areas by diverting excess river flows;
- introducing drip irrigation techniques;

- backfilling or effectively sealing all disused, poorly constructed, and/or highly corroded water wells (particularly to avoid transfer of brackish water in the Monte Caseros zone);
- reducing rural electrical energy subsidies;
- policing and reducing illegal pumping;
- increasing riverbed recharge through works in the Mendoza riverbed; and
- providing canal water to groundwater-only areas.

These measures have had varying impacts on the water balance of the Carrizal Aquifer, though the results are not fully realized. There are, however, remaining challenges:

- Groundwater rights have been granted in perpetuity and there is no mechanism to reduce entitlements to support more efficient use of water.
- There is an absence of legal powers and market mechanisms that would enable the transfer of surface water entitlements to areas without access rights.
- Surface water and groundwater have differential cost structures that apply to users, as groundwater users fully finance the associated infrastructure whereas surface water infrastructure has been either wholly or partly subsidized by the state.
- Local water-user groups focus on surface water issues, and there has been a reluctance to engage in groundwater management issues, which would require reorganization to better reflect the distribution of users.

Notwithstanding the above, the Carrizal Valley strategy appeared to be succeeding according to post-2007 monitoring data that suggest partial water table recovery and groundwater salinity reduction.

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Box 3 - Queensland - Australia

Hafi (2002) highlighted the importance of taking a multiple-water-resource-system perspective in addressing issues of conjunctive use of groundwater and surface water in the Burdekin delta area, Queensland, Australia (Figure Box 3-1). Within this system, there is significant interaction between surface water and groundwater resources and, hence, complementary policies have been formulated for surface water and groundwater management.

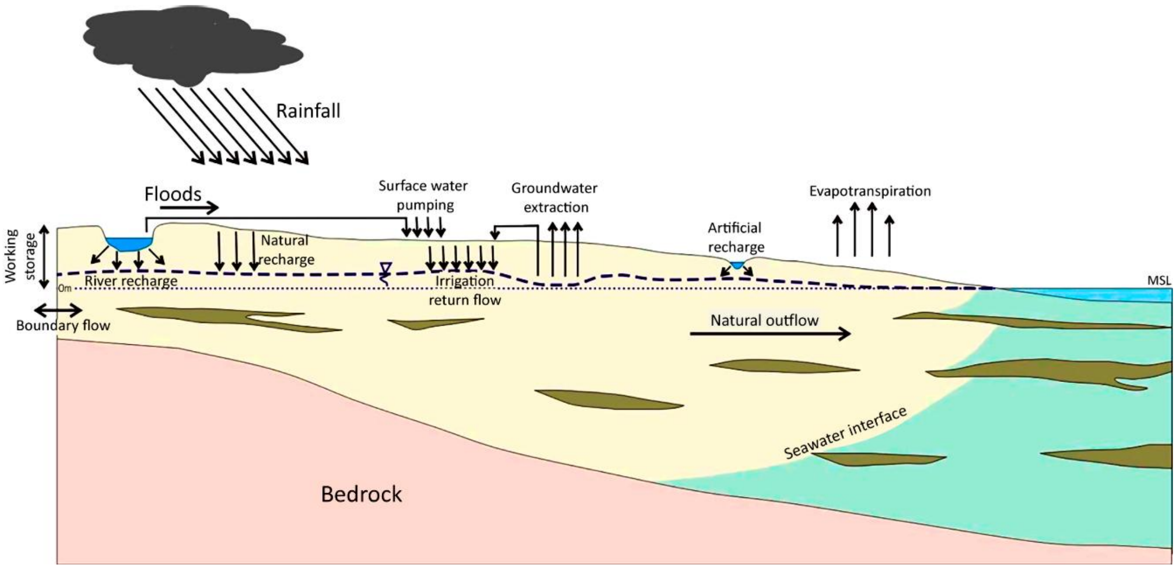

Figure Box 3-1 - Conceptual water budget, Burdekin district, Australia (from McMahon, 2002).

The Burdekin delta is a major sugar production district in Australia and overlies a shallow groundwater aquifer that is hydrogeologically linked to environmentally sensitive wetlands, waterways, and estuaries as well as to the Great Barrier Reef. In addition to irrigation supply, the aquifer also supplies potable water for three towns in the delta. The Burdekin River Delta Aquifer consists of sedimentary deposits up to 100 m below the surface. An important feature of the delta aquifer is that the sediments are not continuous laterally even over short distances. Discontinuity of impervious clay layers exposes the aquifer to infiltration of water from the surface and as a result the aquifer is generally considered unconfined. In terms of the hydrogeological settings, the Burdekin falls into the downstream alluvial delta category.

In the delta, surface water is pumped from the Burdekin River and diverted into canals that deliver to recharge pits as well as channel-intrusion areas and for farm irrigation (Figure Box 3-1). The channel system also delivers water to natural waterways, gullies, and lagoons. Channel intrusion areas are where significant leakage of channels is accepted as being a positive recharge mechanism. The aquifer and the extensive canal, gully, and lagoon system are collectively used for low-cost storage of diverted water and to capture a significant portion of the area's rainfall runoff. When the water diverted from the river is too turbid to be used in recharge pits or is more than recharge capacity, it is made available as a supplementary irrigation supply. In normal years, rainfall recharge from outcrop areas and discharges from flooded rivers are sufficient to recharge the aquifer. However, after several successive years of drought, the aquifer becomes depleted to near sea level mainly due to pumping for irrigation and continuous discharge to the sea.

A numerical groundwater model was used to identify optimal strategies to conjunctively manage groundwater and surface water resources to maximize their economic value. The model provided solutions relating to the optimal groundwater pumping levels required to manage the groundwater resource, such that the water table does not rise to levels that might cause waterlogging in some areas and does not fall to a level that would permit seawater intrusion. This decision support tool been invaluable to water managers in the Burdekin River Delta. It provides information on optimal pumping quotas and the allocation of surface water resources. It further provides a basis for sustainable resource allocation, enabling decisions on the immediate use of supplies to meet short-term demand, and decisions supporting aquifer recharge for storage and future use.

The major conjunctive use regions in the Burdekin delta are managed through a separate act of the Queensland parliament. The local Water Board is controlled by a board comprising largely local water users. The board has substantial powers in the day-to-day operation of the scheme. The success of the scheme is characterized by strong and clear local ownership, combined with significant technical support provided by the government, and has the benefit of a hydrogeologically favorable region of high-transmissivity aquifers.

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Box 4 - Indus Basin - Pakistan

Pakistan's major groundwater resource is in the irrigated areas of the Indus Basin. The hydrogeological setting can be classified as a hyper-arid middle alluvial plain. Agriculture is the single largest sector of Pakistan's economy. Due to arid conditions in most parts of the country, the contribution of direct rainfall to the total crop water requirements is less than 15 percent. The huge gap between water availability and demand is bridged via exploitation of groundwater resources.

Most groundwater exploitation in Pakistan occurs via conjunctive use with surface water. In Figure Box 4-1, conjunctive use refers to the combined use of groundwater and surface water (from rivers and streams) as distinct from water supplied via canals. The gradual increase in combined groundwater and surface water (labelled conjunctive use) corresponds with the gradual decrease in canal water use.

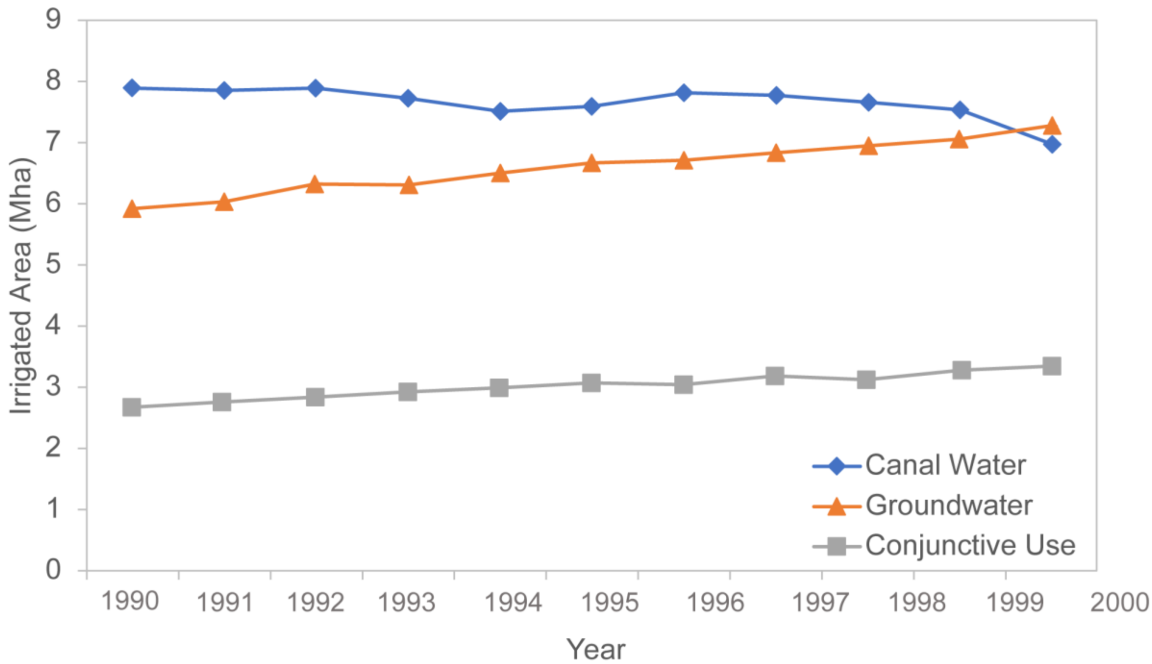

Figure Box 4-1 - Increasing trend in conjunctive use, Punjab, Pakistan (taken from Qureshi et al., 2004).

Irrigated agriculture using only groundwater is limited mainly to three situations:

- areas not supplied by canal networks,
- small systems outside the Indus Basin, and
- at the tail end of canal networks that have lost access to surface water through inequitable distribution of canal-water supplies.

The most productive areas of the Indus Basin commonly incorporate conjunctive use of canal water and high- to medium-quality groundwater. Conjunctive use of groundwater and surface water allows farmers to cope with unreliable surface water supplies and achieve more secure and predictable yields. A combination of factors may be driving the reliability of surface water supplies, including climate variability/change, cyclic droughts, additional development, and continued overexploitation of land use. However, there are adverse impacts of conjunctive use where poor-quality groundwater is used, adding large amounts of salt in the root zone, and hence causing additional salinization problems to those arising from shallow water tables. In some areas, the salinity of the groundwater resource is such that there is full reliance upon canal deliveries to sustain irrigated agriculture. Even in areas where groundwater is deemed to be usable, the brackish nature of the resource commonly requires mixing with surface water prior to application to crops. However, Qureshi and others (2004) noted that farmers are not fully aware of the ratios required when mixing the two water types and therefore negative consequences of irrigating with high-salinity water have been observed.

The ratio of surface water and groundwater conjunctive use in irrigated agriculture identified in research undertaken by Murray-Rust and Vander Velde (1994) averaged 2:5 throughout the distributary canal network, resulting in an average irrigation water electrical conductivity (EC) of 1,400 μS/cm. This value exceeds the current international standard that sets the upper limit for good quality irrigation water at EC 700 μS/cm. To bring that average water-quality condition down to 1,000 μS/cm (still higher than the maximum value recommended by international standards), an average canal–tube to well water conjunctive use ratio of 3:4 would be required. Assuming no change in the total volume of irrigation water used in the service area, this target means that the volume of canal water would have to be increased by more than 50 percent and the volume of pumped groundwater reduced by more than 20 percent of current volumes. It may also require additional groundwater pumping to facilitate flushing of salinity from the soil zone.

In addition to the technical issues, institutional challenges are also significant. Murray-Rust and Vander Velde (1994, p. 229) highlight that to halt the declining trend in sustainability of Pakistan's irrigated agriculture, "*Pakistan's public agencies and supporting research institutions must begin shedding this 'historical baggage,' reorganize internally and establish functional, working linkages with one another*."

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Box 5 - Other CWM Examples

Sahuquillo (2005) discusses several CWM examples under the theme of alternate use of groundwater and surface water for irrigation in a more general discussion of conjunctive use. These examples are from the Mediterranean Basins of Spain and the Central Valley, California, USA.

In the Spanish basin examples, Sahuquillo (2005) reports on the evolution of conjunctive use as a process associated with the expanding irrigation industry during wet years via surface water diversions. As groundwater resources were identified throughout the region, more and more groundwater abstraction was incorporated into the system. In response to an expansion in the irrigated area, more intense use of surface water during wet years increased, leading to substantial increases in overall use. These examples demonstrate a bottom-up approach that was proposed and implemented by the irrigators, and which has now been incorporated into legally sanctioned schemes.

Sahuquillo (2005) discusses in more detail the status of the Mijares Basin, near Valencia, Spain. The basin is characterized by large surface water reservoirs situated over a karstic limestone aquifer, resulting in high leakage rates to groundwater. In addition, the Mijares River also leaks and recharges the local alluvial water table aquifer. Surface water or groundwater is used as the water source depending on water availability, both in stream and in storage. The beneficial aspect of the relationship between surface water and groundwater is that whenever more surface water is available—which is hence used by irrigators—recharge rates to the groundwater system are higher. This process provides a natural counter-cyclical process, where the groundwater resource is recharged during periods of low groundwater demand. More recently, conjunctive use in Spain has included an explosion of canopied agriculture mixed with conjunctive use.

Pulido-Velazquez and others (2004)—and, to a certain extent, Sahuquillo (2005)—discuss an interesting adjunct to the idea of conjunctive use. Both sets of authors provide examples of conjunctive use occurrences where the surface water resource is used to artificially recharge the groundwater resource. Pulido-Velazquez and others (2004) discuss the situation in Southern California, though associated with water supply projects for metropolitan areas rather than irrigation; Sahuquillo (2005) discusses examples associated with treated wastewater near Tel Aviv, Israel, and Barcelona, Spain. While not directly relevant to irrigation supplies, they demonstrate a further type of conjunctive management that could be implemented elsewhere, presumably subject to cost.

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Boxes Part B. Modeling-focused CWM examples

Many journal articles and government reports address model studies of surface water and groundwater interaction and general groundwater management but relatively few exemplify modeling applied to CWM. One of the most important benefits of developing an integrated hydrologic model (IHM) of a watershed and associated aquifer systems is that it requires the compilation and analysis of all data and provides a pathway to the more complete and sophisticated hydrologic budgets needed for CWM and sustainability analysis.

Analysis also helps identify gaps in data and data sharing that are used for model input and gaps in monitoring networks used for model observations, management decision making, and sustainability thresholds. Boxes 6 through 9 present significant examples where CWM is the focus of modeling associated with evolving linkages to governance and water conflicts. These US Geological Survey (USGS) model-example input and output data sets can be obtained from the USGS Water Science Center Offices in the states of California (https://www.usgs.gov/centers/california-water-science-center/science/hydrologic-modeling↗) and New Mexico (https://www.usgs.gov/centers/new-mexico-water-science-center/science/hydrologic-assessment-and-modeling↗), if readers want to explore them in more detail.

Box 6 - Central Valley - California, USA

The Central Valley of California boasts a multi-billion-dollar agricultural industry; it is one of the major food-producing regions of the world and has been the site of conjunctive use and CWM for many decades. This CWM has been accompanied by a long history of monitoring and modeling that has allowed managers to make informed decisions about CWM at the local, county, and state level. Most recently, the Central Valley has been the focus of SGMA and the related mitigation of water resources needed to achieve sustainability over the next few decades. Even with about 40 percent of the valley still under native vegetation, water use has largely been driven for over a century by agricultural land-use development (Figure Box 6-1).

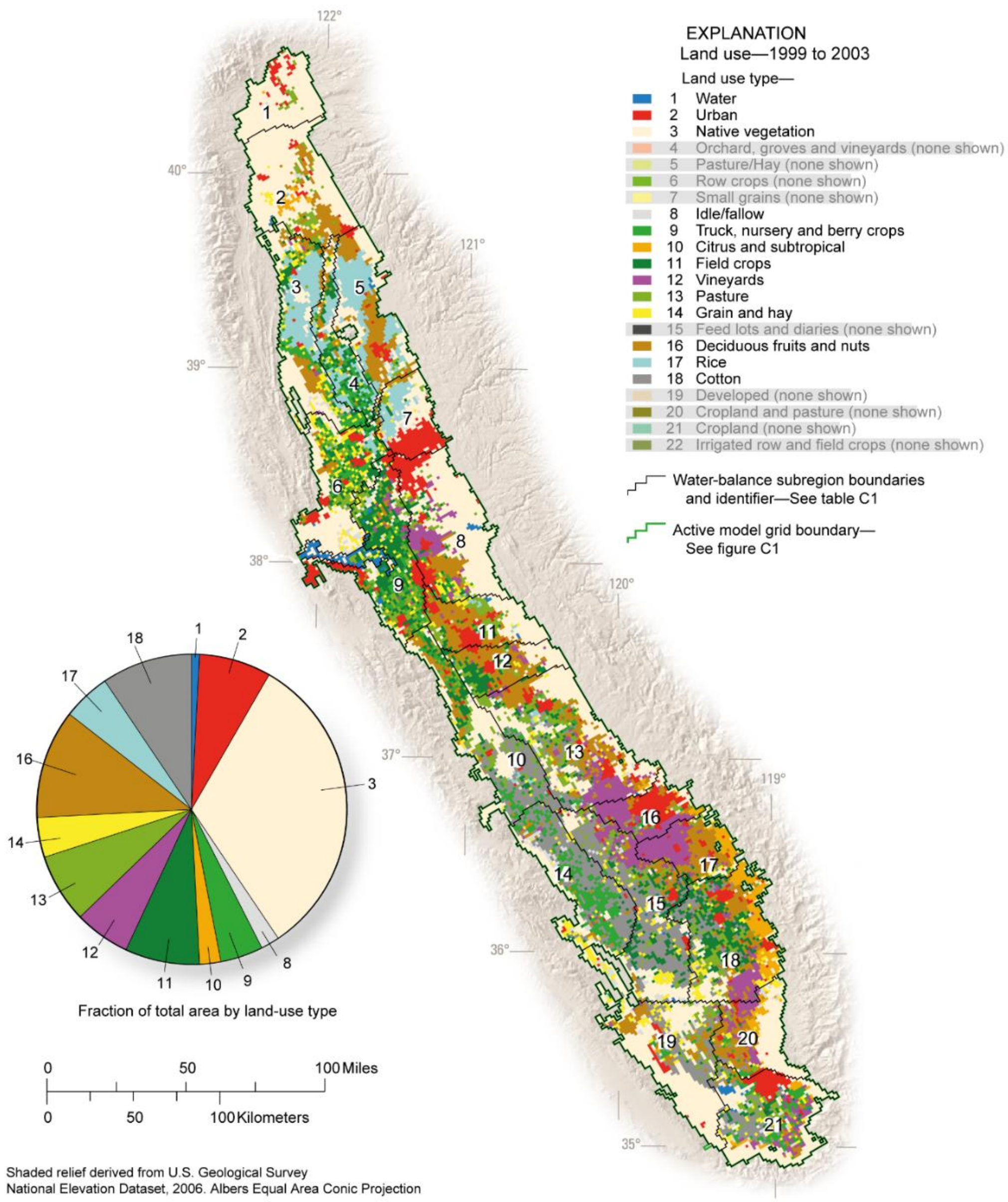

Figure Box 6-1 - Distribution of native, urban, and agricultural land use for the year 2000 within the Central Valley, California, USA (Faunt et al., 2009). Greyed-out land use types did not occur in the valley in 2000.

Demands beyond the major agricultural uses for water include urban supply, maintenance of habitat for wildlife and stream flows for fish migration, as well as hydrocarbon production. The monitoring and modeling of the Central Valley have helped support and clarify CWM and the need to mitigate the undesirable secondary effects identified for California's SGMA (listed in Section 2 - *Fundamental Concepts of CWM*) that threaten sustainability and reliable conjunctive use. This situation not only includes groundwater declines and storage depletion but also interference with surface water flows, land subsidence, and water-quality degradation.

The CVSALTS program (CVSALTS, 2023) separately addresses the management of nutrient and salinity effects on water quality through modeling that gives guidance on management strategies including source control, proposed mitigation, and even the possibility of salt credits like wetland and climate change credits. With continuation of the current megadrought (2000 to 2022)—combined with climate change and continued urbanization and agricultural land use development—the alternatives provided through CWM will need to be combined, informed, and supported by modeling and monitoring. Modeling reveals the intimate relation between climate variability and both groundwater storage and surface water deliveries as part of conjunctive use (Figure Box 6-2). This example of sustained groundwater depletion is also caused by other important indirect drivers that include the reduced surface water deliveries to preserve environmental flows from enforcement of the Endangered Species Act, increased agricultural land use and related irrigation, conversion to permanent crops that "harden the demand" for irrigation over decades, more transition from seasonal to year-round agriculture, sustained water exports, potential salinity flushing, and the installation of deeper wells.

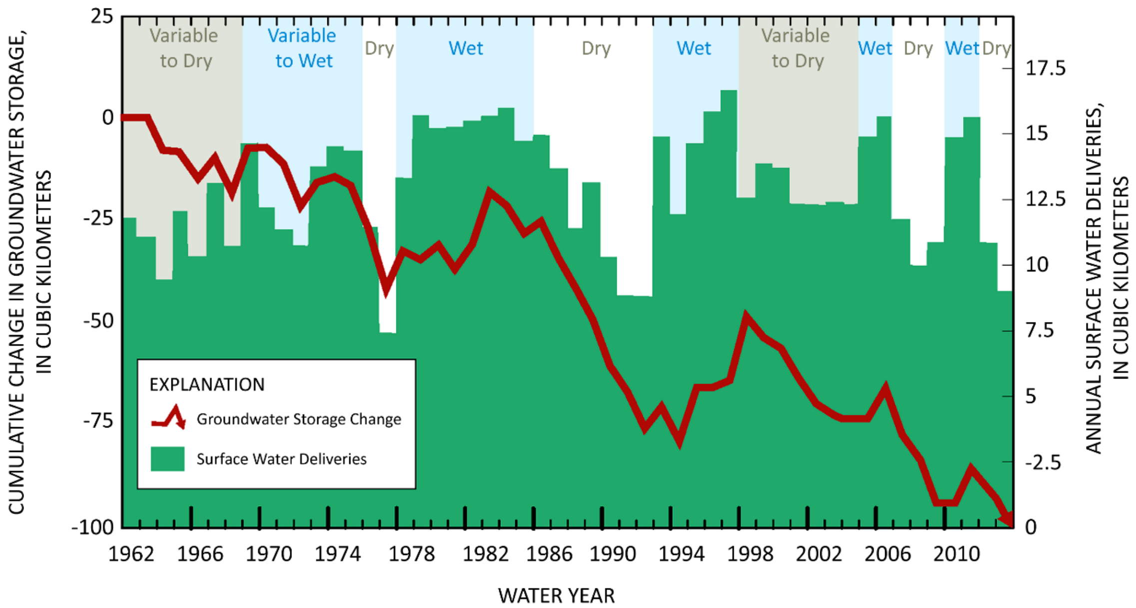

Figure Box 6-2 - Simulation of surface water deliveries and groundwater storage depletion relative to climate variability for the entire Central Valley, California (Faunt, personal communication June 2017).

One of the major and connected secondary effects is land subsidence, with renewed subsidence occurring during droughts when there is reduced surface water importation and increased reliance on groundwater supplies for irrigation, especially in regions without surface water access which experience continued subsidence between droughts (Figure Box 6-3).

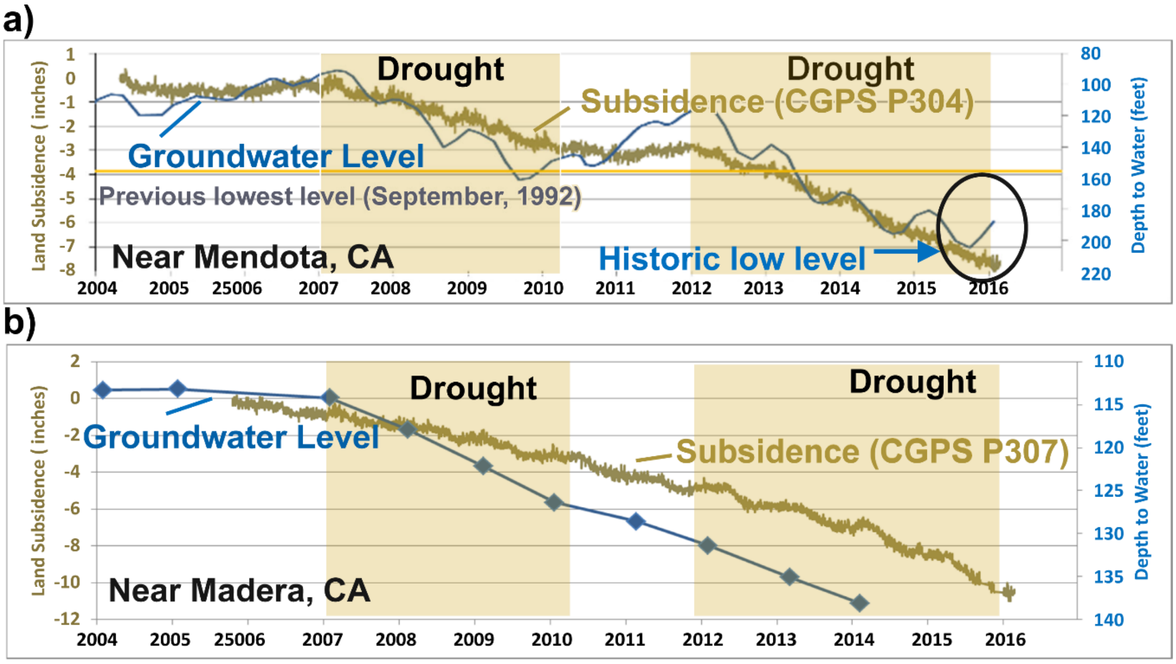

Figure Box 6-3 - Examples of land subsidence and groundwater declines in relation to climate variability and related reduction of surface water deliveries, shows subsidence with increased groundwater pumpage for irrigation, and increased preservation of environmental flows for a) regions with intermittent surface water deliveries and b) regions without surface water deliveries, Central Valley, California, USA (Faunt, personal communication June, 2017).

Hanson and others (2012) linked a climate change model using the GFDL-A2 (greenhouse gas emissions "business-as-usual") scenario of extreme CO_2 emissions from the CMIP3 group of GCMs with a combined Integrated Hydrological Model (IHM) and watershed model (using Basin Characterization Models, BCM) to assess the potential climate change effects on aspects of conjunctive management (Figure Box 6-4).

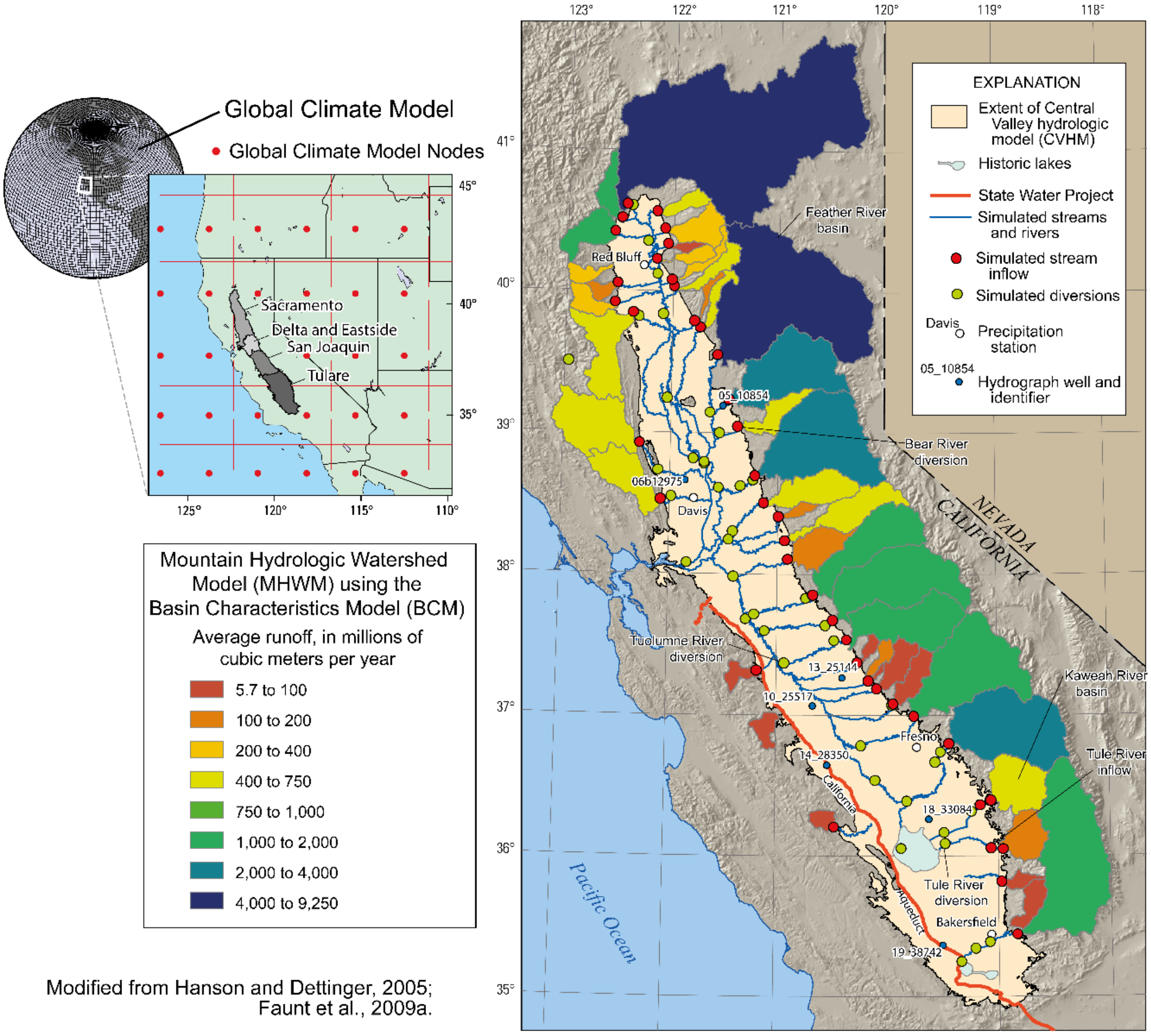

Figure Box 6-4 - Map showing relation of global climate model (GCM) grid to areas of regional hydrologic models in California and the Central Valley of California. The average runoff is color coded for watersheds modeled with the mountain hydrologic watershed model (MHWM) using the basin characterization model (BCM) and its connections to the valley-wide Central Valley hydrologic model (CVHM) with stream inflow that represents the linkage between the BCM and the CVHM models as well as diversion locations, selected precipitation and streamflow gaging stations, and wells (Hanson et al., 2012) (modified from Faunt et al., 2009).

Incorporating the entire watershed and alluvial valley with a climate change scenario used to drive an IHM and watershed model provided a holistic approach to analyzing conjunctive use within the supply-and-demand framework and imperatives of regional CWM. The results demonstrated the transition from predominantly surface water to groundwater supply for agriculture, subject to climate change (Figure Box 6-5) with respect to the overall hydrologic budget as well as changes in net groundwater infiltration (recharge), groundwater storage, and interbed storage (land subsidence). This method can be used to consider conjunctive use adaptation options and associated hydrologic risk assessments.

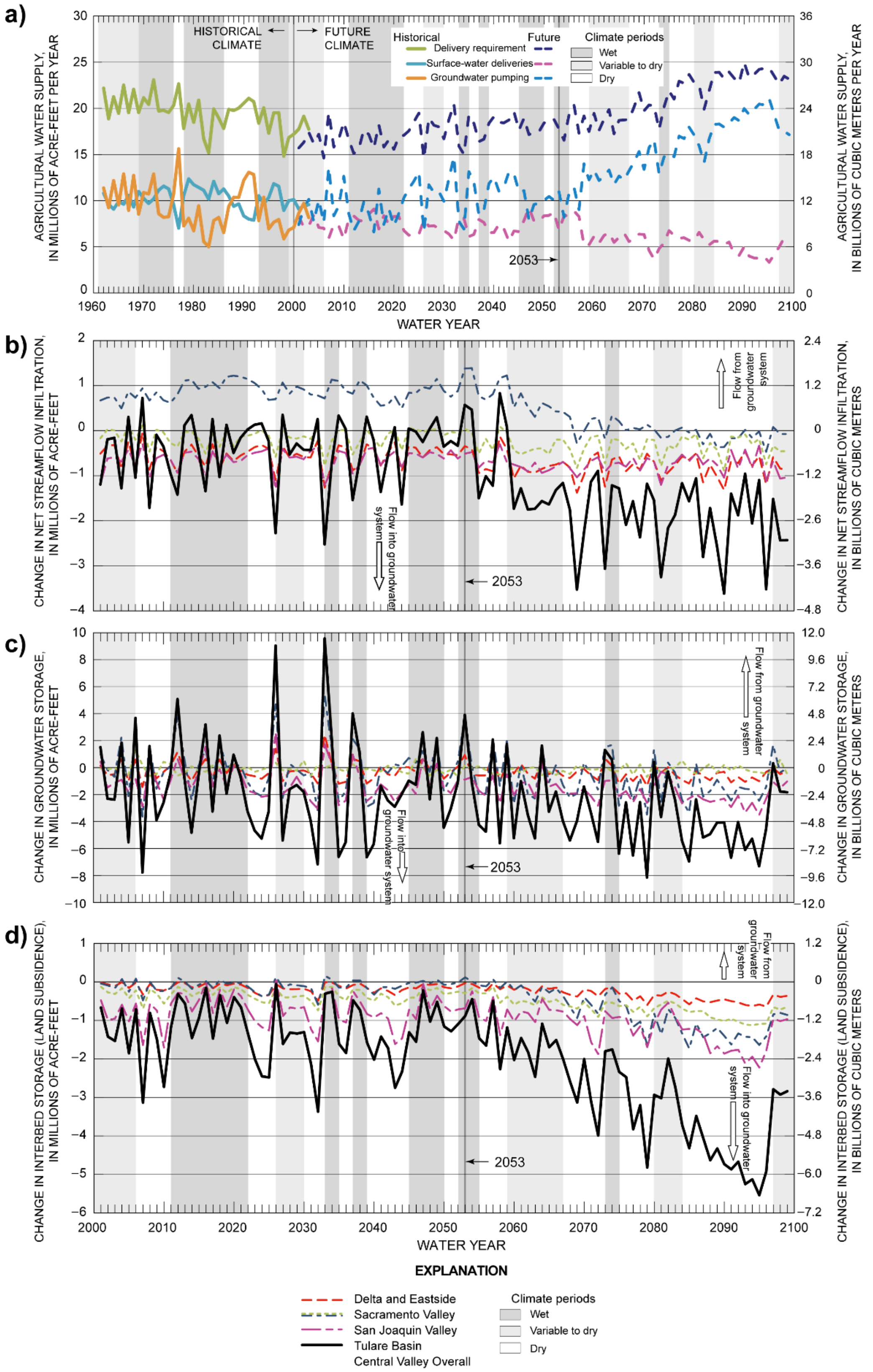

Figure Box 6-5 - Graphs showing the hydrologic budgets with the GFDL-A2 scenario from CVHM for annual changes in a) historical and future agricultural water supply and demand, b) future changes in net streamflow infiltration, c) future changes in groundwater storage, and d) future changes in interbed storage, Central Valley, California, USA (Hanson et al., 2012)

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Box 7 - Lower Rio Grande, New Mexico, Texas, USA, and Conejos-Medanos, Chihuahua, Mexico

The Lower Rio Grande is a special example of CWM modeling because it represents multiple levels of transboundary connections between irrigation districts, states, and countries. This transboundary setting exemplifies the need for joint monitoring, data sharing, and modeling to guide CWM as changes in water resources and land use are also compounded by additional changes in population, industry, and climate. Transboundary aquifer systems (TBA) such as the ones along the USA–Mexico border are also most prone to conflict and overexploitation with different management and water rights (Rivera & Hanson, 2022). Unlike the Colorado River watershed to the west, this transboundary region has no international agreements governing both groundwater and surface water but is subject to the Treaty of the Rivers (Convention between the United States and Mexico: Equitable distribution of the waters of the Rio Grande, 1906; Water Treaty for the utilization of waters of the Colorado and Tijuana Rivers and of the Rio Grande, 1944).

The USGS developed an Integrated Hydrological Model (IHM) and a watershed model (Hanson et al., 2020) for water availability analysis of the Lower Rio Grande Valley of New Mexico and Texas, USA, and Northern Mexico. It was designed to help evaluate water management operating rules and contingencies within the existing CWM at several levels. This overlapped state and irrigation district jurisdictions and federal reservoir operations that collectively represent conjunctive use of surface water and groundwater.

This modeling was an extension of long-term planning for the USBR Rio Grande project and related CWM beyond the previous analysis completed in an Environmental Impact Statement study of reservoir operations and delivery obligations connected to combined groundwater use domestically and internationally that were subject to potential climate change (Ferguson & Llewelyn, 2015; US Bureau of Reclamation, 2016, 2017). Model development included construction of a Transboundary Rio Grande Watershed model with BCM (Flint et al., 2021) and an IHM with MF-OWHM2 (Boyce et al., 2020). The hydrologic models were developed and calibrated to 75 years (1940 to 2014) of historical conditions of water and land use, and parameters were adjusted so that simulated values closely matched available measurements (calibration) using both automated parameter estimation and trial-and-error methods. This historical simulation also reflects some of the evolution of water-resource development and governance from surface water dominated to conjunctive use (Figure Box 7-1).

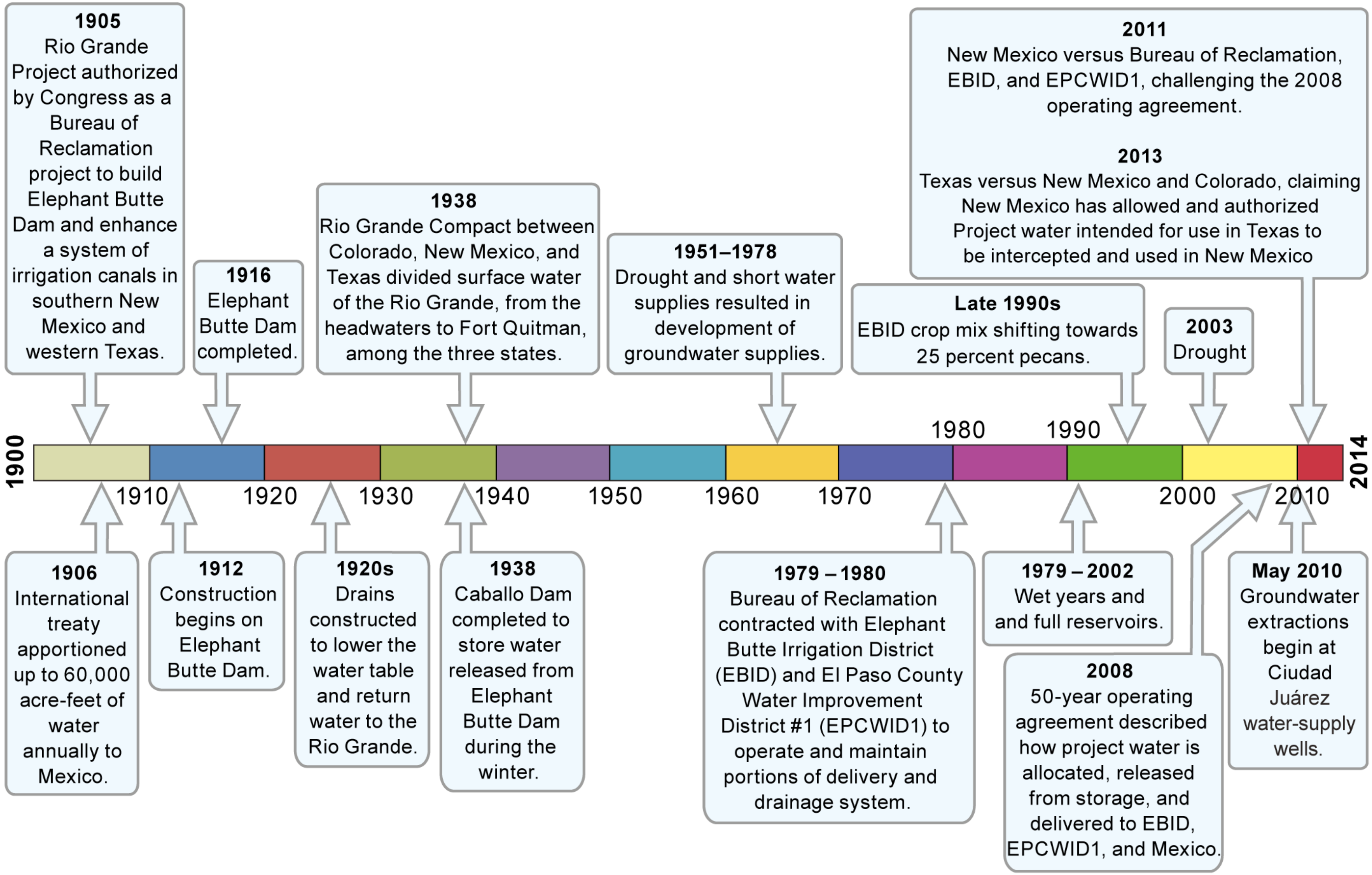

Figure Box 7-1 - Generalized history of water and land-use development for the Transboundary Rio Grande river and aquifer of New Mexico and Texas, USA, and the state of Chihuahua in Mexico (Hanson et al., 2020).

The conceptual model identified surface water and groundwater inflows and outflows that included the movement and use of water both in natural and anthropogenic systems. The groundwater flow system is characterized by a layered geologic sedimentary sequence combined with the effects of groundwater pumping, operation of the Rio Grande Project (RGP), natural runoff and recharge, and the application of irrigation water at the land surface that is captured and reused in an extensive network of canals and drains as part of the conjunctive use of water in the region. It also included a transition in land use with more change in crops grown than addition of agricultural land use areas (Figure Box 7-2), resulting in increased water demand, and hardening of demand with transition to more orchard crops such as pecans.

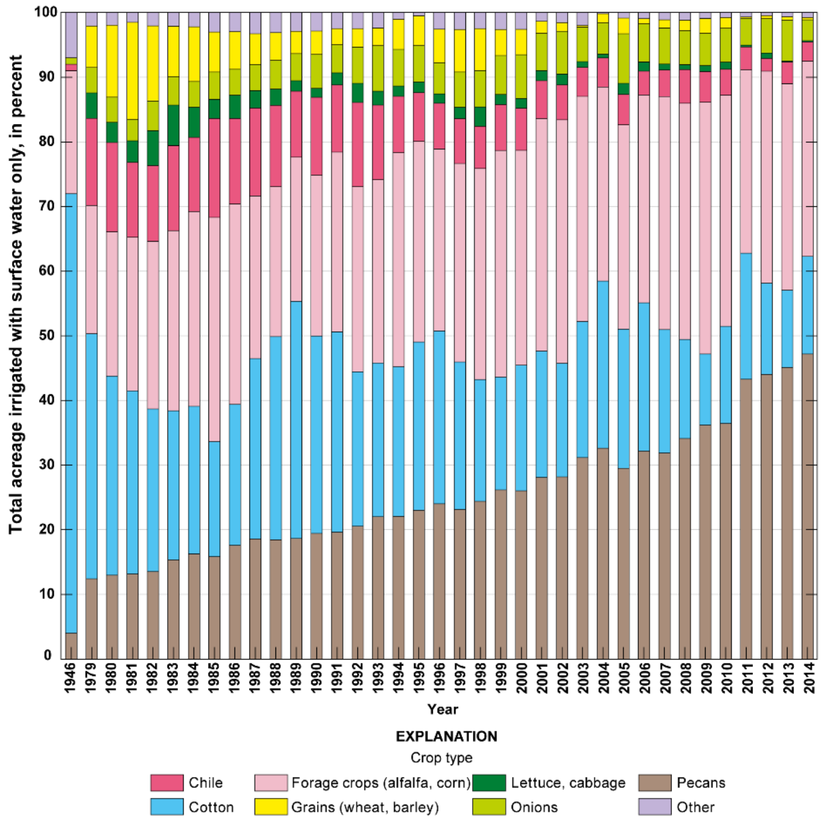

Figure Box 7-2 - Time history of crop types grown throughout the Lower Rio Grande region (Hanson et al., 2020).

Historical groundwater-level fluctuations were aligned with climate cycles, which collectively resulted in alternating wet and dry periods. Periods of drought that persisted for one or more years were associated with low surface water availability that resulted in higher rates of groundwater-level decline and more use of groundwater (Figure Box 7-1). Rates of groundwater-level decline also increased during periods of agricultural intensification with hardening of demand with transition to orchard crops like pecans (Figure Box 7-2), which necessitated increased use of groundwater as a source of irrigation water. Groundwater levels substantially declined in subregions where drier climate combined with increased demand, resulting in periods of reduced stream flows and related reservoir deliveries of surface water for irrigation resulting in increased dependence on groundwater supplies (Figure Box 7-3).

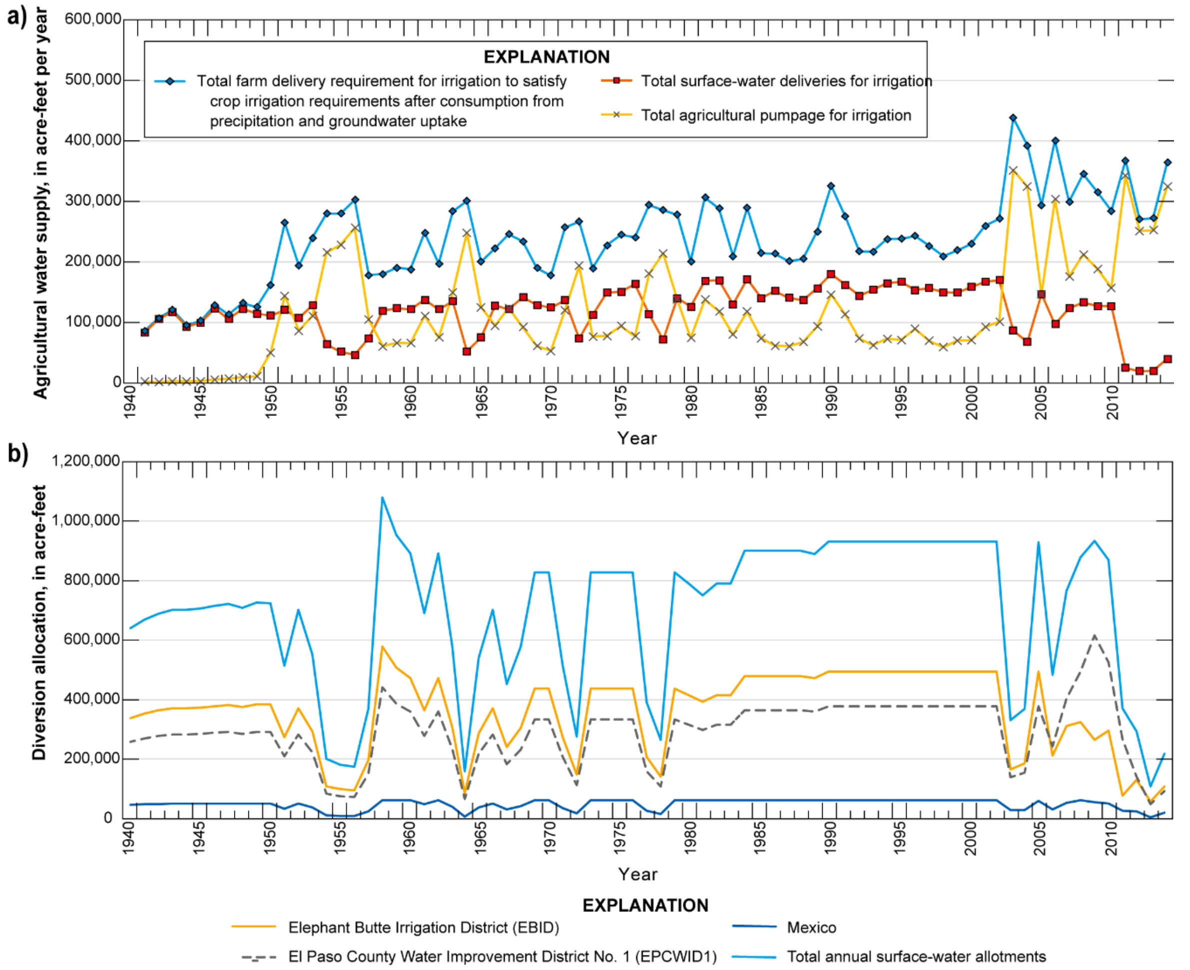

Figure Box 7-3 - Agricultural irrigation components for the Rio Grande Transboundary region of New Mexico and Texas, USA, 1940–2014: a) total agricultural water supply and demand and b) the allotments from the Rio Grande Project (Hanson et al., 2020). 1 acre-foot ≈ 1233 m^3.

A cyclic imbalance between inflows and outflows resulted in the modelled depletion (groundwater withdrawals more than natural recharge) of the groundwater basin during the 75-year simulation period (1940 to 2014). Changes in groundwater storage can vary considerably from year to year, depending on land use, pumpage, and climate conditions. Climatic drivers of wet and dry years can greatly affect all inflows, outflows, and water use. Although streamflow and, to a minor extent, precipitation during inter-decadal wet-year periods replenished the groundwater historically, contemporary water use and storage depletion could have reduced the effects of these major recharge events. The average net groundwater flow-rate deficit for 1953 to 2014 was estimated to be about 1,090 acre-feet per year, which totals to over 2.6 million acre-feet (Figure Box 7-4). This later period was also the beginning of the largest mega-drought in the American Southwest since the late 1500s (Renteria et al., 2022) and underscores that conjunctive use within CWM requires longer planning horizons that may span many decades and include drought contingencies within a diversified portfolio of water supplies.

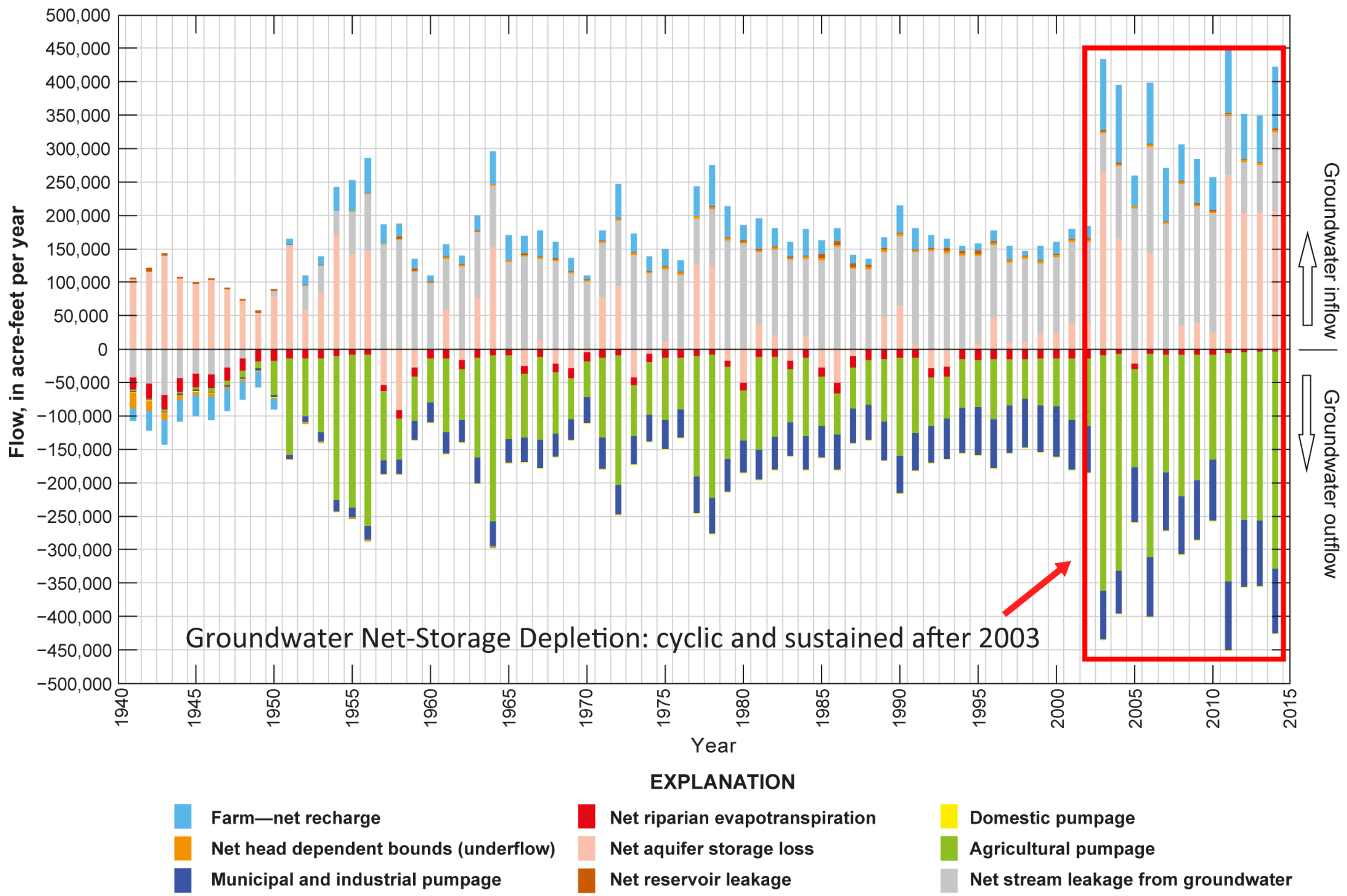

Figure Box 7-4 - Hydrologic Budget time series of the Lower Rio Grande Valley from IHM model results from the Rio Grande Transboundary Integrated Hydrologic Model (RGTIM) showing the effects of increased groundwater demand and related drought (Hanson et al., 2020).

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Box 8 - Pajaro Valley, Conjunctive-Use Modeling

Hanson and others (2014a) developed an integrated hydrologic model of the Pajaro Valley, California, USA. This model was used to assist in the development of the Basin Management Plan, which is aimed at improving long-term planning involving conjunctive use of various water sources and incorporating managed aquifer recharge. MODFLOW with the Farm Process (MF-OWHM, Figure Box 8-1) was selected as the modeling platform to assess historical and future seasonal-to-interannual time frames including changes in climate and land use. This valley has relied largely on groundwater irrigation for a multi-billion-dollar agricultural industry with some minor augmentation from precipitation. The reliance on groundwater in this coastal basin resulted in overexploitation of groundwater resources and caused seawater intrusion. A state appointed agency was formed to manage the water resources, develop best management plans (BMP), and mitigate these effects from overexploitation.

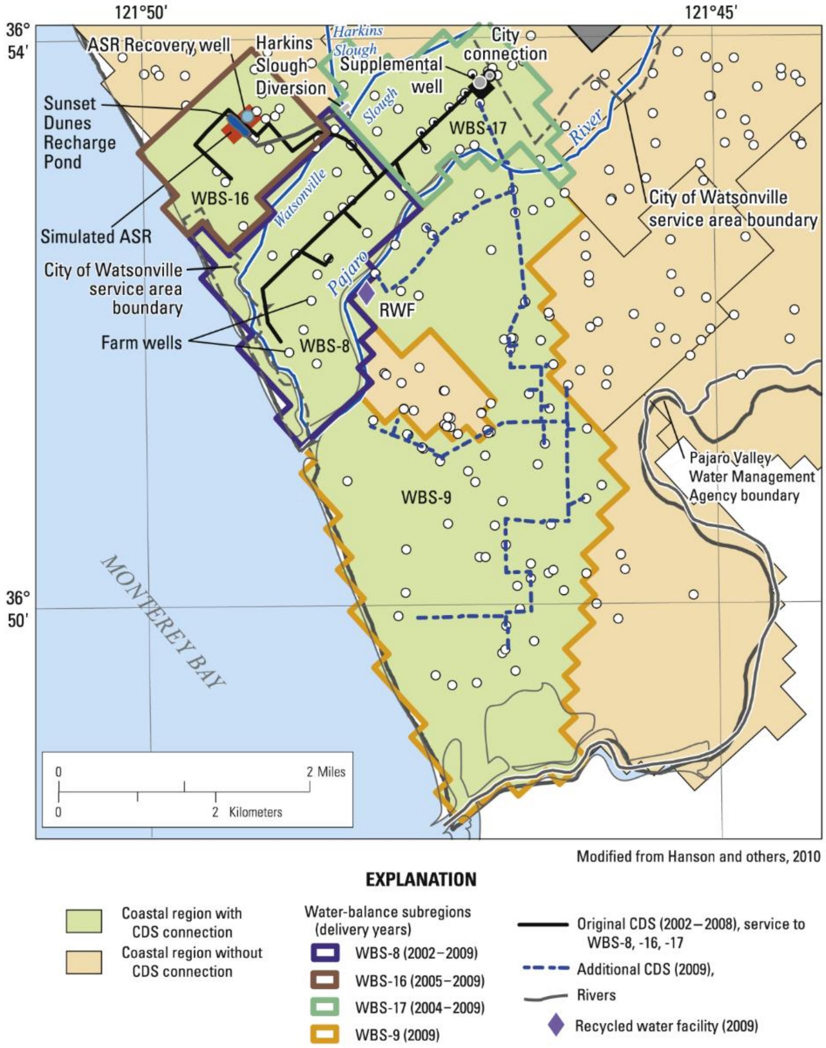

Figure Box 8-1 - Map showing selected water-balance subregions used for water budget accounting in the Pajaro Valley Hydrologic Model (PVHM) using MF-OWHM to assess projected conjunctive use, coastal pumpage and related seawater intrusion (Hanson et al., 2014c).

The model and supporting geohydrologic framework and geochemical analysis helped decision-makers better define the extent of water resources within the supply-and-demand framework and provided the basis for developing and enacting BMP. The BMP included new conjunctive use with the capture of local runoff and creation of an aquifer storage and recovery system (ASR), establishing a recycled water facility to reuse urban wastewater for irrigation, and replacing coastal pumping with a coastal distribution system (CDS) to reduce the effects of seawater intrusion. Options for alleviating the severity of dynamic nonequilibrium of an aquifer are presented in Figure 10 of Section 7 of this book. Because of earthquake hazards, reservoirs were not an alternative to surface water supply and storage. Since surface water diversions are only available to supplement the urban public supply from groundwater, additional reduction in the largest groundwater use for irrigation was needed through the implementation of MAR with ASR combined with captured surface water runoff plus the reuse of recycled treated urban wastewater (WWT) for irrigation. These alternative water sources are now distributed through the Coastal Distribution System to agriculture for irrigation to supplant coastal pumpage that is driving seawater intrusion and overdraft. There was an additional requirement to have farmers retire (but not destroy) their coastal irrigation wells as an initial step towards a reduction of groundwater overdraft and the related secondary effects of seawater intrusion and groundwater quality degradation.

This modeling also identified additional opportunities for conjunctive use that included the reuse of return flow and tile drain flow that could make a significant impact on reducing overdraft of groundwater resources. Modeling was used to project the effectiveness of these new components (Hanson et al., 2014c). The model results were compared to the actual deliveries for the recent historical period of project operations (2002 to 2009) to help assess the ability of this type of IHM modeling to assess the delivery of multiple sources of water within this CWM framework (Figure Box 8-2; Hanson et al., 2014c).

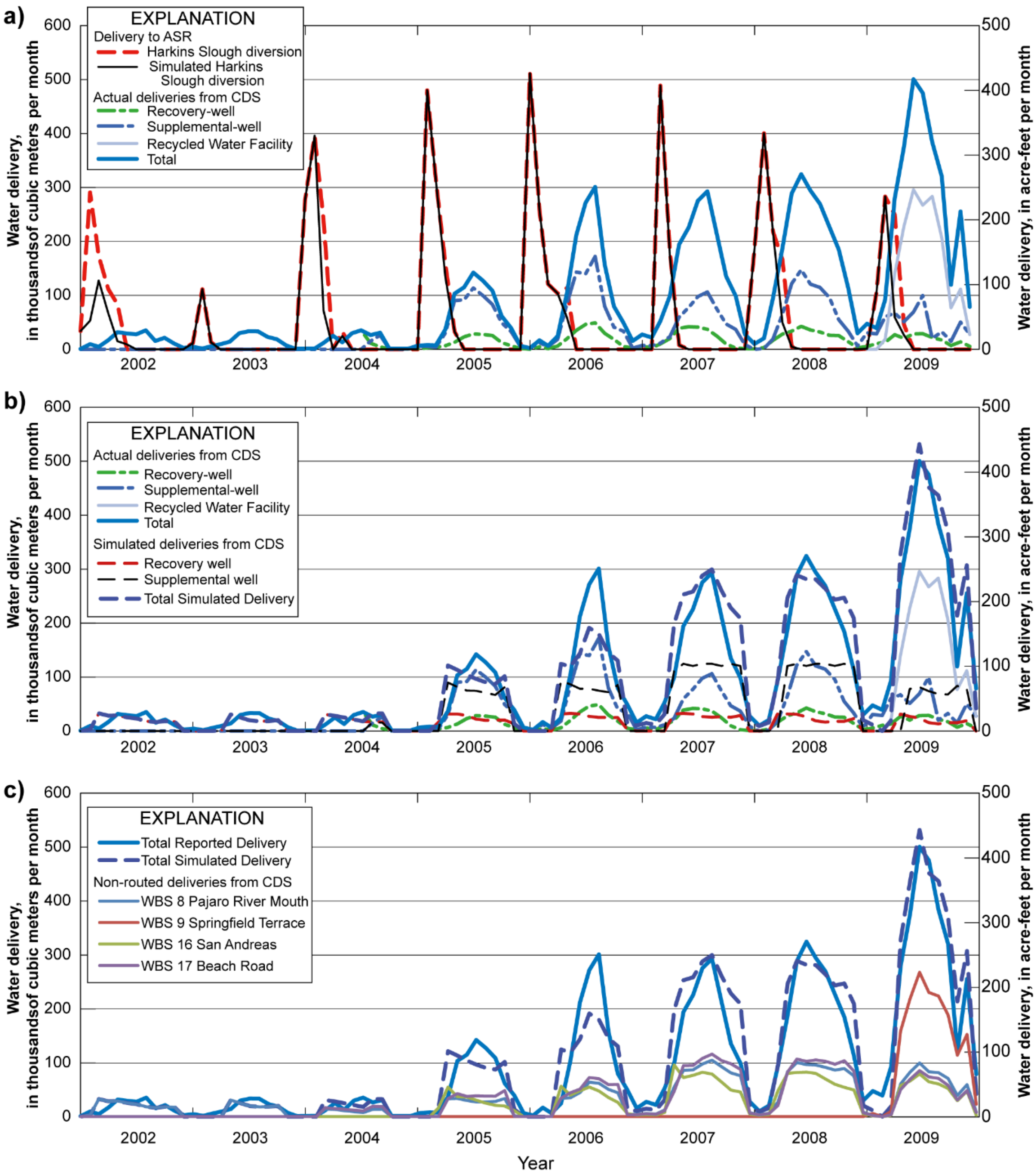

Figure Box 8-2 - Graphs showing the historical operation of the ASR components and their equivalents simulated by MODFLOW with the Farm Process within the Pajaro Valley, California, USA: a) capture of local runoff at Harkins Slough, b) deliveries from the Coastal Delivery System, and c) total deliveries (Hanson et al., 2008, 2014c)

The resulting analysis of projected conditions was insightful as they showed that these additional projects arrested some of the coastal groundwater-level declines and were estimated to reduce the rate of seawater intrusion by about half, though the projected recovery was still largely driven by seawater intrusion plus sustained landward pumping by the City of Watsonville wells and related regional cone of depression (Figure Box 8-3). The strongest boundary condition is the ocean so when pumpage is curtailed in this coastal agricultural area, seawater intrusion is still the major driver of the coastal-region groundwater recovery because groundwater pumpage from the City of Watsonville wells in the Pajaro Valley maintains a landward cone of depression that also indirectly drives seawater intrusion. In short, nothing is "free", if possible, all the drivers have to be turned off. It also underscored that when there are other major groundwater extractions and related regional cones of depression, such as the localized pumpage for urban supply landward of the coast, regional gradients persist that will continue to drive seawater intrusion. This was also revealed by the assessment of the region in the Los Angeles Basin behind the Dominguez Gap Intrusion barrier (Newhouse & Hanson, 2000, 2004)—which also has persistent groundwater pumpage inland of the barrier. These examples suggest that arresting seawater intrusion from barrier systems or through reduced coastal pumpage requires the cessation of pumpage further inland that is driving landward hydraulic gradients in the groundwater flow systems. The success of this BMP development, related projects, and support from the modeling resulted in the State of California accepting these mitigation plans for this critically over-drafted coastal basin under California's SGMA regulations.

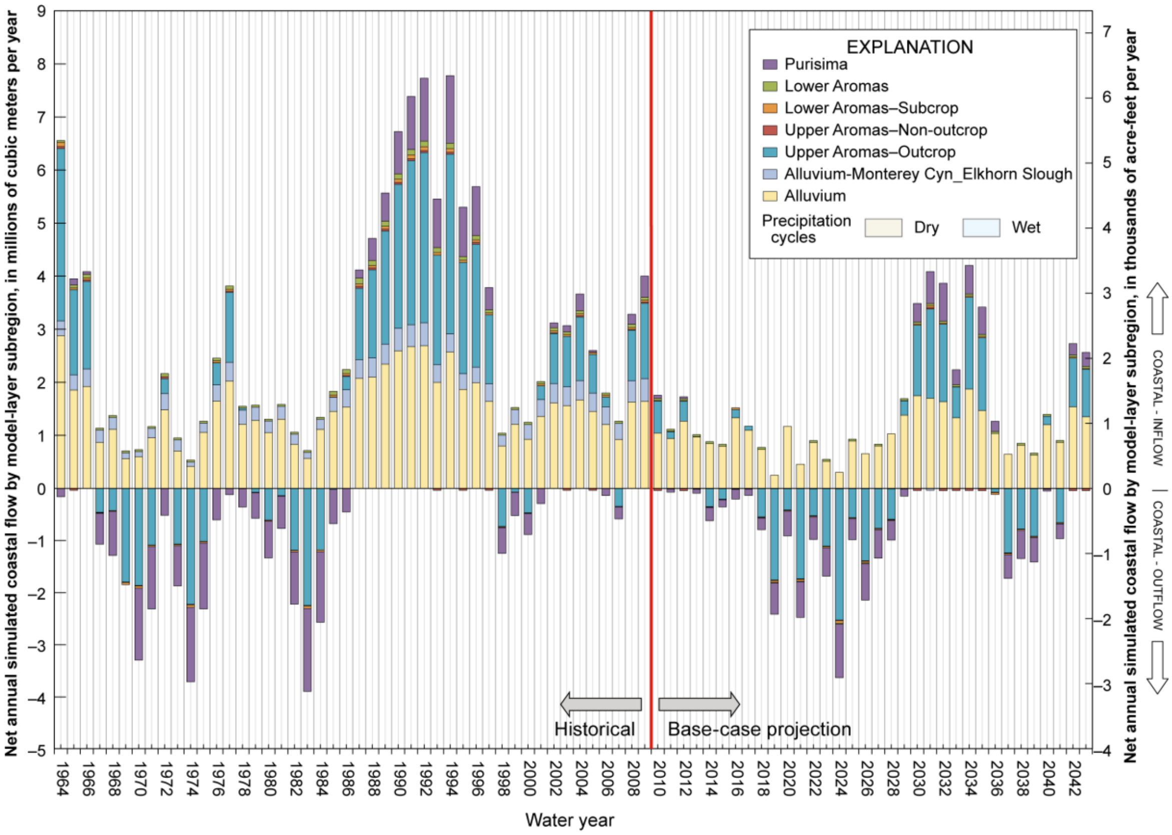

Figure Box 8-3 - Graph showing temporal distribution of coastal inflows and outflows for the simulated historical and projected hydrologic conditions in Pajaro Valley, California, USA (Hanson et al., 2014c).

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Box 9 - Other Modeling Examples

McKee and others (2014) developed a conjunctive use optimization model to evaluate the sustainable yield of the Sparta Aquifer in Arkansas and Louisiana, USA. The goal was to determine the maximum groundwater extraction without violating stream discharge constraints. A steady-state MODFLOW-based model was used to optimize the hydraulic head above the top of the aquifer while maintaining stream flow within the outcrop areas. This model showed that sustainable yield of the aquifer was only approximately 55 percent of the demand with the remainder needing to be met by alternative sources. Typical of many similar conjunctive use optimization models, this case study does not include interactive groundwater and surface water modeling.

Another noteworthy conjunctive use modeling development occurred for the Central Platte Natural Resource District (NRD) in Nebraska (Traylor et al., 2023) using an integrated hydrologic model (MF-OWHM). NRDs were established as management districts throughout Nebraska in 1969 to help manage groundwater and protect natural resources while the Nebraska Department of Natural Resources regulates surface water use. Use of groundwater and surface water supports $2 billion USD per year of agricultural production as well as recreation and wildlife habitat. This model was designed to support the updates of the NRDs integrated management plan as well as phased management or additional regulation of groundwater resources. The model analyzed combinations of eight irrigation and eight climate scenarios, including various drought scenarios and their impact on water use in support of CWM planning and management.

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15 Exercise Solutions

15.1 Conceptual Exercise Solutions

Solution Conceptual Exercise 1

Conjunctive Use is a subordinate component of CWM that is centered on the portfolio of supply sources. CWM includes the management framework of a diverse portfolio of supply sources—as well as replenishment and demand management—for multiple purposes that collectively provide for the sustainability of water resources. Demand management may also include other drivers beyond but linked to water including climate, land use, population and industrial growth, governance, and transboundary sharing.

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Solution Conceptual Exercise 2

Conjunctive Use includes both natural and anthropogenic sources of water. Natural waters include precipitation, surface water, and groundwater. Natural surface water sources can include springs, seeps, streams, runoff, and rivers. Constructed surface water sources include reservoir releases, drain and return-flow water from agriculture, French drain return flows, and urban stormwater return flows. Anthropogenic sources of surface water can include flood-based runoff as Managed Aquifer Recharge (Flood-MAR), urban waste-water treatment plant or industrial discharge, recycled-treated water, desalination (DeSal) water, imported canal waters, and irrigation return-flow drain waters. Groundwater, Managed Aquifer Recharge (MAR), Aquifer Storage and Recovery (ASR), and imported water are also sources of water. DeSal is also an important supplement to diminishing groundwater supplies for agriculture and often ignores the energy costs or waste-stream issues related to this source of water for irrigation applications.

Springs, seeps, and fens can have groundwater or snowmelt sources and may be related to the management of groundwater-dependent ecosystems (GDE) or other forms of habitat that need to be protected and managed. For example, the expansion of bottled water production from springs has threatened or reduced sources needed for habitat or groundwater replenishment in some regions. In addition, many rural areas capture and store discharge from springs and seeps as an additional source for smaller water uses such as domestic and livestock supply.

Conjunctive Use also includes some elements of demand management such as evapotranspiration (ET) management. This is occurring in China, but also is emerging in California, USA, where plans to cover selected canals with solar panels will also reduce ET and generate additional electricity without consuming more land. Other forms of ET management include the use of interior hydroponic warehouses, green houses, hoop houses, covered furrows, and mulch.

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Solution Conceptual Exercise 3

CWM can include MAR, ASR, or Flood-MAR as additional management components to supplement supply, replenish supply, or replace supplies, as well as demand management. However, CWM does not have to include MAR and, in most situations in the world, there is no MAR.

Like other replenishment components, MAR can occur at various scales with some larger scale efforts requiring infrastructure investment and maintenance. These components of CWM also help minimize the temporal disparity between supply and demand that occur at seasonal to decadal time periods or entire climate cycles and represent an additional element of mitigation through demand management. Indirectly, these components may also reduce demand for other sources of water—such as groundwater—as well as reduce the energy footprint related to providing water such as pumping groundwater. In the context of Aquifer Storage and Recovery (ASR), MAR can facilitate groundwater replenishment through water banking and help reduce the temporal disparity between supply and demand for water.

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Solution Conceptual Exercise 4

CWM of surface water can include: operation of reservoirs; development of surface storage such as irrigation ponds, small check dams, gabions, and/or additional reservoirs; developing and using imported water sources and related infrastructure; reuse of irrigation drain-water and effluent discharge; and capture of runoff for MAR or capture of flood flows for Flood-MAR. Surface water sources such as recycled water and runoff may also be considered supplementary or supplanting groundwater sources as a demand-management component of CWM.

CWM of groundwater can include: limiting pumpage or pumping rates of wells; optimizing the location of old and new wells; restricting screens from multi-aquifers that may contribute to geogenic pollution or short-circuiting wellbore flow of seawater intrusion, and acceleration of land subsidence. CWM of groundwater often requires ordinances that limit depth and number of new wells, especially in areas of poor water quality and in coastal regions.

In contrast, some multi-aquifer wells provide the only conduits to allow recharge of deeper aquifer systems, so management of well construction, maintenance, and destruction needs to consider the potential positive and negative effects of these wells in their settings combined with pumped and unpumped flow logs as shown for the Santa Clara Valley, California, USA, in

Figure 4 and Figure 5 of Section 4 of this book.

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Solution Conceptual Exercise 5

The supply drivers within a CWM framework include any and all sources of water. Since this includes precipitation, climate and surface water are included, as are groundwater, recycled water, reused water, imported water, desalinated water, and any replenishment or augmentation activities such as MAR and Flood-MAR. The demand drivers within a CWM framework not only include the local consumption of water from agriculture (as actual ET), public supply and industrial uses, indirect drivers of land use (which strongly influence ET), population growth, expanded industrial or mining development, as well as the reservation of water for protection of environmental stream flows, and habitat maintenance from streamflow or groundwater contributions such as GDEs.

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Solution Conceptual Exercise 6

While there is some gradation between the two, typically informal systems are the development of water supply by local landowners or groups of landowners while a formal system is developed to provide water supply service to a larger group within a planning framework that also supports the development and maintenance of the system service and infrastructure.

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Solution Conceptual Exercise 7

Many of the CWM supply drivers are connected as water travels from precipitation to the land surface and becomes ET, runoff to surface water systems, and deep percolation to groundwater aquifers. Similarly, multi-aquifer wells allow water to flow vertically between aquifers, which may have positive (recharge to deep confined aquifers) or negative (cross-contamination of poor-quality water) consequences.

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Solution Conceptual Exercise 8

The benefits of CWM include the development of a formal water infrastructure and related funding and governance that can promote and support sustainability. This has some additional ancillary benefits including the potential for reduced costs of resource conflicts; more management of other related demand drivers; and integration of water, food, land, and energy security.

The benefits of CWM are lower costs and potentially larger profit over longer periods of time. Commonly, the costs of resource damage are not included in the assessment of management. Secondary effects from overexploitation of resources or too rapid development of resources can have permanent and costly effects on the public, industry, agriculture, and the environment. For example, land subsidence, seawater intrusion, pollution, and groundwater mining can cost millions of dollars and are almost impossible to repair. Further, they are not commonly part of the estimates or equations of development costs and related profits.

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Solution Conceptual Exercise 9

Sustainability is a dynamic balance between supply and demand that can occur within a CWM framework as supply replenishment, reduction of temporal disparity between supply and demand, and/or demand management. This can occur through direct reuse (recycled and captured), MAR, Flood-MAR, ASR, imported water, and DeSal where possible and needed. Supply management can also indirectly support replenishment with alternative sources for some uses an by reducing temporal disparity between supply and demand for water.

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Solution Conceptual Exercise 10

CWM metrics are built fundamentally on a suite of indicators of water use and secondary effects of use and related thresholds that can be used as guides for decision makers across different time periods including annual (operational), multi-decadal (infrastructure and governance), and multi-century (governance and treaties).

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Solution Conceptual Exercise 11

An analysis can span a variety of levels from direct analysis of monitoring data relative to indicators and thresholds to hydrologic budgets and simulated response of indicators with integrated hydrologic models. Any type of CWM analysis should involve the elements of the system that include the supply components and related demand drivers within a supply-and-demand framework. One of the key benefits of developing a hydrologic model is that it requires the conceptualization and estimation of all significant water budget components.

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Solution Conceptual Exercise 12

An allocation model is a lumped-parameter model comprised of "buckets" and connecting arcs that represent the use and movement of the water, but does not simulate the physical processes of the use and movement of water.

An IHM simulates the processes and linkages between the use and movement of the water that govern use and movement of water throughout the hydrosphere, land system, and climate.

An optimization model is a model that can be used with either an allocation or IHM model to provide an optimal solution to a specified objective that is being either maximized or minimized. Like these other model types, optimization models can be static or transient and can have a static or dynamic objective. Dynamic objective models are commonly called Agent-Based models (ABM) and can have dynamic or multiple objectives for multiple entities within a resource supply-and-demand framework.

Return to Conceptual Exercise 12↥

Return to where text linked to Conceptual Exercise 12↥

Solution Conceptual Exercise 13

CWM can be structured through governance and treaties in either a top-down or bottom-up framework of monitoring, analysis, implementation, and regulation. Part of the framework also depends on how water is owned, how rights are administered, and what levels of informal and formal resource systems may occur within the affected regions of water use and movement.

Return to Conceptual Exercise 13↥

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Solution Conceptual Exercise 14

Monitoring and analysis require funding to cover the cost of operation and maintenance. This can be accomplished through treaties, governance, litigation, cooperative agreements, or some hybrid of these such as public-private partnerships. The funding can occur as taxes or incentives that are connected to the use and movement of the water. Similar to carbon or wetland credits, an offset structure can be developed to fund and mitigate deleterious overexploitation or deterioration of resources.

Return to Conceptual Exercise 14↥

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Solution Conceptual Exercise 15

No, not all numerical models can address CWM. Most simple models that only represent either surface water or groundwater flow do not include all the elements of the framework of supply-and-demand drivers that are needed to represent the complete equation of use and movement of water. While simple models may be useful for initial assessments or to assess very localized effects, they cannot provide the complete set of processes that drive the use and movement of water and related drivers such as land use, population, industry, and climate.

Return to Conceptual Exercise 15↥

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Solution Conceptual Exercise 16

The largest barrier to CWM is governance at an appropriate scale—which could be anything from local, to catchment, to regional scales—and should include all the actors that are participating in the use and movement of the water and land resources. Typically, this includes transboundary partners that may extend beyond just the aquifer or river system, and typically needs to include the entire watershed and—in some cases—sources such as exports from adjacent or nearby watersheds. Examples of this type of import include the Conejos-Medanos for Ciudad Juarez, Mexico, and Avra Valley for Tucson, Arizona, USA, and the Imperial Valley for San Diego, California, USA.

Governance also needs to be flexible and accountable to reduce the possibility for resolution outside the governing framework through litigation or hostile behavior. If data are not shared from monitoring networks, this can be an obstacle to cooperation within a CWM framework. All data and analysis must be publicly available so that all can see and assess the supply-and-demand framework and related indicators and thresholds of sustainability. Finally, the governing body and related institutions and stakeholders need to have funding mechanisms that can support the CWM components of monitoring, analysis, communication, and decision making.

Return to Conceptual Exercise 16↥

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Solution Conceptual Exercise 17

The biggest enhancements to integrated institutional and governance arrangements are to a) have flexibility to make modifications within the governing framework and b) maintain funding that can accommodate any needed adaptations or mitigation required for sustainable resources. One example of this approach is the US–Mexico Treaty of the Rivers 1945, which allows for the changes to the treaty called *minutes* that are agreed upon by a local pair of transboundary agencies from each country who have the authority from the treaty to make needed changes and do not require ratification of these changes at a higher level of government. Having governmental limits may also be necessary, as a total free market approach to resource development cannot be subject to business development that is driven by an unbounded “growth” development profit model that could easily exceed the amount of resources and their rate of replenishment.

Return to Conceptual Exercise 17⮥

Return to where text linked to Conceptual Exercise 17⮥

Solution Conceptual Exercise 18

Market- and finance-based mechanisms cannot promote unlimited development of finite resources nor exceed the rate of resource replenishment. The elements of any CWM—whether run privately, by government, or by a shared partnership—need to be economically viable within the market and financial framework. In particular, the financial framework of CWM has to at least cover the cost of operation and maintenance as well as the cost of additional infrastructure development, monitoring, and analysis.

Return to Conceptual Exercise 18⮥

Return to where text linked to Conceptual Exercise 18⮥

15.2 Answers to Follow-up Conceptual Questions

Answer to Follow-up Conceptual Question 1

d) All of the above, because examples of water *operations* include:

a) Installing gutters along the sides of paved streets.
b) Decision to release water from a dam.
c) Homeowner choosing to use a water filter.
d) All of the above.

Return to Follow-up Conceptual Question 1

Return to where text linked to Follow-up Conceptual Question 1

Answer to Follow-up Conceptual Question 2

Monitoring and analysis are important for the following reasons.

Water flows though the atmosphere, surface, and subsurface of the earth. The hydrologic cycle is affected by every change in the flows and the changes can have wide ranging impacts. Monitoring and analysis can be used to measure and understand the relationship between the changes and the impacts.

Use of water by one user can disrupt another user in ways that are difficult to discover.

Return to Follow-up Conceptual Question 2

Return to where text linked to Follow-up Conceptual Question 2

Answer to Follow-up Conceptual Question 3

The answer is (d) because all of the following are examples of water *governance*:

a) Voter campaign literature saying that gutters are needed along paved streets, and that the water needs to be routed so that it is treated before it is allowed to flow to a natural water body.
b) Federal requirements that water levels behind dams do not exceed given levels at different times of the year.
c) A news report about new water quality data in an area indicating high levels of lead in the water.
d) All of the above.

Return to Follow-up Conceptual Question 3

Return to where text linked to Follow-up Conceptual Question 3

15.3 Answers to Technical Questions

Answer to Technical Question 1

If the hydraulic properties of the riverbed and aquifer exhibit layering that causes vertical anisotropy, the impact of pumping on streamflow will be less and will likely be delayed. Similarly, if the river is ephemeral or intermittent, the effects on infiltration will be reduced and delayed. Also, if there is an unsaturated zone between the riverbed and the unconfined aquifer, this will reduce and delay the impact of pumping on streamflow. In contrast, if there are other multi-aquifer wells or if the pumping well is a multi-aquifer well, then wellbore flow could contribute to a reduced effect in the uppermost aquifer layers being pumped by the well. However, when the system reaches a steady condition, a shallow well close to a stream in most unconfined aquifer will have a 1:1 impact on streamflow.

Return to Technical Question 1⮥

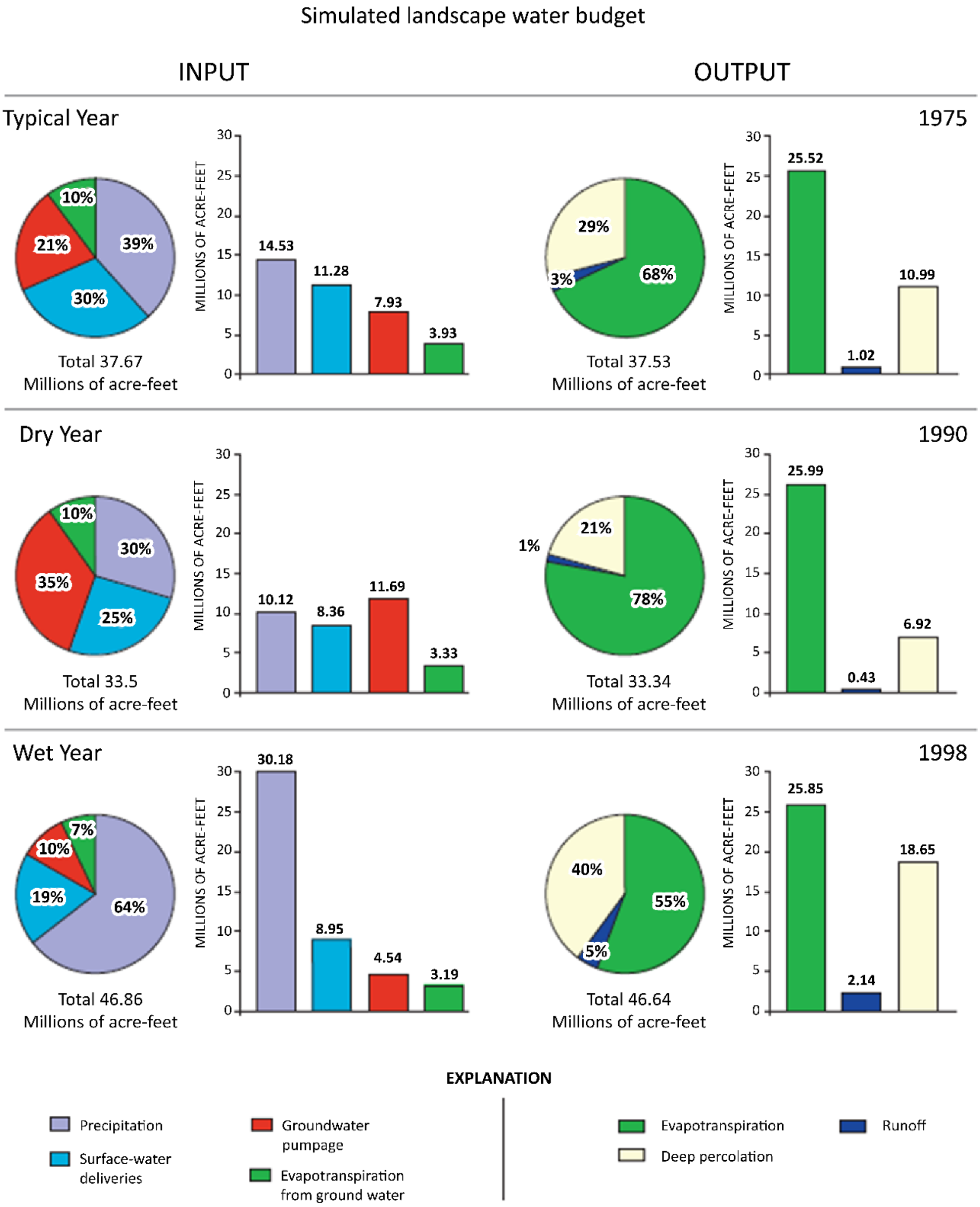
Return to where text linked to Technical Question 1⮥

Answer to Technical Question 2

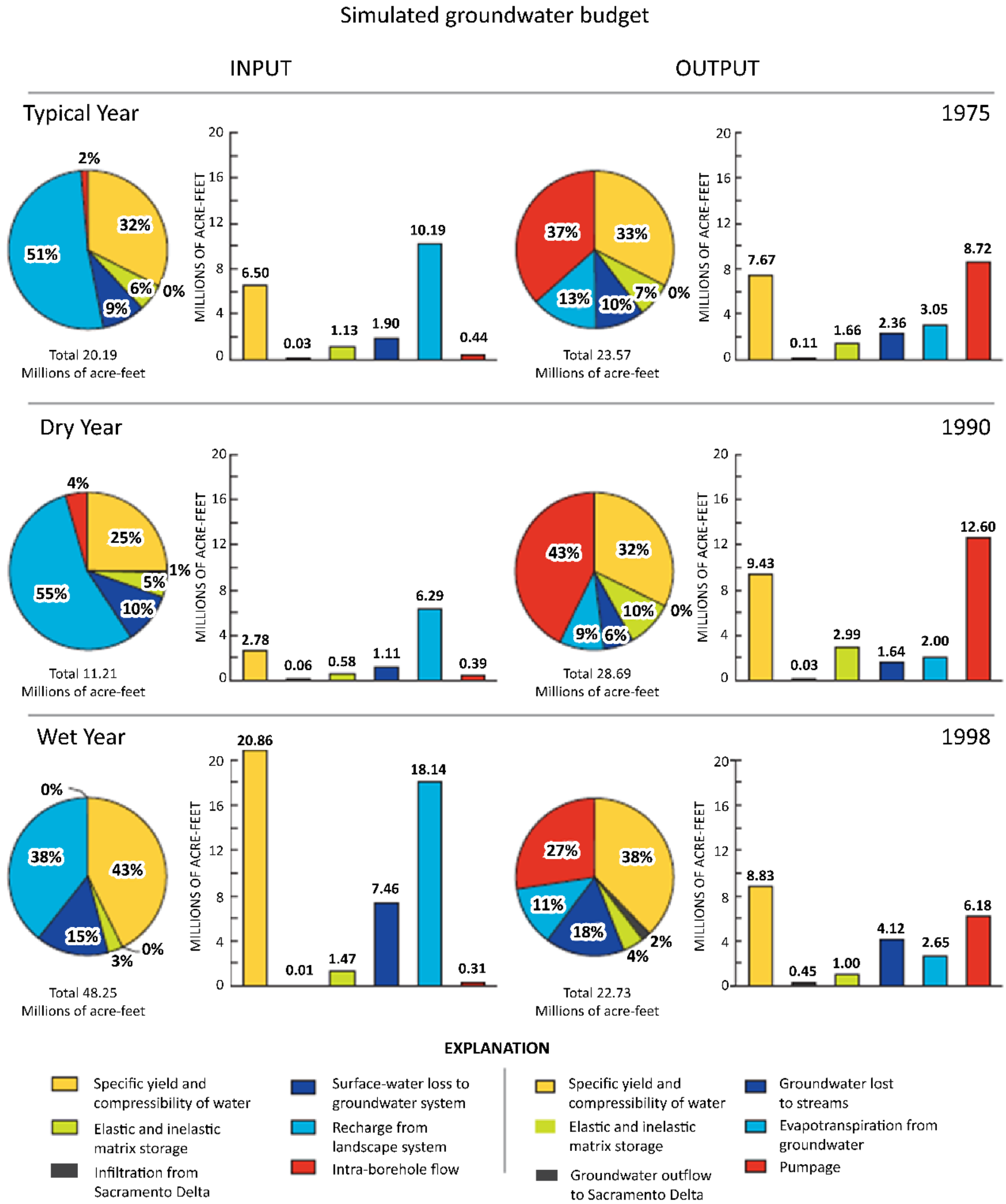
The amount of rainfall that returns to the atmosphere as evapotranspiration (ET) varies considerably both temporarily and spatially. However, in an average rainfall year it is commonly about 60 to 80 percent. Hence, evapotranspiration (ET) is the most important part of the hydrogeologic cycle and greater attention on ET is required. This is especially true for agricultural regions where ET is prolonged and enhanced through irrigation, which can result in more human-induced ET than natural ET and more human-induced recharge than natural recharge from inefficient irrigation.

One of the biggest misconceptions of hydrosphere analysis is that ET exceeds recharge and can be greatly affected by the spatial-scale, setting, structure, and time-scale dependent aspects of the inflow and outflow analysis. For example, for years it was generally accepted that there was little to no recharge in the Central Valley of California, USA based on annual estimates of precipitation along with estimates of actual and potential ET that yielded an annual deficit. However, when the inflow and outflow components are analyzed at smaller time periods, there are periods of considerable surplus precipitation (or other inflows such as deep percolation from inefficient irrigation as artificial recharge).

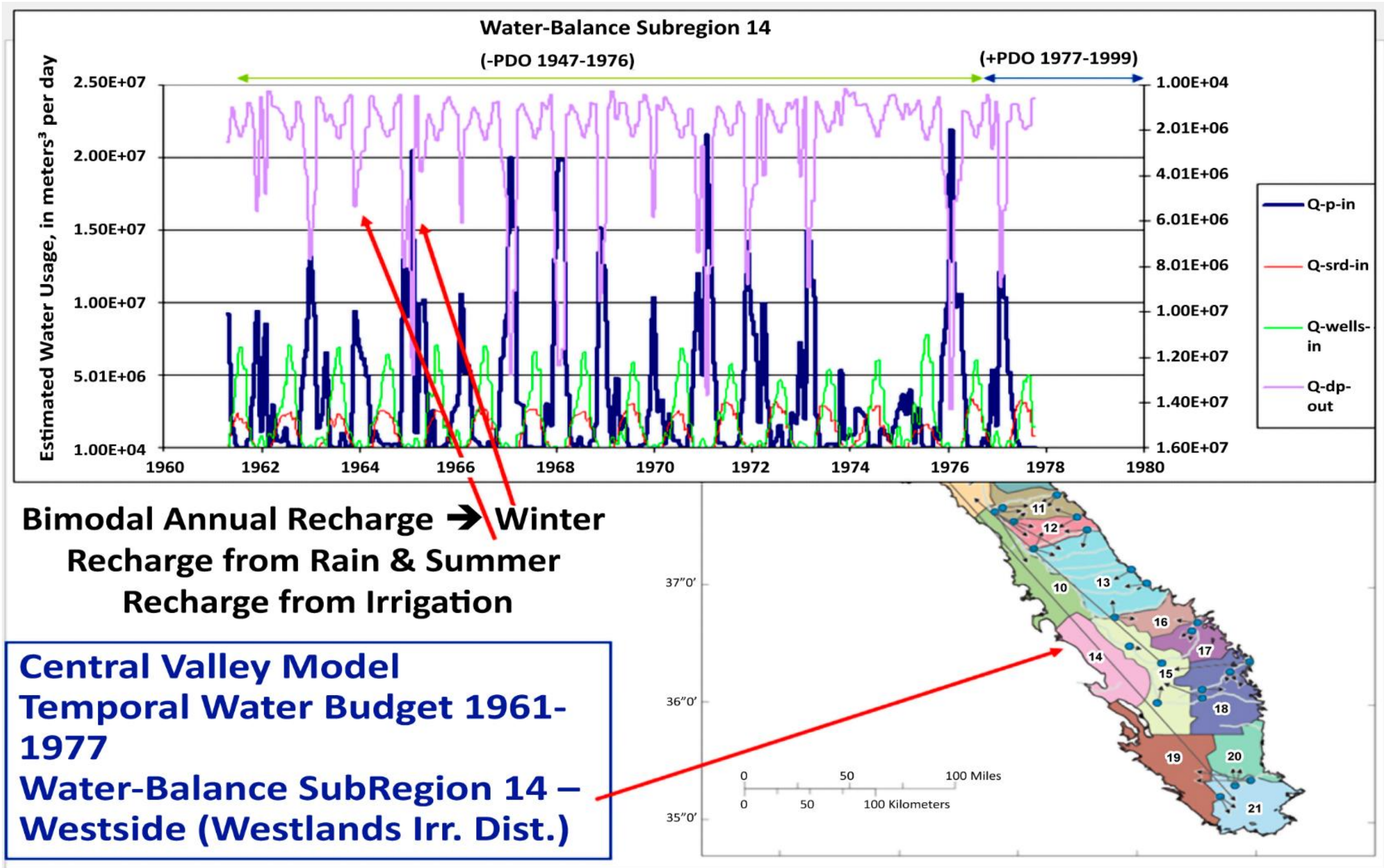
The simulated estimates for the landscape system and the groundwater system are presented in the images below. The estimates show a wide range of percentages of ET from the landscape surface and from groundwater for typical, wet, and dry years. The landscape budget indicates that 20 to 30 percent of the water entering the system becomes deep percolation. In years with typical precipitation and dry years, the simulated groundwater water budget indicates a large net loss from the groundwater system that, in combination, is roughly equal to the gain in wet years. The temporal distribution of recharge related to these changes in interannual climate variability, inter-seasonal ET, sources of applied water, and precipitation result in a bi-modal distribution of deep percolation that recharges groundwater due to variation of these inflows and outflows. Deep percolation from precipitation in the winter is substantially larger than deep percolation from irrigation return flows in the summer. Artificial recharge from inefficient irrigation is commonly a significant source of additional groundwater recharge in many agricultural settings.



Simulated distribution of landscape inflow and outflow budgets for typical (1975), wet (1998), and dry (1990) years for the Central Valley of California, USA (Faunt, 2009). In all types of water years (i.e., typical, dry, and wet), the simulated landscape water budget indicates 20 to 30 percent of the water becomes deep percolation. (1 acre-foot ≈1233.5 m^3)



Simulated distribution of groundwater inflow and outflow budgets for typical (1975), wet (1998), and dry (1990) years for the Central Valley of California, USA (Faunt, 2009). In typical and dry years, the simulated groundwater water budget indicates a large net loss from the groundwater system, which is in combination is equal to the gain in wet years. (1 acre-foot ≈1233.5 m^3)



Simulated landscape inflows and outflows showing bimodal annual recharge from the Central Valley of California hydrologic model (derived from Faunt, 2009). Deep percolation from precipitation in the winter is substantially larger than deep percolation from irrigation return flows in the summer. Q-p-in = precipitation inflow rate. Q-srd-in = surface water delivery inflow rate. Q-wells-in = inflow rate from groundwater pumpage. Q-dp-out = outflow rate to deep percolation.

Return to Technical Question 2↑

Return to where text linked to Technical Question 2↑

16 Abbreviations / Acronyms

ABM	=	Agent-Based Modeling is stochastic modeling that uses individual agents (e.g., people, things, places, and time) with assigned behavior and property attributes in a model to study their interactions and create emergent phenomena that help modelers understand how individual-level decisions and interactions lead to macroscopic outcomes
AI	=	Artificial Intelligence
AMA	=	Active Management Area
AMO	=	Atlantic Multidecadal Oscillation
ASR	=	Aquifer Storage and Recovery
BCM	=	Basin Characterization Model is a USGS Precipitation-Runoff/Recharge gridded model for the simulation of climate and related runoff and recharge
BMP	=	Best Management Plans
CA	=	California Assembly
CA-DWR		California Department of Water Resources
CASGEM	=	California Statewide Groundwater Elevation Monitoring
CDS	=	Coastal Distribution System used in Pajaro Valley California, USA, to distribute treated sewage effluent for irrigation
CCOC	=	A multiple-aquifer well monitoring site in the Santa Clara Valley, California, USA
CONAGUA	=	Mexico's National Water Commission, Mexico's water authority
CONUS	=	Technical term used by US federal administration to define the continental USA: the contiguous 48 states and the District of Columbia
CSIRO	=	Commonwealth Scientific and Industrial Research Organisation, the Australian government agency responsible for science research
CU	=	Conjunctive Use
CVHM	=	Central Valley Hydrologic Model
CVSALTS	=	A program to manage salt and nitrate in the California Central Valley, USA, a collaborative initiative among business, government, and community organizations to address nitrate and salt accumulation affecting water supplies
CWM	=	Conjunctive Water Management
DGI	=	A geoscience company that provides borehole geophysical, televiewer, hydrogeological, and directional survey data

DHI	=	Danish Hydrogeologic Institute
DIA	=	Combined Domestic, Industrial, and Agricultural water use demand on a mean annual basis
EC	=	Electrical Conductivity
EIS	=	Environmental Impact Statement
FAO	=	Food and Agriculture Organization
FEFLOW	=	Finite Element subsurface FLOW System, a groundwater modeling program
FMBI	=	Financial and Market-Based Instruments that include a range of financial and economic measures that can be used to encourage specific actions and trends related to water use
FMP	=	FarM Process, a module of MODFLOW that dynamically integrates supply-and-demand components of irrigated agriculture in the simulation of surface-water and ground-water flow
FREEWAT	=	FREE and open-source software tools for WATer resource management, the European Union’s software tool (GUI) for construction and simulation of hydrologic systems to help with management of conjunctive use of surface and groundwater
GCM	=	Global Climate Model also known as General Circulation Model
GDE	=	Groundwater Dependent Ecosystems
GRZ	=	Groundwater use Restriction Zones
GSA	=	Groundwater Sustainability Agency
GSFLOW	=	USGS Groundwater-Surface water FLOW model that simulates coupled groundwater–surface water flow and climate interactions
GSP	=	Groundwater Sustainability Plan
GUI	=	Graphical User Interface
GW	=	Groundwater
HGS	=	HydroGeoSphere, a 3-dimensional control-volume finite element integrated surface water and groundwater flow model
HMF	=	High-Magnitude Flows
HSPF	=	Hydrological Simulation Program-Fortran, an example of a passively-coupled model that uses a precipitation-runoff (watershed) model to provide recharge as lateral runoff and mountain block underflow from surrounding sub-watersheds that is computed first and then used as input to an IHM
IHM	=	Integrated Hydrological Model

ISARM	=	International Shared Aquifer Resources Management
IWFM	=	Integrated Water Flow Model is a finite-element surface water and groundwater flow model from the California Department of Water Resources
IWRM	=	Integrated Water Resource Management
MAR	=	Managed Aquifer Recharge
MF	=	MODFLOW, the family of US Geological Survey modular finite-difference flow models, which are a group of computer codes that solve and simulate surface water and groundwater flow
Napa	=	A county/valley in northern California, USA
NMFS	=	National Marine Fisheries Service
NRD	=	Natural Resource District
NSW	=	The state of New South Wales, Australia
O&M	=	Operation and Maintenance
OAS	=	Organization of American States
OWHM	=	The USGS MODFLOW model, "One-Water Hydrologic Flow Model" (MF-OWHM), that is an integrated hydrologic flow model of climate, land use, surface water, groundwater flow, and reservoir operation
PARFLOW	=	A fully integrated hydrologic model code; a three-dimensional finite element simulator of surface water and groundwater flow
PDO	=	Pacific Decadal Oscillation
PEST	=	A code used for inverse modeling that includes parameter estimation, sensitivity, and uncertainty analysis
PHAST	=	A computer program for simulating groundwater flow, solute transport, and multicomponent geochemical reactions using free-field empirical and Computational Fluid Dynamics (CFD) methods
PRMS	=	Precipitation Runoff Modeling System (a USGS code)
PVHM	=	Pajaro Valley Hydrologic Model, designed to reproduce the most important natural and human components of the hydrologic system and related climatic factors, permitting an accurate assessment of groundwater conditions and processes that can inform the new BMP, and help to improve planning for long-term sustainability of water resources using the USGS code MF-OWHM
PVWMA	=	Pajaro Valley Water Management Agency
RGP	=	Rio Grande Project

RGTIHM = Rio Grande Transboundary Integrated Hydrologic Model developed to simulate the surface water and groundwater flow of the Lower Rio Grande Transboundary region of New Mexico and Texas of the USA, and Chihuahua, Mexico

SAT = Sistemas de Acuíferos Transfronterizos (in English, a Transboundary Aquifer System)

SCADA = Supervisory Control and Data Acquisition (SCADA) systems, used to control, monitor, and analyze industrial devices and processes, and consisting of both software and hardware components that enable remote and on-site gathering of data from industrial equipment

SCVWD = Santa Clara Valley Water District, California, USA

SDF = Stream Depletion Factor

SFR = StreamFlow Routing Package used to simulate streamflow in MF models

SGMA = Sustainable Groundwater Management Act of California, USA

SW = Surface water

SWAT = Soil and Water Assessment Tool is a finite element model used to simulate climate, land use, and surface water flow

SWB = Soil Water Balance model used to simulate climate, land use, soil water flow, and consumption

SWO = Surface Water Operations is a process within MF-OWHM used to simulate reservoir operations linked to streamflow routing and land use for the USGS FM, FarM Process

UCODE = A computer code used for inverse modeling that includes parameter estimation, sensitivity, and uncertainty analysis

UN = United Nations

UNECE = United Nations Economic Commission for Europe

UNESCO = United Nations Educational, Scientific and Cultural Organization

USAID = US Agency for International Development

USBR = US Bureau of Reclamation

USGS = US Geological Survey

VIC = Variable Infiltration Capacity is a finite difference model used to simulate gridded precipitation-runoff

WBS = Water-Budget Subregions used as water budget accounting units within the USGS code MF-OWHM

WEAP	=	Water Evaluation And Planning model is a reservoir operations simulation model
WHO	=	World Health Organization
WWT	=	Water and Wastewater Treatment
WUA	=	Water Users' Association

17 About the Authors

Richard Evans is principal hydrogeologist with Jacobs. Rick has 40 years of experience in all aspects of water resource development with a focus on groundwater resource management. This experience has included groundwater resource assessment and development, groundwater policy and strategy development, studies on surface water–groundwater interaction, environmental assessments, mine impact, civil engineering projects, climate change, coal seam gas, groundwater-dependent ecosystems, and numerical analysis of groundwater flow systems. He wrote the National Groundwater Management Policy for the Australian Government, which has been adopted by all Australian states. He was awarded the CSIRO Chairmans Medal for his work on the Murray–Darling Basin Plan. He has written more than 80 technical papers and books.

Dr. Evans worked on numerous water resource projects throughout Australia and Asia, principally China. He has a strong interest in the potential for conjunctive water management and managed aquifer recharge to secure both urban and irrigation development throughout the world.

Randall Hanson was a lead USGS research hydrologist for more than 38 years. He led development of wellbore flow, hydrologic modeling, and climate analysis, as well as conjunctive-use water supply analysis projects of regional watersheds nationally and internationally. As part of UNESCO's ISARM-Americas team, he also developed guidelines for the management of transboundary aquifers for the Americas. In 2018, he started One-Water Hydrologic, returning to consulting to help users with the newest USGS version of MODFLOW: MODFLOW-OWHM (MF-OWHM). Randy helped lead, develop, and co-author the USGS MF-OWHM Version 2, *One-Water Hydrologic Flow Model: A MODFLOW Based Conjunctive-Use Simulation Software Techniques and Methods 6-A60* (One-Water). This innovative integrated hydrologic model code provides simulation and analysis of the impact of conjunctive water management on land, climate, and water resources to help assess food and water-security across the USA and internationally. He also led analysis of climate change/variability to facilitate sustainability and adaptation. To accomplish this, he used One-Water in conjunction with global climate models and the USGS HydroClimate Toolkit, for which he led development. Currently, he is involved in California's SGMA conjunctive-use modeling projects using One-Water as well as

CVSALTS2 in the Central Valley of California, transboundary water resources along the Mexico–US border, and analysis of sustainability and climate variability in Rio Conchos, Chihuahua, Mexico.

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