Ecosystem Changes and Water Policy Choices:

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Executive Summary

Feats of engineering and human ingenuity have made it possible for the Colorado River to irrigate 3.5 million acres of farmland and support 30 million people on arid lands throughout the western United States and northwestern Mexico. These agricultural and municipal benefits have been extremely valuable, but at the same time aquatic and riparian habitats below Glen Canyon and Hoover dams and in the Colorado River Delta have declined. These remnant ecosystems support a high concentration of biodiversity, wildlife habitat, fisheries, aesthetic and recreational amenities, and traditional cultures.

The Millennium Ecosystem Assessment (MA) provides a new framework for understanding the dynamics within this complex system that supports policy by clarifying links between ecosystems and human well-being and by exploring the impacts and tradeoffs associated with choices that remain available. While recognizing that biodiversity and ecosystems have intrinsic values, the MA focuses on human well-being, linking it to specific services that ecosystems provide. This case study aims to inform policy and management decisions in the Lower Colorado River Delta and Basin by demonstrating how past decisions reflected the values of their times and how changes in values can create significantly different choices for the future.

After reviewing the MA framework and its application to the Colorado River Basin, the environmental and social history of the Lower Colorado River, and the Law of the River—the body of law which governs the allocation of its waters—this study looks at the ecosystem services provided by the riparian areas of the Lower Basin and their valuation. It then examines the main drivers for change in the region—runaway urban population growth and climate change—and how these are putting pressure on water managers to find more water inside and outside the system.

While climate research projects a potential reduction in basinwide flows on the order of 6 to 45 percent by mid century, a large buffer of agricultural water practically guarantees that the Lower Basin states will not "run out of water" in the foreseeable future, as high water prices can overcome any existing constraints on water transfers to thirsty cities. Beyond these transfers, means of getting more water include augmentation projects, efficiency projects, and municipal and agricultural water conservation programs.

The study then shows how the drivers mentioned above and ongoing drought, while increasing the probability of shortages, have also increased the level of cooperation among the seven Basin States (Colorado, Utah, Wyoming, New Mexico, California, Arizona, and Nevada), which may result in a substantial increase in flexibility in the Law of the River, linked to the creation of system credits ("intentionally created surplus" water or "ICS"). ICS allows for the storage of water during surplus years for use in drought years and if the program could be extended opens the door to dedicating a portion of the stored water for environmental restoration, particularly in the water-deprived Delta. The study examines four possible scenarios for the Lower Colorado River Basin and the Delta and looks at the likely impact of these scenarios on ecosystems, their services, and human well-being to 2050. The scenarios include a climate change scenario ("Dry Future"); a market-based scenario ("The Market Rules") that places no limit on growth and the consumptive use of water resources, missing an opportunity to create environmental flows through market mechanisms; a managed-growth scenario that protects rural landscapes and restores riparian ecosystems as part of a comprehensive vision for the Lower Basin ("Powell's Prophecy"); and an ecosystem-based management scenario that sees the current challenges as an opportunity for increased bi-national cooperation and the restoration of key ecosystems in the Delta and Gulf of California with significant river flows ("A Delta and Estuary Once More").

These scenarios examine different possible futures, given a common past. The tremendous progress accomplished in the Colorado River Basin over the past eighty-five years has come at a great cost to riparian and coastal ecosystems and the human communities that depend on them, particularly in the Delta. However, the ongoing drought and the desire for increased water efficiency in the system are, paradoxically, creating an opening for action on both sides of the border that should not be wasted. The region and its people, if now included in the decision-making process, can create a future that balances human and environmental needs. Recent studies have shown that the Delta is crucial to the survival of several threatened and endangered species and a key stopover for migratory birds along the Pacific flyway. It is also crucial to the cultural survival of indigenous communities on both sides of the border, particularly the Cocopah tribe in the U.S. and their kin the Cucapá in Mexico. The importance of protecting the Delta is being acknowledged by water policymakers on both sides of the border, an unthinkable proposition only a few years ago; indeed, Minute 306 of the International Boundary and Water Commission implicitly recognizes the importance of protecting and restoring the Delta.

Preliminary research shows that relatively modest amounts of water could ensure the protection and restoration of key conservation priorities in the Delta and this could be accomplished at a fraction of the cost of the Lower Colorado's Multi-Species Conservation Program (MSCP). Freshwater flows into the Gulf of California could have the added benefit of revitalizing nurseries in the Upper Gulf of California, on which a highly productive fishing industry depends.

Innovative proposals, such as extending the ICS concept to Mexico, introduce the practical mechanisms onto which new legal and political arrangements can be built. The four scenarios presented shed light on the tradeoffs the Lower Basin is facing and the impacts these choices are likely to have on ecosystems and human well-being, including the people and the wildlife of the Delta.

In the highly regulated Colorado River system, the state of future landscapes is within our control. By dedicating base and pulse flows to the Delta, we can improve ecosystem and human health and resilience. The creation of a common vision for the Lower Basin that brings together key stakeholders from the United States and Mexico and recognizes the value of riparian ecosystems is imperative at this point—not just for the future of the Delta, but for the future well-being of all of the Lower Basin's inhabitants.

Chapter One

INTRODUCTION

1.1. Introduction

The Colorado River Delta, now reduced to approximately 8 percent of its original size, is a mosaic of terrestrial, freshwater, and marine habitats and diverse ecological processes that are sustained primarily by leaks in the plumbing of the Colorado River, from which most of the flow of freshwater is diverted at the U.S.-Mexico border. To the extent that freshwater does reach the Delta, these complex interactions in turn support lush vegetation found in the wetlands, riparian forests and green lagoons that cut through the vast Sonoran desert, and high concentrations of fish and wildlife, including species that migrate from distant places along the Pacific flyway. These habitats also require the regular flow of sediment, most of which is trapped behind the various upstream dams. As a result, the river bed and riparian habitats of the entire lower Colorado Basin have been significantly altered.

Like in other estuaries, these processes, called *ecosystem services*, support human well-being in numerous ways that have not been easily accounted for in previous policies and economic models. Unlike other estuaries in the United States, this bi-national Delta is given low-priority in both countries. In contrast, millions of dollars have been invested in restoration on the U.S. side of the border where, because of floodplain development, dam construction, channelization, and filling of reservoirs, there is very little habitat that can be restored.

Water policy has been primarily focused on ensuring the availability of water for agriculture and hydropower that accompanied the western expansion of the United States. However, when the seven Basin States apportioned among themselves the waters of the Colorado River in the fall of 1922, their total population was less than 6 million—including Nevada, with scantly more than 75,000 souls (Census 1920). The environmental ethic of the 1930s had yet to be born, as had the concept of ecosystem Coincidentally, just around that time, Aldo Leopold embarked on a three-week journey through the Colorado River Delta with his brother, recorded in his famous essay "Green Lagoons," that gives us a wonderful glimpse of the area's bounty before the age of the big dams (Leopold 1949).

Agriculture and hydropower were also the most tangible and dominant economic uses of the time. However, these policies are beginning to shift as agriculture, rapidly growing urban areas, and recreational users demand more in a region where we now know that long-term droughts are a normal occurrence. There is also a growing demand for water to support traditional ways of life and for instream flow necessary to support the provision of ecosystem services.

Placing a dollar value on the more direct and recognizable ecosystem services of providing water for consumptive uses is relatively easy. However, these *provisioning* services frequently come at the expense of water necessary to sustain ecosystem processes that are not valued directly by traditional methods, but that regulate and support the capacity of the ecosystem to provide the more direct benefits. For example, provision of good quality fresh water and food rely on the interaction of climate patterns with biophysical conditions as well as soil and land management practices, all of which play an important role in the flow regime—a term that refers to the combination of factors that regulate the patterns of flow of water and sediment, including periodic high flows and disturbance patterns that maintain the structure of river channels and nourish riparian wetlands. Flow regimes in turn support ecosystem productivity as well as biodiversity of habitats as well as species, which is disproportionately concentrated in aquatic ecosystems, wetlands, and riparian areas. By providing natural options, biodiversity also supports ecosystem resilience and the capacity to cope with periodic rapid changes. Alteration of natural flow regimes in river systems, through land-use changes and diversion of water for human uses, reduces that capacity and therefore, implies a trade-off between these different kinds of services. In addition, alteration of artificial flow regimes through water transfers, as found on the Colorado River, also presents difficult trade-offs.

These trade-offs tend to become more apparent as services become scarce and their future provision is threatened, which can also lead to a reconsideration of their inherent value. This often occurs in the context of extreme events such as Hurricane Katrina, which made the costs of coastal wetland restoration in the Mississippi Delta appear modest in retrospect. Katrina also made it impossible to continue to ignore the well-known benefits of wetlands to the national and global economy as well as to Louisiana, where wetlands protect port facilities that service all shipping in and out of the Mississippi river, oil and gas infrastructure in the Gulf of Mexico, and are the source of 20 percent of the U.S. fish supply (Gramling 2004).

Although unnamed, the Colorado River Basin is also contending with an extreme event—a "perfect storm" generated by a combination of long-term drought, climate change, and population growth. Like Katrina, it is having disproportionate impacts on poor and politically marginalized populations in rural and coastal areas. But unlike Katrina, it has unfolded over a longer period of time. Being mainly outside the United States, the Delta has until recently occupied a blind spot in the water policy arena. Flows of water and silt diminished progressively to practically nothing following completion of the Hoover, Morelos, and Glen Canyon dams (1935, 1950, and 1964). Even after the reservoirs were full, diversions still prevented water from reaching the Delta, which was reduced to a minimal size, estimated at 40,000 acres, until the abnormally wet El Niño years in the mid 1980s and 1990s, when rainfall exceeded reservoir storage capacities and instead replenished the wetlands and riparian habitats in the Delta. In response, these areas increased to 150,000 acres out of the original size of the Delta—approximately 1,930,000 acres (Fradkin 1996; Luecke et al. 1999). The subsequent "explosion of vegetation, wildlife and fisheries" came as a surprise even to experts, and demonstrated the extraordinary resilience of the Delta, if provided with water (Glennon and Culp 2002).

In its diminished state, the Delta continues to exist in Mexico today primarily because of leaks and other inefficiencies in the water delivery system, which have enabled modest restoration efforts undertaken by the Sonoran Institute in partnership with Pronatura and local communities. Plugging these leaks, along with water augmentation projects, are being proposed as key strategies for stretching existing supplies as the population in the southwestern United States continues to grow rapidly and regularly occurring droughts are exacerbated by climate change.

If implemented, these strategies for increasing the water supply in the western United States would only delay the inevitable need to reallocate existing supplies of water, and the opportunity to dedicate water for the Delta could be lost. Whether the turn is for the better or worse, and whether the Delta in 2050 is a better place, all depends on choices made or not made today, and whether management of the Colorado Basin is adjusted to accommodate multiple and often conflicting values and policy objectives. A certain amount of climate change is now inevitable, but our choices in terms of land use, population growth, infrastructure development, and out-of-basin water transfers are our own and will determine the fate of the Lower Basin and the Delta.

Drawing on the conceptual framework of the Millennium Ecosystem Assessment (MA), and the existing base of scientific and other knowledge regarding the Colorado River Basin, this report aims to inform public deliberations about water and growth management, ensure that the Delta is considered in upcoming water policy decisions, and makes a case for allocating at least a modest but permanent flow of water, sufficient to ensure its future. The MA essentially provides a new framework for science that can better support policy by clarifying links between ecosystems and human well-being, and by exploring the consequences and tradeoffs associated with choices that remain available. It begins by presenting an overview of changes occurring in the Basin, the forces driving them, and response options, all of which provide the basis for the four scenarios of the Lower Basin in 2050. These scenarios contrast four different storylines that highlight some of the choices that remain available for responding to the current predicament. These choices depend on the extent to which driving forces can be altered through human behavior, as well as on values and visions of the future that might guide restoration efforts. The scenarios also explore the expected consequences of the alternative courses of action that they present, trade-offs these imply among the various kinds of ecosystem services and among the interests of various stakeholders who benefit from them, and also identify areas of uncertainty.

However, what options stakeholders have for coping with change, whether change is slow or rapid, and what resources will actually be available when necessary, may only become apparent as events unfold, as lessons are learned—the hard way. By making use of the MA framework to identify lessons being learned, this report aims not only to inform decisions in the Colorado River Basin, but also to further development of the approach used in the MA. Through the development of more detailed and site-specific scenarios, it can also serve to frame relevant questions for policy-oriented research and highlight further information needs. This can be expected to improve the operational usefulness of the MA as a tool for ongoing assessment that can enable proactive responses to rapidly changing conditions, and that is a critical component of adaptive management.

1.2. Science, Policy, and the Colorado River Delta

In the Colorado River Basin, throughout recent history, there has been no shortage of scientific information and public awareness of water limitations on development. These limitations have been common knowledge since Powell submitted his Report on the Lands of the Arid Region of the United States in 1879, which presented a rational vision for the development of a region where, according to a survey he conducted, average rainfall was well below the minimum needed for agriculture to be a viable enterprise (Powell 1962). Policy concerns through much of the twentieth century were to develop the western United States through agriculture and to provide water and power for its people (Stegner 1954). These priorities were made evident in the Colorado River

Compact of 1922, the foundation of the Law of the River.

The Law of the River made the desert bloom, but this development has ignored many of the costs, and excluded those most affected from participation in policy decisions. However, the water needs of the Delta represent only a fraction of the total flow of the river, which could have easily met the needs of both the Delta and development plans in which regional water limits are a given. Originally driven by a vision of manifest destiny, this expansion was also based on observations made during the two wettest periods in the last five hundred years. Followed by a period of drought, settlement was made possible by optimistic assumptions that rates of water flow would remain stable, as well as by tremendous but shortsighted feats of human ingenuity applied to the damming and diversion of the river and its tributaries. Through additional scientific information, it is now known that long-term drought is a regular occurrence (Woodhouse et al. 2006), and that water availability is limited not only by rainfall but also by evaporation rates, which are expected to increase as global warming progresses (Hoerling and Eischeid 2007). According to the most recent IPCC report (2007), the 2000 to 2003 drought conditions may become the new average because of increased evaporation rates associated with 1.4 C° warming.

Less appreciated is the role of sediment flows—for which the dams became a trap—and the multiple benefits provided by the Colorado River Delta, which relies on flows of both water and sediment (Adler 2007). Not considered to be either land or water, freshwater or marine, the Delta, along with most other estuaries, has occupied a blind spot, in which watersheds and coastal areas are part of separate domains, as are human communities and economic systems. Unlike the Chesapeake and San Francisco bays, the Florida Everglades, or the Mississippi Delta, the Colorado River Delta is binational and of environmental concern to both the United States and Mexico.

In Powell's proposed plan, free flowing water not captured in reservoirs was regarded as "waste water" so, even had it been followed, little if any water would have flowed across the U.S.-Mexico border to sustain the wetlands and green lagoons of the Colorado River Delta. However, an additional legacy of Powell's plan was that, as the second director of the USGS, he also led and won a battle to reorganize the conduct of scientific research within the federal government, establishing its role as a sponsor of science for public welfare (Stegner 1954; Limerick and Puska 2003; Worster 2001). This has led to a growing base of scientific knowledge, comprehensively reviewed in the MA, and to an increased public appreciation of the critical role that river systems play in supporting the multiple facets of human well-being, only one of which is the provision of clean fresh water for various human uses.

The massive diversion and damming of water for human uses, which also prevents the flow of sediment, has been at the expense of the capacity of the Colorado River ecosystem to continue to provide not only clean freshwater, but many other economically significant benefits—or *ecosystem services*, which are regulated and supported by regular flows of both water and sediment.

These flows are necessary to support and maintain aquatic and riparian habitats throughout the river system, the once extensive green lagoons and wetlands in the Colorado River Delta, found in the middle of the vast Sonoran desert, and the high productivity in the Sea of Cortez. These areas contain a disproportionate concentration of biodiversity and once supported large commercial and sport fisheries, extensive populations of both terrestrial and marine wildlife, numerous species endemic to the Basin, and ways of life and livelihoods of local and indigenous communities on both sides of the border. They also support growing recreational uses, aesthetic values, and lifestyles desired by those who remember four-foot totoaba fish as well as those who are migrating into the region. As a vital link in the Pacific flyway, the Delta is a crucial nesting and feeding area for more than 360 species of migratory and resident bird species, including the bald eagle and the largest known population of the endangered Yuma clapper rail. More than 350,000 shorebirds, representing over 50 percent of all bird species in North America, use the Delta annually for shelter and feeding (Hinojosa-Huerta 2006).

Although costs and benefits of these services are poorly quantified, we do know that restoration of the Delta would provide great benefit at a lower cost than efforts in the Lower Colorado River in the United States, such as the Bill Williams National Wildlife Refuge and the Verde Valley. In the United States, given the level of floodplain development, agricultural uses, and areas inundated by reservoirs, there is much less habitat that can be restored cost effectively (Adler 2007).

1.3. The Millennium Ecosystem Assessment Framework

As ecosystem values are reconsidered, not only in the Colorado River Basin, policymakers have increasingly called upon scientists to better demonstrate the economic significance of links between ecosystems and human well-being, or *ecosystem services*, which was the subject of a comprehensive review by the Millennium Ecosystem Assessment (MA 2005). These services consist of benefits that ecosystems provide for people, in various forms of direct and indirect benefits, providing that they are economically significant, and that users actually have access to them.

Human well-being is defined to include: the abilities to earn a livelihood, to maintain health and good social relations, and to be secure. However, underlying all of these aspects of well-being is a more basic one, to have freedom of choice and action as to how these different kinds of needs are met (Sen 1999). In the framework developed by the MA (2003) (see Figure 1.1), these choices are both enabled and constrained by ecosystem conditions, and the extent to which drivers of change can be altered through human behavior. Among these drivers are the human institutions or rules of the game through which humans respond to these conditions and that govern the allocation and use of natural resources. The choice of responses in turn requires scientific and socioeconomic information about trade-offs that are being made, to support stakeholder negotiations regarding what is acceptable and conflict resolution among the winners and losers.

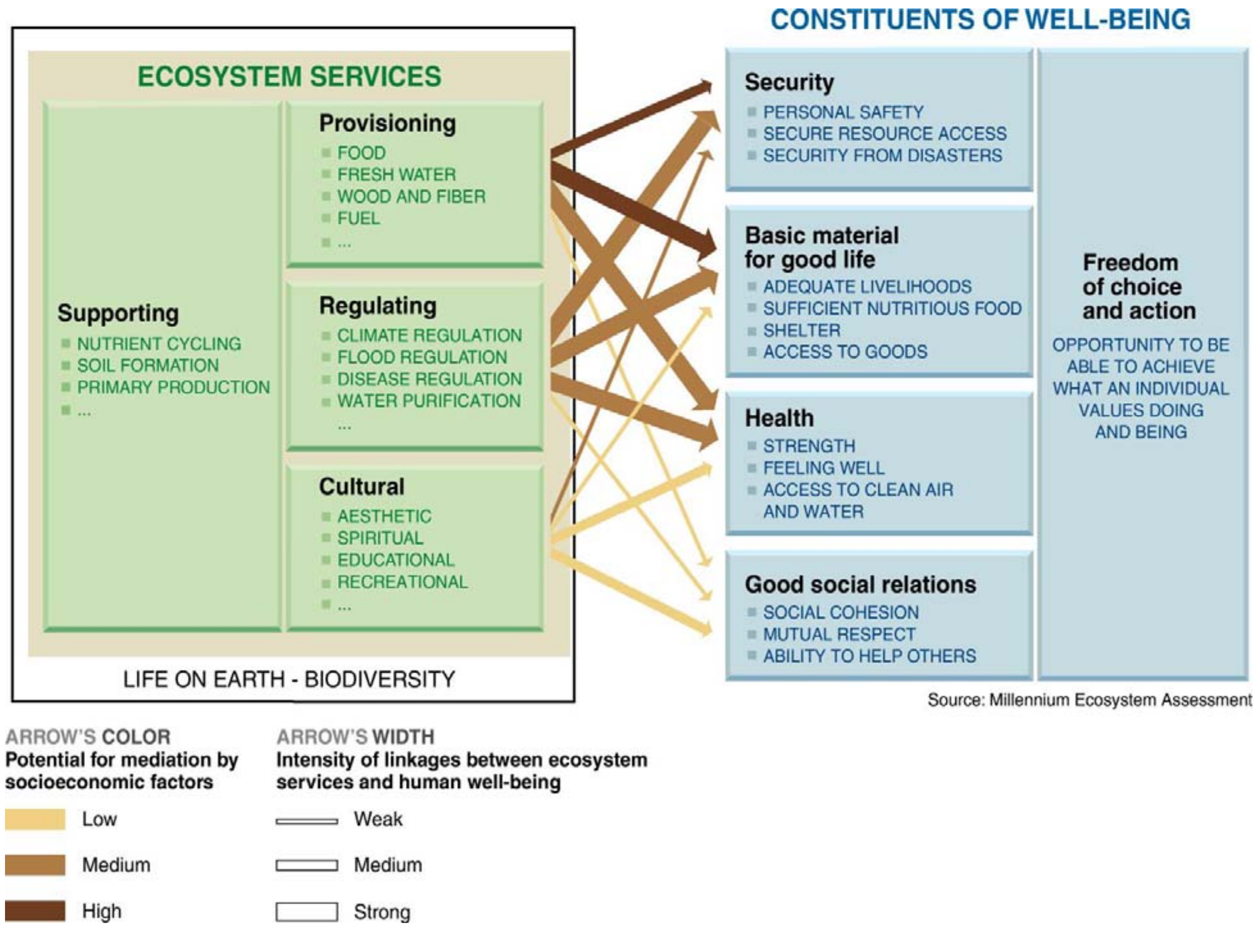


Figure 1. Relationship between ecosystem services and human well-being (MA 2003).

The MA engaged more than 1,300 scientists from all over the world who, in addition to documenting conditions and trends, identified and evaluated policy response options and developed four scenarios of 2050, scenarios that explore the consequences of different courses of action and thereby highlight key choices. The framework was also used to conduct a series of subglobal regional assessments. This comprehensive compilation of relevant and available information was published in a series of technical reports produced by The Millennium Ecosystem Assessment (MA 2005a, 2005b, 2005c, 2005d) as well as several synthesis reports related to subtopics of special interest.

In subsequent applied research efforts carried out by the CGIAR ASB Partnership for Tropical Forest Margins (2007), based on the MA framework, it was found that, at local scales, the development of scenarios can serve as a concrete planning tool (Tomich and Velarde, personal communication). This project also aims to contribute to the further development of the MA framework by exploring policy options and responses as they occur in the context of unfolding events in the Colorado River Basin.

In the review of freshwater policy responses by the MA, case studies suggest that the more effective kinds of arrangements for river basin management are those that have evolved in response to site-specific conditions and extreme events, which raise awareness of impacts and provide an opportunity to open or broaden debates about changes in policy (Aylward et al. 2005). This is a process that is well underway in the Colorado River Basin, to which the scenarios developed in this report only provide input. Actual outcomes may be very different as they are influenced by unforeseeable details of future events and complex interactions among all of the relevant factors — particularly human decisions. To the extent that these scenarios become part of policy dialogues regarding specific changes in water policy, future outcomes will become an important source of feedback that can be expected to improve the usefulness of the MA framework as a tool for building the capacity for proactive responses to rapidly changing conditions.

The various types of ecosystem services can be distinguished as provisioning, regulatory, cultural, and supporting, as outlined in the examples of freshwater ecosystem services in Box 1

Box 1. Types of ecosystem services

- Provision of freshwater for consumptive and nonconsumptive uses (drinking, domestic, agricultural, and industrial uses as well as to support the generation of hydropower).
- Regulation and filtration of flows of water and sediment, which control mean surface runoff, provide a buffer against peak or flood flows, and base or dry season flow and drought conditions, control erosion and sediment load, recharge groundwater and soil moisture, and are essential for maintaining water quality as well as diversity of habitats in riparian, freshwater, estuarine, and marine areas.
- Cultural services or support for recreation, tourism, aesthetic values, indigenous ceremonial uses, and livelihoods as well as ways of life that depend on the natural resources of the Delta.
- Supporting services or maintenance of natural flow and disturbance regimes that drive ecosystem processes such as nutrient cycling and primary production, which in turn support high concentrations of biodiversity and increase the capacity of the system to cope with changing conditions, i.e., its resilience and capacity to provide other kinds of services.

The above list only represents the kinds of benefits that watersheds may provide. However, these cannot be considered “services” unless they also have economic significance. Therefore, site-specific assessments are necessary to identify benefits that are provided in a specific context, and the scale at which they can be detected. This then provides a basis for identifying the economic significance to various stakeholders and for choosing responses, that is, actions required to ensure that benefits continue to be provided, and the levels of compensation needed to cover the costs of these actions and thereby create an economic incentive to implement them.

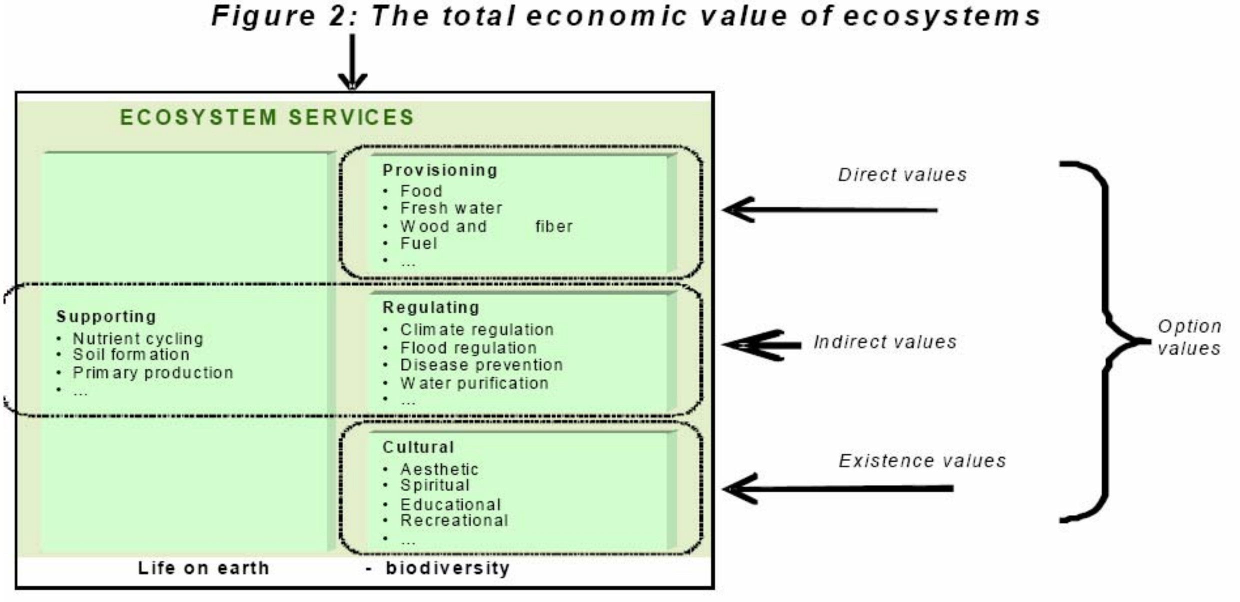
The various kinds of services are also interdependent, in that there is a trade-off not only between different uses, but also between the different types of services, as well as between benefits and costs in the present and future, and between onsite and offsite or upstream and downstream. As the supply of any of these services becomes more limiting, human well-being will increasingly depend on achieving an acceptable balance between these trade-offs (Aylward et al. 2005). Finding this balance is the responsibility of both the United States and Mexico, whose mutual border the Delta straddles.

Typically only provisioning services and, to a lesser extent, water-based recreation and tourism are considered when determining how to allocate water supplies because these have more tangible economic values that are also reflected in existing markets. Economists (Pearce 1993) typically break economic value down into:

- Direct use values, both consumptive (e.g., agricultural and municipal) nonconsumptive (e.g., recreational) uses. These broadly correspond to the MA notion of provisioning and cultural services.
- Indirect use values (e.g., water filtration function of wetlands). These benefits correspond to the MA notion of regulating and supporting services.
- Option values. Provisioning, regulating, and cultural services may all form part of option value to the extent that they are not used now but may be used in the future.
- Non-use values or existence values, the value people place on a resource even if they never use that resource (e.g., the existence value of the vaquita porpoise).

Supporting services are typically valued indirectly, through their role in enabling the ecosystem to provide provisioning, regulating, and supporting services. Valuation becomes increasingly difficult as one moves from direct use to indirect use to option to existence values (MA, 2005). Figure 2 illustrates the relationship between different kinds of ecosystem services and different kinds of values.

Figure 2: The total economic value of ecosystems



Source: Iftikar et al. (2007).

Direct drivers of ecosystem degradation include the construction of dams, excessive withdrawal of water for human uses, land-use change, species introduction, and climate change. These are difficult to change without addressing the indirect drivers, which include patterns of economic growth and development, the need to supply basic needs to expanding populations, economic incentives, and inadequacy of governance and institutional arrangements associated with the use of use of natural resources, that is, the "rules of the game," both formal and informal.

Responses to degradation are rarely separate and discrete. For example, market-based approaches are unlikely to work in the absence of defined property rights and confidence that contractual agreements will be enforced. Water markets may also rely on the establishment of policies that define the amount of water to be allocated for instream flow, and on regulatory caps. In the western United States, these may also depend on outcomes of litigation and the resolution of conflict between various water users affected by the sale of upstream water rights. Therefore, responses ideally consist of complementary and mutually reinforcing initiatives that support a comprehensive and integrated plan. Key underlying challenges are to change the rules of the game and to bridge the gap between policies and plans on paper and how they are implemented in practice.

Conversely, problems in water management tend to reflect more general weaknesses in governance and provide a point of departure for broader policy reforms that will be necessary to build an economy in which ecosystem services are valued. A good example of this is the European Water Framework Directive (WFD), which requires agriculture, transport, energy development, fisheries, and marine policies to be consistent with water policy objectives. Efforts to achieve consistency with the WFD is also intertwined with the development of democratic institutions in the Eastern European countries in the Danube Basin, where basinwide cooperation only became possible with the end of the Cold War, and where lack of capacity to respond to environmental concerns, including water diversions and pollution, contributed to the loss of legitimacy of the former regime (Murphy 1997).

In a chapter on policy response options for the degradation of freshwater services, the MA reviewed different kinds of responses to identify lessons from past experience, and conditions by which they are enabled or constrained. These response categories are listed in Table 1.1.

Table 1.1. Freshwater response options for optimizing human well-being from freshwater and associated inland water ecosystems (Aylward et al. 2005).

Governance	Supply Management	Demand Management
Defining ecosystem water requirements Property rights Participation River basin organizations and transboundary management Regulatory	Economic incentives for reallocation and new supply • Partnerships and financing • Water markets • Cap and trade systems • Payments for watershed services Infrastructure • Large dams • Levees • Locks and canals Technologies • Wetland restoration • Agricultural water conservation • Desalinization • Rainwater harvesting	Economic incentives for consumers • Water pricing • Payments and subsidies for on-farm and household water conservation Water conservation technologies • On-farm water efficiency and management improvements • Municipal and industrial water measurement and savings devices

The scenarios developed in this report present various combinations of these response options in the context of existing constraints and enabling conditions. Key challenges for ensuring water supply for water users in the Basin, for restoration of the

Lower Colorado Basin and the Delta will be those of governance—first and foremost, to reach policy agreement as to the amount of water to be allocated to the ecosystem, as new values emerge. Given conflicting values among stakeholders, reallocation of water is a contested process that involves the renegotiation of rights and responsibilities consistent with the growing value placed on the ecosystem services that it provides. Ultimately it will require inclusion of the Delta in basinwide transboundary management strategies, and effective participation of those affected. These kinds of institutional responses in turn provide a foundation for the use of economic instruments to create appropriate incentives for water conservation and to finance the adoption of technologies either for conservation or augmentation of the water supply (Aylward et al. 2005).

The choice of response options ultimately comes down to finding feasible and equitable ways to cover their costs, which will include the costs of change and uncertainty. Willingness of stakeholders to pay for services, whether as individual users, as taxpayers or as donors to nonprofit organizations, is inextricably linked to confidence in the effectiveness of management actions, which include the institutional arrangements needed to ensure equity and access to benefits by those who pay their costs. Absent such arrangements, economic value is no more than hypothetical, as there would be no incentive to pay or to take actions needed to ensure provision of the service (Tognetti 2005).

Information needed to support negotiation and decision-making is that which demonstrates the trade-offs between the various kinds of benefits that ecosystems provide for specific stakeholders, whether they are local farmers who rely on water for crops, recreational or commercial fishers, or donors with global interests in biodiversity. These trade-offs are difficult to quantify at best. In complex systems, information is never complete and, absent a crystal ball, uncertainty is inherent. Effective participation of stakeholders, including those that use, but may not have rights to water, is essential, because they bring critical information to the decision process about context, and the distribution of costs and benefits. It also provides an opportunity for deliberation and learning that are essential components of an adaptive approach to environmental management. Key obstacles to effective participation of stakeholders in decision-making have been the association of large water resource infrastructure with the need for highly centralized management authority.

A place-based approach to assessment is ideal for determining whether particular ecosystem benefits have economic significance as these depend on their specific location or context, and on the complex interaction among land-use practices, climatic, and other environmental factors, and the scale at which they can be detected (Cutter 1996). For example, higher amounts of water infiltration into the soil, normally found in forested areas, may be entirely evapotranspired by vegetation unless the water table is beyond reach of its roots. Actual infiltration will depend more on the extent of ground cover and soil compaction associated with prior land-use practices than on the presence or absence of trees. However, forest and water relationships only tend to be significant at very small scales. Impacts that are significant and detectable at basinwide scales are pollution, water diversions, and water infrastructure development, enabling large-scale changes in land use, that is, agriculture and urbanization (Bruijnzeel 2004; Calder 1999; FAO 2000). Therefore, allocation of water for the Delta requires consideration of trade-offs in the entire Basin.

Although the MA has provided a framework for research and synthesis of scientific information, and also a massive review of existing information regarding links between ecosystems and human well-being, it was constrained by the lack of the kind of context-specific information needed to demonstrate the economic significance of these links for specific stakeholders, that is, to support a place-based approach to assessment. This presents an institutional challenge to the practice of science itself. Traditionally, the goal of science has been to identify universal principles, and then determine the kinds of situations to which they can be applied. Although generalizations may be found, by focusing instead on interactions among all of the factors relevant to a particular place, in their historical and geographical context at different scales, a place-based approach instead highlights and provides a better understanding of diversity, and of what makes places unique. By gathering information in context, it is integrated to begin with and within a frame of reference defined by stakeholders, rather than in a compartmentalized disciplinary framework. This makes it possible to ask the right questions and "get the right science," which is a prerequisite to "getting the science right." By engaging stakeholders and by contrasting local and scientific knowledge, it can also provide a foundation for social learning and common understanding that is a prerequisite for cooperation and for effective responses (Tognetti 2005). In other words, the challenge now is to build on the MA by using the framework in the context of threats to real people and places, to inform specific decisions. In the next chapter, we begin with a review of the historical and geographical context of water allocation in the Colorado Basin.

1.4. References

Adler, R. 2007. *Restoring Colorado River Ecosystems: A Troubled Sense of Immensity*. Washington D.C.: Island Press.

ASB Partnership for Tropical Forest Margins. 2007. ASB Scenarios Project Web site: www.asb.cgiar.org/ma/scenarios/.

Aylward, B., J. Bandyopadhyay, J. C. Belausteguigotia, P. Borkey, A. Z. Cassar, L. Meadors, L. Saade, M. Siebentritt, R. Stein, S. Tognetti, C. Tortajada, with contributions from: M. Acreman, T. Allan, C. J. Bauer, C. Bruch, A. G. Pereira, M. Kendall, B. Kiersch, C. Landry, E. Mestre, J. King, R. S. Meinzen-Dick, S. Moellendorf, S. Pagiola, I. T. Porras, B. Ratner, A. Shea, B. M. Swallow, T. Thomich, and N. Voutchkov. In press. *Millennium Ecosystem Assessment Report: Policy Responses* (Chopra, K. and Leemans, R., eds.). Washington, D.C.: Island Press.

Bruijnzeel, L. A. 2004. "Hydrological functions of tropical forests: not seeing the soil for the trees?" *Agriculture Ecosystems and Environment* 104(1):185–228.

Calder, I. R. 1999. *The Blue Revolution: Land Use and Integrated Water Resources Management*. London: Earthscan.

Colorado River Compact of 1922, 4 Stat. 1057.

Cutter, S. L. 1996. "Vulnerability to Environmental Hazards." *Progress in Human Geography* 20(4):529–539.

Evans K. S. J. Velarde, R. Prieto, S. N. Rao, S. Sertzen, K. Dávila, P. Cronkleton, and W. de Jong, W. 2006. *Field guide to the Future: Four Ways for Communities to Think Ahead*. Bennett E. and Zurek M., eds. Nairobi: Center for International Forestry Research (CIFOR), ASB, World Agroforestry Centre, 87.

FAO. 2000. Land-Water Linkages in Rural Watersheds. FAO Electronic Workshop, FAO.

Fradkin, P.L. 1996. *A River No More: The Colorado River and the West*, expanded and updated ed. Berkeley: University of California Press.

Glennon, R. and P. Culp. 2002. "The Last Green Lagoon: How and Why the Bush Administration Should Save the Colorado River Delta." *Ecology Law Quarterly* 28, no. 902, 3.

Gramling, R. 2004. A Working Coast: People in the Louisiana Wetlands. *Journal of Coastal Research, Special Issue 44, Saving America's Wetland: Strategies for Restoration of Louisiana's Coastal Wetlands and Barrier Islands*. Royal Palm Beach, FL.

Hinojosa-Huerta, Osvel M. 2006. "Birds, Water and Salt Cedar: Strategies for Riparian Restoration in the Colorado River Delta." Tucson, AZ, The University of Arizona, Doctoral Dissertation.

Hoerling M. and J. Eischeid. 2007. "Past Peak Water in the Southwest." *Southwest Hydrology* 6(1):18–19, 35.

Iftikar, U., M. Kallesoe, et al. 2007. *Exploring the interlinkages among and between Compensation and Rewards for Ecosystem Services (CRES) and human well-being*. Nairobi: World Agroforestry Centre.

Leopold, A. 1949. *A Sand County Almanac and Sketches Here and There*. New York: Oxford University Press.

Limerick, P. N. and C. Puska. 2003. *Making the Most of Science in the American West: An Experiment*. Boulder: Center for the American West, University of Colorado at Boulder, 31.

Luecke, D., J. Pitt, et al. 1999. *A Delta Once More: Restoring Riparian and Wetland Habitat in the Colorado River Delta*. Washington D.C.: Environmental Defense Fund, 64.

Millennium Ecosystem Assessment (MA). 2003. *Ecosystems and Human Well-being: A Framework for Assessment*. Washington D.C.: Island Press.

Millennium Ecosystem Assessment (MA). 2005. *Ecosystems and Human Well-being: Current State and Trends, Vol. 1*. Washington D.C.: Island Press.

Millennium Ecosystem Assessment (MA). 2005. *Ecosystems and Human Well-being: Policy Responses, Vol. 3*. Washington D.C.: Island Press.

Millennium Ecosystem Assessment (MA). 2005. *Ecosystems and Human Well-being: Scenarios, Vol. 2*. Washington D.C.: Island Press.

Millennium Ecosystem Assessment (MA). 2005. *Ecosystems and Human Well-being: Multiscale Assessments, Vol. 4*. Washington D.C.: Island Press.

Murphy, I. L. 1997. The Danube: A River Basin in Transition. Boston: Kluwer Academic Publishers.

National Research Council. 2007. *Progress Towards Restoring the Everglades: The First Biennial Review 2006*. Washington D.C.: National Academies Press.

Pearce, D. W. 1993. *Economic Values and the Natural World*. London: Earthscan.

Pitt, J. et al. 2000. "Two Nations, One River: Managing Ecosystem Conservation in the Colorado River Delta." *Natural Resources Journal* 40 (4):819–827.

Pitt, J. 2006. "Transboundary Freshwater Ecosystem Restoration: The Role of Law, Process and Lawyers: Dredging for Diplomacy? Colorado River Management at the United States-Mexico Border." University of Pacific, McGeorge Global Business and Development vol. 19 no. 47.

Powell, J. W. 1962. *Report on the Lands of the Arid Region of the United States* (Wallace Stegner, ed.). Cambridge, MA: Harvard University Press, 56.

Sen, A. K. 1999. *Development as Freedom*. New York: Anchor Books.

Stegner, W. 1954. *Beyond the Hundredth Meridian*. New York: Penguin Books, 438.

Tognetti, S. S., G. Mendoza, D. Southgate, B. Aylward, and L. Garcia. 2003 . "Assessing the effectiveness of Payment Arrangements for Watershed Ecosystem Services." In *Proceedings of the Regional Forum on Payments for Environmental Services*, held at the Third Latin American Congress on Watershed Management, Arequipa, Perú, June 9–12, 2003.

Tognetti, S. S., B. Aylward, and G. Mendoza. 2005. "Markets for Watershed Services." In *Encyclopedia of Hydrological Sciences* (Anderson M., ed.). New York: John Wiley & Sons, Ltd.
U.S. Census Bureau. 1920. "Census of Population and Housing 1920," accessed at www.census.gov/prod/www/abs/decennial/1920.htm on July 2, 2007.
Woodhouse, C. A., S. T. Gray, and D. M. Meko. 2006. "Updated Streamflow Reconstructions for the Upper Colorado River Basin." *Water Resources Research* 42, W05415, May 11, 2006.
Worster, D. 2001. *A River Running West: The Life of John Wesley Powell.* New York: Oxford University Press.

Chapter Two

ENVIRONMENTAL AND SOCIAL HISTORY OF THE LOWER COLORADO RIVER

2.1 Introduction

> By the late 1800's, scholars commonly referred to the [Colorado] river as the 'Nile of America.' It shared striking similarities with the Nile River of Egypt. Both rivers originated in the mountains and both flowed through a hot and inhospitable desert before reaching the sea. Both were unpredictable, known and feared for their floods and droughts. Both carried massive amounts of sediment that created lush marshlands, lagoons, and river deltas that supported highly diverse wildlife communities. Most important, they provided a fertile floodplain where crops prospered. The agricultural and metropolitan centers of Arizona, Nevada, southern California, and northern Mexico were nurtured from the waters of the Colorado River. (Mueller and Marsh 2002)

The capricious Colorado River was a force to be reckoned with until it was tamed with huge dams and a weighty body of laws in the twentieth century, soon after Americans and Mexicans had acquired the technological ability and political wherewithal to do so. This overview of the Lower Basin's natural and political history shows how our view of the river has developed over time and hints at how it may evolve in the future.

2.2 The Natural Landscape

Today's Lower Colorado River is believed to have formed 5.4 million years ago when the Colorado River deviated from its westward course into the Utah deserts and turned south over the Kaibab Plateau into Arizona due to a sudden rise in the Wasatch Plateau (Young and Spamer 2004). The river began to carve the Grand Canyon and continued southward (Babcock et al. 1974). Around the same time, the active San Andreas Fault caused the separation of the Baja California peninsula and began the formation of the Proto-Gulf of California (Gastil et al. 1975). The peninsula continues to separate from the mainland at a rate of 5 cm per year (Elders et al. 1972).

During the last 2 million years, the Colorado River has been depositing its sediments into the Delta as it flows into the Gulf of California. Many times during the past, these sediments diverted a portion of the river's flow into the deep depression known as the Salton Sink and filling Lake Cahuilla, a predecessor to the Salton Sea (Singer 1998). This ancient lake, which existed periodically, covered up to 2,000 square miles at a greatest depth of more than 300 feet. Measuring almost 100 miles long by 35 miles wide at it widest point, it was six times the size of the present day Salton Sea. By 1600 A.D., the lake had completely evaporated (Singer 1998).

The Lower Colorado River flows

through three different ecoregions: the Colorado Plateau, the Mojave Desert, and the Sonoran Desert, which is dominated by very arid climates, where the annual median temperature is 22°C (72°F) with an annual temperature variance of 18°C (64°F) and average annual precipitation of merely 2 inches in Mexicali (Venegas 2000). Hence, much of the Lower Basin is a dry, warm desert with winter rains, summer monsoon storms, and extreme temperatures.

Paleoclimatology reconstructions using tree rings show that the Colorado River Basin has experienced extended periods of drought in the early 1500s, early 1600s and mid-1800s that are comparable in severity to the drought experienced in the Basin since 2000 (Woodhouse et al. 2006).

Approximately 85 percent of the river's annual flow originates in the Upper Basin within only 15 percent of the basin area (Stockton et al. 1991). The river's water supply depends largely on winter snowfall in the high mountains of Colorado, Wyoming, and Utah. Before the construction of Hoover and Glen Canyon dams, more than 70 percent of the river's flow occurred during the spring runoff months of May, June, and July (Harding et al. 1995). On an annual basis, supply variability is typically several times larger than demand variability.

Before the dams, the Lower Colorado River and its tributaries were notoriously unpredictable, flooding nearly every decade after the spring snowmelt in the Rockies and the summer monsoons. Spring flows past in Yuma averaged more than 75,000 cubic feet per second (cfs) and were estimated to have reached a maximum of 400,000 cfs since 1840 (Wheeler 1876), swelling the river channel to a width of 2 to 5 miles. After the monsoon, however, flows would slow to a trickle in autumn, reaching a pre-dam low of 540 cfs in 1934. At the mouth of the river, the tidal surges were the second largest in the world, reaching 35 feet and sinking boats on many occasions (Mueller and Marsh 2002).

One of the problems affecting use of the river is its salinity. Ten million tons of dissolved salts are transported downstream every year. Average salinity is 750 parts per million (ppm), up from 400 ppm when the first dam was constructed in 1902. This compares to 200 ppm for the Mississippi and 90 ppm for the Columbia River. By the time the river reaches Imperial Dam, it contains 1 ton of mineral salts per acre-foot, or the equivalent of one ounce per gallon (Singer 1998). The river's salinity comes from two sources: the dissolution of salts in the sedimentary layers in the canyons of the Colorado Plateau and the leaching of salts from agricultural irrigation and return flows that drain into the mainstem. The salinity problem is compounded by intense evaporation, which reaches nearly 7 feet per year in the Lower Basin across the total reservoir surface (Singer 1998).

2.3 Pre-European History (pre-1500)

Humans have used the waters of the Lower Colorado and its tributaries for more than eleven thousand years. In a region where rainfall averages 12 to 14 inches per year (WRRC website, 2007), access to perennial sources of water has always been key to survival. While some tribes, such as the Hopi, have shown that it is possible to grow corn on small parcels using only rain harvesting, irrigation is needed for larger-scale development and has been the cornerstone of the arid West's settlement.

Archeologists have uncovered extensive irrigation systems, including small storage reservoirs and miles of canals, which date back to the ancestral Puebloans. The Hohokam, ancestors of today's Pima Indians, farmed the Salt and Gila rivers' floodplains in central Arizona from 300 B.C. to 1450 A.D., digging more than 600 miles of canals, some as wide as 64 feet across, to divert spring runoff up to 16 miles away from the rivers

(Haury 1978). Gary Nabhan, Director for the Center for Sustainable Environments at Northern Arizona University, calls the Hohokam "one of the most remarkable agricultural civilizations in the New World" (2004). In the 1870s, the Pimas and the Maricopas were the largest producers of wheat and other crops west of the Mississippi (Kraker 2004).

2.4 European Arrival (1500–1850)

The Spaniard Francisco de Ulloa was the first Europeans to see the river in 1539. The following year, Hernando de Alarcon entered the Delta from the Gulf of California and the Colorado's tidal bore nearly sunk his three ships (Wagner 1929). There were an estimated seven thousand Cocopah Indians in the Delta at the time (Ward 2003). Exploration until the mid-1800s was sporadic: Spanish missionaries such as Father Kino visited the Delta in the early 1700s, British Lieutenant Hardy sailed up the branch of the river that would later bear his name in 1826, and James Pattie explored the lower river from the north in 1827 with a group of fur trappers (Mueller and Marsh 2002).

2.5 American Exploration (1850–1900)

In 1851, Major Heintzelman, commander at Camp Independence (Fort Yuma) expressed an interest in getting supplies from the Gulf by steamship and described the river in the Delta as being "several miles wide and covered with willow, cottonwood, and mesquite, with usual underwood and grass." (Lingenfelter 1978).

In 1858, Lieutenant Joseph Ives of the U.S. Office of Explorations and Surveys led the first scientific expedition up the Colorado in a specially built shallow draft steamer and reached Fort Yuma in eleven days. The expedition made contact with the Chemehuevi Indians farther upstream and provided the first known illustrations of the river. In spite of getting stuck on numerous sandbars on the lower river, they continued traveling four hundred miles upriver until they reached Black Canyon, near the site of the future Hoover dam, before continuing on foot to Fort Defiance (Mueller and Marsh 2002).

The arrival of the Santa Fe Railroad in Yuma in 1877 made upstream river travel uneconomical, and the shipyard at Port Isabel, in the Upper Gulf of California, was dismantled the following year (Mueller and Marsh 2002).

Major John Wesley Powell mapped and surveyed the last unknown areas of the continental United States with two famous scientific expeditions through the Grand Canyon in 1869 and 1871–1872 and published his exploits, travails, and philosophical ponderings in the classic "The Exploration of the Colorado River and Its Side Canyons" in 1874.

Powell led the U.S. Geological Survey (from here, the Survey) from 1881 to 1894. In 1888, following a series of dry years, Congress, on Powell's recommendation, authorized the Survey to undertake a study of the arid regions of the United States with special emphasis to be placed on investigations of stream capacities and potential sites for dams, reservoirs, ditches, and other irrigation facilities (Stegner 1954). All land west of the 101st meridian would be closed to settlement until a detailed irrigation survey had been completed. The public domain would be gradually reopened for planned settlement based on the study's results (Wilkinson 1993). Consternation accompanied the announcement of the measure in the summer of 1889 as it effectively closed half the country to all homesteading. Under pressure and unwilling to wait several years for the results of the survey, Congress rescinded the 1889 land withdrawal. Powell did not have time to put into place the institutions needed for an orderly settlement of the West (Mueller and Marsh 2002).

While Congress passed the landmark Reclamation Act in 1902, its populist language reflecting Powell's recommendations (the water reclaimed through the construction of dams and reservoirs would only be supplied to bona fide residents living on or near the land, on small parcels of no more than 160 acres, in order to prevent speculation by corporations or absentee landlords), the program itself would be controlled by powerful interests who did not share Powell's desire to establish an agrarian society in the West. His vision was not to become a reality.

> It was the West itself that beat him, the Big Bill Stewarts and Gideon Moodys, the land and cattle and water barons, the plain homesteaders, the locally patriotic, the ambitious, the venal, the acquisitive, the myth-bound West which insisted on running into the future like a streetcar on a gravel road. (Wilkinson 1993, n. 36)

2.6 Dams and the Law of the River (1900s–Present)

By the early 1920s, the Colorado River Basin States were concerned about their share of the river's water and especially concerned that rapidly growing California would establish priority rights to the detriment of other states, following the "first in time, first in right" rule. A Supreme Court ruling in June 1922 that the law of prior appropriation applied regardless of state lines increased the momentum for reaching an agreement. In order to head off unnecessary federal involvement and costly litigation, the seven Basin States agreed on a compact in November to apportion Colorado River water in perpetuity between the Upper and Lower Basin States, each basin receiving 75 million acre-feet (maf) every ten years and 1 maf of tributary contributions (Gelt 1997).

The years surrounding the signing of the Compact were some of the wettest on record and the states based their allocation on agricultural need and Bureau of Reclamation data estimating average annual flows at 16.4 maf. Recent dendroclimatology studies now indicate that the long-term average is actually closer to 14.7 maf (Woodhouse et al. 2006). This overallocation of the Colorado River's waters is currently pressing because of the full development of resources in the Lower Basin since 1990 and the ongoing drought since 2000.

The Boulder Canyon Project Act of 1928, which authorized the construction of Hoover Dam (initially called Boulder Dam) and the All-American Canal, also required the Secretary of the Interior to manage the operations of the dams and associated structures in the Lower Basin. Construction of Hoover Dam began in 1931 and was completed in less than five years. Still the highest (though no longer the largest concrete dam in the world), it can store nearly 28 maf of water in Lake Mead, making it the largest reservoir in North America. The Hoover power plant currently has a capacity of 2,080 megawatts, enough to power 500,000 to 600,000 homes (Reclamation, Hoover Dam FAQ, Web site, 2006).

Concerned about political instability in Mexico, the U.S. Congress funded the construction of a canal wholly on U.S. soil to guarantee deliveries to farmers in the Imperial Valley. Construction of the All-American Canal began in 1934 and it began delivering water to the Imperial Valley in 1940 (Mueller and Marsh 2002). The U.S.–Mexico Water Treaty of 1944 determined Mexico's allocation (1.5 maf) and allowed for the construction of Morelos Dam in 1950, the last diversion structure on the Colorado River, providing water to more than 600,000 acres of farmland in the Mexicali Valley (Mueller and Marsh 2002). The treaty, however, failed to allocate any water for environmental needs, leaving the survival of the Delta to depend on occasional surplus and agricultural flows (Mumme 2001).

The Upper Colorado River Basin Compact of 1948, which apportioned the Upper Basin water supply (51.75 percent to Colorado, 23 percent to Utah, 14 percent to Wyoming, and 11.25 percent to New Mexico—percentages were used rather than actual amounts because by this time the states realized the river's waters had been overallocated in 1922) was followed by the Colorado River Storage Project Act in 1956, which authorized the construction of Glen Canyon Dam and a comprehensive water development plan for the Upper Basin.

Arizona ratified the 1922 Compact in 1944 in order to begin negotiations for a Central Arizona Project (CAP) to deliver Colorado River water to its two major cities, Phoenix and Tucson. California claimed that it had developed a historical use of some of Arizona's apportionment, which, under the doctrine of prior appropriation, precluded Arizona with moving forward with the CAP. In 1952, Arizona asked the U.S. Supreme Court to intervene.

The 1964 *Arizona v. California* decision determined the Lower Basin main stem apportionments (4.4 maf for California, 2.8 maf for Arizona, and 0.3 maf for Nevada), confirmed that the apportionment of Lower Basin tributaries was reserved for the exclusive use of the states in which the tributaries were located, addressed the reservation of water for Indian reservations in California, Arizona, and Nevada, and confirmed the role of the Secretary of the Interior as water master in the Lower Basin.

Table 1. Colorado River Water Allocation[1]

	Allocation (maf)
Upper Basin	**7.50**
Colorado	3.88
Wyoming	1.05
Utah	1.73
New Mexico	0.84
Arizona	0.05
Lower Basin	**7.50**
Arizona	2.80
Nevada	0.30
California	4.40
Mexico	**1.50**
Total	16.50

[1] In the Upper Basin, as mentioned earlier, water is divided by percentage available, after Arizona receives its share of 50,000 acre-feet.

In particular, the court ruled that tribes were entitled to as much water as needed to farm all the "practically irrigable acreage" on their reservations, reviving the Winters Doctrine of 1908, which established that each tribe's water rights were tied to the date its reservation was created. According to this Supreme Court case (Shurts 2003), once tribes affirm their rights in court, these take precedence over subsequent appropriated rights. However, in the past century, of the hundreds of lawsuits that were filed, only three tribes have successfully defended their cases. The 1964 decision awarded more than 700,000 acre-feet per year to the Colorado River Indian Tribes (Kraker 2004).

In 1968, the Colorado River Basin Project Act authorized the construction of the CAP, which now carries 1.5 maf to Phoenix and Tucson, and made this water subordinate to California's in times of shortage.

Minute 242 of the U.S.-Mexico Water Treaty in 1973 specified maximum salinity levels for water delivered to Mexico at the border. The following year, the Colorado River Basin Salinity Control Act authorized a number of projects to improve Colorado River water quality, including the Yuma Desalting Plant (YDP). The MODE Canal, completed in 1977, to divert drainage from the Wellton-Mohawk Irrigation and Drainage District (WMIDD), created the Ciénega de Santa Clara, now the largest marsh wetland in the Delta. The YDP, completed in May 1992 at a cost of $256 million to treat and recapture some of the water, only operated until January 1993 when flooding along the Gila River destroyed some canals that carry agricultural return water to the facility (Van Der Werf 1994). YDP did not operate for the following fourteen years because excess flows in the river made its operation uneconomical. In March 2007, the plant, operating at 10 percent of capacity, was restarted for a ninety-day test run to determine its cost-effectiveness, to test functionality, and to monitor the impact of the brine waste stream that flows into the Ciénega de Santa Clara (Reclamation 2007).

2.7 Post-Dam Era (1980s–Present)

El Niño weather patterns were felt in the region from the late 1970s to the late 1980s. El Niño is an oscillation of the ocean-atmospheric system having consequences to global weather patterns, including increased rainfall in the southwestern United States (Philander 1990). In 1983, high initial reservoir levels forced the Bureau of Reclamation to release large amounts of water from Lake Powell and Lake Mead, registering the highest flows on record in the mainstem—92,000 cfs through Grand Canyon compared to a normal range of 5,000 to 30,000 cfs—and causing major flooding throughout the Delta (Reclamation Web site, 2007). These floods created extensive riparian habitat, including in the previously dry Laguna Salada, but also destroyed a number of farms, homes, and tourist camps along the river in Mexico. The Cucapá tribe was forced to move to higher ground and concentrate dwellings in the community of El Mayor. Jesus Mosqueda, who owns one of the tourist camps along the Río Hardy, one of the tributaries of the Colorado, reached an out-of-court settlement with the U.S. government for damages from the 1983 floods (Bergman 2002). The wet El Niño years in the 1980s reinvigorated the Lower Basin, including Bill Williams and Cibola National Wildlife Refuges, the Salton Sea, offstream wetlands, and the Delta. Over the previous eighty years, more than 90 percent of the Delta's 1,930,000 hectares of riparian, freshwater, brackish, and tidal wetlands that had nourished an incredible abundance of plant, marine, and bird life, making the Delta one of the greatest desert estuaries in the world, had disappeared, leaving in its wake hypersaline mud flats and salt cedar (Luecke et al. 1999). But the floods of the 1980s and the diversion of drainage from the Wellton-Mohawk Irrigation and

Drainage District (approximately 110,000 acre-feet [ac] per year), creating the surprisingly lush Ciénega de Santa Clara, showed that ecosystems were more resilient than had previously been thought.

Today, in spite of its greatly reduced size, the Delta is once again a key stop for migrating birds along the Pacific flyway and supports more than 360 species of birds, including two endangered species, including the California black rail and the bald eagle, and six threatened species, including the Yuma clapper rail. Every year, more than 150,000 migratory shorebirds and 50,000 migratory waterfowl will seek rest and food in the Delta's wetlands (Hinojosa-Huerta 2006).

In addition there are "inefficiencies" in the system that provide ecosystem benefit, most of which are located in the Colorado River Delta. In the Delta, there are certain locations where there are leaks in the water delivery system. Some of these locations are described briefly below.[2]

- All-American Canal (AAC) and Andrade Mesa Wetlands: The AAC is the last diversion of the Colorado River before it crosses into Mexico. It brings water to the Imperial and Coachella Valleys in California. Seepage from the AAC feed the Andrade Mesa wetlands in Mexico. The lining project of the AAC to conserve "inefficient" leakage would help to bring California into compliance with their 4.4 maf Compact allocation by selling the conserved water to the Metropolitan Water District in Southern California.
- MODE Canal and La Ciénega de Santa Clara: To fulfill Minute 242 of the U.S.-Mexico Water Treaty, which addressed salinity levels in the Colorado River water crossing into Mexico, the MODE Canal was built to transport saline wastewater from the Wellton-Mohawk Irrigation and Drainage District (WMIDD) to the Santa Clara Slough in Sonora, Mexico. La Ciénega de Santa Clara was formed in combination with irrigation return flows from Riito Drain. It covers about 40,000 acres of marsh wetlands and mudflats. The operation of the Yuma Desalting Plant (YDP) to use the WMIDD wastewater "more efficiently" would reduce the quantity and quality of water received at La Ciénega.
- Riparian Corridor of the Colorado River: The water in the riparian corridor of the Colorado River in Mexico depends on water transfers from agricultural to urban uses in Mexico, agricultural water use efficiency practices, and wastewater treatment plant development. It also varies based on over-deliveries that result from releases to U.S. farmers that are not diverted as planned.

Minute 306 of the U.S.-Mexico IBWC, approved in December 2000, establishes a framework for cooperation through "joint studies that include possible approaches to ensure use of water for ecological purposes" (U.S. IBWC 2006) in the limitrophe area and the Delta, based on both countries' interest in preserving the riparian and estuarine ecology of the region. The Minute also states that the IBWC "shall examine the effect of flows on the existing riparian and estuarine ecology of the Colorado River" in that region in order to "define the habitat needs of fish, and marine and wildlife species of concern to both countries" (U.S. IBWC 2006). Although the Minute does not require either country to establish minimal flows to the Delta, it does state the countries' interest in doing so if they are needed to preserve key habitat and species.

On the U.S. side, in order to comply with requirements of the Endangered Species Act, multiple agencies at the federal and state level and water and power users in Arizona, California, and Nevada entered in 2005 into a fifty-year agreement, known as the Lower Colorado River Multi-Species Conservation Program (MSCP), at an estimated cost of $626 million (in 2003 dollars), to create 8,132 acres of riparian, marsh, and backwater habitat for twenty-six species, including six threatened and endangered ones, along the Lower Colorado. Besides habitat restoration with native cottonwoods and willows (more than 40 percent of the budget is linked to habitat creation), the program includes substantial funds dedicated to monitoring and research (34 percent of the budget), habitat protection (18 percent), and stocking with native fishes, including 660,000 razorback sucker, 620,000 bonytail, humpback chub, and flannelmouth sucker. The estimated mainstream water use requirement for the newly created habitat is 40,000 to 50,000 acre-feet (af) per year, provided by California (50 percent), Arizona (25 percent) and Nevada (25 percent). (Harris, 2006)

The MSCP currently covers the four hundred river miles between Lake Mead and the Southerly International Boundary, but may include the Grand Canyon in the future. Environmental NGOs, while supporting many elements in the MSCP, backed out of the negotiations for the agreement because it did not extend into the Grand Canyon or to the Delta south of the border, where habitat restoration and species protection is also needed. In addition, the MSCP did not consider the dedication of instream flows in the plan. The agreement allows power and water users in the Lower Basin to fulfill requirements under the Endangered Species Act at a relatively low cost over the long run, capping the cost of restoration in terms of both dollars and acre-feet of water for the next fifty years.

Farther downstream, the Yuma Crossing National Heritage Area is restoring riparian habitat on both sides of the river. In the West Wetlands, a natural preserve of 110 acres is in the process of being created with revegetation, tree farms, a lake, bird sanctuaries, hummingbird and butterfly gardens, walking paths, and equestrian areas. In the East Wetlands, a 1,400-acre area is being restored along a five-mile stretch of the river with native cottonwood and willow trees replacing invasive salt cedar (Greater Yuma Economic Development Corporation Web site, 2007).

Restoration efforts in the Delta are guided by the *Conservation Priorities in the Colorado River Delta* report, the result of an analysis by fifty-five scientific experts and resources managers from universities and environmental NGOs in the U.S. and Mexico published in 2005 (Zamora et al., 2005). Pilot projects along the Colorado River mainstem and its main tributary, the Rio Hardy, are ongoing. Restoration efforts have been led by the NGOs, but for the past two years, Mexican government agencies have been actively participating. The ultimate goal is to develop an 80,000-acre functional riparian corridor from Morelos dam to the Rio Hardy. A key to success is the acquisition of base instream flows and pulse flows for environmental purposes. Pronatura has already secured through water acquisition and placed in a water trust 320 acre-feet. Pronatura and the Sonoran Institute are also seeking to secure additional water for these purposes (Sonoran Institute 2007).

2.8 Conclusion

This brief environmental and social history of the Colorado River demonstrates several important points:

- The Colorado River is a highly engineered system, physically controlled by an elaborate system of dams and canals.
- The Colorado River is a highly regulated system, institutionally controlled by a system of rigid protocols, rules, laws, and treaties.
- Water users, from agriculture to municipal, and including recreational, environmental, and traditional, have growing concerns about where to allocate water.
- Environmental values have evolved over the last one hundred years to incorporate nonprovisioning ecosystem services.
- The Colorado River is a highly resilient system and small amounts of water can do large amounts of restoration work.

Through remarkable feats of engineering, including more than twenty major dams and hundreds of miles of canals and diversions, we have succeeded in taming the notoriously unpredictable Colorado River and use its waters to irrigate millions of acres of farmland in the arid southwestern United States and northwestern Mexico and to support the growth of major cities both within and far beyond the Basin. The Law of the River has provided the legal bedrock onto which these technological wonders and institutional arrangements can rest.

The tremendous progress accomplished over the past eighty years has come at a great cost to Lower Basin riparian ecosystems and the human communities that depend on them, particularly in the Delta. If the Delta had been located entirely within the United States, it is unlikely that it would have been allowed to degrade to such an extent. The sizeable investment in riparian restoration in the Lower Colorado under the MSCP shows the importance of umbrella environmental laws such as the Endangered Species Act in restoring ecosystems. Since most of the Delta falls outside the scope of U.S. law, we will need new legal and political arrangements in the United States and Mexico to ensure its protection and restoration. Paradoxically, the ongoing drought and the desire for increased water efficiency in the system may be creating an opening for action on both sides of the border.

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[2] For more information please see: *Conservation Priorities in the Colorado River Delta* (sonoran.org/index.php?option=com_content&task=view&id=157&Itemid=204) and *Hazard: The Future of the Salton Sea with No Restoration Project* (www.pacinst.org/reports/saltonsea/index.htm).

2.9 References

Bergman, Charles 2002. *Red Delta: Fighting for Life at the End of the Colorado River*. Golden, CO: Fulcrum Publishing, 194–197.

Babcock, R. S., et al. 1974. *Geology of the Grand Canyon*. Flagstaff, AZ: Museum of Northern Arizona, 185.

Colorado River Compact of 1922, 4 Stat. 1057.

Congress, Boulder Canyon Project Act, 70th Cong., H.R. 5733, Congressional Record, no. 642 (1928).

Congress, Senate, Colorado River Storage Project, S. 500, Public Law, no. 485 (1956).

Elders, W., R. W. Rex, T. Meidav, P. T. Robinson, and S. Biehler. 1972. "Crustal Spreading in Southwestern California." *Science* 178 (4056):15–24.

Gastil, G., R. Phillip, and E. Allison. 1975. "Reconnaissance Geology of the State of Baja California." *The Geology Society of America Memoir* 140, 170 p.

Gelt, Joe. 1997. "Sharing Colorado River Water: History, Public Policy and the Colorado River Compact," *Arroyo* 10, no. 1 (Aug. 1997), accessed at cals.arizona.edu/AZWATER/arroyo/101comm.html on Dec. 19, 2006.

Greater Yuma Web site. 2007. Accessed at on June 13, 2007 at www.greateryuma.org/nationalheritagearea.html?GCCID=e6a74205f313379e0e0fee06668ddc4a.

Harding, B. L, T. B. Sangoyomi, and E. A. Payton. 1995. Impacts of a severe drought on Colorado River water resources. *Water Resources Bulletin* 31, no. 5:815–824.

Harris, Christopher S. 2006. "Habitat Restoration Along the Lower Colorado River: Challenges and Opportunities," at cals.arizona.edu/AZWATER/conf2005/presentations/ L.%20CO%20River%20Multispecies/Harris.pdf, accessed on Dec. 19, 2006.

Haury, E. W. 1978. *The Hohokam: Desert Farmers and Craftsmen*. Tucson: The University of Arizona Press.

Hinojosa-Huerta, Osvel M. 2006. "Birds, Water and Salt Cedar: Strategies for Riparian Restoration in the Colorado River Delta" Tucson, AZ: The University of Arizona, Doctoral Dissertation.

Kiffen, F. B. 1932. *The natural landscape of the Colorado River Delta*. University of California, Publication of Geography, vol. 5, 149–220.

Kraker, Daniel. 2004. "The New Water Czars." *High Country News* 36, no. 5 (March 15, 2004).

Lingenfelter, R. E. 1978. *Steamboats on the Colorado River, 1852–1916*. Tucson: The University of Arizona Press.

Luecke, D., J. Pitt, et al. 1999. *A Delta Once More: Restoring Riparian and Wetland Habitat in the Colorado River Delta*. Washington D.C.: Environmental Defense Fund, 64.

Mueller, G. A. and P. C. Marsh. 2002. *Lost, a Desert River and its Native Fishes: A Historical Perspective of the Lower Colorado River*. Fort Collins, CO: U.S. Geological Survey, Fort Collins Science Center. Information and Technology Report USGS/BRD/ITR 2002-0010.

Mumme, Stephen P. 2001. "Reinventing the International Boundary and Water Commission," Americas Program Analysis. Silver City, NM: Interhemispheric Resource Center, July 2001. Accessed at www.americaspolicy.org/briefs/2001/bl79.html, on Dec. 19, 2006.

Nabhan, G. 2004. Quoted in Kraker, Daniel, "The New Water Czars." *High Country News* 36, no. 5 (March 15, 2004).

Philander, S. G. H. 1990. *El Niño, La Niña and the Southern Oscillation*. San Diego, CA: Academic Press, 289.

Reclamation. 2007. "Yuma Desalting Plant." Brochure received at Yuma Desalting Plant Demonstration.

Reclamation Web site. 2007. Historical Flows Below Hoover Dam, www.usbr.gov/lc/riverops.html, accessed June 27, 2007.

Shurts, J. 2003. Indian Reserved Water Rights: The Winters Doctrine in Its Social and Legal Context. Norman: University of Oklahoma Press.

Singer, E. 1998. "Geology of the Imperial Valley." In *Keys to Soil Taxonomy*, 8th ed. Washington, D.C.: USDA-NRCS.

Sonoran Institute. 2007. "Colorado River Delta Restoration: 10 Years Past and Future." Tucson, AZ.

Stegner, W. 1954. *Beyond the Hundredth Meridian*. New York: Penguin Books, 438.

Stockton, C. W., D. M. Meko, and W. R. Boggess. 1991. "Drought history and reconstructions from tree rings." In F. Gregg and D. H. Getches, principal investigators, *Severe, sustained drought in the southwestern United States*. U.S. Department of State, Man and Biosphere Program.

United States International Boundary and Water Commission (U.S. IBWC). 2000. Minute 306—Conceptual Framework for U.S.-Mexico Studies for Future Recommendations Concerning the Riparian and Estuarine Ecology of the Limitrophe Section of the Colorado River and its Associated Delta. Signed, December 12, 2000, El Paso, Texas. Accessed at www.ibwc.state.gov/Files/Minutes/Min306.pdf, on Dec. 19, 2006.

USGS Web site, Geological Survey Information. 2006. 74–24, at www.cr.nps.gov/history/online_books/geology/publications/inf/74-24/sec6.htm, accessed Dec. 19, 2006.

Van Der Werf, Martin. 1994. "Draining the Budget to Desalt the Colorado." *High Country News* 26, no. 3.

Venegas, R. 2000. "El uso de la flora urbana en ciudades de clima árido seco extremoso." In *Ciudad, Salud y Medio Ambiente*. México: UAP-RNJU.

Wagner, H. R. 1929. Spanish Voyages to the Northwest Coast of America in the Sixteenth Century. San Francisco: California Historical Society, 50.

Ward, E. R. 2003. *Border Oasis*. Tucson: University of Arizona Press.

Water Education Foundation (WEF) Web site. 2007. Colorado River Facts, www.water-ed.org/coloradoriver.asp, accessed Jan. 11, 2007.

Western Regional Climate Center (WRCC) Web site. 2007. Average Statewide Precipitation for Western U.S. States. At www.wrcc.dri.edu/htmlfiles/avgstate.ppt.html, accessed Jan. 11, 2007.

Wheeler, G. M. 1876. *Annual report on the geographical surveys West of the one-hundredth meridian, in California, Nevada, Utah, Colorado, Wyoming, New Mexico, Arizona, and Montana: Appendix JJ*. Annual Report of the Chief of Engineers for 1876: Washington, D.C., Government Printing Office.

Wilkinson, Charles. F. 1993. *Crossing the Next Meridian: Land, Water and the Future of the West*. Washington, D.C.: Island Press, 236–238.

Woodhouse, C. A., S. T. Gray, and D. M. Meko. 2006. Updated Streamflow Reconstructions for the Upper Colorado River Basin. *Water Resources Research* 42, W05415 (May 11, 2006).

Young, R. A. and E. E. Spamer. 2004. Colorado River: Origin and Evolution. Grand Canyon, AZ: Grand Canyon Association, 280.

Yuma Sun. 2007. "Trial run of Yuma desalting plant ends," June 2, 2007.

Zamora-Arroyo, F., J. Pitt, S. Cornelius, E. Glenn, O. Hinojosa-Huerta, M. Moreno, J. Garcia, P, Nagler, M. de la Garza, I. Parra. 2005. "Conservation Priorities in the Colorado River Delta, Mexico and the United States." Sonoran Institute, Environmental Defense, University of Arizona, Pronatura Noroeste Dirección de Conservación Sonora, Centro de Investigación en Alimentación y Desarrollo, World Wildlife Fund-Gulf of California Program, 1–103.

Chapter Three

ECOSYSTEM SERVICES AND DRIVERS OF CHANGE IN THE LOWER COLORADO BASIN

3.1 Introduction

Given that ecosystem services are benefits that ecosystems produce for people, they cannot be properly considered "services" unless changes in their condition have economically significant consequences for human well-being. In other words, they cannot be defined without reference to their social context and the values upon which human choices are based.

As is seen in the preceding chapter, there have been tremendous changes in the Colorado Basin, which, just over the last century, has become almost entirely an engineered system. By diverting water for various human uses, these changes have brought tremendous benefits to many people, in the form of what are defined as provisioning services. Even the environment now relies on this artificial water delivery system, which can also be engineered to provide timed releases of water that mimic natural flow patterns. But it cannot replace the full pattern of complex interactions that make up the flow regime, which supports and regulates the capacity of the ecosystem to produce a much broader range of benefits.

The change in flow regime, which includes water temperature, the regular flow of sediment, and patterns of disturbance, has endangered species, created suitable environments for nonnative species, reduced the Colorado River Delta to less than 10 percent of its original size (Luecke et al. 1999), and altered the livelihoods and ways of life, both negatively and positively, of people dependent on these services. Despite the technological prowess in Colorado River management, there have been some unexpected surprises, external to this controlled system. Recurring droughts are exacerbated by climate change, which, along with temperature increases, increase water evaporation, may increase the length of droughts, and generally bring greater variability and uncertainty to the hydrologic cycle. Although drought is a natural phenomenon in the Basin, the explosion of population in the western United States and northwestern Mexico, combined with overextended use of water in agriculture, increases vulnerability to it. In the last seven years, the Lower Basin has had one of the worst droughts in history with a 50 percent loss in storage. Shortages are imminent and, if these conditions remain, choices will become fewer and more difficult to make.

Nonprovisioning services tend to be overlooked and not accounted for because the benefits of water diversion have been of greater value to society than other ecosystem services, and because the negative consequences tend to fall disproportionately on marginalized stakeholders who have little if any bargaining power and may be beyond political boundaries. However, as is demonstrated by the restoration of other estuaries within U.S. borders, such as the Chesapeake Bay, the San Francisco Delta, and the Everglades, links between ecosystems and human well-being also tend to become more apparent as limits are reached and as the supply of specific services diminishes or is threatened. For example, restoration of the Chesapeake Bay is driven by threats to water quality and to Chesapeake Bay ecosystems, which support various kinds of recreational and commercial fishing and are culturally important in the region. Chesapeake Bay water quality management concerns date back to the early part of the century, when degradation of water quality related to discharge of untreated sewage from the urban areas first began to conflict with the oyster fisheries (Santopietro and Shabman 1992). This conflict eventually led to requirements for sewage treatment facilities and marked the beginning of a trend toward more comprehensive policies for protection of the Bay ecosystem. This type of situation provides an opportunity for learning and for stakeholders to reconsider their values, or what trade-offs they are willing to make between multiple and often competing objectives.

Valuation of ecosystem services is therefore an ongoing process of negotiation in which a key challenge is be to identify policy goals and more specific trade-offs between these goals, and uses of the different kinds of ecosystem services produced in the Lower Colorado Basin. Regardless of whether these values are expressed in a monetized form, a precise determination of costs, benefits, and their distribution, for purposes of making policy choices, presumes the ability to link numerous actions with future outcomes. Given changing conditions, and the impossibility of ever obtaining complete information in a complex system, decision-making can be better informed by developing realistic scenarios to explore the consequences of policy options, drawing on the best available information and scientific judgment. In an adaptive management framework these kinds of scenarios provide a working hypothesis that can then be compared to lessons learned in practice, through an ongoing process of place-based assessment. In this chapter, we provide an overview of key policy choices and trade-offs that are discussed in the subsequent chapters, and further explored and contrasted in the scenarios in Chapter 6. We also point to the kinds of information needed to better inform negotiations among stakeholders regarding the equitable allocation of existing supplies of water and access to other benefits, across the national boundary.

3.2 Ecosystem Services of the Colorado River

Although ecosystem values are contested and are changing, allocation of the water budget of the Colorado River, as described in chapter 2, reflects values that existed at the time that relevant policy decisions were made. These values are inherent in rights to water and rules of the game that determine who has access to various kinds of benefits. Negotiation of the Colorado River Water Compact, and the subsequent body of law that makes up the Law of the River was motivated by the inadequacy of the Doctrine of Prior Appropriation, which would have enabled the faster growing state of California to appropriate a much larger share of water than other Basin States. At present, changing conditions, better understanding of the variability of the river flow, and growing environmental values, have made trade-offs between ecosystem services more evident. These factors have all raised questions about the adequacy of the Compact for meeting all of the growing and more diverse demands on the water supply, how this increasingly limited supply should be allocated in the future, and whether the rules need to again be changed to accommodate changing values as well as to respond to new conditions.

In 1995, the population within the Colorado River Basin itself was over 6 million (Soley, Pierce et al. 1998), but including out-of-basin water transfers, the river currently supports about 30 million people. The surface water is directly consumed, but also supplies water for agricultural, livestock, industrial, mining, and thermoelectric uses (Table 3.1).

Table 3.1. Common consumptive uses of Colorado River water in millions of gallons per day in 1995 (Soley, Pierce et al. 1998).

Mgal/d[3]	Public Supply	Domestic	Commercial	Irrigation	Livestock
Upper Colorado	106	0.4	0.7	6990	50
Lower Colorado[4]	698	0.2	7.5	4200	6.8

Mgal/d	Industrial	Mining	Thermoelectric	Total
Upper Colorado	4	3.5	146	7310
Lower Colorado	5.5	26	17	4970

This surface water also produces hydroelectric power (Table 3.2).

Table 3.2. Colorado River water used for hydroelectric in million gallons per day and amount of power generated in gigawatts per hour in 1995 (Soley, Pierce et al. 1998).

Mgal/d; GWh[5]	Water Use Hydro	Power Generated
Upper Colorado	17,900	7,220
Lower Colorado	23,400	9,740

The Colorado River irrigates more than 2.7 million acres of farmland in the Lower Basin (Reclamation Web site, 2007). The table below shows the acres of farmland irrigated by Colorado River water for selected agricultural areas (Reclamation DEIS 2007; SDSU 2004).

Table 3.3. Total land in irrigated farms for selected agricultural areas in the Lower Basin.

Region	Acres	Estimated market value of production
Arizona	1,366,109	$2.1 billion
CAP counties	829,957	
Western Arizona counties	536,152	
Southern Nevada	65,206	
Imperial Valley	437,896	> $1 billion
Mexicali Valley	609,839	

[3] A million gallons is equivalent to twenty thousand, fifty-gallon baths. See ga.water.usgs.gov/edu/mgd.html for more conversions.
[4] These numbers are in-basin uses and do not include California, which uses more than 25 percent of the flow of the Colorado River. Also, the totals add up to more than one would expect because Colorado River water is often reused along its course.
[5] A gigawatt hour is equivalent to the power needed to run 10,000,000, 100-watt light bulbs for one hour.

An analysis of 780,000 acres of irrigated crops in Arizona estimates that 3.5 million acre-feet of water were used in 1994 to produce more than $780 million in harvested crops, such as cotton, alfalfa, wheat, lettuce, barley, cantaloupe, and citrus (Morrison et al. 1996). Economic value produced per acre-foot of water consumed ranged from $95 for alfalfa to $3,316 for lettuce (Morrison et al. 1996).

The Colorado River provides water for municipal and industrial uses in Phoenix, Tucson, and numerous other Arizona cities through the Central Arizona Project; Las Vegas, Boulder City, and surrounding areas through the Southern Nevada Water Authority; Los Angeles, San Diego and nearly two hundred other cities in Southern California (Reclamation DEIS 2007); and Mexicali, Baja California, San Luis Rio Colorado, Sonora, and surrounding towns in Mexico. The total population served in the Lower Basin is estimated to be around 20 million people (Census 2005).

More difficult to quantify are the cultural services, including educational, aesthetic, and spiritual, that the Colorado River provides. Aside from hydroelectric power, other instream uses include recreation, which has become an important and growing use, even if data regarding its market values are fragmentary. For example, it is estimated that the total economic impact on the local economy of visitor spending in Grand Canyon National Park, one of the most visited in the United States with almost 4.4 million visitors in 2006, was $429 million in direct sales, $157 million in personal income, $245 million in value added, and almost 7,500 jobs once secondary effects are included (Stynes 2005). Lake Mead National Recreation Area, with nearly 8 million recreation visits in 2003, generated an estimated $233 million in direct sales, $82 million in personal income, $130 million in value added, and 6,000 jobs (Stynes 2003). In addition, the Delta's remaining wetlands play an important social role for a number of small communities, including ejidos, tourist camps, and Cucapá settlements in the region. If they were to disappear, these communities' social fabric would almost certainly disintegrate (Williams 1983; Valdés-Casillas et al. 1998).

Table 3.4 below lists the services provided by the Lower Basin's riparian ecosystems, including the Delta's, broken down by type of service, along with examples:

Table 3.4 Ecosystem services provided by the Lower Colorado River Basin's riparian areas.

Type of Ecosystem Service	Ecosystem Service	Trends in Human Use of Ecosystem Service[6]	Enhancement or Degradation of Ecosystem Service[7]	Examples
Provisioning	Water	Up	Down	Drinking water for municipal uses, water for industrial applications
	Food	Up	Down	Agricultural products (wheat, cotton, alfalfa, etc.), aquaculture, fishing and hunting, mesquite seeds
	Fiber and fuel	Down	Down	willow bark
Regulating	Hydrological flows	Up	Down	groundwater recharge
	Pollution control	Up	Down	retention, recovery and removal of excess nutrients and pollutants
	Natural hazards	Up	Down	flood control
Cultural	Spiritual and inspirational	Down	Down	sacred indigenous sites
	Recreational	Up	Down	recreation, tourism, transportation
	Aesthetic	Up	Down	appreciation of natural features
	Educational	Up	Down	opportunities for formal and informal education and training
Supporting	Soil formation	NA	Down	sediments and nutrient transport
	Nutrient cycling	NA	Down	
	Pollination	NA	Down	support for pollinators
	Biodiversity	NA	+/–	key stopover on the Pacific flyway, habitat for endangered species, breeding and nursery grounds for Gulf species (totoaba, shrimp, etc.)

[6] For provisioning services, human use increases if the human consumption of the service increases (e.g., greater food consumption). For regulating and cultural services, human use increases if the number of people affected by the service increases. Supporting services are not counted because people do not directly use them; changes in supporting services influence the supply of provisioning, regulating, and cultural services that are then used by people. The timeframe is in general the past fifty years, although if the trend has changed within that time frame, the indicator shows the most recent trend (MA 2005).

[7] For provisioning services, enhancement means increased production of the service through changes in area over which the service is provided (e.g., spread of agriculture) or increased production per unit area. Production is degraded if current use exceeds sustainable levels. For regulating and supporting services, enhancement refers to a change in the service that leads to greater benefits for people while degradation means a reduction in the benefits obtained from the service, either through a change in the service (e.g., wetland loss reducing flood control capacity) or through human pressures on the service exceeding its limits (e.g., groundwater recharge capacity). The timeframe is in general the past fifty years, although if the trend has changed within that time frame, the indicator shows the most recent trend (MA 2005).

As was discussed in chapter 1, water diverted for human consumptive uses comes at the expense of water necessary for ecosystems to produce regulating and supporting services, in which water is a limiting factor. Although the values of regulating and supporting services are less tangible from a market perspective and seldom accounted for, their degradation has consequences for human well-being and presents very real trade-offs. Degradation of supporting services undermines the basic production capacity and biodiversity of ecosystems, which is disproportionately concentrated in aquatic, riparian, wetland, and estuarine areas. These areas provide habitat, breeding, and feeding areas for numerous terrestrial, aquatic, and marine species, migratory birds for which it is a stopover on the Pacific flyway, as well as commercial and sport fisheries. In addition, these areas both rely on and regulate the flow of water and sediment, which is the outcome of complex patterns of interaction between climate, precipitation, topography, vegetation, and human alterations. The regulatory functions also provide benefits of water storage that contribute to sustained base flow as well as flood control, groundwater recharge, and removal of pollutants through filtration by the soil. These functions increase the resilience and capacity of the ecosystem to provide other kinds of services and to cope with changing conditions.

Often overlooked is the insurance value of supporting and regulatory services. Any allocation of water to instream flow reduces vulnerability to future reduction in flows, as it can provide a buffer against variability in the total flow. However, because of incentives inherent in the existing structure of western water rights, water is in many instances consumed for noncritical uses such as watering lawns. This is often preferred to removal of lawns in favor of vegetation with lower water requirements, simply as a way for individual water right holders to maintain a right to it, thereby providing a buffer that ensures access to a proportionally smaller amount during lower than normal flow conditions. With a proposed change in the rules that allows credits to be received for water conserved that can be used during a shortage, conserved water could be stored instream where it can provide social benefits.

To some extent, values can be inferred from policy objectives and willingness to pay in the form of taxes and donations rather than as individual buyers. However, before more precise and monetary trade-offs can be evaluated, it will be necessary to provide an opportunity for stakeholders to learn about the options available, and to establish new policy objectives against which they can be compared. These kinds of opportunities for social learning, reconsidering values, and establishment of new policies tend to be driven by extreme events that demonstrate the inadequacy of existing institutions. Willingness of stakeholders to pay the costs of water conservation will depend not only on levels of benefits relative to the cost, but also on whether the distribution of costs and benefits is accepted as fair, and whether there is confidence in the effectiveness of conservation measures.

Preliminary efforts have been made to quantify the value of Colorado River flows to stakeholders in the Delta (e.g., San Luis Rio Colorado residents, visitors and American homeowners along the Rio Hardy, fishermen in the Upper Gulf, and American birdwatchers on *La Ruta de Sonora* tours) by Mexico's National Institute of Ecology (Rivera 2006) using mainly willingness-to-pay surveys. While the values obtained pale in comparison to the values of agricultural production in the irrigation districts in the United States and the Mexicali Valley in Mexico, they indicate a growing recognition on the part of stakeholders of the need to restore riparian habitat along the Colorado mainstem and the Rio Hardy for recreation and biodiversity protection.

Restoration in the Delta will bring a number of ecological, economic and social benefits (Zamora-Arroyo and Lellouch 2007). These include increased riparian and marsh wetland habitat for migratory and resident birds, including waterfowl, pheasant, dove, and quail; increased revenues from tourism, currently estimated at $300,000 per year along the Rio Hardy alone, which could double if treated water from the Las Arenitas plant increases the river's perennial flow; increased hunting and fishing opportunities in the Mexicali Valley, currently valued at $1.2 million; increased social cohesion for the region's smaller towns and ejidos; and greater recreational opportunities for the region's more than 1 million residents (Zamora-Arroyo and Lellouch 2007). In recognition of the Delta's tourism potential, the Baja California Department of Tourism will be launching the Rio Hardy Scenic Route (Ruta del Rio Hardy) later this year.

3.3Main Drivers of Change—Population and Climate

This section presents a discussion of the most important drivers (See chapter 1, section 3) in the Lower Colorado River Basin: population growth (indirect) and climate change (direct). These two drivers have the greatest impact on the demand and supply, respectively, of water resources in the Basin (National Research Council 2007).

3.3.1 Population Growth

The number of people and their impact drives change in water use in the Colorado River Basin. In the United States, the population is projected to reach about 420 million by 2050 (Census 2005). Much of that growth is happening in the western United States, which has the fastest growth rate of any region (Markham 2006).

Impact can be seen in the distribution of people, especially as the United States becomes more metropolitan. There is a movement toward cities and suburban areas. In fact, eight of the top ten fastest growing cities are in Arizona, Nevada, and California. The country's three fastest growing cities were Gilbert, Arizona (266 percent growth from 1990–2000); Henderson, Nevada (170 percent growth); and Las Vegas, Nevada (141 percent growth; Census 2005).

In addition, age is an important indicator of impact. Twenty-six percent of the U.S. population was born between 1946 and 1964. The Baby Boomers are wealthier, spend more money, consume more resources, and have more homes per capita than any previous generation (Gillion 2006). Also people 65 and older tends to settle in states such as Arizona and Nevada (Markham 2006). On the flip side, a high percentage of youth are located in the western United States, which will sustain population growth in this region.

It has been noted that household dynamics also play a large role in resource consumption (Liu et al. 2003). In general, there are more houses in the United States and on average these houses have increased by more than 700 square feet (Markham 2006). In fact, five of the top ten states in growth in new housing units (Nevada, Arizona, Utah, New Mexico, and Colorado) are located in the Colorado River Basin (Markham 2006).

The states of Baja California and Sonora in Mexico are also growing rapidly. Of the approximately 3 million people that live in Baja California, over half are located in Tijuana, which is in part supported by water from the Colorado River. The population of Tijuana itself is projected to increase to more than 2.2 million by 2010 (SEDETI 2006). Mexicali is the other large city in the Mexican Delta and its current population is greater than 850,000 people with a projected increase to approximately 960,000 people in 2010 (Bravo 2001). In the state of the Sonora, the major city is San Luis Río Colorado, which had greater than 157,000 people in 2005 (INEGI 2006). In combination with the U.S. border towns of San Diego, Calexico, and San Luis, these urban centers in the Delta continue to grow and demand more water.

Between 2000 and 2030, the Lower Basin States' population is projected to grow by 60 percent, adding nearly 11 million people; both Arizona and Nevada are projected to more than double, adding nearly 8 million new residents (Census 2005b). This amount of growth is going to place tremendous pressure on urban water supplies and accelerate the shift from agricultural to urban uses, even if aggressive conservation methods are adopted by the region's largest cities.

3.3.2 Climate Change

There is increasing evidence that the majority of global warming observed in the last fifty years is attributable to human activities (IPCC 2007). The IPCC projects an increase in globally averaged surface temperature between 1.4 to 5.8 degrees Celsius between 1990 to 2100 (IPCC 2007). Global warming is expected to have a regional effect in the Southwest of at least a 1 to 2°C increase over the next fifty years (Barnett et al. 2004).

- Increases in temperature raise evaporation rates. A four degree temperature increase, could imply a 5 percent or more increase in evaporation rates in the Southwest.
- The relationship between temperature and precipitation is not fully understood. Some models predict a decrease in precipitation, while others an increase. However, there is more agreement on the type of precipitation expected with temperature increases; a greater proportion of precipitation will fall as rain than as snow. The implication of this change is that there will be less snow pack, decreasing this water source from the system and extending the length of time between annual runoff from snowmelt (spring to spring) (Dettinger et al. 2004; Stewart et al. 2004).
- Runoff is dependent on precipitation, so accordingly, there is uncertainty in runoff rates in the Southwest given temperature increases. However, the relationship between precipitation and runoff is clearer; a small decline in precipitation yields a proportionally larger decrease in runoff (Stewart et al. 2004).
- Even though the relationship between temperature and precipitation needs further study, there is general consensus that the system is very fragile and small changes in temperature will increase the variability in the system. Larger scale climatic events, such as El Niño/La Niña are expected to increase in intensity. There is much less certainty as to the extent, although it is believed that stronger El Niños will bring more precipitation to the Southwest and stronger La Niñas will bring greater drought (Merideth 2001). Drought cycles could be lengthened, which in the climatic past is not unprecedented (Hoerling and Eischeid 2007).
- In addition, the IPCC predicts that global mean sea level will rise by 0.05 to 0.32 m between the years of 1990 and 2050 with significant regional variations. This rise is mainly due to thermal expansion in the oceans and melting glaciers and ice caps (IPCC, 2001). Maps of the areas of the Gulf of California, which are susceptible to

climate induced sea level rise, show slight inundation of the mouth of Colorado River given a one meter elevation change (Environmental Studies Lab 2007, www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/sea_level_rise/gulf_california/slr_gc_i.htm). There currently exist no groundwater models to simulate salt water intrusion and other potential impacts in the Delta.

- Three recent models have projected decreased flows on the Colorado River through the twenty-first century. These projections range from a reduction of 11 percent by 2100 (Christensen and Lettenmaier 2006) to a reduction of 45 percent by midcentury (Hoerling and Eischeid 2007). The discrepancy in these models reflects differing assumptions, but fundamentally reduced flows will not be surprising. "The Southwest is likely past the peak water experience in the 20th century preceding the signing of the 1922 Colorado Compact: a decline in Lees Ferry flow will reduce water availability below current consumptive demands within a mere 20 years" (Hoerling and Eischeid 2007).

3.4 Conclusion

The ecosystem services provided by the Colorado River are great: drinking water, growing crops, providing energy, recreating, supporting pollinators, and reducing pollution, to name a few. The relative importance of these services has changed over time and recently, greater value has been placed on instream uses of water, included in the recreational, cultural, regulating, and supporting services categorized by the Millennium Ecosystem Assessment. However, the combined forces of population increases and larger probable droughts in the Southwest will increase the demand for water. As evaporation rates increase with temperature, agricultural lands will need more water to grow crops and cities will need more water for consumption for drinking, urban landscaping, and electrical power. If Colorado River flows are predicted to decrease, how will policymakers find more water in the system?

3.5 References

APN. 2006. "Grand Canyon National Park." Accessed at www.americanparknetwork.com/parkinfo/gc/ on October 3, 2006.

Barnett, T., R. Malone, et al. 2004. "The Effects of Climate Change on Water Resources in the West: Introduction and Overview." *Climatic Change* 62 (1–3): 1–11.

Bravo, S. G. 2001. *Housing Issues in Mexicali and the Imperial Valley*. San Diego, CA: Center for Border and Regional Economic Studies, 10.

Census. 2005. *Statistical Abstract of the United States 2004 to 2050*. Washington D.C.: U.S. Census Bureau.

Census. 2005b. "Interim Projections: Ranking of Census 2000 and Projected 2030 State Population and Change: 2000 to 2030." Accessed at www.census.gov/population/projections/PressTab1.xls on June 20, 2007.

Christensen, N. S. and D. P. Lettenmaier. 2006. "A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin," submitted to Hydrology and Earth System Sciences in Nov. 2006.

de Groot, R. and P. S. Ramakrishnan. 2005. *Cultural and Amenity Services. Ecosystems and Human Well-being: Current State and Trends, Vol. 1*. R. Hassan, R. Scholes, and N. Ash, eds. Washington D.C.: Island Press, 455–476.

Dettinger, M., D. Cayan, et al. 2004. "Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099." *Climatic Change* 62:283–317.

Environmental Studies Lab, Department of Geoscience, University of Arizona. 2007. "Maps of Susceptible Areas." Accessed at www.geo.arizona.edu/dgesl/research/other/climate_change_and_sea_level/sea_level_rise/gulf_california/slr_gc_i.htm on January 19, 2007.

Finlayson, C. M. and R. D'Cruz. 2005. *Inland Water Systems. Ecosystems and Human Well-being: Current State and Trends, Vol. 1*. R. Hassan, R. Scholes, and N. Ash, eds. Washington D.C.: Island Press, 455–476.

Fulton, W., R. Pendall, M. Nguyen, and A. Harrison. 2001. *Who Sprawls Most? How Growth Patterns Differ Across the U.S.* Washington D.C.: The Brookings Institution, Center on Urban and Metropolitan Policy, 1–24.

Gillion, S. 2006. Boomer Nation: The Largest and Richest Generation Ever, and How It Changed America. New York: Free Press.

Hoerling M. and J. Eischeid. 2007. "Past Peak Water in the Southwest." *Southwest Hydrology* 6 (1): 8–19, 35.

INEGI. 2006. "Población total por municipio según grandes grupos de edad, 2005." Accessed at www.inegi.gob.mx/est/contenidos/espanol/rutinas/ept.asp?t=mpob93&c=3839&e=26 on October 4, 2006.

IPCC. 2001. *Climate Change 2001: Synthesis Report—Summary for Policymakers*. Geneva: International Panel on Climate Change, 34.

LHCCC. 2006. "Community Profile." Accessed at www.havasuchamber.com/profile.htm on October 3, 2006.

Liu, J., G. C. Daily, et al. 2003. "Effects of household dynamics on resource consumption and biodiversity." *Nature* 421:530–533.

Luecke, D., J. Pitt, et al. 1999. *A Delta Once More: Restoring Riparian and Wetland Habitat in the Colorado River Delta*. Washington D.C.: Environmental Defense Fund, 64.

Millennium Ecosystem Assessment (MA). 2003. *Ecosystems and Human Well-being: A Framework for Assessment*. Washington DC: Island Press.

Millennium Ecosystem Assessment (MA). 2005. *Ecosystems and Human Well-being: Current State and Trends*. Washington DC: Island Press.

Markham, V. D. 2006. *U.S. National Report on Population and the Environment*. New Canaan, CT: Center for Environment and Population.

Merideth, R. 2001. *A Primer on Climatic Variability and Change in the Southwest*. Tucson, AZ: Udall Center for Studies in Public Policy, 32.

Morrison, J., S. Postel, and P. Gleick. 1996. *The Sustainable Use of Water in the Lower Colorado River Basin*. Oakland, CA: A joint report of the Pacific Institute and the Global Water Policy Project.

National Research Council. 2007. *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability*. Washington, D.C.: A report by the Committee on the Scientific Bases of Colorado River Basin Water Management.

Rivera, E. S. and Y. Carrillo Guerrero. 2006. Beneficios económicos de los flujos de agua en el delta del Rio Colorado: consideraciones y recomendaciones iniciales, *Gaceta ecológica* 80 (Instituto Nacional de Ecología, México).

Santopietro, G. D. and L. A. Shabman. 1992. "Property Rights to the Chesapeake Bay Oyster Fishery: History and Implications." *Society and Natural Resources* 5:165–176.

SDSU. 2004. *Agriculture in Our Binational Region*. Calexico, CA: San Diego State University, Imperial Valley Campus.

SEDETI. 2006. *Prontuario de Indicadores Oportunos de la Ciudad de Tijuana, B.C.: Demográficos y del Empleo*. Tijuana, México: Secretaría de Desarrollo Económico de Tijuana, 9.

Soley, W. B., R. R. Pierce, et al. 1998. Estimated Use of Water in the United States in 1995. Denver, CO: USGS, 79.

Stewart, I., D. Cayan, et al. 2004. "Changes in Snowmelt Runoff Timing in Western North America under a 'Business as Usual' Climate Change Scenario." *Climatic Change* 62:217–232.

Stynes, D. 2003. "Visitor Spending and Economic Impacts For National Park Units." Database accessed at web4.msue.msu.edu/mgm2/default.htm on July 28, 2007.

Stynes, D. and Y. Y. Sun. 2005. Economic Impacts of Grand Canyon National Park Visitor Spending on the Local Economy, 2003. Department of Community, Agriculture, Recreation and Resource Studies, Michigan State University. East Lansing, Michigan.

U.S. Bureau of Reclamation DEIS. 2007. Draft EIS—Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead. Boulder City, NV.

U.S. Bureau of Reclamation Web site. 2007. Accessed at www.usbr.gov/lc/ on July 30, 2007.

Watson, R. T. and A. H. Zakri. 2005. *Living Beyond Our Means: Natural Assets and Human Well-Being*. Washington D.C.: UN, 28.

Williams, Anita Álvarez de. 1983. Cocopá. In *Handbook of North American Indians, Vol. X*, Alfonso Ortiz, ed. Washington, D.C.: Smithsonian Institution Press, 99–113.

Woodhouse, C. A., S. T. Gray, et al. 2006. "Updated streamflow reconstructions for the Upper Colorado River Basin." *Water Resources Research* 42:1–16.

Valdés-Casillas, Carlos, O. Hinojosa-Huerta, M. Muñoz-Viveroz, F. Zamora-Arroyo, Y. Carrillo-Guerrero, S. Delgado-Garcia, M. López-Camacho, E. Glenn, J. Garcia, J. Riley,

D. Baumgartner, M. Briggs, C. T. Lee, E. Chavarría-Correa, C. Congdon, and D. Luecke. 1998. Information Database and Local Outreach Program for the Restoration of the Hardy River Wetlands, Lower Colorado River Delta, Baja California and Sonora, Mexico. A report to the North American Wetlands Council.

Zamora-Arroyo, F. and M. Lellouch. 2007. "Why we should dedicate treated water from Las Arenitas plant to the Hardy River: Economic, social, and ecological benefits," Sonoran Institute report. Tucson, AZ.

Chapter Four

WAYS TO GET MORE WATER

4.1 Introduction

Chapter Three demonstrates how water supplies are facing the pressures of climate and population change. Given that the environment is changing, how can water supplies be increased? This chapter lists numerous ways to augment supply, separated into three categories: augmentation projects, efficiency projects, and conservation programs.

Creativity and resourcefulness have always been a key trait of Westerners, especially when it comes to finding water in an arid land. In the nineteenth century, this implied settling close to rivers and streams or digging wells; in the twentieth century it took the form of huge dams and water diversion projects; in this century, it may involve developing new sources that were in the realm of science fiction just a few decades ago.

As California, Arizona, and Nevada are already using their full allocation of Colorado River water, increases in water use in the Lower Basin needed to fuel continued urban growth will have to come from a shift from the agricultural sector, transfers from the Upper Basin, or the development of new supplies both inside and outside the Basin. The Upper Basin currently consumes approximately 4 maf of its 7.5 maf annual allocation. Lower and Upper Basin States diverge in their projections of Upper Basin depletion and growth rates, with the Upper Colorado River Commission projecting use of 5.4 maf versus 4.8 maf for the Arizona Water Banking Authority (EWSR 2005).

In this chapter, projects such as cloud seeding in the Upper Basin (weather modification), aggressive development of groundwater in Nevada, and the construction of desalination plants in California, perhaps in exchange for additional Central Arizona Project (CAP)-like canals in Arizona, are considered. With all these potential new sources, the real threat to unlimited growth in the Southwest may be related to quality of life issues rather than water scarcity.

4.2 Augmentation Projects

4.2.1 Cloud Seeding in the Upper Basin

Recent research by the Bureau of Reclamation (Hunter et al. 2005) estimates that cloud seeding could generate an additional 1 maf per year of additional storage in basinwide snow pack during an average precipitation year and approximately 500,000 af per year in a drought year, *assuming a 10 percent increase in precipitation* (the accepted range is 5 to 20 percent for winter precipitation). The former estimate falls within the range of older findings, which estimate the yield at 900,000 to 1,870,000 af per year (Grant 1969; Elliott et al. 1973; Weisbecker 1974). A study prepared for the Upper Colorado River Commission estimates a cost on the order of $5 per acre-foot (Griffith and Solak 2006). However, studies over the past sixty years have not proven that cloud seeding can enhance water supplies for the Colorado River Basin (NRC 2003) and more studies are needed to understand the atmospheric processes that are being altered (Bruintjes 2007).

4.2.2 Aggressive Development of Ground and Surface Water in Nevada

The Bureau of Land Management (BLM) is currently preparing an Environmental Impact Statement

(EIS) of a proposed Southern Nevada Water Authority (SNWA) project to develop groundwater resources in Clark, Lincoln, and White Pine counties to provide as much as 180,000 af to the Las Vegas valley through a system of 115-195 wells, pipelines, pumping stations, and facilities for water treatment and power supply, the majority of which would be located on public land managed by the BLM (BLM Web site, 2007). The project is projected to cost $2 billion (*Reno Gazette Journal* 2005).

The SNWA also has an agreement to store up to 1.2 maf of water in Arizona's underground water bank for Southern Nevada's future use and had approximately 300,000 af stored in the Southern Nevada water bank. In recent years, Nevada has been withdrawing approximately 450,000 af per year from the Colorado River and returning 150,000 af per year of treated wastewater, thereby remaining within its 300,000 af per year consumptive use allocation (SNWA 2006).

In addition, surface water diversions from the Virgin and Muddy rivers could divert 113,000 af per year from the Virgin River, with an option to purchase an additional 5,000 af per year from Virgin Valley. SNWA can also use approximately 7,000 af per year from the Muddy River. These projects are currently on hold, but are estimated to cost up to $1.1 billion (Brean 2005).

4.2.3 Desalination Off the California or Sonora Coasts and Increased Canal Capacity in Arizona

As of the spring of 2006, there were twenty-one desalination plants proposed off the coast of California that, as a whole, could produce 603,000 af per year, the equivalent of 6 percent of the state's urban water demand (Cooley et al. 2006). In the future, states such as Nevada and Arizona could help finance such projects to augment their own water supply or perhaps in exchange for additional CAP-like canals to meet the growing demands of Phoenix and Tucson (Jenkins 2006). Alternatively, the Lower Basin States could build a Palo Verde–size power plant (3,825 MW) and modular desalter with a capacity of 1.5 maf in the area of El Golfo de Santa Clara to Puerto Peñasco along the Sea of Cortez in Sonora, Mexico and claim a portion of that water from the Colorado River at Imperial Dam for use by CAP, Metropolitan Water District (MWD), or SNWA. CAP canal capacity could be increased from the current 1.5–1.6 maf to 2.0–2.1 maf by upgrading pumping capacity and raising the canal lining (Dozier 2006). The main limiting factor in this method of water supply enhancement is energy costs, which are continually being reduced (NRC 2007).

4.2.4 Transbasin Imports

There are four suggested potential sites for transbasin imports: Clarks Fork to the Green River, Snake River to North Horse Creek, Bear River to Hams Fork Creek, and the Mississippi River to the Navajo River. The first three could be imported into Wyoming and the last could be imported into Colorado (Donnelly 2007).

Table 4.1. Projected supply gains and cost of various water augmentation projects.

Project	Supply (acre-feet per year)	Cost ($)
Nevada ground and surface water	305,000	3.1 billion
Desalination—ocean water	20,000–100,000	22–160 million
Desalination—brackish water in Yuma	100,000	40–190 million
Desalination—brackish water in So. CA	4,000	1.6–7.6 million
Desalination—brackish water in No. CA	40,000	16–76 million
Mississippi River Importation	675,000	925 million
Total	**839,000–919,000**	**4.1–4.5 billion**

4.3 Efficiency Projects

4.3.1 Lining of All-American Canal

The All-American Canal (AAC), which was built through sand in the 1930s, conveys approximately 3.1 maf per year. It stretches for 82 miles from Imperial Dam on the Colorado River to the Westside Main Canal, 160 miles east of San Diego. After a complex series of agreements among San Diego County, Imperial Valley, MWD, and federal authorities, work on a 23-mile concrete replacement along with the lining of a 35-mile stretch of the nearby Coachella Canal has begun, to be paid for by the state and San Diego County water ratepayers. The projects, with a total cost of $354 million, will be completed by the end of 2008. The lining of the AAC will result in the conservation of 67,700 af of water per year and of the Coachella canal, 132,000 af per year (Reclamation Web site, 2006).

Impacts from the lining of the AAC will include loss of seepage to Mexican farmers and to the 9,700-acre Andrade Mesa wetlands, which lie on both sides of the border. The Mexicali Economic Development Council, in conjunction with some environmental nongovernmental organizations, fought the lining in U.S. courts, causing a one-year project delay. In addition, the lining has strained diplomatic relations between the U.S. and Mexico.

4.3.2 Yuma Desalting Plant

The Main Outlet Drain Extension (MODE) Canal was completed in 1977 to divert drainage from the Wellton-Mohawk Irrigation and Drainage District (WMIDD) in compliance with salinity standards established by Minute 242 of the U.S.-Mexico Water Treaty. This diversion created the Ciénega de Santa Clara, now the largest wetland in the Delta. The Yuma Desalting Plant (YDP), completed in May 1992 at a cost of $256 million to treat and recapture some of the water, only operated until January 1993, due to engineering problems, expense, and surplus conditions that allowed Treaty requirements with Mexico to be continually met (Reclamation 2007).

The restarting of the YDP would produce 108,000 af per year at peak capacity but would also threaten the Ciénega de Santa Clara. The YDP/Ciénega workgroup was created at the invitation of Sid Wilson, CAP General Manager, to develop solutions that would both offset the impact of the continued bypass of return flows from WMIDD and preserve the Ciénega de Santa Clara. The Inspector General's Office estimates annual operating costs will be approximately $33.7 million. The water produced by the plant would cost $290 an acre-foot for Yuma groundwater. By comparison, the water Phoenix buys from the Salt River Project costs $20 an acre-foot (Van Der Werf 1994; Salt River Project 2007).

4.3.3 Drop 2 Reservoir

The Bureau of Reclamation is looking to build an 8,000 af reservoir along the All-American Canal near the border with Baja California that would capture overdeliveries of water to Mexico on average of 75,000 af per year (Reclamation Web site, 2006). Under an arrangement being discussed by the seven Basin States, Nevada would pay the estimated $147 million cost of the project in exchange for some of the water savings it generates. The reservoir is expected to come on-line in 2009 (Brean 2006; Reclamation 2007).

As a part of the agreement, the SNWA would temporarily suspend its plans to divert water from the Virgin and Muddy rivers to Las Vegas in order to avoid a long and costly legal battle among Basin States over the use of tributary water (Brean 2006).

4.3.4 Mexicali II (Las Arenitas) Wastewater Treatment Plant

The Mexicali II wastewater treatment plant, which went online in the spring of 2007, has a capacity of 31 ft^3/s (76,032 m^3/day) and is making the treated water available at $271 per acre-foot (price as of June 2007). The plant is designed to capture all of the effluent from Mexicali that was previously draining into the New River. At full capacity, the plant's discharge would be 22,500 af per year and could be used to supplement flows in the Río Hardy, a tributary to the Colorado River currently fed by agricultural drainage. The project, with a price tag of $30 million, includes three major components: a wastewater pumping station on the outskirts of Mexicali, a 16.5 mile 48-inch pipe and a wastewater treatment plant ("Las Arenitas") near the existing geothermal plant south of the city (CESPM 2007).

4.3.5 Water Efficiency Improvements in Mexico

Observations of water management in the Mexicali Valley suggest that there remain significant opportunities for improving water delivery and use through system automation, operational changes to improve the timing and quantity of deliveries, conversion to high capacity farm turnouts, canal lining, spill interception, land leveling, installation of canal turnouts for rapid delivery, improved cropping patterns, changed field irrigation practices and adaptation to low water-use technologies, improvements to drainage, and improved maintenance procedures. Water conserved from these efforts could be beneficial in terms of providing replacement supplies in the face of shortages, reducing dependence of local farmers on groundwater supplies, and providing environmental benefits (Pacific Institute 2006).

For example, the Mexicali Irrigation District (DDR 0014) reports approximately 645,000 af per year in conveyance losses that are recoverable (as opposed to conveyance losses that recharge groundwater supply). Based on some extremely rough estimates, of this total conveyance loss, approximately 150,000 af per year may be attributable to seepage from major canals. Much of this latter seepage apparently occurs along approximately 70 kilometers (km) of unlined canal sections, which could potentially be lined, by one estimate, for around $600 million pesos (US$56 million). These include the Reforma canal (28 km, estimated lining cost $150 million pesos or US$13.7 million), the Revolución canal (20 km, no lining estimate available), the Alimentador del Sur canal (5.5 km, no lining estimate available), and the Nuevo Delta canal (16 km, lining cost $300 million pesos or US$27.4 million). None of these sections reportedly cross or recharge aquifers from which significant amounts of groundwater are recovered or that support river flows or wetlands (Pacific Institute 2006).

4.3.6 Removal of Water-Consuming Invasive Species

Introduced in the U.S. as an ornamental and for use in erosion control beginning in the 1850s (NISIC Web site, 2006), tamarisk or salt cedar (*Tamarix ramosissima*) has crowded out native willows and cottonwoods on large portions of the Lower Colorado River mainstem. In Grand Canyon National Park, it now represents 10 percent of the vegetation (USGS 2005) and below Lake Mead, it is even more prevalent. Since the floods of the early 1980s, salt cedar has become the dominant riparian species in the Colorado River Delta.

It also consumes considerable amounts of water. In Colorado, for example, it is estimated that salt cedar occupies 55,000 acres and consumes 170,000 acre-feet of water per year than the native replaced vegetation (Colorado DNR 2004). A variety of efforts are being used throughout the Basin to try to eradicate the invasive species, including herbicide injection, stump removal, deliberate flooding, and the use of a leaf beetle (*Diorhabda elongata*) and its larvae to eat the plant's leaves.

Individual states, such as Colorado and New Mexico, have developed strategic plans to control the plant. The Salt Cedar and Russian Olive Control Demonstration Act, passed in November 2006, authorizes $80 million in funding for large-scale demonstration projects and associated research over a five-year period and the development of long-term management and funding strategies. Demonstration projects for control and revegetation will allow agencies to assess restoration effectiveness, water savings, wildfire potential, wildlife habitat, biomass removal, and the economics of restoration (Tamarisk Coalition Web site, 2006).

The following table summarizes the projected cost and supply to be gained from the efficiency projects mentioned in this section.

Table 4.2. Projected supply gains and cost of various water efficiency projects.

Project	**Supply (acre-feet per year)**	**Cost ($)**
Lining All-American Canal	67,700	354 million
Lining Coachella Canal	132,000	(see AAC)
Yuma Desalting Plant	108,000	256 million
Drop 2 Reservoir	25,000–100,000	147 million
Mexicali II Treatment Plant	22,500	26 million
Canal Lining Mexico	150,000	56 million
Tamarisk Removal—Lower Virgin	17,000	1.7 million
Tamarisk Removal—Lower Colorado	154,000	3.9 million
Total	**676,000–751,000**	**$845 million**

4.4 Conservation Programs

4.4.1 Municipal Water Conservation Programs

Water conservation is not a new idea. In the country as a whole, more than forty states now have some type of water conservation program and nationwide surveys indicate more than 80 percent of water utility customers support some form of water conservation (Kranzer 1988). The programs and practices water suppliers can adopt to significantly reduce consumption include metering, reducing water pressure, imposing water use restrictions, enacting zoning ordinances, changing price structures, and educating the public.

The ongoing drought has forced local officials to introduce municipal water conservation programs. In Nevada, for example, the Southern Nevada Water Authority (SNWA) imposed drought restrictions on fountains, golf courses, man-made lakes, vehicle washing, and lawn watering, offered incentives totaling $53 million since 1999 to residents willing to replace their lawns with water-efficient landscaping ($2 per square foot for the first 1,500 sq. ft., and $1 per sq. ft. thereafter), and imposed high penalties for water waste violations. Water savings from these programs were estimated at 50,000 af per year in 2003 (SNWA Web site, 2005) and in 2006, the average Southern Nevada household used 24 percent less water than in 2002 (Vogel 2007).

Most of the savings to be realized in household water consumption will occur outside the house, as that is where the majority of the water is used. In Phoenix, for example, almost 70 percent of household water is used to water lawns, fill pools, and run evaporative coolers (McKinnon 2005). Of the portion used indoors, the EPA estimates that nearly 75 percent is used in the bathroom, and more than half of that amount is used for toilet flushing (EPA Web site, 1992).

A three-year study of actual water savings from forty-two different programs offered by thirty utilities between 1994 and 2003 (audits, device giveaways, washing machine rebates, landscape conversions, toilet rebates, toilet distributions, rates, etc.) by the Water Conservation Alliance of Southern Arizona found that low-flow toilet distribution programs show the greatest savings per participant (27,000 gal. per year vs. predicted savings of only 12,000 gal. per year) and the lowest cost to the utility per af of water saved ($181), followed by landscape conversion programs (22,000 gal. per year), however these had a much larger cost per af of water saved ($1,099), second only to audit programs ($1,284) (ECoBA 2006). The study also shows that customers taking advantage of audit programs and washing machine rebate programs are significantly higher than average water users while those taking advantage of landscape conversion programs are significantly lower than average water users in their community.

One of the most effective municipal water conservation tools is a tiered pricing system, which encourage efficiency while ensuring that essential uses remain affordable to all. Studies have shown that urban users will reduce their water consumption in response to price increases. In Tucson, a 10 percent increase in water rates provided about 3 percent more revenue while triggering a 7 percent reduction in use (Billings and Day 1989). Tucson now uses a four-tiered pricing system where residential consumers who use a lot of water pay rates more than three times those in Las Vegas. Thanks in part to this rate structure, per capita water use in Tucson in only 60 percent that of Las Vegas (Vogel 2007). However, this pricing system was controversial to implement because it creates a "hardened" demand for water. Cities such as Las Vegas and Phoenix realize that having a "water buffer" in groundwater, lawns, and pools gives flexibility during droughts.

4.4.2 Agricultural Efficiencies

Approximately 85 percent of the water used in the Lower Basin in 1995 was for agriculture (Soley, Pierce et al. 1998). The sector can reduce its water consumption in three main ways: by investing in irrigation efficiency, by switching to lower water-use crops, and by retiring agricultural land. Farmers' decisions regarding the irrigation methods they use, the crops they grow, and the amount of land they irrigate, while likely rational at the farm level, are skewed by incentives (water prices and crop subsidies) that ignore the real scarcity of water. Consequently, water is misallocated in the agricultural sector and more is used than is efficient or desirable from a broader social and environmental perspective (Morrison et al. 1996).

Although flood irrigation is used in many parts of the Lower Basin in order to reduce soil salinity, there are still efficiencies that can be gained. These include maximizing for profit instead of yield to reduce the heightened marginal cost of the last additional units of water. In addition cropping patterns can rotate between salt tolerant and sensitive crops. Finally, economic incentives and technical support can be given to farmers who adopt agricultural efficiencies. Agricultural efficiencies are difficult to incentivize because water that is conserved cannot be saved and its "beneficial use" is lost, which is why many farmers flood irrigate.

The table below, taken from a report by the Pacific Institute and the Global Water Policy Project, illustrates potential water savings that could be achieved in Arizona under an environmentally sustainable agricultural water use scenario. The total estimated water savings, 1.2 maf, is roughly equivalent to the groundwater overdraft in the state (1 maf) plus the state's hypothetical environmental obligation to the Colorado River Delta (127,500 af), assuming environmental flows on the order of 750,000 af per year (see scenario in section 6.5) and a contribution from Arizona proportional to its Colorado River water entitlement under the Law of the River (Morrison et al. 1996).

4.4.3 Conjunctive Use

Conjunctive use of surface and groundwater combines the use of both to minimize the undesirable physical, environmental, or economic effects of each solution and to optimize the water demand/supply balance. Conjunctive use locations exist in the Phoenix, Pinal, and Tucson Active Management Areas in Arizona. Depending on the availability of surplus water for storage, conjunctive use could yield an extra 40,000 af per year in supply (Donnelly 2007).

Table 4.3. Potential water savings from sustainable agricultural water use in Arizona (Morrison et al. 1996).

Measure	**Assumption**	**Estimated Water Savings (acre-feet per year)**
Improvements in irrigation efficiency	Half of all irrigated cotton and major vegetable and citrus crops is placed under drip irrigation, reducing consumptive water losses from 30 percent to 5 percent; half of irrigated alfalfa, wheat, and barley is upgraded through surge, low-energy precision application (LEPA), or other means to reduce average consumptive water losses from 30 percent to 15 percent.	445,0004
Shifts in cropping patterns	One quarter of cotton and alfalfa irrigated areas is shifted to higher-value citrus and vegetable crops with an average total consumptive use of 2.76 acre-feet.	362,000
Total		**807,000**

4.5 Conclusion

This chapter lists numerous ways to augment supply, including major public works projects, efficiency projects, and conservation programs. Enhancing water reliability will be costly, but it is possible and probable, especially with the increasing demands from the growing population and reductions in supply from climate change. To adapt to these drivers of change, technological and management solutions to augmenting water supplies need to be met with institutional change.

4.6 References

Billings, R. B. and W. M. Day. 1989. Demand management factors in residential water use: The southern Arizona experience. *Journal of the American Water Works Association* 81(3):58–64.

Brean, H. 2005. "Moapa Valley Residents Weigh in on Water Plans," *Las Vegas Review-Journal*, July 13, 2005.

Brean, H. 2006. "Nevada Would Pay for Border Reservoir in Deal for More Water" *Las Vegas Review-Journal*, Jan. 14, 2006.

Bruintjes, R. 2007. Seeding Is Not Just Believing, *Southwest Hydrology* (March/April 2007):26–33.

Bureau of Land Management Web site. 2007. Frequently asked questions on SNWA groundwater development project. Accessed at www.nv.blm.gov/GWProjects/snwa_project/faq.htm on May 22, 2007.

CESPM. 2007. Comisión Estatal de Servicios Públicos de Mexicali. Personal communication from Ing. Francisco Morales, June 22, 2007.

Colorado Department of Natural Resources. 2004. 10-Year Strategic Plan on the Comprehensive removal of Tamarisk and the Coordinated Restoration of Colorado's Native Riparian Ecosystems. Accessed at dnr.state.co.us/NR/rdonlyres/D30D7294-5E0B-4BCB-BE7D-DB2E7F1A1CEE/0/Complete_Tamarisk_10_year_ plan.pdf on August 3, 2006.

Cooley, H., P. Gleick, and G. Wolff. 2006. Desalination with a Grain of Salt—A California Perspective. Pacific Institute, Oakland, CA. Accessed at www.pacinst.org/reports/desalination/desalination_report.pdf on May 22, 2007.

Donnelly, D. 2007. "Strategies for Augmenting the River: Evolving Issues and Solutions" CLE International presentation at a meeting on the Law of the Colorado River in Las Vegas, NV on May 10, 2007.

Dozier, L. 2006. Notes for WRCC Annual Conference. Accessed at cals.arizona.edu/AZWATER/conf2006/presentations/Dozier%20Larry.pdf on May 22, 2007.

ECoBA. 2006. Evaluation and Cost Benefit Analysis of Municipal Water Conservation Programs. Water Conservation Alliance of Southern Arizona. Accessed at www.watercasa.org/research/ecoba/PDFs/INTRO.pdf on May 22, 2007.

Elliott, R. D., J. F. Hannaford, and R. W. Schaffer. 1973. *Twelve Basin Investigation; Analysis of Potential Increases in Precipitation and Streamflow Resulting from Modification of Cold Orographic Clouds in Selected River Basins of the western United States*. North American Weather Consultants Report No. 15-18 to the Bureau of Reclamation.

EWSR. 2005. *Enhancing Water Supply Reliability* newsletter. Issue 4, Summer 2005. Accessed at www.ag.arizona.edu/AZWATER/EWSR/4qr.newsletter.summer.05.pdf on May 22, 2007.

Grant, Lewis O. 1969. An operational adaptation program of weather modification for the Colorado River Basin; interim report for the period, July 1968–June 1969. Dept. of Atmospheric Science, Colorado State University, Ft. Collins, CO.

Griffith, Don A. and M. Solak. 2006. The Potential Use of Winter Cloud Seeding Programs to Augment the Flow of the Colorado River. White paper prepared by North American Weather Consultants, Inc. for the Upper Colorado River Commission. Sandy, UT.

Hunter, S. M., S. Meyer, and R. Aman. 2005. Water Augmentation from Cloud Seeding in the Colorado River Basin. Bureau of Reclamation Technical Service Center, 9 p.

Jenkins, M. 2006. "The Perpetual Growth Machine." *High Country News* 38, no. 11 (June 12, 2006).

Kranzer, B. S. 1988. Determinants of Residential Water Conservation Behavior. An Investigation of Socio-economic and Psycho-dynamic Factors. Carbondale, Southern Illinois University, Ph.D. dissertation.

McKinnon, S. 2005. "Cities Push Water Conservation: Use Less without Sacrifice," *Arizona Republic*, Jan. 6, 2005.

Morrison, J., S. Postel, and P. Gleick 1996. The Sustainable Use of Water in the Lower Colorado River Basin. A joint report of the Pacific Institute and the Global Water Policy Project, Oakland, CA.

National Invasive Species Information Center website (2007). Accessed at www.invasivespeciesinfo.gov/council/ismonth/archives/tamarisk/tamarisk.html on November 10, 2006.

National Research Council. 2003. *Critical Issues in Weather Modification Research*. Washington, D.C.: The National Academies Press, 144 pp.

National Research Council. 2007. *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability*. Washington, D.C.: The National Academies Press, 222 pp.

Pacific Institute. 2006. Conservation before Shortage, Appendix B: Taking ICS to Mexico: International Opportunities in the Seven States Agreement. Accessed at www.pacinst.org/topics/water_and_sustainability/colorado_river/shortage_proposal/CBS_II_appendix_B.pdf on May 22, 2007.

Reclamation. 2007. Yuma Desalting Plant. Accessed at www.usbr.gov/lc/yuma/facilities/ydp/yao_ydp.html 2on July 19, 2007.

Reno Gazette Journal. 2005. "Opponents unite against water plan," May 6, 2005.

Salt River Project. 2007. "Summary of SRP Water Allocation and Water Fees for 2007." Accessed at www.srpnet.com/water/irrigation/pdfx/pricesummary0807.pdf on July 19, 2007.

Soley, W. B., R. R. Pierce, et al. 1998. *Estimated Use of Water in the United States in 1995*. Denver, CO: USGS, 79.

Southern Nevada Water Authority Web site. 2005. Accessed at www.snwa.com/html/drought_restrictions_incentives.html on May 22, 2007.

Southern Nevada Water Authority. 2006. SNWA Water Resources. Accessed at www.nvgroundwaterproject.com/assets/pdf/snwa_resources_booklet.pdf on May 22, 2007.

Tamarisk Coalition Web site. 2006. Accessed at www.tamariskcoalition.org on June 20, 2007.

U.S. Bureau of Reclamation. 2006. All-American Canal Web site accessed at www.usbr.gov/dataweb/html/allamcanal.htmlon May 22, 2007.

U.S. Bureau of Reclamation (2007). Drop 2 Storage Reservoir Project Overview and Status. Presentation access at www.iid.com/Media/IID-Drop-2-Project-Overview-&-Status.pdf on Aug. 15, 2007.

U.S. Environmental Protection Agency. 1992. "How We Use Water in These United States." Accessed at esa21.kennesaw.edu/activities/water-use/water-use-overview-epa.pdf on Dec. 19, 2006.

USGS. 2005. The State of the Colorado River Ecosystem in Grand Canyon: A Report of the Grand Canyon Monitoring and Research Center 1991–2004. USGS Circular 1282. Reston, VA: USGS.

Van Der Werf, Martin. 1994. "Draining the Budget to Desalt the Colorado." *High Country News* 26, no. 3.

Vogel, E. 2007. "Water Pricing Policy Questioned—Tiered Rate Structure Suggested to Promote More Conservation." *Las Vegas Review-Journal*, March 2, 2007.

Weisbecker, L. W. 1974. The Impacts of Snow Enhancement; A Technology Assessment of Winter Orographic Snowpack Augmentation in the Upper Colorado River Basin. Stanford Research Institute, University of Oklahoma Press, Norman, Oklahoma.

Chapter Five

INSTITUTIONAL AND GOVERNANCE CHALLENGES

5.1 Introduction

Inclusion of the Delta in agreements regarding allocation of water in the Colorado River Basin is ultimately a challenge of governance that has several aspects. Following the MA framework, a key challenge will be to agree on water policy objectives consistent with emerging values of ecosystem services, and to achieve consistency between these objectives, the Law of the River and policies in other sectors, particularly agriculture—which accounts for approximately 80 percent of water use in the Basin, and with development patterns, for which there is no single policy. The framework for Colorado River water management is the Law of the River, which encompasses numerous operating criteria, regulations, and administrative decisions included in federal and state statutes, interstate compacts, court decisions and decrees, an international treaty, and contracts with the Secretary of the Interior, as elucidated in chapter 2.

Allocation of water is and will always be a contested process that involves the renegotiation of rights and responsibilities as values change, just as occurred during the Industrial Revolution, when hydropower was considered to have greater value to society than the natural flow of the river, resulting in a loss to those who had riparian rights. These kinds of changes tend to be implicit in the development of physical water infrastructure such as irrigation systems and dams. Similarly, ecosystem management also implies the negotiation of new rights, which come bundled with responsibilities to protect the ecosystem, and in which the use of land, water and other natural resources are limited to those uses that do not impair its function (Sax 1993).

In the western United States, water rights are defined by the doctrine of prior appropriation, which constrains who gets water and in what amount. These rights are hierarchical in that senior rights hold priority over junior rights. In addition, rights can be lost if the water is not put to a beneficially consumptive use. Transfer of these rights is also difficult and has high transaction costs because the Secretary of the Interior has to approve any diversion from the mainstem of the Colorado River. Therefore, the Law of the River is rigid and creates a system where rights are coveted and protected, even if use is inefficient and the difficulty in transferring rights only establishes further inflexibility.

Despite the rigidity of the system that the Law of the River creates, it has arguably functioned well. Users have received their allocation of the Colorado River and the Secretary of the Interior has never declared a shortage in the Basin. However, the future of water supply in the Colorado River Basin is facing increasing pressures. Climate change is projected to raise temperatures and increase the length of drought periods in the western United States. Population is growing in the Basin, placing greater demands on water. Recognition of ecological uses for water and for sustaining inland water ecosystems and the services they provide is increasing. Climate change, population growth, and changing norms, which are creating new uses for water, all place pressure for changes in the Law of the River. These adaptations can only be created by governance changes that result from cooperative behavior between actors within water management institutions.

Governance changes are clearly occurring, as can be seen in the development of Lower Colorado River Basin Shortage Guidelines, and coordinated management strategies for lakes Powell and Mead under low reservoir conditions by the Bureau of Reclamation as required under the National Environmental Policy Act. The chapter begins with a brief explanation of river operations by the Bureau of Reclamation and of the elements common to all the alternatives examined by Reclamation in this Environmental Impact Statement (EIS). Then it gives an overview of the five EIS alternatives, focusing more particularly on the Seven States alternative, which has become the basis for Reclamation's preferred alternative. This alternative represents unheard of cooperation among Basin States as the Law of the River adapts to a changing environment. The chapter ends with a summary of recent changes to the national water law in Mexico, and conclusions that highlight further challenges ahead.

5.2 Colorado River Operations

5.2.1 Long Range Operating Criteria

The Long Range Operating Criteria (LROC) for the Colorado River Reservoirs was created in 1970, pursuant with Section 602 of the 1968 Colorado River Basin Project Act. At the start of every year, the Secretary transmits an Annual Operating Report to Congress and the governors of the Basin States explaining the previous year's operation and the projected operation for the following year. This projection includes the quantity of water necessary to be in storage by September 30th of that year. This LROC primarily establishes a minimum objective annual release from Lake Powell of 8.23 maf.

- If active storage in the Upper Basin cannot fulfill the Colorado River Compact and U.S.-Mexico Water Treaty obligations or the active storage in Lake Powell is less than that of Mead, then only 8.23 maf will be released.
- If the Upper Basin projects high active storage, then release from Lake Powell can be at a rate greater than 8.23 maf/y. This increase occurs if there is a consumptive use in the Lower Basin, to maintain equal active storage in lakes Mead and Powell, and to avoid anticipated floods from Lake Powell.

5.2.2 Interim Surplus Guidelines

The 1970 LROC remained fully intact until very recently. In the 1950s, California began to use more than their apportionment of 4.4 maf. To bring California into compliance, the Basin States and the Department of Interior agreed on the Interim Surplus Guidelines (ISG) in 2001. The ISG provided California with a way to reduce its overreliance on Colorado River water. If California met benchmarks met by the ISG, it would have access to extra water during a grace period, called the "soft landing." The ISG also added specificity to the LROC with respect to how surplus determinations are made to the Lower Basin states of Arizona, California, and Nevada through the year 2016. Essentially, a potential annual surplus determination is tied to a range of elevation levels in Lake Mead.

- If Lake Mead is at or below 1125 ft., a normal or shortage year is declared.
- If Lake Mead is between 1125 ft. and 1145 ft., a Partial Domestic Surplus is declared.

- If Lake Mead is above 1145 ft., a Full Domestic Surplus is declared.
  In a Partial or Full Domestic Surplus, the surplus water is delivered in varying quantities for domestic use by the Metropolitan Water District (MWD), the Southern Nevada Water Authority (SNWA), and Arizona.

5.2.3 Shortage Guidelines

The ISG are to remain in place through 2016, but as part of the proposed Shortage Guidelines, it may be extended to 2026. From 2000 to 2006, the Colorado River experienced the worst drought conditions in approximately one hundred years of recorded history. During this period, storage in reservoirs dropped to less than 60 percent of capacity. As stated before, the Secretary has never declared a shortage under the LROC, but that declaration seems more possible than before. Therefore, in May 2005, the Secretary began to develop shortage guidelines for the Lower Colorado River and coordinated management strategies for Lake Powell and Lake Mead (Reclamation 2006b). Reclamation has implemented a public participation program and has conducted scoping meetings to prepare an environmental impact statement (EIS). The draft of this EIS was released in February 2007 the final EIS by November 2007, and a Record of Decision by December 2007.

The key elements in the five alternatives are:

- Creation of shortage guidelines: Alternatives range from complete draw down of Lake Mead to 895’ to absolute shortage protection at 1000’.
- Coordinated reservoir operations: Alternatives range from comanagement of Lake Mead and Lake Powell based on a consistent delivery of 8.23 maf from Lake Powell under most conditions, to balancing both reservoirs under low-reservoir conditions.
- Storage and delivery of conserved water: Alternatives range from no storage for conserved or nonsystem water to storage before shortage using intentionally created surplus (ICS) credit system.
- Interim surplus guidelines: Alternatives range from not changing the ISG to extending modified ISG to 2025.

5.3 Shortage Guidelines Alternatives

The draft EIS presents five alternatives for determining shortage criteria and management strategies for Lakes Mead and Powell: No Action Alternative, Basin States Preliminary Alternative, Conservation Before Shortage Alternative, Water Supply Alternative, and Reservoir Storage Alternative.

- No Action Alternative. The Secretary will continue to make operating decisions in accordance with the LROC. The effects of this are unknown because shortage criteria are currently not explicit.
- Basin States Preliminary Alternative.[8] This alternative proposes coordinated management of Lake Powell and Lake Mead and establishes an “Intentionally Created Surplus” (ICS) credit system to store water during surplus years for use in drought years.
- Conservation Before Shortage (CBS) Alternative.[9] This alternative builds off of the Basin States Alternative, but utilizes ICS credits before shortage is determined, linking levels of Lake Mead to amounts of water saved. This water is then dedicated for environmental use.
- Water Supply Alternative: This alternative proposes to maximize

water deliveries at the expense of storage in times of shortage to meet downstream entitlements.

- Reservoir Storage Alternative: This alternative proposes to maximize storage to meet hydroelectric and recreational demands.

These alternatives and their comparative elements are located in the matrix below (Table 5)

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[8] The Basin States Preliminary Alternative can be downloaded at: www.usbr.gov/lc/region/programs/strategies/documents.html.

[9] Conservation Before Shortage II Alternative can be downloaded at: www.usbr.gov/lc/region/programs/strategies/documents.html.

Table 5.1. Lower Basin shortage guidelines and coordinated management of Lake Powell and Lake Mead—Matrix of alternatives (Reclamation 2007)

Table 5.1 Matrix of Alternatives

Alternatives	Shortage Guidelines to Reduce Deliveries from Lake Mead (elevation in feet, msl)	Coordinated Reservoir Operations (Lake Mead & Lake Powell) (elevation in feet, msl)	Lake Mead Storage and Delivery of Conserved System and Non-system Water	Interim Surplus Guidelines (ISG) for Deliveries/Releases from Lake Mead
No Action	▪ Determination made through the AOP process, absent shortage guidelines ▪ Reasonably represented by a two-level shortage strategy - probabilistic protection of Lake Mead elevation 1,050 and absolute protection of Lake Mead elevation 1,000	▪ Minimum objective release of 8.23 maf from Lake Powell unless storage equalization releases are required ▪ Operation at low reservoir levels reasonably represented by a 8.23 maf release from Lake Powell down to Lake Powell dead pool	▪ No water management mechanism for storage and delivery of conserved system and non-system water	▪ No modification or extension of the ISG which end in 2016 ▪ After 2016, determination made through the AOP process, absent surplus guidelines; reasonably represented by the spill avoidance (referred to as the 70R) strategy
Basin States	▪ Shortages (i.e., reduced deliveries in the U.S.) of 333, 417, and 500 kaf from Lake Mead at elevations 1,075, 1,050, and 1,025 respectively [1] ▪ Initiate efforts to develop additional guidelines for shortages if Lake Mead falls below elevation 1,025 (Note: Includes re-consultation with Basin States)	▪ Under high reservoir conditions, minimum objective release of 8.23 maf from Lake Powell unless storage equalization releases are required ▪ Under lower reservoir conditions, either reduce Lake Powell release or balance volumes depending upon elevations at Lake Powell and Lake Mead	▪ Storage and delivery of conserved system and non-system water through Intentionally Created Surplus (ICS) ▪ Maximum total ICS in Lake Mead of 2.1 maf ▪ System assessment of 5% when ICS is created	▪ Modification of ISG to eliminate Partial Domestic Surplus condition ▪ Extension of the modified guidelines through 2026
Conservation Before Shortage	▪ Shortages are implemented in any given year when necessary to keep Lake Mead above SNWA's lower intake at elevation 1,000 (absolute protection of elevation 1,000)	▪ Under high reservoir conditions, minimum objective release of 8.23 maf from Lake Powell unless storage equalization releases are required ▪ Under lower reservoir conditions, either reduce Lake Powell release or balance volumes depending upon elevation at Lake Powell and Lake Mead	▪ Prior to shortage, conservation of different volumes of water tied to Lake Mead elevation ▪ Storage and delivery of conserved system and non-system water through ICS ▪ Water for environmental uses ▪ Maximum total storage of conserved system and non-system water up to 4.2 maf ▪ System assessment of 5% when ICS is created	▪ Modification of ISG to eliminate Partial Domestic Surplus condition ▪ Extension of the modified guidelines through 2026
Water Supply	▪ Release full annual entitlement amounts until Lake Mead is drawn down to dead pool (elevation 895)	▪ Minimum objective release of 8.23 maf from Lake Powell unless storage equalization releases are required ▪ Balancing if Lake Powell is below elevation 3,575 or Lake Mead is below elevation 1,075	▪ No water management mechanism for storage and delivery of conserved system and non-system water	▪ Extension of the existing ISG through 2026
Reservoir Storage	▪ Shortages (i.e., reduced deliveries in the U.S.) of 500, 667, 833, and 1,000 kaf from Lake Mead at elevations 1,100, 1,075, 1,050, and 1,025 respectively [1]	▪ Minimum objective release of 8.23 maf from Lake Powell if Lake Powell is above elevation 3,595 unless storage equalization releases are required ▪ 7.8 maf release from Lake Powell between Lake Powell elevations of 3,560 and 3,595 ▪ Balancing below Lake Powell elevation 3,560	▪ Storage and delivery of conserved system and non-system water ▪ Maximum total storage of conserved system and non-system water of 3.05 maf ▪ System assessment of 10% of stored conserved system and non-system water	▪ Provisions of existing ISG terminate after 2007, and during period from 2008-2026, surplus determinations are limited to 70R and Flood Control conditions
Preferred	▪ Shortages (i.e., reduced deliveries in the U.S.) of 333, 417, and 500 kaf from Lake Mead at elevations 1,075, 1,050, and 1,025 respectively [1] ▪ Initiate efforts to develop additional guidelines for shortages if Lake Mead falls below elevation 1,025 (Note: Includes re-consultation with Basin States)	▪ Under high reservoir conditions, minimum objective release of 8.23 maf from Lake Powell unless storage equalization releases are required ▪ Under lower reservoir conditions, either reduce Lake Powell release or balance volumes depending upon elevations at Lake Powell and Lake Mead	▪ Storage and delivery of conserved system and non-system water through ICS ▪ Maximum total ICS in Lake Mead of 2.1 maf (with opportunity to increase up to 4.2 maf) ▪ System assessment of 5% when ICS is created	▪ Modification of ISG to eliminate Partial Domestic Surplus condition ▪ Extension of the modified guidelines through 2026

[1] These are amounts of shortage (i.e., reduced deliveries in the United States). As in the Draft EIS, the Final EIS will include modeling assumptions that identify water deliveries to Mexico pursuant to the 1944 Water Treaty.

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5.4. Basin States Alternative

The Basin States Alternative represents cooperation in the face of crisis. The ongoing extended drought in the western United States, the desire to maintain levels of growth, and fear of interstate litigation have brought states to the table to comanage the Colorado River. Their proposal gives the following ranges for the key elements mentioned previously:

- Creation of shortage guidelines: Lake Mead deliveries will be reduced by 0.4 maf, 0.5 maf, and 0.6 maf when elevation levels reach 1075 ft., 1050 ft., and 1025 ft., respectively.
- Coordinated reservoir operations: Maintain the minimum objective release of 8.23 maf from Lake Powell under high reservoir conditions, or balance the lakes under low reservoir conditions.
- Storage and delivery of conserved water: Establishes a system to conserve up to 2.1 maf in lake Mead and to deliver up to 1 maf/yr. of conserved water.
- Interim surplus guidelines: Eliminates the Partial Domestic Surplus condition in the ISG and extends the ISG to 2025 to match the Shortage Guidelines dates.

The one element that has yet to be discussed and which is the most creative is the storage and delivery of conserved water. The ability to "save for a rainy day" (irony intended) or to conserve water in surplus years to ease the impact of shortage years introduces remarkable new flexibility under the Law of the River.

5.5 Preferred Alternative and the Inclusion of Mexico

On June 18, 2007, Reclamation issued a preferred alternative that is almost identical to the Basin States Alternative (Reclamation 2007). It does not include a system for voluntary and compensated conservation of water tied to Lake Mead elevation prior to the declaration of a shortage, as recommended by the Conservation Before Shortage Alternative, but it leaves open the possibility of extending the intentionally created surplus (ICS) concept to Mexico, a consideration that is outside the scope of the EIS process.

A consortium of U.S. environmental organizations collectively representing more than 4 million members nationwide urged Reclamation in its preferred alternative to explicitly allow for the participation in the ICS mechanism of the U.S. federal government and others that are not currently Colorado River water contractors, including U.S. NGOs, so that water could be dedicated to environmental purposes in the Delta and elsewhere in the Lower Basin (DEIS comments 2007). Allowing for the participation of Mexico in the future would make it possible for Mexico to store water in Lake Mead in exchange for conservation, for example, water efficiency improvements in the Mexicali Valley (see chapter 4) that it could then use for pulse flows to the Delta.

The Mexican Section of the binational IBWC/CILA submitted comments on the proposed alternatives (before the issuance of a preferred alternative). Mexico strongly objects to what it perceives to be an incorrect interpretation of the extraordinary drought clause of the 1944 Treaty and to the suggested reduction in Mexico's allotment that Reclamation uses in its shortage models. Mexico claims that any reduction in its allotment must be relative to the total for both the Upper and the Lower basins (of which Mexico's share is 9.1 percent) rather than be based on its share of only the Lower Basin amount (16.7 percent) (DEIS comments 2007). The treaty itself is not clear when it comes to shortages declared due to extraordinary drought, stating only that "the water allotted to Mexico. . . will be reduced in the same proportion as consumptive uses in the United States are reduced" (IBWC 1944).

In addition, Mexico indicates a strong interest in being part of any discussion about the sustainable use of Colorado River resources, in being a proportional beneficiary of any conservation measures agreed to by the seven Basin States, and in the possibility of storing water in the system for use at a later date (the "extension of ICS to Mexico" idea) (DEIS comments 2007).

5.6 Legal Reform in Mexico

Mexico has moved one step forward in implementing basin-level management. In 2004, the country reformed its National Water Law, which governs the use of rivers, lakes, and aquifers in the country (Mexico 2004). The new decree reorganizes the National Water Commission (CNA in Spanish) under the Ministry of Environment and Natural Resources (SEMARNAT) to increase its national governance role as well as form regional groups organized by hydrological basins, know as "Organismos de Cuenca." The reforms also strengthen the government's enforcement authority, authorizing new sanctions and increasing fines for polluters, as well as recognizing the environmental use of water.

More importantly, the National Water Law allows for the transfer of water rights and use between entities. For example, an entity could acquire water rights from a farmer with marginal farm land at a negotiated fair price. Then this entity could change the type of use of the water from agricultural use to conservation use following the specifications of Article 43 of the Regulations of the National Water Law.

5.7 Minutes of Treaty

The International Boundary and Water Commission (IBWC) was created from the 1944 U.S.-Mexico Water Treaty, which is amended using "Minutes." Some of these Minutes have shown great promise in benefiting environmental and human welfare and the IBWC provides a forum for discussion and negotiation of these issues. For example, Minute 242, mandated that Colorado River only of a specific salinity crossed into Mexico to prevent harm to agricultural and municipal infrastructure and people (IBWC 1973). In Minute 261, the IBWC was given authority over problems concerning health or safety or impairing beneficial uses of international water (IBWC 1979). Finally, Minute 306 proposes to conduct joint studies to research ecological uses for water (IBWC 2000). The IBWC consulted with the U.S. State Department in negotiating and agreeing to Minute 306, which is a major step toward management of this binational Delta.

5.8 Conclusion

This chapter gives a brief explanation of river operations on the Colorado River below Glen Canyon Dam. It then describes proposed changes to the Law of the River under the framework of the Shortage Guidelines EIS. These proposed changes open up a new realm of possibilities. Allowing for conservation of water behind Lake Mead not only opens up the possibility for dealing with drought in the western United States; it also opens up the possibility for creating pulse flows on the Colorado to be used for environmental purposes. In spite of its many constraints, the Law of the River has the ability to evolve to meet the competing demands of an extended drought, high growth and the desire to protect and restore key ecosystems and their services.

Further steps will be necessary to ensure effective participation in a transboundary management strategy, and to find ways to cover the costs of ecosystem services that are feasible and fair—particularly the upfront costs of change. Willingness of stakeholders to pay for services, whether as individual users, as taxpayers or as donors to nonprofit organizations, is inextricably linked to confidence in the effectiveness of management actions, and whether the distributions of costs and benefits is accepted as fair. Absent the institutions needed to ensure this, economic value is no more than hypothetical, as there would be no incentive to pay or to take actions needed to ensure provision of the service. Such arrangements provide a foundation for the use of economic instruments to create incentives to achieve policy objectives, and for transforming the economy to one in which ecosystem services are valued.

5.9 References

DEIS comments. 2007. "Comments on Draft Environmental Impact Statement." Accessed at www.usbr.gov/lc/region/programs/strategies/DEIScomments/index.html on June 21, 2007.

IBWC. 1944. "Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande—Treaty Between the United States of America and Mexico." Accessed at www.ibwc.state.gov/Files/1944Treaty.pdf on June 21, 2007.

IBWC. 1973. "Permanent and definitive solution to the international problem of the salinity of the Colorado River." Accessed at www.ibwc.state.gov/Files/Minutes/Min242.pdf on July 19, 2007.

IBWC. 1979. "Recommendations for the solution to the border sanitation problem." Accessed at www.ibwc.state.gov/Files/Minutes/Min261.pdf on July 19, 2007.

IBWC. 2000. "Conceptual framework for United States-Mexico studies for future recommendations concerning the riparian and marine ecology of the limitrophe section of the Colorado River and its associated Delta." Accessed at www.ibwc.state.gov/Files/Minutes/Min306.pdf on July 19, 2007.

Mexico. 2004. Reforms to the *Ley de Aguas Nacionales*, published in the *Diario Oficial*, April 29, 2004.

Reclamation. 2006a. "Long Range River Operations." Accessed at www.usbr.gov/lc/riverops.html on December 27, 2006.

Reclamation. 2006b. "Development of Lower Colorado River Basin Shortage Guidelines and Coordinated Management Strategies for Lakes Powell and Mead Under Low Reservoir Conditions." Accessed at www.usbr.gov/lc/region/programs/strategies.html on December 27, 2006.

Reclamation. 2007. "Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead" accessed at www.usbr.gov/lc/region/programs/strategies.html on June 21, 2007.

Chapter Six

SCENARIOS: WAYS TO ALLOCATE WATER

6.1 Introduction

If anything is apparent, it is that change is inevitable, albeit at times slow. Chapter 1 shows how emerging concepts of ecosystem services change how we value our environment. Chapter 2 gives a brief environmental and social history of the Lower Colorado River. Chapter 3 describes how changing climate and increasing population in western North America are placing pressure on an already overallocated supply of Colorado River water. Chapter 4 demonstrates how, while costly, water supplies can be augmented. Chapter 5 shows that institutional change is possible and indeed occurring in response to these external pressures.

Together these chapters show that changes have been and are occurring and that the costs of adapting to these changes are not only infrastructure and operational costs of possible projects and programs, but also the price paid by different social groups, and the cost to the environment. And it is the *allocation scheme*—how we manage the water—more than absolute supply that determines the winners and losers.

This section presents synopses of four possible futures for the Lower Basin. Each scenario looks at a set of policies that were followed and the outcomes that they produced. As a whole, they are intended to show how our choices today will affect our quality of life to 2050.

6.2 Dry Future

> A big tamarisk can suck 73,000 gallons of river water a year. For $2.88 a day, plus water bounty, Lolo rips tamarisk all winter long.
>
> Ten years ago, it was a good living. Back then, tamarisk shouldered up against every riverbank in the Colorado River Basin, along with cottonwoods, Russian olives, and elms. Ten years ago, towns like Grand Junction and Moab thought they could still squeeze life from a river.
>
> "The drought could break any time. Why can't they give us a couple more years? It could break any time." But even as he says it, Lolo doesn't believe. Ten years ago, he might have. But not now. Big Daddy Drought's here to stay. (Bacigalupi 2006)

After experiencing one of the worst droughts in recent history between 2000 and 2004, water managers and others in the Lower Basin were hoping for a reprieve. Storage in lakes Powell and Mead had dropped to approximately 50 percent of capacity and inflows were still significantly below average. The reprieve came in the form of a few wetter than normal years and modest increases to system storage, leading managers to conclude that the drought was over.

It was not. In the ensuing years, temperatures increased in the arid West and drought conditions worsened significantly. Evapotranspiration exceeded precipitation throughout the Basin, reducing runoff. The climate models devised early in the twenty-first century were essentially correct: drought had become a regular condition.

A shortage of 333,000 af was declared when Lake Mead's elevation reached 1,075 feet in 2009. In 2011, the lake's level dropped below 1,025 feet and the Southern Nevada Water Authority was forced to use its just-completed Intake No. 3. By 2013, the level had dropped to below 1,000 feet, Las Vegas was running out of water and the Basin States were not able to reach an agreement on how to proceed. The drought, in fact, was to last for another fifteen years.

Relative to a mean flow of 14.7 maf inferred from the tree ring record (Woodhouse et al. 2006), streamflow declined by 25 percent to 11 maf by 2030 and by 39 percent to a mere 9 maf by 2050 (Hoerling and Eischeid 2007). This reduction in flows was at least double that predicted by earlier hydrologic models (Christensen et al. 2004; Milly et al. 2005; and Christensen et al. 2006). The Upper Basin was no longer able to regularly meet its obligations to the Lower Basin, and the Compact, which had endured for more than a century, became engulfed in litigation over the Upper Basin contribution to Mexico, tributary use, and the 602 (a) storage requirement, and eventually had to be scrapped.

Acting by decree, the U.S. Supreme Court eliminated the division into two basins and instead allocated the Colorado's waters to the Basin States according to the number of inhabitants in each state served by those waters in 2030. While "democratic," this reallocation of resources rewarded the Lower Basin States (Nevada, Arizona, and California) for ignoring until then any limits on their growth imposed by the arid landscape. While the river's flow had declined by 25 percent to 11 maf in 2030, California was allocated 4.4 maf, Arizona 2.2 maf and Nevada 0.9 maf. The Upper Basin States, which had not yet fully developed their water resources under the Compact allocation, were the big losers as their allocation went from a 50/50 split to a 25/75 split based on population (Census 2005). Colorado's allocation dropped from 3.9 maf under the Compact to a mere 1.2 maf. The farming industry on the western slope was devastated.

Under the U.S.-Mexico treaty of 1944, Mexico's allocation was reduced proportionately, crippling the agricultural economy of the Mexicali Valley in spite of the significant improvements in water efficiency. The allocation of water within the states proved to be even more contentious than the allocation of water among the Basin States. Between 1990 and 2005, roughly 80 percent of river's average flow of 13 maf, or 10.4 maf went to agriculture, and 20 percent, or 2.6 maf, was delivered to the Basin's rapidly growing cities. Urban planners had projected at the time that the shift of water from farms to cities would accelerate and that the legal and political impediments to doubling cities' allocations would be easily overcome. Their view proved to be unrealistic.

Farmers, many realizing the economic and political power they had and most simply attached to their livelihoods and way of life, held onto their water rights and the cost of water to urban users rose dramatically, reaching $300,000 per af at its apex, versus $3–50 per af for agricultural users. Those who sold at that price instantly became millionaires and moved to the region's thirsty cities or left the area altogether. Overall, however, the pressure to move lower value supplies to higher value uses was not sufficient to overcome entrenched property rights and force a reallocation of scarcity along economic lines.

Still, agriculture suffered a 40 percent reduction in water supply compared to the beginning of the twenty-first century, and farmers were forced to switch to lower water-intensity crops as federal subsidies on water-intensive crops were eliminated, and drip irrigation replaced flood irrigation wherever possible. The alfalfa and cotton industries were particularly hard hit because of their lower returns. The economic dislocation in rural areas caused by the changing cropping patterns was severe, causing tens of thousands of migrant workers from Mexico to flood cities on both sides of the border, building shantytowns on the outskirts and stressing infrastructure and social services.

The interstate water market remained very small, constrained by the new Compact and the extended droughts, and this exacerbated local shortages and put even greater pressure on prices. States, like Nevada, that had believed runaway urban growth would help force the hand of other Basin States in water negotiations, were able to get a better deal in the new Compact, but then were faced with the seemingly impossible task of stemming the continuing influx of new residents lured by the promise of affordable housing, endless sun, and a booming job market. The very thing that attracted new residents—a better quality of life—was nullified by the sheer number of people seeking it. The increasingly drastic restrictions placed on outdoor and indoor water use—no lawns, no pools, and low flow showers with mandatory timers—only increased the sense of limitation. Many wondered how the vision of the frontier, with its promise of endless expanses and its emphasis on self-reliance, could have gotten them to this point. Life was better in New York, Chicago, and Seattle, in spite of the weather.

Cities with higher per capita consumption rates, such as Phoenix, had a "water buffer" that allowed them to fare better than cities that already had developed a conservation ethic, such as Tucson, or cities that had already had to impose significant restrictions on use, such as Las Vegas. But no major urban center in the arid West was able to escape the limits placed by the environment. Reality had finally caught up with the myth of the endless frontier.

The environment, of course, did not fare well in this context. As the cost of water rose, so did the marginal cost of environmental protection. The MSCP, a fifty-year agreement reached in 2005 to create 8,132 acres of riparian habitat at a cost of $626 million, survived but the rest of the Colorado below Lake Mead was transformed into a large pipeline for conveying water to thirsty cities. Riparian areas were relandscaped to include only a few token trees for recreation, and an aggressive campaign to uproot the vegetation along the river was undertaken, eliminating most of the water-sucking and invasive salt cedar, and many of the remaining cottonwood and willow stands. The southwestern willow flycatcher and other endangered species were long forgotten, except for a few specimens maintained in botanical gardens.

The struggle to save the Delta was a thing of the past—there was no longer any Delta to be saved—relegated to environmental history books like the efforts to prevent the construction of big dams (Hetch Hetchy, Glen Canyon, Three Gorges) or to save the last remnants of old growth forests in North America. Talk of an environmental use for water was so removed from reality that even die-hard environmentalists remained silent. Humans had more pressing matters to take care of than to worry about such things.

6.3 The Market Rules

> Every individual . . . generally, indeed, neither intends to promote the public interest, nor knows how much he is promoting it. By preferring the support of domestic to that of foreign industry he intends only his own security; and by directing that industry in such a manner as its produce may be of the greatest value, he intends only his own gain, and he is in this, as in many other cases, led by an invisible hand to promote an end which was no part of his intention. (Smith 1776)

> The rich . . . divide with the poor the produce of all their improvements. They are led by an invisible hand to make nearly the same distribution of the necessaries of life which would have been made, had the earth been divided into equal proportions among all its inhabitants. (Smith 1759)

Adam Smith's invisible hand was difficult to discern in the allocation scheme for the Colorado River's water at the beginning of the twenty-first century. The seven Basin States, acting in their own self interest, had divvied up more water than actually existed, keeping roughly 90 percent for themselves and leaving but 10 percent for Mexico and none for the river delta or its estuary. Within the states, some 80 percent of the water was allocated to agriculture, based on prior established rights, and the rest was being consumed by cities. But things were changing.

An agreement reached among the Basin States and Mexico in 2010, based on alternatives originally proposed in the Bureau of Reclamation's interim shortage guidelines EIS of 2007 (Reclamation 2007), allowed for the interstate storage and delivery of water, with no preestablished limit, to any other state in the Basin, including Mexico. A weakly regulated interstate water market made it possible for water to flow wherever the market dictated. Farmers in western Colorado, Yuma, and Mexicali were able to sell not only their water but also their water rights to the public water authorities, thereby accelerating the rural to urban shift throughout the Southwest and fueling the cities' runaway growth. The loss of agricultural lands in the Mexicali Valley contributed to an increase in illegal immigration in the United States as farm hands left the fields for the region's booming cities. It didn't take long, for example, for the Southern Nevada Water Authority to exercise its financial might and purchase water not only from Arizona, which had stored significant amounts underground, but also from Upper Basin States and Mexico.

Nevada funded cloud seeding research in the Upper Basin. No significant water gains on a basinwide basis were ever shown over the long run, but Nevada received 75,000 af for its investment. The state also helped to finance the lining of canals and other infrastructure improvements in the Mexicali Valley, capturing half of the water savings, or another 75,000 af per year. Both Nevada and Arizona helped to fund desalination plants off the coast of California, allowing each state to gain access to 150,000 af per year of California's water. Plans to build a giant desalting complex off the coast of Sonora never panned out because of the political issues surrounding the building of an adjoining nuclear power plant.

Within the states themselves, when it became clear to farmers and irrigation districts that their preferred water rights would not be guaranteed for much longer because of the intense political pressure to sell their water to cities, water flowed more easily to the Southwest's urban areas. Within two decades, the percentage of the river's water allocated to urban uses had doubled, both allowing for and feeding cities' growth. The limits imposed by the arid environment were pushed further into the future as the quality of life of urban residents deteriorated, with increasing air pollution, longer commutes, and dwindling open space.

Arizona and Nevada, the two fastest growing states in the nation, more than doubled their population by 2030, gaining nearly 8 million new residents (Census 2005). Phoenix and Tucson became one "megapolitan" area with 7.8 million people and nearly continuous urban settlement. By 2050, the "Sun Corridor" had grown to nearly 10 million people and encompassed Prescott, a hundred miles north of Phoenix, and Sierra Vista, seventy-five miles southeast of Tucson. Arizona raised the sides of its Central Arizona Project Canal, enabling it to carry another 300,000 af per year to the Sun Corridor and postponing for awhile the construction of a second canal into the heart of the state.

Every day, an astonishing 350 new single-family homes went up in the megapolitan area, further stretching the cities' water infrastructure and resources. The yearly water assessment on homeowners for the Central Arizona Groundwater Replenishment District grew from an average of $70 per year to more than $2,000 (Jenkins 2006).

The increase in water prices did encourage conservation, confirming previous studies that suggested that residential water was indeed a price-sensitive commodity, it just hadn't reached a level where consumers had noticed it before (Campbell et al. 1999). But the increases in conservation were not able to keep pace with the increases in population, and the Lower Basin States continued to deplete their underground water supplies.

The Colorado River Delta, which had come back to life briefly in the wet El Niño years of the mid-1980s and again in the late 1990s, was no match for the growth and market forces sweeping over the Lower Basin. The Intentionally Created Surplus (ICS) concept was extended to Mexico, creating a mechanism that allowed for the dedication of base and pulse flows to the Delta, perhaps in exchange for infrastructure improvements in the Mexicali Valley. Unfortunately, policymakers did not recognize the urgency of doing so when the water market was created in 2010, and when they did, the window of opportunity for purchasing these environmental flows had already closed as water had become prohibitively expensive. Conservationists were able to gain greater recognition of the benefits of ecosystem services but by then the circumstances restricted action and the accidental flows sustaining the Delta petered out.

6.4 Powell's Prophecy

> The problem for the Delta, too, is ultimately less one of technical fixes than of borders and horizons. The contemporary focus on efficiency is a significant shift away from the mindset that tried to outflank the harsh realities of the desert with dams and concrete. It seems to fit the curves of the Western landscape far better than a dam. Yet instead of vanquishing the demons of aridity, efficiency has only chased them

> into the dark. And it has now run up against the quintessential problem of the West.
>
> The entire Western pioneering enterprise was, at its core, an effort to push the world's boundaries ever farther. Far horizons offer eternal promise: another river, just over the next ridge, to be tapped for its water; another planet to mine. But we have never expanded our field of vision enough to include all the real costs of *being* here. We have not civilized the West so much as savaged it—leaving [Delta restoration proponents] Francisco Zamora and Osvel Hinojosa rattling a tin cup in an effort to pay down the ecological debt run up by every single person who depends on water from the Colorado River.
>
> Untangling the competing demands on the river will be an incremental and possibly perpetual endeavor. It is tempting to argue that the enterprise of developing the Colorado was made feasible in the first place only by writing off the cost of its environmental effects on the Delta. But that simply is not true: Those costs are mere fractions of the total amount of water in the river and the money spent to develop that water. They are so small that including them in the dealmakers' calculations from the very beginning would have never come even remotely close to breaking the entire river-development proposition. And so we are now left with a choice: endlessly pursuing yet one more house-of-mirrors fix—or, finally, trying to set the equation right. (Jenkins 2007)

John Wesley Powell understood better than anyone else in the late nineteenth century the constraints imposed by the aridity of the West and attempted to stave off a hurried settlement of the land. He wanted time to assess the water supply and the natural limits imposed by the land. He wanted to rearrange existing boundaries, organizing government by watershed. However, the watershed boundaries still ended at the Mexican border and excluded the Delta and coastal areas. He envisioned local committees of competing interests, including ranchers, farmers, loggers, miners, and townspeople. They and they alone would decide how land, forests, and water would be used (deBuys 2004). Powell's vision for the arid West, although written into the Reclamation Act of 1902, was no match for the powerful forces that would sweep across the region in the twentieth century and lead to the construction of an astounding infrastructure of dams and diversions along the Colorado to supply burgeoning cities hundreds of miles outside the Basin.

The drought that began striking the western United States in 2000 led the Basin States to learn from past mistakes and to reconsider the wisdom and adequacy of Powell's vision as well as the values placed on ecosystem services that had largely been taken for granted. This movement began timidly with an agreement among the states to put forward an alternative for the Bureau of Reclamation's interim shortage guidelines EIS in 2007 (Reclamation 2007) and eventually led to the development of a comprehensive vision for water resources management in the arid West. This vision included managed urban growth, the protection of rural landscapes, and the restoration of riparian ecosystems throughout the Lower Basin, including the Delta.

When it became clear, based on tree-ring studies (Woodhouse et al. 2006) that the drought was not a freak occurrence but rather a recurring condition, likely to be exacerbated by climate change, the states realized that they would need to protect themselves from protracted and severe droughts and place constraints on the runaway growth of their cities' water consumption. The mechanisms needed to do this turned out to be relatively simple. In 2010, states such as Arizona and California, with 80 percent of their Colorado River allotment used for farming, set 25 percent as the limit on how much of this water could be sold to urban areas, and imposed more stringent requirements on the replenishing of groundwater.

This policy acted as a formidable incentive for aggressive urban water conservation programs. By 2020, water demand had hardened for cities, and best practices, which originated in Tucson and were later adopted in Las Vegas brought average single-family residential consumption to less than a hundred gallons per person per day. The most effective measure was not mandatory restrictions on outdoor watering but rather a tiered water pricing system that made wasteful use prohibitively expensive.

Hardening water demand also encouraged cooperation between cities and environmentalists because having certainty in allocation was more productive than truculence in the face of scarcity. The Bureau of Reclamation decided to implement the Conservation Before Shortage alternative in its 2007 EIS (Reclamation 2007), extending the Intentionally Created Surplus (ICS) credits to include Mexico. Water efficiency projects in Mexico funded by Nevada, such as the lining of canals in the Mexicali Valley, generated a significant number of ICS credits for the state, which allowed it to meet the growing demand of Las Vegas while urban water conservation programs were put in place. Under the agreement, the credits, stored in Lake Mead, were charged a 5 percent assessment that was then used for ecological purposes.

As more value began to be placed on the capacity of the Delta to support and regulate the processes of both the mosaic of terrestrial and aquatic ecosystems linked to it, with their high concentrations of biodiversity and in an otherwise dry area, and cherished ways of life enabled by them (see chapter 7), the United States and Mexico established an ecological use for water and used the current and future value of these services to weigh the costs and benefits of water management actions. This led them to establish a base flow of 50,000 af per year and a pulse flow of 260,000 af every four years to the Delta and to undertake active habitat restoration in established priority areas (Zamora-Arroyo et al. 2005). These flows included agricultural return water, treated municipal wastewater, as well as the 5 percent water storage assessment.

The results in the Delta were impressive as the riparian ecosystem, severely degraded in previous decades, quickly bounced back to life. Base and pulse flows were reestablished by 2015 and the addition of water made restoration work much easier. Cottonwood and willow stands germinated easily on the banks. Further upland, mesquites outcompeted salt cedar. The quality and quantity of water were much improved, allowing fish and bird species to repopulate the areas, along with a multitude of other native Delta flora and fauna. The reconnection of the river to the sea, although slight, restored estuarine conditions, increasing the breeding areas for commercial species, such as shrimp, and native fish species, such as the corvina and the endangered totoaba.

By 2020, communities were also being restored. The Cucapá indigenous people, who had depended on a flowing river to hunt and fish, returned to these livelihoods. Ecotourism as an industry grew, bringing citizens from Mexicali and Tijuana, as well as the United States, to see a restored Delta. By 2050, the establishment of an ecological use for water, restoration of priority areas, cooperation among stakeholders, and stewardship by local communities had become a model for balancing conservation and development worldwide.

With managed urban growth, protected rural landscapes, and partially restored ecosystems, Powell's vision for an orderly settlement of the arid West that respected the natural limits imposed by the land was adapted and given a new life in the twenty-first century and was extended to include the Delta.

6.5 A Delta and Estuary Once More

> Our own interest lay in relationships of animals to animal. If one observes in this relational sense, it seems apparent that species are only commas in a sentence, that each species is at once the point and the base of a pyramid, that all life is relational to the point where an Einsteinian relativity seems to emerge. And then not only the meaning but the feeling about species grows misty. One merges into another, groups melt into ecological groups until the time when what we know as life meets and enters what we think of as non-life: barnacle and rock, rock and earth, earth and tree, tree and rain and air. And the units nestle into the whole and are inseparable from it. Then one can come back to the microscope and the tide pool and the aquarium. But the little animals are found to be changed, no longer set apart and alone. And it is a strange thing that most of the feeling we call religious, most of the mystical outcrying which is one of the most prized and used and desired reactions of our species, is really the understanding and attempt to say that man is related to the whole thing, related inextricably to all reality, known as unknowable. This is a simple thing to say, but the profound feeling of it made a Jesus, a St. Augustine, a St. Francis, a Roger Bacon, a Charles Darwin, and an Einstein. Each of them in his own tempo and with his own voice discovered and reaffirmed with astonishment the knowledge that all things are one thing and that one thing is all things—plankton, a shimmering phosphorescence on the sea and the spinning planets and an expanding universe, all bound together by the elastic string of time. It is advisable to look from the tide pool to the stars and then back to the tide pool again. (Steinbeck 1941)

No one foresaw the sea changes in thinking and policy that would sweep through the Lower Colorado River Basin in early 2017. Only a decade earlier, as changes in climate began to exacerbate existing patterns of regularly occurring drought, the possibility of restoring the functionality of the region's ecosystems, particularly the Delta and its connection to the Upper Gulf of California, was seen as such a pipe dream that even the most optimistic of environmentalists were not seriously considering it.

Lack of government willingness and capacity to respond in any meaningful or constructive way to a series of crises from 9/11 and Hurricane Katrina to the even more insidious long-term western drought that had gone unnoticed since 2001, had destroyed the public trust, and created a climate of denial and indifference. Even if ecosystem services were protected, it was not clear that those who paid the cost would ever see or have access to the benefits of doing so. But little by little, this perception, that any attempt to alter prevailing trends would be futile, also crossed a threshold and became a crisis that paved the way for a New Social Compact, just as the Mississippi Flood of 1927 and the Great Depression had paved the way for the New Deal of the 1930s (Barry 1997).

The foundation of this new compact was the recognition that ecosystems and diversity (both biological and cultural) are the foundation of human security and freedom, without which there would be few if any options from which to choose. In this new era of post–Cold War reconstruction, markets and geo-political agendas became subservient to the goal of meeting basic human needs and were harnessed to support these new and changing values.

Still, the goal of restoring the Delta was troubling and immense because so little was known about what could be accomplished and what it would take (Adler 1997). It also required some tough decisions to be made about what should be restored, and about trade-offs that were likely to increase conflict with those who benefited from the status quo.

The Upper Gulf was a nursery area for many commercially important species. With upstream damming and diversions from the Colorado River, it became an inverse estuary, where salinity was generally higher in the north (39 ppt) than in the south (35.5 ppt) (Lavin 1998). Fisheries were declining because of both poor management and poor estuarine environmental conditions.

The importance of freshwater flows to the health of the Upper Gulf, particularly its fish and shrimp nurseries, was known (Galindo-Bect et al. 2000; Rowell et al. 2005), as were the concepts of ecosystem-based management (Yaffee 1999), but the idea of investing a full 5 to 10 percent of the Colorado River's annual flow to the restoration of riparian and marine ecosystems was almost unthinkable. Yet, this is exactly what happened in 2017.

The Upper Gulf also happened to be home to the totoaba (*Totoaba macdonaldi*) and the vaquita porpoise (*Phoceana sinus*), the world's smallest and most endangered marine mammal. It is estimated that no more than six hundred individuals of this flagship species still exist (Barlow et al. 1997) and the vaquita is listed as endangered in both the United States and Mexico. When research showed that vaquita mortality was a function not only of fishing by-catch but also of the lack of freshwater flows, the pressure to restore significant river flows to the Upper Gulf grew very strong. But it wasn't until 2015, when the U.S. Supreme Court ruled that the Endangered Species Act did in fact apply extraterritorially that such flows became mandatory. This confirmed the Council on Environmental Quality's earlier interpretation of the National Environmental Policy Act (NEPA) asserting that U.S. agencies can be held accountable for the impacts of their actions outside of the United States even when the precipitating action takes place within the country. (McGinty 1997).

Research on shrimp populations in the Upper Gulf estimated freshwater input needs at 70 m^3/s, or nearly 1.8 million acre-feet over an entire year (Cortez-Lucero 2004) and research on the vaquita found similar freshwater requirements. Based on the science, environmental organizations demanded that a full 10 percent of the Colorado River's flows, or roughly 1.5 million af, be dedicated to the Upper Gulf. After a year and a half of negotiations, these organizations reached a compromise with the seven Basin States and the Bureau of Reclamation that approximately 5 percent of the river's flow, or 750,000 acre-feet would be allowed to reach the Upper Gulf in order to save the totoaba and the vaquita. As the ecosystem began to respond to the increased flow of water, increased public support reduced the political risks involved and made it possible to take more chances and learn some lessons about also restoring the flow of sediment.

Thanks to science and the Supreme Court's ruling, the United States and Mexico embarked upon an ecosystem-based management of the river, establishing an ecological use for water and setting out to restore healthy estuarine conditions. Pre-dam sediment flows were simulated through the installation of pumps and bypass tubes around all the dams in the Lower Basin. The acquisition of large amounts of water for the Delta and estuary, funded by an environmental assessment of $12 per acre-foot (Flessa 2004; Flessa 2006), reflected the growing value, not only of water, but also of riparian and estuarine ecosystems that regulate and support the quality of life in the region. This fee was borne primarily by city residents to cushion the negative cost impacts on agriculture and restore the amenities, tourism revenues, and lifestyles enabled by the Delta. The assessment was also regarded as a bargain because it made the entire region more resilient and able to cope with rapid climatic and other global changes, and it created a sense of place among residents of the Lower Colorado River Basin that transcended the national border and strengthened social ties. Given skyrocketing populations, cities throughout the Southwest and northwestern Mexico worked together to develop regional goals for water conservation and planning and used tiered-pricing systems to bring average per capita water use below the previously lowest levels in each region. Irrigation districts on both sides of the border also shared best practices and turned toward lower water use crops in order to maximize efficiencies.

The environmental results brought about by these freshwater flows were astounding. Not only was the riparian corridor restored (at a cost of only $150 million for 50,000 acres) with base and pulse flows for overbank flooding, but, by 2020, the fisheries in the Upper Gulf and, especially, the vaquita population, had begun to recover. An agreement was reached with fishermen to ban commercial fishing with gill nets in about 1,545 square miles to a line cutting across the Upper Gulf about seventy miles south of the mouth of the river. Fishermen's transition to ecotourism was funded with a fraction of the $180 million environmental assessment mentioned above.

The freshwater flows benefited other species as well. Shrimp fisheries reached their highest tonnage in catch since the mid-1900s, and the totoaba, which was listed as endangered in the United States in 1979, was delisted in Mexico because increasing spring runoff from the Colorado River enhanced habitat for juveniles and increased the carrying capacity of the region by regulating temperature and salinity in the Upper Gulf (Cisneros-Mata 1995).

By 2030 communities throughout the region were also being restored. People who had depended on a flowing river to hunt and fish returned to these livelihoods. Well-regulated fisheries in the Upper Gulf created sustainable communities that fished shrimp, totoaba, and corvina. Ecotourism, as an industry, grew, bringing citizens from Mexicali and Tijuana, as well as the United States, to see a restored Delta and a thriving estuary.

By 2050 the restoration of the Colorado River Delta and its estuary, using adaptive management techniques, had become a model for ecosystem-based management worldwide, showing that conservation and economic development could go hand in hand. But it had hardly reached an endpoint. As the Delta and its people began to flourish and the process of making difficult choices among competing values was restored, science began to be used more effectively to learn about connections between the Delta and the Upper Gulf of California and to inform difficult decisions about land uses that affect them.

The totoaba and the vaquita porpoise, doing better but still threatened, helped to bring international attention and additional resources needed to achieve more ambitious goals, even if these were still contested. Public attention inevitably turned toward future development patterns and the fate of Glen Canyon that had resurfaced as the water levels fell in Lake Powell during the drought of the early twenty-first century. But by 2050, there were more options on the table. Choices could still be made.

6.6 Conclusion

This chapter presents four scenarios for the future of the Lower Colorado River Basin to 2050 with respect to water resources. Each scenario reflects a different worldview and differing assumptions about the best uses of water in an environment where supplies are increasingly buffered by climate change and demand, driven by urban population growth, continues to increase. The policies followed in these scenarios lead to very different outcomes in terms of ecosystem services, highlighting the trade-offs that will need to be made, particularly in the Colorado River Delta. Which of these scenarios we choose, based on our recognition of the importance of environmental restoration and attention to environmental justice, will determine quality of life in the Lower Basin far into the twenty-first century.

> Perhaps the biggest challenge involved in moving toward sustainable water use in the Lower Colorado River Basin is motivating people to desire a sustainable future, and to agree on what it might look like. It is clear that deeply ingrained attitudes and vested interests in the status quo represent a formidable obstacle to changing water use and management practices in the basin. Equally clear, however, is that continuing down the current path of inefficient and highly subsidized agricultural water use, escalating urban demands, and neglect of ecosystems, Native American communities, and future generations is a recipe for conflict and ecological decline. . . . In this situation, moving toward a sustainable river basin as a cooperative whole, represents a necessity, not a luxury. An inclusive planning process and improved institutional structures are urgently needed, and in order to be successful, will require that all parties begin to think about their own needs within a broader, basin-wide context. . . . The time to begin is now (Morrison et al. 1996).

6.7 References

Bacigalupi, P. 2006. "The Tamarisk Hunter." *High Country News* 38, no. 12 (June 26, 2006).

Barlow, J., T. Gerrodette, and G. Silber. 1997. First estimates of vaquita abundance. *Marine Mammal Science*, 13:44–58.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer. 2004. The effects of climate change on the hydrology and water resources of the Colorado River Basin, Climatic Change, 62 (1):337–363.

Christensen, N. S. and D. P. Lettenmaier. 2006. "A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin." Submitted to Hydrology and Earth System Sciences in Nov. 2006.

Campbell, H. E., E. H. Larson, R. M. Johnson, and M. J. Waits. 1999. *Some Best Bets in Residential Water Conservation. Results of Multivariate Regression Analysis, City of Phoenix, 1990–1996*. Phoenix: The Morrison Institute for Public Policy, Arizona State University.

Cortez-Lucero, G. 2004. Respuesta de la población de camarón en el Alto Golfo de California a las fluctuaciones de las descargas del Rio Colorado. Tesis de Maestría. Instituto Tecnológico del Mar, No. 03, Guaymas, Sonora, México. 71 pp.

Cisneros-Mata, M. A., G. Montemayor-Lopez, and M. J. Roman-Rodriguez. 1995. "Life History and Conservation of *Totoaba macdonaldi*." *Conservation Biology* 9 (4):806.

deBuys, W. 2004. *Seeing Things Whole: The Essential John Wesley Powell*. Washington D.C.: Island Press.

Flessa, K. W. 2004. "$200 per acre-foot: Nature's services and the natural value of water in the Colorado delta and estuary." Gulf of California Conference, Tucson, AZ.

Flessa, K. W. 2006. "Simple water fee could salvage ecosystems." *Arizona Republic*, August 21, 2006. Accessed at www.azcentral.com/arizonarepublic/opinions/articles/0821flessa-water.html on September 11, 2007.

Galindo-Bect, M., E. P. Glenn, et al. 2000. "Penaeid shrimp landings in the upper Gulf or California in relation to Colorado River freshwater discharge." *Fishery Bulletin* 98:222–225.

Hoerling, M. and J. Eischeid. 2007. "Past Peak Water in the Southwest" *Southwest Hydrology* 6 (1):18–35.

Jenkins, M. 2006. "The Perpetual Growth Machine." *High Country News* 38, no. 11 (June 12, 2006).

Jenkins, M. 2007. "The Efficiency Paradox." *High Country News* 39, no. 2 (February 5, 2007).

Lavin, M. F., V. M. Godinez, and L. G. Alvarez. 1998. "Inverse-estuarine Features of the Upper Gulf of California." *Estuarine, Coastal and Shelf Science* 47:769–795.

McGinty, Kathleen A. 1997. Memorandum to Heads of Agencies on the Application of the National Environmental Policy Act to Proposed Federal Actions in the United States with Transboundary Effects.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia. 2005. "Global patterns of trends in streamflow and water availability in a changing climate." *Nature* 438:347–350.

Morrison, J., S. Postel, and P. Gleick. 1996. The Sustainable Use of Water in the Lower Colorado River Basin. A joint report of the Pacific Institute and the Global Water Policy Project, Oakland, CA.

Rowell, K., K. Flessa, D. Dettman, and M. Roman. 2005. "The importance of Colorado River flow to nursery habitats of the Gulf Corvina (*Cynoscion othonopterus*)." *Canadian Journal of Fisheries and Aquatic Sciences* 62:2874–2885.

Smith, A. 1776 [1937]. *The Wealth of Nations*. Toronto, Canada: Random House.

Smith, A. 1759. *The Theory of Moral Sentiments*. Mineola, NY: Dover Publications.

Steinbeck, J. 1941. *The Log from the Sea of Cortez*. New York: The Viking Press.

U.S. Bureau of Reclamation. 2007. Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead Draft EIS. Accessed at www.usbr.gov/lc/region/programs/strategies/draftEIS/index.html on March 20, 2007.

U.S. Census Bureau. 2005. Ranking of census 2000 and projected 2030 state population and change, accessed at www.census.gov/population/www/projections/projectionsagesex.html on March 20, 2007.

Woodhouse, C. A., S. T. Gray, et al. 2006. "Updated streamflow reconstructions for the Upper Colorado River Basin." *Water Resources Research* 42:1–16.

Zamora-Arroyo, F., J. Pitt, S. Cornelius, E. Glenn, O. Hinojosa-Huerta, M. Moreno, J. Garcia, P. Nagler, M. de la Garza, and I. Parra. 2005. "Conservation Priorities in the Colorado River Delta, Mexico and the United States." Sonoran Institute, Environmental Defense, University of Arizona, Pronatura Noroeste Dirección de Conservación Sonora, Centro de Investigación en Alimentación y Desarrollo, World Wildlife Fund—Gulf of California Program: 1–103.

Chapter Seven

SCENARIO TRADE-OFFS

7.1 Introduction

In arid lands, freshwater is a finite resource that cannot be distributed in such a way that all the ecosystem services it provides are maximized. Trade-offs between provisioning, regulating, supporting, and cultural services need to be made. Western societies, because they focus on meeting short-term needs, have typically favored provisioning services at the expense of all the others. The Lower Colorado River Basin is no exception.

Under our four scenarios, very different choices are made among ecosystem services. The climate change crisis in "Dry Future" undermines consumptive uses and leads institutions to ignore the long-term importance of attending to regulating and supporting services. Maintaining cultural traditions for impoverished indigenous minorities and recreation opportunities is a luxury when livelihoods are threatened. In "The Market Rules," the market, because it is focused on the short-term gain of those holding water rights, seeks to maximize the provisioning services to urban areas and loses the opportunity to sustain supporting and cultural services. Groundwater recharge, a crucial regulating service, is compromised even though its importance is recognized because water augmentation schemes cannot keep up with the pace of urban growth. In both of these scenarios, the well-being of rural communities in the Southwest suffers, the importance of biodiversity to human well-being in the long run is ignored, and water is not dedicated to the Delta's ecosystems.

In "Powell's Prophecy," the regulating, supporting, and cultural services provided by the Delta's ecosystems are recognized as important and their function is enhanced through the creation of base and pulse flows, which mimic some of the pre-dam behavior of the river. The reduction in provisioning services to cities and agriculture is minimal and more than compensated for through effective urban and agricultural conservation programs. In the last scenario, "A Delta and Estuary Once More," a 5 percent reduction in provisioning services leads to significant increase in regulating, supporting, and cultural services. The nonconsumptive, ecological use of this water represents an investment in the long-term health of the Lower Basin's riparian and estuarine ecosystems.

7.2 Trade-Off Diagrams

The "spider web" diagrams below illustrate the *relative* change in the provision of ecosystem services under the four scenarios. The black polygons indicate the state of each category of ecosystem services relative to a starting point of zero, indicated by the green pentagons. A positive value (between 0 and 1) indicates an increase in the supply of a particular category of ecosystem services, while a negative value (between 0 and –1) indicates a decrease. Therefore, the larger the black polygons, the greater the provision of services across all categories.[10]

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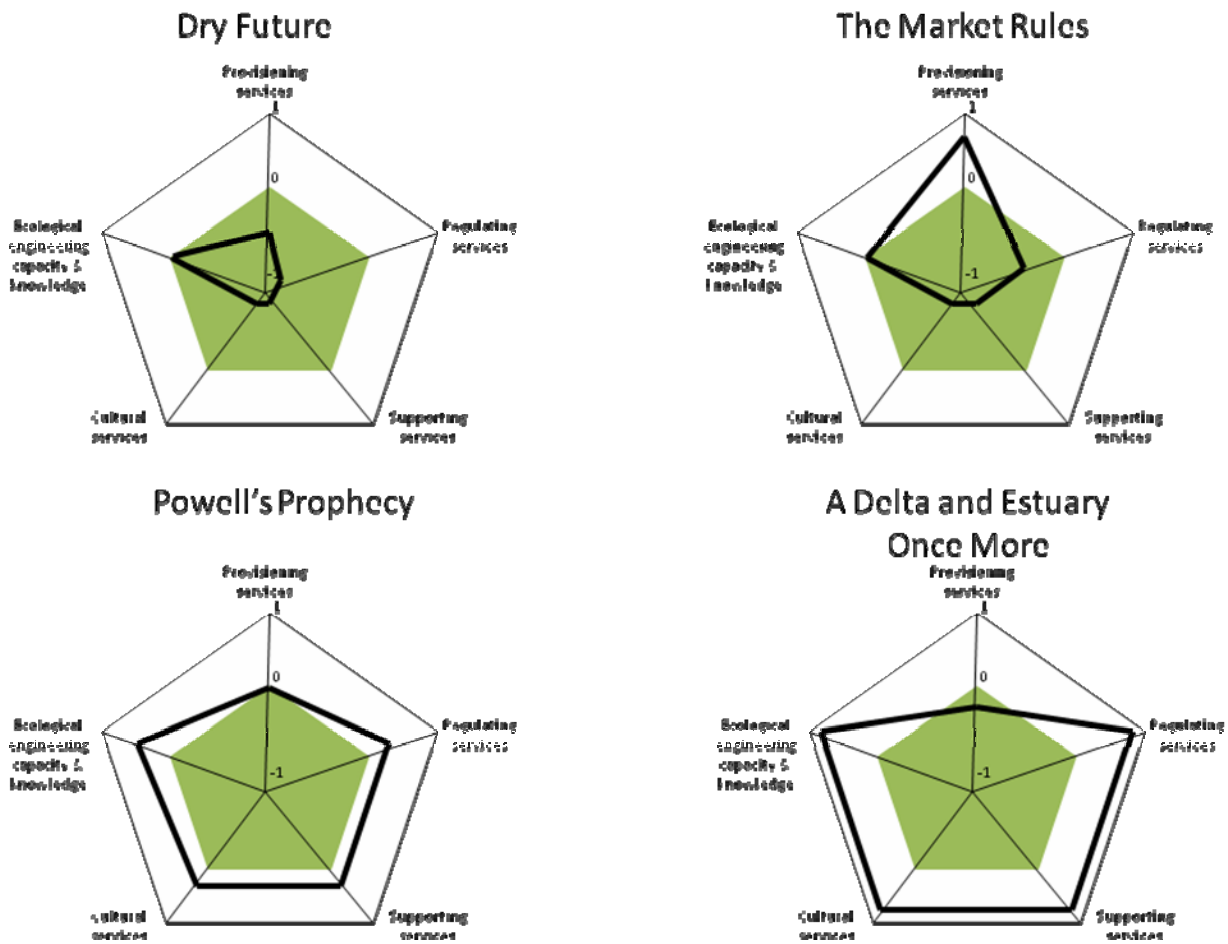
[10] *Ecological engineering* is "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both. It

involves the design, construction and management of ecosystems that have value to both humans and the environment. Ecological engineering combines basic and applied science from engineering, ecology, economics, and natural sciences for the restoration and construction of aquatic and terrestrial ecosystems." (Mitsch 1998).



7.3 Institutional and Financial Barriers and Scientific Uncertainties

The four scenarios describe the potential outcomes of water policies that emanate from four very different perspectives on the use of natural resources and the long-term link between ecosystem health and human well-being. In the first scenario, "Dry Future," a catastrophic reduction in Colorado River flows due to climate change increases the level of conflict among water interests in the United States and Mexico and forces institutions to scrap longstanding agreements under the Law of the River to deal with the crisis. The limits imposed by the arid environment can no longer be ignored and the costs in terms of human well-being are great. In such a context, ecosystems continue to get the short straw as the marginal cost of environmental restoration rises with the increasing scarcity and value of water.

In the second scenario, "The Market Rules," a basinwide water market allocates supply to the highest bidders, that is, runaway cities and burgeoning metropolitan areas such as Las Vegas, Phoenix-Tucson, and Los Angeles-San Diego, and technology (e.g., desalination) is used to keep the urban growth machine alive. The value of the Delta's riparian and estuarine ecosystems remains external to the market, which could have balanced the myriad of water uses.

"Powell's Prophecy" outlines a scenario where water and other policymakers develop a vision for the Southwest that places significant value on quality of life. Growth is managed in order to protect rural landscapes throughout the region and to restore riparian ecosystems, particularly in the Delta. The fourth scenario, "A Delta and Estuary Once More," uses an improbable but not impossible combination of events—research showing that the endangered totoaba and vaquita in the Upper Gulf of California need large freshwater flows to survive and a decision by the U.S. Supreme Court requiring their protection, extraterritorially, from harmful U.S. action—to implement ecosystem-based management throughout the Lower Basin, including the release of significant flows for the Delta and estuary.

All but the first of these scenarios require a significant degree of cooperation among the seven Basin States and Mexico. As chapter 5 indicates, this cooperation has already begun to take place, egged on—paradoxically—by the ongoing drought and the fear of unilateral action by the Secretary of the Interior if and when a shortage is declared. However, Mexico has yet to be included in the conversation. Although they are not used to speaking directly with water interests in Mexico, the seven Basin States realize that it will be to their benefit to engage in discussions with Mexico so that a win-win solution can be found, even in the eventuality of a reduction in supply.

Of all the states, the one that is least attached to maintaining the status quo is Nevada, as it will soon be reaching the limits of its 0.3 maf allocation from the Colorado River. The state is actively pursuing new ways to increase supply (pipeline from northern Nevada, surface water diversions from the Virgin and Muddy rivers, storage in Arizona's underground water bank for future use, development of Drop 2 reservoir) and to reduce demand (restrictions on outdoor water use in Las Vegas). Unless negotiations among the states break down completely, the other Basin States have a strong incentive to keep Nevada in the conversation so that the U.S. Supreme Court does not determine future water allocations.

Although climate change science has made significant progress in the last few years and researchers are now able to estimate the likely effect of climate on future Colorado River flows, the range of these projections is still large, spreading from a 6 percent decrease (Christensen and Lettenmaier 2006), to a 45 percent decrease (Hoerling and Eischeid 2007) by mid century (other studies include Stockton and Boggess 1979; Revelle and Wagoner 1983; Nash and Gleick 1991, 1993). The first scenario uses the high end of this range to illustrate the economic and social dislocation that would be caused by such a large reduction in supply, but even reductions of half this magnitude would have disastrous effects. State water authorities are no doubt taking these projections seriously in order to prepare for the future. As always, the precautionary principle should be used until the range of projections narrows.

The last two scenarios offer the prospect of guaranteed environmental flows to the Colorado River Delta. The minimum base and pulse flows of 50,000 and 260,000 af, respectively, in "Powell's Prophecy" are based on observations of riparian areas' resilience after the floods of 1997 and an estimate of the amount of water needed to maintain the Delta's 150,000 acres of wetlands and riparian areas (Zamora-Arroyo et. al. 2005). The precise impact of such sustained and periodic flows is unknown. The effect of 750,000 af flows in "A Delta and Estuary Once More," while no doubt beneficial to riparian and estuarine areas, also needs to be modeled in greater detail.

The last scenario depends on scientific research on freshwater flows for the health of marine species in the Upper Gulf, particularly the endangered vaquita porpoise. Much remains to be known about freshwater volumes and timing. Funding for this type of research, whether it be on the vaquita, the totoaba, shrimp, or clams, is particularly important because large fisheries depend on the Upper Gulf's continued productivity. In addition, fisheries and freshwater management need to be coordinated, if impacts are to be seen.

Finally, the last scenario is dependent on the use of 5 percent of the river's water for a comprehensive restoration of the Delta and estuary. It proposes a $12 per af basinwide environmental assessment to fund the purchase of a portion of the flows needed (the rest would come from agricultural return water and treated municipal waste) and the cost of restoring 50,000 acres, for a total of $180 million. While this amount is large, it is well within the realm of the thinkable. For comparison's sake, under the Multi-Species Conservation Plan, state and federal authorities agreed to spend $626 million over fifty years for the restoration of only 8,132 acres of riparian habitat in the Lower Colorado River Basin. The riparian and estuarine areas to be restored under the last scenario would be vastly greater.

7.4 Conclusions

The four scenarios demonstrate how ecosystem services and human well-being in the future will be affected by water policy decisions made today. While there exists significant uncertainty about the impacts of climate change on Colorado River flows, policymakers can prepare for the future by making choices consistent with policy goals, to support the well-being of populations in the Lower Colorado River Basin by including the Delta in management strategies, thereby increasing the resilience of natural systems throughout the Lower Basin, and the capacity for governance through cooperation in the development of a common vision for the future.

7.5 References

Christensen, N.S. and D. P. Lettenmaier. 2006. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. Submitted to Hydrology and Earth System Sciences in Nov. 2006.

Hoerling, M. and J. Eischeid. 2007. "Past Peak Water in the Southwest." Southwest Hydrology 6 (1):18–35.

Mitsch, W. J. 1998. "Ecological engineering—the 7-year itch." *Ecological Engineering* 10:119–130.

Nash, L. L. and P. Gleick. 1993. "The Colorado River Basin and climate Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation," EPA Policy, Planning and Evaluation. EPA 230-R-93-009 December.

Revell, R. R. and P. E. Waggoner. 1983. "Effects of a Carbon Dioscide-Induced Climatic Change on Water Supplies in the Western United States." In *Changing Climate*. Washington D.C.: National Academy of Sciences, National Academy Press,

Stockton, C. W. and W. R. Boggess. 1979. "Geohydrological Implications of Climate Change on Water Resource Development. Final Report." U.S. Army Coastal Engineering Research Center, 224.

Chapter Eight

CONCLUSIONS, RECOMMENDATIONS, AND AREAS FOR FURTHER STUDY

8.1 Conclusions

Two powerful forces are affecting the Lower Colorado River Basin: rapid urban growth and climate change. Population growth will continue to exert tremendous pressure on water supplies, even if major urban centers implement aggressive conservation programs. Between 2000 and 2030, the Lower Basin States' population is projected to grow by 60 percent, adding nearly 11 million people (Census 2005b). The second driver of change, climate, is likely to reduce Colorado River flows; while impacts are inherently uncertain, current research suggests a 6 to 45 percent reduction by mid century (Christensen and Lettenmaier 2006; Hoerling and Eischeid 2007). Climate change is also expected to lengthen periods of drought and dendrochronology research reveals that severe and sustained droughts are a defining feature of the Colorado River Basin.

New flexibility in the Law of the River, as exemplified by the Basin States' agreement on shortages will enable policymakers to adapt more easily to these pressures, allowing for the storage, transfer, and exchange of water across state boundaries. The proposed intentionally created surplus (ICS) mechanism, if extended to Mexico could facilitate the allocation of water to ecosystems in the Colorado River Delta.

In spite of the current crisis and although mostly outside the United States, the Delta is no longer in a collective blind spot. Given conditions in the Colorado River Basin—long-term drought combined with climate change and continued population growth—what options are available is less the subject of speculation and increasingly the subject of policy deliberations regarding trade-offs among differing interests. The subject of water allocation is back on the negotiating table and a broader range stakeholders are becoming more actively engaged in considering the future of a region that now includes the Delta. At a recent symposium on the future of the Colorado River Compact, Pat Mulroy, Director of the Southern Nevada Water Authority and dubbed Las Vegas's "Water Czar," expressed a commitment to ensuring water for the Delta. In Nevada, the drought, combined with strong leadership, have already made it possible to implement impressive water conservation measures.

Based on restoration efforts, and on what has been learned from observing responses of the Delta to inputs of water from El Niño events of the 1980s and 1990s, as well as what is known about historical flows, it has been estimated that restoration of the Delta will require a base flow of 50,000 af and a pulse flow of 260,000 af every four years (Luecke et al. 1999). These dedicated flows would also maintain the option of further restoration in the future.

This could be achieved through a combination of measures presented in the third scenario, "Powell's Prophecy," which include tiered water pricing, limits on urban transfers, and a 5 percent assessment on water credits obtained by funding efficiency projects in Mexico. The fourth scenario, "A Delta and Estuary Once More," envisions a more ambitious restoration effort that would restore 10 percent of the flow of the river in 2017 and also begin to restore the flow of sediment trapped by dams. The costs would be voluntarily paid for through an environmental assessment on urban water users who could anticipate lifestyle benefits as well as a reduction of conflict and a cushion against impacts on the agricultural sector. Although unthinkable at present, this last scenario also envisions that current crises trigger changes in beliefs and values to which markets become subservient. In contrast, when "The Market Rules," the Delta is forgotten as water flows to the wealthier and rapidly growing states of Nevada and Arizona. "Dry Future" considers the consequences of not taking action and is not a future anyone would be likely to choose for themselves.

In contrast with the neglect of the Colorado River Delta, it is worth noting the amount of water and funding allocated to restoration of the U.S. portion of the Lower Colorado River. On the U.S. side of the border restoration of 8,132 acres of riparian habitat is being attempted at the cost of $626 million (2003 dollars) under the MSCP. Currently, only 23,000 acres of native vegetation, that is threatened by salt cedar invasion remains (MSCP 2004). However, in the U.S. portion of the Lower Colorado, 210,000 acres have been lost to inundation for reservoirs and an additional 300,000 to 350,000 acres have been lost to agricultural uses and to floodplain development since the 1930s (Adler 2007). In other words, more than fifteen times the area that is remnant or is being restored existed eighty years ago along the Lower Colorado River. Increasing restoration in the Delta would not only close the crevasse between what existed and what is being attempted, but it would also be much more cost-effective than the MSCP (Adler 2007).

8.2 Recommendations

8.2.1 Extend proposed water banking and trading mechanisms to include Mexico and entities that are not currently Colorado River water contractors

The extension of the intentionally created surplus (ICS) mechanism to Mexico and entities that are not currently Colorado River water contractors, would, according to Reclamation's own analyses, decrease the probability of shortages and make it possible for environmental organizations or the Mexican government to create dedicated pulse flows below Morelos Dam in order to restore riparian habitats in the Delta and benefit the species that depend on them, such as the southwestern willow flycatcher and the Yuma clapper rail. Providing Mexico with the means to store water in Lake Mead for future use would allow Mexico to improve its management of Colorado River water, creating incentives for water conservation and enabling flexibility in water uses. It would also improve relations between the United States and Mexico on the politically sensitive issue of shortages.

8.2.2 Dedicate base and pulse flows to restore key riparian areas in the Colorado River Delta

The creation of base and pulse flows is key to the survival of the Delta at this juncture. Research suggests that a base flow of 50,000 af per year and pulse flows of 260,000 af every four years would be sufficient to maintain and restore existing riparian areas, as mentioned in the "Powell's Prophecy" scenario. Dedicating these environmental flows will require a change in the definition of beneficial water use in the United States to include the use of water to protect the capacity of ecosystems to regulate and support the provision of freshwater for the full range of human benefits.

Pilot projects should be set up in Mexico and in the United States to retire marginally productive agricultural lands and put the conserved water back into the river. As water allocation permits, large-scale restoration efforts in the Delta should be funded to create ecologically functional areas, recreational opportunities for residents and visitors, adequate areas for indigenous cultural uses, and habitat for species of concern for both countries, including migratory birds.

Realizing water efficiencies in Mexico is likely to be much more cost-effective than in the United States For example, the lining of canals alone in the Mexicali Valley could produce savings on the order of 150,000 af per year at a cost of only $56 million compared to $354 million for lining the All-American and Coachella canals in the United States or $85 million for building the Drop 2 reservoir (for 25,000–100,000 af); projected ground and surface water augmentation projects in Nevada are an order of magnitude more expensive than these latter projects.

Restoration efforts in Mexico would also be significantly more cost-effective than in the United States. For example, the creation and restoration of only 8,132 acres of riparian habitat under the Multi-Species Conservation Plan will cost $626 million, whereas the restoration of 50,000 acres in the Mexican Delta could likely be accomplished at a cost of only $120 million.

8.2.3 Encourage water conservation by setting urban and agricultural targets, reducing subsidies on water-intensive crops, and sharing best practices across the region

Water use efficiency in the Lower Basin could be greatly improved by adopting best practices in both the municipal and the agricultural sector, and these practices are likely to be part of any future scenario for the Basin, as shown in Chapter 6. Tucson, for example, managed to reduce its per capita water consumption by more than 25 percent over just three years in the mid-1970s by raising water rates and promoting desert landscaping and limited lawn watering. Since then, the city has instituted a tiered water pricing system for residential users and summer surcharges for commercial and industrial customers that has further reduced peak demand. Tiered pricing structures have also proven effective in increasing irrigation efficiency in California's San Joaquin Valley and could be used in the Lower Basin. In addition to these pricing incentives, low-interest loans and rebates for capital improvements in both homes and fields are a cost-effective means of promoting conservation.

If the Lower Basin is ever to become sustainable, then changes in state and federal policies are likely required, such as reducing federal subsidies on water-intensive crops such as cotton and alfalfa, improving water efficiency standards and regulations, and linking land development to long-term water supplies, as is done in Arizona, for example, through the Central Arizona Ground Replenishment District.

8.2.4 Create mechanisms to safeguard the well-being of rural communities in the U.S. and Mexico affected by the ongoing transfer of water from the agricultural to the municipal sector

Given that agriculture uses 80 percent of the Colorado River's water and that growth in southwestern United States and northwestern Mexico cities is likely to continu e unabated, the ongoing transfer of water from the agricultural to the municipal sector is all but inevitable. There exists a great potential for cooperation to meet the increasing urban demand, to protect rural landscapes and livelihoods, and to satisfy environmental needs simultaneously that should not be wasted.

A sustainable water future for the region can be attained by managing urban growth and improving agricultural efficiency. Recognizing the importance of agriculture to the economy, history, and culture of the region, mechanisms need to be created to facilitate water transfers while protecting the economic livelihood and social fabric of affected rural communities. These could include setting a cap on the percentage of Colorado River water allocated to municipal uses in rural areas, as mentioned in the "Powell's Prophecy" scenario, and providing economic assistance to communities where relatively unproductive land is converted.

Incorporating elements of ecosystem-based management into existing plans for U.S. and Mexican water agencies, cities, and irrigation districts would highlight some of the trade-offs in water allocation. The reorganization of the Mexican water agency along hydrographic basins is a first step in this direction.

8.3 Areas for Further Study

To achieve the goal of protecting ecosystem services, it will be necessary to develop new policies and institutions for water governance that enable effective participation of those affected on both sides of the border, based on the establishment of rights to ecosystem services and responsibilities for actions necessary to ensure they continue to be produced. This is not only to build stakeholder awareness of links between ecosystem services and human well-being; by engaging in the process, stakeholders can bring important information regarding the context and conflicts between multiple objectives, contribute to the development of feasible policies, provide feedback regarding obstacles encountered in implementation, and help to identify opportunities for action or for conflict resolution that might otherwise be overlooked.

These policies and institutions provide a foundation for the use of economic instruments to achieve objectives for conservation of water and of all ecosystem services in which water is a critical factor, such as wildlife habitat. Willingness of stakeholders to pay for services will depend not only on actual benefits they expect to receive, but on the fairness and effectiveness of the above mentioned institutional arrangements that determine who pays, who is paid, what is produced, and whether there is sufficient cooperation necessary for effectiveness. The four scenarios presented above attempt to raise some of these questions so that stakeholders can engage in a negotiation about the best course to follow.

Experiences from other water policy initiatives, such as the Murray Darling River Basin in Australia, in which water is allocated under a cap, reserving a specified amount for environmental flows, can be an important source of lessons learned. However, a key challenge is to establish an ongoing place-based approach to assessment so as to learn lessons directly from experiences in the Lower Colorado Basin, in response to unfolding events and new policies. By monitoring the implementation of new policies, as well as ecosystem variability, better understanding can be obtained regarding stakeholder vulnerabilities, resilience, unexpected outcomes, and conflicts among multiple uses. This kind of assessment can then provide critical feedback to inform policy as part of an adaptive approach to management. It can also create opportunities for social learning that lead to reconsideration of the values of ecosystem services, which depend as much on stakeholder confidence in institutional capacity to deliver as on ecosystem capacity.

Some specific scientific research questions that need to be further addressed include the following:

8.3.1 Improve projections of the impacts of climate change on river flows and riparian areas

Current research suggests a reduction of Colorado River flows between 6 percent and 45 percent by mid century (Christensen and Lettenmaier 2006; Hoerling and Eischeid 2007). Gaining a better understanding of variability of the total flow will aid decision makers.

8.3.2 Strengthen economic valuation studies on the ecosystem services provided by the Lower Basin's ecosystems

Preliminary efforts, using willingness-to-pay methods, have been made to quantify the value of Colorado River flows to stakeholders in the Delta (Rivera 2006), based on current levels of knowledge and awareness. To better inform policy decisions, stakeholders need to be presented with more information regarding choices that are available, their expected consequences, and implications for human well-being. Information is also needed regarding the conditions under which stakeholders are willing to pay, such as the kinds of arrangements that would be accepted as fair and in which there is confidence that they will be effective.

8.3.3 Develop a hydrological model for the Delta

Developing and testing a surface and subsurface hydrological model for the Delta in the United States and Mexico will be valuable in assessing the impacts of base and pulse flows. If treated experimentally, scientific knowledge can be garnered and policies and management plans can adapt according to those findings.

8.3.4 Study the resilience of key elements of the natural and cultural systems in the Delta

"Resilience, for social-ecological systems, is related to (i) the magnitude of shock that the system can absorb and remain within a given state; (ii) the degree to which the system is capable of self-organization; and (iii) the degree to which the system can build capacity for learning and adaptation" (Folke 2002). Understanding the resilience in the Colorado River Delta's natural and cultural systems will enable us to better cope with surprises, such as climate change and population growth in the future.

8.4 References

Adler, R. 2007. *Restoring Colorado River Ecosystems: A Troubled Sense of Immensity*. Washington D.C.: Island Press.

Census. 2005b. "Interim Projections: Ranking of Census 2000 and Projected 2030 State Population and Change: 2000 to 2030." Accessed at www.census.gov/population/projections/PressTab1.xls on June 20, 2007.

Christensen, N. S. and D. P. Lettenmaier. 2006. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin, submitted to Hydrology and Earth System Sciences in Nov. 2006.

Folke, C. et al. 2002. "Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations." *AMBIO* 31 (5):437–440.

Hoerling, M. and J. Eischeid. 2007. "Past Peak Water in the Southwest" Southwest Hydrology 6(1):18–35.

National Research Council 2007. *Progress Towards Restoring the Everglades: The First Biennial Review 2006*. Washington D.C.: National Academies Press.

Rivera, E. S. and Y. Carrillo Guerrero. 2006. Beneficios económicos de los flujos de agua en el delta del Rio Colorado: consideraciones y recomendaciones iniciales, *Gaceta ecológica 80*, Instituto Nacional de Ecología, México.

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