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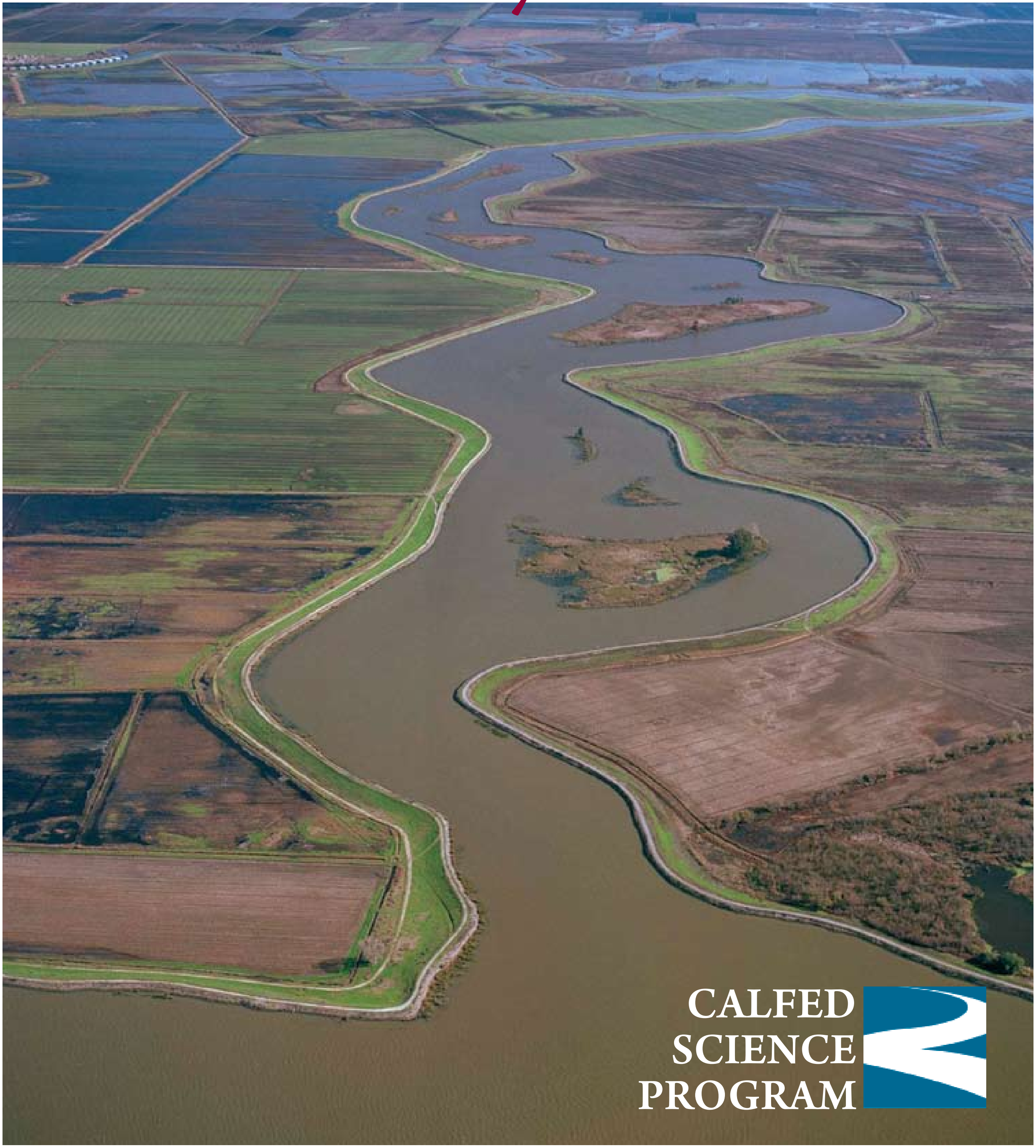
The State of Bay-Delta Science



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The State of Bay-Delta Science, 2008

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Cover photograph:
Potato Slough meanders through the Central Delta between Venice Island and Bouldin Island.
Courtesy of the California Department of Water Resources

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Preface

The State of Bay-Delta Science, 2008 summarizes and synthesizes our current scientific understanding of the Bay-Delta. Research on the Bay-Delta system increased dramatically with the creation of the CALFED Bay-Delta Program in 2000 and this new research has both improved our understanding of how the Bay-Delta functions and has challenged some long-held beliefs about the Bay-Delta. The eight chapters of this State of Bay-Delta Science report focus on our new understanding of the California Delta and what it means for policymaking.

The chapters are written by respected scientists from government and academia who are intimately familiar with the Bay-Delta. Our target audience, however, is not other scientists but managers, policymakers and interested laypeople. The editorial board has worked hard to ensure that the language of *The State of Bay-Delta Science, 2008* is accessible to an informed, non-technical audience but is still scientifically accurate. We hope that this volume will become a fundamental reference for all those who are deeply concerned with the future of the California Delta and its resources. It is also intended to establish a baseline of scientific understanding that will improve and evolve as research on the Bay-Delta continues. From time to time the CALFED Science Program will update the State of Bay-Delta Science report so that it will continue to be an up-to-date reference.

The State of Bay-Delta Science, 2008, begins with an introduction that presents important new policy perspectives for the Bay-Delta based on our new scientific understanding. These perspectives challenge both our traditional understanding of the California Delta and our policies for managing it. Subsequent chapters provide the detailed scientific support for these new perspectives. Chapters 1 and 2 provide an historic and geographic context for science in the Bay-Delta Program. Chapters 3 through 6 synthesize current information and understanding around the four pillars of the CALFED Bay-Delta Program, water quality, ecosystem restoration, levee integrity and water supply. Chapter 7 deals with scientific issues that cut across all four pillars. Chapter 8 summarizes the process of integrating science into public policy and concludes with recommendations for the future direction of science in the Bay-Delta.

Despite the attention that has been directed at the Bay-Delta in recent years, problems of water supply, water quality, ecosystem function and levee integrity continue to intensify. Long-range planning for management of these issues is complicated by climate change, sea-level rise and ongoing subsidence of soils in Delta islands. The growing scientific understanding of the vulnerability of the California Delta and the risks to California's water supply and environment posed by continuing with long-established policies, led Governor Schwarzenegger to establish the Governor's Delta Vision Blue Ribbon Task Force, which is tasked with developing a new vision for the Bay-Delta. The Task Force and several high-level planning processes are addressing the problems of the Bay-Delta, and all these planning processes depend heavily on scientific understanding of the system. Policymakers and the public need to be well informed scientifically to be able to assess alternative policies and to make sound decisions about water and environmental management. This report provides the necessary foundation of information for sound decision-making.

Michael Healey
Editor in Chief, *The State of Bay-Delta Science, 2008*
Sacramento, CA, August 20

Introduction: New Perspectives on Science and Policy in the Bay-Delta

Michael Healey,[1] Michael Dettinger,[2]
Richard Norgaard[3]

The environmental resources of the San Francisco Bay and Sacramento-San Joaquin Delta have long contributed to the state's diverse society and its prosperous economy. However, in pursuit of well-being and prosperity over the past 150 years, Californians have dramatically changed the Delta's geography, hydrology, and ecology.

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[1] CALFED Science Program

[2] United States Geological Survey and Scripps Institution of Oceanography

[3] University of California, Berkeley

(Photo by: California Department of Water Resources)

Today, the Bay-Delta is degraded and its capacity to provide all the environmental and societal benefits the public demands (viable populations of desired species, wild habitats for recreation and solace, land for agriculture, and the conveyance of reliable and high quality fresh water) continues to decline.[1]

As the Delta has changed, science has played an increasingly important role in contributing to the way people perceive and respond to problems. As our science of the Bay-Delta has progressed, our understanding has improved. Our comprehension of how the Delta functions is today quite different from that of a few decades ago. We now know that change is constant, that it is neither possible nor desirable to "freeze" the Delta at any point in time, that the challenges of water and environmental management are inextricably intertwined, and that the capacity of the Delta to meet environmental and water supply expectations is likely at a limit.

The problems of the Bay-Delta are broad-based and do not easily fit within traditional discipline-based problem-solving. Looking to the future, we now no longer consider earthquake-induced levee failures and "Katrina-style" flooding to be science fiction. Realistic views of the future include dramatic changes, such as accelerated sea-level rise, changes in the availability of fresh water, and continued species invasions. The scientific community is grappling with the implications of these complex problems, which affect the direction of research, the interactions among scientists and practitioners, and the communication of science to policymakers.

The CALFED Bay-Delta Program was established in 2000 to address the problems of water reliability, ecosystem restoration, levee integrity, and water quality in the Delta and its tributaries. Since then, CALFED-supported science has helped to clarify the extent and seriousness of the problems in the Delta, and has identified a spectrum of potential solutions. These solutions and how to implement them are now under debate as part of the Delta Vision process.

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[1] Discussed in greater detail in Chapters 1 and 2

The New Science of the Bay-Delta

Routine scientific monitoring of the Bay-Delta began more than three decades ago under the auspices of the United States Geological Survey and the Interagency Ecological Program. The long-term data-sets provided by this monitoring, combined with recent problem-focused research and analysis stimulated by CALFED, has greatly increased our understanding of the Bay-Delta system. Nevertheless, much still remains to be learned, and changing background conditions (e.g., climate change, population growth, species invasions) are continually challenging our ability to predict the future from the past. Problems that policymakers must address are increasing in complexity, and solutions call for new forms of collaboration among scientists from different disciplines. Helping in this collaboration, the CALFED Science Program has acted to expand and facilitate communication among scientists, and between scientists and policymakers through its journal *San Francisco Estuary and Watershed Science*, newsletters like *Science News*, model-development, biennial science conferences, and many workshops. CALFED has helped scientists to look beyond their specific disciplines and see the Delta as a whole—laying the important groundwork for the Delta Vision,[2] Delta Risk Management Strategy,[3] and the Bay Delta Conservation Plan.[4]

The result of all this scientific activity has been a new perspective of the Delta, and recognition that the environmental services provided by the Delta will continue to degrade—with some disappearing—if we continue our current policies for water and environmental management. Our policy framework of the past has served California well, but our enhanced understanding of the Delta shows that we need new policies if the Delta is to continue to provide the range of services that Californians demand. This introduction to *The State of Bay-Delta Science, 2008* is framed around our new perspectives arising from recent Delta science. It highlights the most important changes in how we now understand the Delta and provides the principal policy implications (see Table I.1).

Perspective One

The Delta is a continually changing ecosystem. Uncontrolled drivers of change (population growth, changing climate, land subsidence, seismicity) mean that the Delta of the future will be very different from the Delta of today.

Despite the fact that change is what characterizes the Bay-Delta, our policies and even some of our science have often assumed that the Delta of the future would be much the same as the Delta of today. A growing body of science, however, shows that large-scale changes are commonplace in systems like the Bay-Delta. Powerful external forces are driving change in the Bay-Delta. A more realistic viewpoint is that change is inevitable and is necessary for the system to function properly since estuaries and deltas are dynamic, constantly changing ecosystems.

The present Delta formed when the sea level rose following the last ice age, which ended 10,000 BCE. As the rivers of the Central Valley carved away at the fringing mountains, the Delta approached its pre-colonial geometry about 5,000 BCE. In the past 150 years, Californians have imposed rapid changes on the Delta, creating islands and channels where

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[2] For more information on the Delta Vision, visit www.deltavison.ca.gov

[3] For more information on the Delta Risk Management Strategy, visit www.drms.ca.gov

[4] For more information on the Bay-Delta Conservation Plan, visit www.resources.ca.gov/bdcp

Table I.1. New Perspectives on the Delta Derived from Recent Science

Perspective One: The Delta is a continually changing ecosystem. Uncontrolled drivers of change (e.g., population growth, changing climate, land subsidence, seismicity) mean that the Delta of the future will be very different from the Delta of today.

Perspective Two: Because the Delta is continually changing, we cannot predict all the important consequences of management solutions. The best solutions will be robust but provisional, and will need to be responsive and adaptive to future changes.

Perspective Three: It is neither possible nor desirable to freeze the structure of the Delta in its present, or any other form. Strengthening of levees is only one element of a sustainable solution and is not applicable everywhere.

Perspective Four: The problems of water and environmental management are interlinked. Piecemeal solutions will not work. Science, knowledge and management methods all need to be strongly integrated.

Perspective Five: The capacity of the Sacramento-San Joaquin water system to deliver human, economic and environmental services is likely at its limit. To fulfill more of one water-using service we must accept less of another.

Perspective Six: Good science provides a reliable knowledge base for decision-making, but for complex environmental problems, even as we learn from science, new areas of uncertainty arise.

Perspective Seven: Accelerated climate change means that species conservation is becoming more than a local habitat problem. Conservation approaches need to include a broad range of choices other than habitat protection.

there had been marsh and tidal creeks, changing freshwater flows and sedimentation patterns, discharging chemical wastes, and introducing new species. This rapid change continues today, with human populations increasing, land uses and associated discharges changing, species from other regions invading (see Figure I.1), native species struggling with new challenges, the climate warming, and the sea level rising.[5]

Continual environmental change must be accommodated in any program to sustain valued species. Instead of seeking some constant, optimal conditions, sustainable management of the Delta's ecosystem will rely on habitats that go through repeated or uncertain cycles of change. Broadly speaking, we understand that our native organisms evolved in a variable environment and are better adapted to the large temporal and spatial variations more characteristic of California's natural landscapes than to the static conditions provided in heavily engineered settings.

The muting of natural habitat rhythms is not the only influence to which Bay-Delta organisms must respond. A rising sea level implies that the location of certain habitat types that we typically think of as fixed will change. Our system of land and water management as a whole must be able to respond to sea-level rise, which could be three feet or more over the next century. From a scientific perspective, changing background conditions means that our measurements of the Bay-Delta system will never converge toward any "normal" values. Furthermore,

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[5] Discussed in greater detail in Chapters 1–4

as environmental change continues, the problem a scientist starts out to address may change into a new problem for which hard-won measurements and analyses of the past may no longer be relevant. For example, the invasion of the overbite clam in Suisun Bay changed the structure of the food web, making historic understanding of food web dynamics less relevant to emerging conservation problems (see Figure I.1). As California warms, and precipitation in the mountains changes from snow to rain, as sea-level rises, and as water quality constraints continue to evolve, many of today's water supply problems may be barely addressed before they are subsumed by the next challenge. Science needs a finite period to understand any natural process or trend, usually several years for environmental problems. For example, precipitation patterns vary from year to year and decade to decade. Several years of data are required for the scientist to understand local hydrodynamics and water supplies. In times of sporadic change, science may be hard-pressed to understand what is happening well enough to inform policy. A stronger infrastructure and firmer support for science will help narrow this gap in capacity.[6]

One of the main contributions of science to discussions of the future Delta has been precisely this realization that neither the undisturbed past, nor an armored current condition, can resist the continually evolving conditions and problems in the Delta. We now have a much clearer picture of how quickly the system is changing, the direction of change, and how uncertainties about future change limit firm statements about ecological cause-and-effect or management outcomes.

For science, this means improving our capacity to monitor and evaluate change. For policy, it means identifying and implementing policies that are both responsive to change yet robust, flexible and adaptable.[7]

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[6] Discussed in greater detail in Chapters 6 and 8

[7] Discussed in greater detail in Chapters 3–8

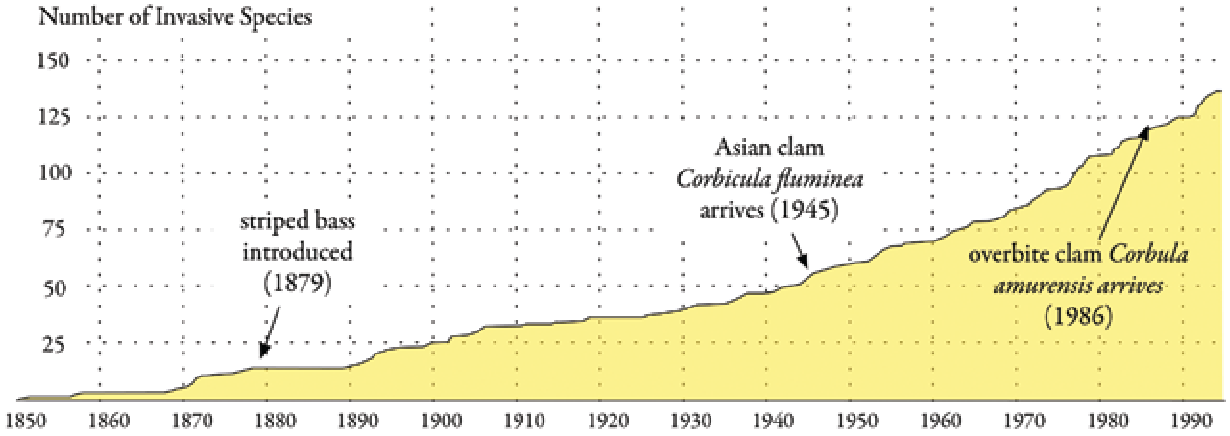

Figure I.1. The estimated number of invasive species in the San Francisco Estuary from 1850 to 1995. (Source: Adapted from Cohen and Carlton 1998)

Perspective Two

Because the Delta is continually changing, we cannot predict all the important consequences of management solutions. The best solutions will be robust but provisional, and will need to be responsive and adaptive to future changes.

The desire for permanent, or at least very long-term, solutions is commonplace in environmental and engineering designs. No one wants to repair a broken system repeatedly. CALFED's Ecosystem Restoration Program is unique in its emphasis on using physical and ecological processes to help rebuild sustainable ecosystems that would produce the services we desired (e.g., viable species populations, particular habitat types) with little required maintenance. Recent science in the Delta, however, has led to the perspective that continual environmental change is itself a key to sustaining valued aquatic species. This means that any management plan for the Delta must retain or restore flexibility and variability if key species, processes, and services are to be maintained. The desire for permanent solutions has pervaded other elements of CALFED, but this is changing. Levees were once viewed as permanent bulwarks against flood, but we now recognize that levees are only one tool for managing flood flows and that some levees should be designed to fail or be overtopped. In the past, we designed water supplies for urban and agricultural use to be stable and reliable, but now we recognize that both supply and quality change with time, so that reliability derives from the capacity for adaptation.[8]

In the face of pressures from growing human populations, from aging levees, from degrading land surfaces, and from climate change and sea-level rise, we can only expect that solutions that seem reliable today will become unreliable in the future. Our ability to predict those challenges is unlikely to improve enough to make permanent decisions possible any time soon. These challenges limit our ability to manage and control the Delta ecosystem. They even limit our ability to monitor and identify changes. Under these circumstances, no single once-and-for-all solution for Delta problems can realistically be expected. Rather, water and environmental management designs that will be the most cost-effective and most likely to succeed will be practical, responsive in the face of anticipated changes, yet capable of adapting. The need for adaptability recognizes that all solutions are temporary; procedures and diverse options for adaptation need to be built in. To satisfy these needs, we should formally establish adaptive management procedures and strategies within agency policies.[9]

As we acknowledge the temporary nature of solutions, we increasingly recognize that the best policies are enabling instead of prescriptive. To increase the potential for learning and the likelihood of success, the most valued policies will be those that allow a diversity of responses and can evolve as conditions change. Since future conditions are uncertain, surprise is inevitable—engaging a variety of policy solutions can help to spread the risk.

Perspective Three

It is neither possible nor desirable to freeze the structure of the Delta in its present, or any other form. Strengthening of levees is only one element of a sustainable solution and is not applicable everywhere.

The Delta's levees grew with agricultural development of the vast marshlands, meandering channels, tidal sloughs, and muddy islands that existed before the Gold Rush. Laborers first raised the low natural levees that surrounded Delta islands by hand, then by dredging sands and silts from channels. The

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[8] Discussed in greater detail in Chapters 3–6

[9] Discussed in greater detail in Chapters 3–6, and 8

Figure I.2. Levee failures can result in extensive damage to homes and agricultural fields. Flooding also imperils our water supply. (Photo by: California Department of Water Resources)

resulting levees are haphazardly engineered, with heavy mineral sediments commonly sitting on top of less stable peat. Despite the levees' structural weakness, they define the Delta's geography, water channels, land uses, habitats, flood flows, and tidal patterns.[10]

Until recently, we believed that stable levees were the foundation of a sustainable Delta. We viewed levee stability as absolutely necessary for water supply reliability, a crucial determinant of water quality, and the protector of the Delta's ecosystems and agriculture. Meanwhile, exposure of the islands' peat soils to air, fire, wind, and compaction, has resulted in the ground surface in many Delta islands subsiding as much as twenty-five to thirty-two feet below the water level of adjacent channels. The levees themselves have aged and weakened, breaking regularly, despite the development of massive flood-control systems upstream (see Figure I.2). Channelization of tidal and riverine flows by the levees has created artificial salinity and mixing conditions that favor invasive species over native species.[11]

Recent analyses of levees and levee risk show that the likelihood of levees failing in the future is high, that levees are limiting our options for ecosystem restoration, and that levees are a weak link in the state's water and flood management system. Maintaining them in their current form would be very costly and difficult, even if historical conditions continued. But Delta conditions are changing in ways that heighten the risks posed by our dependence on levees. The levees may be shattered in an earthquake, face increasing pressure from floods and rising sea level, and continue to weaken with age and land subsidence. Decision-makers increasingly recognize that the present levee system is not a dependable foundation for the future Delta. Given the mounting pressure on the levees, it is likely that future levee failures will be multiple, flooding many islands, posing a severe risk to human life, and disabling the state's water system for months or possibly years (see Figure I.2).

For these reasons, sustainable policies for managing the Delta need to discard any remaining belief that we can strengthen levees enough everywhere to protect Delta lands and infrastructure into the future. The use of levees is just one of several ways of managing and maintaining critical landscapes in the

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[10] Discussed in greater detail in Chapters 2 and 5

[11] Discussed in greater detail in Chapters 3–6

Delta, such as human uses and settlements. In some places, for example, we should strengthen levees to provide reliable long-term protection for existing urban development, or critical water supply channels. In other places, levees could hamper ecosystem restoration, effective flood management, and other long-term goals. We need more holistic and comprehensive approaches to floods, emergency preparedness, and habitat restoration. Levees and other hard engineered works will be part of the solution, but using multiple approaches is likely to provide more reliable and sustainable solutions to the wide range of Delta problems. We should design much of the Delta's levees and land use to absorb occasional overtopping and failure. Land use policies reflecting such realities as subsidence, the rising sea level, and the impracticality of assuring the same level of flood protection everywhere are more realistic than policies built solely on levee strength. Urban planning that acknowledges the risks, directs development from the most flood-prone areas, and promotes flood-safe construction is also part of a sustainable solution.

Perspective Four

The problems of water and environmental management are interlinked. Piecemeal solutions will not work. Science, knowledge and management methods all need to be strongly integrated.

Western science has succeeded by breaking problems into their constituent parts and conducting research to understand each part in isolation. We expect to understand the whole from understanding the parts. The success of this approach in both the physical sciences and engineering has even influenced the way we organized governmental agencies: hydrologists in water agencies, fisheries biologists in fisheries agencies, etc. But the success of the reductionist approach in the physical sciences has not been paralleled in the environmental sciences. A clear understanding of the whole has not emerged from our understanding of the parts. "Environmental problems" can arise and persist because of weaknesses in the application of reductionist science to problems in complex ecological systems.

Science in the Delta has used both reductionist and interdisciplinary methods and research. To address the complex issues of the Bay-Delta, scientists from different backgrounds have learned to share information and to look at problems in new ways, much as numerous disciplines including physicists, ecologists, and economists have come together in the study of climate change. CALFED's research funding across agencies, to bring scientists from many disciplines together with resource managers in workshops to address particular topics, mirrors the most recent developments in science worldwide. An example of this integration is the research conducted to understand the Pelagic Organism Decline (POD). Researchers designed a multifaceted conceptual model that has connected declines in pelagic organisms to a spectrum of interlinked causes ranging from water exports to agricultural practices, and from invasive species to sediment transport. The interlinking of Delta science on water supply, water quality, and ecosystem health with land uses, flood management, and levee engineering are heavily influencing planning for a sustainable vision of the Delta.[12]

Much environmental science in the Bay-Delta comes from the long-term monitoring programs conducted by the Interagency Ecological Program, the San Francisco Estuary Institute, and other programs and agencies. This monitoring has provided the data for nearly all the crucial analyses of trends and variability in the estuary's ecosystems. However, the monitoring has been based on the assumption that simply measuring the numbers of organisms, or the quality of water will allow proper ecosystem management and restoration. We now realize that to understand changes in the abundance and distribution of particular species, we must also understand the dynamics of their predators and prey. To understand the impact of water quality on species and the ecosystem, we must also understand the processes that distribute chemicals in the environment and through the food chain. Furthermore, entire groups of organisms, important physical parameters, and important contaminants have gone unmonitored. Recent scientific successes have shown that a mixture of multidisciplinary monitoring, modeling and field and laboratory studies is needed to synthesize, track and understand changes in the Delta. Attempts to understand the POD have shown both the strengths and the weaknesses of existing databases and monitoring. As science has integrated more aspects of the system into its analyses, it is becoming clear that to understand the Delta we must mobilize the full range of tools and methods of science ranging from ecotoxicology to genetic fingerprinting, from biotelemetry to systems modeling.[13]

Problems of the future will be as multifaceted and complicated as those we face today. Research supporting management, as well as management itself, will be most successful if they embrace this complexity in search of effective and adaptive solutions. Our limited ability to predict the results of management actions in the Delta reflects our inexperience with linking the methods from the many separate disciplines that contribute to Bay-Delta science. Building these linkages remains an important area for scientific progress in the future. Collaboration that brings together researchers and managers in interagency research and workshops to build linkages has been very influential in advancing Bay-Delta science and management. Bay-Delta science also provides a model for scientific management efforts elsewhere. However, we can do much more to encourage and strengthen the integration of disciplines and the integration of science into management.

Perspective Five

The capacity of the Sacramento-San Joaquin water system to deliver human, economic and environmental services is likely at its limit. To fulfill more of one water-using service we must accept less of another.

Since European settlement, California's streams have been tapped to meet ever-increasing human demand for water. In the twentieth century, federal and state water projects increased storage and conveyance capacities, resulting in spectacular prosperity for the state. Now, California has grown to a population of thirty-six million, with an economy that is the seventh-largest in the world, largely on the strength of its large-scale integrated approach to water management. However, opportunities for increasing supply to satisfy growing demand are becoming limited, and environmental problems are creating a growing need to reallocate water to the ecosystem. As California's population grows, increasing urban water needs will have to be met

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[12] Discussed in greater detail in Chapters 4 and 7

[13] Discussed in greater detail in Chapter 7

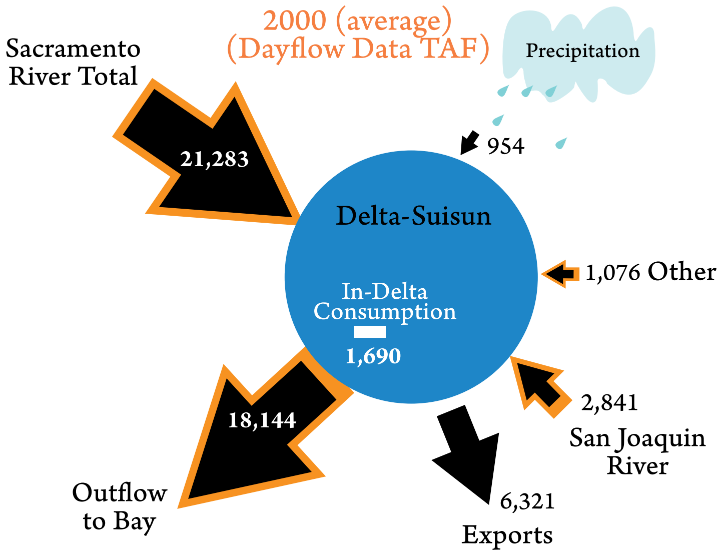

Figure I.3. Delta Water Balance showing inflows and outflows during an average water year, in thousand acre-feet. (Source: URS Corporation 2007)

mainly by improving water management instead of by developing new supplies within the Sacramento-San Joaquin system (see Figure I.3).[14]

The transition from a belief in growth through water development to growth by working within water limits began during the last quarter of the twentieth century as Californians reached real limits and became increasingly aware of the environmental impacts of water development on habitat loss, species declines, and water pollution. Severe droughts in 1976 through 1977 and 1987 through 1992 brought home the fact that water is precious, while also showing the possibilities for water conservation. We have replaced our old way of thinking about water as flowing 'wasted to the sea' with the recognition that every drop of water flowing in a river to the sea contributes to valuable ecosystem functionality. Today, individual water consumption is less than it was thirty years ago, and water planners are often more concerned with water reliability and quality than with increasing supply.[15]

Frequently, conflicts between water limits and the water needed to meet societal and environmental goals come to a head in the Delta. Priorities have changed in recent years, and water deliveries are now timed to meet environmental functionality as well as the needs of water users. Proposals to improve water supply reliability increasingly recognize that reliability will depend on having multiple supply, storage and conveyance choices. Waste products of the human economy are also discharged into water, and the far-reaching impacts of certain wastes are becoming increasingly clear. Stimulated by concern over the impact of selenium and mercury on fish and birds in the Bay-Delta, science has shown the complex environmental and ecological impacts of these contaminants. Selenium is released during oil refining and from soil irrigated along the west side of the San Joaquin Valley. Irrigation drainage waters poisoned waterfowl in Kesterson Reservoir. When redirected into the San Joaquin River, this selenium flowed into San Francisco Bay where it poisoned bottom-feeding fish and ducks. Today, we have virtually eliminated selenium from refinery discharges, and we have reduced selenium contamination from agricultural runoff through better land and

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[14] Discussed in greater detail in Chapters 4 and 6

[15] Discussed in greater detail in Chapters 1, 2, and 6

water management. However, completely eliminating selenium discharge into the San Joaquin River would be very costly, and most proposed solutions simply transport the problem elsewhere. Mercury is a naturally occurring contaminant in California's Coastal Ranges, but during the Gold Rush, it was mobilized and widely distributed through mining processes. Mercury is a pervasive contaminant in water, sediments, and biota of the Bay-Delta. It is also a serious obstacle to wetland restoration because restoration can remobilize mercury locked in sediments. Comparable conflicts between contamination of drinking water and ecosystem needs have also emerged for organic carbon and bromide. Carbon and bromine are natural components of Delta waters, but during disinfection of drinking water, they form cancer-causing byproducts. Drinking water standards are becoming more restrictive, and removing these contaminants from the Delta's water is extremely costly, making the Delta an increasingly poor Source of drinking water. Yet, alternative Sources of drinking water pose their own problems and raise other hard choices.[16]

There are multiple policy challenges in satisfying the demand for water. Demand itself changes as our population and economy grow and change, but we are limited in our supply of water. Water must meet different quality standards depending on its intended use, and these standards are changing. The quality of available water is also changing in response to land use and waste discharge. Rising sea level, changing hydrology, and risks to levees from earthquakes, among others, make the Delta a poor Source of high quality water in the long run. While environmental needs for water remain ill-defined, future policies will likely put greater priority on environmental water, further constraining alternative uses. Given the limits of the Sacramento-San Joaquin water supply, water policies that emphasize efficiency of use, flexibility of allocation, and local self-sufficiency may provide the most likely pathways to real water supply reliability.

Perspective Six

Good science provides a reliable knowledge base for decision-making, but for complex environmental problems, even as we learn from science, new areas of uncertainty arise.

In a complex system like the Bay-Delta that is changing rapidly, scientific uncertainties will always be present. Chaos and complexity theory tell us that, even if we had a perfect description of the Bay-Delta's condition at a single moment in time, any prediction of its condition in the future would become increasingly inaccurate the further ahead we tried to look. This is the ecological equivalent of weather prediction. We can be very certain that the weather a minute in the future will be as it is now. Predicting tomorrow's weather is more uncertain, even with sophisticated models. Predicting weather two months or two years from now is highly uncertain. Furthermore, we cannot know all the details of any complex system at any moment in time—partly because most of the system is invisible to us. The Delta farmer, for example, does not actually see his land subsiding. The increased risk of levee failure is also invisible, until the levee fails. Local conditions, problems, and available solutions in the Delta are always changing—often in ways we do not understand or have not yet imagined. The prospect of continual change means that a definitive understanding of important aspects of the system is virtually impossible. We are limited in our ability to reduce this uncertainty because the time required to gain scientific understanding is comparable to the time-span over which the system itself is changing (and the time-span over which decisions that impose still more changes will be made).[17]

Early in the twentieth century, science came to be seen as the foundation of reliable long-term solutions to society's problems. Levees and water supplies were engineered with the confidence that any

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[16] Discussed in greater detail in Chapters 3 and 6

[17] Discussed in greater detail in Chapters 1 and 3–7

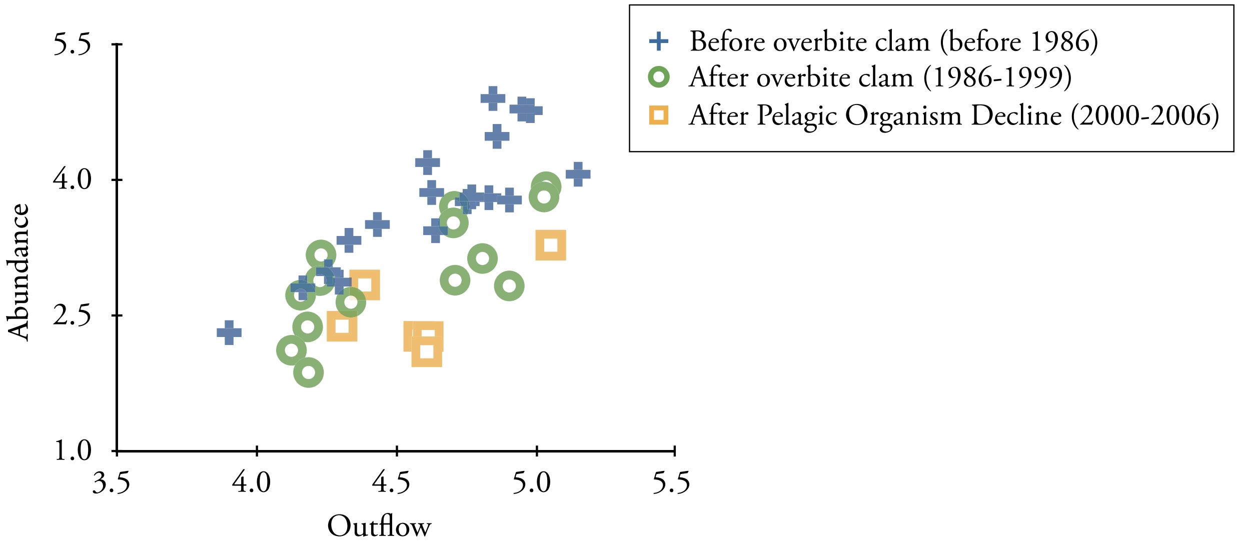

Figure I.4. The changing relationship between longfin smelt abundance and Delta outflow. (Source: Adapted from Kimmerer 2002)

problems resulting from their design or installation could be addressed as needed. Water quality problems are often discovered long after we begin discharging contaminants instead of being anticipated when discharge begins. Habitat loss and species declines have also frequently been addressed incrementally, with little reflection on the gaps in knowledge that mask underlying causes. We now recognize that these approaches are a recipe for long-term failure.[18]

Ecosystems are complex adaptive systems that respond to outside influences in unexpected ways. For a time, the ecosystem may absorb a stressor seemingly without response, only to suddenly change or collapse. The POD may be an example of such a sudden response. Ecosystem science is currently not good at predicting when stress will trigger these sudden responses. This results in significant scientific and management challenges. Flexible and adaptive management systems are the best defense against such surprises. The type of multi-agency and multidisciplinary integration of science that CALFED has promoted has helped institutions to interpret and respond to new information in a timely way. Events leading up to the decision to stop the State Water Project pumps on May 31, 2007 illustrate this collaborative process. Monitoring on May 12 showed high numbers of Delta smelt captured at the pumps, causing the Department of Water Resources to reduce pumping. Further data collected on May 25 and 31 showed continued high catches, and scientists and managers agreed to the shutdown on May 31.[19]

Recent scientific studies have suggested that new kinds of uncertainty about the Delta system are emerging. From a coarse scale, global climate models suggest that precipitation patterns, river discharge patterns, and storm events affecting the Delta will change in the future, but regional projections of these events are highly uncertain. From a finer scale, historic data showed a relationship between outflow from the Delta and the abundance of some pelagic fish species, a relationship that was the basis of managing outflow to control salinity in-

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[18] Discussed in greater detail in Chapters 1, 3, and 4

[19] Discussed in greater detail in Chapters 4, 6, and 8

trusion in the Delta (the X2 management regime). However, data collected since the POD suggest that the relationship has changed, or broken down, confounding the hypotheses that linked outflow to fish populations (see Figure I.4).

We now understand that policies must accommodate these underlying uncertainties. An example of such an accommodation is the multibarrier approach for drinking water quality maintenance, where—in the face of uncertain sources, threats, and needs—we develop multiple, redundant safeguards on water quality. Integrated approaches to water supply reliability that draw on several different sources and conveyances to mitigate the uncertainties and risks of each are another example of accommodating inherent uncertainties through a diversity of management options. Similarly, flexible approaches need to be developed for ecosystem restoration and levee integrity. Adaptive experimentation to maximize learning opportunities and a precautionary approach to management decisions would help to avoid the overuse of resources that has characterized past water management.

Perspective Seven

Accelerated climate change means that species conservation is becoming more than a local habitat problem. Conservation approaches need to include a broad range of choices other than habitat protection.

The recovery of species listed as threatened or endangered is the main driver of today's science and conservation planning in the Delta. Although the problems of the Bay-Delta are ecosystem-level problems, we see them revealed through the disappearance of individual species or habitats, and it is these losses that capture our attention. When CALFED began, listed races of Chinook salmon were the primary focus of research and management. Shortly after all parties signed the Record of Decision (ROD), the POD emerged, and after 2004 began to drive science and water management decisions. As a listed and a POD species, the Delta smelt has received a great deal of attention (see Figure I.5). Although the causes for the decline of Delta smelt remain uncertain, (there are quite likely multiple causes including export pumping, toxic substances, and food web changes), there is also a growing recognition that global warming may make the future Delta intolerable to Delta smelt and oth-

Figure I.5. As the climate changes and water temperatures warm, the Delta may no longer be able to support the imperiled Delta smelt. (Photo by: California Department of Water Resources) er valued species, undermining local attempts to protect them. Even as science increases our ability to manage the changes that we can control, it also shows us the implications of such uncontrollable changes as climate. In the face of such externally imposed challenges to Delta species, conservation becomes more than a local problem of habitat management. Instead, it engages wider questions such as whether we should establish refuge populations of smelt, or other species where the physical environment remains suitable; whether cryopreservation of DNA, or maintenance of captive populations need to be part of our conservation tool-kit; and whether artificial genetic modification to change the environmental tolerance of a species should be attempted.[20]

Invasion of the Delta by non-native species is also an issue of great concern that is linked to native species loss. We know, for example, that the invasive overbite clam appropriates most of the primary production in Suisun Bay, starving the food web leading to Delta smelt. We also know that the invasion of Brazilian waterweed has enhanced the habitat of largemouth bass and sunfish to the disadvantage of native species. Under the United Nations convention on biodiversity, invasive species are a primary threat to biodiversity, and signatory nations, though the United States is not one, must develop plans for preventing and managing the adverse impacts of species invasions. In our changing global environment, we may need to adopt a broader perspective on species introductions. The Bay-Delta is already one of the most invaded estuaries in the world, and further invasions are almost certain to occur. As climate changes and the Delta becomes inhospitable to native species, it may nevertheless provide a refuge for species from warmer habitats that are themselves facing intolerable local conditions. Relocating species for conservation purposes may become as important as protecting local habitats.

The kinds of environmental changes expected for the Bay-Delta in the near future call for a rethinking of both policy and management of native and alien species. Critical habitat, as required under the Endangered Species Act, may no longer be where a species lives today, but somewhere farther north, at a higher elevation, or in an unexpected setting. Conservation policy will have to be open to exploring many ways to preserve biodiversity.

The Way Forward

These new scientific perspectives on the Bay-Delta and its environmental challenges highlight the growth in scientific understanding of the Delta and of ecosystem management that has occurred during the past decades. These perspectives highlight the impending globally and locally driven changes to the Bay-Delta to which policy must respond. Globally, climate change is expected to raise sea level three feet or more over the next century, change precipitation and storm patterns, and raise local temperatures several degrees. Locally, population growth, land subsidence, earthquakes, and species invasions will drive ecological change and increase risks of flooding. Scientifically, we now recognize that change and uncertainty are essential characteristics of our local ecosystem dynamics. We often manage natural resources under an assumption of permanence, that the future will be like the present, and that management should aim for the "optimum" condition. This is not an achievable goal. Future infrastructure, both for management and for science, needs to be robust but flexible, inclusive and adaptive, resilient and sustainable in the face of change. Uncertainty is pervasive and although absolute solutions are unlikely to be found, science will continue to be a main source of information for policymaking. Building and maintaining the scientific infrastructure to help meet future challenges is essential to any sustainable way forward.

Scientific input to water and environmental management has a long history in California. CALFED

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[20] Discussed in greater detail in Chapters 4 and 7

Table I.2. Future Directions for CALFED Science

Scientific contribution to environmental problem-solving	Strengthening CALFED's capacity
Objective information about the system and its behavior	1. Secure long-term support for CALFED Proposed Solicitation Package program at about $20 million annually to support research that targets key unknowns 2. Support development and implementation of a comprehensive strategy for monitoring and assessment that takes advantage of rapidly emerging technology 3. Integrate adaptive experimentation and adaptive management into design and implementation of the Delta Vision strategic plan and the Bay Delta Conservation Plan so that program performance can be assessed in a timely manner 4. Integrate the CALFED Bay-Delta Program more fully into statewide and national networks of information sharing and instrumentation to support ecosystem management and restoration
Evaluation of system responses to policy options	1. Support development of cross-disciplinary, systemwide models of physical and biological processes in the Delta (e.g., the United States Geological Survey's CASCaDE project, http://sfbay.wr.usgs.gov/cascade/) 2. Establish CALFED Science as a focus for high level, integrative modeling of system response (e.g., through elaboration of Delta Regional Ecosystem Restoration Implementation Plan models, linkage to regional databases, etc.) 3. Strengthen the capacity for objective policy analysis through use of these models in conjunction with adaptive management and performance measures
Formalized and informed debate about science and policy for environmental and water management	1. Strengthen existing tools (e.g., workshops, discussion papers) for engaging science and policy 2. Strengthen capacity to translate science into policy relevant knowledge 3. Strengthen public outreach about science issues to inform the broader debate about science and policy

has brought science more fully into the policy processes. The CALFED Science Program has introduced a new and forward-looking approach that integrates the broad spectrum of scientific and technical advice needed to address today's highly complex problems. Tools used by the Science Program have included interdisciplinary workshops, support for research that cuts across agency mandates, and integration of science with the practical knowledge of resource managers. These tools have strengthened our understanding of challenges in the Delta, as well as the options available to address them.

When CALFED began, expectations were that we could resolve ecosystem issues through modest changes in water management and minimal reallocation of water. The POD has now forced water management agencies to consider significant water reallocations. Initially, CALFED considered Delta stabilization and levee integrity a primary goal: now the Delta Vision process is imagining a mixture of levee protection in some areas, and alternative land and flow management options in others. The evolution of policy from an emphasis on engineered solutions to an emphasis on engineered natural designs that work with natural processes reflects advances in ecosystem science, new environmental conditions, and changing societal expectations.

Within the above context, the way forward appears to include several extensions of the goals and strategies with which CALFED began. Generally, science provides three important elements to the debate about resource management problems:

1. Objective information about the system and how it behaves;
2. Models of physical and biological systems that illustrate how different policies might affect the problems; and
3. A shared, formalized language and a forum that permits informed debate.

The way forward for CALFED science is to strengthen its capacity to make these contributions (see Table I.2).

Science As a Source of Objective Information About the System and Its Behavior

There are systemic weaknesses in the science infrastructure that supports water and environmental management in the Bay-Delta. One of these weaknesses is a lack of consistent support for targeted research on key unknowns in the Bay-Delta ecosystem. The CALFED Science Program has begun a competitive program of research grants for critical research, but has lacked the secure funding to carry this program into the future. Given the pace of change, future management decisions will depend increasingly on scientific synthesis, insight, and advice from scientists with hands-on experience in the Delta. Assured support for policy-relevant research is the best way to ensure that information and advice will be available when needed.

Since its inception, CALFED has striven to enhance and extend observation networks, including development of the Comprehensive Monitoring Assessment and Research Program (CMARP): unfortunately, CMARP has yet to be implemented. More recently, the CALFED Science Program has been working with the implementing agencies to develop performance indicators for their CALFED initiatives, but this effort is still at a conceptual stage. We also see a desperate need to monitor existing and future project performance objectively. More comprehensive monitoring would provide the raw materials for timely decisions about project direction and contribute to improved physical and biological models of the Delta. The CALFED Science Program is working to develop a feasible, more integrated framework for monitoring across implementing agencies.

The ROD specifies that adaptive management should be the tool for integrating science more fully into management.[21] CALFED agencies have made considerable progress in implementing adaptive management, but weaknesses remain. Support for monitoring and assessment, which is central to the adaptive process, is intermittent, as is the use of prospective analysis to explore policy alternatives. The CALFED Science Program has the capacity to help agencies make further progress in formally establishing adaptive management.

CALFED has a strong Bay-Delta focus, but is addressing a set of problems that exist in various guises throughout California. Nationally, there are several major projects focusing on water and envi-

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[21] Discussed in greater detail in Chapter 8

ronmental conflicts, for example the Upper Mississippi, Great Lakes, Everglades, and Columbia Basin projects. These projects would benefit from statewide and national networks of information-sharing. The CALFED Science Program is regarded as a successful model in science coordination and integration and could be a leader in establishing such a network.

Science As a Set of Tools for Evaluating System Responses to Policy Alternatives

The complexity and interlinked character of the Bay-Delta system and all its most vexing problems call for a new generation of system-scale, cross-disciplinary models. CALFED has supported several steps toward developing such tools, including an ambitious attempt to develop interlinked species conceptual models, and various efforts to link physical models with ecosystem responses. Such modeling needs to be strongly supported so that policymakers can be informed by mature scientific models of Delta processes. Forecasting the consequences of policy choices will always be uncertain, but models provide the most objective means of bringing complex ecosystem data into policy analysis.

At present, there is little capacity in the CALFED Science Program, or the implementing agencies, for cross-disciplinary modeling of ecosystem behavior. For the future, the CALFED Science Program should serve as a node or catalyst for the development of integrative models. As part of the Science Program, such models would have legitimacy and would provide another avenue for coordination and communication among diverse interests in the Delta. Policy analysis increasingly relies on quantitative risk analysis and numerical analysis. For the CALFED Science Program to remain relevant, it will need to build its capacity to apply these tools and to connect them in ways that provide a complete picture of ecosystem response.

Science As a Facilitator of Informed Policy Debate

Finally, CALFED needs to expand and strengthen its ability to bring science into policy debates. Notably, as the Governor's Delta Vision Blue Ribbon Task Force completes its new vision, and following its debate and implementation, it will be all the more important that independent scientific information and methods are near the center of decision-making.

The CALFED Science Program uses a variety of communication and outreach tools for scientists. These include the on-line journal *San Francisco Estuary and Watershed Science*, and the biennial science conference; for policymakers, workshops and discussion papers; and for the public, newsletters such as *Science News* and public lectures. These avenues need to be strengthened and expanded in the future to ensure a smooth and effective flow of scientific information to policymakers and other interests.

Science is crucial to any policy debate and objective, peer-reviewed science provides the most reliable basis for policy decisions. Making reliable science available to policy debates has always been a weak link in the science-policy process. The Science Program has a good track record of facilitating this information flow, but it needs to be sustained and improved.

CALFED and the CALFED Science Program were created in recognition of the need for stronger coordination, integration and communication to address problems of water supply, water quality, levee integrity and ecosystem performance. The CALFED Science Program has had considerable success facilitating these processes within the scientific community and has also stimulated new science to address important gaps in knowledge. As a result, our understanding of Delta processes has improved and policymakers are better informed. These science-based activities will be even more important in the future.

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1. Science and the Bay-Delta

Michael Healey[1]

Managing both water and the environment in California's Bay-Delta presents a great challenge to decision-makers (see Figure 1.1). The Delta is a critical hub in the many-armed water supply and distribution system that serves all of California. The Central Valley rivers that converge to form the Delta drain 40 percent of California's landmass and discharge 47 percent of the State's available water. Water from these rivers is extensively dammed, diverted and exported. Water exported from the Delta sustains billions of dollars in agriculture and provides drinking water for twenty-three million Californians (Carle 2004).

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[1] CALFED Science Program

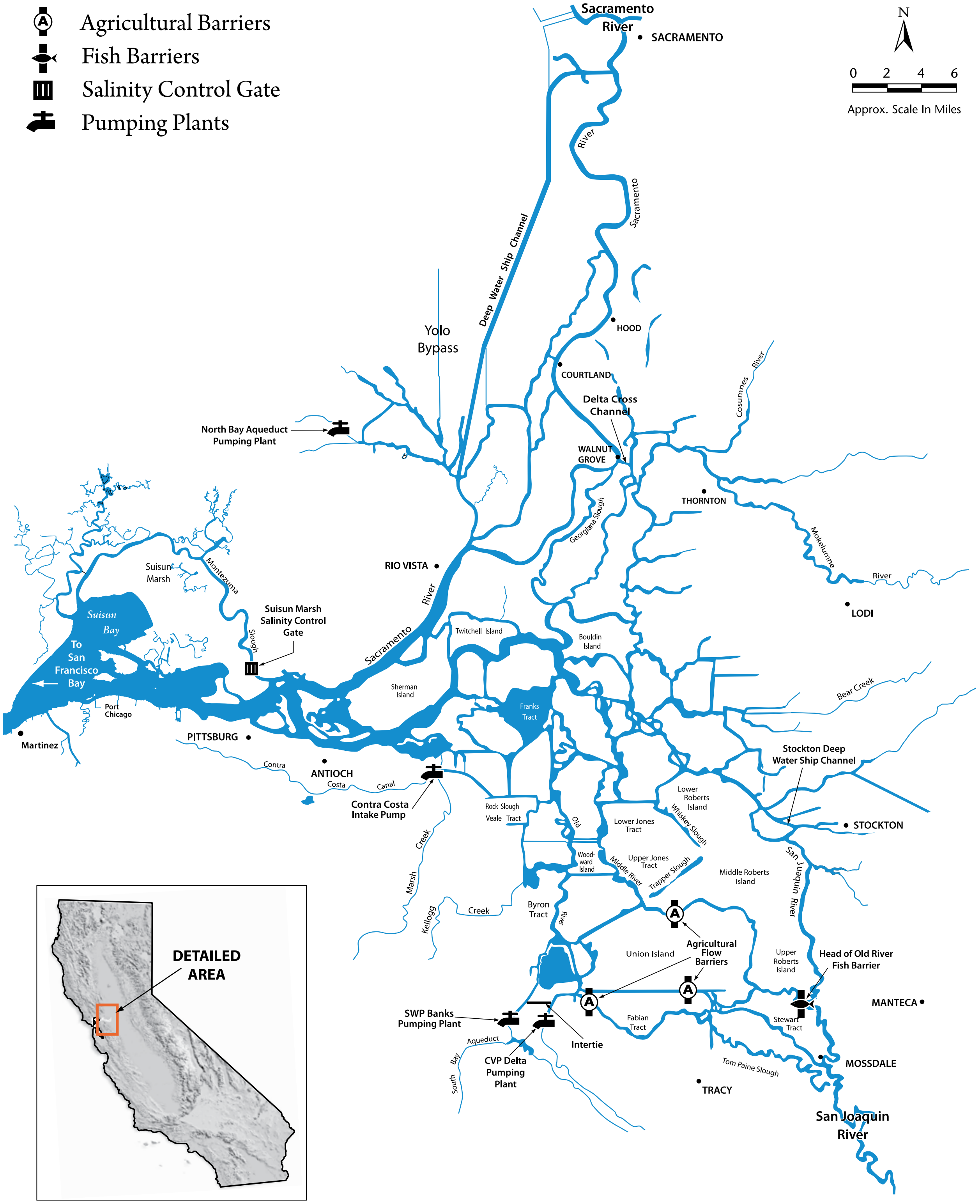

Figure 1.1. Map of the Sacramento-San Joaquin Delta (the Delta) showing major landmarks. (Source: California Department of Water Resources)

But the Delta is much more than a distribution hub for California's water (URS Corporation 2007). The many islands in the Delta and adjacent lands sustain productive and valuable agriculture that depends on water drawn from the Delta for irrigation. Contra Costa County, on the southern margin of the Delta, draws its domestic water supply from the Delta, while Napa and Solano Counties draw water from the North Delta through the North Bay Aqueduct. Sacramento and Stockton on the north and east margins of the Delta are both seaports. Shipping channels cut through the Delta to connect these ports to San Francisco Bay. Major highway and service corridors traverse the Delta from north to south and east to west. The Delta is an important aquatic playground for many area residents and visitors. It also sustains significant recreational and commercial fisheries.

Ecologically, the Delta is home to a diverse array of ecosystems and more than seven hundred plant and animal species. It is a critical resting and feeding area on the Pacific Flyway for migratory birds as well as an important breeding ground for many waterfowl species. The Delta and adjacent lands are home to some distinctive species and subspecies, including the salt marsh harvest mouse *(Reithrodontomys raviventris)*, Suisun song sparrow *(Melospiza melodia maxillaries)*, Sacramento splittail *(Pogonichthys macrolepidotus)* and Delta smelt *(Hypomesus transpacificus)*. Thirty-one of these species are listed as threatened or endangered under state and federal endangered species statutes, challenging the capacity of regulatory agencies to maintain biodiversity in the Delta (see Figure 1.2).

Some Bay-Delta problems facing decision-makers are long-standing (for example, conserving salmon and flood protection), whereas others are more recent (for example, climate change and the pelagic organism decline). Solutions for these problems depend on a detailed understanding of the physical and ecological processes within the Bay-Delta. Over the past 150 years, science has come to play an increasingly important role in both government and private decision-making. Jasanoff (1994) characterized science as a 'fifth branch' of government in which committees of scientists and science advisors provide technical and policy input to virtually every major problem. Major private institutions also engage scientific support either through consulting firms or in-house science departments. Decisions about water and the environment in the Bay-Delta are similarly highly dependent on a scientific infrastructure. Both water and the environment are critical to the California economy and well-being, and both arouse strong emotions. These alone are reason enough to seek decisions based on objective

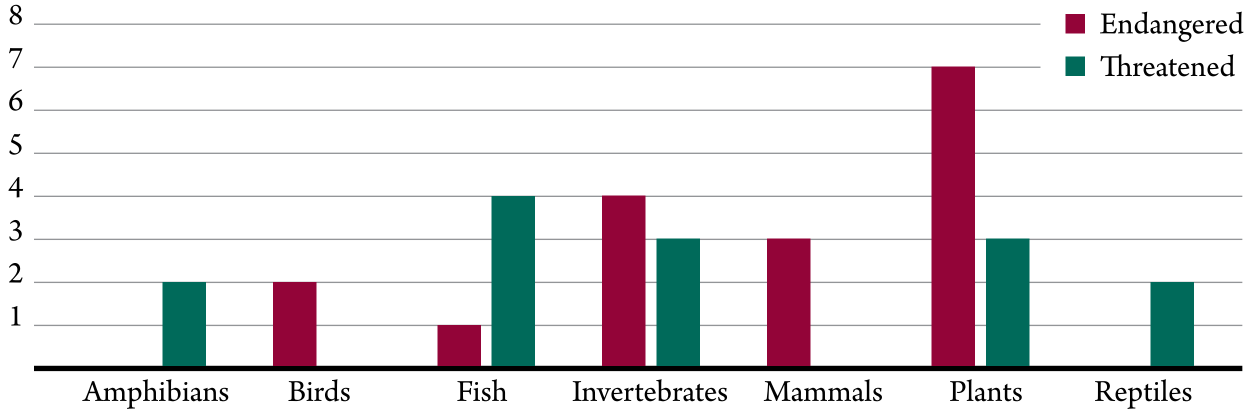

Figure 1.2. Numbers of species of different types of organisms in the Bay-Delta listed as threatened or endangered under state and federal law. (Source: Sacramento Fish and Wildlife Office: www.fws.gov/sacramento/es/spp_lists/regionActionPage.cfm)

information. Yet, the essential information decision-makers need is often scattered among many different sources and is not always easy to access. *The State of Bay-Delta Science, 2008* summarizes our current scientific understanding about water quality, ecosystem health, levee integrity and water supply in the Bay-Delta system. The report is intended to be an information source for government and industry decision-makers, as well as interested members of the public. It is also intended to be a living document, evolving and changing as the Bay-Delta and California's society evolve and change over time but remaining current and relevant for water and environmental decision-making.

Science is not a new activity in the Bay-Delta but has a long history of contribution to water and environmental management. Indeed, the Bay-Delta is one of the most thoroughly studied estuaries in North America and benefits from a strong infrastructure of public, private and academic research capacity. Nevertheless, our understanding of how the Bay-Delta functions is continually improving and evolving. Techniques for incorporating science into decision-making are also evolving and improving; however, this remains a weak spot in the governance system. This chapter describes the history of using science to solve Bay-Delta problems and sets the stage for the following chapters that address specific aspects of the CALFED Bay-Delta Program.

A Long History of Science

The First Period: Taming the Floods

The history of the Delta from California's statehood (1850) can be divided into three periods, each characterized by a different kind of science and a different scientific emphasis. The first period, from 1850 to 1920, encompasses early attempts to contain the annual floods and claim the rich floodplains from the rivers. This period can be characterized as one of exploitation and appropriation; a time of colonization and acquisitive entrepreneurialism. The onset of the California Gold Rush (1848 to 49) brought thousands of new residents who sought their fortunes in mining, farming, fishing and other enterprises. Miners appropriated water and washed hillsides into streams and down to the Delta. Farmers enclosed and drained wetlands to establish farms. Fishers set nets and built canneries to reap the bounty of Chinook salmon *(Oncorhynchus tshawytscha)* that returned to the Sacramento and San Joaquin Rivers virtually year-round. All these enterprising businessmen developed or adapted technology in a highly individualistic way, frequently using trial-and-error as their principal method. When the placer gold in stream beds ran short, gold miners moved onto the terraces, sluicing off the surface material by diverting streams and subsequently mobilizing whole hillsides of gold-bearing gravels with high pressure hoses (see Figure 1.3). As placer gold became scarcer still, miners developed gold dredges that could chew through thousands of cubic yards of gravel in a day. Both hydraulic mining and gold dredging are said to be Californian inventions (Cutter 1948), and both illustrate the enterprising, inventive spirit of the times. Science during this period was entrepreneurial, the science of free-wheeling invention and on-site testing, with inevitable surprises and disasters.

Along the Central Valley floor and within the Delta, sediment flushed down from the gold mines clogged channels, hampering navigation and greatly increasing the risk of flooding. Debris torrents buried farms and orchards under many feet of gravel and mud. Public outcry over this devastation eventually ended hydraulic mining in California (Hundley 2001). Early attempts to contain the annual floods with levees were haphazard and lacked any effective design. Until the turn of the century, most local landowners, officials and engineers had little experience with levee construction and showed no inclination to learn from experience elsewhere (Kelley 1989). Their laissez-faire, trial-and-error

Figure 1.3. Hydraulic mining with high-pressure water hoses in the foothills of the Sierra Nevada. This method of placer mining was invented in California. (Photo by: California Department of Water Resources)

approach to levee construction resulted in many early levee failures and has left a legacy of poorly designed levees that constitute a present-day hazard.[1] At the turn of the century, the progressive movement introduced a heavy emphasis on data-gathering and planning by experts. Systematic data-gathering and analysis became standard practice, and early in the new century a network of gauging stations began providing data on river flows. Despite the emphasis on data and analysis, the limited theoretical understanding of rivers together with engineering hubris slowed progress toward bringing the floods under control (Mitchell 1994; Kelley 1989). Unnoticed at the time, sediment from the gold mines brought with it thousands of pounds of mercury that were used for extracting gold. This mercury was deposited in the sediments of the Delta. Mercury from Sierra gold mining and from mercury mines in the Coast Range continues to dribble into the Delta to this day, creating both a public health and an environmental problem.[2]

Agriculture expanded rapidly in the Delta and in the Central Valley during this period as farms gained protection from the annual floods. Wheat was the principal crop, and California farmers developed new, specialized harvesting techniques and invented the multi-bottom plough for working large tracts of flat alluvial soil. However, failure to develop new strains of wheat or to look after the fertility of the soil led to greatly reduced yields, and wheat farming was largely abandoned early in the twentieth century (Olmstead and Rhode 2004). As in other sectors, the emphasis in agriculture was on developing new technology rather than on soil stewardship.

Science for the Sacramento and San Joaquin salmon fisheries was more organized if still primarily empirical (that is, based primarily on the analysis of measurements made in the field). The first commercial fisheries began in 1850, but records of total catch date from 1874. Unfortunately, the catch record reveals a steady decline in salmon abundance, leading Clark (1929) to declare that the fishery was badly depleted. Hapgood, Hume, and Company established the first salmon cannery on the Pacific coast in 1864 at Washington (now West Sacramen-

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[1] Discussed in greater detail in Chapter 5

[2] Discussed in greater detail in Chapter 3

Figure 1.4. Photograph of the Baird Hatchery established by Livingston Stone on the McCloud River. This was the first salmon hatchery built on the Pacific Coast. (Photo by: California Department of Water Resources)

to) on the banks of the Sacramento River. By 1881, twenty canneries were operating on the River and in the Bay, but by 1919 declining fish runs resulted in closure of the industry.

Entrepreneurial science also affected the fisheries. State and federal governments constructed hatcheries to produce salmon eggs for export to both the East Coast and to far-away countries like New Zealand and Australia. In 1872, Livingston Stone established the first salmon hatchery on the Pacific coast on the McCloud River, a tributary of the Upper Sacramento (see Figure 1.4). The express purpose of this hatchery was to collect eggs to be shipped east and out of the country to establish new salmon runs. Of the many millions of eggs transplanted, only those sent to New Zealand succeeded in establishing a self-sustaining run. In 1885, California began collecting salmon eggs to replenish its own depleted runs. In the late 1880s, the technique of holding salmon fry at the hatcheries and feeding them to be released at a larger size was developed and has remained the standard technique to the present day. Over the decades from 1885 to 1920 tens of millions of salmon eggs were incubated at hatcheries and the fry released into the Sacramento River with no discernible benefit for the fishery (Clark 1929).

Another standard fishery-enhancement technique during this period was introducing exotic species into the system to create new fisheries. Between 1871 and 1920, twenty-two non-native fish species were introduced to the Sacramento-San Joaquin basin, including American shad *(Alosa sapidissima)* in 1871 and striped bass *(Morone saxatilis)* in 1879. At the time, scientists believed that species introductions were a necessary means to improve local fisheries. Species introductions remained an important tool of scientific fishery management until the second half of the twentieth century. In all things, nature was to be subject to human control and management for both individual and social enrichment.

In summary, the science of this first period was entrepreneurial and empirical. There were few data on the local environment that decision-makers could use in formulating policy and apparently little interest in asserting any centralized control over resources until the end of the nineteenth century (Hundley 2001). During the progressive era (from approximately 1900 to 1920), the emphasis shifted almost entirely to favor scientific data-gathering and centralized planning. Most of the science that was undertaken was applied science, initiated in response to pressing social concerns, such as flooding, debris torrents and declining fisheries. In general, the theoretical underpinnings of science and engineering were relatively weak, and reliable data were scarce. This, coupled with a strong conviction that humans were destined to control nature, contributed to decisions that, in hindsight, appear ill-considered. By 1920, however, annual flooding had been brought under some control, agriculture was firmly established, and striped bass were making a substantial contribution to fisheries. This helped set the stage for California to become an agricultural and economic powerhouse. All the state needed was a proper distribution of its water.

The Second Period: Redistributing the Waters

The second period, lasting from about 1920 to 1970, can be characterized as the water development period. During this period, state and federal agencies built the great dams on the Sacramento, the San Joaquin and their tributaries to capture and store spring flood waters for release during the dry season. It was also during this period that the Central Valley was replumbed so that the Delta became the hub of California's extensive water redistribution system. Science moved increasingly to the center of policy and planning during this period. Improved understanding in engineering and biology reduced some of the uncertainty in decision-making, and a strong faith in technology gave priority to engineered solutions, such as dams and canals to address water supply problems, and hatcheries to address declining fisheries. Empirical science continued as a dominant source of information, but steadily improving sampling designs and analytic tools gave greater credibility to these studies. Experimental science (that is, science or engineering based on theory and manipulation of laboratory systems) emerged as a powerful complement to empirical science during this period.

Various studies were conducted before 1920 with a view to implementing a comprehensive water management system for Northern California. However, it was not until Colonel Robert Bradford Marshall, Chief Geographer for the United States Geological Survey, proposed a plan that included storage reservoirs along the Sacramento River system and two large canals to transfer water from the Sacramento Valley to the San Joaquin Valley that the concept took root (Marshall 1920). In 1921, the state legislature directed the State Engineer to come up with a water plan. Between 1920 and 1932, fourteen reports detailing water flow, drought conditions, flood control, increasing Delta salinity and irrigation issues became the basis for the first California State Water Plan. Science, particularly engineering science, had become a foundation of government policymaking. In 1933, the California Legislature authorized the future Central Valley Project (CVP), which was subsequently constructed by the federal Bureau of Reclamation in 1937. The State Water Project (SWP) was initiated in the late 1950s and doubled the capacity for exporting water from the Delta (see Figure 1.5). As part of the infrastructure for the CVP, the Delta Cross Channel was constructed in 1951 to move Sacramento River water efficiently into the southern Delta from which it is exported south. With the construction of the CVP, flows into the Delta began to be managed to maintain the Delta as a freshwater basin and ensure that water exported or used for irrigation in the Delta was of suitable quality.

The CVP and SWP represent the full flowering of the multiple-use concept applied to water resources. The idea that water management systems should serve multiple purposes (water supply, flood control, irrigation, power production, navigation) was first advanced early in the twentieth century but did not take hold in United States water projects until the New Deal. Management of such large, multipurpose projects required new techniques for decision-making and optimization. Development of these techniques occurred in diverse fields, including economics, engineering and mathematics under

Figure 1.5. The California Aqueduct winds its way down the San Joaquin valley, carrying water south from the Delta. (Photo by: California Department of Water Resources)

such labels as game theory, optimal control theory and linear programming. Linear programming, which was developed in the 1940s, has proved to be a particularly powerful tool for distributing water efficiently from multiple sources to multiple end uses having different social or economic values (Dantzig 2002).

Agriculture continued to expand during the second period as farmers learned to pay more attention to biological aspects of crop production and received increasing support from expanding institutions of science. In 1905, California Governor George Pardee established the University Farm (now the University of California, Davis) as a practical agricultural college for turning out scientifically trained agriculturalists. Farmers began experimenting with new crop varieties introduced from all over the world, and plant breeders also got into the act. Early in the 1900s, The United States Department of Agriculture (USDA), California's agricultural research system and local cooperatives formed an effective working arrangement to acquire and spread knowledge about crops and how to maintain quality during packing and shipping. This collaboration led to improved handling techniques, which helped build California's reputation for providing high quality horticultural products (Olmstead and Rhode 2004). It also represents an early and successful example of scientific collaboration among technical experts, university academics and practitioners that has become a hallmark of the application of science to solve problems of the Delta.

Attention during this period was beginning to shift toward environmental conservation. In 1966, Kelley published what was probably the first broadly based attempt to understand the ecology of the Delta and estuary. The Delta Fish and Wildlife Protection Study was a cooperative study by the California Department of Fish and Game (DFG) and the California Department of Water Resources (DWR). The study was organized in 1961 to investigate the effects of future water development on fish and wildlife resources dependent upon the Bay-Delta, and to recommend conservation and mitigation measures (Kelley 1966). Earlier scientific work had focused on specific species, with a heavy emphasis on fish culture as the solution to conservation. The Delta Fish and Wildlife Protection Study examined the physical environment of the estuary, as well as zooplankton and fishes. The California Water Bond Act provided funding and, according to Kelley (1966), it was the first time the "user pays" principle had been used to support science for conservation.

As the massive state water export pumps came on line in 1968, fishery managers became concerned about how the changing hydrology of the Delta would affect the migration of returning salmon. The Delta Cross Channel spilled Sacramento River water into the South Delta, potentially confusing Sacramento River salmon searching for their home stream. Furthermore, export pumping reduced flows in the San Joaquin, led to low dissolved oxygen in the Stockton Deep Water Ship Channel, and reversed flows in the Old and Middle Rivers as water was sucked upstream to the pumps. Hallock et al. (1970) showed that these changes were sufficient to block the upstream migration of San Joaquin salmon, but they did not have serious consequences for Sacramento River salmon. Additionally, seaward-migrating juvenile salmon, striped bass and other species were being drawn into the pumps, creating the potential for serious losses to important Delta fisheries. The environmental costs to the Delta from California's water development were beginning to emerge.

In summary, the second period of Delta history saw the firm establishment of science as the source of reliable information for policy formulation and decision-making in the Delta. Both empirical and theoretical understanding of hydrodynamics and ecological processes in the Delta and its watersheds improved greatly. The emphasis continued to be on engineering solutions to perceived Delta problems and on the overwhelming importance of water development, although toward the end of the period, concern about the ecological and environmental impacts of development was starting to emerge.

The Third Period: Restoring the Environment

The most recent period extends from about 1970 to the present and can be characterized as the environmental period. The emphasis during this period has been on finding ways to address the growing environmental problems of the Delta without sacrificing the benefits of intensive water development. This change in emphasis reflected growing societal concern about environmental quality that emerged in the 1960s, stimulated by publications such as Rachel Carson's *Silent Spring* (1962) and the first "Earth Day" gathering in 1970. This sea change in public attitude had far-reaching consequences for scientists and environmental managers. The most tangible evidence of the change in public values was a host of federal environmental bills passed by the early 1970s, including the National Environmental Policy Act (1969), the Clean Air Act (1970), the Clean Water Act (1972), and the Endangered Species Act (1973). President Richard Nixon established the United States Environmental Protection Agency (EPA) in 1970 to provide a single focus for federal environmental regulation. California passed complementary legislation with the Porter-Cologne Water Quality Control Act (1968), the California Environmental Quality Act (1970), and the California Endangered Species Act (1984). In 1992, the federal Central Valley Project Improvement Act (CVPIA) amended the CVP to include protection, restoration, and enhancement of fish, wildlife and associated habitats in the Central Valley. The CVPIA also established a water reserve of 800,000 acre-feet specifically for fish and wildlife benefits.

The new legislation and agencies at both federal and state levels brought environmental concerns to the fore and created a whole new policy framework into which the CVP and SWP had to fit. More and better data on the Delta ecosystem were needed. To meet this growing need for ecological data, the Interagency Ecological Program was established to coordinate the data-gathering activities of ten state and federal agencies. Similarly, the United States Geological Survey began a long-term program of ecological research and monitoring in San Francisco Bay. The Anadromous Fish Restoration Program (AFRP) was established to oversee the fishery restoration required by the CVPIA (United States Fish and Wildlife Service 2007).[3] The AFRP restoration plan was developed jointly by state and federal agencies based on a synthesis of available scientific information on the fish species of concern (salmon, Central Valley steelhead (*Oncorhynchus mykiss irideus*), striped bass, American shad, sturgeon)(United States Fish and Wildlife Service 1995). The science of ecology had now become a central factor in water policy. An excellent example of the integrative science of this period is the book, *San Francisco Bay: the Urbanized Estuary* edited by John Conomos (1979). This book featured chapters dealing with geology, hydrology, sedimentology, oceanography, chemistry, toxicology, phytoplankton, zooplankton, marshes, bottom-dwelling organisms, invasive species, fisheries and fishery ecology in the Bay-Delta as well as synthesis chapters that integrated across disciplines. The book's authors emphasized the scientific evidence for the growing impact humanity was having on the ecosystems of the Bay and Delta and laid out most of the problems and conflicts that we continue to struggle with today.

The Birth of CALFED

As the population and economy of California have grown, so have demands on its finite water supplies and the Delta. The new environmental legislation of the 1970s established regulations that made it very difficult to meet the growing demand for water by continually augmenting supply. The drought of 1987 through 1992 demonstrated just how vulnerable California was to water shortages. Growing conflicts between water quality, fish protection and water supply also demonstrated how little flexibility there was in the water management system for meeting multiple objectives. In the early 1990s, regulatory actions to protect endangered species, combined with serious drought and the dedication of 800,000 acre-feet of water for fish and wildlife protection (required under the CVPIA), caused a near crisis for California water management agencies. In 1992, under pressure from the EPA to safeguard endangered fish in the Delta, California's State Water Resources Control Board circulated a controversial draft decision that limited water exports from the Delta. This created a panic among water users. In response, California Governor Pete Wilson and United States Interior Secretary Bruce Babbitt pulled California and federal agencies together to work toward a coordinated solution. The agreement that emerged from this negotiation, the Bay-Delta Accord, eventually became the CALFED Bay-Delta Program (CALFED).[4]

CALFED's mission is to develop a long-term comprehensive plan to restore ecological health and improve water management for beneficial uses of the Bay-Delta system. The program has four broad objectives:

1. Provide a reliable water supply satisfying current and projected beneficial uses;
2. Provide good water quality for all beneficial uses (drinking water and environmental water);
3. Reduce the risk to land use, water supply, infrastructure and the ecosystem from catastrophic breaching of Delta levees; and
4. Restore ecosystems and ecosystem functions ensuring sustainable populations of valuable plant and animal species.

From the beginning, the CALFED member agencies recognized that the Bay-Delta's problems and their solutions were interrelated. Problems in one program area could not be solved effectively without addressing problems in the other

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[3] For the history of the AFRP program, see http://www.delta.dfg.ca.gov/AFRp/rationale.asp

[4] For the history of the CALFED Bay-Delta Program, see http://www.calwater.ca.gov/calfed/about/History/index.html

Figure 1.6. The Jones Tract levee failure and flooding of June 3, 2004. The levee was repaired and the Jones Tract restored at an estimated cost of $90 million. (Photo by: California Department of Water Resources)

areas. To ensure the integration of problems and solutions, CALFED adopted a broad approach to addressing issues related to its objectives. The single most important difference between CALFED and past attempts to solve Bay-Delta problems was the comprehensive nature of CALFED's interrelated resource management strategies. The CALFED approach also engaged water users and environmental non-governmental organizations in the search for solutions. CALFED member agencies committed to solutions that were based on peer-reviewed science and to adaptive management as the means to incorporate scientific rigor into policy design and implementation (Jacobs et al. 2003).

The CALFED Record of Decision (ROD) was signed in 2000 and established the CALFED Science Program, making its primary obligation to bring high quality science to all elements of CALFED. The science needed to achieve CALFED's objectives was not thoroughly defined in any overall strategic plan, but it is possible to infer the critical questions from the state of scientific knowledge in the year 2000 and the program's direction. The scientific questions and some assumptions about them will be outlined here. Subsequent chapters will discuss the current state of knowledge in detail, organized under CALFED's four objectives of water quality, ecosystem restoration, levee integrity and water supply.

The role of science and the kind of scientific information needed to achieve program objectives differed dramatically among the CALFED objectives. Levee integrity, for example, was primarily an engineering problem. The 1,100 miles of levees in the Delta, as well as critical levees upstream, needed to be brought up to modern standards to reduce the risk of catastrophic failure (see Figure 1.6). Investigation was needed to determine the condition of the levees and where the greatest risks of failure were so that managers could prioritize levee improvements. At the time, managers assumed that stresses on the levees in the future would be essentially the same as those in the past, so that no research on future drivers of risk was needed. This is one of many early assumptions that CALFED has abandoned as new science has come available.[5] There are

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[5] Discussed in greater detail in Chapter 5

also important connections between levees, species and environmental conservation. For example, by isolating rivers from their floodplains, levees have contributed to declines in some species. However, the scientific questions concerning levees and species conservation have to do with biology and ecology rather than levee integrity, and CALFED addressed them under the umbrella of ecosystem restoration rather than levee integrity.

Water supply reliability was also seen as primarily a problem of engineering and effective operations management. Although no new dams were envisioned, CALFED needed analysis and feasibility studies to determine the benefits and costs of additional off-channel storage. Scientific study and model development also had the potential to improve forecasting of annual water supply from snowpack and weather, but existing forecasting tools were adequate for most purposes. A fundamental assumption about water supply forecasting was that average water yield and inter-annual variation in yield would be the same in the future as they had been in the past. This assumption has been set aside as scientific understanding of the likely impacts of climate change on river hydrology has improved.[6] Water supply reliability is also closely linked to environment and species conservation. Indeed, concern about supply reliability following the allocation of more water for environment and species conservation was a primary stimulus for establishing CALFED. However, these scientific issues have to do with biology and ecology rather than water supply per se, so CALFED addressed them under the umbrella of ecosystem restoration.

Concerns about water quality raised many unresolved scientific questions. A key issue for CALFED was how to convey high quality water from the Sacramento River to the export pumps on the south margin of the Delta. The historic conveyance was through channels in the Delta, and this was considered to have both environmental benefits and costs. Through-Delta conveyance leads to high losses of fish at the export pumps, and water passing through the Delta accumulates organic carbon and bromide, reducing its quality for drinking water. In the late 1970s, the California legislature debated constructing a canal or pipeline to bring Sacramento River water directly to the pumping facilities, but Californians rejected this idea in a 1982 referendum. CALFED adopted through-Delta conveyance as its preferred alternative but committed to assessing whether water and environmental objectives could be met under this alternative during Stage 1 of the program (2000 to 2007). Increasing concern about drinking water safety and continuing declines in fish species from water-export pumping suggests that through-Delta conveyance is not working well. An isolated conveyance system of some sort is again under serious consideration.

Water quality for the Delta and San Francisco Bay suffers from the broad range of toxic chemicals contributed by agriculture, industry, sewage treatment plants, shipping, highway traffic and urban stormwater runoff. The ocean also contributes salts and bromide that affect water quality. We do not understand the sources and fates of contaminants entering the Delta well.[7] Concerns for drinking water quality are primarily salinity, turbidity, organic carbon and bromide. The most important concern for agricultural water use is salinity. Concerns for environmental water quality include nutrients, dissolved oxygen, pesticides, mercury and selenium. But these are only the top candidates from a long list of potential water and sediment quality issues. Even to address this short list of concerns thoroughly would involve a major research program, and the necessary support has never been provided for this research. Strategically, CALFED separated domestic water quality issues from environmental water quality issues. Drinking water quality was conceived as a problem of meeting specific target concentrations for bromide and organic carbon in export water, or achieving a level of public health

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[6] Discussed in greater detail in Chapter 6

[7] Discussed in greater detail in Chapter 3

safety equivalent to meeting those targets. Drinking water quality standards are being revised regularly, however, making it increasingly difficult to meet the objective of safe drinking water using the Delta as a primary source. CALFED conceived of environmental water quality as a problem of ecosystem health and ecosystem restoration and addressed it as part of the Ecosystem Restoration Program (ERP).

Ecosystem restoration was the program objective with the greatest initial need for science. The ROD recognized this and prescribed that early in CALFED's Stage 1 the emphasis for the Science Program would be on ecosystem restoration. Initially, however, the ERP did not use science as a tool to identify potential restoration actions. These came instead from the experience of field biologists in the United States Fish and Wildlife Service and DFG. However, the ERP was also the only CALFED program to develop a strategic plan that addressed science needs (Ecosystem Restoration Program 2000). In its strategic plan, the ERP recognized twelve critical scientific uncertainties that provided direction for necessary research (see Table 1.1).

Table 1.1. Twelve Areas of Uncertainty from the Ecosystem Restoration Program Strategic Plan

1. Quantifying the impact of non-native invasive species on Delta ecology and species of concern
2. Defining flow schedules that will be most effective in rebuilding and sustaining species of concern
3. Defining the scales of flow, sediment supply, organic material inputs and channel migration in tributaries needed to keep the riverine system functioning in a way that will sustain species of concern
4. Defining the degree and kind of exchanges between river and floodplain that are necessary to support healthy ecosystem functioning to sustain species of concern
5. Understanding the ecological and species benefits of flood bypass habitat and optimal temporal scales of inundation to benefit species of concern
6. Understanding the importance of tidal and seasonal wetland habitats in sustaining species of concern
7. Impacts and dynamics of the many contaminants entering the Delta or stored in Delta sediments in relation to ecosystem restoration and species health
8. Understanding the interrelationships and exchanges between upland, riparian and aquatic habitats and their respective roles in sustaining species of concern
9. Defining the mechanisms underlying the empirical relationship between species' life stage performance and the salinity standard X2
10. Defining the mechanisms underlying the large and abrupt decline in aquatic productivity of the Bay-Delta ecosystem in the past decade
11. Quantifying the impact of export pumps on fish species and life stages
12. Understanding the importance of the Delta as nursery habitat for Chinook salmon races and Central Valley steelhead

(Source: Ecosystem Restoration Program 2000, pp. 56-65.)

Although these uncertainties identify important science needs for ecosystem restoration, they hardly scratch the surface of the many unknowns connected with restoring ecosystems and species in the Bay-Delta and upstream tributaries. Ecosystem restoration is a recently developed branch of ecology and its theoretical foundation is thin. Practical attempts to restore ecosystems are patchy and have had mixed results (see Tompkins and Kondolf 2007; Konisky et al. 2006; Bond and Lake 2003; Kennish 1999). The greatest experience is with restoring terrestrial ecosystems in which it is often sufficient to reestablish specific plant species or communities to ensure conditions suitable for target animal species. After terrestrial ecosystems, the greatest experience is with restoration of stream ecosystems. Stream ecosystem restoration has focused on the design and installation of specific physical structures and on restoring 'natural' flow regimes. Restoration of river deltas and estuarine systems has hardly been attempted, with the exception of work on salt marshes. Furthermore, the Bay-Delta differs from other major estuaries in many of its attributes, compelling the development of unique solutions to its ecological problems. Thus, understanding and experience of restoration were in reverse order to the ecosystems targeted for restoration under CALFED.

In addition, CALFED proposed a novel approach, the restoration of ecological processes rather than specific habitat structure. With so many listed species to deal with, restoring ecological processes made more sense than trying to restore individual species. Furthermore, the ecosystems CALFED planned to restore were physically and biologically dynamic so that the only way to ensure success was to put in place the physical processes that created and sustained them. The Delta's ecosystem, however, was so highly altered by species invasions and extirpations at all levels in the food web that processes had to be managed to favor a few desirable species, mainly fish. Because there was little practical experience with this approach for CALFED to draw upon, tools had to be invented as the ERP was implemented. Although the CALFED ERP was a bold departure from traditional endangered species management, it was still focused on improving local habitats, an approach that is becoming less practical as global climate change unfolds. As CALFED transitions into Stage 2, a broader range of conservation tools, such as establishing refuge populations in other locations, captive breeding and seed banks will need to be envisioned.

As there was considerable theoretical and practical experience with river restoration, CALFED immediately initiated restoration programs for key river-dwelling species, like salmonids, in the Sacramento and San Joaquin Rivers. In the Delta, however, where experience with restoration was very limited, CALFED emphasized targeted research and improving our understanding of ecosystem processes as a prelude to restoration. Through its support for research and its coordination of projects among agencies, CALFED made progress in both restoration and increased understanding of the Delta during Stage 1. Its rigorous Proposal Solicitation Package (PSP) also helped the CALFED Science Program accomplish another objective: bringing more rigorous scientific review into the CALFED Program.

Because the outcome of any restoration project is uncertain, the ERP was motivated to implement adaptive management more strongly than the other components of CALFED. Adaptive management injects the problem-solving capability of the scientific method into the implementation of management actions, turning management into a means of learning more about the ecosystems being managed (Lee 1999). The ERP developed an effective process of adaptive management but never fully implemented it. Other CALFED program elements have generally accepted the ERP model of adaptive management, but, although progress has been made, adaptive management has not yet been fully implemented in any CALFED action.

CALFED's commitment to ensuring a firm scientific foundation for program activities and to pursuing greater scientific understanding of the problems of water quality, ecosystem restoration, levee integrity and water supply has paid considerable dividends. Understanding the Delta and watershed processes has increased dramatically during CALFED's Stage 1. Scientific understanding of the way the watersheds, the tributary rivers, the Delta and San Francisco Bay, and their component ecosystems function has changed significantly. In terms of the tools and understanding needed to manage the Delta and its important species, to achieve water quality and water supply objectives and to minimize flood-damage risk, we are far ahead of where we were when CALFED was established. As a consequence of this increase in scientific understanding, many strongly-held views about what was possible and necessary for effective water and environmental management are being set aside, and California is actively planning for a new approach and vision (Governor's Delta Vision Blue Ribbon Task Force 2007). In addition, issues that were not considered of great significance when CALFED began, such as climate change, sea-level rise and invasive species, are now regarded as among the most significant drivers of change that a new water management model must address (Lund et al. 2007). Key scientific discoveries that have stimulated the need and the willingness to reconsider California's long-established model of water management are discussed in the following chapters.

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2. Geophysical Setting and Consequences of Management in the Bay-Delta

Steven Culberson,[1] Loren Bottorff,[2]
Mark Roberson,[3] Elizabeth Soderstrom[1]

At the heart of California is the four hundred mile-long Central Valley—a large, relatively flat, fertile valley between the coastal mountain ranges and the Sierra Nevada, running from Mount Shasta in the north to Fresno in the south. Its northern half is drained by the Sacramento River and is referred to as the Sacramento Valley, whereas its southern half is drained by the San Joaquin River and is the San Joaquin Valley.

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[1] CALFED Science Program

[2] URS Corporation

[3] CALFED Bay-Delta Program

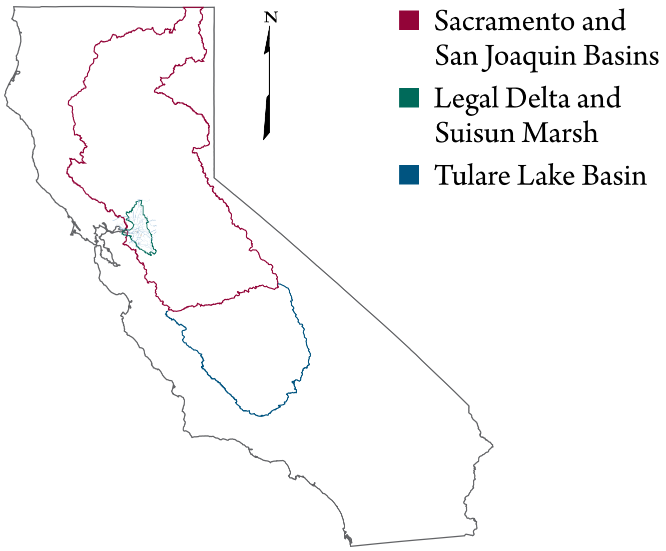

Figure 2.1. California's Central Valley, highlighting the location of the Sacramento-San Joaquin Delta. (Source: URS Corporation 2007)

The two valleys and their rivers meet in the area between Sacramento and Stockton and form the Sacramento-San Joaquin Delta, a geometrically complex network of interconnected canals, streambeds, sloughs, marshes, and peat islands, which drain into the Suisun and San Francisco Bays (see Figure 2.1). This unique estuarine resource is an integral part of California's water system, and assumes varied levels of importance when viewed from global, national, state and regional contexts.

The Delta is part of an estuary system. Like all estuaries, the ecological processes of the Bay-Delta are intricately linked to the coastal ocean and tidal influence, as well as inland rivers, resulting in high variability at many scales and across many linkages.[1] From a global context, the 1,315-square-mile Delta is one of a few dozen inland delta systems in the world. Before images from low Earth orbit were available, inland deltas or megafans were considered by geologists to be generated by large rivers, at major mountain fronts and most likely related to arid climates. We now know inland deltas exist worldwide, in all climates and that neither major mountain fronts nor large rivers are necessary for their development since they are often generated by relatively small rivers. California's Bay-Delta is unique among inland deltas because it is characterized by a wet winter and dry summer precipitation regime. The Mediterranean climate in California is important because it drives a crucial mismatch between the timing of California's water demands and water supplies. The Delta's climate is also unusual in its extreme variability (Cayan et al. 2003), which routinely yields extended periods of drought or periods of widespread flooding. Indeed, the year-to-year variations of the combined flows from the Central Valley are notably larger (relative to their long-term averages) than other large western rivers, the Columbia and Colorado, for example.

On a national scale, the Bay-Delta system is the largest estuary on the West Coast. The Delta includes fifty-seven islands, eleven-hundred miles of levees, and hundreds of thousands of acres of marshes, mudflats and farmland. Ecologically, the Delta is home to an array of ecosystems and more than seven hundred plant and animal species,

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[1] Discussed in greater detail in Chapter 7

including many unique to this estuary. The Bay-Delta eco-region is an important resting and feeding area on the Pacific Flyway, and an important breeding ground for many waterfowl species. From an economic perspective, the Bay-Delta plays an important role nationally—California has the estimated seventh-largest economy in the world, generating a Gross Domestic Product of about $1.5 trillion annually, and is the world's fifth-largest supplier of food and agricultural commodities (California Department of Finance 2005). Of the 8.5 million acres of irrigated farmland in California, about 3 million acres are irrigated from Delta-associated water supplies, resulting in at least $27 billion in agricultural income—45 percent of the nation's agricultural production.

From a state perspective, the Bay-Delta system is one of few estuaries in the world used as a major drinking water supply; the system provides some or all of the drinking water for two-thirds of the state's population (twenty-three million people). The Delta also provides estuarine habitat for many resident and migratory species, some state and/or federally listed as threatened or endangered, including winter- and spring-run Chinook salmon *(Oncorhynchus tshawytscha)*, Central Valley steelhead *(Oncorhynchus mykiss irideus)*, Delta smelt *(Hypomesus transpacificus)*, Sacramento splittail *(Pogonichthys macrolepidotus)*, Southern green sturgeon *(Acipenser medirostris)*, giant garter snake *(Thamnophis gigas)*, salt marsh harvest mouse *(Reithrodontomys raviventris)*, Suisun song sparrow *(Melospiza melodia maxillaries)*, California clapper rail *(Rallus longirostris obsoletus)*, Valley elderberry longhorn beetle *(Desmocerus californicus dimorphus)*, Delta green ground beetle *(Elaphrus viridis)*, Suisun thistle *(Cirsium hydrophilum* var. *hydrophilum)*, and soft bird's-beak *(Cordylanthus mollis* ssp. *mollis)*.[2]

Regionally, many islands in the Delta and adjacent lands sustain productive agriculture. Water supply is critical. In addition to the water exported through the Central Valley Project (CVP) and the State Water Project (SWP), nearly 90 percent of municipal water used in the East Bay is diverted from the Delta or transported across it in aqueducts. The cities of Sacramento and Stockton have seaports, and regularly maintained shipping channels cut through the Delta. The Delta also serves as a transportation corridor with roads, bridges and auto ferries connecting islands and tracts. A variety of utilities (electrical transmission, natural gas, petroleum and water pipelines) also cross islands, sloughs and tracts. With more than seven hundred miles of waterways, water-based recreation and tourism is increasing in the Delta. There are 191 hunting clubs in Suisun Marsh and the Delta, and boating accounts for more than 6.4 million visitor-days annually.

California's statewide physiographic setting, climate, ecology, water flows and water resource infrastructure is context for the challenges facing California's water resource managers. This chapter focuses on the climate, hydrology and history of watershed modifications and water resources development. The chapter concludes with a discussion of major drivers or forces that have shaped and will continue to shape this waterscape into the future.

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[2] See Chapter 1 and United States Fish and Wildlife Service 2007 for a full list of threatened and endangered species, see http://ecos.fws.gov/tess_public

California's Mediterranean Climate

California has a Mediterranean climate, characterized by hot, dry summers and mild, wet winters. One important feature of this climate is that precipitation patterns are highly variable from year to year (inter-annually) and within years (seasonally) (see Figure 2.2). For example, although the average December precipitation for the period is about eight inches, the maximum December precipitation is over thirty inches, and minimum December precipitation is near zero. It is difficult to find any year that can be truly classified as average. Another feature of California hydrology is that more rain and snow fall in the northern part of the state than in the southern portion.

The variability of precipitation and runoff has important implications for the ecology of the state's watersheds, rivers and adjacent floodplains. For example, many native fishes use temperature and flow cues in rivers and streams to begin migration, spawning, or other life-stage activities (Williams 2006; Moyle 2002). The timing of spring snowmelt runoff in the Sierra Nevada or warming in the Delta in the summertime have important consequences for environmentally tuned ecosystem processes and functions, such as species shifts in aquatic communities or emergence of seedlings or flowering structures (Cayan et al. 2001; Sickman, Leydecker, and Melack 2001; Kondolf 2000), and may be partly responsible for patterns in occurrence and abundance for many species (Cronk and Fennessy 2001; Western 2001).

> "It is a mistake [...] to think of California in terms of averages and regular cycles of precipitation. The evidence, both recent and in tree rings dating from prehistoric times, reveals great variation. [....] The long-term record reveals a similar pattern of alternating cycles of severe drought and heavy precipitation (Hundley 2001, p.10).

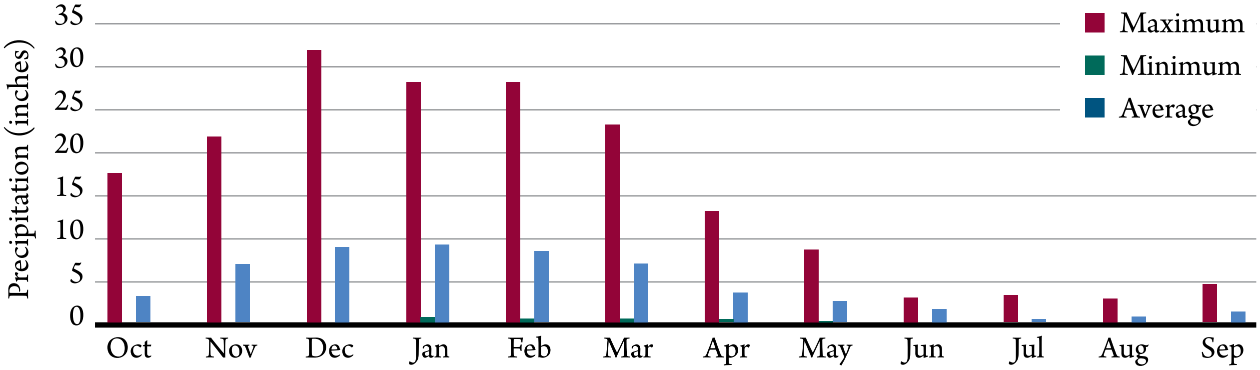
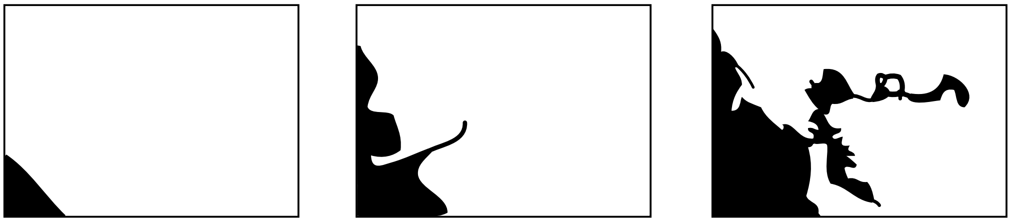


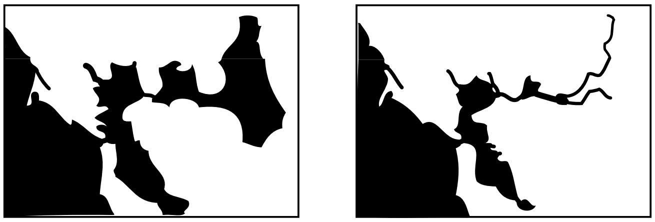
Figure 2.2. Northern Sierra monthly precipitation from 1921 to 2006 (averaged across precipitation measurements at Mt. Shasta City, Shasta Dam, Mineral, Brush Creek RS, Quincy, Sierraville RS, Pacific House and Blue Canyon). A year that produces the average precipitation values for each month would be extremely rare. (Source: California Data Exchange Center 2007)



15,000 Years Ago
(End of last Ice Age—sea level approximately 400 feet below present level; rivers not shown)

10,000 Years Ago
(Formation of Farallon Islands and intrusion into the "Golden Gate")

5,000 Years Ago
(Formation of Bay and Delta Basins)



125 Years Ago
(Landward edge of undiked tidal marsh)

Today
(Includes changes due to hydraulic mining sediment deposition, land reclamation, and filling of wetland areas)

Figure 2.3. Marine water intrusion into the Central Valley created the estuary we find today. (Source: The Bay Institute 1998)

These important relationships are further complicated when a given species also shows life-stage dependencies on Delta water quality (temperature, turbidity and salinity) patterns. Ecologists and hydrologists are increasingly finding evidence that many such complicated relationships are at the root of population abundance patterns (Nobriga et al. 2008; Feyrer, Nobriga, and Sommer 2007; Monsen, Cloern, and Burau 2007). It is also likely that invasive species exploit changes in local or regional water quality conditions to acquire or increase relative competitiveness over native and endemic species (Spalding and Hester 2007; Byers 2002). Indeed, longer-term (interdecadal) relationships between estuarine and coastal ocean processes have been shown to alter the biotic community structure found in the inland estuary of the Bay-Delta (Cloern et al. 2007).

Central Valley Hydrography, Past and Present

Approximately twenty thousand years ago, sea surface level was about four hundred feet lower than today, and the Delta did not exist in its current location until sea level began to rise about ten thousand years ago (see Figure 2.3). Aquatic species have used the ten thousand-year history of the incursion of tidal coastal ocean water into the Central Valley to fine-tune their use of the San Francisco Estuary's water resources to their particular life-history requirements. The variability of the Californian Mediterranean climate and regional and local environmental conditions is increasingly understood as being important to how endemic and native species have adapted and thrived over this history (Moyle 2002). Anadromous fish have passed through the Central Valley and into its tributaries for much longer than the Delta has existed.

In addition to precipitation-derived runoff, the Bay-Delta is influenced by the Pacific Ocean in the form of twice-daily tides that deliver a large amount of coastal ocean water and tidal energy to the Delta's hydraulic network. Tidal rise and fall varies with location, from less than one foot in the eastern Delta to more than five feet in the western Delta. The direction and magnitude of flows in Delta channels also vary during the tidal cycle, from 330,000 cubic feet per second (cfs) in the upstream (landward) direction to 340,000 cfs in the downstream (seaward) direction during a typical summer tidal cycle at Chipps Island (Hoffard 1980). The magnitudes of the tidal flows diminish at locations farther into the Delta, but nonetheless, for most of the Bay-Delta, twice-daily tides and varying inputs from rivers and streams result in highly dynamic conditions within a single day. Hydrodynamic conditions change continuously in the Delta, from one tide to the next, one day to the next, and one year to the next. Management of Delta water resources and ecosystems that depend on Delta water must contend explicitly with this inherent variability.

Estimates of unimpaired runoff—the flows that would have occurred without upstream dams and water diversions—provide an approximation of the range of annual flows into the Delta under natural (non-managed) conditions (see Figure 2.4). The period of record for the Central Valley (1906 to the present) illustrates the degree of variability in the unimpaired outflow from the Bay-Delta watersheds to San Pablo Bay. In 197, the outflow was five million acre-feet (MAF) and in 1983 it was about sixty MAF. This is an unusual degree of variability in outflow from a western North American river basin and poses unique challenges for water management (Cayan et al. 2003).

On a seasonal basis, flow variation has been greatly reduced as a result of storage dams. Winter and spring flows below dams are much reduced, whereas summer and autumn flows are increased (see Figure 2.5).

The modulation of the discharge curve indicates a general effect water project management has had on freshwater discharges throughout the Bay-Delta. This effect is more pronounced during drought years than in average or wet years but is present regardless of water-year type. However, even in the era of pronounced water development in California, the variability in Delta inflows is remarkable (see Figure 2.6; Lund et al. 2007).

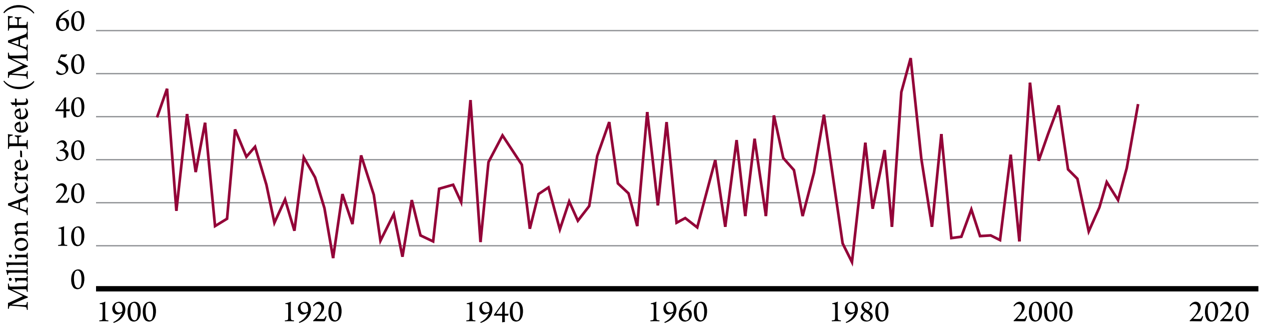


Figure 2.4. Combined Sacramento-San Joaquin River average annual unimpaired runoff for water years 1906 to 2006. The unimpaired runoff—an estimate of flows without upstream dams or diversions—shows the highly variable flow conditions from year to year. (Source: California Data Exchange Center 2007)

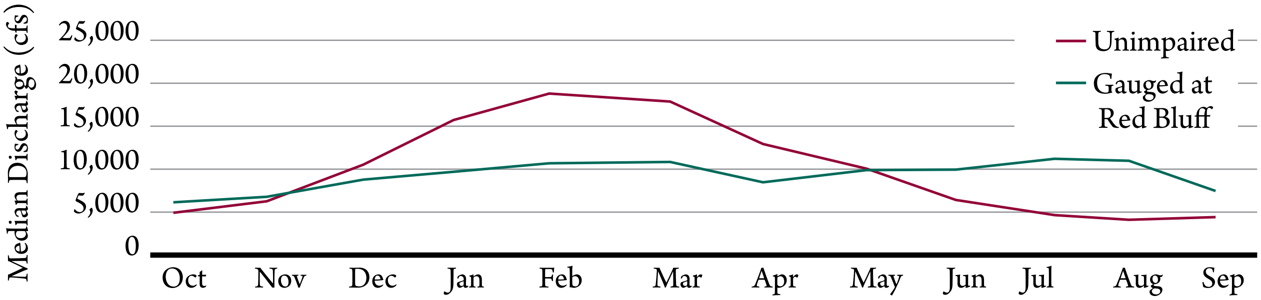


Figure 2.5. Seasonal distribution of observed versus unimpaired flow in the upper Sacramento River. (Source: The Bay Institute 1998)

With regard to the coupling of hydrology and species-specific life-history requirements, there is evidence that native species may be having difficulty persisting in the face of these hydrologic changes. Flood and floodplain-dependent species like the Sacramento splittail, migratory species like the various runs of Central Valley salmon, and pelagic species dependent upon Delta habitat like the Delta smelt are showing long-term declines in abundance, possibly due in part to alteration of the natural hydrograph of the Delta (Feyrer, Nobriga, and Sommer 2007; Williams 2006).[3]

Groundwater hydrology has also changed as a consequence of water development within the Central Valley (Alley 1993). Prior to about 1940, groundwater moved toward valley stream channels, and much of the valley was a discharge area. By 1970, pumping for agriculture and other uses had drawn groundwater reservoirs down hundreds of feet. Importation of irrigation water (from rivers or from the CVP) together with continued overuse of groundwater means the Central Valley is now primarily a groundwater recharge area, and most groundwater discharge is a result of pumping rather than natural seepage. As a result, salts and selenium accrete in Central Valley soils, poisoning agricultural runoff water. The storage capacity of Central Valley aquifers may also be substantially reduced as a result of compaction resulting from overdrafting and water table drawdown (Ireland, Poland, and Riley 1984).

Despite California's extensive system of water storage and flow management, there is growing evidence that our capacity to manage water supply and water quality is limited. For example, there is no getting around the fact that natural patterns of precipitation and runoff drive Central Valley hydrology, and that the salinities found in the Bay-Delta are driven as much by natural climate variability as they are by freshwater management (Knowles 2002). In addition, in spite of the billions of dollars invested in levees and flood control, a 150-year record of levee breaks in the Central Valley reveals that: (1) the frequency of levee breaks has not declined, and (2) the relationship between peak flows and the likelihood of levee failure has not changed (Florsheim and Dettinger 2007).[4]

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[3] Discussed in greater detail in Chapter 4

[4] Discussed in greater detail in Chapter 5

History of Watershed Modification and Water Resource Development

Several descriptions of California water resources development and watershed modification (Hundley 2001; The Bay Institute 1998; Kelley 1989; Reisner 1986) bear witness to the extent and degree to which humans have altered California's waterscape from its original natural condition and ecology. The contemporary Delta cannot be thought of as a natural system—it is a highly managed water supply and flood control system, with total upstream storage capacity roughly equal to the average annual total runoff from the watershed (see Figure 2.7). Many of the conflicts in California water management trace their origin to the difficulty of providing both ecological water and water for human uses from the common Delta water resource base.

An understanding of how human use of the land has changed through time, and how those uses have transformed physical and biological processes within the watershed, is fundamental to understanding how the Bay-Delta provides, or fails to provide, ecological services today. Reviewing land use change helps to assess how riverine and landscape function and quality have changed in relation to human influences.

Significant diversion and modification of stream flows in Sierra watersheds began during the Gold Rush (1850 through 1880) to facilitate gold mining (Hundley 2001; The Bay Institute 1998; Kelley 1989). Upstream mining operations had serious impacts on the Delta region. Hydraulic

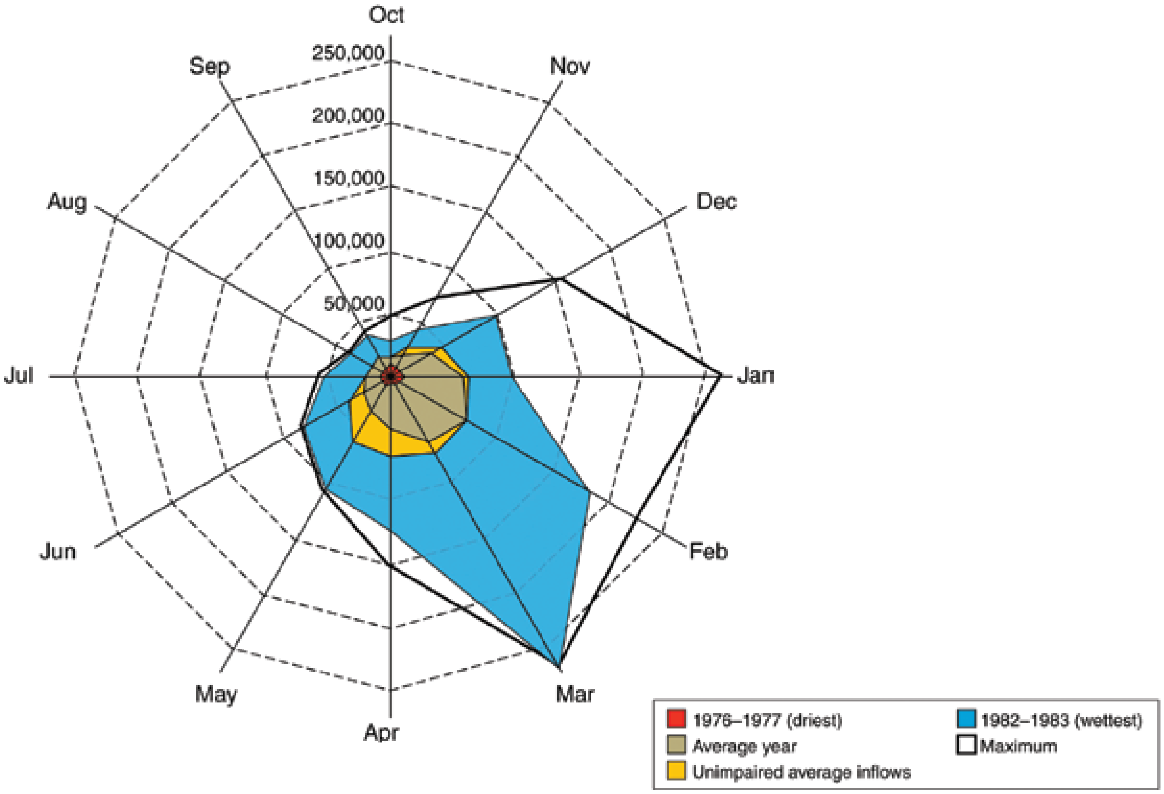

Figure 2.6. Seasonal and annual variability of Delta inflows, from 1956 to 2005 in cubic feet per second(cfs). (Source: Lund et al. 2007)

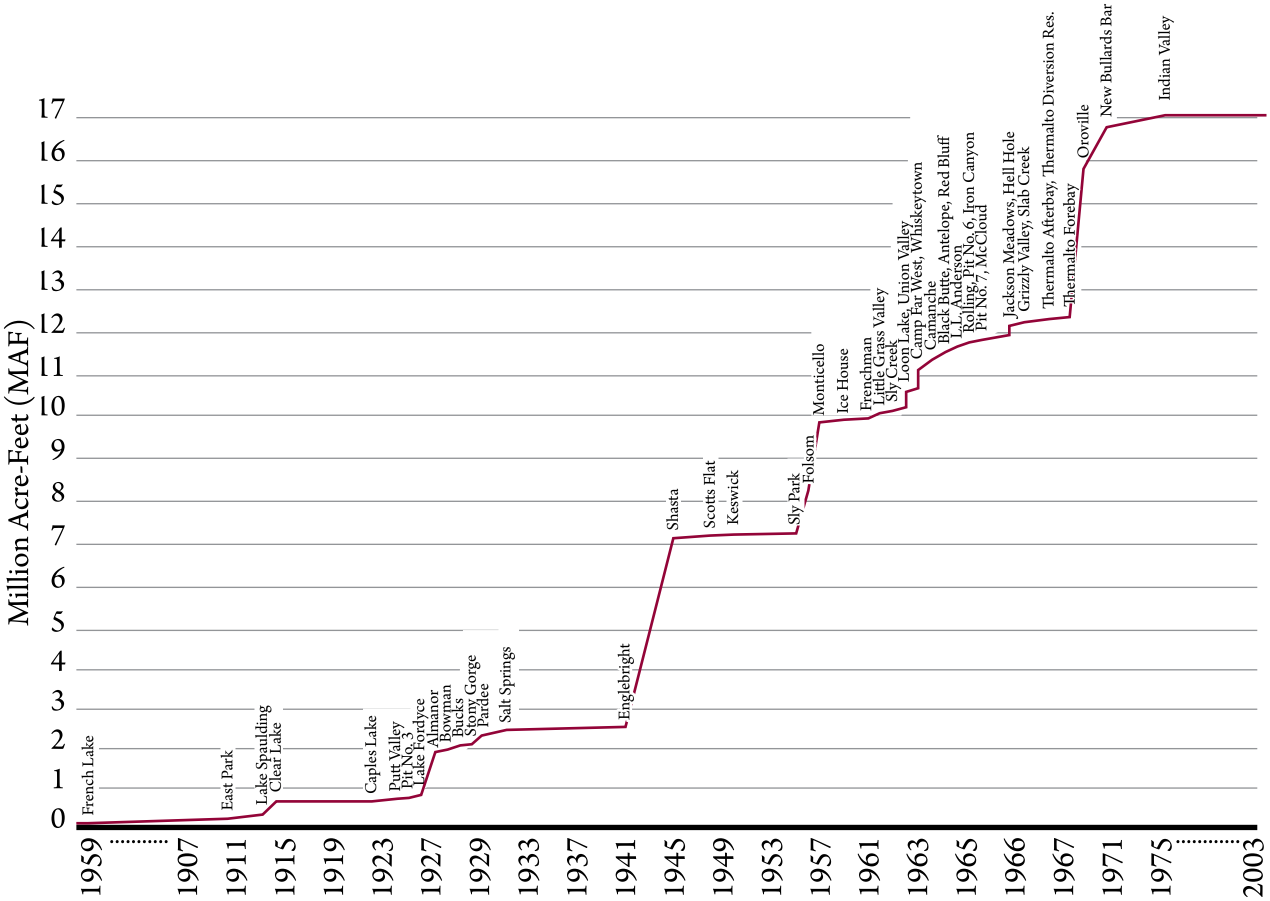

Figure 2.7. History of the development of Sacramento River water storage capacity, shown as million acre-feet (MAF) versus year, with each data point representing the indicated added storage reservoir. (Source: Chung 2007)

mining washed more than eight hundred million cubic yards of mining debris through the Delta. This is enough sediment to bury the whole 1,315-square-mile Delta area to a depth of about ten inches. Concentrated in the channels, the depth of sediment would be as much as five and one half feet! When washed down into the Central Valley this sediment raised streambeds and elevated water levels in upstream rivers and the Delta, causing frequent floods. Levees were built higher to protect surrounding homes and farmlands, and rivers were progressively disconnected from their floodplains. Shortly thereafter, major upstream water diversions for crop irrigation in the Central Valley began as local and regional markets for agricultural products grew. Water diversions from rivers and streams upstream of the Delta are now estimated at approximately four to ten MAF per year.

Alteration of sloughs and reclamation of lands within the Delta itself began for agricultural purposes, but became increasingly important as settlement of low-lying areas near Sacramento and other new centers of commerce and shipping developed. Levee construction for flood management within the Delta and along tributary rivers and streams isolated the floodplains from the periodic flooding. As many as 297,000 acres (460 square miles) of historic Central Valley floodplains have been separated from their parent rivers and streams.

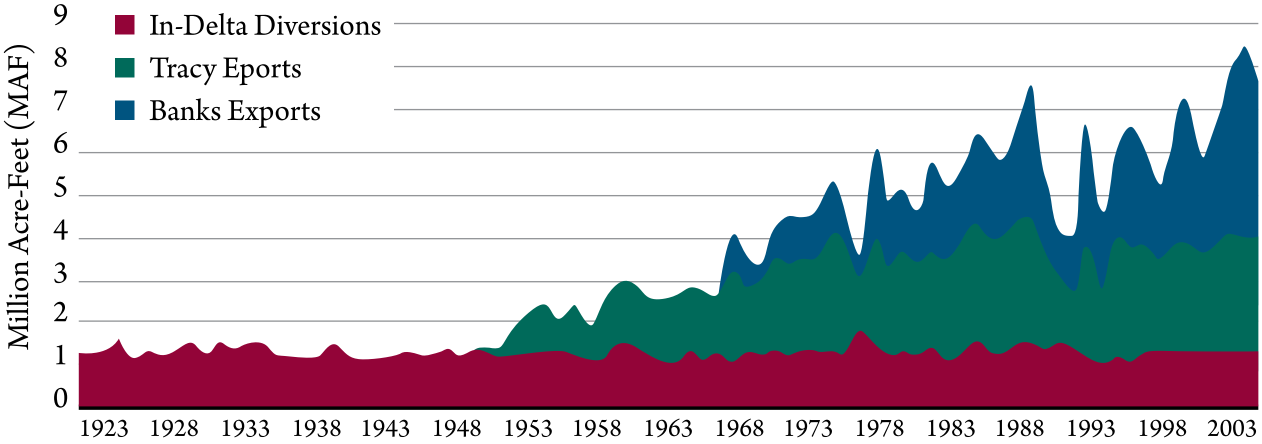

Figure 2.8. Delta Water Diversions and Exports. Delta diversions and exports have grown over time. In-Delta diversions for irrigation have been about the same since the early 1900s. Federal exports (Tracy) began in the early 1950s, and state exports (Banks) began in the late 1960s. (Source: URS Corporation 2007)

Historically, periodic flooding of these areas provided valuable habitat for many species and reduced flood stage farther downstream. The Delta itself absorbed flood flows to become a vast shallow lake. At its greatest extent prior to reclamation, the Delta covered 1,931 square miles of tidally influenced open water, mud flat and marsh. Today the network of Delta levees has substantially reduced the area exposed to the tides to about 618 square miles.

Water project construction occurred most aggressively between 1930 and 1980, a period of rapid urbanization and agricultural development throughout California. Large-scale water management was achieved through construction of dams for water supply, flood control, hydroelectric development, and through the establishment of several regional and statewide aqueducts. The Delta was incorporated into this water management system as the means by which to convey Sacramento River water to the export pumping facilities in the South Delta, where currently about eight MAF is exported annually (see Figure 2.8). The thriving state economy is closely tied to these water development projects. Collectively, the storage capacity of the reservoirs within the Delta's watershed is about thirty-two MAF, or about 1.3 times the average annual flow to the Delta. These reservoirs allow water managers flexibility for moving water in time and place by capturing water during high-flow periods and releasing it during low-flow periods. Reservoir management is complicated by the fact that most serve the dual purposes of flood control and water storage. To achieve these dual purposes, managers maintain free (flood control) space in reservoirs during the season of heavy storms, then capture as much flow as possible (mostly from snowmelt in some basins) from late-season (springtime) high flows. The stored water is released later during low-flow periods when water demand for agriculture is high.

California has less storage capacity than the two other large western United States river systems—the Columbia and Colorado Rivers (California storage capacity is thirty-two MAF; Columbia River storage capacity is fifty MAF; Colorado River storage capacity is sixty MAF). Whereas California's storage capacity is a bit more than one year's average runoff, compared with the Columbia (much lower at 30 percent of annual runoff) and the Colorado (much higher at four times annual runoff), the volumes are much different. The Columbia has relatively little year-to-year flow variability and relatively little storage; the Colorado has moderate year-to-year flow variability and a large storage capacity; the Central Valley has high flow variability, medium storage relative to runoff, and the lowest volume storage capacity (Cayan et al. 2003).

There are approximately two thousand water diversions for irrigated agriculture in the Delta. These diversions are capable of diverting up to 5,000 cfs during peak periods of water use, and amount to additional withdrawal of about 1.7 MAF per year from the Delta.[5]

Delta water management occurs primarily by manipulating water project infrastructure (dams, gates and pumps). The geometry and alignment of some Delta channels have been modified to increase the flow of freshwater from the Sacramento River to the export facilities in the southern Delta, and to facilitate shipping to the ports of Stockton and Sacramento. In some channels, gates and barriers were added. Channel cuts made through some Delta islands have connected previously isolated sloughs. Delta hydrologists speculate that a consequence of these modifications has been an increase in hydrodynamic mixing within the Delta, and decreases in the variability of salinity, temperature, water clarity, residence time, nutrient loads and primary productivity (Enright, Culberson, and Burau 2006), with potentially large implications for the Delta ecosystem (Monsen, Cloern, and Burau 2007).

Bay-Delta water quality depends on tides, freshwater inflow, state and federal water quality regulation and natural and engineered structures. There is only limited and localized management or regulation of tides: what is managed is the location of the salinity gradient where marine and freshwater mix. This is done through the management of Delta inflows and export pumping. Freshwater inflow to the Delta depends on natural runoff, upstream diversions, return flows and storage or releases from upstream reservoirs that alter the natural runoff. The CVP and SWP use the Sacramento and San Joaquin Rivers and Delta channels to transport natural river flows to the South Delta export facilities, which changes the natural flow direction in some channels.

Human-caused changes in land-use patterns and the hydraulic geometry of river and Delta channels, have had lasting and variable impacts on water quality and the hydrodynamics (how water transport through Delta channels varies over time and with location) of the Bay-Delta as a whole (Enright, Culberson, and Burau 2006; Grossinger and Striplen 2006). As the watershed is increasingly altered, the water chemistry and temperature of the runoff will resemble the historical conditions less and less. There is evidence that changes to date have significantly altered pelagic and shallow water aquatic habitats to the detriment of native or otherwise-desirable Delta species (Sommer et al. 2007; Williams 2006).

Consequences of Water Development in California

Urbanization, industrialization and irrigated agriculture realized more-or-less directly via the development and management of California's water resources contribute substantially to the state economy. Irrigated agriculture alone contributes an estimated $27 billion annually to California's $1.5 trillion economy (California Department of Finance 2005). The indirect economic contribution of Delta-based water resources management

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[5] See Figure 1.3 in Introduction: New Perspectives on Science and Policy in the Bay-Delta

could amount to tens of billions of dollars more per year. In short, the state economy is fueled to a large degree by its Delta-based water management infrastructure. Urban development and population growth since about 1950 have largely been a function of the availability of water to urban users and agricultural producers in Southern California, the San Francisco Bay Area and in the Sacramento and San Joaquin Valleys. Additional land has been made available through flood control and reclamation of tidal and riparian areas throughout the state, including the Delta.

Environmental impacts of state economic and population growth and water resources development have presented policy challenges since environmental resources were first exploited (hydraulic mining debris impacts in the Central Valley during the 1880s, or over-fishing of salmon in the Sacramento River by the 1920s, for example), and these impacts have received enhanced attention since the adoption of national and state protection of endangered species and ecosystems beginning in the 1970s (Endangered Species Act, California Endangered Species Act). Recent examination of the impacts of water project development in the state has documented species population losses due to destruction of habitat, alteration of flow timing and changes in water chemistry, water velocities and runoff quantities (Healey 2007). As the Delta watershed becomes increasingly urbanized, toxic storm water runoff becomes more difficult to manage. Cheap and dependable water supplies throughout the state have created the expectation that affordable water supplies will expand in conjunction with an expanding economy, regardless of any natural limits on supply. Under-appreciation of levee failure risk has contributed to questionable building practices that leave entire communities vulnerable to catastrophic flooding (Lund et al. 2007). Sacramento, Stockton and adjacent areas including the Delta remain vulnerable to flooding similar to that experienced in New Orleans following Hurricane Katrina in 2005 (Seed 2005; URS Corporation and Jack R. Benjamin and Associates, Inc. 2007).

Future Changing Conditions and Drivers of Change

Lund et al. (2007) list the drivers of change affecting the current and future ecosystem, landscape and water project infrastructure of the Delta (not to mention human populations dependent upon these resources): subsidence; sea-level rise; seismicity; regional climate change; alien species; and urbanization. The Millennium Ecosystem Project[6] identifies a broader list of direct and indirect drivers of ecological change in nine categories that encompass the list by Lund et al. (2007), but also includes economic and sociopolitical drivers as well as science and technology drivers (Nelson et al. 2006). Under the umbrellas of sociopolitical drivers and science and technology drivers are legal instruments, such as listing species for protection under state and federal Endangered Species Acts, and declarations that certain water bodies are impaired or regulated under the Porter-Cologne Water Quality Control Act and the federal Clean Water Act. Adherence to regulations under these laws requires changes to water resource management perhaps equal in magnitude to any recent environmental or ecological changes in the Delta. Indeed, a shutdown of the SWP pumps in the winter of 2007 was due to endangered species (Delta smelt) concerns from a federal judge adjudicating state authority in pumping Delta water under state and federal Endangered Species Acts.

From a strictly hydrological viewpoint, we may be experiencing unprecedented change in climate and regional precipitation patterns that have not been

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[6] See: www.millenniumassessment.org/en/index.aspx

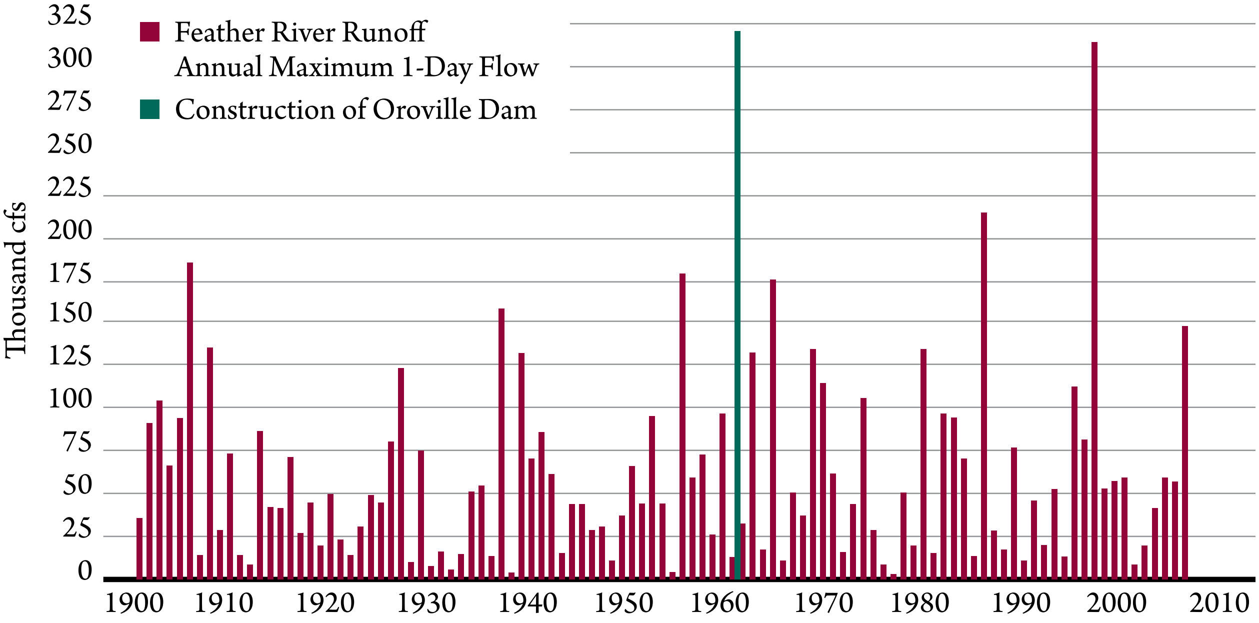

Figure 2.9. Changes in peak runoff flows (in thousand cfs) in the Feather River, from 1902 to 2006. (Source: Snow 2007)

adequately incorporated into our water resources management or infrastructure. By some accounts, peak runoff volumes have increased since the development of the state and federal water projects (see Figure 2.9). [7]

Historic hydrographs for Delta tributaries, developed during the twentieth century, may not reveal the full variability of peak flows that current or proposed dams are likely to encounter during their lifespans (Florsheim and Dettinger 2007; Snow 2007). Higher peak runoffs and diminishing snowpack will challenge our current water infrastructure and regulatory practices (California Department of Water Resources 2005; California Energy Commission 2006).[8] Even the most conservative (coolest) projections of twenty-first-century warming are expected to result in 30 percent declines in snowpack water content; more extreme projections would result in declines of 70 percent or more (California Energy Commission 2006).

Environmental conditions over the next several decades may change quickly, prompting movements in habitats, species communities and available resources throughout the Central Valley (Millar et al. 2006). Some species already at risk may face environmental conditions, such as warming of water beyond their physiological capability (Bennett 2005). Trends in peak runoff indicate earlier warming of streams in the spring that may lead to changes in timing of spring salmon migration patterns (Williams 2006). Changes in fish migration timing and distribution throughout the year may conflict with current water operation strategies and may affect future water deliveries, storage, or water quality. Sea-level rise will change Delta hydrodynamics, increase salinity levels and challenge our aging levee systems. A further future complication may be the occurrence of persistent long-term droughts (droughts of ten to twenty years or more), unknown in the recent past, but fairly regular when examining the paleodrought record of the inter-American west (Stahle et al. 2000; Stine 1994).

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[7] Discussed in greater detail in Chapter 6

[8] Discussed in greater detail in Chapter 6

Table 2.1. Paradigm Shifts Identified in *Envisioning Futures*

New Paradigm	Old Paradigm
The San Francisco Estuary is unique in many attributes, especially its complex tidal hydrodynamics and hydrology	The San Francisco Estuary works on the simple predictable model of East Coast estuaries with linear gradients of temperature and salinity controlled by outflow and edging marshes, both salt and fresh water, supporting biotic productivity and diversity
Alien species are a major and growing problem that significantly inhibits our ability to manage for desirable species	Alien (non-native) species are a minor problem or provide more benefits than problems
Changes in the management of one part of the entire estuary system affect other parts	The major parts of the San Francisco Estuary can be managed independently
Delta landscapes will undergo dramatic changes as the result of natural and human-caused forces such as sea-level rise, flooding, climate, and subsidence	The Delta is a stable geographic entity in its present configuration
The big pumps in the southern Delta are one of several causes of fish declines and their effect depends on species, export volume and timing of water diversions	The SWP and CVP pumps in the southern Delta are the biggest cause of fish declines in the estuary

(Source: Lund et al. 2007, pp. 219-222.)

Accumulation of Scientific Knowledge and Changing Ecological Understanding

Inasmuch as the "state of the science" leads us to focus on details, there is a danger that we will lose sight of the larger picture. Contentious water development and allocation issues have frequently been treated as arguments over specific contract or regulatory requirements, over specific measures of compliance or achievement, or over whose expert opinion is to be believed. When the atmosphere is adversarial, it is easy to lose sight of the degree to which our foundational scientific knowledge has changed over time. Moyle (Lund et al. 2007) describes a number of paradigm shifts in the way we understand the Delta and its ecosystem that have occurred over the past decade. These paradigm shifts express very clearly how much our understanding of the Delta has evolved and grown as a result of CALFED and other science: Table 2.1.

To these we add five paradigm shifts: Table 2.2.
Not only does the Bay-Delta evolve and change with time, so too does our understanding evolve and change. What we may have valued about

Table 2.2. Additional Paradigm Shifts

New Paradigm	Old Paradigm
Coastal ocean influences and species are an important source of variability in the Bay-Delta	The Delta is primarily driven by riverine influences, species and outflow magnitude
Tidal channel geometry is a major factor contributing to hydrodynamic mixing within the Delta, as well as ecosystem viability and water quality, throughout large parts of the Delta	Reconfiguring a Delta slough is best considered a local operational concern
Sediment supplies to the Delta are changing and are having important ecological implications	The Delta is a cloudy and muddy mixing zone; the legacy of hydraulic mining is the source of any problems
Delta wetlands can be an important source of flood control and water quality maintenance	Wetlands are of little value but can be reclaimed for economic benefit
Restored wetlands can in some cases become sources of recycled contaminants so that wetland restoration needs to be designed and located to minimize any negative consequences	Restoration of wetlands always has multiple positive benefits for species, flood control and water quality

the Bay-Delta fifty years ago may not be what we value today, and may not be what we value fifty years hence. The suite of species driving restoration and protection programs today are not those which drove these programs twenty years ago and are not likely to be those which will drive such programs twenty years from now. Our state of knowledge, and the state of our science, is constantly being updated. Management practices will improve to the extent that we update them to reflect our growing understanding. *The State of Bay-Delta Science, 2008* summarizes the new knowledge available to inform debate about future management practices to sustain the Bay-Delta as a key component of California's water supply system and as a living, working ecosystem.

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3. Water Quality

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Sustainable water policy in California will require maintaining or improving water quality. The Delta is an important source of drinking water for Californians, but sustaining a quality sufficient for human and agricultural consumption presents a number of problems and challenges to water managers. Similarly, poor environmental water quality is recognized as one of the influential stressors contributing to the ecological problems of the Delta (Bennett 2005; Kimmerer 2004).

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Both drinking water and ecosystem water quality are affected by the legacy of toxic discharges to the Delta, as well as inputs of new chemicals whose effects are poorly understood. The characteristics that define high quality drinking water often seem to conflict with the characteristics needed for high quality water for ecosystems. On the other hand, the only real solutions to complex water quality issues will be those that consider the demands from all beneficial uses and directly address balances to potential conflicts. Continued advances in scientific understanding are essential to addressing these challenges, but scientific insights must also be better incorporated into the ongoing dynamic interplay between water quality and water policy.

Risks to beneficial uses of Delta water (including uses by humans and ecosystems) have been identified and increasingly clarified in the last decade. Direct evidence that ecological changes in the Delta are caused solely by poor water quality is difficult to obtain. The system is complex, as is the problem of linking specific water quality problems to specific ecological changes. But much evidence supports the potential for water quality to cause problems. Toxicity is observed in water and sediments. The generation of methylmercury is linked to wetland restoration. New pesticides (like pyrethroids) are appearing in water and sediments and are, at least in tests, linked to ecological toxicity. Sources and types of organic matter can be linked to cancer-causing water-treatment byproducts in drinking water (Presser and Luoma 2006; Weston, You, and Lydy 2004; Brown 2003). There is also a growing body of knowledge explaining how ecological effects of water quality are manifested. For example, selenium inputs to the Bay-Delta threaten sturgeon and diving ducks more than Delta smelt *(Hypomesus transpacificus)* or longfin smelt *(Spirinchus thaleichthys)*. Mercury and polychlorinated biphenyls (PCBs) threaten larger, older and higher trophic-level organisms more than organisms at the base of food webs. New contaminants have also been identified with effects we can only surmise from their significant role elsewhere (for example, endocrine disruption in wildlife, Tyler, Jobling, and Sumpter 1998). These must be recognized and incorporated into our priorities accordingly.

Some of the advances in understanding water quality have very specific connections to important policy issues. Water managers and public health officials have known for twenty years that cancer-causing byproducts can be produced when drinking water is disinfected. We now know that Delta water contains a number of precursors of those byproducts, including organic carbon, bromide, nutrients and algae. Water managers now understand that a high quality source of water is just as necessary as the treatment if we are to sustain the Delta as a reliable source of drinking water.

The fate of irrigation drainage has been a policy bottleneck for decades. In the 1980s, it was shown that improper disposal of irrigation drainage poses serious threats to wildlife because of the selenium associated with salts in the drainage. The linkage between selenium contamination and toxicity to wildlife was unambiguous when drainage was disposed of in Kesterson Reservoir. In the last ten years, it has become clear that wildlife in San Francisco Bay, including white sturgeon *(Acipenser transmontanus)*, Sacramento splittail *(Pogonichthys macrolepidotus)* and some migratory birds (Presser and Luoma 2006; Linville et al. 2002) may be especially vulnerable to selenium inputs, making out-of-valley solutions to irrigation problematic.

Nowhere is the interplay between water quality and water policy more significant than in the renewed debates about systems for conveying water for export. Some proposals for new infrastructure involve reducing Sacramento River inflows to the Delta while increasing San Joaquin River inflows. Under present-day water management, when the Delta inflows include a high proportion of San Joaquin water, water quality in the Delta is noticeably poorer, and the effects of changing inflows from the two rivers are made complex by tidally-driven circulation (Monsen, Cloern, and Burau

2007). Water quality policy is already affected by the degraded quality of the interlinked waters of the Bay-Delta. Human health advisories currently limit fish consumption because fish are contaminated with PCBs, selenium and mercury. Compliance with water quality objectives is an ongoing problem, as evidenced by active or proposed Total Maximum Daily Load (TMDL) investigations for PCBs, selenium and mercury. All could be influenced by policies that affect conveyance.

> Management of drinking water, conveyance, irrigation drainage, levee repair, risks from chemical contamination and ecosystem restoration all have benefited from advances in understanding of water quality over the last decade. Perhaps the greatest advance, however, is the general recognition that water quality issues must be viewed holistically, acknowledging the interlinked needs and conflicts of human and ecological uses.

In this chapter, we will discuss specific examples of how science has contributed to the interplay between water quality and water policy (see Table 3.1). Our examples illustrate how new science is necessary not only to flesh out the details of particular water quality issues, but also to yield new ideas for solutions, or shift the dialogue in new and constructive ways. The Delta suffers from many water quality issues that cannot be covered in detail in a short synthesis. The examples we have chosen highlight only some of the most important water quality impacts to the diverse constituencies of the state. Drinking water supply, ecosystem health and agricultural management are all critical aspects of our quality of life and the state economy, and all rely on addressing water quality issues in informed and creative ways.

High Priority Water Quality Issues

Salinity

Salinity has the single broadest influence on drinking water, agricultural water and environmental conditions in the Bay-Delta. Salinity is a common issue for all aspects of the water supply management system. It affects every beneficial use. For agricultural supplies, salinity levels are a concern because salt in irrigation water can reduce crop yield, build up in shallow groundwater and reduce soil quality. Salination of soils and disposal of the drainage from those soils in the western San Joaquin Valley is one of today's great policy challenges. Salinity also reduces the reusability of the water supply. For municipal drinking water and industrial supplies, salinity is extremely expensive to remove. In fact, the entire water supply system was built to avoid treating salinity. High-salinity waters corrode pipes and produce hard water deposits, affecting industrial processes and shortening the lives of appliances. High-salinity waters taste bad, add a daily load of salt to the human diet and reduce the yield of water supplies. Physical removal of salts from water requires large amounts of energy and produces large amounts of very saline water that must be disposed of. Estuarine salts also contain high levels of bromide. Bromide reacts with ozone in drinking

> Water supply reliability is reduced by high salinity. In the Bay-Delta system, water serves one use, then it is discharged back into a conveyance or groundwater basin or run through a treatment plant, and then it serves another use. The ability to reuse water ultimately depends on its initial salinity and the accumulation of salinity throughout the process.

Table 3.1. Examples of the Interplay of Water Quality, Water Policy and Science

Water Quality	Role of New Science	Water Policy
Disinfection byproducts have adverse effects in drinking water	**Expand known concepts:** Water from different sources yields different types of byproducts	High quality source water is essential at drinking water diversion points
Hydrodynamics influence drinking and environmental water quality	**New concepts yield new solutions:** Use tides and small changes in levees to avoid trapping salinity near drinking-water diversion points	Work with natural processes to improve cost-effectiveness of managing source water quality
Levees are crucial to the Delta	**Shift policy dialogue:** Levee breaks affect salinity in the Delta	**New policy dialogue:** Is it feasible or desirable to allow salinity to vary in the Delta?
Disposal of irrigation drainage remains unresolved	**Quantify known risks:** Substantial ecological risks from selenium exist in disposal of drainage in San Francisco Bay	In-valley solutions to irrigation drainage seem essential
Water management and water quality rely on Delta infrastructure	**Identify unsuspected risks:** Changes in conveyance could change inputs of San Joaquin River water and thereby affect Delta water quality	Drainage issues are an essential consideration in decisions about conveyance changes.
Endangered species influence water supply reliability, but ecosystem restoration for those species is affected by water quality	**Identify potential conflicts:** Restoration also affects water quality by producing dissolved organic matter and perhaps methylmercury	Consider water use conflicts and processes that could exacerbate those conflicts when locating restoration sites
Multiple stressors seem to contribute to declines in pelagic organisms in the Delta	**Characterize stressors:** Numerous pesticides are found in the Delta, as are elevated levels of selenium, mercury, copper and probably chemicals typical of human sewage and agricultural runoff	Improve uses of best-management practices to reduce pesticide inputs. Consider impact on pesticide inflows to the Delta as decisions are made among conveyance choices. Resolve irrigation-drainage policy disputes

water treatment to form the carcinogen bromate. Water managers seek to minimize the salinity in source waters. That is challenging when waters for human uses are drawn from an estuary, as in the Delta.

Salinity is a natural component of any estuary. Elevated, fluctuating salinity is of benefit to organisms that evolved in estuaries. The artificial stabilization of salinity, which has been undertaken in the Delta to maximize drinking water quality, may create habitat more suitable for invasive than for native species (Lund et al. 2007), a negative ecological effect.

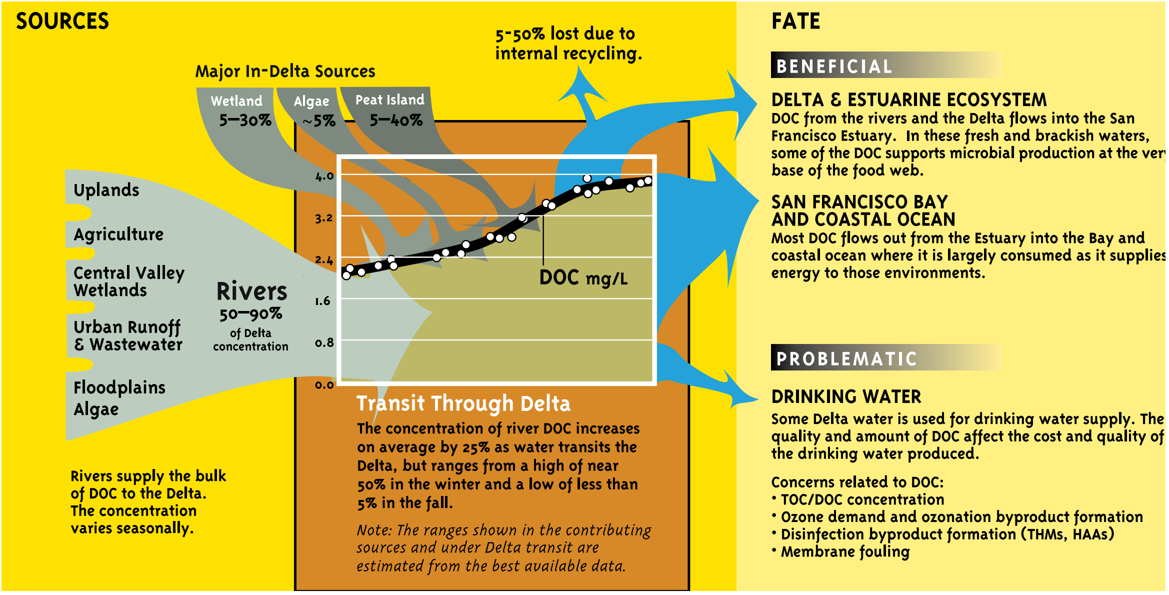
> Three-dimensional interactions among transport, mixing and residence times in the Bay-Delta ultimately determine salinity as well as the fate of other water quality constituents. Advances in understanding to date suggest that opportunities for creative solutions to salinity tradeoffs have and will continue to develop as details of these interactions are better understood.

Much has been learned about the coupling among hydrology, water chemistry and fishery ecology in the Delta. The system is a complex network of interconnected and tidally influenced channels. It is fortified by 1,100 miles of levees built to protect agriculture on the Delta islands and, increasingly, human communities. But the levees also simplify the physical character of the ecological habitat. The complex channel geometry created by the levees and channels interacts with the tides to affect transport, mixing and residence times of water in the Delta (Monsen, Cloern, and Burau 2007). The Delta is physically connected to the Bay (seaward) and to the rivers (landward). That connection is increasingly affected by an overlay of human management. Salinity is influenced by upstream flow regulation at the reservoirs and flow regulation within the Delta at various gates, barriers and export facilities. Management actions modify the timing of water flowing into the Delta and determine the proportional inflows from different sources. They also directly affect circulation patterns. However, it is now recognized that the twice-daily tides are also extremely influential, causing powerful flow reversals through much of the Delta that amplifies dispersive mixing in both directions. Geometric features of Delta waterways, such as bends, junctions, shallow water areas and levees all influence water transport and residence times. Improved understanding of Delta hydrology has led to new proposals for managing salinity in the system that perhaps can inform the potential conflict between keeping salinity low for drinking water and fluctuating salinity for native species.

Natural Organic Matter

Natural organic matter (NOM) in water is another critical consideration in water policy (Brown 2003). NOM comes from the natural biological activity within ecosystems. When transported in rivers or by tides, it links different elements of the landscape.

> Natural Organic Matter (NOM) comprises the dissolved and particulate material of biotic origin found in environmental systems, and it is an essential component of aquatic food webs. The same material is a source of disinfection byproducts when drinking water is treated with chlorine or when toxic algae are present. Thus, NOM is important to ecological systems, but it also adds both cost and a human health risk to treatment of drinking water. In addition, NOM influences the fate and effects of contaminants that pose ecological risks.



Rivers supply the bulk of DOC to the Delta. The concentration varies seasonally.

The concentration of river DOC increases on average by 25% as water transits the Delta, but ranges from a high of near 50% in the winter and a low of less than 5% in the fall.

Note: The ranges shown in the contributing sources and under Delta transit are estimated from the best available data.

DOC from the rivers and the Delta flows into the San Francisco Estuary. In these fresh and brackish waters, some of the DOC supports microbial production at the ver base of the food web.

Most DOC flows out from the Estuary into the Bay and coastal ocean where it is largely consumed as it supplies energy to those environments.

Some Delta water is used for drinking water supply. The quality and amount of DOC affect the cost and quality of the drinking water produced.

Concerns related to DOC:
- TOC/DOC concentration
- Ozone demand and ozonation byproduct formation
- Disinfection byproduct formation (THMs, HAAs)
- Membrane fouling

Figure 3.1. A conceptual model of the sources, transport and fate of natural organic matter (NOM), depicted as dissolved organic carbon (DOC), in the Bay-Delta. (Source: United States Geological Survey 2008)

NOM also carries with it contaminants such as pesticides or mercury (Bergamaschi, Kuivila, and Fram 2001). Figure 3.1 shows the complex sources and cycles of NOM in the Delta.

In some cases, association with NOM may increase contaminant exposure and uptake; in other cases, exposure is reduced. When water is treated for potable use, a small fraction of NOM may react to form disinfection byproducts (DBPs), which can cause cancer and therefore represent a public health concern. Some DBPs are regulated by the United States Environmental Protection Agency (EPA), and regulations have become more stringent as we have learned more about these substances.

NOM can be referred to either as total organic carbon, particulate organic carbon, or dissolved organic carbon, as defined by the method of analysis. This terminology does not capture the diverse mixture of thousands of different compounds that comprise NOM. For example, NOM is produced by local algal and microbial production, is a byproduct of decomposition, comes from animal metabolism and waste products, leaches out of soils, flows downstream in rivers and out of marshes, and is discharged from sewage treatment and industrial plants. The amount contributed by various sources varies by year, by season, and by event. Advanced analytical studies have shown that these compounds undergo numerous reactions in the water and degrade at varying rates. Different types of NOM have different ecological benefits and produce different types of DBPs.

Knowledge of the sources of NOM is critical to choices about sources of drinking water. During all seasons, approximately 50 to 90 percent of NOM in the Delta is contributed by the rivers (Bergamaschi et al. 2000), with concentrations determined by a combination of runoff timing and basin-wide biogeochemical processes. This river-borne material is, on average, more bioavailable (more useful ecologically) and reacts to form fewer DBPs (less dangerous) than material found elsewhere in the surface water system. Floodplains, urban runoff, and wastewater returns in the watershed also contribute NOM, although the relative importance of these sources is not yet known. Within the Delta, peat islands and tidal wetlands contribute NOM. Contributions from these sources peak at the same time as the watershed contributions and vary in their importance. Island drains contribute a greater proportion of NOM in early winter. Freshwater wetlands contribute a greater proportion from early spring into the summer.

Sedimentary particles in the water column affect water quality by adsorbing contaminants and nutrients as well as attenuating sunlight in the water column, thereby influencing plant growth. Nutrients and contaminants such as mercury and PCBs are primarily associated with sediment particles. The movement and fate of sediment determines the movement and fate of these contaminants. Therefore, changes in suspended sediment concentrations have implications for water policy.

Suspended Sediment

Suspended sediment is a natural component defining the quality of water. Suspended sediments are not a toxin, but they greatly influence both water quality and water policies. Historically, sediments accumulated in the Delta; it is a depositional environment. In modern water systems, suspended sediments carry many of the most dangerous contaminants. The fate of these toxins is affected by how, where and whether the suspended material deposits onto the bottom sediments and ultimately is buried. Recent measurements show that suspended sediment concentrations have declined since dam building began in the watershed because reservoirs capture and accumulate sediments (Wright and Schoellhamer 2004). The rivers no longer deliver as much new sediment to the Bay-Delta, but continue to pick up sediments in the Delta and transport them seaward. The result is erosion of accumulated sand and mud. This erosion has the potential to uncover and mobilize previously buried contaminants, such as dichlorodiphenyltrichloroethane (DDT) and PCBs. Historic sediment deposition has also created important intertidal and shallow subtidal habitat used by a variety of organisms from mudworms to waterfowl. Erosion of intertidal sediments will change habitats for these organisms. Many wetlands restoration projects depend upon natural sediment inputs to make up for decades of sediment loss or subsidence. Important questions exist about whether sufficient sediment is available to support such projects, or whether the contamination associated with those sediments will influence the success of the ecological restoration. In addition, changes in water turbidity and the distribution of turbid water in the Delta associated with changes in water management, have direct and indirect impacts on fish, invertebrates and plants in the Bay-Delta. A recent workshop reported that Delta smelt are preferentially found in turbid water. Reduced turbidity could contribute to further

Effects of declining suspended sediment concentrations could include:

- Reduced sediment supply for restoration of wetlands;
- Erosion and exposure of heavily contaminated sediments deposited historically in the estuary;
- Accelerated growth of aquatic plants in the Delta and nuisance algal blooms in the Bay; and
- Greater predation and less suitable habitat for native fish species.

declines in this threatened species. Finally, by allowing greater light penetration, decreased turbidity in parts of the Delta may account for increased growth of undesirable, submerged, aquatic vegetation (for example, *Egeria*) or undesirable phytoplankton (for example, *Microcystis*).

Selenium

> Selenium is a contaminant that occurs at high concentrations in irrigation drainage and this puts native species at risk, has the potential to harm human health (there are consumption advisories on some birds and fish) and will influence the future of agriculture in the western San Joaquin Valley. As selenium is recycled in the Delta and the Bay, it is transformed to a more bioavailable form by microorganisms, phytoplankton and aquatic plants. The recycled selenium is taken up by phytoplankton and then by the animals that consume these plankton. It is then passed on to predators. The species at greatest risk are those at the top of the food web, in particular bottom-feeding fish, such as sturgeon, and bottom-feeding migratory birds, such as scoters.

A massive reservoir of selenium exists in the soils of the western San Joaquin Valley associated with the salts that have accumulated there (Presser and Luoma 2006). Selenium poses a well-understood potential for ecological risks, but manifestation of those risks will depend upon policy decisions about the fate of irrigation drainage as well as decisions about water management that influence San Joaquin River inflows to the Delta and the Bay.

In the 1980s, refinery inputs of selenium to Suisun Bay were responsible for selenium contamination of the food web. Those inputs were reduced by the late 1990s, but much was learned about selenium in the process of investigating their influences. In general, selenium water column concentrations are not particularly high in either the Bay or the Delta. Nevertheless, selenium concentrations in some predators in the Bay are sufficiently elevated to threaten their reproduction. The dominance of the Sacramento River in the Delta seems to reduce food web contamination there under present conditions.

> A critical issue that merits greater attention is whether selenium contamination will increase if San Joaquin River inflows to the Delta and the Bay increase as a result of conveyance changes. Adaptive management (discussed in Chapter 8) provides an approach to monitor selenium contamination, address further scientific analysis of selenium in Bay-Delta food webs and could be a useful component of options for managing irrigation drainage.

Of particular concern in the Bay (and in the Delta, should conditions change) are bottom-feeding migratory waterfowl (scoter and scaup), and predators like sturgeon, Sacramento splittail, salmon (*Oncorhynchus* spp.) and Dungeness crab (*Cancer magister*). The origin of these ecological threats lies in the way that selenium is recycled within the Bay and perhaps the Delta. Bacteria and phytoplankton transform selenium to a bioavailable form in places where water flow is slow and the biological transformation has time to take place. The bioavailable selenium is then taken up by invertebrates, notably the overbite clam (*Corbula amurensis*), which seems to have a particularly good ability to accumulate selenium. The predators of the clams then absorb a particularly high dose of selenium with their food (Stewart et al. 2004).

Presser (1994) described the reproductive toxicity and deformities suffered by young birds and fish caused by selenium discharges into Kesterson National Wildlife Refuge in the 1980s, verifying the toxic potentiality of this contaminant in the system. Recent measurements show that selenium concentrations in predators captured in the Bay, like white sturgeon and Sacramento splittail, are sufficient to threaten similar levels of reproductive toxicity with these species (see, for example, Linville et al. 2002) despite the reductions in refinery inputs. Preliminary data suggest that selenium contamination peaks during the fall, correlating with when San Joaquin River water is detected in Suisun Bay. The strongest risks are to white sturgeon because of their population biology, and there should be concern about selenium effects on the endangered green sturgeon *(Acipenser medirostris)*. Selenium concentrations in migratory waterfowl are also high enough to affect reproduction, but more needs to be understood about these species.

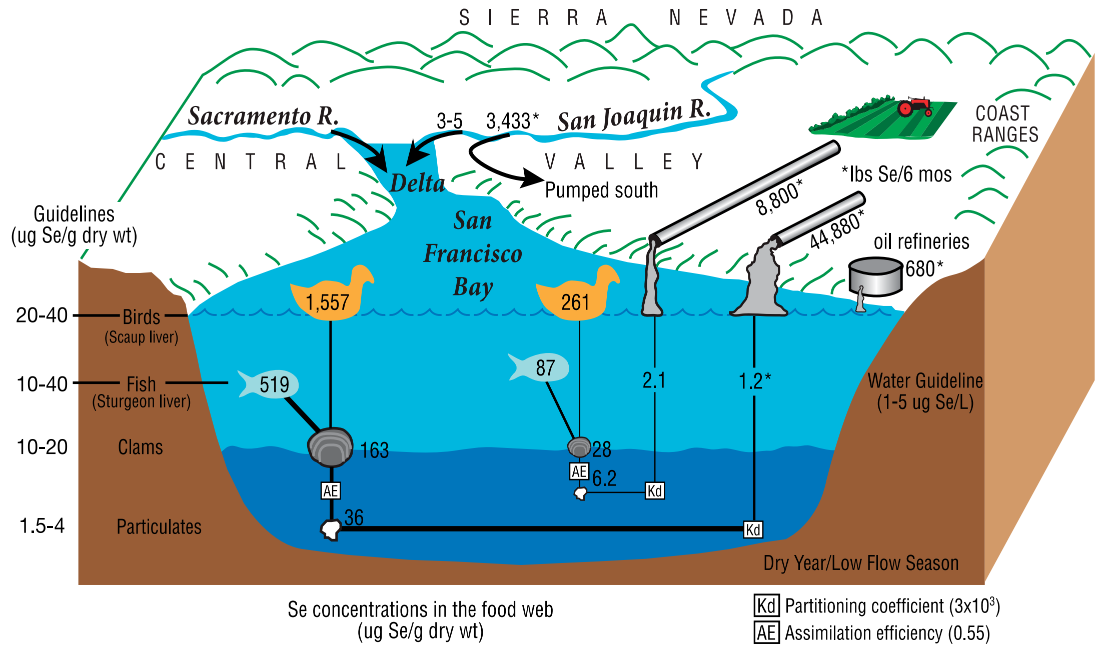


Figure 3.2. Distribution of selenium in Bay-Delta food webs under a proposed discharge from the San Luis Drain into San Francisco Bay. The historic major sources of selenium in the Bay-Delta are the inflow from the San Joaquin River and oil refineries around the Bay. The proposed discharge of irrigation water from the San Joaquin Valley into the Bay via the San Luis Drain would greatly increase the amount of selenium discharged into the Bay (see discharge pipes on the right side of the diagram). Projected selenium loads are based on the maximum discharge of treated drainage (the high estimate) or on the regulated discharge of treated drainage (the low estimate). Each estimated load results in a selenium concentration in water, a transformed concentration in particulate material, and a modeled value of bioaccumulated concentration in invertebrates, fish and birds. Projected concentrations (in µg/g dry weight) in sediment, invertebrates and predators can be compared with the guidelines for protective concentrations shown in the left-hand column; projected concentrations in water (in µg/L) can be compared with the guideline for protective concentrations shown in the right-hand column. (Source: Adapted from Presser and Luoma 2006)

One proposal for dealing with high selenium in agricultural drainage is to collect it and dispose of it into the North Bay via a pipeline. Analysis indicates that the ecological risks posed by this mode of disposal are high (see Figure 3.2; Presser and Luoma 2006). A similar analysis is necessary if ocean disposal is to be considered as an alternative. Investigation of the linkages between San Joaquin River inflows to the Delta and selenium contamination should be a high priority as conveyance proposals move forward.

To apply the concept of adaptive management to the selenium problem, a framework incorporating both monitoring and additional controlled studies is needed to determine the best disposal option for agricultural drain water. Long-term studies that track selenium in resident bivalves and selenium sources (for example, with stable isotopes) could allow evaluation of whether concentrations of bioavailable selenium are increasing as changes in water management are made. Greater understanding of specific selenium toxicity to birds and fish is also needed.

Pesticides

California has one of the largest agricultural economies in the world. In 2000, 188 million pounds of pesticide active ingredients were used statewide. Of that, 67 percent was applied in the Central Valley. Many of these pesticides enter rivers, streams and the estuary in complex mixtures. The timing of inputs is related to application rates, the timing of applications, runoff events and other transport processes (Kuivila and Jennings 2007). The classes of pesticides highly resistant to degradation (for example, DDT) were banned from use in the 1970s because of their toxicity to predatory birds and other long-lived organisms. But residues and breakdown products of many of these pesticides remain in sediments of the Bay-Delta system (Smalling, Orlando, and Kuivila 2007). Toxic effects have also been demonstrated from less persistent pesticides applied in recent decades (for example, organophosphates and carbamates). Observations of environmental toxicity associated with organophosphates and carbamates influenced a recent shift to another class of potent chemicals (pyrethroids). Ecological effects of pesticide contamination, thus, reflect the cumulative influence of pesticides used historically, as well as ongoing and constantly changing new pesticides.

> Pesticides are found in streams, rivers, the Delta, and San Francisco Bay. Agricultural inputs are dominant, but urban inputs are also significant in areas of high population density. The nature of pesticide contamination changes over time in response to changes in land use, agricultural practices and water quality policies. Impacts result from a legacy of pesticides that are recalcitrant to degradation and are stored in the sediments, as well as from modern pesticides that enter waterways in the runoff that follows rainfall events.

Over the past two decades, our understanding about the potential for pesticides to enter surface waters and, in some cases, harm aquatic life has improved considerably. For example, in the late 1980s and early 1990s, a variety of investigations revealed that toxicants discharged from rice fields were present in tributaries. In addition, tests performed on agricultural water leaving rice fields in the Colusa Drain verified that this mixture of chemicals was toxic to striped bass *(Morone saxatilis)* embryos and to ghost shrimp *(Callianassa californiensis)*. Pesticide use patterns also correlated with declines in the success of these species (Bailey et al. 1994). These and other investigations have resulted in changes in the type and manner of pesticide use in rice culture.

Studies of the distribution and effects of organophosphate pesticides (specifically diazinon and chlorpyrifos) sprayed during the winter rainy season on dormant crops like stone fruit and almonds showed that runoff during rainstorms introduced pulses of pesticide mixtures into the rivers (Bergamaschi, Kuivila, and Fram 2001). Toxicity was also shown in samples of water from the Sacramento River and several Delta sloughs during these times. This combination of toxicity testing and chemical analysis demonstrated that the amounts and the manner in which these pesticides were applied posed a threat to aquatic resources. Preventive best management practices, aimed at reducing the movement of the pesticides away from the site of application, included switching to a pesticide that adheres strongly with organic matter and soils (pyrethroids) or planting cover vegetation. In a test orchard, ground cover reduced pesticide runoff and toxicity by 50 percent, but the runoff was just as toxic when pyrethroids were used as when organophosphates were used (Werner et al. 2004). Soil particles and carbon are flushed into waterways during the rainy season, carrying the attached pyrethroids with them in a toxic form. Nevertheless, agricultural and urban users are increasingly switching to pyrethroids, including more potent forms of this class of chemical. Pyrethroids are now widespread in creeks and irrigation canals in the Central Valley, a large percentage of which now show toxicity in their sediments (Weston, You, and Lydy 2004). Inputs from urban areas are also significant. Systematic monitoring and assessment is needed to more fully understand distributions, trends, fate and effects of pesticides, especially pyrethroids, in the Delta.

Many toxicologists concur that one of the most important topics for investigation at this time is the fate and effects of pesticide mixtures that reflect the complex uses of pesticides in the Bay-Delta watershed (Werner et al. 2004). In addition to organophosphates and pyrethroids, herbicides are applied throughout the watershed and copper-containing herbicides are applied to control invasive aquatic plants in the Delta. The implications of pesticide mixtures for populations of native species are a very important research need. This is one issue where support for interdisciplinary studies has not kept pace with concerns; it is also an issue where adaptive management could improve the cost-effectiveness and relevance of both policy and future investigations.

> The link between agricultural and urban inputs of pesticides and toxicity has been demonstrated for at least two decades. It is clear that the problem is complex, including: a legacy of contamination; pulse inputs from ongoing applications; difficult analytical chemistry; complex biogeochemical cycling; and incomplete knowledge of links between toxicity and implications for wildlife populations. Nevertheless, pesticide toxicity remains an appreciated, but under-funded aspect of water quality—despite its much-cited policy implications for endangered species, water supply reliability and water quality in the Delta.

Mercury

Hydraulic gold mining and mercury mining combined to spread mercury contamination throughout much of Northern California from the 1850s through the mid-1900s (Alpers et al. 2005). The resulting contamination is a well-recognized policy concern.

Sophisticated environmental chemistry has been instrumental in separating real and perceived threats associated with this contamination. The sources of the mercury, the geographic distribution of contamination, and the biogeochemical controls on the methylation of inorganic mercury are much better understood now than they were a decade ago. Generation of methylmercury from inorganic mercury by bacteria in sediment is the origin of mercury threats to food webs and human health in the Bay-Delta. Where more methylmercury is generated (for example, in wetland sediments), food web contamination is often, but not always, greater. Careful studies have shown that the controls on mercury methylation include:

1. The amount of inorganic mercury available to methylating bacteria; and
2. The activity and distribution of the bacterial groups capable of methylation and de-methylation (Marvin-DiPasquale and Agee 2003).

> Concern about mercury stems from an historic legacy of widespread mercury contamination upstream of the Delta, high toxicity of methylmercury to food webs, threats to the health of people who consume certain species of fish from the watershed, and the possibility that restoration of wetlands could exacerbate the issue.

These controls are in turn influenced by many specific environmental factors in the sediment, including the presence of oxygen and sulfate, and the composition and quantity of organic material. Food web studies illustrate how methylmercury is taken up by plants at the base of the food web then magnified about four fold in concentration each time it is passed from prey to predator (see Figure 3.3).

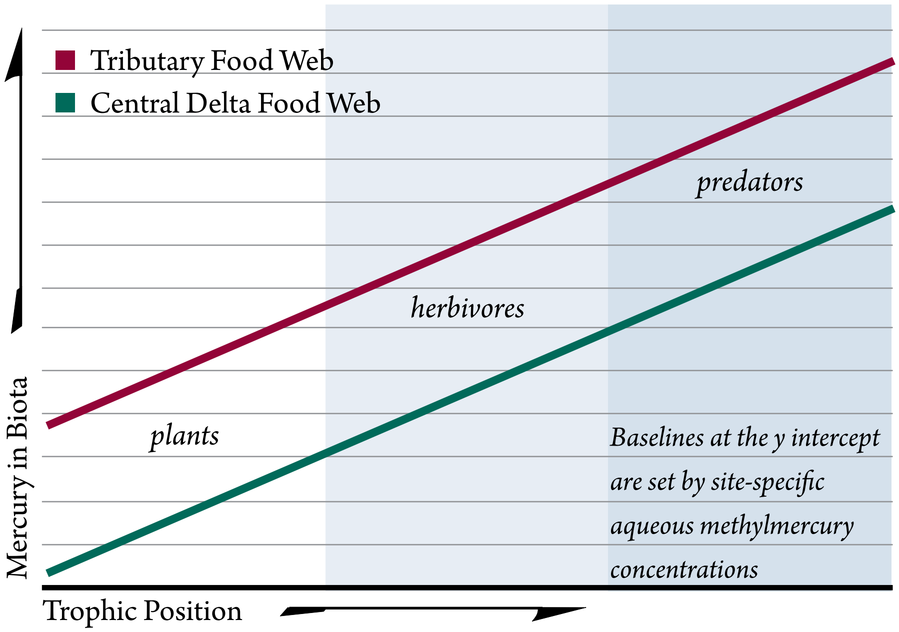


Figure 3.3. Schematic showing similar patterns of increasing mercury concentrations in biota with increasing trophic position (biomagnification) in tributaries and the Central Delta. Differences between locations appear to be established at the base of the food web and are correlated with site-specific aqueous methylmercury concentrations. (Source: Adapted from Marvin-DiPasquale et al. 2007)

Mercury-contaminated sediments are widely dispersed throughout the Bay-Delta (Heim et al. 2007), and fish are also contaminated with methylmercury in large areas of the Bay-Delta. Yet, concentrations observed in fish are not uniformly elevated. Hotspots of contamination in fish exist in areas such as the Cache Creek watershed in the northern Delta or the Guadalupe River watershed in the southern Bay. There are also areas, such as the Central Delta, where mercury contamination in the food web is less than expected. The sediments of the Central Delta wetlands are contaminated by mercury, but concentrations of methylmercury in fish are low. The Cosumnes River has elevated inorganic mercury inputs and is more contaminated than the Central Delta (see Figure 3.3). The most contaminated areas are the high-marsh plain of the Petaluma River salt marsh and other upland wetlands where both reactive mercury concentrations and microbial activity are high. Contamination with methylmercury on the high-elevation wetlands may be related to the frequency, duration and timing of floods.

> Mercury biomagnification occurs throughout the Bay-Delta, but the degree of contamination varies among different types of habitats. Important factors are site-specific methylmercury generation, flooding characteristics and perhaps water exchange in confined wetlands. Where contamination is the worst, some evidence exists that bird reproduction can be affected. High concentrations in some fish have also resulted in restrictions on human consumption of those species. It remains a concern that restoration activities could exacerbate the mercury problem, but it now appears that not all habitats are equally vulnerable.

Policymakers will have to consider carefully the potential for mercury contamination as the ecological restoration program moves forward. Research suggests that at least some wetland restoration could exacerbate mercury contamination. Understanding the specific characteristics of each restoration site as influenced by the restoration project's design could inform decisions about how to minimize the risk. Any increase in methylmercury generation could also result in expanded fish consumption advisories and health threats. Pregnant women are currently advised by local regulatory agencies not to eat large striped bass caught from the Delta. That health risk will become greater if contamination increases or expands to more species.

Legacy and Emerging Issues

No short summary can cover the myriad of water quality issues in this complex and changing arena. The Delta watershed covers over 40 percent of California, and the populations of the Sacramento and San Joaquin Valleys are projected to increase by nearly three million people by 2025 (Johnson and Hayes 2004). Population growth, traditional activities and new technologies will all make the goal of improving water quality more of a challenge, as will the trend toward greater urban, suburban, or industrial land uses. As the population grows, inputs from some types of unregulated chemicals, such as pharmaceuticals, personal care products, flame retardants and prescription drugs, are likely to increase as well. For example, polybrominated diphenyl ethers (PBDEs) are flame retardants found in many household and commercial products. PBDEs are of concern because of their chemical similarities to the chlorine-based pesticides and commercial chemicals (for example, PCBs) that cause disruption of reproduction in predator species. PBDEs are found in high concentrations in the Bay-Delta food webs compared to elsewhere in the world (Hoenicke et al. 2007). But neither the toxicological nor the ecological significance of these chemicals is well understood.

Legacy chemicals remain a concern in the watershed. While PCBs were banned in the 1970s and concentrations are declining in the Bay-Delta, the declines are much slower than in many other systems (Davis et al. 2007). Unremediated hotspots of contamination seem to be the primary sources. Concentrations are near the threshold at which they might affect reproduction in predatory birds, but the primary concern is the effects on human health from consumption of contaminated fish. PCB contamination seems to be most concentrated in the Central and South Bays and therefore may be less significant in the Delta than elsewhere.

There are also responses to chemicals that have not been linked to any particular water quality cause, but may be a result of exposure to complex mixtures of contaminants. For example, immune suppression in salmon is linked to exposure to low concentrations of toxicants that act synergistically. Neurotoxic responses to copper and other chemicals can disrupt homing behavior or behavioral functions in migratory organisms like salmon. Certain man-made substances act like hormones and can disrupt endocrine function and affect the ability of species to reproduce. For example, Williamson and May (2002) analyzed four hundred adult Chinook salmon *(Oncorhynchus tshawytscha)* fin samples from the Sacramento and San Joaquin Rivers. They found that 38 percent of the male salmon exhibited complete sex reversal, as indicated by the presence of ovaries expressing a Y-chromosome specific marker. Suspected causes include hormones in agricultural runoff, certain pesticides and sewage effluent, but investigation of both the problem and its causes are just beginning. Science has not yet been able to demonstrate the significance of most emerging sources of potential toxicity but, given the toxic responses in resident fish species from unknown causes (Bennett 2005; Whitehead et al. 2004), they should not be ignored.

Summary

The message from the biota and from detailed chemical studies is that water and sediment contamination is a stressor of concern in the Bay-Delta, although the contribution to declines in the populations of native species remains unquantified. The greatest certainty for the future is that there will be change and surprises, due to linked interplays between water quality and water policy. The challenge for science in this situation is to anticipate and track environmental change as well as understand causes. Flexible, informed management seems the most effective policy approach to addressing such a future. Adaptive management and ongoing rethinking of our monitoring and applied research are examples of how such flexibility can be implemented (see for example, Table 3.2).

Table 3.2. Examples of Water Quality Needs in a Changing Future

Scientific and Management Community
• Maintain a vigorous scientific community that is able to respond adaptively to changes and challenges in the Bay-Delta system. • Support ecologically based toxicology because many of the constituents, exposures and outcomes we are trying to manage are not simply load-related but are the result of complex environmental processes. • Mine existing monitoring data for evidence of important water quality drivers and trends. • Build and continuously update and improve linked hydrologic and biogeochemical models across the system, and challenge them with monitoring data. • Develop a framework that encourages both applied research nested within monitoring programs, and evaluations that examine relationships between water quality and fish species declines. • Promote research and monitoring programs that enable meaningful interactions with water users such as farmers and urban communities.
Monitoring Needs
• Build in mechanisms that assure timely and diverse analyses as well as publication of monitoring data as it is collected.* • Conduct synoptic campaigns to identify spatial and temporal variability. • Co-locate hydrodynamic and water quality constituent measurements in the Bay-Delta. • Sample at frequencies appropriate to the rates of change in hydrology and concentration. • Identify and capture infrequent events in targeted monitoring programs. • Monitor suites of chemicals that are indicators of major biogeochemical processes, and build long-term records. • Develop tiered and strategic approaches for analysis of water quality parameters. • Co-locate biological and water quality monitoring sites and times. • Develop a program that assesses sub-lethal and interactive effects of contaminants. • Develop a program to monitor and predict exposure to emerging contaminants such as human and veterinary pharmaceuticals, flame retardants, plasticizers, cleaning products and other compounds with potential adverse environmental effects.

*The San Francisco Estuary Institute's *Pulse of the Estuary* is an excellent example of how such analyses can be targeted to policy and management of the system.

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4. Aquatic Ecosystems

Wim Kimmerer,[1] Larry Brown,[2] Steven Culberson,[3] Peter Moyle,[4] Matt Nobriga,[3] Jan Thompson[2]

We live in a time of rapid change and rapid discovery in ecosystems of the region. This discovery is changing how we view the Bay-Delta system and its responses, even as the system itself is changing. Knowledge is accumulating rapidly through field studies, laboratory experiments, modeling and analysis of data from a large suite of long-term monitoring programs. Yet key questions central to management and to the future trajectory of the ecosystem remain unanswered.

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This chapter describes the current state of science for the aquatic ecosystem of the upper San Francisco Estuary. It emphasizes processes in the Sacramento-San Joaquin Bay-Delta as part of a habitat continuum between rivers and the Pacific Ocean. Because of the rapid development of the science, this report will soon be overtaken by new discoveries. In addition, with over 500 scientific publications on the estuary in the last decade, this chapter can provide only some examples of recent developments rather than a thorough review. We have therefore chosen to focus on the upper estuary, and to emphasize recent developments on topics relevant to management. We rely principally on published work, using research in progress to indicate potential future directions.

The state of the science in the Bay-Delta is essentially the state of the scientific community's view of the ecosystem. This view has shifted substantially in the last two decades (Lund et al. 2007, Appendix A) because of changes in the legal and societal framework, the multiple problems besetting the estuary, and the breadth of disciplines and backgrounds of the scientists working on the problems. Scientists previously viewed the Delta in isolation as a network of river channels, with striped bass as the key species of interest. The current scientific perspective is broader and more holistic. It conceives of the Delta as part of an estuary with close connections to the watershed and the ocean, numerous species of concern, and a rich and complex physical and biological structure.

There is broad agreement that the Delta is in poor condition. In describing the state of the ecosystem, however, we avoid the term "ecosystem health," which, as a metaphor, implies a normative state that does not exist. As long as there is water, there will be an aquatic ecosystem with a distinct structure and function; it just might not do what society wants. Thus the state of the ecosystem has value only in relation to societal values, particularly the extent to which it provides ecosystem services. These include extractive services such as fishing and water diversions, active and passive recreation, and aesthetic or ethical services, such as maintenance of natural landscapes and endemic species (Daily 1999). The Delta no longer delivers these services as it once did. Science has an important role in explaining why this is happening.

Key Themes for the Ecosystem

Three themes that underlie this chapter are key to how we learn about the estuarine ecosystem and the context in which that learning occurs:

1) the ecosystem is temporally variable—tides rise and fall, floods come and go, species migrate in and out, and this variability is essential to its function;
2) the ecosystem is spatially variable and is dominated by several spatial gradients that are also essential to ecosystem function; and
3) monitoring and research help us understand the ecosystem, but our understanding will always be incomplete and will always lag behind changes in the system.

Temporal Variability

Temporal variability has been investigated using data from numerous monitoring stations and natural records of past conditions (see Figure 4.1). Variation in freshwater flow is the most important natural driver of change. Freshwater flow in the rivers varies substantially over time-scales from days to millennia, with evidence for long, deep droughts in the prehistoric record.[1] Variation in flow between years has important consequences for species abundance in the estuary (Jassby et al. 1995), and the seasonal oscillation between winter wet and summer dry conditions, together with seasonal and

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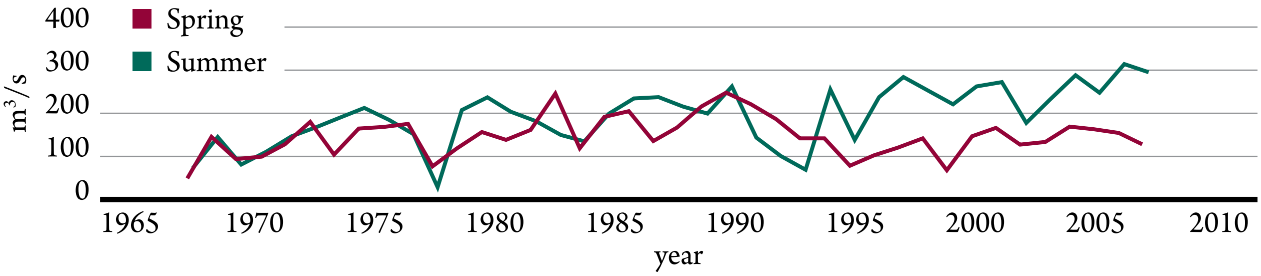
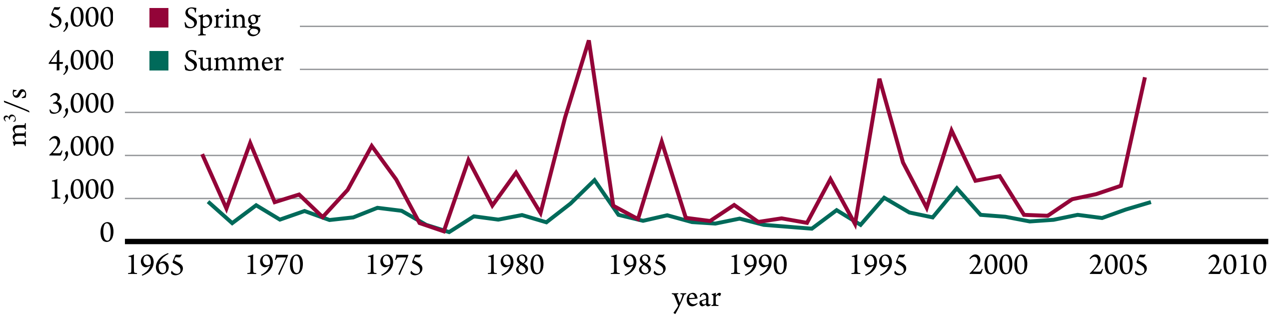
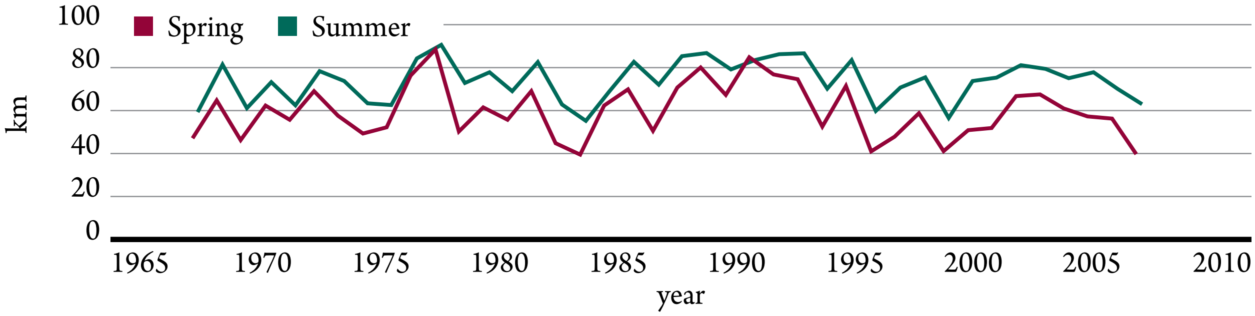
[1] Discussed in greater detail in Chapters 2 and 6



Delta Export Flow. Measured in cubic meters per second (m^3/s).



Delta Inflow. Measured in cubic meters per second (m^3/s).



X2. Measured in kilometers from the Golden Gate.

Figure 4.1. Changes in Delta inflow, export flow, and X2 over time. Delta inflow and export flow are measured in cubic meters per second (m3/s) and X2 is measured in kilometers from the Golden Gate. Inflow and export flow are annual means by season. (Source: IEP Dayflow accounting program 2008)

daily patterns of sunlight and temperature, set the stage for biological cycles. Notwithstanding the ecological importance of variation in freshwater flows, the most obvious cause of daily variation in the estuary is the tidal cycle. Variation due to tidal flows must be accounted for in nearly all investigations of estuarine ecology.

The history of the ecosystem is one of high short-term variability (for example, year-to-year variation in fish abundance) overlying a number of long-term trends (for example, increasing numbers of introduced species). Many of the longer-term trends reflect a few brief periods of substantial change (Examples in Figure 4.1). Key among the long-term trends are increasing water clarity, species introductions and resulting changes in ecosystem function, decreases in phytoplankton production in Suisun Bay and the Delta, and decreases in abundance of fish in the northern estuary.

Future sources of temporal variability include deliberate human actions to resolve conflicts as well as the projected influence of changing climate and rising sea level. On a time-scale of decades, large changes are likely to occur through regional human activities, such as the rising demand for water and changes in the configuration of the Delta. Large-scale levee failures due to earthquakes and other factors will likely result in many islands being irreversibly flooded.

Spatial Variability and Gradients

The Delta is an integral part of the Bay-Delta system; a transition zone between inflowing rivers and the ocean. Gradients in elevation, freshwater flow, and tidal influence set the stage for a host of associated physical, chemical and biological gradients (see Figure 4.2). Most notable among these is the strong gradient of increasing salinity as one moves from the rivers to the ocean. Each estuarine species has its own distribution with regard to salinity. These distributions are determined by each species' physiological tolerance for salt, how it responds to estuarine circulation and how it responds to other species such as predators (Kimmerer 2004; 2006). Distributions can change seasonally and with the life-stage of the species.

An additional kind of gradient is the declining influence of many environmental factors with distance. For example, the effects of export pumping are strong near the pumps in the South Delta but weaker far from the pumps in the North and West Delta. In contrast, connections among different regions are mediated by movements of water, substances and organisms. These connections blur the boundaries between regions. For example, the rise and fall of ocean tides is felt far into the Delta, and conditions in the ocean can affect abundance of fish such as salmon that migrate between ocean feeding grounds and freshwater spawning grounds.

Thus, while we can consider the river–estuary system as a continuum of habitats, we can also legitimately isolate portions of it for research, management and restoration. This is one reason for the emphasis on the Delta: it is part of a large, important ecosystem and at the same time the focus of the conflict between water use and ecosystem protection.

Additional, smaller-scale spatial variation and gradients also exist within the Delta. For example, the residence time of water varies greatly between open channels and dead-end sloughs, and habitat for various kinds of fish is distributed very unevenly throughout the Delta. The relative importance for ecological processes of river flow, export flow, and tidal flow vary with location in the Delta (Kimmerer and Nobriga 2008).

Monitoring and Research

We learn about the ecosystem in three main ways. *Monitoring* tracks temporal changes in system properties and allows an assessment of the state of the system. *Laboratory and field research* is used to detect mechanisms, test or compare alternative hypotheses and determine parameter values for models. *Con-*

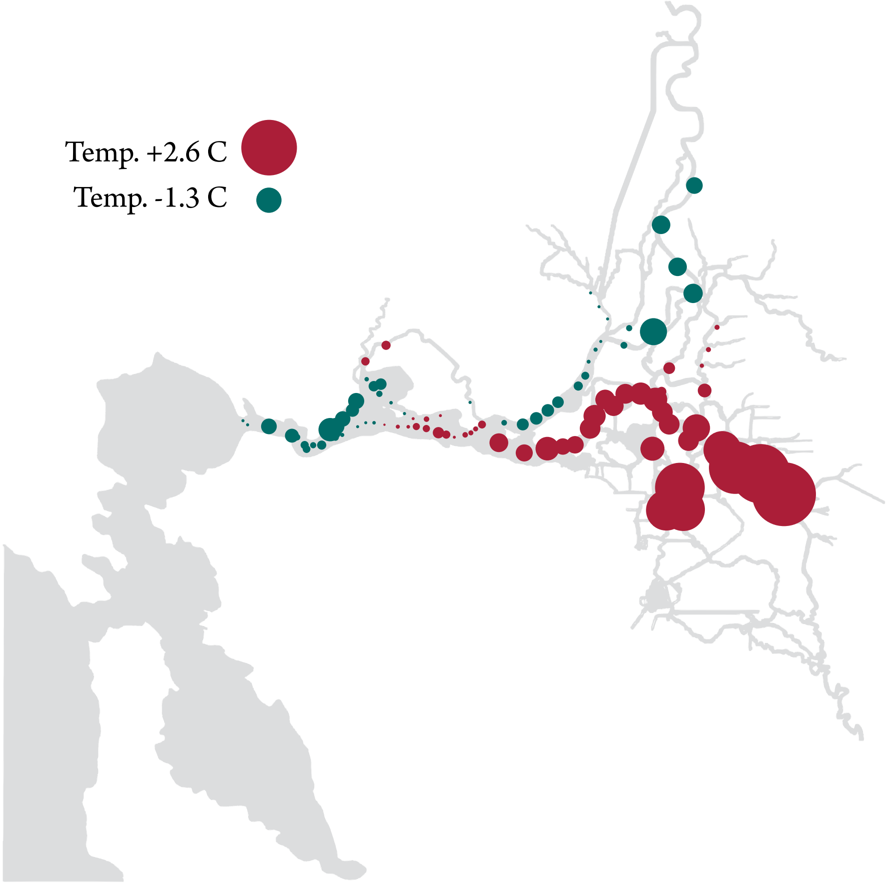


Figure 4.2. Gradient in temperature in the Delta during September based on data gathered during midwater trawl sampling from 1990 to 2001. Many other physical attributes of the Delta also show strong spatial gradients. Red dots show places where temperature was higher than the overall mean for the Delta and green dots show places where temperature was lower than the mean. The size of the dot indicates how much higher or lower the temperature was. The legend in the upper left of the figure gives a scale for the dots in degrees centigrade (i.e., -1.3 C is the lowest temperature and +2.6 C is the highest temperature). From the figure it is apparent that in September the San Joaquin is very warm and cools as it moves toward its confluence with the Sacramento whereas the Sacramento is cool and warms toward the confluence. Suisun Bay and Carquinez Strait are cooler than the Delta. (Source: Kimmerer 2004)

ceptual and simulation modeling are used to organize our understanding about the system and to examine the consequences of alternative concepts or potential management actions. Each of these components is crucial to the success of the scientific enterprise in providing information useful for management.

Monitoring got an early start in the Bay-Delta. Regular salinity monitoring began in 1920, followed by more comprehensive monitoring in the rivers and the estuary by several state and federal agencies, notably the United States Geological Survey. More integrated monitoring in a portion of the estuary began in 1970 under the auspices of the Interagency Ecological Program (IEP), and the San Francisco Estuary Institute's Regional Monitoring Program (RMP) was started in 1993. Temperature, salinity and other properties in the estuary are now recorded by continuous monitoring stations.

Shipboard monitoring programs collect samples for water quality, phytoplankton, zooplankton, benthic communities, and the distribution and relative abundance of fish.

The level and quality of monitoring in the Bay-Delta ecosystem is high, but monitoring alone is inadequate for understanding how the system functions. This was realized early on, and broadly based estuarine research was initiated in the 1960s by the California Department of Fish and Game and IEP workers and their collaborators (Stevens 1966; Turner and Kelley 1966; Arthur and Ball 1979). However, it was only with the substantial infusion of research funds through the CALFED Ecosystem Restoration Program and Science Program that a concerted effort was begun to understand the system, rather than simply document trends. This has been supplemented more recently with the IEP investigations into the Pelagic Organism Decline (POD) (Sommer et al. 2007). Research on the Delta is typically multidisciplinary, with numerous and productive interactions among scientists, engineers and agency staff.

Even with the current high level of monitoring and research, inherent limitations exist in our ability to understand how the ecosystem responds to change, whether natural or man-made. First, biological populations change through dynamic processes of birth, development, growth, death and migration. Yet, most data on populations are from monitoring of distribution and abundance over only part of the life-cycle. Second, water in the estuary is turbid, rendering the aquatic ecosystem effectively invisible. We observe it mainly using nets, which sample a very limited part of the system and lose important information about its spatial structure. This sampling is also expensive, and is never sufficient to provide reliable estimates of the abundance of key species. Third, the system is always changing. New species invade and alter food web structure. More refined data analyses change our understanding of important processes (Jassby et al. 2002). Changing management interests alter the emphasis of monitoring, research and analysis—for example, the change from emphasis on striped bass *(Morone saxatilis)* to Delta smelt *(Hypomesus transpacificus)*. Finally, patterns in a complex and variable system can be detected only over time, with a lot of data and always with considerable uncertainty. As a result, understanding often lags far behind ecological change.

Food Webs

All ecosystems capture nutrients and solar or chemical energy, transform energy and nutrients among living and non-living forms, and consume the energy in metabolism. Energy for growth, metabolism and reproduction of virtually all organisms comes from the sun through photosynthesis by plants. This energy is supplied in the form of organic matter to aquatic ecosystems either directly from phytoplankton or other plants, or indirectly from exogenous sources (for example, marshes, farms). Energy and nutrients are transformed by the feeding of organisms within the estuarine food web. How these transformations occur, and how they are influenced by human activities and the particular geographical and physical context of the estuary, are the principal topics of estuarine ecological research. Research on the food webs and habitats supporting fish in the estuary has been particularly vibrant in the last decade.

Organic Matter Supply

Most of the organic matter in the Delta is non-living material, mostly dissolved in the water, delivered by rivers from upstream (Jassby et al. 2000). However, most of that non-living organic matter is of low food value to consumer organisms in the Delta (Sobczak et al. 2002). Furthermore, to be useful as food to larger consumers such as fish, the energy content of this dissolved organic material must first be consumed by bacteria and other very small organisms, leading to inefficient energy transfer (Sobczak et

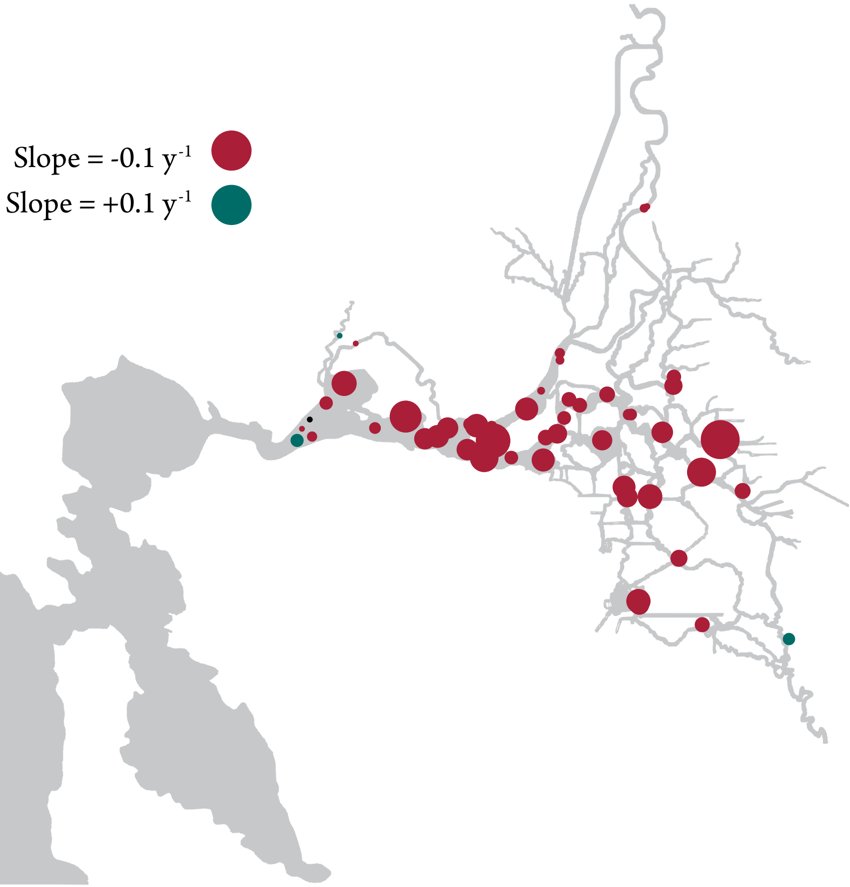


Figure 4.3. Long-term changes in turbidity in the Delta and Suisun Bay. Turbidity has important effects on ecosystem function. Red dots indicate decreases in turbidity over time and green dots indicate increases in turbidity. The size of the dot shows the relative increase or decrease in turbidity. The legend in the upper left of the figure shows the relationship between dot size and the rate of change in turbidity with time. (Source: Kimmerer 2004)

al. 2005). Although much less abundant than the dissolved organic material, phytoplankton (microscopic aquatic plants) is the main source of organic matter for the food webs that support fish (Müller-Solger et al. 2002; Sobczak et al. 2002).

The growth of phytoplankton in the Bay-Delta is often limited by light because high concentrations of suspended sediment make the estuary very turbid, and light often does not penetrate far into the water (Cloern 1999). Because light penetration is so low, phytoplankton grows most abundantly in shallow areas, and deep channels receive a subsidy of phytoplankton from these shallow productive areas (Lucas et al. 1999; Lopez et al. 2006). Water in the Delta has become less turbid over the last three decades (see Figure 4.3). This is because rivers are now carrying less sediment into the estuary (Wright and Schoellhamer 2004), and invasive aquatic weeds are filtering sediment out of water in the Delta. This has led to an increase in phytoplankton growth rate, which may have contributed to a recent increase in the mass of phytoplankton in the Delta (Jassby 2008).

Nutrient concentrations in Delta water are high enough that they probably do not limit phytoplankton growth (Jassby et al. 2002). However, low growth rate of diatoms (a kind of phytoplankton important in aquatic food webs) has been linked to high concentrations of ammonium, a form of nitrogen released by sewage treatment plants (Dugdale et al. 2007). Additionally, a decline in chlorophyll concentration in the Delta in the early 1990s was associated with a decline in phosphorus inputs from sewage treatment plants and in total phosphorus in the Delta (Van Nieuwenhuyse 2007), suggesting that nutrient concentrations do influence phytoplankton growth. These results appear to conflict with a moderate increase in phytoplankton production (as measured by chlorophyll) in the Delta in the last decade (see Figure 4.4; Jassby 2008). Thus, the ecosystem-level effects of variation in nutrient concentrations are unclear. In the particular case of ammonium, an improvement in sewage treatment would reduce the rate of input, but at this stage the response of phytoplankton would be difficult to predict, and potential effects on fish are unknown.

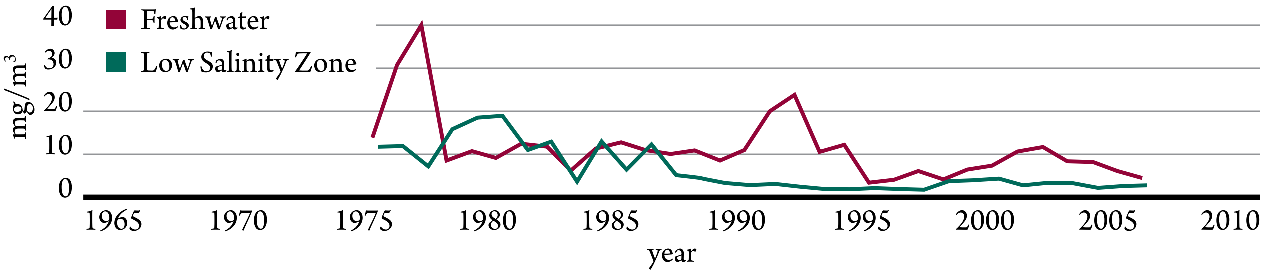
Phytoplankton production in the Delta declined 43 percent between 1975 and 1995 (Jassby et al. 2002) to about 35 percent of the median production among the world's estuaries, although it has since increased (Jassby 2008). The first stage of the decline occurred in the 1970s due to unknown causes, and the second occurred in 1987 in the western Delta and Suisun Bay and was associated with the introduction of the overbite clam (*Corbula amurensis*) (see "The Benthic Pathway" below). Most of the phytoplankton input to the Delta is from local production; of the total, about 68 percent was buried or consumed within the Delta each day and another 23 percent was removed by in-Delta agricultural and export diversions, based on data from 1975 through 1993 (Jassby et al. 2002).

Microcystis aeruginosa is a colonial cyanobacteria (formerly called "blue-green algae") that forms intense blooms in the Delta. These blooms can produce toxins, and may be interfering with feeding by zooplankton (Lehman et al. 2005). The more or less simultaneous increase in *Microcystis* blooms with the decrease in pelagic fish may be coincidental, but the link is being investigated.

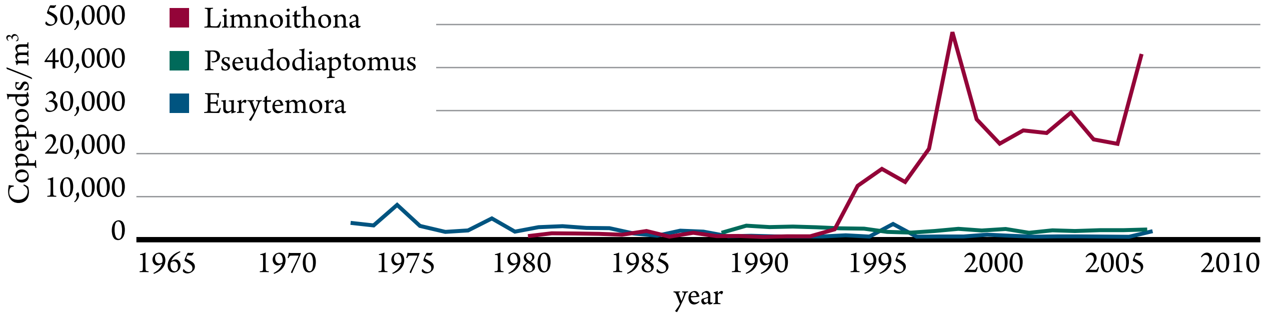
The Zooplankton Pathway

Phytoplankton production supplies energy and nutrients to small organisms including bacteria and zooplankton. Bacteria, which consume dissolved organic matter, are key elements of all aquatic food webs, but in the Bay-Delta they have been studied only in the low salinity zone. Bacteria are small but so abundant in the low salinity zone that their total mass in the estuary is about ten-fold higher than that of fish. Bacteria there consume more organic carbon than is produced locally by phytoplankton (Murrell et al. 1999), implying an organic carbon subsidy from another part of the system. Bacteria can be consumed by small single-celled organisms such as ciliate protists, and by the overbite clam (Werner and Hollibaugh 1993). Research is ongoing on the importance of bacteria and ciliates in the food web.

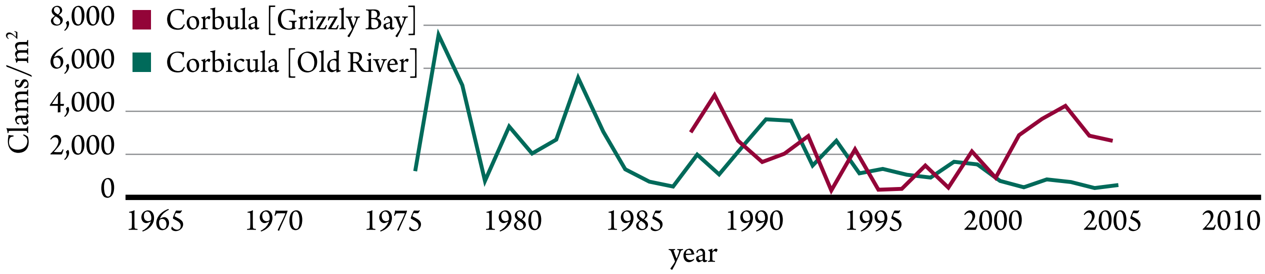
Zooplankton comprise a very broad assemblage of animals ranging from microscopic to a few millimeters in size. Nearly all of the fish species of the estuary have a larval stage that is both part of and a predator on the zooplankton, particularly on copepods. Many fish continue to eat zooplankton as juveniles or adults. As in other estuaries, most of the zooplankton of the San Francisco Estuary are small (less than one half millimeter long) including rotifers and the nauplius larvae of copepods (Orsi and Mecum 1986). Larger zooplankton (approximately one to twenty millimeters long) include cladocerans in freshwater, and copepods, mysid shrimp and the larval forms of benthic invertebrates and fish throughout the estuary. Predatory gelatinous plankton such as jellyfish are common in harbors and channels (Rees and Gershwin 2000), but are not common in the open waters of the estuary, although they have become seasonally abundant in Suisun Marsh in recent years.



a. Changes in chlorophyll concentrations in the Delta and Suisun Bay over time. Chlorophyll, measured in milligrams per cubic meter (mg/m3), is the mean value from March through October for each year in each region. (Source: IEP Environmental Monitoring Program 2008)



b. Changes in the abundance (copepods per cubic meter) of three copepods—*Eurytemora*, *Pseudodiaptomus*, and *Limnoithona*—over time in the low salinity zone of the Delta. *Eurytemora* abundance is the mean value from March through May for each year. *Pseudodiaptomus* abundance is the mean value from June through October for each year. *Limnoithona* abundance is the mean value from March through October for each year. The low salinity zone is the region of the Delta with a mean salinity of 0.5 to 6 practical salinity units, excluding the South Delta. (Source: IEP Environmental Monitoring Program 2008)



c. Abundance of overbite clam (*Corbula amurensis*) in Grizzly Bay and the Asian clam (*Corbicula fluminea*) in Old River over time. Overbite clam and Asian clam abundance (clams per square meter) is the mean value from March through October for each year in each region. (Source: IEP Environmental Monitoring Program 2008)

Figure 4.4. Changes in chlorophyll concentrations, copepod abundance and clam abundance in the estuarine ecosystem over time.

Rotifers and larger zooplankton have declined in abundance in parallel with the phytoplankton (compare chlorophyll and copepod panels, Figure 4.4). Zooplankton are generally considered consumers of estuarine phytoplankton, particularly diatoms in the freshwater regions of the Delta (Müller-Solger et al. 2002). However, in both brackish (Bouley and Kimmerer 2006; Gifford et al. 2007) and saline (Rollwagen Bollens and Penry 2003) regions of the estuary, several zooplankton species feed heavily on ciliate protists, implying a more complex and less efficient food web than previously believed. Every quantitative study of reproduction or feeding by zooplankton in the estuary has demonstrated food limitation (Müller-Solger et al. 2002; Kimmerer et al. 2005).

The species composition of the zooplankton has changed over the thirty-five years of monitoring, particularly in the low salinity zone. Before 1987, the mysid shrimp *Neomysis mercedis* was the most abundant large zooplankton in the upper estuary and an important food item for young fish such as striped bass. After the overbite clam was introduced, the abundance of *N. mercedis* declined sharply, presumably because the overbite clam competes with *N. mercedis* for food. Other mysid shrimp species that have been introduced to the Bay-Delta are smaller and less abundant than *N. mercedis* was, and therefore provide less food to fish (Feyrer et al. 2003). Introduced amphipod crustaceans are an alternative prey for fish that formerly consumed mysids (Feyrer et al. 2003; Toft et al. 2003). The abundance of amphipods is not monitored effectively, however, which represents a significant gap in our understanding of the estuarine food web.

Copepod species composition has changed radically through declines in the abundance of some species and introductions of new species largely from turbid estuaries of mainland Asia (Kimmerer and Orsi 1996; Orsi and Ohtsuka 1999). The tiny, introduced copepod *Limnoithona tetraspina* is now the most abundant copepod in the upper estuary (see Figure 4.4; Bouley and Kimmerer 2006). These copepods feed only on moving cells (not diatoms), and are small and sedentary so they are not important food for many fish species.

The Benthic Pathway

Bottom-dwelling (benthic) organisms differ fundamentally from those that live in the overlying water in that they have limited ability to move. Most of them have planktonic larvae, but once these larvae settle to the bottom they do not move far if at all. This means that their response to changes in salinity is qualitatively different from that of the plankton. Organisms that live in the water column (such as the plankton) can move with the water and are not subjected to rapid changes in salinity. In contrast, benthic organisms can be bathed in water of very different salinity at each end of the tidal cycle, and long-term exposure to unfavorable salinity can interfere with feeding or be lethal. Distributions of benthic organisms change in response to seasonal and interannual changes in salinity mainly through die-back and recolonization.

Most of the energy produced by phytoplankton is consumed by benthic organisms, principally by two species of clam (see Figure 4.4). The overbite clam, first reported in the estuary in 1986, is the most abundant bivalve in brackish water. The Asian clam *Corbicula fluminea*, first reported in 1945, is the most abundant in freshwater. Although other benthic species can be important at some locations and seasons, these clams are overall the most important in consuming plankton and in the transfer of contaminants through the food web. Their distributions overlap at very low salinity, and the zone of overlap moves as salinity moves landward in the dry season and seaward in the wet season.

The overbite clam lives within the top few centimeters in all sediment types and all water depths in the estuary. It ranges from above the San Joaquin-Sacramento River confluence in dry years (Hymanson 1991) through Central and South San Francisco

Bay. Abundance can exceed 10,000 per square meter and usually peaks in summer or fall (Hymanson et al. 1994). Abundance in the shoals of San Pablo Bay declines during extended periods of high freshwater flow, and drops to zero in the winter due to predation by migratory ducks (Poulton et al. 2004). A similar seasonal pattern has been observed in Grizzly Bay (Thompson 2005). White sturgeon *(Acipenser transmontanus),* Sacramento splittail *(Pogonichthys macrolepidotus)* and Dungeness crab *(Cancer magister)* also eat overbite clams (Stewart et al. 2004).

Overbite clams reproduce in spring or fall when food is sufficient (Parchaso and Thompson 2002), and larvae stay in the plankton about two to three weeks, dispersing throughout the estuary (Nicolini and Penry 2000). The overbite clam can consume phytoplankton, bacteria and copepod larvae (Werner and Hollibaugh 1993; Kimmerer et al. 1994). The co-occurrence of the decline in phytoplankton (see Figure 4.4) with the invasion of the overbite clam suggests that the clam is over-grazing the system: grazing rates in Grizzly Bay are often at least as fast as phytoplankton growth rate (Thompson 2005; Cloern and Nichols 1985).

The Asian clam is ubiquitous in the Delta and in Suisun and San Pablo Bays during wet years (Hymanson et al. 1994). Abundance of young clams can exceed 200,000 per square meter during high settlement periods in Franks Tract, a submerged island (Lucas et al. 2002). Asian clams are most abundant in the Central Delta; they limit phytoplankton biomass in Franks Tract (Lucas et al. 2002), whereas low abundance of clams on Mildred Island allows it to be a phytoplankton Source for the surrounding channels (Lopez et al. 2006).

Taken together, these clams exert strong control over the phytoplankton and possibly zooplankton and other small organisms throughout the northern estuary from the Delta to Suisun and possibly San Pablo Bays. Because of their overlapping range, there are few places without clams, and many places where phytoplankton cannot accumulate because of clam grazing. Thus, together they limit the capacity of the ecosystem to produce food for fish and other organisms.

Apart from their roles as consumers of phytoplankton, overbite clams play a key role in the cycling and bioaccumulation of contaminants in the food web. Overbite clams accumulate selenium from their food to concentrations sufficient to affect reproductive success in their predators (Stewart et al. 2004).[2] Overbite clams are important food for diving ducks; they are easier to forage upon and more nutritious than other prey bivalves, but their thicker shell reduces digestibility (Richman and Lovvorn 2004). This, together with depletion of clams during summer (Poulton et al. 2002), may result in food limitation for migratory ducks.

Fish

Many of the Estuary's fish are introduced species (Dill and Cordone 1997), particularly in fresh to low salinity habitats (Moyle 2002; Brown and Michniuk 2007), and less so in the marine environment. Many estuary-dependent fish species have declined in abundance during the approximately three to four decades of monitoring (see Figure 4.5). Although these declines could be seen as continuous, many consist of short periods of rapid decline, and some show periods of increase. For example, abundance of young striped bass declined steeply around 197, probably because of an increase in mortality of older adults due to changes in ocean conditions (Kimmerer et al. 2001). Delta smelt abundance declined in the 1980s but was back up in the mid-1990s, both for unknown reasons.

Many of the estuarine-dependent fish species respond positively to freshwater flow. Numerous reasons for the relationships between fish abundance and freshwater flow have been discussed. The rea-

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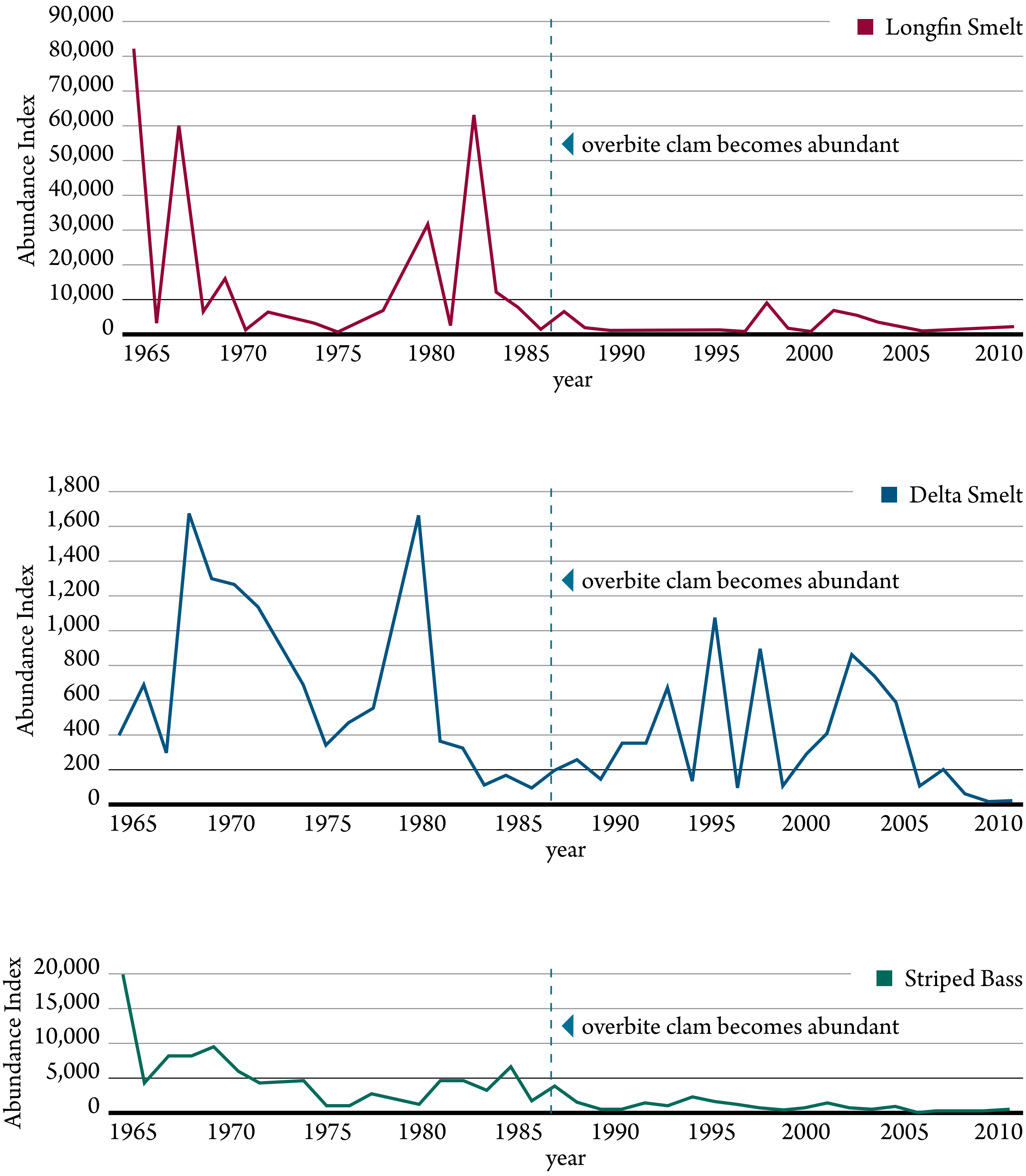
[2] Discussed in greater detail in Chapter 3



4.5. Changes in abundance indices for longfin smelt, Delta smelt, and striped bass over time in the Delta. (Source: Fall Midwater Trawl Survey 2008) son probably is not due to an increase in food supply, since the zooplankton that most young fish feed on do not increase in abundance with flow (Kimmerer 2002). This suggests that aspects of physical habitat may be more important in determining the response of fish to flow, including habitat quantity (as seen for splittail feeding on floodplains, Feyrer et al. 2007) and estuarine circulation patterns.

Some species of estuarine-dependent fish declined in abundance around the time the overbite clam became abundant (see Figure 4.5; Kimmerer 2002). The impact of the overbite clam on estuary-dependent fishes may have been muted because the northern anchovy *(Engraulis mordax)* became less abundant in low salinity waters, presumably because of the decline in food there (Kimmerer 2006). Because anchovies can filter-feed, they are capable of consuming small organisms more efficiently than most other fish, which pick out prey individually. The departure of anchovies may have reduced predation on zooplankton and therefore competition with other plankton-feeding fish, and also allowed the small copepod *Limnoithona* to thrive (Kimmerer 2006; Bouley and Kimmerer 2006). This sequence of events would not have been predictable in advance, and provides a cautionary tale for predicting the outcomes of future introductions.

Since around 2001 attention has focused on the decline of several open-water fishes (Delta smelt, longfin smelt *(Spirinchus thaleichthys)*, juvenile striped bass, and threadfin shad *(Dorosoma pretense)*; see Figure 4.5) and some prey species; this decline was labeled the POD (Sommer et al. 2007). The causes of the POD remain uncertain, although potential contributing factors are the changed estuarine food web, export pumping, declining habitat quality, and toxic effects (Baxter et al. 2008). All of these are subject to ongoing research coordinated by the POD Management Team. As with the longer-term downward trends of fishes (see Figure 4.5), the POD is very likely due to more than one cause.

Of the POD species, the Delta smelt is arguably the most imperiled estuarine fish in the United States, and knowledge of its biology has been increasing rapidly (Bennett 2005). The areal extent of its spawning habitat and the geographic distribution of larvae and juveniles depend on freshwater inflow (Dege and Brown 2004; Hobbs et al. 2007), although the fall index of smelt abundance is unrelated to flow (Jassby et al. 1995; Kimmerer 2002). In drier years, when Delta smelt are distributed eastward into the Delta, entrainment losses at the export pumps may be high (Kimmerer 2008). Preliminary results of the POD investigations suggest high entrainment during winter may have an especially damaging effect on the Delta smelt population (Baxter et al. 2008). Furthermore, habitat suitability for Delta smelt has declined because of increasing water clarity (smelt are most common in turbid water), high temperature in summer, and salinity intrusion in fall (Feyrer et al. 2007; Nobriga et al. 2008). This change in habitat suitability is correlated with the number of juveniles produced per adult fish, but only since the overbite clam invasion occurred (Feyrer et al. 2007).

In addition to the POD species, a great deal of effort has been expended to understand and minimize the impacts of poor conditions in the Delta on Chinook salmon *(Oncorhynchus tshawytscha)* and Central Valley steelhead *(Oncorhynchus mykiss)*. Many young salmon enter the Delta as fry and rear there instead of in the streams, yet little is known about the contribution of these fish to the population. Salmon that migrate through the Delta encounter a risky habitat with large numbers of predators and presumably a confusing directional signal, made unnatural by the general southward flow of water toward the export pumps (Brandes and McLain 2001). Some of these fish are lost to the export pumps (Kimmerer 2008), but there has been no comprehensive attempt to estimate overall losses through the Delta and how they vary with flows, export flows, and barrier placement. Studies conducted to date (Newman and Rice 2002; Brandes and McLain 2001) have focused only on subsets of this problem. Particle tracking models show that most particles, which simulate salmon, that are released in the San Joaquin River under most flow conditions are lost to entrainment into the export pumps (Kimmerer and Nobriga 2008). Survival indices for salmon smolts released at various sites on the San Joaquin River have been low and not very responsive to flow, also suggesting poor survival under most conditions (SJRGA 2006).

Marshes and Shorelines

The Delta was once mainly tidal marsh, and the entire estuary was bordered by tidal marshes including the extensive Suisun Marsh. These former marshes doubtless were an important component of the Delta ecosystem. Although only about 5 percent of the original marsh remains estuary-wide, some remnants exist in the Delta and more in Suisun Marsh and farther seaward (Atwater et al. 1979).

Most of the research on marshes in the Bay-Delta is on salt marshes of the lower estuary, with particular recent emphasis on the effects of introduced cordgrass on marsh function (Callaway and Josselyn 1992). Within the Delta, research has emphasized extant or restored marshes as fish habitat (Brown 2003a) or their effects on water quality.[3] This emphasis arose because of plans by CALFED to expand the extent of tidal marshes in the hope of increasing organic matter supply to the estuarine food web and providing habitat for fish. However, the organic matter produced in marshes can also contribute to the production of methylmercury and can impair drinking water quality (Davis et al. 2003; Brown 2003b).[4] Furthermore, many of the fish species of greatest concern are open-water species unlikely to use these habitats to any great extent (Brown 2003a).

Shorelines and shallow regions in the Delta have become heavily overgrown with the invasive Brazilian waterweed *Egeria densa*, whose extent has been increasing (Brown and Michniuk 2007). Waterweed beds support large populations of invertebrates that comprise a fairly self-contained food web distinct from that of neighboring open water (Grimaldo 2004). Waterweed beds appear to provide conditions suitable for spawning and rearing of introduced predatory fish such as black bass (Grimaldo et al. 2004; Brown and Michniuk 2007). These introduced predatory fish are capable of consuming larvae, juveniles and adults of smaller species of native fishes and probably minimize any benefit waterweed beds might have for native fish populations (Brown 2003a; Nobriga and Feyrer 2007). Native fish larvae are rare along the edges of waterweed beds (Grimaldo et al. 2004). These beds of waterweed are major impediments to restoration of the Delta and make it difficult to predict how the system may respond to future management actions.

The principal exception to the rather pessimistic findings above is floodplains such as the Yolo Bypass and the Cosumnes River, which are inundated only during winter floods. These areas provide important feeding habitat for Chinook salmon and splittail (Sommer et al. 2001; Feyrer et al. 2006). They are less subject to invasion by non-natives than permanently flooded areas (Moyle et al. 2007), presumably because the limited duration of inundation does not overlap with the higher spawning temperatures needed by most non-native fishes. These findings suggest that seasonally inundated areas may be more valuable for restoration than shallow areas that are permanently underwater (Feyrer et al. 2006; Moyle et al. 2007). However, seasonal flooding and drying of aquatic habitats may increase production of methylmercury. [5]

Much of Suisun Marsh consists of private lands managed to support waterfowl for hunting. The long history of research in Suisun Marsh has fo-

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[3] Discussed in greater detail in Chapter 3

[4] Discussed in greater detail in Chapter 3

[5] Discussed in greater detail in Chapter 3

cused predominantly on marsh channels as habitat for estuarine fishes (Moyle et al. 1986). Very few published studies have focused on the function of the marsh itself (Culberson et al. 2004), although research is underway on aspects of marsh function and the influence of invasive plants.

Freshwater Flow and Tide

Freshwater flow into the estuary is a key driver of ecosystem response, and arguably the most important process for reSource management in the state. Manipulating freshwater flow is one of the few management tools available in the system. Variability in freshwater flow (see Figure 4.1) affects the tidal freshwater reaches of the Delta through its effects on inputs of sediment and related substances and on water residence time, which regulates accumulation of phytoplankton biomass. In addition, increasing freshwater flow increases the area and volume of freshwater habitat by moving the salt field seaward. Movement of the salt field, in turn, affects processes in brackish to saline regions of the estuary out into the Gulf of the Farallones (Walters et al. 1985). This movement is indexed by a variable called "X2", the distance (in kilometers) up the axis of the estuary from the Golden Gate to where the tidally-averaged bottom salinity is two practical salinity units (psu) (Jassby et al. 1995). X2 is used in managing flow into the estuary, and is considered a measure of the physical response of the estuary to changes in freshwater flow (Kimmerer 2002). It is related to abundance of several populations of estuarine-dependent species (lower abundance occurs at low flow and high values of X2; Jassby et al. 1995), although those relationships changed after both the decline attributed to the overbite clam (Kimmerer 2002) and the more recent POD (Sommer et al. 2007); now few of the species that spawn in freshwater show relationships with X2.

The effects of freshwater flow within the estuary are modified by tidal flows (see Figure 4.6). Tides mix and transport salt, other substances and organisms within the estuary. The tides do not merely slosh back and forth; tidal flows in the branching channels of the Delta are quite complex and can result in considerable mixing. For example, scientists are investigating the role of tidal flows in Franks Tract, which may act as a kind of tidal pump that transports ocean salt into the Delta. In brackish parts of the estuary, salt is transported upstream by asymmetrical flow patterns arising from interactions between the net seaward flow due to the rivers and tidal flows and influenced by the complex channel–shoal structure of the estuary. Organisms such as larval fish may use the tidal flows to maintain position within the estuary by moving up and down in the water column (Bennett et al. 2002).

Roles of Diversions

Water diversions in the Delta range from small pumps and siphons that serve individual farms to the massive state and federal facilities in the southern Delta (Figure 4.1 shows export volumes). There is little evidence that the small diversions in the Delta have any effect on fish populations, in spite of the expenditures made to install or upgrade fish screens on these diversions (Moyle and Israel 2005). The South Delta export facilities entrain so many fish that it is often assumed that export pumping has massive effects on fish populations within the Delta. Losses of Delta smelt and Sacramento basin Chinook salmon ranged from zero up to 20 percent to 30 percent, depending on flow conditions and assumptions about pre-salvage mortality (Kimmerer 2008). Export pumping has been blamed in part for declines of species such as striped bass (Stevens et al. 1985), Chinook salmon (Kjelson and Brandes 1989), and Delta smelt (Bennett 2005). However, no quantitative estimates have been made of the population-level consequences of the losses of fish caused by export pumping. It is difficult to know the impact of these losses in the context of much

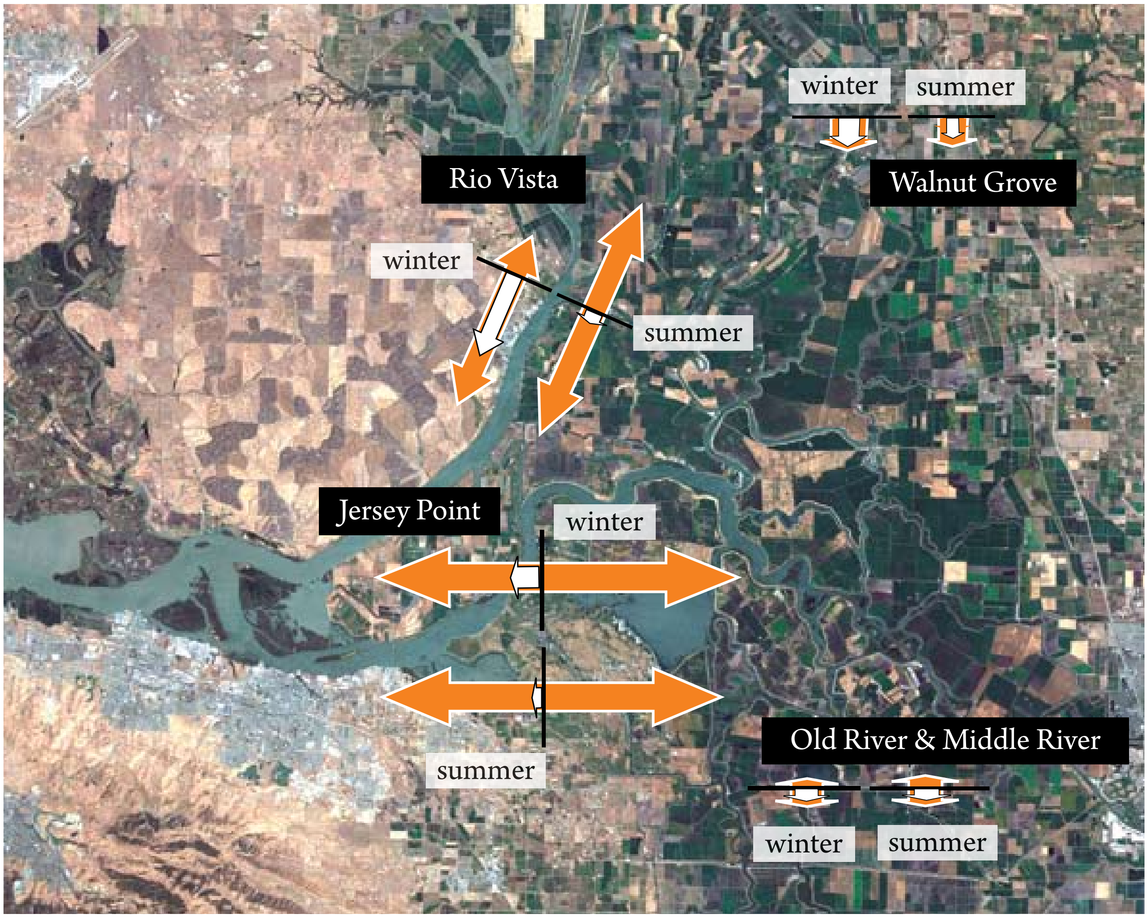

Figure 4.6. Tidal and net flows in different regions of the Delta in winter and summer. Orange arrows show tidal flow (with the exception of Old and Middle Rivers, upstream tidal flows are upward or to the right, downstream flows are downward or to the left; Old and Middle Rivers flow north, so upstream flow is downward and downstream flow is upward). White arrows show the net flow (net flow is the average movement of water in the channel). Tidal flows dominate through most of the Delta and are particularly high in the West Delta. Net flows are greatest where the rivers enter the Delta. Net flows are upstream (going south) in the South Delta because of export pumping. (Source: Satellite image courtesy of NASA Landsat Program, http://landsat.gsfc.nasa.gov/. Monitoring data depicted was provided by the United States Geological Survey. The sizes of the arrows are for illustration purposes only.)

larger variability in survival and reproduction of these species. Export pumping also alters flows in Delta channels, which may have indirect effects on fish, and removes phytoplankton and zooplankton from the Delta. These losses can be substantial, but their effects on the ecosystem are unknown.

Water Residence Time and Connectivity

Aquatic habitats vary in their degree of hydrologic isolation, which can be described in terms of residence time of the water. Long residence time corresponds to isolated habitats in which local conditions control variability in water chemistry and biological activity. When residence times are short, habitats are well connected and variability is controlled by the movement of water. Estuarine scientists generally believe that spatial variability in conditions is favorable for long-term persistence of the ecosystem. Cloern (2007) used a simple model to explore exchange between a productive donor region and a recipient region of net consumption and found that overall production was maximum at intermediate levels of hydrodynamic connectivity. This concept of donor and recipient habitats is probably important throughout the system. For example, the low salinity zone, usually in Suisun Bay, receives dissolved organic matter, phytoplankton, and zooplankton from the Delta, and the Delta receives large inputs of dissolved organic matter, phytoplankton and zooplankton when the Yolo Bypass floods.

Connectivity also arises through movement of organisms, from the small-scale feeding excursions of resident fish predators in waterweed beds, to the large-scale upstream and downstream migrations of anadromous fish, and even the 4,000-kilometer seasonal migrations of waterfowl. Long-distance migrations link the estuary to distant regions responding to different environmental factors. For example, salmon and striped bass can be affected by ocean conditions that have no discernible direct effect on the estuary. An extreme example of biological connectivity is that between the export pumping plants in the Delta and upstream reservoirs, which are linked by operator requests for changes in river flow to support changes in pumping rate.[6]

Connectivity between estuarine channels through marshes to terrestrial environments was largely cut off by levee construction many decades ago. The consequences of this early change in the Delta can only be guessed at. Research is ongoing on the potential functions of these linkages throughout the estuary.

Persistent Problems for Management

Several problems that have persisted for decades continue to impede effective management and restoration of the Bay-Delta system. Although these have been mentioned in previous sections, we raise them here by way of emphasis. We do not offer solutions, but suggest that these problems must be considered as constraints on future management decisions.

Export Pumps and Fish

There is a common perception that the effects of the export pumps in the southern Delta on fish populations are substantial. There are several good reasons for such a perception. First, large numbers of fish are collected at the fish facilities (Brown et al. 1996) and large numbers of them very likely die during the entrainment and salvage process (Gingras 1997). Second, endangered species legislation focuses on protecting individuals as a means of protecting populations. Third, some calculations have shown proportional losses of listed species to be rather high (Kimmerer 2008), although the capacity of these species to overcome such losses is unknown. Fourth, amounts of water exported have increased steadily since the 1960s, while species have declined. Nevertheless, there is no conclusive evidence that export pumping has caused population declines. The lack of unequivocal evidence of large effects of pumping on fish populations does not rule out such effects and, for rare species such as Delta smelt, caution dictates that potential effects should not be ignored.

Another reason for the focus on pumping effects is that controls on export pumping provide the principal tools for managing most species in the Delta, particularly pelagic species. Freshwater outflow is another potential tool that has been applied in the form of the X2 standards, but the efficacy of that

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[6] Discussed in greater detail in Chapters 2, 5, and 6

control has been weak for some species since about 2000, and nonexistent for Delta smelt (Sommer et al. 2007).

Toxic Effects

Toxic effects of contaminants, including heavy metals and organic compounds, present a very difficult problem. Hundreds of contaminants of many different chemical forms are present in the system (Hinton 1998). Analysis and detection are expensive, and in some cases methods are insufficiently sensitive to detect toxic levels (Oros et al. 2003). Monitoring is incomplete because of the expense and difficulty of some analyses, and because no monitoring program could provide enough spatial and temporal coverage to ensure reliable detection of all toxic chemicals. Several persistent contaminants such as mercury and selenium are abundant in the watershed or in Delta sediments, can accumulate in food webs, and can impair human health.[7] Many of the organic contaminants are present only sporadically, making their effects even more difficult to detect. Bioassays have revealed evidence of toxic effects on invertebrates and fish in the Delta (Kuivila and Foe 1995; Whitehead et al. 2004), but the cause of the toxicity is unknown.

The sporadic and unpredictable occurrence of toxic "hits" is worrisome in that damage to biological populations can arise without any detectable signal of a toxic event. In addition, such events can confound any analysis of population dynamics or experimental work on Delta species. Examples include the low growth rate of phytoplankton in water collected from Suisun Bay (Dugdale et al. 2007), and occasionally poor survival of zooplankton collected for experiments (Kimmerer et al. 2005), both of which could be due to toxic effects.

Clam Effects

The Asian and overbite clams exert a dominant influence on the food web of the Delta. Although there may be a period of a month or two, depending on the season, with low clam abundance near the low salinity zone, that seems insufficient to offset the effects of the two clams. Furthermore, tides and river flow transport chlorophyll and planktonic organisms from areas of high concentration without clams to areas of low concentration with clams, thus depleting even areas fairly remote from the direct influence of clams (Kimmerer and Orsi 1996; Jassby et al. 2002).

The presence of these clams and their rapid colonization of newly available habitat severely limit opportunities to improve conditions in the Delta for fish and other species of concern. Their high filtration rates ensure that, wherever clams are abundant, phytoplankton concentrations will remain low, limiting the growth of consumer organisms. The direct effects of the overbite clam on zooplankton (effects of the Asian clam have not been examined) also reduce the food available to higher trophic levels. The bioconcentration by clams of contaminants such as selenium adds an additional difficulty to this problem. Control of clam populations does not seem feasible, so these problems will persist.

When zebra mussels and quagga mussels enter the estuary, more change will ensue. There is no reason to expect this change to be beneficial, and it will likely result in a further decline in the availability of phytoplankton to support the desired Delta food web.

Waterweed Effects

Many waterways of the Delta are choked with Brazilian waterweed, impeding boat traffic but also trapping sediments, forming habitat for a host of mainly introduced species, slowing water circula-

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[7] Discussed in greater detail in Chapter 3

tion and increasing local water temperature. The sediment trapping increases water clarity, which reduces the suitability of the habitat for native species, particularly Delta smelt (Feyrer et al. 2007). The non-native fish species form the basis for an important recreational fishery, but they also prey upon native fishes (Nobriga and Feyrer 2007). A major thrust of restoration in the Delta has been developing shallow habitat suitable for native fish. If such habitat is taken over by waterweed, any benefit is eliminated. At present there is no known method for getting rid of waterweed other than through mechanical removal and poisoning, both of which present other problems.

Introduced Species

Apart from the specific examples above, the general topic of introduced species is important for understanding changes in the estuary and watershed, and for management. Species are introduced when an initial group of individuals is transported to the Bay-Delta, in the ballast water of a cargo ship or in a shipment of bait from another estuary, for example. If the initial density of the organisms and local conditions are favorable, the new species can begin to increase in abundance. Disturbed physical habitat can be conducive to successful colonization, although that seems less obvious in open-water environments. Introduced species often go through a period of "overshoot," in which abundance climbs very high and then settles down to some lower level. For example, the Chinese mitten crab *(Eriocheir sinensis)* was first detected in 1992, peaked in abundance in 1998, and then declined to less than 1 percent of its peak population (Rudnick et al. 2003).

In examining the effects of introduced species on the ecosystem, it is helpful to distinguish between introduction events and the ongoing presence of species that were introduced some time ago. Introductions or range extensions can result in sudden and permanent rearrangement of the ecosystem. In the case of "ecosystem engineers" such as the Brazilian waterweed, this rearrangement includes a change in physical habitat. However, once a species has become established, it is part of the ecosystem, and its effect on other species is qualitatively similar to other interactions between species. Following an introduction, the rearranged system may have less capacity to support native species or other species of concern to people. However, if the ecosystem undergoes change well after a non-native species has become established, it makes little sense to attribute that change to the introduced species unless it can be shown how the introduced species could have caused the change. Thus, explaining the POD as an effect of introduced species raises the question of how the introduced species could have caused the POD. This is a basic question about the ecology of the rearranged system.

Threatened and Endangered Species

The status of threatened and endangered species is often a driver for concerted management action. Several dozen native species are listed or have been proposed for listing in the Central Valley, including nine species of fish.[8] Endangered species legislation prescribes a rather narrow approach to species conservation focused on protecting individual organisms and critical habitat. In contrast, ecosystem-based management starts from the assumption that declining species are a symptom of ecosystem-level problems that, if reversed, could reverse declines in individual species. This is difficult to test, and difficult to implement when legal requirements dictate a species-specific approach.

Impending changes in the Delta will likely place additional stresses on listed species. Human actions, such as a change in the way water is moved through the Delta, may have positive or negative effects that are difficult to predict. Catastrophic events, such as levee failures (Mount and Twiss 2005), would likely have negative effects through direct mortality and

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[8] Discussed in greater detail in Chapter 1

changes in habitat configurations. Climate change has the potential to make the Delta uninhabitable for some species, including Delta smelt and San Joaquin salmon.

Reversing declines for species such as Delta smelt is particularly difficult. Delta smelt is unresponsive to freshwater flow, and few of the likely contributing factors (for example, low food supply, declining turbidity, abundant predatory fish) are very responsive to human control. Export pumping, although blamed for many of the Delta's ills, is only one of several potentially harmful factors.

New tools are being developed by ecologists and conservation biologists that could be used to enhance species preservation in the face of climate change. For example, captive broodstocks of Sacramento winter-run Chinook salmon and Delta smelt have been established as a hedge against catastrophe (Arkush and Siri 2001). Other tools include assisting species range extensions so that they can keep ahead of changing global climate, seed-banking and cryopreservation of genetic material and genetic manipulation to improve resistance to new environmental conditions. Most of these tools are "last-ditch" measures of untested utility.

Forecasting the Future

Change is the one certainty for the Delta. Ongoing climate change with resultant sea-level rise, increasing human population, new invasive species, and the effects of expected but sporadic events such as floods and earthquakes will combine to ensure the Delta of the future will be very different from that of today. Partly in response to these expected changes and partly to solve current problems, intentional changes to the Delta's configuration, such as an alternative means of moving water around the Delta, are likely.

The scientific community will be called upon to forecast what these changes will mean for the ecosystem. This forecast will be difficult for several reasons. The first is the inadequate coverage by our monitoring programs of the ecosystem processes that underlie much of the variability we see in the system. The second is the extreme complexity of the ecosystem, with its layers of spatial, temporal and biological variability. The third is the high uncertainty about future species introductions which, as we have seen, can radically alter the system's response to management and natural inputs. Finally, the extent of the future changes in the physical configuration of the Delta are uncertain.

To begin this essential forecasting process will require a concerted effort by the scientific community. Any anticipated changes in Delta configuration must be identified and examined for their likely consequences. Key uncertainties must be identified and research undertaken to reduce them. To accomplish all this will require mobilization of new resources, additional talent and newly developed methods.

Conclusions

The principal challenge facing managers of the estuary is how to maintain ecosystem services, given the obvious conflicts among them and the long-term changes likely for the ecosystem. Although much of the management focus so far has been on conflicts related to water diversions, in the long term additional human activities are likely to conflict even more with desired ecological services, such as the maintenance of rare or endangered species. Without substantial action, the ecosystem is likely to diverge further from what society would prefer. It will certainly change substantially within the next fifty years or so, as a consequence of the interactions among climate change (increased floods and longer droughts), sea-level rise, land subsidence, levee failure, invasions of new species and changes in land and water management.

Although scientific information is essential for management decisions, we are well aware of the limits of science. For example, the information available a few years ago to assess the causes behind the POD consisted mainly of data on distribution and abundance of the fish species and their presumed food. The acceleration of research into the likely mechanisms for the declines illustrates that monitoring alone is insufficient to develop an understanding of the processes by which species' populations change.

Some previous management decisions made with little or no scientific involvement have not been effective (Lund et al. 2007). Prime examples are the assumptions by CALFED that physical habitat could be constructed as an alternative to freshwater flow, and that the existing ecosystem could be maintained in its present configuration. Thus, we think it is important to keep science integrated into planning processes. Yet inherent mismatches exist between the information needs and time pressures of managers and the ability of the scientific community to provide the necessary information. When such a mismatch exists, it may be wise to be guided by the precautionary principle of taking actions that do the least harm to desirable organisms. On the other hand, the time for taking tentative, timid actions has passed. The most desirable future state of the Bay-Delta's ecosystem is likely to come about only through large-scale actions that are guided by the most current understanding of system processes, while acknowledging inherent uncertainties.

Although it is tempting to call yet again for adaptive management, previous such calls have not been very successful. Instead, we recommend that scientific investigations and ways of thinking be incorporated further into the management process. At the same time, the scientific community should continue its quest for new ways of approaching problems, testing new ideas, developing new tools (for example, molecular methods, new sensors and modeling approaches) and focusing on what we need to know to provide the forecasts that are so clearly in demand.

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5. Levee System Fragility

Johnnie Moore,[1] Roy Shlemon[2]

The approximately 1,100 miles of levees that support the framework of the modern Sacramento-San Joaquin Delta were not engineered and planned as a system. They were built piecemeal to protect local human structures and activities as the Delta developed (see Chapter 1; Lund et al. 2007; Hundley 2001; Kelley 1998). The bulk of the present-day Delta levees were in place by about 1930 (Florsheim and Dettinger 2005; Thompson 1957) and allowed agriculture to expand, cities to grow, and infrastructure to be built on the islands behind the levees. Originally, the islands were close to sea level, but as they were farmed a combination of water extraction, burning and oxidation of peat and organic-rich soils and wind erosion rapidly decreased the elevation of the island interiors (Lund et al. 2007; Mount and Twiss 2005). Because of this erosion, farmers are now working peat layers that were deposited as long as 6,700 years ago (Drexler, de Fontaine, and Knifong 2007). Human actions have removed, in 140 years, what natural processes took over 6,000 years to form. As a result of this loss of soil, much of the Delta now lies well below sea level (see Figure 5.1).

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[2] Roy J. Shlemon and Associates, Inc.

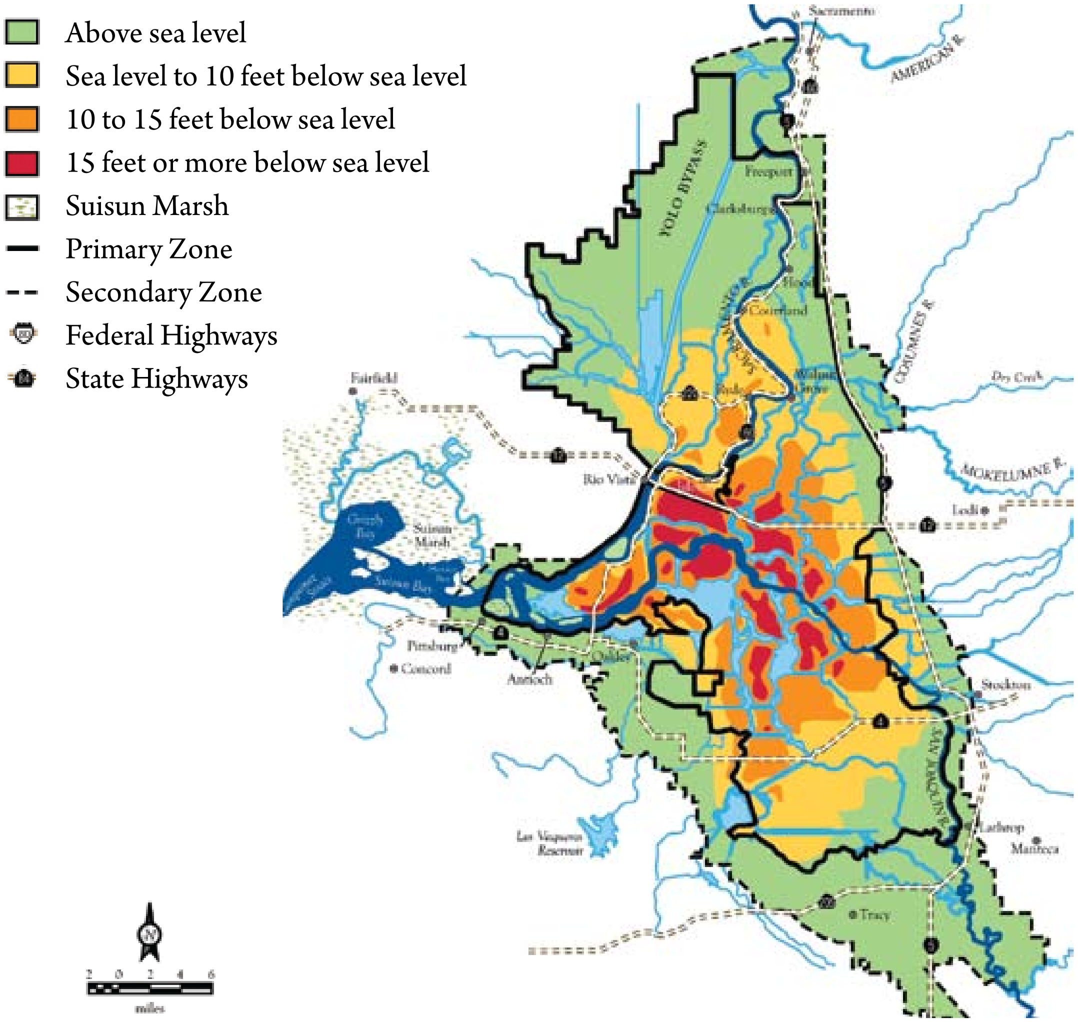

Figure 5.1. Delta topography. (Source: Lund et al. 2007, Figure 3.5)

The levees now function as dikes, continuously protecting islands from inundation by both the river and the sea, instead of just protecting the land during high-river flows. This vast complex of narrow man-made ridges constructed of river sand, and delta plain mud and peat now surrounds about 2.5 billion cubic meters of space that is below sea level (Mount and Twiss 2005). The islands really constitute a set of bowls containing over 200,000 hectares of land. The vulnerability to flooding of the land within these bowls depends on the fragility of the levees surrounding them.

Delta levee fragility depends on two main characteristics of the levee system:

1. Strength of the levee itself and its foundation, and
2. External forces acting on the levee.

When external forces overpower the strength of the levee, the levee fails, allowing water to flood the island. There is a long history of levee breaches: from two hundred to three hundred in the Delta and its associated rivers over the last 150 years (see Florsheim and Dettinger 2007; 2005). If the climate and the Delta were a static system, we could rely on these past events to predict the frequency, if not the location, of levee failures in the future. As the levees age, and if maintenance does not keep up with deterioration, we might expect a gradual increase in the levee failure rate. Again, that would assume that the external forces on the levees remain unchanged. In fact, the external forces on the levees are continually increasing (for example, from sea-level rise and subsidence) and the levees are becoming progressively more fragile. Maintenance is becoming more difficult and costly, likely leading to an increase in levee failures over time. Catastrophic failures of multiple levees may also occur simultaneously, driven by either large floods or earthquakes (Mount and Twiss 2005; Torres et al. 2000), which would have far-reaching disastrous effects, not only within the Delta, but as far away as Southern California. Because of the importance of the Delta as a water distribution system (Lund et al. 2007), it is critical that we understand the levee system and identify the additional scientific studies needed to assess the susceptibility of the levees to failure. That is the focus of this chapter.

Evolution and Structure of Delta Levees

Prior to about 1850, sandy-bedded channels cut through the Delta's tidal marshes carrying mineral sediment from the highlands to San Francisco Bay. Tides moved this sand back and forth in the western Delta, but it ultimately moved out into the Bay. During floods, sand was also carried out of the channels and onto the surrounding delta plain in crevasse splays, and mud suspended in the floodwater was transported farther out into the marshes on the delta plain. All this was part of the dynamic interplay between water and land that characterizes a natural delta. Near the active channels, the sandy crevasse splay deposits inter-fingered with marsh, mud and peat, forming a natural levee that sloped away from the channel onto the delta plain. These natural levees were low features that just maintained the channel and graded into the surrounding tidal marsh complex (see Figure 5.2), connecting the marsh and floodplain to the channels. As the main channels and their natural levees migrated and avulsed across the delta plain, they left behind a mosaic of sand and mud lenses inter-bedded with the thick peat deposits formed in the marsh.

When Delta marshes were drained and reclaimed, the first levees were constructed on the existing natural levees. Sediment from the channel or the adjacent marsh was used to raise the crest of the natural levee, protecting the surrounding land from high flows. This allowed the islands to be drained and farmed. Farming, and the associated burning of the peat to reduce pests, oxidized the organic-rich sediment in the islands (see Figure 5.2) and caused them to subside well below their original elevation (Deverel, Wang, and Rojstaczer 1998; Deverel and Rojstaczer 1996; Rojstaczer and Deverel 1995). The levees protected the resulting islands from flooding, but also kept out the rich mineral sediment that had been deposited during high flows onto the surrounding delta plain. The floors of the islands were subsiding due to soil loss, but the adjacent river channels were also rising due to sediment deposits in the channel bed. The height of the levees had to be increased through time to keep up with subsidence and channel bed rise, and the bases of the levees spread onto the adjacent marsh and partially sank into the mud and peat beneath the levee. Continual maintenance was needed to increase the height of the sinking levees and repair damage from large floods. Nearly all the material for levee maintenance was originally taken from the marsh and delta plain adjacent to the levee. The present levees are a combination of the original sedimentation that formed the natural levee and additional layers from various Sources that were added as the levees were raised, resulting in a complex internal stratigraphy that in many places is structurally weak.

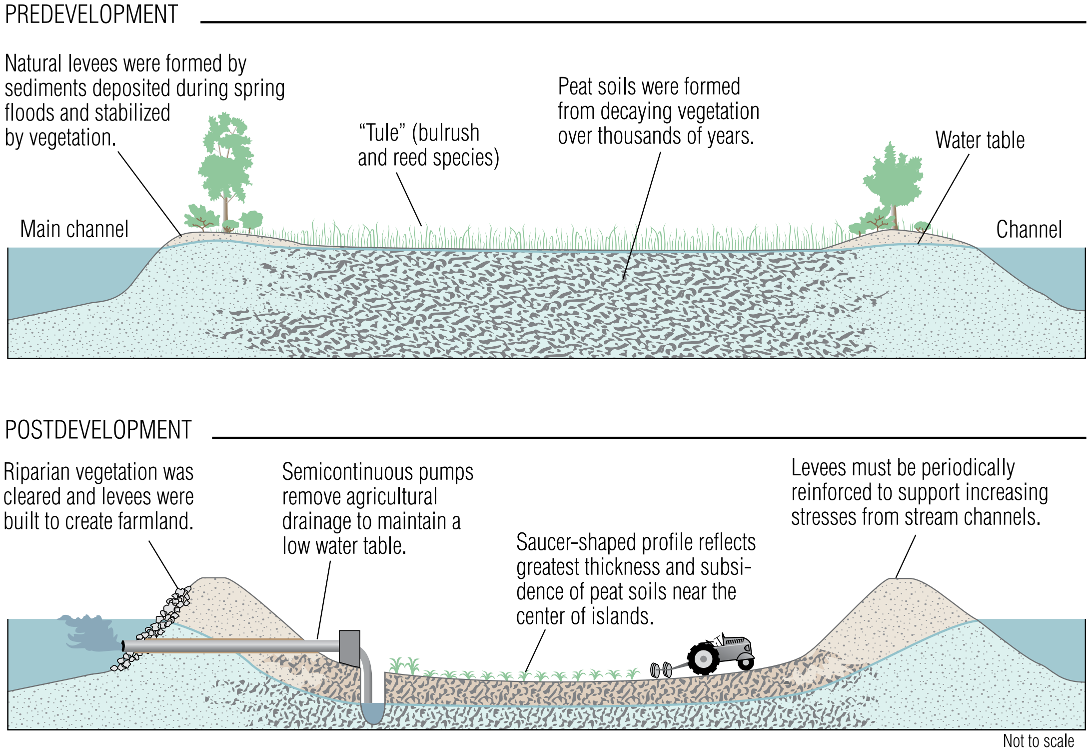

Figure 5.2. Development of modern levees on preexisting natural levees and subsidence of islands as peat soils are farmed. (Source: Ingebritsen and Ikehara 1999)

Measuring Levee Structure and Fragility

Determining the internal structure of 1,100 miles of levees to establish their safety and predict how they may respond to floods and earthquakes is an extremely difficult task. Assessing levee strength and fragility requires determining their internal structure at a fine scale. Ideally, levee managers need to identify incipient cracks, burrows, saturated zones, and other potential weaknesses within the levee or its foundation. Some of these features can be found by diligent surface inspection, but most are hidden within the levee. Details about the inter-layering of the material within and adjacent to the levee are also critical for building realistic numerical models of how levees will respond to stress and for planning large-scale levee maintenance.

There are two approaches to determining the detailed internal structure of levees to estimate their strength: boreholes (discussed below) and geophysical methods (discussed later). Traditionally, borings are used to establish both the type and strength of materials forming the levees, as well as the materials lying beneath and adjacent to the levees. Boreholes can also be used to determine water levels and pressures within and beneath the levees, as well as the strength of materials by conducting tests within the borehole or by testing materials recovered from the drilling in the laboratory. Delta levees have been bored extensively but not uniformly (URS Corporation and Jack R. Benjamin and Associates, Inc. 2007a). Boreholes can penetrate many tens of feet into the levee and its foundation and give a vertical picture of the subterranean structure of the levee. A limitation of borehole data is that it represents only the few inches of the borehole, and the material is ground up by the drilling process so original layering or structure can only be determined coarsely. Core samples can be taken in areas adjacent to the levees, and these give a more detailed picture of the underlying material (Brown and Pasternak 2004). With multiple boreholes or cores taken across the levee and adjacent areas, a cross-section of the levee can be constructed. However, the complex inter-layering of the materials may make it difficult to correlate details from one borehole to another.

To construct engineering models of levees, the complex inter-layers of the levees are commonly grouped and depicted as simple parallelograms resting on continuous layers of underlying sand, mud, or peat. This allows computer-modeling experiments to be carried out to examine levee response to increased water pressure from floods or shaking due to earthquakes (URS Corporation and Jack R. Benjamin and Associates, Inc. 2007a; Tobita, Iai, and Ueda 2006). However, these approaches simplify a complex system and may deviate substantially from the original distribution of materials.

The materials making up levees (sand, mud, and peat) are inherently weak structurally. Wet peat has a very high porosity (80 to 97 percent), a bulk density of about 1,120 kilograms per cubic meter (kg m^{-3})[1] (water is 1,000 kg m^{-3}) and has very little strength. Mud (made up of clay and silt) can also have very high porosity when deposited (typically 70 to 90 percent), with bulk densities from 1,730 to 1,900 kg m^{-3}. Of all the levee materials, sand has the lowest porosity (30 to 50 percent), and, when wet, a bulk density from about 1,900 to 2,080 kg m^{-3} depending on how consolidated it is. All these materials are easily compacted when loaded, but the differing porosity and permeability between layers can cause the pressure in pores between sediment particles to build within individual layers as weight is added. These materials are compacted in the levee itself, but beneath the levee, especially adjacent to the levee, they are much less compacted and their water content is very high. In high-water-content layers, the pore pressure can build up to the point that the levee is virtually floating and liable to slip sideways under pressure. Thus, the upper part of the levee is generally stronger than its foundation or the adjacent channel or island. These differences can lead to very different responses during floods or earthquakes, causing differential movements that cause cracking, subsidence, or failure due to liquefaction.

Because the land surface in the interior of adjacent islands is well below the level of water in the channels, water moves from the channel into the surrounding subsurface, saturating these materials (see Figure 5.2). The levee crests are relatively dry, but the soils in the interior islands are wet except the uppermost layers that are drained by pumping. The results are that, when loaded, all the saturated materials beneath the levee and islands are easily compacted as the water is squeezed out. Well-packed sand is less compressible than mud or peat. However, if the pore water cannot escape as sand is loaded, pore pressures can build up sufficiently to actually support the overburden. Under these conditions, the sand has very little strength. The sand can liquefy and flow as the grains move within the over-pressurized pore water. This kind of liquefaction is commonly induced by shaking during earthquakes.

The basic structure of the levees, although inherently fragile because of the materials involved, still functions to hold back a huge mass of water in the adjacent channels and sloughs. The partially compacted materials act as a relatively efficient dam, allowing the islands to be pumped dry to farm. However, water continues to flow through the levee and the adjacent island materials so that the islands are kept dry only by continual pumping. Internal disruption of the levee can weaken the dam by allowing water to channel or pipe through the levee. Large conduits allow high velocities to flow through the levee, eroding them from within. If a large amount of material is removed, this may lead to failure. Cracks can develop from differen-

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[1] All bulk density numbers from:
http://www.simetric.co.uk/si_materials.htm

tial settling, and burrowing animals can weaken the levees. Both beavers and muskrats build very extensive burrows that can undermine the integrity of levees. Roots from large, woody plants have also been thought to weaken levees as they grow and push through the levee material. United States Army Corp of Engineers' regulations require the removal of vegetation over two inches in diameter from federally approved levees (Weiser 2007). When trees die or are cut down, rotting roots leave voids in the levee that may also weaken the structure or allow water to pipe through the levee. On the other hand, recent studies have found that roots from woody vegetation add strength to levees by binding the weak material together, as they do in natural levees (Weiser 2007; Gray and Sotir 1996).

Borehole logs have been the main source of information about the internal structure of Delta levees. However, new geophysical techniques are now available that can add more detail at a particular site or over a larger area of the levee. Cone Penetrometer Tests (CPT) directly measure the force needed to push a steel cone through levee and island material. Instrumented cones are used to gather detailed information on levee structure at different depths. As with boreholes, these data are specific to the sampling site.

Other geophysical techniques can be used to measure the internal properties of levees over large areas between borehole and CPT sites. Tools are now available to measure the electrical resistance of the subsurface materials at multiple locations and depths. These measurements can even be made remotely by flying over the levee (United States Army Corps of Engineers 2007; Department of Water Resources, Bay-Delta Office 2007). Many measurements can be made quickly using multi-electrode cables, and the results can be easily transformed into two- or three-dimensional images of the subsurface (see Figure 5.3; Niederleithinger et al. 2005) that allow modeling of levee structure. Ground Penetrating Radar shows promise for measuring the internal dissimilarities of levees to identify incipient failure zones. Other geophysical methods, such as using sound waves to make a subsurface image of the levee as is done in oil exploration (Miller and Ivanov 2005), can also be used to determine levee composition and structure. Although these methods allow a more complete and rapid assessment of levees than is possible with boreholes alone, they do not give unequivocal results. This has stimulated the development of integrated approaches for the assessment of levees (United States Army Corps of Engineers 2007; Dunbar et al. 2002) that are now being used

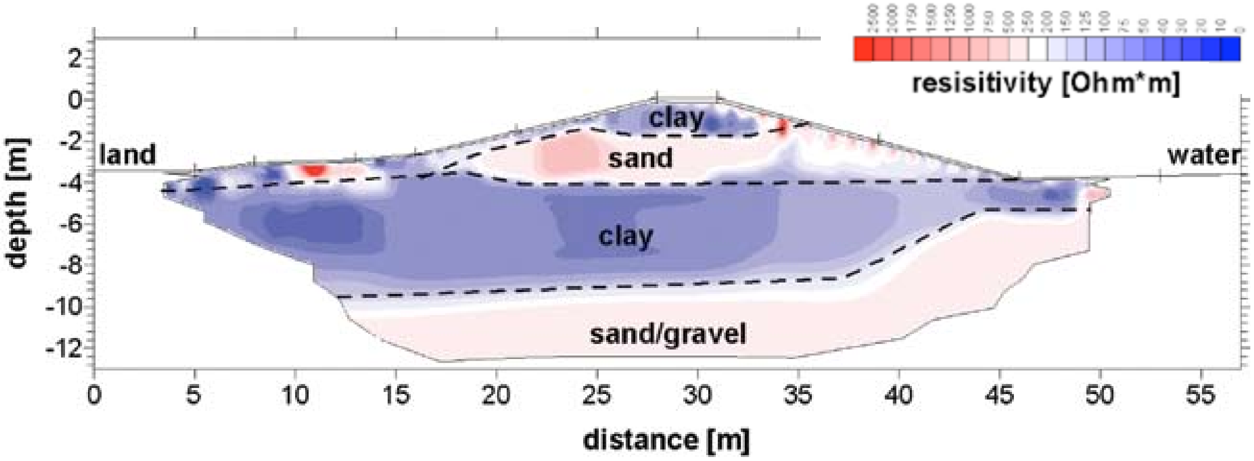

Figure 5.3. An example of the subsurface structure of a levee as determined by resistivity measurements. (Source: Niederleithinger et al. 2005)

locally. For example, the California Department of Water Resources (DWR) initiated an evaluation of some levees in the Central Valley using rapid assessment methods, relying on a combination of LiDAR, (Light Detection and Ranging; RaDAR with light substituted for radio waves; light waves, being much shorter measurements, can be more precise) aerial electromagnetic surveys, geomorphic and geologic analyses, bathymetric surveys of channels, and boreholes. They plan to survey three hundred miles of urban project levees in this manner in two to three years. However, it is important that these techniques are evaluated to determine their efficacy before they are used throughout the Delta. In a recent report by the Interagency Levee Policy Review Committee (2006), the authors noted that remote techniques "do not meet the needs of levee assessment, and more research is required to develop and certify new methods to rapidly and accurately assess levee geotechnical integrity." The committee identified a big gap between proven techniques for assessing levee fragility and current practice.

The DWR rapid assessments (and future assessments) offer opportunities to develop and test levee-assessment capability further. These should be designed as experiments, with well-characterized sections of levees acting as controls for the remote techniques. The goal would be to determine the structure, composition, water content, and dissimilarities of the levee itself, as well as that of the levee's deep foundation and adjacent materials. The objective should go beyond finding weaknesses within the levee itself and identifying areas for repair. Instead, the goal should be to establish the comprehensive structure of the entire levee system so that numerical models could be used to simulate potential responses to stresses (for example, floods and earthquakes). This is the most basic scientific investment in understanding levee fragility throughout the Delta.

Determining Levee Response to Seismic Shaking

Levees can fail under seismic accelerations in several ways: slumping, spreading, sliding, and settling (see Figure 5.4) (Brandenberg and Stewart 2006). All these failures lower the profile of the levee and allow overtopping by the water in the channel. During any or all of these failures, the levee can also crack, allowing water to flow through the cracks, eroding the levee and leading to failure. The recent Delta Risk Management Strategy (DRMS) draft *Phase I Report* assesses the stability of levees under a range of earthquake scenarios (URS Corporation and Jack R. Benjamin and Associates, Inc. 2007a). This was done by using the existing data on levee structure and geotechnical properties to build simplified numerical models of levees and their foundations throughout the Delta. Using computer simulation programs, the model levees were then stressed with differing accelerations from possible earthquakes.

The response of these model systems is highly dependent on the geotechnical information used and how the levees are depicted. Real conditions have to be simplified because of the computational requirements for depicting very complex systems and because responses may not be linear. The levee models are applied to segments of levees for each island throughout the Delta, and the probability of failure is estimated for each segment (URS Corporation and Jack R. Benjamin and Associates, Inc. 2007a). The final determination of levee response to seismic shaking is a combination of geotechnical measurements of levee materials, simplification of those measurements into a levee and foundation model, and application of the models to parts of the levee system. There is uncertainty in all these components. Although difficult, it is also critical to determine how uncertainty in each component combines in the final analyses of levee

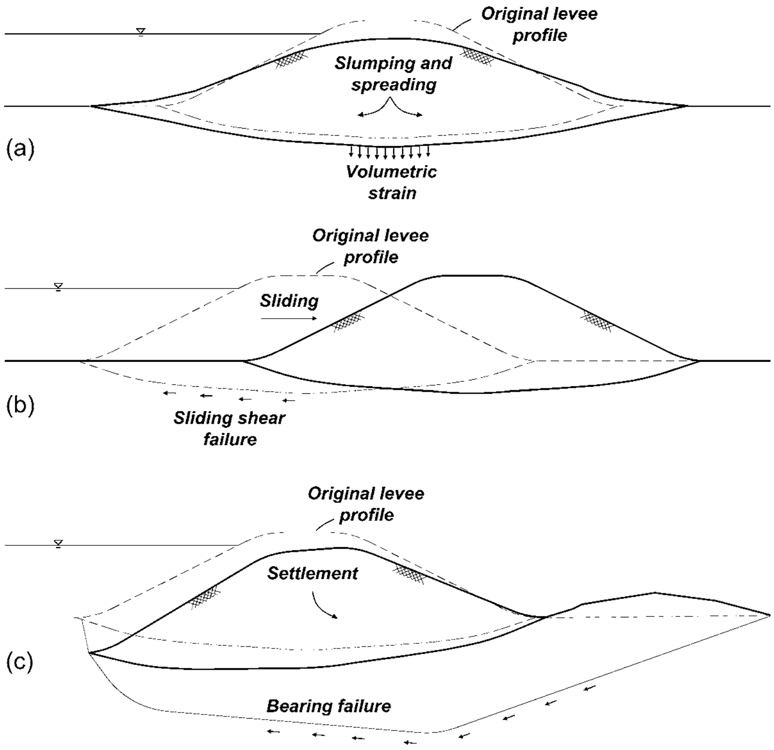

Figure 5.4. Potential levee failure modes due to seismic loading. (Source: Brandenberg and Stewart 2006)

fragility under seismic loading. The combined uncertainty tells the scientist what confidence to place in the estimate of potential levee failure under possible earthquake scenarios.

Assumptions about levee behavior can be tested physically, but this has not been done for Delta levees. Japanese scientists have used large centrifuges to examine levee response to seismic shaking (Tobita, Iai, and Ueda 2006). They found that model levees responded mostly by "spreading and sinking," so that the crest dropped well below its original position. They also found that their numerical models did a good job of predicting the outcome of the physical experiments.

The United States National Science Foundation (NSF) has established the Network for Earthquake Engineering Simulation (NEES) as a national collaboratory of shared experimental equipment. One large centrifuge, which is part of this consortium, is at the University of California, Davis and can spin and shake models of soil layers and soil-structure systems.[2] This centrifuge would be ideal for testing physical models to confirm the predictions of numerical models of levee risk in the Delta.

All centrifuge experiments are limited by the weight and size of the physical model being tested. Because the physical model that can be shaken in a centrifuge is small compared to a real levee, it may also be important to test models closer to full size. The NEES program also maintains six large-scale testing facilities that can test 'life-sized' structures.[3] These facilities could be approached to do large-scale experiments on levee response to shaking.

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[2] See NEES @UC Davis Center for Geotechnical Modeling at http://nees.ucdavis.edu

[3] See NEES Large-Scale Testing Facilities at http://www.nees.org/Research_Sites/LargeScaleLabs

All laboratory experimental systems are inherently simple when compared to a real levee system, where materials and structures have evolved through human manipulation and natural processes over a century. Direct measurements of these complex systems would give a much deeper understanding of levee response to shaking. NEES also has the capability to do such large-scale field tests through its mobile laboratories housed at the University of California, Los Angeles.[4] This facility could be used to conduct research on levees to measure on-site responses to seismic shaking. Laboratory vehicles carry equipment that can generate precisely controlled ground vibrations that simulate earthquakes without damaging the levee. Associated sensors measure how the levee and its foundation react during these experiments. These measurements can be scaled up to estimate the effects of shaking that would be induced by a real earthquake.

Because computer models are currently the only source of information on levee response to earthquakes, they drive the levee manager's determination of levee risk, which influences investment decisions in levee maintenance and rebuilding. It is critical to verify these models. Conducting experiments with physical models in the laboratory and on levees in the field would give a much deeper understanding of levee response to earthquakes and provide a basis for validating the predictions of the computer models. The most productive approach would be to begin with small-scale laboratory experiments and work up to large-scale field experiments.

Establishing Seismic Risk in the Delta

One of the main drivers of levee risk in the Delta is the potential for catastrophic, destructive shaking from a large earthquake that destroys many levees and thereby floods many islands in a very short time (Mount and Twiss 2005; Torres et al. 2000). The acceleration from seismic shaking is used to drive levee failure models. For decades, the United States Geological Survey has developed maps of active faults, probabilities of ground acceleration and potential earthquake hazard for the Bay Area.[5] Similarly, the California Geological Survey has a very well-developed seismic-hazards section.[6] Assessments of the probability of peak ground acceleration (PGA) (see Figure 5.5) are derived from analyses of active faults within the region, and so are dependent on the fault maps and earthquake-recurrence intervals used.

The DRMS draft *Phase I Report* developed new analyses of active faults and the probabilities of PGA in the Delta region and used those values to determine the potential for levee failure in various regions. These and other recent summaries (URS Corporation and Jack R. Benjamin and Associates, Inc. 2007b; Unruh and Sawyer 1997) identify mapped faults immediately adjacent to the Delta and state that the probability of an earthquake greater than magnitude 6.7 occurring over the next 35 years is 62 percent.

The probability of larger earthquakes over longer periods of time is also quite high. However the accuracy of these predictions depends on the fault maps used. Holocene faults not considered in these analyses, with no lineament or obvious geomorphic expression, have been postulated to cut directly

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[4] See NEES Field and Mobile Facilities http://www.nees.org/Research_Sites/FieldMobileLabs

[5] See: http://earthquake.usgs.gov and http://quake.usgs.gov

[6] See: http://www.conservation.ca.gov/cgs/shzp/Pages/Index.aspx

across the Delta, particularly under Sherman Island (Shlemon and Begg 1975). Consideration of these faults in the analysis would increase the probability and potential strength of shaking within the Delta and the risk to levees.

Levee Response to Subsidence and Sea-level Rise

The stability of Delta levees is tied to subsidence of Delta islands because increased subsidence adds more stress to the levee system due to increased erosion and increased hydraulic head (Mount and Twiss 2005). The oxidation of organic matter (peat) in Delta soils is the largest driver of subsidence (Deverel and Leighton in press; Ingebritsen and Ikehara 1999; Deverel, Wang, and Rojstaczer 1998).

Mount and Twiss (2005) used past elevations of Delta islands to develop empirical linear models of subsidence from 1925 to 1981 and post-1951. They found that the rate of subsidence had decreased in the later decades, and used that rate to predict future elevations of Delta islands to 2050. They then added the increased pressure on levees from sea-level rise to determine a 'levee force index.' This was the first attempt to estimate future conditions in the Delta and suggest how those conditions would increase levee fragility by increasing external forces. Mount and Twiss also suggested that the probability of catastrophic failure of the levees from earthquakes or large floods would increase substantially in the future, and it was highly probable that a major, catastrophic change in the Delta landscape would occur in the next fifty years. This emphasizes that, "punctuated landscape change in the Delta is

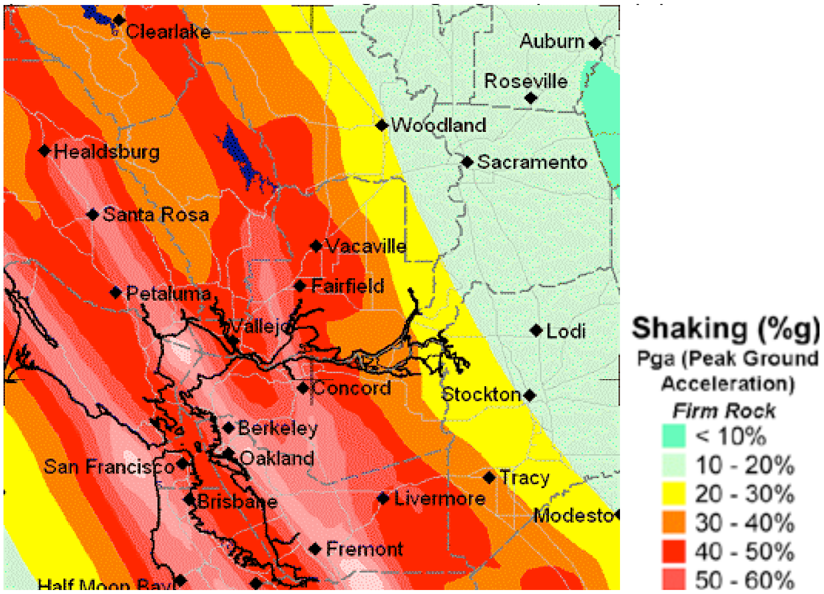

Figure 5.5. Map of peak ground acceleration in the Bay-Delta region. The different colors show the shaking potential (as a percentage of g, the acceleration due to gravity) at a 10 percent probability of occurrence in 50 years. The higher the percent g value the higher likelihood of damage. For example, Fairfield has a 10 percent chance of shaking at a level of 50 to 60 percent of g in the next 50 years. Note that the western and Central Delta have shaking potentials equal to those in much of the Bay Area. (Source: California Geological Survey 2008, http://redirect.conservation.ca.gov/cgs/rghm/pshamap/pshamain.html)

not a remote, hypothetical possibility, but is highly likely during [the next] 50 years" (Mount and Twiss 2005).

Deverel and Leighton (in press) included more recent Delta elevation data (up to 2006) and developed a model of subsidence based on soil organic carbon content, land use and temperature. Their results indicate that historically oxidation accounted for approximately 40 percent of total subsidence, consolidation for approximately 30 percent, and wind erosion and burning for approximately 30 percent. Because organic matter content is decreasing, subsidence rates are decreasing. However, oxidation now accounts for 50 to 90 percent of present subsidence, and consolidation from dewatering and increasing overburden loading accounts for the remainder. Their model did an excellent job of hindcasting past elevations (within ± 1 cm/year) and showed that subsidence was not linear but exponential. They used the model with projected increases in temperature and sea level to simulate elevation changes from 1998 to 2050. They found that the central areas of the Delta would subside the most, an additional 5 feet approximately (maximum value) below sea level by 2050, resulting in about 2.6 million acre feet (MAF) of total "accommodation space" (the volume of water that would be required to fill the subsided space behind Delta levees) below sea level (Mount and Twiss 2005).

Using more recent topographic data, URS Corporation and Jack R. Benjamin and Associates, Inc., Inc. (2007a) estimated maximum subsidence in the Central Delta islands at approximately 5 feet, with a slightly higher accommodation space (2.66 MAF) by 2050, approximately 9 feet (3.23 MAF) by 2100, and from 15 to 19 feet by 2200 (greater than 5 MAF). By 2200, they project the Central Delta will be 30 to 40 feet below present sea level.

There is still controversy about the amount of sea-level rise that will occur over the next fifty to one hundred years, with estimates ranging from less than 1 foot to up to 2.6 feet by 2100 (Intergovernmental Panel on Climate Change 2007; United States Environmental Protection Agency 2007; Titus and Narayanan 1995). However, the most recent research (Meier et al. 2007), taking into account ice flow in both glaciers and ice sheets, estimates sea-level rise of 0.5 ± 0.2 feet by 2050 and 1.8 ± 0.75 feet by 2100. Assuming a similar rate over the following hundred years, sea level would rise by about 3.5 feet by 2200. When coupled with subsidence, this will result in the Central Delta lying 34 to 45 feet (locally as much as 50 feet) below sea level, substantially lower than at present.

Both island subsidence and sea-level rise will cause forces on Delta levees to increase in the future. Sea-level rise alone will require that levees be raised to keep pace with that rise. If the levees subside somewhat along with the islands, then levees in much of the Central Delta will need to be raised higher than the sea-level rise alone. It is certain that if the levees are to be maintained, they will need to be raised several feet and widened substantially to accommodate the new sea level and subsidence in the islands over the next two hundred years. Levees along most of the rivers leading into the Delta will also need to be raised several feet, just to keep up with sea-level rise. Both Delta and river levees will also need to be strengthened because the increased hydraulic head from subsidence and sea-level rise will add substantially more stress to the levees' structures and increase their fragility. Because most levees are built on deformable foundations, the large additional weight from increasing height and width will lead to more levee subsidence. It may be extremely difficult, therefore, to build levees large enough and strong enough to accommodate the projected increases in subsidence and sea-level rise. Models based on a much deeper understanding of levee structure than is presently available will be needed to determine if maintaining the levee system is technically or economically feasible. If not, a major rethinking of the role of levees in the Delta will be needed.

Flooding and Storm Surge Effects

Over approximately the last 150 years, there have been from two hundred to three hundred levee breaches in the Sacramento-San Joaquin River system. Florsheim and Dettinger (2007) have shown that there is a direct relationship between high river flows and levee failures. All the years in which levees broke were years in which peak flow was above average. These above-average flows now occur about every two to three years. There is also a strong positive relationship between river levee breaks and Delta levee breaks (see Figure 5.6, and Florsheim and Dettinger 2005).

In the last hundred years, 166 Delta islands have flooded as the result of levee breaks. Florsheim and Dettinger (2007) and URS Corporation and Jack R. Benjamin and Associates, Inc. (2007a) show that there is no evidence from trends in the historic data that recent investments in levee maintenance and upgrading has had any effect on failure rate. The linkage of levee failures to high river flows, and the increased hydraulic forces caused by Delta subsidence, suggests that projected increases in high-flow frequency associated with climate change could dramatically increase the rate of levee failures (Florsheim and Dettinger 2007; URS Corporation and Jack R. Benjamin and Associates, Inc. 2007a).

There have been several attempts to downscale global climate models and couple them with runoff models to predict future river runoff in California (Vicuna et al. 2007; Cayan et al. 2006; Tanaka et al. 2006). Model output for flows under different climate warming scenarios is quite variable, and it is difficult to scale from the longer time-scales of climate models to daily response. However, Tanaka et al. (2006) suggest that under a warmer and wetter climate, runoff during the winter may increase as much as three times. Vicuna et al. (2007) examined more models and found large variability in predicted future streamflows with some streams showing lower flows and others higher flows during the winter months (see Figure 5.7). Although these simulations give a mixed view of future runoff amounts, and may not have high enough resolution to make predictions of individual flow events, they do show that it is likely that the amount and timing of streamflows will change significantly in the future (Dettinger 2005).

Adding to the changes in streamflows will be increases in storm surge (short-term increases in sea level due to storms) (Cayan et al. 2007; Bromirski, Cayan, and Flick 2005; Bromirski, Flick, and Cayan 2003; Flick 1986). Data on storm-surge events show substantial increases over the last 150 years in the Bay-Delta (Bromirski, Cayan, and Flick 2005; Bromirski, Flick, and Cayan 2003). Modeling of projected changes for the next hundred years shows further increases in storm-surge events (see Figure 5.8; Cayan et al. 2007).

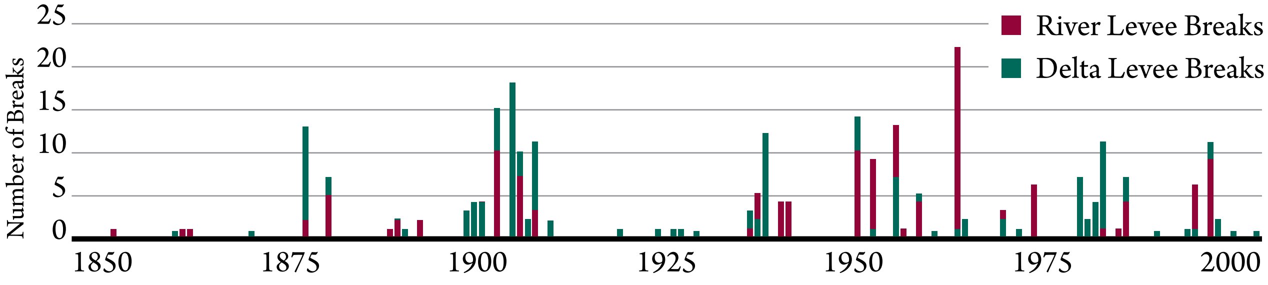

Figure 5.6. Historical failure of Delta levees and river levees. (Source: Adapted from Florsheim and Dettinger 2005; 2007)

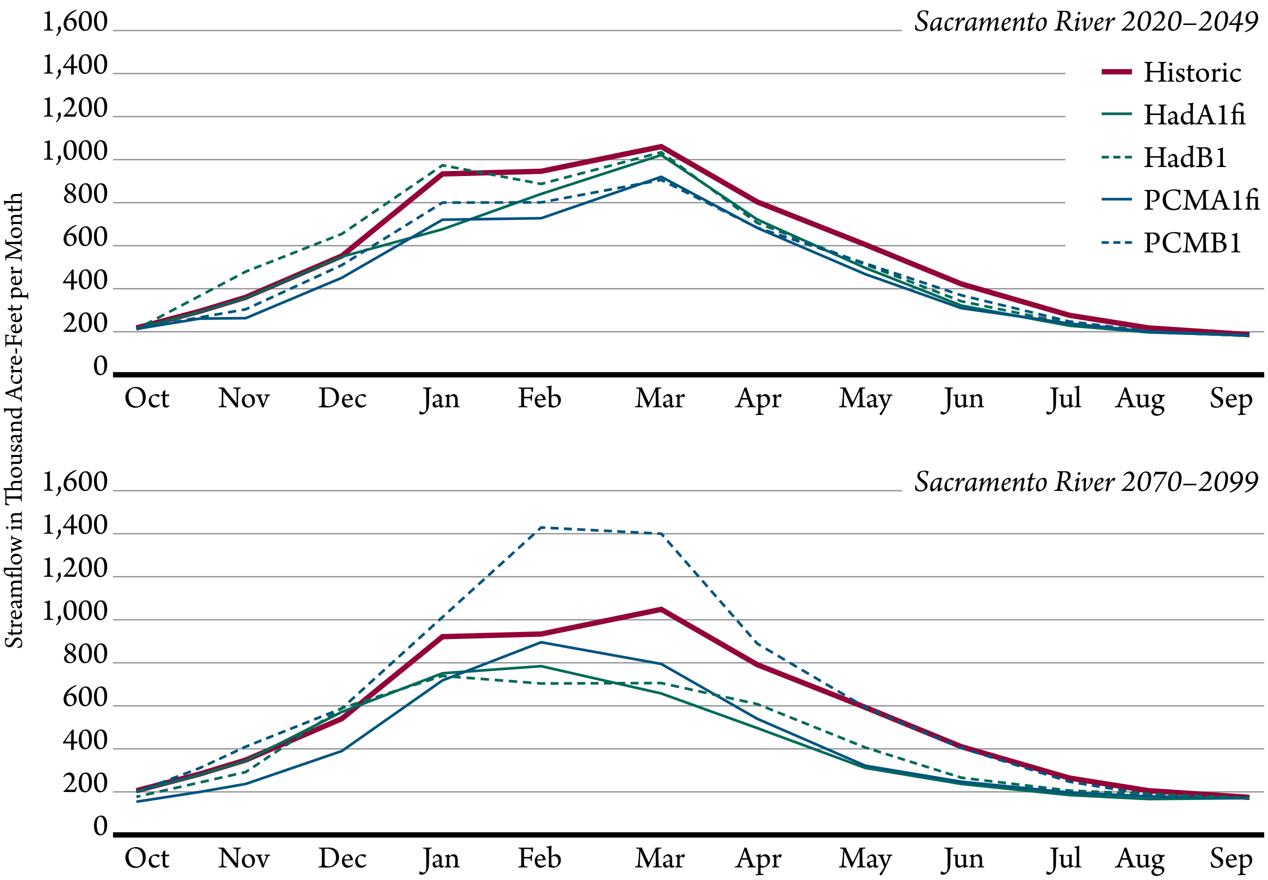

Figure 5.7. Changes in monthly streamflow for the Sacramento River under two different climate models with two different future scenarios of greenhouse gas emissions. The bold line is historic data. (Source: Adapted from Vicuna et al. 2007.)

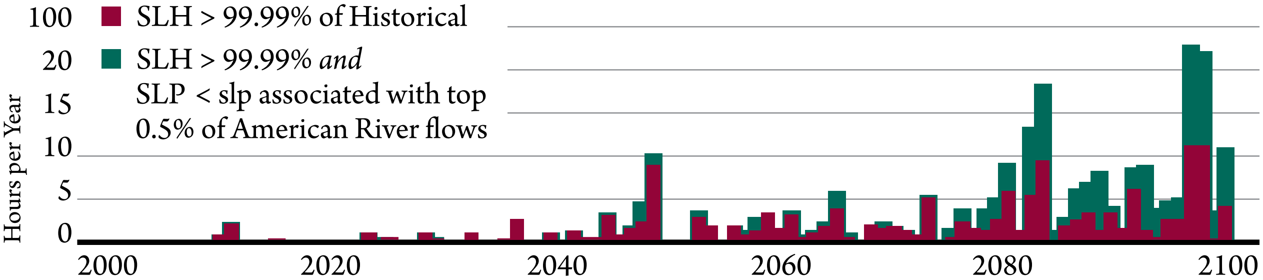

Figure 5.8. Projected increase in extreme sea levels over the next century due to global warming. SLH = sea level height. SLP = sea level pressure. These are indicators of large storm systems and high river flows. Measured in hours per year. (Source: Adapted from Cayan et al. 2007)

Because storm surges are often associated with large rainstorms, they also coincide with high river flows. This will likely add another one half to one foot of sea-level rise during extreme runoff events.

The historical average frequency of levee breaks is about 1.5 per year (URS Corporation and Jack R. Benjamin and Associates, Inc. 2007a). Increased storm surge, mean sea-level rise, and island subsidence, combined with the potential for higher river flows in the future, raise the possibility that levee failures and island flooding will become much more common. This would greatly increase the cost of levee repair and response to flooding. Predicting future hydrographs throughout the Delta region, determining the uncertainty of those predictions, and assessing how the water management system could deal with those changes are critical areas for future investment in science.

Major Themes for Future Scientific Investigation

The above discussion leads to five important themes that need scientific investment:

1. Digital Levee System: Existing data and models should be assembled into a digital database on the levee system. The long-term objective should be to develop a system-wide description of levee composition and a set of computer models that can be used to determine system-level responses to stressors. The database should be used to develop a probabilistic assessment of levee structure and response to stressors, not simply a geotechnical tabulation of levee characteristics. The digital levee system would provide an objective basis on which to plan future investments in levee modification, repair, removal or replacement centered on levee stability and Delta response.

2. New Levee Configurations: With the "Digital Levee System" and directed, large-scale experiments, response to new configurations can be explored. These may include building and testing large-scale models (both computer and physical) of "super levees," with foundations set deep into the Delta's more stable Pleistocene deposits and high enough to restrain rising sea levels for thousands of years. Or, they might include small "hydraulic levees," built by techniques similar to tailings dams and set well back from present levees. Experiments could be conducted to determine the response of levees protecting island reservoirs to large earthquakes. Such experiments might reveal whether seismic-resistant levees can be constructed at all.

3. Reversing Subsidence: A serious effort must be made to find innovative solutions to subsidence, because it is a major underlying cause of instability. Bringing subsided islands back to sea level will require a very long view (hundreds or perhaps thousands of years) and experimentation with new, potentially risky, approaches. Ideas worth exploring include:

1. Constructing low set-back levees behind present levees and allowing the strip between to fill with sediment from artificial crevasse splays and marshes,
2. Increasing sediment loads entering the Delta (by rerouting sediment from upstream reservoirs) and allowing the sediment to deposit in subsided islands,
3. Dredging tidal sediments for island fill,
4. Growing tules in islands and allowing peat to accumulate, and
5. Using mixtures of crops and wetland systems that stimulate organic accumulations.

4. Alternative Flood and Storm Response: Mitigation of flood risks from sea-level rise, high flows, and storm surge requires a watershed-wide response. Modified reservoir operations, gates or weirs that allow some flood flows to be absorbed upstream, as well as gates and weirs that allow deliberate island flooding to absorb additional flows or storm surge in the Delta, all need to be explored. New paradigms of Delta water management, taking into account long-term goals of mitigating subsidence and levee fragility, need to become a prominent part of water planning.

5. Ecological Effects of Levee Stabilization: Levee management has concentrated on *resiliency* —the magnitude of change that can be absorbed by the system without major transformations. As new approaches for maintaining or changing the present levee and island system (for example, flooding islands, setting back levees, levee protection, etc.) are instituted, it is critical to understand how the Delta ecosystem will respond to these modifications. There needs to be a major investment in understanding how the present, highly modified Delta ecosystem functions and how any changes to the system (both intentional and unintentional) affect fundamental processes of the ecosystem. The long-term goal should be to build both a physical and ecological system that is sustainable and highly resilient to future change.

Conclusions

For many decades the Delta has been managed as a large, complex, but relatively static water-distribution system. It is now clear that this is no longer a realistic view of the Delta (Lund et al. 2007). Complex combinations of stresses that are growing more intense, coupled with deteriorating infrastructure, will force major changes in management in the Delta. The past is no longer a guide to the future of the Delta. The insights presented in Mount and Twiss (2005) on "punctuated landscape change" (the nearly instantaneous transformation of a "terrestrial delta" into an "estuarine delta"), followed by the severe impacts of Hurricane Katrina on the Mississippi River Delta and Gulf Coast, have increased awareness about the vulnerability of the Delta and the fragility of its levee system (Sever 2006). We now know that future risks are no longer restricted to occasional individual breaks or flooding of one island. They are much larger, involving many islands simultaneously and affecting infrastructure, transportation, water distribution, energy distribution, ecosystems, and human lives and welfare across a large region.

Integrity of the Delta in some form is critical to secure the future of Delta ecosystems, culture, and water supply (Governor's Delta Vision Blue Ribbon Task Force 2008). But concerns about the environment, endangered species, and the impact of potential climate change have likewise altered the political landscape. The Delta must now be considered in the context of alternative "watershed solutions" that both revitalize Delta ecosystems and continue to supply needed water to a growing population (Lund et al. 2007). This is a very big challenge because the future of the Delta is now more difficult than ever to predict and more costly to plan for.

We now have a deeper understanding of the complicating factors in the Delta and the increasing fragility of its levees. All the stressors discussed above will increase levee fragility tremendously over the next fifty to two hundred years. Higher and better-constructed levees may not meet these long-term challenges to the levee system, but may instead only prolong the inevitable failure and invite increasing damage to life and property as natural processes finally overwhelm engineered structures. The options to deal with these challenges all require a much deeper scientific, engineering, and technical understanding of the levee system and its resiliency under future conditions. This will require addressing the specific scientific and technical needs identified herein, as well as investment in new ideas and innovative new approaches.

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6. Water Supply

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Water is the lifeblood of the California economy. However, the natural distribution of water in California, abundant in the north but scarce in the south, is almost the reverse of the distribution of population and demand for water (Carle 2004). California's 1930 State Water Plan (Department of Public Works 1930) recognized the large inequalities in the geographical and seasonal distribution of water compared to the demand for it. The document states that "the most complete conservation and utilization of water resources, therefore, involves construction of storage reservoirs and utilization of underground basins for full development of water supplies, and also conveyance conduits to carry the supplies from areas of surplus waters to areas with insufficient local water supplies to meet their demands." Successive administrations have responded to this need, and California now has one of the most advanced water supply systems in the nation.

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[1] CALFED Science Program

[2] United States Geological Survey and Scripps Institution of Oceanography

[3] URS Corporation

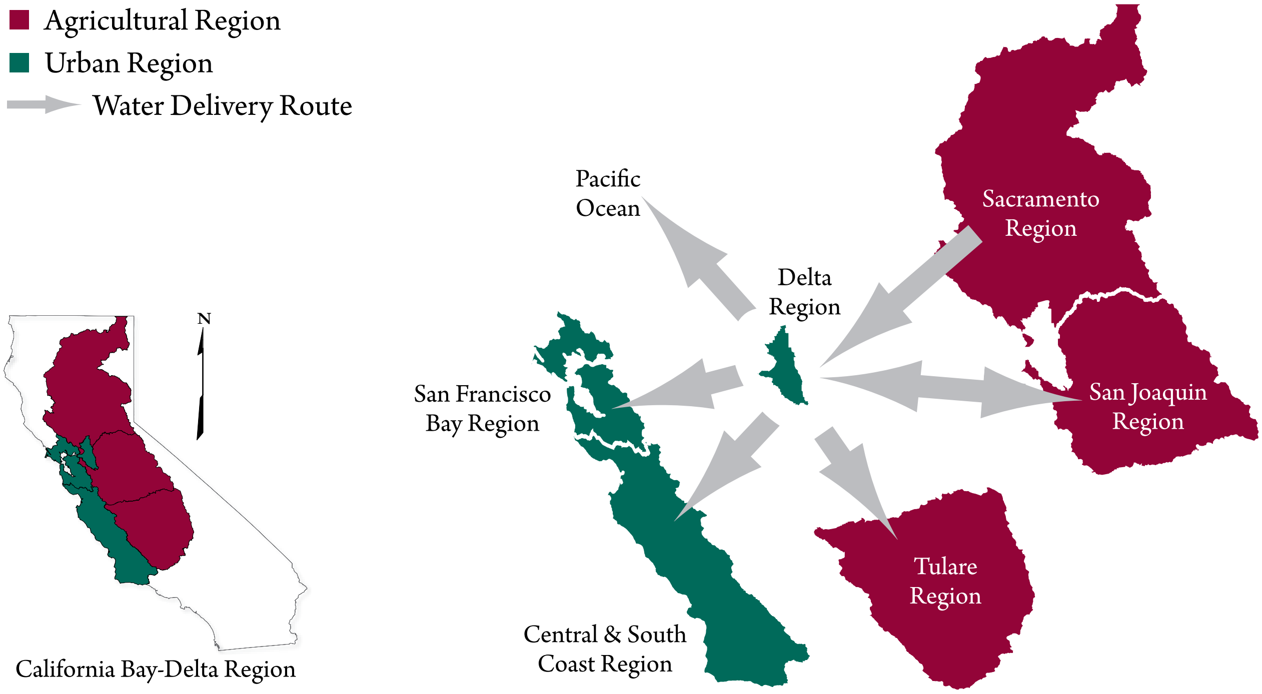

Figure 6.1. Conceptual model of exchange of Delta water supply among California regions. (Source: California Department of Water Resources)

The system is large, complex, highly managed and owned and operated by thousands of entities. The Delta is an important hub in the distribution system, and what happens in the Delta has profound implications for the water supply for twenty-three million Californians and billions of dollars in agricultural production (see Figure 6.1). Details of the water management process and future projections can be found in the California Water Plan (California Department of Water Resources 2005).

This chapter examines recent science related to water supply within the Delta, its watershed and its service area. Water supply is the amount of water available for consumptive and non-consumptive uses. As demonstrated in Chapter 2, California's Mediterranean climate creates wide variations in precipitation, evaporation and in the amount of water that flows in rivers and streams or infiltrates into the ground. As a consequence, water supply varies widely from year to year and season to season. Water supply is also closely related to water quality because quality influences how the water can be used. Water managers often refer to water supply "reliability" as a measure of how well water supplies match various users' needs for water.

We will summarize the science of water supply in this chapter in relation to three major issues:

1. Water supply measurement and forecasting,
2. Managing distribution and allocation of water for beneficial uses, and
3. Understanding the environmental costs and benefits of water allocation, with particular emphasis on the Delta.

Although these issues have always been important to California water policy, they are taking on new significance. Natural water supplies from Central Valley rivers are fully allocated or over-allocated in most years, and there appear to be no attractive options for major new storage. This means that existing water supply must be used smarter and more efficiently and that each new demand for water will necessitate difficult trade-off decisions. Global climate change is expected to change patterns of precipitation, which will have important effects on water availability. As a consequence, management systems and allocation rules will have to be changed to deal with changing conditions. Finally, the declining abundance of native species in the Delta is fueling renewed debate about how much water is needed to sustain a productive ecosystem and how increasing environmental water will reduce water available for other beneficial uses. These challenges highlight the need for a robust science of water supply management that integrates across the multiplicity of demands for a limited supply of water.

Water Supply Measurement and Forecasting

Data Collection

Early Delta water managers had little real data to go on and depended on empirical relationships from eastern United States or European rivers and their own experience to estimate engineering and project needs. Nowadays, data on precipitation, streamflow, snowpack, hydrodynamics, evaporation, water quality, meteorological conditions and biological conditions from a distributed network of sampling stations provide a basis for flow forecasts, inform analyses of management actions and provide feedback for adaptive management. Most of this information is readily available (see Table 6.1).

Precipitation is measured at thousands of gauges by various agencies around the state for purposes such as flood prediction and management, fire risk assessment and water supply management. Nearly all of these gauges are either standard precipitation storage gauges or tipping bucket gauges. These gauges work reasonably well if they are properly placed and shielded from high winds (which is not often done). Standard weather radars have the potential to estimate precipitation in the gaps between gauges. In California, however, the value of weather radar is limited by the rugged terrain. Overall, California's precipitation network is fairly dense and robust, except at higher altitudes. More ground-based precipitation measurements, combined with more remote sensing of storm-generating conditions in the atmosphere, will be required to make substantial improvements in precipitation

Table 6.1. Some of the Key Information Sources on California Water

- **California Data Exchange Center (CDEC)**— provides a wide variety of precipitation, snow, streamflow and other hydrologic data.[1]
- **United States Geological Survey (USGS) Surface-Water Data for California**— provides real-time and historical streamflow data including flow in many constructed diversion facilities.[2]
- **Interagency Ecological Program (IEP)**— provides a wide variety of biological, hydrodynamic, water quality and other data for the Delta.[3]
- **California Irrigation Management Information System (CIMIS)**— provides a network of 120 automated weather stations that are useful in estimating crop water use so irrigation can be scheduled more efficiently to save water, energy and money.[4]

(Source 1: http://cdec.water.ca.gov)
(Source 2: http://waterdata.usgs.gov/ca/nwis/sw)
(Source 3: http://www.iep.ca.gov)
(Source 4: http://wwwcimis.water.ca.gov/cimis/welcomeFaq.jsp?faqType=general)

tracking and forecasting and to document precipitation changes associated with global climate change or local air pollution effects. Air temperature measurement also plays a vital role in flood forecasting by indicating the mix of rain and snow that will fall in the mountains. The California-Nevada River Forecast Center currently uses temperature measurements from about six hundred sensors to produce its forecasts.

California has measured the water content of snowpacks annually since the 1920s, and these measurements form the primary input to the April-to-July water supply forecast by the California Department of Water Resources (DWR). The depth and weight of the snow is measured monthly from February to May or June, at up to 280 snow course sites in high-altitude basins. The state also collects continuous measurements of snow water, temperature and precipitation at 136 snow instrumentation sites. Solar radiation, winds and soil moisture are also measured at some sites. Current snow monitoring methods are unable to characterize the variation in snowpack between stations and sometimes provide inaccurate measurements of snow water content, potentially affecting estimates of water yield. Both of these limitations are being challenged by current research. Many instruments for measuring snow properties have been miniaturized and made more reliable and cheaper. At some snow research sites, measurements are made at dozens of places arranged in clusters that characterize snow variations much better than a single snow instrumentation site. DWR's Cooperative Snow Surveys Program has deployed cosmic-ray detectors of snow water content on an experimental basis, and they may soon offer more accurate estimates of snow water content. Remotely-sensed data are now being incorporated into snow surveys and water supply forecasts. Snow-covered areas can be mapped using satellite imagery. Attempts are underway to combine satellite imagery with computer models of watersheds to estimate snow water amounts across much of the Sierra Nevada. These estimates, in combination with near-term weather forecasts, may soon allow the state to forecast water supplies, hazards and other conditions days to weeks in advance. Currently, rain is monitored mainly at low altitudes and snow conditions at high altitudes, while middle altitudes receive little attention. As the climate warms and the snowline retreats upwards, the lowest snow instrumentation sites will be rendered less and less effective while more of the rain zone will remain under-observed, unless monitoring of middle elevations is increased.

Streamflow gauging stations measure streamflow at over two thousand locations on the state's rivers. The number of gauging stations peaked about 1975 and has since declined about 10 percent (gauges that measure flows upstream of dams have been reduced by 25 percent). The technologies used to measure streamflow in the state have not changed qualitatively for almost a century, so the data have a high degree of historical consistency. However, the instruments and methods for recording river stage and discharge have evolved; floats and mechanical flow meters are being replaced by pressure gauges and acoustic Doppler meters. These newer technologies will gradually supplant older methods.

Groundwater is an important component of Central Valley hydrology and water supplies. In recent years, water levels have been measured regularly at hundreds to thousands of wells in the Central Valley to track over-consumption (overdraft), flow directions and amounts of water in aquifer storage.

Water Supply and Streamflow Forecasting

Seasonal water supply forecasts are required by California law and are essential to annual planning for water allocations. Flood forecasts are essential to management of flood-control structures and mitigation of flood risks. A collaborative team from the National Weather Service (NWS), DWR and the United States Bureau of Reclamation (USBR) produces seasonal water supply forecasts (April-to-July flow totals) and flood forecasts.

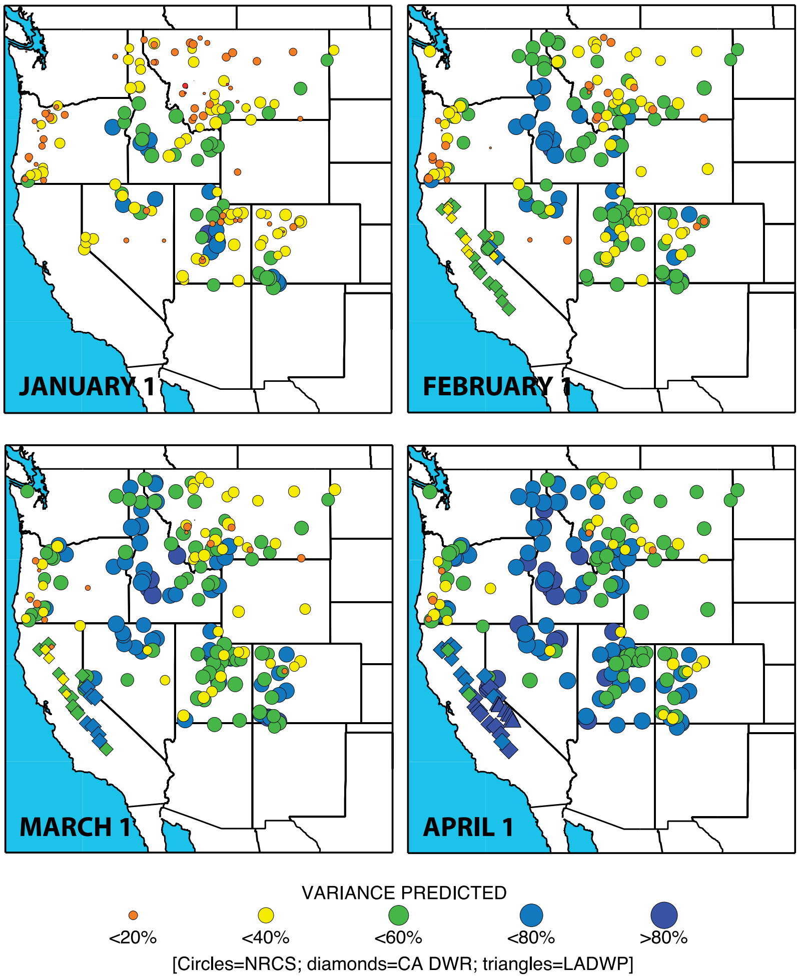

Figure 6.2. Success in predicting April to July water supplies (streamflow volumes) on selected western rivers, as measured by correlations between observed and hindcasted flow totals over each station's period of forecast records. (Source: Mantua et al. forthcoming)

Seasonal forecasts of streamflow are developed monthly from January through May (and sometimes June) by regression models that relate future flow totals to the amount of snow on the ground on April 1, to precipitation, and to observed streamflows. Before April 1, forecasters estimate the inputs to the forecast equation from conditions at the time of the forecast extrapolated to April 1, assuming average weather conditions. For some basin-scale locations, forecasters estimate the flows that have a 10 percent and 90 percent chance of being exceeded. These forecasts are quite accurate, predicting (in hindsight) over 80 percent of the historical variations of April-to-July flow totals (see Figure 6.2). Forecasts for California have been particularly good compared with the rest of the western United States. This is partly because of differences in forecasting methods, but also because California's Mediterranean climate is more favorable to long-lead forecasts of summer flows.

At present, both DWR and the Natural Resources Conservation Service (NRCS) are exploring computer models of flow-generation processes as a means to improve forecasts and in anticipation of climate changes that may invalidate the historical calibrations on which the statistical models depend. Both DWR and NRCS are very dependent on the long time series of precipitation, snowpack, and seasonal streamflow measurements to check and double check their models. This need to validate forecasts against historical data has thus far limited attempts to replace the statistical models with more data-demanding process models.

For flood forecasting, technicians couple the Sacramento Soil Moisture Accounting Model with the Anderson Snow Model in the NWS River Forecasting System to produce forecasts at about seventy locations around the state. They then compare the forecasts with observations and hydrologists' experience to provide final flood forecast guidance through NWS and State-Federal Flood Center communication channels. Forecasting technicians also provide reservoir inflow forecasts, which are developed through the same system, to appropriate water management agencies. The Sacramento Soil Moisture Accounting Model divides the flood-generating basins into a high-altitude subarea (usually above snowline) and a medium-to-low-altitude subarea. Technicians simulate water balances and snowpacks separately for the two subareas, and the resulting outflows are routed through the outlet channels by a unit-hydrograph method (Miller, Bashford, and Strem 2003; Anderson 1973; Burnash, Ferral, and McQuire 1973). This modeling approach is more physically realistic than the regression equations used for seasonal forecasting, but is still sufficiently simple that new kinds of data and changes in climate or land cover are difficult to incorporate. The National Oceanic and Atmospheric Administration (NOAA) is engaged in model testing and data improvements in the American River watershed to improve flood forecasting.[1] As with seasonal flow forecasts, the risks associated with changing forecast methods are large for forecasters, forecast users and the public, so any decision to change forecast models and inputs must meet stringent criteria for success.

One of the most advanced experiments in updating forecast models and water supply management in Northern California is the Integrated Forecast and Reservoir Management (INFORM) project led by the Hydrologic Research Center in Southern California (Georgakakos et al. 2005). INFORM links weather (and climate) prediction models to hydrologic models and thence to reservoir and water supply management models. The study is focused on the Folsom, Oroville, Shasta and Trinity reservoirs, and is being run in parallel with existing management approaches. The economic and other benefits from INFORM are being compared to those from current management practices to determine the value of incorporating weather forecasts into water supply management. Results to date have been quite positive, indicating that moderately improved water management efficiencies may soon be available.

One of the key difficulties that water managers face is a drought. The NWS and National Integrated Drought Information System[2] now routinely produce drought forecasts a season ahead but with varying accuracy of prediction.[3] Drought forecasts more than a season ahead are largely speculative. In the event of a drought, impacts are managed mainly on the basis of lessons learned from historical droughts. Additional information on droughts comes from paleoclimatic reconstructions of prehistoric droughts using tree ring widths and other indicators (see for example, Roos 1992). Experience has shown that cool-ocean La Niña conditions in the tropical Pacific frequently bring drought conditions to California, especially in the southern half of the state. Consequently, global-scale climatic conditions can be used to predict the odds of a drought occurring or continuing (if the Pacific appears to be entering a La Niña state) but the reliability of such prediction is generally low at lead times of more than a few months. More important-

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[1] See for example, http://www.cosis.net/abstracts/EGU06/10308/EGU06-J-10308-1.pdf, and www.cosis.net/abstracts/EGU06/09567/EGU06-J-09567.pdf

[2] See http://www.drought.gov

[3] To view the National Integrated Drought Information System's reports, see http://www.cpc.ncep.noaa.gov/products/expert_assessment/seasonal_drought.html

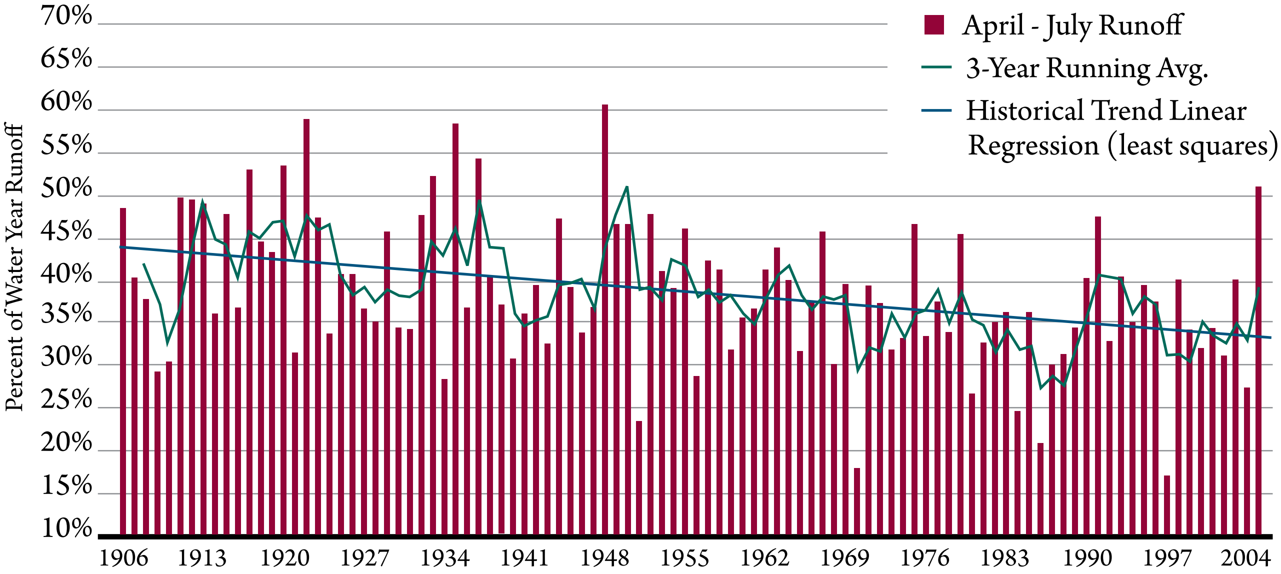

Figure 6.3. Sacramento River Spring Runoff, an indication of snowmelt, has been decreasing for years. Measured in percent of Water Year Runoff. (Source: California Department of Water Resources 2005.)

ly, Northern California is situated in the transition zone between areas where La Niña favors drought and areas where La Niña favors wet winters (Cayan and Webb 1992). This zone is a particularly difficult place to predict precipitation or drought. Droughts of terrifying length and intensity have been detected in paleoclimate records that extend back more than one thousand years (Stine 1994). These droughts are so far beyond any that have occurred during the European era in California that they severely challenge any feasible management scenarios (Harou et al. 2006). We cannot predict when or if such a long-term drought will occur in the future. Proactive approaches to adaptation and mitigation are the most practical responses.[4]

Scientists have worked hard over the past decade to determine the likely effects of climate change on water supply reliability in California. Analyses suggest that temperatures will warm, more precipitation will fall as rain rather than snow, and snowmelt will be earlier so there will be less water stored in snowpacks by spring (Knowles, Dettinger, and Cayan 2006; Knowles and Cayan 2004; Mote 2003). Streamflows will also peak earlier (Stewart, Cayan, and Dettinger 2005; Dettinger and Cayan 1995; Roos 1991), and growing seasons will be longer (Cayan et al. 2001). Other expected impacts of warming include increased flood risk, higher stream temperatures, less groundwater recharge (see for example, Dettinger and Earman 2007), greater warm-season water demands and poorer water quality. Streamflow monitoring shows that spring runoff, as a fraction of total yearly runoff, has been decreasing for a long time (see Figure 6.3).

State agencies and University of California, Davis (UCD) researchers have explored management responses to global climate change and other water supply challenges with the DWR-USBR CALSIM II water supply simulation model (California Department of Water Resources 2006) and the UCD CALVIN (California Value Integrated Network) water-economics model (Lund et al. 2003; Jenkins et al. 2001). Development continues on these and other models, such as the Central Valley Model (CVMod, Van Rheenan et al. 2004) and the Water Evaluation

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[4] See for example, http://www.drought.unl.edu/, and http://www.drought.gov/portal/server.pt

and Planning Model (WEAP, Yates et al. 2005). In general, these models indicate that changes in precipitation will have a greater effect on California water supply than changes in temperature. Unfortunately, model projections of precipitation are much less certain than projections of warming (Dettinger 2005), so that model results only provide limited help with planning. Modeling studies have also focused on monthly changes and do not represent the important conflict between creating reservoir storage space for cool-season flood management versus keeping reservoirs full to maximize warm-season water supply. Until this tension is integrated into water supply studies, the full extent of supply vulnerability will remain uncertain.

Managing Distribution and Allocation of Water for Beneficial Uses

The California water storage and distribution system includes dozens of reservoirs, thousands of miles of stream channels and canals, and thousands of diversion points both large and small. This complex system must be managed to satisfy the demand of thousands of users pursuing different beneficial uses of water with different priorities of access. Computer models provide the only feasible means of implementing water management policy efficiently. Over the past decade, two models in particular, CALSIM and CALVIN, have been developed to understand management of water distribution and allocation. However, neither CALSIM nor CALVIN is used to manage state water distribution and allocation programs. Operational decision-making on a day-to-day basis relies on operator expertise, past experience, and a series of regulatory requirements throughout the system.[5]

CALSIM is a generalized water resource planning model used primarily to evaluate water supply reliability in relation to infrastructure or modes of system operation. DWR and USBR developed CALSIM in the late 1990s. CALSIM replaced models that each agency had been using independently to plan water operations for the Central Valley Project (CVP) developed by USBR, and the State Water Project (SWP) developed by DWR. CALSIM allows integrated modeling of water supply and management across much of the Central Valley water management infrastructure and establishes a common platform for water management decision-making. CALSIM has gone through two iterations (CALSIM I and CALSIM II) and is entering its third (CALSIM III). As the default model for inter-regional or statewide analysis of water in California, CALSIM is critical to integrated water resource management planning. Because CALSIM allows exploration of management policy under different hydrologic regimes and different water distribution and storage infrastructures, it is also critical to planning for changing future conditions involving climate change, shifting water demands and environmental regulations.

CALSIM uses linear programming and optimization routines to route water through the distribution network over time. It currently updates calculations in monthly time steps. Water management policies and priorities are implemented in the model through user-defined weights applied to various flow routes in the system. CALSIM draws its water input information from the extensive system of flow monitoring and forecasting discussed earlier and sets of reservoir operating rules. Reservoir operating rules can be modified in exploratory runs of the model to evaluate alternative management scenarios.

In 2003, a panel of modeling experts reviewed CALSIM II and provided recommendations for improving the modeling of water supply reliability (Close et al. 2003). The panel described CALSIM as state of the art in modeling complex water basin management and identified a number of key strengths, including the fact that CALSIM provides a common hydrologic representation of

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[5] See DWR Project Operations Center at http://wwwoco.water.ca.gov/indexo.html

the CVP-SWP system, which enhanced efficiency of water supply planning and delivery. Because CALSIM is data-driven, it is generally more flexible and transparent than its predecessors or other traditional water-resources simulations. The model also incorporates better groundwater and water quality representation than previous models, although these features of the model are still somewhat limited.

The panel also noted a number of weaknesses in CALSIM that could be addressed as new iterations of the model are developed. The model had not been thoroughly calibrated against historic experience, so the accuracy of model predictions could not be assessed. Furthermore, the model provided limited coverage of non-CVP-SWP water and of the California water system south of the Delta. A statewide water supply management model is an important future step toward fully integrated water supply management. The model also represents complex, non-linear hydrologic processes with linear equations. This is a necessary simplification for taking advantage of linear optimization, but it might be avoided in future models if hydrologic modeling were separated from optimization. Finally, the model in its current configuration is too cumbersome for either real-time evaluation of policy alternatives during a critical water situation (that is, a drought or flood) or for wide-ranging exploratory analysis of policy or infrastructure changes. Work currently underway on the next iteration of the model, CALSIM III, will address many of the review panel's concerns.

CALVIN is an integrated economic-engineering optimization model of California's intertied water system. It was developed at UCD in the late 1990s for water policy, planning, and operations studies (Draper et al. 2003; Jenkins et al. 2001). CALVIN is maintained and administered by UCD's Statewide Water Management Modeling Group.[6] CALVIN's objective is to minimize the operating and scarcity costs of water supply, subject to water balance, capacity, and environmental constraints. The CALVIN model is an enhancement of the Hydrological Engineering Center Prescriptive Reservoir Model (HEC-PRM) code developed by the United States Army Corps of Engineers (Hydrologic Engineering Center 1991). As a combined, economically driven, engineering and optimization model, it produces traditional engineering outputs as well as useful economic results. It is also capable of providing shadow values (the extra benefit or cost that results from a small relaxation in modeled constraints—often used to price intangible values like clean air or water pollution) for infrastructure, environmental and policy constraints. Unlike traditional simulation modeling approaches, CALVIN does not reflect the water system operating rules specified by the State Water Resources Control Board and environmental regulations. A water rights system controls allocation, but the model allows exploration of changing hydrology, demand and infrastructure (Jenkins et al. 2004; Draper et al. 2003). As with CALSIM, CALVIN has not been calibrated against historical experience to assess the accuracy of model predictions.

CALVIN is the first model to represent explicitly the waters of the entire Central Valley, imports from the Trinity system, and Colorado and Eastern Sierra supplies to major water users of California. CALVIN's geographic domain stretches from the Shasta-Trinity system to the All-American Canal adjacent to the Mexican border. In addition, CALVIN simultaneously optimizes across surface water and groundwater supplies and major water demands. The CALVIN model covers 92 percent of California's population, 88 percent of its irrigated acreage, and includes 704 distribution nodes (including 51 surface reservoirs, 28 groundwater basins, 19 urban economic demand areas, 24 agricultural economic demand areas, 39 environmental flow locations, 113 surface and groundwater inflows, and numerous conveyance and other links).

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[6] For more on CALVIN, see
http://cee.engr.ucdavis.edu/faculty/lund

UCD researchers have used CALVIN to explore the potential for California's water system to adapt to a variety of future water supply conditions, including projected changes in temperature and precipitation under climate change (Tanaka et al. 2006). Model projections indicate that the California water system is quite flexible and has the capacity to adapt to rather severe representations of population growth and climate change (Harou et al. 2006). Adaptation will be costly in absolute terms but should not seriously threaten California's prosperity. However, adaptation could have major effects on the environment and agriculture. Agriculture in the Central Valley is particularly vulnerable to climate change. Wetter hydrologies could increase water available for agriculture, but the driest climate-change hydrology would reduce agricultural water by about one third.

Because of continued population growth and global climate change, water use in Southern California is likely to become predominantly urban in this century, with Colorado River water being diverted from agriculture to urban uses. Given the high dependence of Southern California on imported water and the physical limitations on import infrastructure, this region is already committed to high levels of wastewater reuse and desalination to meet future water needs (Tanaka et al. 2006).

Although modeling analysis of water supply management suggests that adaptation to anticipated future climate change and population growth is possible, the challenges are formidable and the costs will be high. New technologies for water supply and treatment must be coupled with highly integrated and cooperative management if the challenges are to be met. Otherwise, conflict and controversy over water allocation and use will intensify.

Implications of Delta Hydrology for Water Supply and Ecosystem Function

Delta Hydrology

The complex flows in Delta channels are difficult to monitor accurately, but in the past decade accuracy has been improved by deployment of acoustic sensors. Accurate and continuous discharge measurements were needed to allow the long-term average, net, or residual flows to be identified in the midst of major and minor tidal reversals and salinity effects.[7] The Delta-Flows Network provides long-term flow data at thirty-five acoustic Doppler current profilers and velocity monitors operating throughout the Delta (Jon Burau, pers. comm. 2007). These data are used daily by water project operators and scientists to improve operations and understanding of the subtle workings of the Delta.

Increasingly sophisticated models are generating more fully rendered hydrodynamic understanding of conveyance routes and structures of interest in analyses of Delta operations or responses of the ecosystem to hydraulic manipulation. Models such as DSM2 HYDRO developed by DWR, RMA2 developed by Rsource Management Associates (Resource Management Associates 2007), and associated particle tracking modules (PTM) appear to provide reliable hydrodynamic simulations of proposed changes in Delta configuration. Other models (Delta TRIM and TRIM3D) have been used to address hydrodynamic functions underlying biological and geochemical processes in the Bay-Delta (Monsen, Cloern, and Burau 2007; Monsen, Cloern, and Lucas 2002). For simula-

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[7] See for example http://ieeexplore.ieee.org/iel4/6109/16339/00755228.pdf?arnumber= 755228

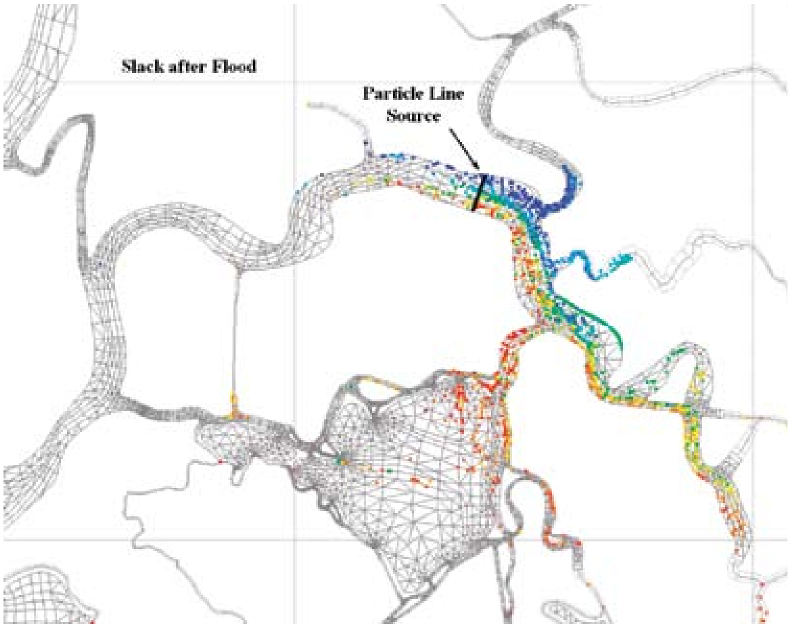

Figure 6.4. Particle Tracking: San Joaquin River near Mokelumne River. Details of the finite element grid used within RMA2. The image shows the locations of particles at some time after their simulated release. Results are shown for illustration purposes only. (Source: Resource Management Associates 2007)

tion models like those mentioned here, increasing model resolution and geographic extent came at greatly increased computational complexity and cost. Therefore, it is important to avoid overextending or over-resolving particular model outputs. In other words, one needs to be careful when applying existing models to novel situations. We reemphasize what has been exhaustively stated elsewhere (see for example, Jorgensen and Bendoricchio 2001), that models are tools for exploration of understanding. Care in their application is always warranted and use beyond their stated purposes is done at the user's peril. Nonetheless, these models have proven valuable in characterizing alternative Delta configurations and in aiding our understanding of the hydrodynamics resulting from various proposed modifications to Delta geometry or inflows.

Franks Tract and Mildred Island Dynamics

One- and two-dimensional representations of Franks Tract and Mildred Island within RMA2 simulations have revealed the complex flow and mixing patterns within the tidal portions of the Delta (see Figure 6.4).[8] Studies to date have revealed key ways in which these flooded islands enhance salinity intrusion and mixing locally and regionally (see for example, California Department of Water Resources 2007). On the incoming tide, seawater enters the open bowl of the flooded island but, because of the complex tidal flows through channels around the flooded islands, the salt water is not all flushed

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[8] See Through-Delta Facility, Franks Tract, and Delta Cross Channel working group meetings: http://www.calwater.ca.gov/calfed/library/Archive_Conveyance.html#meeting

out on the ebbing tide. The flooded islands thus act like large 'mixing bowls,' increasing the dispersive mixing and the residence time of the salinity that enters on the flood tide. The net result can be a 5 to 10 percent increase in local and regional salinity over weeks or months and, under some conditions, even more salt can be trapped for longer periods.

Additional investigations using Delta TRIM model simulations have yielded surprising insights regarding biological and ecological responses to hydrologic forcing (Monsen, Cloern, and Burau 2007; Monsen, Cloern, and Lucas 2002). For example, numerical simulations of flows near Mildred Island have shown that when the export pumps are operating at high capacity, Sacramento River water contributes proportionally more to water found within the flooded basin of Mildred Island, but when the pumps are turned off, San Joaquin River water returns. This is a graphic illustration of how the export pumps can alter local hydrodynamics and water quality. These effects also have ecological implications, since the two water sources differ in water properties and water quality.

Improvements in Export Water Quality

More sophisticated hydrodynamic modeling has allowed water managers to explore ways to reduce salinity and dissolved organic carbon (DOC) in export water by modifying channel geometry. Even low concentrations of salt and DOC in drinking water can greatly increase water treatment costs. Reductions in both salt and DOC in exported water have been found in simulations run with barriers or modified flow regimes in the area around Franks Tract or Mildred Island (RMA, as described in California Department of Water Resources

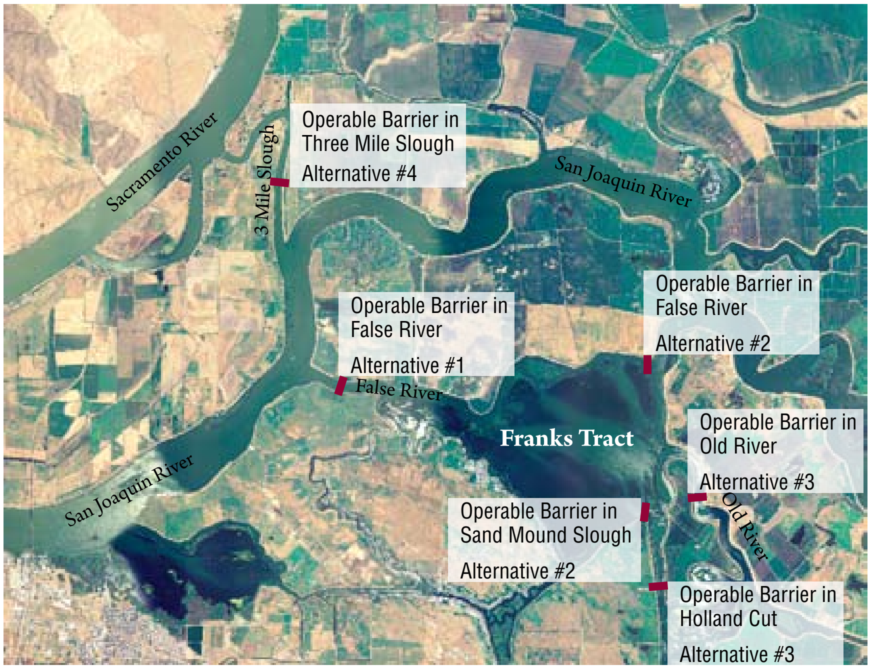
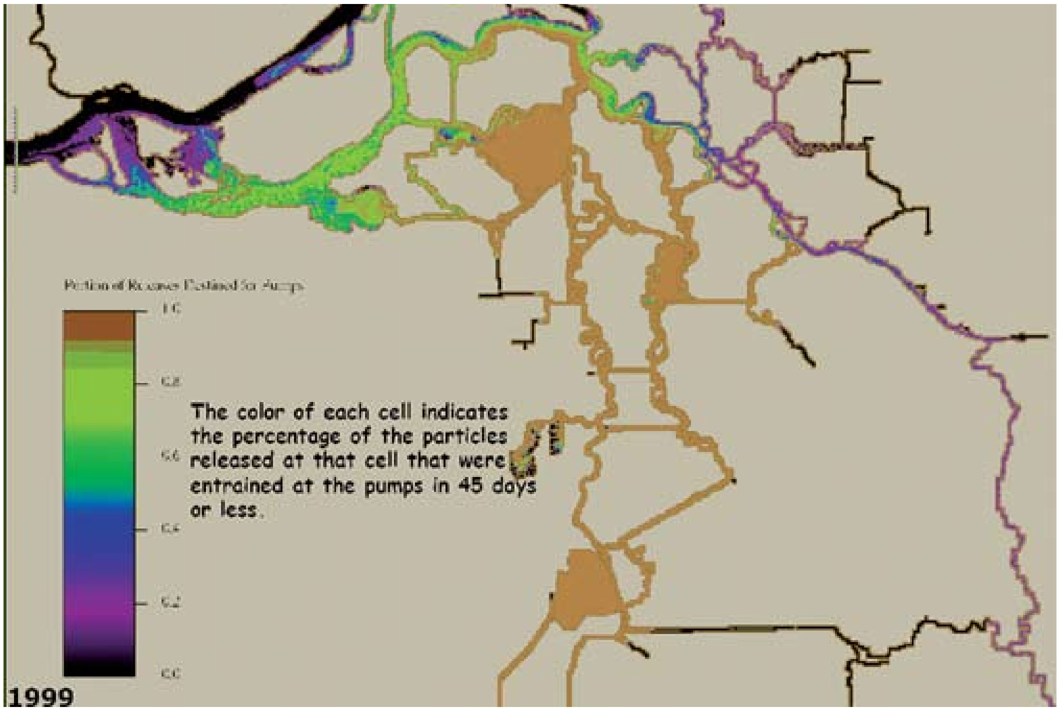


Figure 6.5. Franks Tract Project Alternatives. DWR and USBR propose to implement the Franks Tract Project to improve water quality and fisheries conditions in the Bay-Delta. The project would consist of constructing and operating one or more flow control facilities in the Franks Tract area that would allow better management of hydrodynamic conditions to improve salinity levels and protect at-risk fish species in the Central and South Delta. (Source: California Department of Water Resources 2007, see also http://baydeltaoffice.water.ca.gov/ndelta/frankstract/index.cfm)



The color of each cell indicates the percentage of the particles released at that cell that were entrained at the pumps in 45 days or less.

Figure 6.6. Percent of Particles Entrained at Pumps for Aug 15 Particle Release. Display of results from particle fate mapping using August 15, 1999 as the simulated condition for the Delta. (Source: P. Smith, USGS, unpublished material)

2007). Specifically, the installation of an operable barrier in the western end of False River has been shown to reduce the amount of higher-salinity water moving into Franks Tract from the San Joaquin River by approximately 2 to 18 percent. Further simulation experiments using updated versions of RMA2 and DSM QUAL demonstrated that an operable barrier within Three Mile Slough could improve export water quality as much as or more than repairs or modifications to Franks Tract (see Figure 6.5). In one simulation, researchers found a reduction of up to 27 percent in salinity for the simulated month of September 2002 (Strategic Value Solutions, Inc. 2007; California Department of Water Resources 2007).

Particle Tracking Experiments in the Delta and Suisun Marsh

Two reports have employed the particle-tracking module (PTM) with DSM2 to explore how Delta hydrology might affect the dispersal of neutrally buoyant particles (such as plankton or fish larvae). Culberson et al. (2004) examined the likelihood of entrainment into a diversion located in Goodyear Slough in Suisun Marsh and found that entrainment decreased quickly with distance from the diversion. In a much more exhaustive study, Kimmerer and Nobriga (2008) found that entrainment rates are related to a number of factors (including release location, timing of particle release, phasing of tides and hydrology). Nevertheless, large portions of the Delta are within the entrainment zone of the export facilities in the South Delta. The timing and volume of the exported flows are critical to the rate particles are entrained.

Using a different modeling approach, Pete Smith (pers. comm. 2007) also found that entrainment is probable for much of the South and Central Delta under a range of conditions. Figure 6.6 illustrates Smith's results for a low natural flow (typical of late summer). Over a period of forty-five days of simulated particle movement, particles released throughout the South and Central Delta were very likely to be entrained at the pumps. Sacramento River flows at Freeport averaged 16,000 cubic feet per second (cfs) over the course of the simulation and the San Joaquin River flows at Vernalis were 2,000 cfs. Export pumping averaged 11,300 cfs over the simulation period and the barrier at the head of Old River was simulated as installed and closed. In this example, 300,000 to 400,000 particles were released to develop an accurate measure of the proportion of particles that arrived at the pumps from different areas of the Delta during the forty-five-day simulation run. At other times of the year, or under different hydrologic conditions (during winter high outflows, for example), or under changed export flows, the proportion of particles entrained would be different.

Although these model results are very instructive, we do not know if organisms like larval fish and plankton can be adequately represented as neutrally-buoyant particles. Improved modeling approaches will need to explore more fully the behavior of organisms in a given hydrodynamic environment and the extent to which the Delta may be described using typical environmental characterizations. Applying more complex behavior to particles within these models (for example, swimming) will demand a higher resolution of the finite element grids and three-dimensional rather than two- or one-dimensional models.

Conclusions

California has a limited supply of fresh water to share among ecosystem, agricultural, and urban uses. This water supply is not 100 percent reliable for any of these uses. Water supplies vary with time, water demands vary with time, and they do not always match. The California water system is already highly developed and managed, with limited opportunities to allocate water for new uses without impacting water available for existing water uses. There is very little flexibility left in water operations to respond to growing demands or other changing conditions. As pointed out in the California Water Plan Update (California Department of Water Resources 2005), water managers need to diversify their portfolio by using all available management strategies. No single strategy, such as surface storage or water use efficiency, can meet future needs.

Science has played a major role in informing decisions about water supplies and their allocation through improved monitoring, computer modeling, research, water management strategies, planning, and project operations. Science will continue to be a major source of policy-relevant information as water managers search for ways to optimize water use in the face of changing demand and supply under a growing and evolving economy, a changing climate and an expanding population.

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7. Integration Among Issues of Water and Environmental Management

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Chapters 3 through 6 of this report address the state of science related to the four pillars of the CALFED program: water quality, ecosystem restoration, levee integrity, and water supply. These chapters point out how scientific thinking about the Bay-Delta has changed in recent years. During the last decade, the joint work of academic institutions, government agencies, and stakeholders has contributed to a better understanding of the challenges that face all Californians—challenges that occupants and users of the Bay-Delta face in particular.

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[2] CALFED Science Program

[3] Roy J. Shlemon and Associates, Inc.

[4] California Department of Water Resources, retired

Each of the earlier chapters addresses the interacting components within its subject area; however, the interactions that cut across the chapters are not addressed. Yet, these interactions often define the system as a whole, its dynamics and its frailties. And it is to these cross-cutting interactions that we often must look to understand the problems of the Bay-Delta and potential solutions to those problems. In this chapter, we reiterate the drivers of change in the Bay-Delta and define through examples what we mean by linkages among components of the system. We then use a slightly more detailed analysis to demonstrate how these drivers and linkages lead to interconnectedness in the Bay-Delta system. Seismic-induced catastrophic levee failure, manifestations of climate change like prolonged drought, threats of species extinction and approaches to ecosystem restoration all cut across ecosystem restoration, water supply, water quality and levee integrity in ways that are integral to the hard choices that must be made about the future of the Bay-Delta.

Drivers of Change

Six of the major drivers of change that affect the Delta, its integrity and future health have been highlighted in recent scientific discussions (Lund et al. 2007; Mount, Twiss, and Adams 2006): seismicity; land subsidence in Delta islands; sea-level rise; regional climate change; population growth and urbanization; and exotic invasive species. The availability of high quality water for agriculture, urban uses, and ecosystems is affected by climate and the other five drivers. But it is also a driver of change itself. Concerns about availability of high quality water drive the management of endangered species, the fate of irrigation drainage and treatment of drinking water, for example. Chapter 4 emphasizes several specific ways in which human activities are important drivers in the Bay-Delta ecosystem. Human uses of water for agriculture, for industry, for drinking and as a waste dump can conflict directly with ecosystem uses of water. Likewise, building levees and draining wetlands for agriculture, constructing roads and utility corridors, urban development and other human uses of land all have negative impacts on native aquatic and terrestrial species. It is well-recognized that management policies need to balance human uses of water and land in the Delta with respect for, and stewardship of, nonhuman species and natural ecosystems (Governor's Delta Vision Blue Ribbon Task Force 2008). But there is no consensus on how to accomplish that goal, partly because of the complexity of the drivers of change. Scientific studies continue to show us that every policy choice involves tradeoffs. Providing water to support the needs of both people and the ecosystem requires that we understand the drivers of change, develop management strategies that embrace the change they will bring, and face up to the hard choices that must be made.

Linkages Among Components

The drivers of change illustrate the cross-cutting ecological, social and economic interactions that are characteristic of every challenge we face in the Delta. Solutions to such complex, multifaceted challenges are not impossible. But they lie in a broad, holistic view of the system that is sometimes lost when we feel compelled to focus on the most immediate crisis. In addition, it is likely that we will continually have to reexamine and redesign every solution on a regular basis if we are to keep up with the pace of change. As our understanding grows, it is increasingly apparent that the drivers and the Bay-Delta ecosystem itself are in a constant state of change. Chapter 8 emphasizes that dealing with the drivers of change will require that water management strategies of the future, including changes in infrastructure, be "robust to uncertainty and designed to respond to conditions that might change rapidly." Solutions will have to evolve as the system changes. The need to adapt California's massive water management system to a very different climate in the future is a good example. Such examples suggest that robust solutions are more likely if they are multifaceted and flexible.

It is also important that we recognize the tradeoffs among linked issues, even if they might seem insurmountable. Understanding tradeoffs can point toward mitigation or even unexpected solutions; denying tradeoffs can lead to deadlock or unpleasant and unpopular surprises. High concentrations of salts, including selenium, in the irrigation drainage of the western San Joaquin Valley that contaminate soil, the San Joaquin River and the Bay-Delta, is an example of a complex problem that raises many contentious tradeoffs. Large-scale solutions that involve pumping the contaminated drainage out of the valley appear simply to transport the problem or create new problems elsewhere. Not dealing with the problem brings its own unpalatable consequences. All the proposed solutions demand difficult tradeoffs, but even as the debate continues over large-scale out-of-valley fixes, positive progress in addressing some tradeoffs is being made through multiple small-scale, local actions. The lessons of this example are that large-scale engineering solutions, even if technically feasible, may create more problems than they solve, and may be neither very robust nor flexible. Small-scale solutions, on the other hand, may address local problems efficiently and involve tradeoffs that are more tractable.

The complex linkages that make problem-resolution difficult are not always obvious, especially in the heat of debate. Table 7.1 presents six sets of such linkages to show how a number of difficult considerations affect every issue. These sets of linkages are themselves interrelated. Some of the interrelationships sketched in Table 7.1 are illustrated by the life cycle of one of the icon species of the Bay-Delta, the Chinook salmon (*Oncorhynchus tschawytscha*) (see Text Box 7.1).

Text Box 7 7.1. Chinook Salmon
(Oncorhynchus tschawytscha)

(Photo by: California Department of Water Resources)

The ecology and management of Chinook salmon illustrate large geographic-scale linkages involving the Bay-Delta, its watershed, and the Pacific Ocean. Prior to major dam construction, Chinook salmon spawned in upstream tributaries and the main channels of both the Sacramento and San Joaquin Rivers. Much of their historic spawning habitat has been lost due to dam construction, but four races of Chinook still spawn in the Sacramento-San Joaquin systems, more than any other river system (Williams 2006; Healey 1991). Some Chinook fry use the tributaries and the main channels of the rivers as nursery habitat, whereas others simply pass through these waterways on their way to the Delta or the Bay. In terms of flow, temperature, and water quality, all Central Valley river habitats have been degraded by land and water development (Williams 2006). The Delta also provides nursery habitat for Chinook salmon. However, the kinds of tidal marsh and adjacent tidal channel habitats that Chinook typically use in other estuaries have been largely eliminated by the construction of levees to create agricultural land in the Delta. Whether the Delta was a valuable nursery for Chinook salmon in the past is unknown, but scientific study over the past few decades suggests that it is of limited value in its present configuration. Salmon passing through the Delta do not grow very well and appear to suffer high mortality in the Central and South Delta (in part because of entrainment into the export pumps and into Clifton Court Forebay, where they are vulnerable to a suite of non-native predators, including striped bass and largemouth bass). Continuing species invasions in the Bay-Delta have also eliminated preferred prey species (large copepods and mysid shrimp). Evidence for the importance of former floodplain habitats emerged when migrating salmon in the flooded Yolo Bypass were found to grow very rapidly (Sommer et al. 2001). Unfortunately, intermittent flooding of remnant floodplain habitats, like Yolo Bypass, can also enhance the production of methylmercury, the most bioavailable and toxic form of mercury).*

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* Discussed in greater detail in Chapter 3

(Text Box 7.1 continued)

In the ocean, Chinook salmon are vulnerable to a number of factors that are known to affect overall abundance, including recreational and commercial fisheries and changing ocean conditions. Maturing adults returning from the ocean must find their way through the Delta and upstream to spawning areas. The cues that salmon use to find their way during this migration (flow patterns, odors in the water) and water quality conditions that permit the fish to migrate at all (dissolved oxygen, temperature, toxic contaminants) are greatly affected by water development and by discharge of toxic substances from urban, industrial and agricultural development. For Chinook salmon bound for the San Joaquin River in particular, low flows through the Stockton Deep Water Ship Channel can result in low oxygen levels that block upstream migration, while export pumping can reverse flows in Old and Middle Rivers, confusing and delaying upstream migration.

The linkages for salmon, thus, run from the oceans to the highest accessible headwaters. Human activities from water exports to waste disposal affect their well-being. Natural conditions from flooding to temperature determine the success or failure of populations. Salmon are an icon for how the Bay-Delta ecosystem is interconnected in complex and intimate ways.

Four Examples of Complex Multifaceted Problems

Detailed analysis of an issue can illustrate linkages among processes affecting the Bay-Delta, and thereby point toward potential surprises and perhaps even unsuspected avenues of resolution. Below, we briefly discuss four case studies as a way to illustrate such linkage analyses. These are all cases that have been increasingly recognized to be critical as scientific understanding of the Delta has grown. The linkages that characterize each case are many and diverse. Most experts reason that ecosystem-based management, taking some risks with adaptive experimentation, and learning from both successes and mistakes are the most effective ways to address the issues raised by such cases (Healey 1998).

Case Study 1: Catastrophic Levee Failures Due to Earthquake

Managers have long recognized the risks posed by a major earthquake in the Delta, but the potential deleterious economic, social and ecological impacts are now a much more serious concern. This is in part because implications are now better-understood. The risk of massive levee collapse is a good example of an issue with impacts that extend through levee integrity, water supply, water quality and ecosystem function (see Text Box 7.2). Consequences include massive large-scale flooding, loss of water for export, destruction of local infrastructure, loss of property and perhaps loss of life (Mount and Twiss 2005). These consequences will be even more devastating if Delta urbanization and land subsidence continue unchecked. Such a disruption would also have complex but uncertain ecological implications, both negative and positive (Lund et al. 2007).

Case Study 2: Regional Climatic Variability and Unidirectional Climatic Change

California's water managers once viewed climate variability and change as beyond their purview. With advances in the science, it is now well recognized that climate change and variability have broad implications for every aspect of water and environmental management and are essential considerations in any plan for the future. The trends toward reduced water storage due to the loss of snowpack, earlier runoff, larger floods and more extreme events have obvious fundamental implications for life in semi-arid California. But the interconnectedness of the issue is perhaps best illustrated by a linkage analysis of one scenario: prolonged drought. A regional drought has implications for freshwater inflows to the Delta. But a drought would also affect: water quality; the availability of water for export to other parts of the state; the survival of endangered species; the health and safety of Delta occupants;

Table 7.1. Six Examples of Linkages Among System Components that are Characteristic of the Bay-Delta System, Including its Watershed

1. **Hydraulic linkages** between tributaries flowing into the Delta (both upland streams and major rivers), export pumping, Delta outflows and tidal inflows illustrate how the larger system is hydraulically interconnected.

   Some closely interrelated factors include: irrigation withdrawals; agricultural return flow; land use; conveyance policy; water demand; municipal and stormwater discharge; and seasonal migration of anadromous fish.

2. **Levee integrity** is linked to island subsidence, seismicity, sea-level rise, changing precipitation patterns, increasing storm intensity, lack of maintenance, Delta land use patterns, erosion, reservoir management and storm surge.

   Some closely interrelated factors include: human population growth; demand for agriculture; emergency response; water supply; and water quality.

3. **Ecosystem integrity** is linked to species invasions, environmental water supply and water quality, management of endangered species, urban runoff, urban development, use of agricultural lands, legacy chemicals, Delta geometry and hydrodynamics and land use change.

   Some closely interrelated factors include: international shipping; horticulture and aquarium trade; geomorphic and hydrologic variability; and oceanic regime change.

4. **Climate** or regional responses to warming at the global scale is linked to changing precipitation and runoff patterns, reservoir storage capacity, reservoir operating rules, water use efficiency, sea-level rise, water exports, fluctuations in prices for farm commodities and markets for agricultural products.

   Some closely interrelated factors include: drought; flood; population growth; urbanization; ecosystem restoration; levee integrity; and crop types.

5. **Water exports** are linked to dissolved organic carbon, seawater intrusion, Delta geometry, levee integrity, conveyance, species conservation, water quality standards, seismicity and land subsidence in Delta islands.

   Some closely interrelated factors include: climate change; ecosystem restoration; drinking water quality; salt accumulation in soil; water treatment costs; and desalination technology.

6. **Delta infrastructure** is linked to transportation, utilities, levee integrity, population growth, urban expansion, ecosystem restoration, water demand for agriculture, emergency response, energy costs and climate change.

   Some closely interrelated factors include: seismicity; flood; water supply; water quality; and species recovery.

Text Box 7.2. Delta Levees

(Photo by: California Department of Water Resources)

As time goes by, the probability of a massive earthquake causing multiple levee failures and flooding islands in the Delta increases. This is because the probability of a damaging earthquake in the Delta increases over time and because the water pressure acting on the levee system is increasing. Gradual subsidence of Delta islands, primarily caused by oxidation of organic soils as they are worked for farming, is slowly increasing the water pressure difference between the Delta channels and island floors. A continuing slow rise in sea level due to climate warming is adding to the pressure difference. The Intergovernmental Panel on Climate Change (IPCC) has projected an average sea-level rise of about five inches by 2050 and thirteen inches by the year 2100 (Intergovernmental Panel on Climate Change 2007). The IPCC has likely underestimated the true sea-level rise as their models under-represent recent rates of sea-level rise, and do not include effects of melting Arctic and Antarctic ice sheets (Church and White 2006). Furthermore, focusing on average sea-level rise masks the fact that climate change and sea-level rise will impact the Bay-Delta principally by increasing the frequency, duration, and magnitude of water-level extremes.* These extreme events occur at various periodicities and are associated with high tides, storm surges, and high river flows. A recent California Energy Commission study showed that under a sea-level rise of twelve inches, extreme high water events in the Delta (i.e., those that exceed 99.99% of historical high water levels and severely impact levees) increased from exceptionally rare to an average of around six hundred hours per year (Cayan et al. 2006). The study also showed that roughly one hundred of these hours would coincide with very high runoff conditions, further amplifying the impacts of sea-level rise. In sum, under even a modest twelve-inch sea-level rise, high water levels currently considered extreme would become common.

If a large earthquake occurs during the dry season, multiple levee failures could be expected. Brackish water from San Francisco Bay would rush into the Delta, increasing concentrations of salt, bromide and dissolved organic materials. Hydrodynamic models

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* Discussed in greater detail in Chapter 5

the vulnerability of trans-Delta highways, pipelines, and water conveyance systems; and a host of other social, economic and ecologic factors (see Text Box 7.3). The belief that society can be fully insulated from droughts and floods by appropriate water storage and management is being replaced by realization of the need to adapt to changes that are already underway. Water planners are starting to recognize that drought and flood will pose greater challenges in the future, not only because the climate is changing, but also because of population growth.

Case Study 3: Management of Endangered Species

A central objective of environmental management in the Delta is maintaining or restoring healthy populations of native species. Current management is not achieving this objective. Thirty-one plants and animals have been listed as threatened or endangered within the Delta[1] and new species are continually being proposed for listing. The California Fish and Game Commission recently proposed the longfin smelt (*Spirinchus thaleichthys*) as a candidate for endangered species protection. Efforts to reverse the decline of the Delta smelt (*Hypomesus transpacificus*) are behind recent water management decisions driven, in part, by court orders. Delta smelt is only the most recent species to be in the limelight. Prior to the Delta smelt, Chinook salmon were the focus of management attention, and at various other times California red legged frogs (*Rana aurora draytonii*), Valley elderberry longhorn beetles (*Desmocerus californicus dimorphus*) and California clapper rails (*Rallus longirostris obsoletus*) have been the focus. The pelagic organism decline (POD) of the last few years represents a real-time incipient extinction of four species that has commanded focused attention (Sommer et al. 2007). The suddenness with which the POD reached critical proportions, and the difficulty in isolating its cause or causes, have left some observers wondering if the Delta has

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[1] Discussed in greater detail in Chapter 1

reached a point where such critical events might become more commonplace in the future.

The status of threatened and endangered species is typically the driver for concerted management action. The current concern about the Delta smelt exists because it is a listed species, not because it is critically important to overall ecosystem function. Endangered species legislation prescribes a rather narrow approach to species conservation focused on eliminating, as much as possible, any human-caused mortality or interference with normal life history functions and protecting critical habitat. Around the Delta, critical habitats have been protected, and in some cases restored or enhanced, for listed species. But few of these species have shown signs of significant recovery. Impending future changes to the Bay-Delta will place additional stresses on listed species. Climate change, in particular, has the potential to make the Delta uninhabitable for some species, including Delta smelt. A range of new tools that could be used to enhance the potential for species preservation in the face of global change is being debated among ecologists and conservation biologists. Although not mandated by law, these tools need to be brought into the debate about the conservation of native species in the Delta.

The tools range from establishing and maintaining populations in captivity to assisting with species range extensions so that they can keep ahead of the changing global climate, and from seed-banking and cryopreservation of genetic material to genetic manipulation for improving population resistance to new environmental conditions. Not all approaches are suitable for all kinds of organisms and most are still primarily experimental. Holt and Pickard (1999) provided a summary of potential approaches on a scale of practicality, with local habitat protection being the most practical and molecular genetic manipulation least practical (see Figure 7.1).

Nevertheless, as global change proceeds and increasing numbers of important and charismatic species risk extinction, alternative tools are coming to the

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(Text Box 7.2 continued)

suggest the waters of the Delta could become too salty to use for drinking water or agriculture in at least some locations. Restoring a freshwater regime in the Delta could take months and require releasing large amounts of stored reservoir water along with some means of redirecting more of the flow of the Sacramento River into the eastern Delta. The tidal prism (the volume of water brought into the Delta by the tide) would increase and this would push salinity farther into the Delta so that even more fresh water would have to be released from upstream reservoirs to keep it in check. The fresh water needed to push back the sea might not be available if the massive levee failure happened near the end of a dry period.

A different scenario of levee failure could involve a large flood, bigger than most of our past floods. The risk of such a flood from a huge Pacific storm is present every winter. With climate warming, California will see more winter precipitation fall as rain, so greater runoff during winter storms can be expected from the higher mountain river basins (Dettinger and Earman 2007). During historic large floods, levee breaks upstream from the Delta have absorbed much of the flood peak and reduced the peak runoff entering the Delta. Upstream levees are much stronger than in the past, so the majority of flood flows will be routed downstream to the Delta, increasing the peak Delta water level and raising the risk of multiple island inundations. Collapse of island levees would damage property, change the Delta 'as a place,' and pose a public-safety risk, whatever the cause. Floods are more predictable than earthquakes, so damage might be less from a flood, but only if the proper emergency response plans are in place. Because the high river flows would hold the seawater at bay, there would be less of an immediate threat to water transfer and export from a flood than from an earthquake. But if the levees were not repaired soon after the floods subsided, salt water would begin to intrude into the Delta and affect the quality of export water.

The ecological consequences of a massive levee failure are not fully known, but such a massive change in the physical nature of the system would undoubtedly be accompanied by ecological change. The time of year, the location of levee breaches, and whether or not levees were repaired and islands pumped dry again would influence the ecological impact. At one extreme, if levees were left unrepaired, the direction of change could be toward physical and chemical traits characteristic of the past: a fluctuating salinity regime with a more complex mosaic of channels and tidal ponds or lakes. Some species, perhaps even native species, could benefit from such a change (Lund et al. 2007), although net outcomes remain difficult to predict. At the other extreme, if we repaired levees quickly and effectively, any ecological changes could be temporary. However, as with Prospect Island in 2007, the process of repairing levees and pumping islands dry could result in major fish kills.

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(Text Box 7.2 continued)

Adaptation to reduce the risk of a massive levee failure in the Delta is conceivable. The likelihood of effective adaptation improves as we understand the risks better, although adaptations are not without tradeoffs. For example, we could increase upstream flood storage to reduce the pressure on Delta levees, perhaps by increasing flood control space in foothill reservoirs. We could also design upstream levees to overtop at high river stages to allow localized flooding that would reduce the flood stage downstream and relieve pressure on Delta levees. Delta levees could be armored (but at great cost) to resist earthquakes and sea-level rise. A canal for water conveyance could reduce the vulnerability of water exports to levee failures in the Delta. Some, however, argue that these adaptations amount to only postponing the inevitable. Business as usual in the Delta is not sustainable (Lund et al. 2007). What is clear is that we will continue for some time to debate the tradeoffs between protecting Delta agriculture and communities with such measures and their high economic cost. That debate will be made more complicated by the view of many scientists that the ecological benefits or costs of different adaptation strategies are not clear-cut (Lund et al. 2007).

In summary, a single large event like an earthquake or major flood could set in motion a cascading series of changes that would affect all aspects of the Delta. A massive levee failure would obviously compromise the integrity of the levee system. Salt intrusion and the potential release of organic matter and contaminants sequestered in island soils would compromise water quality for both human and ecosystem uses. Salt intrusion and other contaminants would imperil water exports and domestic water supply for twenty-three million Californians. The physical template of the ecosystem would be changed and species would respond in various ways. The new ecosystem would be different, but it is difficult to say how it would differ without knowing more

fore. Some have already been employed successfully, including captive breeding and reintroduction of the black-footed ferret (Dobson and Lyles 2000) and translocation of gray wolves into Yellowstone Park.[2] In fact, an existing captive-breeding program for Delta smelt is being strengthened as a hedge against extinction for this species.[3] For some species, free-living refuge populations might also be established in other locations to reduce the potential for extinction.

Banking of seeds is an established technique for preserving genotypes or species threatened with extinction[4] and could be used to preserve some threatened plant resources from the Delta. Related, but much less established, is cryopreservation of gametes or embryos of animal species (Holt and Pickard 1999). These techniques are well developed for some domestic animals but have been little used for wild species. Other aspects of molecular biology, such as physiological and molecular responses to environmental change and capacity for phenotypic or genetic adaptation (Reusch and Wood 2007), may also provide tools useful in conservation. The expanding list of examples of rapid genetic evolution in wild populations, including Pacific salmon (for example, see Kinnison and Hendry 2001), suggests that some species may be able to adapt to some forms of environmental change. However, in most cases, genetic adaptation will probably not be able to keep up with environmental change. We may be able to help some species develop tolerances through selective breeding or genetic engineering. Improving heat tolerance in plants is already reasonably successful (Iba 2002) and has been accomplished experimentally in the common fruit fly, *Drosophila* (Reusch and Wood 2007; Feder et al. 1996).

Many difficulties remain with these alternate tools for species preservation, but they do constitute a growing tool-kit for conservation of Bay-Delta species that goes well beyond local habitat conservation. As their promise develops, managers will also have to be vigilant against the temptation to export problems (that is, to move an endangered species because it is inconvenient to maintain at its current location) (Hunter 2007; McLachlan et al. 2007). In a rapidly changing Delta, however, alternatives to traditional conservation may provide the

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[2] See: www.nps.gov/yell/naturescience/upload/wolfrpt06.pdf

[3] Sacramento Bee, September 28, 2007, B3

[4] See for example, the Millennium Seed Bank Project: www.kew.org/msbp

only means of preserving significant genetic information from Delta species.

Species decline and, ultimately, species extinction is a consequence of a multiplicity of interlinked and interacting factors in the Delta. Several of the Delta's listed species spend only part of their lives in the Delta (for example, the California least tern (*Sternula antillarum*) and the Chinook salmon). These species illustrate the fact that the Delta is fundamentally a component of a much larger ecosystem. The Delta is linked through hydrology to upstream and adjacent oceanic habitats and even further afield through fish such as the steelhead trout (*Oncorhynchus mykiss*) and birds such as the sandhill crane (*Grus canadensis*) that migrate long distances. Conservation of these species depends on not only protecting critical Delta habitats but also critical habitats in other parts of their range. These species present a particularly difficult conservation challenge and an example of very large-scale geographic cross-cutting.

The abundance and well-being of species that live their whole lives in the Delta are also determined by a multiplicity of cross-cutting linkages. The Delta smelt, which has been creating many challenges for water managers, illustrates these linkages very well (see Text Box 7.4).

Case Study 4: Ecosystem-Based Management

Although the Endangered Species Act and the Clean Water Act provide legal justification for many of the management actions in the Bay-Delta, the CALFED Ecosystem Restoration Program (ERP) recognized in the late 1990s that a species-by-species approach to resolving the problems in the Delta was unlikely to be successful. Instead, the ERP adopted an ecosystem approach based on the conceptual model that restoring effective ecosystem function in the Delta would benefit listed species. CALFED began implementing this approach in the Delta's tributary watersheds to restore habitat conditions for salmonids, but never applied it in the Delta. As a result, management approaches in the Delta have continued to focus on the emergency needs of the species in most dire straits—currently the Delta smelt—and to address primarily the factor linked to smelt declines that is most easily managed: water exports. In the absence of an effective framework for implement-

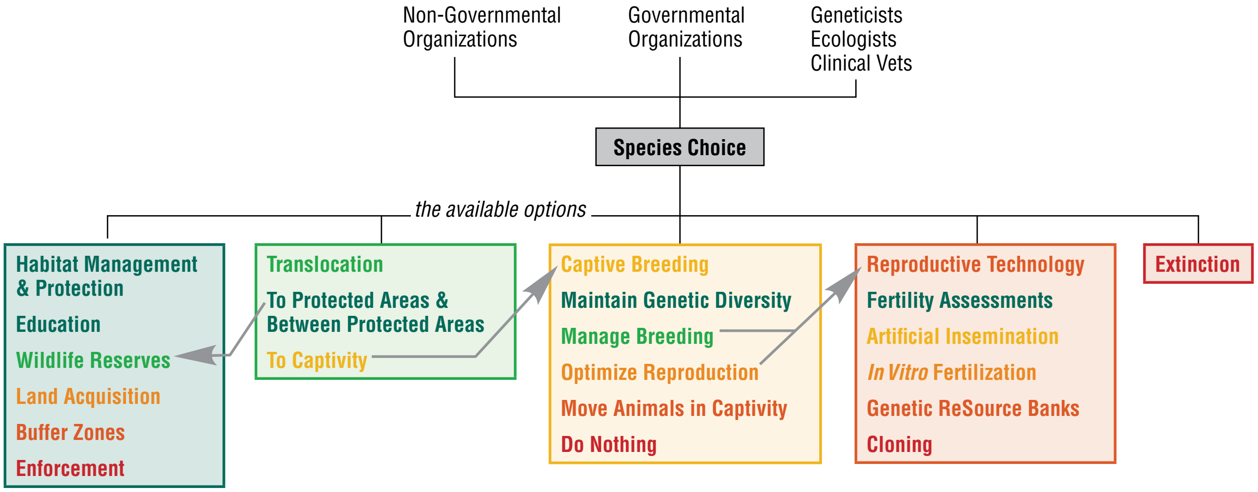

Figure 7.1. Potential approaches to species conservation on a scale of most to least practical under current technology. (Source: Holt and Pickard 1999)

about what islands would be affected and whether levees would be repaired.

(Photo by: California Department of Water Resources)

Text Box 7.3. Prolonged Drought

A 'nightmare scenario' for the greater Delta ecosystem is a long-term drought. Using tree rings to reconstruct California's past climates, scientists have discovered droughts much worse than any experienced since European colonization. Because California's available water is already oversubscribed, a prolonged drought would strain the system in unprecedented ways. Under severe drought conditions, the economic, social, and environmental balance would be severely tested.

An extreme drought would have many implications for California's water. The limitation on available supplies is most obvious. All water uses, including agricultural, urban and environmental, would face shortages. But for the Delta, an extreme drought would also mean less water to hold back the high-salinity waters of the western Delta. Temporary channel barriers might be used to reduce salinity intrusion into the Central Delta and to shield the reduced amount of exported water from becoming too salty for domestic use. However, the ecological implications of such a solution would have to be seriously considered.

For agriculture, there would be a greater need for water earlier in the year and a greater risk that water would not be available through the growing season. A high proportion of agricultural land is now in permanent crops such as orchard or vineyard, so a prolonged water shortage could be very costly and not limited to just one year's loss of annual crops. In times of drought, cities have been able to lease water rights from farmers and thereby suffer little real water shortage. The present drought in Australia, for example, has resulted in virtually all available water in the Murray-Darling system being diverted to urban uses, with the near elimination of water for agriculture.

The ecological implications of drought would also be significant. In the Central Valley, drought historically has resulted in a reduction of rice acreage. Because birds migrating along the Pacific Flyway depend heavily upon rice fields as resting and feeding habitat (historic wetlands having been virtually eliminated), a

ing an ecosystem approach, the single-species/single-factor approach will continue to be the default response to a crisis like the POD.

The science of species and ecosystem management tells us that a crisis-driven focus on a single solution is neither the most practical nor the most effective way to address the broad problem of native species declines. Large ecosystem management projects across the world are increasingly turning to ecosystem-based management as the practical alternative to species-focused management. Examples of ecosystems that are being managed by this approach include the Everglades, the Greater Yellowstone Ecosystem, the interior Columbia Basin and the Great Barrier Reef. Ecosystem-based management has different definitions in different contexts (Healey 1998; Grumbine 1994). But most agree it is an integrated and science-based approach to the management of ecosystem. Its major goal is to sustain the health, resilience and diversity of ecosystems while allowing for sustainable use by humans of the goods and services these ecosystems provide. As such, ecosystem-based management involves:

- Sustaining ecosystem performance and the activities it supports;
- Obtaining and maximizing the long-term socio-economic benefits resulting from these activities without compromising the ecosystem; and
- Generating knowledge about the Delta environment and the impact human activities exert on it.

The goals of the CALFED Record of Decision (ROD) are consistent with ecosystem-based management, as are the goals of the recently completed Delta Vision process.

Ecosystem-based management evolved because experts recognized that protection of native species and biodiversity via the ecosystem approach was more likely to be successful than managing for individual species over the long term. Under ecosystem-based management, each species is seen as a component of a larger system rather than as an isolated entity. Ecosystem-based management also encourages a broad examination of ways to nurture species survival and well-being, rather than narrowly focusing on a specific stressor. Most important, the ecosystem view forces a recognition that there are tradeoffs among species, species conservation, and other beneficial uses of land and water. Highly migratory species like Chinook salmon and steelhead that occupy habitats extending from the headwaters of large rivers through the Delta to the open Pacific Ocean and back again, integrate the effects of conditions across a very broad range of environments (see Text Box 7.1). Conservation of these species involves both local and very broad-scale tradeoffs. By contrast, local species like the salt marsh harvest mouse (*Reithrodontomys raviventris*), integrate across a much narrower range of environmental conditions within the Delta, both natural and human-affected. For the harvest mouse, what happens in the Delta is central to their well-being; for salmon it is but one of several critical ingredients. These are the types of species that intersect under ecosystem-based management—and for which such management seems critical. Resolving the approaches that allow successful management of both might be a first step forward.

Any design for a sustainable Delta must address the endangered species problem in a meaningful way. But, as we argue above, the approaches most likely to yield solutions lie in a long-term, holistic, ecosystem-based vision. The ingredients for implementing a robust vision for the Delta are beginning to be assembled. Ecosystem-based ideas for the Delta are beginning to move beyond reconstruction of lost habitats for individual species. The suggestion, put forward in Chapters 3 and 4, that varying salinity and hydrology might be a creative means of favoring native species over invasive macroflora is one example of this more holistic ecosystem-based approach. Recognition is growing that enhancing primary productivity and food webs is only effec-

reduction in rice acreage could have significant impacts on migratory waterfowl. A prolonged drought would also increase the risks

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(Text Box 7.3 continued)

for races of Chinook salmon that are already listed under the Endangered Species Act (ESA). Reservoirs would become depleted and warm as a drought persists, and hot summers would exacerbate the problem. The winter-run race of Chinook salmon, for example, persists because cold water can be released from deep in Lake Shasta. A significant drawdown of Lake Shasta during a drought could jeopardize that supply of cool water.

Other salmonids, including spring-run Chinook, spend an extended period in cool headwater streams as both returning adults and juveniles. Rising water temperatures would reduce the few headwaters available to them. The conflicts between legal protections for endangered species and the demand for water for other uses would likely intensify in the Delta itself during an extended drought. Since the mid-1990s, water export rules have changed to minimize the number of listed species captured by the pumps. But this process has not been tested during a drought. Protecting endangered species by reducing exports during a severe drought could mean reducing water supply reliability at a time when water is increasingly precious. In addition, California's reduced access to Colorado River water would further limit the available water in Southern California, especially if the drought extended into the Colorado Basin. Thus, if poor conditions in rivers exacerbate risks to ESA-listed species, the pressure to further reduce export-related losses of fish in the Delta could intensify. At the same time, the pressure to relax such restrictions would intensify in response to the economic and social costs of a less reliable water supply. This conflict would likely be further exacerbated by uncertainty about the ecological benefits of reducing export-related losses of fish.

An isolated facility to convey Sacramento River water to the export pumps would separate environmental and export water and might reduce some of these problems. But there are water quality tradeoffs associated with such a facility that are worthy of consideration. For example, selenium is transported to the Bay-Delta by the San Joaquin River. During the 1987 to 1994 drought, there was no selenium input to the Bay-Delta from the San Joaquin River because its entire outflow was cycled back to the export pumps. Many of the plans for an isolated facility involve diverting Sacramento River water to the south and allowing water from the San Joaquin River to flow into the Delta. During a drought, therefore, both the duration and magnitude of selenium contamination accompanying San Joaquin River inputs to the Delta would increase.

There are many uncertainties in these scenarios. The greatest uncertainty lies in the extent that climate change would worsen the effects of a drought on water supply, energy production and environmental water. As conditions change, we will not know if past experience is any guide to the future. We may need entirely

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Text Box 7.3 (continued)

new models and management rules.* For example, there is no historic experience of a situation in which a year of essentially no rain (like 197) occurred in the middle of a prolonged drought. Yet, the tree ring record of California's climate over the past several centuries shows a sequence of several years of declining

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* Discussed in greater detail in Chapter 6

tive if it directly transfers that energy into native species, not if it simply improves the lot of exotic species.

There is also increasing recognition that significant changes outside the Delta are necessary to reduce stress on the Delta. For example, success for migratory fish species in the Delta cannot be achieved without better management of habitat and water flows in the rivers. Similarly, changes in reservoir operations, floodplain connectivity and storage capacity may make it possible to divert more water in wet years and less in drier years. Finally, policies to reduce demand and improve water use efficiency will make existing supplies go much further.

The Governor's Delta Vision Blue Ribbon Task Force has produced a robust vision for the Delta that gives equal weight to ecosystem conservation and water supply, but also recognizes the value of the Delta as a unique place. In helping to implement this vision, the science community needs to initiate a dialogue that defines a holistic system-level perspective: one that embraces all native species (not simply those now listed) at all their life stages, and the environmental conditions that allow those species to grow and flourish. However, the vision must also embrace and satisfy the reasonable human demands for water from the Delta and its tributaries. Without a sustainable balance of water for human and ecosystem uses, the Delta will not retain its character of place.

Holistic, ecosystem-based management of the Bay-Delta has little successful precedent in California's history,[5] but it is our only choice if the future Delta is to provide the full range of services demanded by Californians. Ingredients for accomplishing this are suggested in other chapters. Some of these include:

- Human uses will have to be changed and moderated to accommodate the physical and chemical variability that is essential to sustaining productive ecosystems and avoiding extinctions.[6]
- Modern science strongly indicates that changes in climate will have dramatic effects on the Delta.[7] These changes cut across all components and all issues in the Delta. We must recognize the multiple consequences of this change for water and ecosystem management and design policies accordingly.[8]
- Potential solutions will not move every CALFED goal forward equally (Lund et al. 2007). However, as all CALFED goals are interconnected, it will not be possible to race ahead with one while ignoring the others. Adopting a holistic view of the Bay-Delta and what we want it to be like in the future will help keep all the parts moving forward together.

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[5] Discussed in greater detail in Chapter 1

[6] Discussed in greater detail in Chapter 4

[7] Discussed in greater detail in Chapter 6

[8] Discussed in greater detail in Chapter 8

Conclusions

CALFED invested in scientific studies and enhanced communication of scientific knowledge to stakeholders after 1997. That investment, together with analyses stimulated by recent crises such as the POD, has prompted changes in our underlying concepts of Delta function. Specific policy changes have yet to result. The Governor's Delta Vision Blue Ribbon Task Force has recommended rather sweeping changes in water and land management policy. Major changes in water management policy may cause hardship for some water users but the water community (including stakeholders, agency managers, academics and agency scientists) appears willing to be both flexible and receptive to new ideas. This is one prerequisite for managing a complex system in the face of uncertainty. It remains to be seen whether we will be flexible enough, whether resources will be available, and whether policies can change fast enough to keep up with events.

In earlier times, engineering solutions were found to challenges that seemed equally as daunting as those we face today. Advances in science and engineering gave us some control over the most damaging forces of nature.[9] But a broad consensus has developed, based on our improved knowledge of the Bay-Delta, that to continue exclusively with the old approach to solving problems is unsustainable. New opportunities lie in working with the forces of nature rather than opposing them. We are entering an era in which balancing stewardship with sustainable water use is essential. A proper balance of soft and hard solutions is needed to satisfy a broad spectrum of human values. Flood control must not only protect property but also sustain native species habitats. Waste management must not only protect public health but also protect ecosystem health. The examples in Text Boxes 7.1 through 7.4 illustrate

precipitation followed by a year with one third of the rainfall of 197. A similar sequence could occur in the future. Our ability to forecast such events is much better than in the past, and precaution suggests that we should prepare for a drought-related worst-case scenario just as we prepare for the eventual earthquake.

(Photo by: California Department of Water Resources)

Text Box 7.4. Delta Smelt

(Hypomesus transpacificus)

The Delta smelt is an endemic species to the Delta, occurring nowhere else in the world. Their abundance has been declining for many years, but since 2000, their numbers have dropped alarmingly. The multiplicity of cross-cutting linkages affecting Delta smelt explains why there is so much uncertainty about why the decline has been so precipitous. Delta smelt are hard to study scientifically because they are small, delicate, and live in muddy water. Because they are unique to the Delta, we cannot use information from other species or populations to help us understand their dynamics (the same is true for other endemic Delta species, such as Lange's metalmark butterfly (*Apodemia mormo langei*) or Antioch dunes evening primrose (*Oenothera deltoides* ssp. *howellii*)).

Smelt spawn in freshwater regions of the Delta, but the low salinity zone of the Delta (the western Delta and Suisun Bay) is their primary home. The Delta smelt is also an annual species, meaning that loss of juvenile production in one year can virtually wipe the species out.

During the late winter, smelt move into the freshwater Delta to spawn, where they are vulnerable to various stresses imposed by water export operations, for example, predation in Clifton Court Forebay, death in the pumps, and predation if they are captured during entrainment then released (Kimmerer 2008). One emerging theory is that increasing water exports in late winter may selectively take a high toll on the largest Delta smelt. These more hardy individuals migrate to spawn early in the season and produce the most smelt fry (the "big momma" hypothesis; W. Bennett, pers. comm.). Mortality of this cohort is especially disruptive to the success of the population. An interesting interconnection is that accelerated pumping in the late winter was begun to reduce pumping effects on migrating salmon smolts in the spring, but this change in water management has negatively affected Delta smelt. Kimmerer (2008) estimated the total loss of adult smelt of all sizes from water exports to be between 1 and 50 percent with

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[9] Discussed in greater detail in Chapter 1

a median estimate of 15 percent. Delta smelt fry and juveniles are also lost to exports later in the year, although the exact numbers are difficult to estimate. Kimmerer (2008) also estimated that mortality of larvae and juveniles due to water exports could be as high as 25 percent, although the median estimate was 13 percent.

(continued)

(Text Box 7.4 continued)

Fry that survive to move to the western Delta and Suisun Bay face another big problem. In the low salinity zone, food for the Delta smelt has become much less abundant and now consists mainly of a zooplankton species (*Limniothona tetraspina*) that is spiny and has low food value (Kimmerer 2004). The ultimate cause of the decline in food availability for Delta smelt was the invasion of the overbite clam (*Corbula amurensis*) in the 1980s. These animals feed voraciously on phytoplankton and were able to reduce phytoplankton biomass substantially in Suisun Bay. The loss of phytoplankton was followed by a collapse of species of large sized zooplankton (*Eurytemora affinis*) that depended upon the phytoplankton for food Eurytemora was a high quality food for Delta smelt but the species is now virtually absent from Suisun Bay. The decline in food availability and food quality for Delta smelt in Suisun Bay has resulted in adult smelt that are smaller and produce fewer eggs and fry.

A final factor with which the Delta smelt must contend is water toxicity. Routine testing of water in the Sacramento and San Joaquin Rivers reveals occasional water samples that are acutely toxic to test organisms. The most likely cause is high concentrations of pesticides, although much remains to be learned about the Source of the toxicity. Although it is not possible to demonstrate kills of Delta smelt have been caused by releases of toxic substances, several water samples collected in 2007 from the North Delta, in a region where smelt are commonly found, were acutely toxic to test organisms.

Our knowledge of Delta smelt has grown very rapidly in the last decade. It is clear that the well-being of Delta smelt collides, in complex ways, with drivers ultimately linked to human activities, including water diversions, invasions of exotic species, climate

the cross-cutting linkages among valued attributes of the Bay-Delta and the challenges they present to policymakers. These problems have been described as wicked problems because their exact nature is difficult to define.[10] These are problems for which there is no clear policy solution and for which all solutions are temporary.[11] The era of "build it and move on" solutions is at an end. The era of flexible, adaptable solutions, where problems are not so much solved as managed so that conditions are gradually made better, is beginning.

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[10] Discussed in greater detail in Chapter 8

[11] Discussed in greater detail in Chapter 8

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8. Science in Policy Development for the Bay-Delta

Michael Healey [1]

Science is an integral part of the policymaking process. Much has been written about the uneasy relationship between scientists and policymakers, stemming from the differences in motivations, objectives and time dependencies of the two professions (Lawton 2007; Pouyat 1999; Committee on Science and Policy for the Coastal Ocean 1995). While the tension between science and policy is real, the interrelationship has been fruitful and continues to be so. In this chapter, I explore conceptual models of the roles of science in the policy process, assess how science has contributed to policy development in the CALFED context and conclude with some recommendations about how to ensure that science continues to provide the knowledge and understanding needed as new water and environmental management policies are developed.

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[1] CALFED Science Program

Although scientific input to water and environmental management policy has a long history in California and elsewhere,[1] CALFED and the CALFED Science Program embarked on a novel and forward-looking approach to integrating the broad spectrum of scientific and technical advice needed to address the highly complex problems of today. The CALFED Record of Decision (ROD) identified a fundamental role for science in supporting and informing all of the CALFED program elements. Science was to be included in policy and program design in three primary ways. First, the CALFED Science Program was to ensure that CALFED policies and programs were based on high quality science. Second, the participating agencies were to implement program elements using science-based adaptive management. Third, the Independent Science Board (a team of internationally recognized scientists) was to provide high-level scientific review and oversight of CALFED. The ways in which science was integrated into the program and the governance structures linking science to the program were themselves experiments in strengthening the science and policy interface (Jacobs, Luoma, and Taylor 2003). The tools used by the CALFED Science Program included interdisciplinary workshops, support for research that cut across agency mandates and knowledge integration that incorporated the experiential knowledge of practitioners. In applying these tools, the CALFED Science Program took a step beyond the standards of interdisciplinary inquiry that are being adopted by the scientific community, and, thus CALFED Science provides a model for other large, complex projects that integrate science and policy. That the CALFED Science Program achieved and sustains a high level of credibility while other elements of CALFED have had more variable public and political support suggests that the experiment was at least partially successful.

Science and the Policy Process

The policy process can be conceived as a cycle of six steps that include policy development, implementation, review, and revision (see Figure 8.1).

Science plays specific roles in each of the six steps in the policy process and in the overall process through adaptive management. The conceptual model (see Figure 8.1) suggests a unidirectional flow of information and decision-making in policy development and evolution. The reality is much messier and iterative (Lawton 2007), with science and policy working together in a socially constructed and

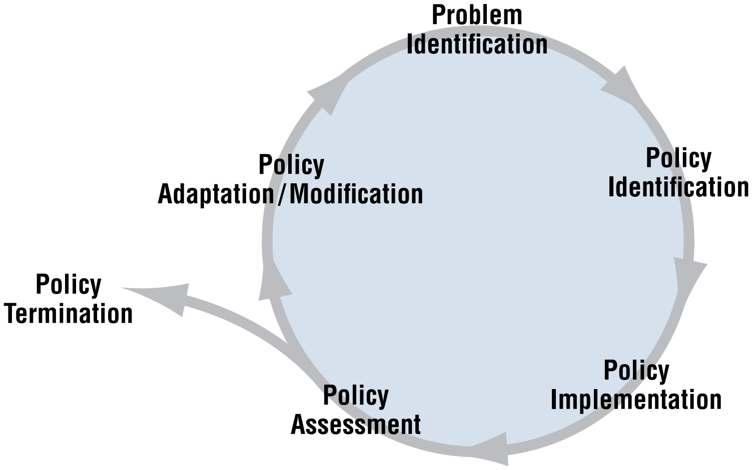

Figure 8.1. A conceptual model of the policy cycle. (Source: Adapted from Knecht 1995)

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[1] Discussed in greater detail in Chapter 1

mutually reinforcing way (Jager 1998). There are other models of the policy process such as the Advocacy Coalition Framework (Sabatier and Jenkins-Smith 1999), which conceptualizes policy development as a contest between coalitions of interests, and Institutional Analysis and Design (Imperial 1999; Ostrom Gardner, and Walker 1994), which conceptualizes policy development as a negotiation among networks of institutions. These alternative models provide important insights into the policy process and capture some elements of policy development better than the cyclical model in Figure 8.1. Nevertheless, the model provides a useful framework within which to discuss the science-policy interface (Sato 1999).

The first step, problem identification (and agenda setting, in which a problem gets included in the political agenda) can result from a few highly visible events that have scientific legitimacy or from a long accumulation of information and experience that eventually confirms that existing policies are not working and new policies are needed (Healey and Hennessey 1994; Brewer and DeLeon 1983). The protracted process that led to the Bay-Delta Accord and ultimately to CALFED is an example of the latter process, whereas the flurry of policy analysis and review stimulated by the pelagic organism decline (POD) is an example of the former process. Science can initiate the policy process by focusing attention on hitherto unanticipated or underrated problems. For example, recent scientific assessments of seismic risk to Delta levees, sea-level rise, future precipitation patterns and land subsidence in Delta islands have led decision-makers to acknowledge that the existing policy infrastructure to manage the Delta's water and environment is unsustainable (URS Corporation 2007; Mount and Twiss 2005). An active search for new policies is now underway, for example, Delta Vision[2] and the Bay-Delta Conservation Plan.[3]

Science, or more specifically, scientific uncertainty, can also be used to divert or postpone the policy process (Henessey and Healey 2000; Ludwig, Hilborn, and Walters 1993). There are many chilling examples of this phenomenon in public health (Gee and Stirling 2003) but decision-makers have also frequently used scientific uncertainty to delay action on the environment (for example, the debate over the impacts of acid precipitation in the 1970s (Forster 1993) and, more recently, over climate change).

The environmental consequences of water development projects were generally accorded low importance in policy development during most of the twentieth century, such impacts being considered the price of progress (Healey and Hennessey 1994). However, with passage of the National Environmental Policy Act in 1969 and the flurry of both state and federal environmental legislation in the 1970s and 1980s (Pouyat 1999),[4] the environmental consequences of development came to the forefront in decision-making. Environmental issues, nevertheless, remained a subject of mitigation rather than a primary driver of decisions about water development and management. At the beginning of CALFED, this was still the vision; ecosystem issues were to be resolved through habitat restoration, without substantial changes in water management and without reallocation of water. In part, this was a pragmatic decision. Despite decades of research, the amount of water needed to sustain environmental services in the Delta could not be specified with certainty. Incremental remedial changes in water management within the existing allocation system seemed to make more sense as a policy approach (Lindblom 1968). With the POD, however, especially the dire condition of Delta smelt, water management agencies are now being forced to consider radical water reallocation, even though the scientific foundation of a solution remains unclear.[5]

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[2] See Delta Vision at http://deltavision.ca.gov

[3] See Bay-Delta Conservation Plan at http://resources.ca.gov/bdcp

[4] Discussed in greater detail in Chapter 1

[5] Discussed in greater detail in Chapter 4

Most of the problems CALFED has faced are like the POD: they involve multiple variables and are difficult to define. Ecosystem restoration and water quality assurance are good examples. Such problems are large in scale, socially and economically significant and transcend the established institutional design for problem-solving. They are the class of problems that Rittel and Webber (1973) termed "wicked." Specific aspects of wicked problems include:

1. The problem involves an evolving set of interlocking issues and constraints; hence, there is no definitive formulation of "the" problem. Perceptions of the problem and its causes are likely to differ dramatically among interests;
2. Since there is no definitive formulation of the problem, there is also no definitive solution;
3. Solutions are not right or wrong, only better or worse;
4. Experience with analogous problems in other contexts may not be relevant;
5. Potential solutions are costly and usually irreversible; and
6. There is no immediate or ultimate test of a solution. Rather, all solutions have successive waves of consequences and it is impossible to know how all will play out.

Problems with these characteristics are difficult not only for policymakers but also for science because every potential solution involves multiple and often conflicting hypotheses. For wicked problems, science can offer useful insight and information but not solutions. Agreement on the problem to be tackled by science or by policymakers requires negotiation among stakeholders. Core values play a central role in how different actors perceive the problem, and a collaborative approach to defining both the problem and potential solutions is essential (Weible 2006).

The second step in the policy cycle is policy identification. In both water and environmental management, science is both a source of policy ideas and a means of policy legitimization. Because science is socially constructed and socially supported, however, the kinds of policy alternatives offered by science tend to reflect current social norms (Jager 1998). As noted in Chapter 1, for the first century of water development in California, science and policy focused on engineering-based solutions. The solution to flooding was levees. The solution to farming large tracts of soft soils was multi-bottom ploughs. The solution to declining salmon runs was hatcheries. With the environmental revolution of the 1960s and 1970s, maintaining a healthy natural environment became strongly associated with quality of life and policy prescriptions shifted toward sustaining natural processes rather than substituting engineering processes. This was the point at which Bay-Delta problems became predominantly wicked. Initially, the focus of policy was on conservation and preservation of remaining natural areas but, as this proved insufficient, the restoration or rehabilitation of natural habitats gained popularity. At first, restoration was built on a foundation of engineering design to recreate particular habitat configurations such as replacement marshes or habitat complexity. The CALFED Ecosystem Restoration Program (ERP), however, was founded on a policy of restoring ecosystem function such that naturally productive systems would recreate themselves. This evolution of policy from engineered solutions to engineered natural designs to working with natural processes reflects both advances in ecosystem science and changing expectations of society. It also reflects a shift from species-based to ecosystem-based approaches to environmental management (Healey 1998; Grumbine 1994), which signaled a further unfolding of wickedness attributes. A similar evolution of understanding has driven policy evolution in water quality. As science has identified a growing list of risks in drinking water, disinfection byproducts in particular, regulations have become more stringent, and attention has shifted from reliance on treatment to multifactorial and more holistic approaches to ensuring drinking water quality (Mitchell 2004). That is to say, the problem of drinking water quality has become more wicked.

The evolution of policy is driven by a confluence of three elements: a broadly recognized problem, viable policy alternatives and political actors willing to champion one or another policy alternative (Heikkila and Gerlak 2005; Kingdon 1995). The importance of willing political actors is often overlooked. However, CALFED got its start because California Governor Pete Wilson and United States Interior Secretary Bruce Babbitt wanted to resolve water conflicts and were willing to spend their political capital to get it started. Delta Vision is in progress because California's current Governor, Arnold Schwarzenegger, wants a sustainable solution to the problems of water and environmental management in the Bay-Delta. Without the necessary political support, policy alternatives well supported by science may never be accepted. But before solutions can be championed, viable policy alternatives must be identified. This is a political process, but final policies must be perceived as legitimate and science can play a major role here.

Science is particularly important in policy legitimization because it facilitates the debate about policy alternatives. As Weinberg (1972) points out, science provides three things to the debate about environmental problems and their solution:

1. Models of physical and biological systems that illustrate how different policies might affect a problem,
2. Objective information about the system and how it behaves, and
3. A formalized language that permits informed debates.

Good examples of very generalized physical and biological models that structure and legitimize policy debate are the paradigm shifts presented in the Public Policy Institute of California's report, *Envisioning Futures for the Sacramento-San Joaquin Delta* (Lund et al. 2007) and in the new perspectives on how the Bay-Delta functions that have helped structure this report.[6] The new perspectives on the Bay-Delta lead to fundamentally different policies for managing water and the environment and these policies can be debated by reference to objective scientific observations of the Bay-Delta and its waters. Through debate, one or another model of the system with its associated policies will gain legitimacy and can then form the basis of future management programs. This kind of debate established the legitimacy of the policies that defined Stage 1 of CALFED: integrated resource management and the maintenance of established patterns of water use and allocation. The debate is under way again in the Delta Vision process and the Bay-Delta Conservation Plan, because as the policies of Stage 1 have proved unable to halt or reverse the continued loss of ecosystem services and because new scientific discoveries have suggested a new set of paradigms to guide policy (Lund et al. 2007).[7] It is through this process of debate that wicked problems can be made at least partially tractable. Science has an important role to play in resolving wicked problems, but because there is no way to analyze all the potential cascading consequences of any proposed solution, the consequences of policy implementation will remain highly uncertain until long after a policy is implemented.

The third step in the policy process is policy implementation. Here, science provides practical tools and information on which to base programs of implementation. Pouyat (1999) argues that environmental science has been good at identifying problems but it has been poor at providing solutions, and this is a source of considerable frustration to policymakers. Although there are certainly situations in which environmental and ecosystem science could not offer clear-cut solutions (the POD is a current example), there are many problems for which CALFED-supported science has offered clear policy and program direc-

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[6] See Introduction: New Perspectives on Science and Policy in the Bay-Delta, and Chapter 2

[7] Discussed in greater detail in Chapter 2

tion. For example, the Trush, McBain, and Leopold (2000) model for river channel restoration that has been adopted in upstream tributaries, or dam removal to provide migratory salmonids (*Oncorhynchus* spp.) with access to additional habitat. In some cases, the policy solutions, although clear, are costly or disruptive of established processes, making implementation problematic. Preventing new species invasions or further land subsidence in Delta islands are examples of environmental issues in the Bay-Delta for which solutions are costly or socially disruptive. Nevertheless, through applied research, The CALFED Science Program has stimulated the emergence of new potential solutions or improvements to old solutions. For example, periodic floodplain inundation appears to be an important technique for improving habitat conditions for Sacramento splittail (*Pogonichthys macrolepidotus*) and juvenile salmon in the Delta (Sommer et al. 2001), and the installation of hydraulic barriers on channels around Franks Tract or in Three Mile Slough may greatly reduce salinity intrusion into export water. The CALFED Science Program has thus performed the dual function of identifying problems and suggesting practical solutions. Given that the problems are wicked, however, it is inevitable that as solutions are implemented, new issues will arise that may change the nature of the problem, or our perception of the problem. As a consequence, all solutions must be regarded as provisional. This is particularly the case in the Bay-Delta, where major changes will continue to be imposed by drivers (like sea-level rise) that are not under control of management (Mount, Twiss, and Adams 2006).

The fourth step in the policy process is policy assessment. This is a critical phase, particularly in adaptive management (which will be discussed in more detail below) but one that is often not given sufficient emphasis in planning for policy implementation. The ROD assigned the CALFED Science Program the responsibility to ensure a sound scientific foundation for monitoring and evaluating all elements of CALFED. Several attempts have been made to develop comprehensive monitoring and evaluation for CALFED, but none have been fully successful. In 1997, the United States Geological Survey (USGS), San Francisco Estuary Institute (SFEI) and the Interagency Ecological Program (IEP) began to develop a comprehensive monitoring assessment and research program (CMARP) for CALFED. CMARP was never completed, although SFEI maintains a database listing ongoing monitoring activities.[8] More recently, the CALFED Science Program has been working with agencies to develop a framework for project and program performance evaluation for each of the four main elements of CALFED.[9] The framework proposes using three levels of indicators: administrative indicators to track expenditures, projects implemented, etc.; driver indicators to track stressors or management actions that may influence or direct project performance; and outcome indicators to track the ultimate consequences of stressors or management actions. This program is still largely at the conceptual stage, although some program elements have made progress toward implementation. The performance measures are forward-looking and intended to provide an objective basis for assessing future management actions.

Although assessment of future actions is important, an ability to assess performance during CALFED Stage 1 is also needed. In 2006, the Bay-Delta Public Advisory Committee (BDPAC) created a finance and program performance subcommittee that, with the help of CALFED staff, undertook a broad-scale assessment of project performance during Stage 1 (Bay-Delta Public Advisory Committee 2007). This assessment was largely based on subjective evaluations of performance using highly aggregated indicators but provided a useful overview of

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[8] See SFEI CMARP Monitoring Program Inventory at www.sfei.org/cmarpquery

[9] See CALFED Bay-Delta Program Performance Measures Report, October 2007 at http://www.science.calwater.ca.gov/pdf/monitoring/monitoring_phase_1_report_final_101707.pdf

CALFED performance based on expert opinion. The indicators developed by BDPAC (2007) can also be used for future program assessment once they are connected with objective data through the framework for project and program performance evaluation being developed by the agencies. Developing these connections is likely to require a reexamination of existing monitoring programs, but should lead to a much stronger foundation of information for project and program evaluation.

The fifth and sixth steps in the policy cycle are adaptation or modification and policy termination. These steps, as with policy evaluation, are highly dependent on scientific monitoring that is properly designed and implemented. At present, the connection between monitoring data and policy adaptation or termination is still rather ad hoc. Nevertheless, monitoring data have provided researchers and resource managers the opportunity to explore trends and develop models of species dynamics or ecosystem function, and these analyses have helped with policy evolution (for example see, Lund et al. 2007; Jassby, Cloern, and Cole 2002; Jassby and Cloern 2000). These analyses have contributed to our understanding that the current management system for the Bay-Delta is not sustainable, and to our greatly improved understanding of the Bay-Delta ecosystem. But the analyses are frequently disconnected from the policy process rather than integral to it.

Adaptive Management

Although science makes important contributions to each step in the policy process, science also has the capacity to inform the process as a whole through adaptive management (Lee 1994). Adaptive management is a management process by which policies are implemented as though they were experiments, although this experimentation is more akin to medical science than to natural science or engineering. The scientific method is fundamentally reductionist; problems are broken down into their component parts, each part is studied in isolation, and the whole is reassembled from the understanding of its parts. This approach has worked well in the physical sciences, allowing chemists and engineers to be reasonably confident in their predictions. It has been less successful in ecology and environmental science where predictions have high uncertainty. Ecosystems respond in complex and nonlinear ways to stressors, sometimes absorbing stress for a long period with seemingly little change, then rapidly changing to a new stable configuration. An approach that integrates science more fully into policy implementation would allow better, more timely assessment of how the system is responding. Adaptive management seeks to accomplish this integration.

The multifactorial (wicked) nature of environmental problems and the difficulty of sorting out cause and effect are well illustrated by the POD. Despite intensive study and analysis, researchers cannot determine whether the rapid decline of four pelagic species in the Bay-Delta has a common cause or is merely coincidence. Nor is it possible to narrow the potential causes much, to assess the relative importance of the various candidate causes with existing data, or to specify the quantitative benefits of any potential solution. Adaptive management provides a rational process for addressing problems like the POD for which there are several competing but uncertain explanations, and for which management cannot be delayed until causes are better understood. The appropriate approach is to treat any management action to address the POD as an experiment that can help us understand what is driving the decline. The management program, thus, becomes a source of new information about the cause of the decline (Lee 1994). Adaptive management provides a powerful tool for increasing our understanding of ecological systems at the same time as we are managing them. Given the wicked nature of the problems, however, we can expect that increased understanding will not solve the problem but only point the way to better management approaches.

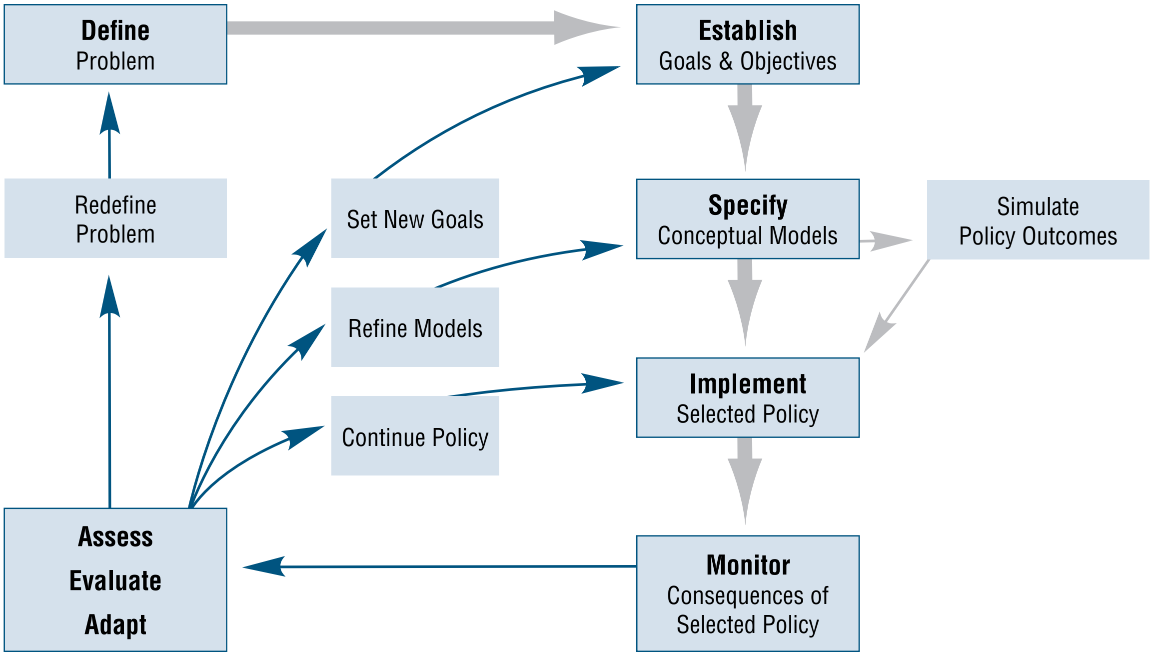

Figure 8.2. Conceptual model of the adaptive management cycle. (Source: Adapted from Ecosystem Restoration Program 2000)

The CALFED ROD prescribes that all elements of CALFED employ adaptive management. The process was most fully developed for the ERP (Ecosystem Restoration Program 2000) and consisted of a cycle of six steps: problem identification, goal-setting, conceptual modeling, restoration projects, monitoring, and assessment and adaptation (see Figure 8.2). Although the various conceptualizations of adaptive management in the resource management literature differ somewhat in their details, these steps are common to all (for example, Wilhere 2002; Lal, Lim-Applegate, and Scoccimarro 2001). Over time, the conceptualization of adaptive management developed for the ERP has been incorporated into other program elements. Implementation, however, has been weak. According to the Little Hoover Commission, "The ROD has not been reinforced by adaptive management" (2005, p. 37), and "[...] adaptive management has not become a way of doing business at CALFED" (2005, p. 70). The benefits of adaptive management described by the Little Hoover Commission have yet to be realized by CALFED.

CALFED is not alone in experiencing difficulty in implementing adaptive management (Walters 1997). In part, this reflects the wicked nature of the problems for which adaptive management has been prescribed. It also reflects the fact that adaptive management constitutes a significant change from the traditional agency approach to management problems. Nevertheless, progress is being made. In Australia, for example, Gilmour, Walkerden, and Scandol (1999) report on thirteen adaptive management projects and suggest ways to improve the implementation of adaptive management. CALFED has also made progress, particularly in some of its tributary restoration projects (Adaptive Management Forum, Scientific, and Technical Panel, and the Information Center for the Environment, University of California Davis 2004). Particular impediments to adaptive management in CALFED appear to be those elements that fall outside normal agency operating procedures, such as pre-project modeling and identification of specific outcomes, and post-project monitoring and evaluation. This is not to say that planning and evaluation does not occur. However, planning and evaluation in current practice are not typically structured as part of an overall adaptive management strategy.

Future Directions for Bay-Delta Science

Science has been and will continue to be an important part of the policy process as the Bay-Delta evolves and changes over the coming decades. Mount, Twiss, and Adams (2006) identified six primary drivers of change in the Bay-Delta (land subsidence, sea-level rise, regional climate change, seismicity, exotic species, and population growth and urbanization). These drivers are forcing significant change in the ecosystem of the Bay-Delta, underscoring the argument that current patterns of use in the Bay-Delta are not sustainable (Lund et al. 2007). Uncertainty about the future of the Bay-Delta is high, although the drivers of change clearly tell us that the future will be very different from the present. This both increases the need for reliable information and renders historic scientific understanding less reliable. Future science for the Bay-Delta will need to be responsive, creative, bold and collaborative. It will need to be engaged more directly with managers and policymakers, and draw analogies from elsewhere to help craft policy for a changing environment. The Bay-Delta and its problems are unique, but as an ecosystem it must still reflect the rules of ecology. The uncertainties of the future give greater urgency to implementing adaptive management so that information and understanding can be both a stimulus for, and a result of, management intervention. For the changing Bay-Delta, however, adaptive management will be primarily a means to enhance information and understanding rather than a tool to enhance predictability.

As science and management have addressed the wicked problems of CALFED, the weakness of the science infrastructure has become apparent. Although all aspects of the science infrastructure for CALFED and the Bay-Delta system are inadequate, I want to address specifically the deployment of science. Given the wicked nature of the problems to be addressed, science needs to be deployed in a way that is more collaborative and integrative yet still allows the power of individual creativity. As Conklin (2006) discussed, designing policy and management to address wicked problems requires intense discussion and social networking among the important actors. The traditional model of the scientist as an isolated, individualized problem- solver is not consistent with an efficient, effective design process for wicked problems. Instead, scientists, other professionals, policymakers, managers and other interests need to engage in intense discussion as a means to develop a shared understanding of positions and perceptions about the problems to be addressed (Connick and Innes 2003). The scientist can then undertake analyses to explore and assess opportunistic solutions and return to the debate able to contribute whatever new insights have emerged from the analysis. This is an open-ended process in which provisional solutions must be identified, implemented, and evaluated *even as debate about the problem proceeds*. At times, therefore, scientific analysis will be concerned with the consequences of management actions (adaptive experimentation) and at other times with clarifying new issues that emerge as the system and the problems evolve. Since there is no final solution to wicked problems, the iterative process of discussing and negotiating the nature of the problem, using the results of that phase to inform the analysis, implementing provisional solutions, followed by further discussion and negotiation will continue indefinitely.

The collaborative process established under the CALFED Program is consistent with the need to foster discussion and build shared understanding among interests when dealing with wicked

Table 8.1. Future Directions for The CALFED Science Program

Scientific Contribution to Environmental Problem-Solving	Strengthening CALFED's Capacity
Provide objective information about the Bay-Delta system and its behavior	1. Secure long-term support for the CALFED Proposal Solicitation Package (PSP) program at about $20 million annually to support research that targets key unknowns 2. Support development and implementation of a comprehensive strategy for monitoring and assessment that takes advantage of rapidly emerging technology 3. Integrate adaptive experimentation and adaptive management into design and implementation of the Delta Vision Strategic Plan and Bay-Delta Conservation Plan so that program performance can be assessed in a timely manner 4. Integrate the CALFED Bay-Delta Program more fully into statewide and national networks of information-sharing and instrumentation to support ecosystem management and restoration
Evaluate the response of the Bay-Delta system to policy options	1. Support development of cross-disciplinary, system-wide models of physical and biological processes in the Bay-Delta (for example, the USGS CASCaDE project) 2. Establish within the CALFED Science Program the capacity for high-level, integrative modeling of system response (for example, through elaboration of DRERIP models, linkage to regional databases, etc.) 3. Strengthen the capacity for objective policy analysis through use of these models in conjunction with adaptive management and performance measures
Facilitate formalized and informed debate about science and policy for environmental and water management	1. Strengthen existing tools (for example, workshops, discussion papers) for engaging science and policy 2. Strengthen the CALFED Science Program's capacity to translate science into policy-relevant knowledge 3. Strengthen public outreach about science issues to inform the broader debate about science and policy

problems (Innes, Connick, and Booher 2007). CALFED has provided an important forum where scientists from different backgrounds have been able to share ideas and look at problems in new ways. The CALFED Science Program has funded research across agencies and brought scientists from multiple disciplines together in workshops to address complex problems, an approach that mirrors the most recent developments in science worldwide (for example, in research on climate change). To a degree, the CALFED Science Program has actually stepped ahead of the global science community by also bringing the experience of water managers and other interested parties into the process. The need for this kind of coordination and synthesis of science will increase as a new vision for the Bay-Delta is debated and implemented. As Conklin (2006) points out, the forces promoting fragmentation of ideas and interests are strong. A shared need for scientific legitimacy is an equally powerful force promoting collaboration and a search for coherent solutions.

To meet these challenges, the CALFED Science Program needs a clear plan for moving forward. Weinberg's (1972) three ways in which science contributes to policy debates (objective information, models of policy effects and formalized language) were discussed earlier. The way forward for the CALFED Science Program is to strengthen its capacity to make these contributions (see Table 8.1).

Science as a Source of Objective Information About the System and its Behavior

There are systemic weaknesses in the science infrastructure that supports water and environmental management in the Bay-Delta. One of these weaknesses is the lack of consistent support for targeted research on key unknowns in the Bay-Delta ecosystem. The CALFED Science Program has initiated a competitive program for grants in support of critical research, but has lacked the secure funding to carry this program into the future. Given the pace of change, future management decisions will be increasingly dependent on scientific synthesis and insight and on advice from scientists with hands-on experience in the Bay-Delta. Assured support for policy-relevant research is the best way to ensure that information and advice will be available when needed.

Since its inception, CALFED has striven to enhance and extend observation networks, including attempts to develop CMARP. As noted earlier, CMARP has yet to be implemented, and other attempts to develop performance measures are incomplete. The ability to monitor existing and future project performance objectively is desperately needed. More comprehensive monitoring would provide the raw materials for timely decisions about project direction and contribute to improved physical and biological models of the Bay-Delta.

The ROD specifies that adaptive management should be the tool for integrating science more fully into management. CALFED implementing agencies have made considerable progress in implementing adaptive management, but weaknesses remain. Support for monitoring and assessment, which is central to the adaptive process, is intermittent, as is the use of prospective analysis to explore policy alternatives. The CALFED Science Program has the capacity to help the agencies make further progress in institutionalizing adaptive management.

CALFED has a strong Bay-Delta focus, but is addressing a set of problems that exist in various guises throughout California. Nationally, several major projects focus on water and environmental conflicts (for example, the Upper Mississippi,[10] Great Lakes,[11] Everglades,[12] and Columbia Basin[13]). These projects would all benefit from statewide and national networks of information sharing. The CALFED Science Program is regarded as a successful model in science coordination and integration and could be a leader in establishing such a network.

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[10] See Mississippi River Environmental Program www.mvp.usace.army.mil/environment/default.asp?pageid=74

[11] See Great Lakes Water Quality Agreement Review 2007 http://binational.net/glwqa_2007_e.html

[12] See The Journey to Restore America's Everglades www.evergladesplan.org/index.aspx

[13] See See Columbia River, Northwest Power and Conservation Council http://www.nwcouncil.org

Science as a Set of Tools for Evaluating System Responses to Policy Alternatives

The complexity and interlinked character of the Bay-Delta system and all of its most vexing problems require a new generation of system-scale, cross-disciplinary models. Several steps toward developing such tools have been supported by the CALFED Science Program, including an ambitious attempt to develop interlinked conceptual models for valued species and various attempts to link physical models with ecosystem responses. Such modeling needs to be more strongly supported so that policy can be informed by mature scientific models of Bay-Delta processes. Forecasting the consequences of policy alternatives will always be uncertain, but models provide the most objective means of integrating complex ecosystem data into policy analysis.

At present, there is little capacity in CALFED or the implementing agencies for cross-disciplinary modeling of ecosystem behavior. For the future, the CALFED Science Program should serve as a node or catalyst for the development of integrative models. As part of the CALFED Science Program, such models would have legitimacy and would provide another avenue for coordination and communication among diverse interests in the Bay-Delta. Policy analysis increasingly relies on quantitative risk analysis and numerical analysis. To remain relevant, the CALFED Science Program will need to build its capacity to apply these tools and to connect them in ways that provide a complete picture of ecosystem response as a whole.

Science as a Facilitator of Informed Policy Debate

CALFED needs to expand and strengthen its ability to bring science into policy debates. Notably, as a new vision for the Bay-Delta is completed, debated and implemented, it will be all the more important that independent scientific information and methods are near the center of the storm. Making reliable science available to policy debates has always been a weak link in the science-policy process. The CALFED Science Program has a good track-record of facilitating this information flow, but it needs to be sustained and strengthened.

The CALFED Science Program employs a variety of communication and outreach tools for scientists (the online journal *San Francisco Estuary and Watershed Science*, the CALFED Science Conference), policymakers (workshops, discussion papers), and the public (newsletters, public lectures). These avenues need to be strengthened and expanded in the future to ensure a smooth and effective flow of scientific information to policymakers and other interests.

CALFED and the CALFED Science Program were created in recognition of a need for stronger coordination, integration and communication among interests to address problems of water supply, water quality, levee integrity and ecosystem restoration. The CALFED Science Program has had considerable success facilitating these processes within the scientific community and has stimulated new science to address important gaps in knowledge. As a result, understanding of Bay-Delta processes has improved and policymakers are better informed. These science-based activities will be even more important in the future, and a strong science infrastructure will be a foundation of successful strategic planning.

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