From the Sierra to the Sea

The Ecological History of the San Francisco Bay-Delta Watershed

Middle Fork

The Bay Institute

Second printing, July 2003

The Bay Institute of San Francisco is a non-profit research and advocacy organization which works to protect and restore the ecosystem of the San Francisco Bay/Delta estuary and its watershed. Since 1981, the Institute's policy and technical staff have led programs to protect water quality and endangered species, reform state and federal water management, and promote comprehensive ecological restoration in the Bay/Delta.

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The cover is taken from an engraving showing the entrance to the middle fork of the Sacramento River near modern-day Steamboat Slough, in C. Ringgold's 1852 series of navigational charts and sailing directions for San Francisco Bay and Delta.

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San Francisco Bay-Delta
Watershed

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CONTRIBUTORS AND ACKNOWLEDGEMENTS

This report would not have been possible without the generous financial support of the David and Lucile Packard Foundation, the United States Environmental Protection Agency, the CALFED Bay-Delta Program, the Metropolitan Water District of Southern California, the National Fish and Wildlife Foundation, and California Urban Water Agencies. We would also like to acknowledge the Marin Community Foundation, the William and Flora Hewlett Foundation, and the Fred Gellert Family Foundation for their generous contributions to The Bay Institute's general operating budget.

Funding for the second printing was provided by the CALFED Bay-Delta Program in collaboration with the San Joaquin River Parkway and Conservation Trust, Inc. (www.riverparkway.org).

This report is the product of the dedicated effort of many individuals and organizations. We want to acknowledge the patience and perseverance of all the individuals who contributed. Bill Alevizon (formerly Staff Ecologist, The Bay Institute; currently consulting ecologist) was the senior author and editor, and project manager for the early drafts of the report. Peter Vorster (Staff Hydrologist, The Bay Institute) was the project manager for the final report and provided technical editing, GIS and figure preparation, historical conditions research, and water balance development. Alison S. Britton Consulting/Design Services produced the report with the assistance of Kent Sumrall of the Bay Institute. Kate Britton compiled and proofed the references. Ann Dickinson prepared the files for the second printing.

The GIS maps were produced by Brian Cohen of GreenInfo Network with contributions and data provided by John Cain of the Natural Heritage Institute, Steve Greco of the University of California at Davis, Jo Ann Gronberg of the United States Department of the Interior, Robin Grossinger of the San Francisco Estuary Institute, Dave Hanson of the United States Bureau of Reclamation, Dan Scollon of the Bay Institute, Steve Skartvedt of Golden Gate National Recreation Area, Jennifer Vick of Stillwater Sciences, and Paul Viesze of the California Department of Fish and Game.

The final report built upon contributions by the original drafting and research team composed of Bill Alevizon and Nicole Wainwright (The Bay Institute), Jennifer Vick, Michelle Orr, and Phil Williams (Philip B. Williams and Associates), and Rod Fujita and Karen Levy (Environmental Defense Fund). Valuable contributions were also provided by the reviewers of the various drafts of this report. The reviewers included Elaine Archibald (Archibald and Wallberg), Gary Bobker and Grant Davis (The Bay Institute), Richard Denton (Contra Costa Water District), Phyllis Fox (Environmental Management), Robert Nuzum (East Bay Municipal Utilities District), Pete Rhoads (Metropolitan Water District of Southern California), Doug Shields (United States Department of Agriculture, Sedimentation Laboratory), Randy Bailey (Bailey

Environmental), and Charles Simenstad (University of Washington). Bruce Herbold (United States Environmental Protection Agency), Elise Holland (The Bay Institute), Brian Atwater (University of Washington), Judd Monroe (consulting environmental planner), Steve Johnson (the Nature Conservancy), and Fred Nichols (United States Geological Survey) reviewed sections of the report. Several reviewers provided significant additional information and many constructive revisions to the final draft. In particular we wish to acknowledge the efforts of Phyllis Fox and Elaine Archibald in that regard. Although the contributions of all the persons mentioned above were invaluable, none of the foregoing are responsible for the final version of this report.

We also want to acknowledge contributions from the following organizations and individuals who supplied data and other information used in the report: the California Department of Water Resources (Tariq Kadir and others), Roger Putty (Montgomery Watson), David Dawdy, the United States Geological Survey, the Water Resources Archives and the Bancroft Library at the University of California at Berkeley. Phyllis Fox made her extensive personal collection of archival material available. Many other individuals too numerous to list answered our questions and provided information. We thank you.

EXECUTIVE SUMMARY

I. Background and Introduction

A vast watershed connects the mountain streams surrounding California's Central Valley with San Francisco Bay and the ocean beyond. Over the course of the last two centuries, much of the natural productivity, biodiversity and ecological integrity of the watershed has been destroyed by modifying the environment without fully understanding the long-term environmental consequences. Long the site of some of the nation's most intensive conflicts over the use of land and water resources, this system is now emerging as the focus of one of the most ambitious ecological restoration efforts ever undertaken in the United States.

This report was designed to provide a coherent and defensible *ecological framework* and information base for restoration. The need for such an historical, broad-scale perspective on system ecology stems from two fundamental principles of ecological restoration - the need to manage toward a natural template and to manage at ecosystem and landscape levels.

> **(1)** ***Manage toward the natural template***. Natural conditions and processes shaped the life history requirements of native species. While we may not fully understand the requirements or inherent adaptability of any particular species, we do know that these were closely tied to the historic attributes and variability of the systems in which they lived and evolved. Therefore, this report attempts to provide a description of the natural ecosystem. The period prior to 1850 - a time before the system was significantly altered by human activities - was chosen as the basis for the "natural" undisturbed watershed. Comprehensive restoration in the truest sense of the term - a return to pre-disturbance conditions - is *not* a realistic goal, or even a possibility, for most of the watershed. Nonetheless, careful consideration of environmental conditions at a time when the system was in a relatively undisturbed state provides a necessary baseline from which to develop the conceptual framework and practical tools necessary for effective restoration and management planning at the ecosystem and landscape levels.
>
> **(2)** ***Manage at ecosystem and landscape levels.*** The basic conservation and management unit for aquatic systems should be an area large enough to support self-sustaining populations of native species. Ecosystem and landscape-level approaches to restoration / management efforts focus upon large-scale spatial areas, and the habitats contained within. This

fundamentally differs from species-level efforts, which instead are based upon attempts to identify and address the "needs" or "limiting factors" of particular *species*. Broad-scale, area-based approaches address a number of essential conservation needs that single-species approaches do not. They provide a means to protect species about which little is known, and a means to protect a wide variety of species while they are still common. Nonetheless, it must be emphasized that broad ecosystem-level conservation strategies and restoration programs are meant to *complement* rather than *replace* species-level conservation strategies. Both are necessary to address conservation needs.

To provide the information necessary to support restoration efforts, this report addresses four fundamental areas:

(1) The natural system prior to 1850 is described in Chapter 2,

(2) Changes to the natural system are documented in Chapter 3,

(3) The resulting ecological response and contemporary system are described in Chapter 4, and

(4) Recommendations for guiding system-wide restoration efforts are presented in Chapter 5.

II. The Watershed: Two Centuries of Change

The watershed is far too large and ecologically heterogeneous to be considered a single ecosystem in the usual sense of the term. Rather, it is more appropriately (for management purposes) considered a mosaic of a number of different ecosystems that are integrated into a larger landscape. The watershed (and this report) are divided into five separate aquatic ecosystems -- upland river-floodplain, lowland river-floodplain, the Delta, San Francisco Bay, and the nearshore ocean. This report addresses only aquatic ecosystems, because the impetus for habitat restoration in this system is to provide habitat for declining fishes. The report also focuses on the lowland-river floodplain and the Delta because these are the current targets of most restoration activities. Other habitats not directly connected to these principal aquatic ecosystems, such as lowland prairies or mountain forests, are not addressed. This report documents each of these aquatic ecosystems and factors causing their decline using eyewitness accounts, scientific investigations, historic maps, and local and regional histories.

The Sacramento and San Joaquin Rivers collect water from a vast drainage area, stretching from the Cascades to the Tehachapi, and from the Sierra to the sea. These rivers first begin to mix with ocean waters in the Delta. From there, water flows into and through a series of large embayments collectively known as greater San Francisco Bay. The estuary discharges to the Pacific Ocean through the Golden Gate. This aquatic "circulatory system" is the life blood of the five major, interactive aquatic "ecosystem types" described in this report.

The natural landscape and associated biological communities have been drastically altered by California's population boom of the last 150 years. Harvest of plants and animals, the introduction of exotic species, livestock raising, farming, mining, urbanization, development of navigable waterways, flood control, and the redistribution of water resources have altered the landscape and its native biota in many ways, both directly and indirectly. The precise linkages and mechanisms that have mediated any particular population or species-level change are unknown in many cases, but in total the effects of these combined human interventions on system ecology is staggering. The most severe of these are summarized below, at both the landscape and ecosystem levels.

II.A. A Watershed-Scale Perspective

Under natural conditions, flood waters in the lowland Central Valley spilled over natural levees and coursed through an intricate network of distributary sloughs into vast tule marshes that flanked the main river channels. Enormous flood plains and natural flood basins functioned similar to reservoirs, filling and draining every year. This delayed the transmission of flood flows, reducing peak flows and velocities, and increased summer flows as the waters spread out over the floodplain slowly drained back into the river later in the year. At the watershed scale, changes in system hydrology appear to have had the greatest and most pervasive effects. These changes include reclaiming the marshes to make way for agriculture, replumbing the entire valley to control flooding, and constructing one of the largest water delivery systems in the world. These changes, along with more localized interventions, have substantially altered the ecology of each of the watershed's aquatic ecosystems, as summarized below.

Native vegetation was the first casualty of the rapid growth that followed in the wake of the Gold Rush. Riparian forests or woodlands occurred along virtually all of the streams and rivers of the Central Valley, including the broad natural levees of the Sacramento and Feather Rivers. These forests and woodlands were the most accessible woody vegetation on the valley floor and were rapidly used for fencing, lumber, and fuel by early settlers; they were also cleared to make way for farms. By the 1880s, a significant portion of the riparian forest had been harvested.

The freshwater marshes, which stretched from Willows to Bakersfield in a continuous swath of green, were nestled in river bottoms, in the Sacramento Valley flood basin, and in the Delta. They proved more intractable to the plow and engineering prowess than the riparian forests and did not succumb to the advance of civilization until the turn of the century. These marshes originally functioned as vast floodplains that were inundated by the tides in the Delta and overbank flooding in the Sacramento and San Joaquin Valleys, and were sustained throughout the year by an intricate network of sloughs that connected them with the main channels. The Delta marshes with their rich peat soil were reclaimed first. The valley marshes were not reclaimed until natural flooding was controlled in the 1920s by the complex system of weirs and bypasses that now drain the Central Valley, dredging technology and engineering skills advanced, and state laws were passed to finance and organize reclamation districts to carry out the work on a large scale. Most of the marshes were under cultivation by 1930, ushering in the rush to supply water to the farms and cities that replaced them.

Today, this once richly-endowed landscape is crisscrossed with a maze of aqueducts and canals that deliver water to farms and cities where formerly wildlife thrived. This "aqueduct empire," comprising some 31 million acre feet of reservoir storage, 100,000 groundwater pumps and 1,300 miles of aqueducts and canals, redistributes and transports 30 million acre feet of water every year, and together with marsh reclamation and flood control, has transfigured the "circulatory system" of the watershed. Almost no natural floodplain storage remains. Nearly every major waterway draining the encircling mountains has been interrupted by a series of dams, in most cases terminating in the foothills in a large "terminal" storage reservoir. These have disrupted wetland and riparian corridors and their native fishes and wildlife that formed the natural biological links among aquatic ecosystems. The main changes evident below the terminal storage dams are a pronounced reduction and temporal shift in flows, reduced monthly and inter-annual variability, and shifts in water quality. Average winter/spring flows are now substantially lower, and summer/fall flows slightly higher than they were under natural conditions, except in those drainages, particularly in the San Joaquin and Tulare Lake Basins, where much of the flow is diverted into canals.

On a valley-wide basis, the volumes of large floods remain largely unchanged, although only in very heavy snowpack years do flood flows approach historic levels in the San Joaquin Valley. Rather than regularly spilling out onto floodplains, flood flows today are instead confined to riprapped and artificially leveed river channels (or bypass channels) and quickly conveyed out of the river systems and into the lower estuary and the Pacific Ocean.

In addition to hydrologic changes, sediment transport through the system has been greatly altered. Sediment delivery rates for the upland rivers of the heavily-mined basins remain two to eight times greater than natural, and large deposits remain in some channels from hydraulic mining in the 19th century. Today, rivers below the dams have no source from which to replace sediments removed from their channels.

II.B. Upland River-Floodplain Systems

Riparian forest was naturally distributed along most of the entire length of upland river and stream channels, supporting highly diverse assemblages of insects, amphibians, reptiles, birds and mammals. There has been a widespread and substantial loss and degradation of riparian zones throughout the region. Perhaps as many as 25% of the species dependent upon riparian habitat of the upland region are now at risk of extinction.

It has been estimated that due to dams and other barriers, about 90% of historical salmon spawning habitat in the Sacramento-San Joaquin system is no longer accessible to these fishes. The amount of large woody debris in streams, which normally originates in nearby forests, has declined markedly throughout much of the Sierra, degrading in-stream habitat by reducing complexity. Non-native fishes are now widespread and abundant throughout much of the upland system, and continue to adversely affect the distribution of a wide range of native species.

Water quality problems plague much of the upper watershed. Downstream of dams, altered channel morphology and benthic sediment characteristics, as well as elevated turbidity and temperatures are widespread. Mining, logging, urbanization, and recreational use have increased sediments, nutrients, and bacterial and chemical pollution of once pristine mountain streams.

II.C. Lowland (Alluvial) River-Floodplain Ecosystems

Under natural conditions, vast riparian forests teeming with wildlife inhabited natural levees along every stream channel in the Central Valley, stretching like a green ribbon for miles on both sides of the channel in some areas. Permanent marshes, choked with tules, dotted with lakes, and crisscrossed with distributary sloughs, nestled between the riparian forests and oak woodlands/savannas and vernal pools that stretched across the plains as far as the eye could see.

This report estimates that there were about one million acres of potential riparian habitat, about 900,000 acres of tule marsh, and 415,000 acres of vernal pools in the Sacramento and San Joaquin Basins alone, and additional unquantified acreages of oak woodland/savanna. Huge expanses of this vegetation were also present in the Tulare, including some 477,000 acres of tule marsh and 256,000 acres of riparian oak woodland in the Kaweah delta alone. Today, this vegetation has been almost entirely lost, mostly converted to agricultural production. Less than 5% of historical wetlands, 11% of vernal pools, and about 6% of the riparian zone remain in a quilt of disconnected patches too small to sustain dependent species. Remaining patches of riparian forest, for example, exist as narrow, fragmented corridors less than 100 yards wide, and only a small fraction of those are in nearly pristine condition.

The naturally meandering rivers described above are today generally constrained in straightened leveed sections. Confinement of the main channel between riprapped levees eliminated most meander cutoffs and oxbows, pool/riffle sequences, sunken woody debris and other habitat complexities. Water quality remains severely degraded, due to the combined effects of inactive mine discharges and urban and agricultural runoff. The Tulare Basin lakes are but a faint memory, having been converted to agriculture and hydrologically disconnected from the east side tributaries and San Joaquin River, except in unusually wet years. Floodplain habitat that supported this landscape has been dramatically altered. Most of the natural flood basins are now effectively isolated from the river, except during major floods. Once miles-wide active floodplains are now limited to narrow terraces between levees and flood bypass channels.

Herds of large mammalian herbivores - deer, antelope and elk - and their mammalian predators once depended upon the forests and marshes. They have been reduced to a few scattered remnant populations, as have many of the small mammals that typically occupied these habitats. Birds have been particularly hard-hit, with many once-common species now reduced to remnant populations or extinct. Waterfowl no longer blacken the skies above the Central Valley marshes. Fish populations have dramatically declined due to a long succession of assaults, including marsh reclamation, hydraulic mining, pollution, flood control, and water resource development. The lowland rivers are now dominated by introduced species rather than native fish assemblages.

II.D. The Delta

Prior to 1850, the Delta was probably the richest ecosystem of the watershed in terms of abundance and diversity of game animals and birds. It was largely a vast, sea-level swamp, composed of huge tracts of intertidal wetlands transected by a complex network of waterways. The Delta of today bears little resemblance to its historical condition. Today, over 95% of the original 550 square miles of tidal wetlands are gone. Many miles of tidal sloughs no longer exist, nor does most of the riparian vegetation that once bordered the larger waterways. In its place is a patchwork of intensely-farmed “islands,” riprapped and elevated levees, straightened and deepened channels, permanently flooded remnants of former wetlands now too far underwater to allow the re-establishment of emergent vegetation, and the center of one of the largest man-made water delivery systems in the world. Massive State, Federal, and local agency pumping plants, and over 1,800 unscreened agricultural diversions now transfer water, fish and drifting estuarine life out of the aquatic environment.

Pollution in the Delta is a serious concern today, because it is a source of drinking water and is occasionally toxic to aquatic organisms. Delta waters contain elevated concentrations of pathogens, pesticides, trace metals, salinity, and organic carbon which is a disinfection by-product precursor.

The combination of habitat loss and successful invasion by a virtual army of non-native species has almost completely obliterated the Delta’s native biological community. Benthic assemblages are dominated by non-natives. The native resident fish fauna has been replaced by a largely introduced assemblage. Two of the three historically dominant fish species are no longer found here. Waterfowl, once extremely abundant in the Delta’s tidal marshes, are now drastically reduced in numbers. Of the diverse and abundant native mammalian assemblage formerly found in the Delta, only a few aquatic species - otter and beaver , along with the raccoon - are still seen, though in vastly reduced numbers and at scattered locations. Nutrient and energy sources, and food webs have been greatly modified.

II.E. Greater San Francisco Bay

San Francisco Bay has undergone major habitat alterations over the course of the last two centuries. About 75% of the estimated 242,000 acres of highly productive native tidal marshes and mudflats has been converted to a variety of urban/industrial uses, altering trophic dynamics and food webs. Native biological assemblages of the Bay have been drastically altered by a combination of overharvesting, habitat loss and degradation, pollution, and the introduction of exotics. The topography of the Bay floor continues to be periodically disturbed by dredging to maintain shipping channels. Changes in upstream hydrology and erosion, sediment transport and deposition rates have affected sediment types and distribution - and therefore benthic invertebrate assemblages - throughout the Bay.

II.F. The Nearshore Ocean

Most substantive interactions (regular exchange of water, nutrients, and organisms) between the nearshore ocean and the rest of the watershed are concentrated within a comparatively restricted area near the Golden Gate. Some oceanic processes or events may occur beyond these boundaries that influence watershed ecology. These may include, for example, changes in oceanic conditions such as temperatures, currents, and water quality that affect the migration patterns of anadromous fish or marine density-dependent mechanisms, such as food supplies or predation, that limit populations. However, while these are generally considered well beyond the scope of practical management or restoration efforts, they must be recognized to understand the probable success of restoration efforts.

Shoreline habitats throughout the region have been severely modified in many cases. Pollution offshore is generally not high relative to inshore coastal sites of Central California but nevertheless exists from historic dumping. Over-harvesting of once-plentiful abalone and other shellfish has undoubtedly affected rocky intertidal communities. Ocean harvest of salmon has steadily increased at a rate of about 0.5% per year for the last 40 years, for a total increase of about 20%.

III. Applications: Building a Practical Framework for Ecosystem Restoration and Management

Restoration efforts in this highly developed and populated watershed must necessarily reflect a compromise between conflicting needs. Ensuring the long-term protection of the watershed's ecosystems and habitats requires comprehensive, ecosystem-level efforts. The comprehensive restoration of the *entire* geographic range of the watershed is neither feasible nor desirable. It is incompatible with the needs of 30 million human inhabitants of the state, needs which *also* must be met. Further, the degree of disturbance and (in some cases) irreversible changes in the watershed render it technically and economically unfeasible to undo two centuries of unchecked damage. What then might be the strategic solution to this apparent conflict? Two fundamentally different options are available: A limited number of particularly desirable ecological characteristics (e.g., increased population levels or production) can be rehabilitated.

This approach, called partial restoration or rehabilitation may provide substantial "*ecological benefits even though full restoration is not attained*" (NRC 1992). Alternatively, comprehensive restoration to full ecological integrity throughout the watershed can be attempted.

Planning efforts to date suggest that only *a combination of both approaches* - full-scale restoration at selected sites, and rehabilitation throughout the entire watershed - will achieve the diverse long and short-term biological conservation / resource enhancement goals encompassed by the CALFED program in a manner compatible with current and projected human population levels and their resource needs.

IV. Concluding Recommendations

This report examines the ecological history of the Bay-Delta-River watershed, and considers alternative strategic approaches to ecological restoration that might lead to long-term protection of the system's native species, ecological structure and function. Based upon these analyses, we make the following broad recommendations:

(1) An ecosystem approach to natural resource restoration and management is the most effective available means to meet the need for long-term protection of ecological integrity and biodiversity within the watershed. Specific long-term restoration actions should be primarily (although not exclusively) aimed at enhancing and protecting essential ecosystem processes and structural features. This approach must be complemented with efforts that address the immediate needs of threatened and endangered species. The granting of protected status and preparation of recovery plans for individual species must remain a viable tool in our comprehensive species protection strategies.

(2) A restoration strategy should be adopted to assure a connected network of representative areas of each of the ecosystem and habitat types defined herein.

(3) Flows, sediments, and water quality conditions must be adequate to support essential ecosystem functions. Sufficient connectivity must be provided among restored sites to allow the natural migration and movement of wide-ranging species.

(4) New restoration / management actions must address the needs of surviving remnant populations.

Adopting the recommendations of this report will not resurrect the rich, complex, undisturbed ecosystems of the San Francisco Bay-Delta-River system of 200 years ago. Nonetheless, applying an understanding of "natural" watershed ecology will serve as an invaluable guide to comprehensive restoration. The most successful restoration program for this watershed will ultimately be one that applies the precepts of modern restoration ecology within the practical limits of resources available and the constraints set by other legitimate societal needs. Such efforts - properly designed and executed - have the capacity to protect, restore and sustain native ecosystems, and the full range of remaining native plants and animals that depend on them. They will also reduce conflicts over protection of endangered species, provide for more economically and environmentally sound flood management, enhance recreational opportunities, ensure high water quality for urban and industrial uses, and create an aesthetically more pleasing environment. It is our best opportunity to preserve the unique ecological heritage of California's Bay-Delta-River watershed for ourselves and future generations.

CHAPTER ONE
Introduction

I. Background

A vast watershed connects the mountain streams surrounding California's Central Valley with San Francisco Bay and the ocean beyond. Long the site of some of the nation's most intensive conflicts over the use of land and water resources, this system is now emerging as the focus of one of the most ambitious ecological restoration efforts ever undertaken in the United States. Millions of years of tectonic forces, erosion and changing sea levels created the basic physical features of this landscape, and the ecological opportunities that eventually resulted in the biologically rich and unique complex of aquatic ecosystems that developed here during the last ten thousand years. Over the course of the last two centuries however, much of the natural productivity, biodiversity and ecological integrity of the watershed has been destroyed as people began to increasingly modify the environment without fully understanding the long-term consequences of their actions. Only recently has it come to be fully appreciated that the resultant habitat loss and degradation have caused losses of native species that may proportionately exceed those occurring in some of the world's tropical rain forests (Moyle and Williams 1990).

An unprecedented opportunity now exists to begin to reverse these negative trends. In 1995, the Federal government and the State of California initiated a three-year program to develop a long-term comprehensive plan that will restore ecological health and improve water management for beneficial uses of the Bay-Delta system. Recent legislation and agreements, including California's Proposition 204, the Bay-Delta Accord of 1994, and the Central Valley Project Improvement Act of 1992, have authorized the expenditure of over a billion dollars to begin the task of restoring the Bay-Delta-River system. This report is intended to assist those efforts by providing a conceptual overview and framework of natural ecological structure, function and organization of the watershed, and an historical perspective on the way this has changed over the last two centuries.

II. General Approach of the Report

Planning and management efforts directed towards comprehensive restoration and long-term protection of complex ecosystems require a basic understanding of the natural structure, function and organization of the systems addressed, even if these conditions are no longer attainable. Such understanding is an essential prerequisite to assessing and monitoring the ways and degree to which target sites now diverge from a "healthy" or "natural" condition (i.e., one that we know sustainably supported high abundances and diversity of native species). This in turn facilitates (1) identification of restoration actions essential to program success, and (2) measurement of progress towards desired system states after restoration actions have been undertaken.

This effort recognizes that comprehensive restoration in the truest sense of the term - as a return to pre-disturbance conditions - is *not* a realistic goal, or even a possibility, for most of the watershed. Nonetheless, careful consideration of environmental conditions at a time when the system was "healthy" (i.e., in a state we would deem desirable, even if not once again fully attainable) provides a necessary reference baseline from which to develop the conceptual framework and practical tools necessary to effective restoration and management planning at the ecosystem and landscape levels.

To meet the most fundamental information needs of such programs, this report addresses four pivotal questions:

> (1) What is an appropriate and practical **conceptual framework of ecosystem structure and organization** (i.e., ecological typology) for purposes of managing and restoring the system's natural resources?
>
> (2) Within that framework, what **essential** structural and functional ecological **attributes** of the system define natural ecological "health" or integrity of the system?
>
> (3) What types of **human interventions** have substantially modified these identified attributes over the course of the last two centuries, and in what ways, and to what degree, have the attributes been altered?
>
> (4) How might the answers to the above questions best be **practically applied** to guide restoration planning efforts?

In attempting to answer these questions, this report summarizes and integrates available historic and current geological, hydrological and biological information to describe past and present conditions of this system. Discussion and analysis are focused at the large-scale, ecosystem level of ecological organization because, "*The interconnections among plants, animals, and physical features...are so complex that modification of one component automatically affects all the others to a greater or lesser degree...the only level of ecological theory that will ultimately provide the necessary guidance to management is a theory of ecosystems*" (Cooper 1969, p. 310). Thus, effective long-term species protection mandates "*preventative rather than reactive management, and a focus on landscapes rather than populations.*" (Angermeier and Karr 1994, p. 690).

The term "ecosystem" is used in this report in its modern restoration / management application - as *a defined, ecologically distinctive geographic area occupied by a characteristic biological community*. By definition then, an "*ecosystem level*" approach to restoration / management refers to efforts primarily aimed at identifying and addressing, *in the aggregate,* suites of key attributes (both biological and abiological) of spatially defined areas.

This fundamentally differs from species-level efforts, which instead are based upon attempts to identify and address the "needs" or "limiting factors" of particular species. The geographic scope of such species-focused efforts does not change the underlying basis of the approach - even if spread across extensive portions of a landscape, they should not be confused with or mistaken for ecosystem-level efforts, which fundamentally differ in character and depend upon a quite different information base, as summarily described above.

Ecosystem-level approaches address a number of essential conservation needs that single-species approaches do not; they provide a means to protect species about which little is known, and a means to protect a wide variety of species while they are still common. Nonetheless, it must be emphasized that broad ecosystem-level conservation strategies and restoration programs are not designed to, and should not be expected to, provide a disproportionate advantage or immediate benefit to any particular species. These are meant to complement rather than replace species-level conservation strategies, and most workers would agree that both are necessary to address conservation needs. Thus, more highly-focused, species-oriented efforts must remain a viable option in our species protection strategies. It is our contention, and an underlying organizing principle of this report, that addressing fundamental environmental problems at the ecosystem scale is an absolute prerequisite to the long-term success and ultimate effectiveness of either broadly focused (i.e., long-term biodiversity protection) or narrowly focused (i.e., species recovery, population enhancement) restoration efforts at any and all geographic scales.

The watershed of California's Central Valley represents a landscape - an ecological unit of considerably greater scale and ecological heterogeneity than that of a single ecosystem as defined above. Rather, it may be considered a mosaic of different "ecosystems" that are functionally and structurally integrated to varying degrees. It is at these larger scales that this effort is focused.

The habitats and species that constitute the watershed's ecosystems must be considered in the broader context of the underlying geomorphic, hydrologic, and ecological processes that created and maintain them. There is increasing consensus among restoration ecologists and conservation biologists that without adequate support at the ecosystem level (as defined herein), the results of restoration actions at any level are likely to be less sustainable or effective.

Because restoration "*should address the causes and not just the symptoms*" of ecological degradation (NRC 1992), restoration actions are generally more properly focused upon direct manipulation of the underlying abiological ("physical") factors that are most instrumental in ultimately determining and sustaining the ability of the system to support native species and communities. Restoration actions should be chosen and specifically designed to properly manipulate those factors that, in concert, create the right *conditions* (ecological opportunities) that will promote biological goals, rather than for the purpose of attempting to directly manipulate biological variables themselves. Once provided, biological processes will naturally proceed to once again translate such opportunities into functional ecosystems that may be reasonably expected to approximate (but never duplicate) past or present expressions of the same ecosystem type. As Berger (1990) pointed out, "*all restorations are exercises in approximation and in the reconstruction of naturalistic rather than natural assemblages of plants and animals with their physical environment.*"

III. Methods

The information base developed and presented here was compiled from a variety of information sources - narrative accounts, drawings, sketches, and maps of early explorers and settlers of the region, historical compilations and analyses performed by other workers, and the results of modern examinations of remaining fragments of natural habitat, surface geology and soils, and paleoecological studies. Several thousand sources of information on the historic and current biology, ecology, history, geomorphology, and hydrology of the watershed were briefly considered, and the most useful of these were more carefully reviewed, and appropriate information extracted and summarized.

The bulk of this report summarizes available information on the natural structure and function of the different kinds of ecosystems that make up the watershed, and the ways in which these systems have been altered by human intervention. What might constitute the most appropriate time frame from which to derive a useful comparison of historical (i.e., natural) versus current system ecology? For most of its geologic history, the watershed was an unusually dynamic environment; thus, probably no single restricted period (e.g., century) might properly be considered "representative" of this complex system as it existed for thousands of years. For several practical reasons, the period around 1850 was chosen as the basis for the characterization developed here of the "natural" or "historic" watershed. Prior to 1850, this landscape was comparatively undisturbed by human activity. That period marks the point in central California's history just prior to the population explosion and rapid proliferation of environmentally destructive activities that soon followed the discovery of gold in the region. Also, it is the earliest historic period for which we have a sufficient body of recorded information (narratives, maps, drawings, etc.) from which to build an overview description of system structure and function even partially based upon direct observation. Finally, historic accounts provide ample documentation of the healthy, rich, and diverse biological communities occupying the region circa 1850. Therefore, conditions that existed at that time are, from a restoration / management perspective, considered a desirable "target state".

Several original analyses were performed as part of this effort. These included calculations of habitat area, and a rough water balance for freshwater outflow from the system. The techniques and data sources used in these analyses are briefly described in conjunction with the presentation of their results in Chapters Two and Four. Spatial descriptions of ecosystems and habitat types were mapped in Geographic Information System format to the extent allowed by available data. A brief Appendix describes the relevant technical information associated with this data base.

IV. Report Organization

The report is organized into five chapters. Following this introduction, Chapter Two provides a broad overview of the natural ecology of each of the watershed's ecosystem types. Discussion of each of the system's component ecosystem types is organized within a framework of structural features (habitats and biological assemblages) and processes (hydrological, geomorphic and ecological). Chapter Three discusses the major kinds of human interventions that have substantially altered the ecology of the watershed during the last two hundred years. Chapter Four describes the major documented ecological changes wrought by the net effects of these interventions on each of the watershed's ecosystem types described in Chapter Two. Chapter Five utilizes the information presented in earlier chapters to outline a recommended strategic approach to restoration in the Bay-Delta-River watershed by integrating modern principles of applied restoration ecology with the findings of this report. This concluding chapter also demonstrates ways in which the information base developed here might be translated into some practical and highly useful restoration / management planning and evaluation tools.

CHAPTER TWO
Ecosystems of the Watershed - Natural Structure, Function and Organization

I. Introduction

This section summarizes and synthesizes available information on the "natural" (i.e., pre-disturbance) ecology of the aquatic portion of this ecologically diverse watershed. The aquatic portion of the watershed either contains standing or flowing water for part or all of the year, or is directly dependent on that condition. From either an ecological or a practical management perspective, the Bay-Delta watershed is far too large, complex and biologically heterogeneous to be treated as a single ecosystem in the usual sense of the term. It is probably more productively viewed as a mosaic of distinctive but interrelated *ecosystem types*, interconnected by the movement of water, sediments, and animals into the larger landscape referred to in this document as "the watershed." The summary overviews presented here of the ecology of each of the ecosystem types were created through analysis and integration of historical information, modern studies of remnant portions of the native systems, and inference from investigations of ecologically similar "reference" systems occurring elsewhere.

Five different aquatic "ecosystem types" - two fresh water, two estuarine and one marine - are distinguished and described below. Freshwater systems include two distinctive types of river-floodplain systems - *upland* (mountain) and *lowland* (alluvial). The estuarine part of the watershed consists of an upper portion - the Sacramento-San Joaquin Delta, along with the lower estuary - greater San Francisco Bay. A legal (but ecologically arbitrary) boundary near Chipps Island separates the two. The marine portion of the system is a proximate portion of the nearshore ocean just beyond the Golden Gate, encompassing an area referred to as the Gulf of the Farallones. Figure G1 shows the distribution of the five ecosystem types.

For practical reasons, the structural make-up of the ecosystem types discussed is described in terms of component sub-units called *habitat types*, defined here as *structurally and biologically distinct subdivisions of ecosystems that maintain substantial interactions with other such ecosystem components.* For example, lowland river-floodplain "ecosystems" are considered mosaics of riverine, riparian, and wetland habitat types. Each kind of area is occupied by a somewhat distinctive resident biological assemblage, but also fulfills part of the habitat requirements of more wide-ranging species of the ecosystem, and also regularly exchanges both organisms and non-living materials with other habitat types. This use of the term "habitat" clearly differs from its other common connotation - the living space used by a particular *species* - which is, in most cases, unique to that species, and represented by either a limited portion of a single habitat type (in the sense of the term as defined above) or, alternatively, portions of a number of adjoining habitat types.

Thus, the "habitat" of a particular species is generally not a readily definable, recognizable, or practically managed geographic unit.

II. Environmental Context

II.A. The Geographic Context

The aquatic ecosystems of the watershed drain nearly 61,000 square miles, or 42% of California's land area. This area encompasses the Central Valley, the Sacramento-San Joaquin Delta, and greater San Francisco Bay (Figure G1). The Central Valley comprises a large basin bounded by the Sierra Nevada and Cascade Range on the east, the Coast Ranges on the west, the Klamath Ranges on the north, and the Tehachapi Range on the south. It is divided into two major valleys - the Sacramento Valley in the north and the San Joaquin Valley in the south - which are drained by the Sacramento and San Joaquin Rivers. The southern third of the San Joaquin Valley (Tulare Lake Basin) is geomorphically and hydrologically distinct, and exchange of surface waters between the two basins is usually limited to periods of high flow.

The freshwaters that drain the Central Valley first encounter saline waters pushed inland by ocean tides in a large, complex system of wetlands and waterways that encircle and radiate from the mouths of the Sacramento and San Joaquin Rivers. This area is referred to as the Delta, and forms the upper portion of the estuary. From the Delta, waters draining the Central Valley flow into four large embayments (Suisun, San Pablo, Central, and South Bays) collectively known as greater San Francisco Bay, and also referred to here and elsewhere as the "lower" estuary. The estuary discharges to the Pacific Ocean through the Golden Gate.

II.B. The Geologic Context: Formation of the Watershed

The broad-scale topography of the estuary's watershed was formed by 240 million years of tectonic and erosional forces acting upon a young continent. The subduction of the eastward-moving edge of the Pacific plate along with tectonic uplift along the eastern boundary of the Sierra Nevada range have been the major forces shaping the large-scale features of this landscape. These processes raised two mountain ranges - Coast and Sierra Nevada - that define the east and west margins of the Central Valley. These ranges differ substantially in composition and mean elevation. The lower, coastal mountains to the west are primarily composed of sedimentary rock, formed by the crumpling and uplift of marine sediments skimmed off the top of the Pacific Plate during its subduction under the North American plate. The higher Sierra Nevada mountains to the east were formed by the upwelling and slow cooling of molten minerals from the earth's mantle, which crystallized to form granite. The low mountains formed by this upwelling granite were uplifted along a series of faults bordering the range's eastern margin, raising the mountains to their current height. Between these two ranges, a structural trough formed the Central Valley. During the millions of years of its evolution, the valley was alternately flooded by coastal seas, and exposed as a basin surrounded by slopes that collected and drained the watershed. Thus, alternate layers of coastal marine and alluvial sediments eventually deposited to depths of 50,000 feet (Page 1986).

Although the general underlying geological structure of the watershed we know today was defined by about 2 million years ago, many topographic features changed dramatically with the advance and retreat of the great ice sheets of the Pleistocene epoch, which extended from 2 million to 15 thousand years bp (before present). During each glacial episode, sea level dropped several hundred feet, exposing much of the continental shelf and draining what remained of the shallow inland sea that had filled portions of the Central Valley. This reduction in sea level, combined with tectonic uplift, caused the major rivers of the Central Valley to incise deep channels. Their combined outflows traversed a deep gorge through the Coast Range (today's Golden Gate), and then flowed across a coastal plain that extended out to the Farallon Islands. During this same period, the movement of ice also shaped the alpine terrain of the Sierra and Klamath ranges, while the subduction of the Pacific Plate formed the chain of volcanoes we now know as the Cascades. The southern end of this chain extends into the Central Valley, and now forms the Sutter Buttes.

Most of the alluvial sediments comprising the valley floor were derived from the Sierra Nevada, as a result of repeated glaciations. The ice sheets of the last ice age removed most of the soils above 5,000 feet in elevation. At that time, glaciers filled the upper valleys, where they typically formed extensive moraines (deposits of heterogeneous ground-up rock) at their termini. As the glaciers melted, these moraines eroded and washed downstream, eventually depositing as a series of coalescing alluvial fans along the east side of the Central Valley. As the slope of the Sierra continued to increase as a result of rapid uplift during the Pleistocene epoch, stream power increased and channels cut deep valleys through the glacial deposits. While the Coast Ranges were lower in elevation, sediment delivery from these mountains was proportionately much higher than that from the less erodible granite of the Sierra Nevada. This resulted in the deposition of large alluvial fans along the westside tributaries.

About 15,000 years ago, a climatic warming trend known as the "Holocene Transgression" signaled the final retreat of the Sierran glaciers. Rapid melting continued for about 9,000 years, causing global sea level to rise at a rate of approximately 20 mm/yr (Atwater et al. 1979). The major sedimentary features of the watershed were formed during this period. River channels deposited large amounts of sediments, building new channels and floodplains within their entrenched valleys and resulting in the remarkably flat and uniform floor of the Central Valley. The rising ocean first inundated a coastal plain that is today's continental shelf, and then continued to intrude inland of the Golden Gate. By 10,000 years bp, San Francisco Bay had started to form. By 6,000 years bp, tidal influence had extended into the Delta (Atwater 1979) (Figure II-A), and the general form and large-scale features of the watershed we know today had emerged. Over the last six millennia, these features continued to evolve through geomorphic, hydrologic and ecological processes into the ecosystems described in this report.

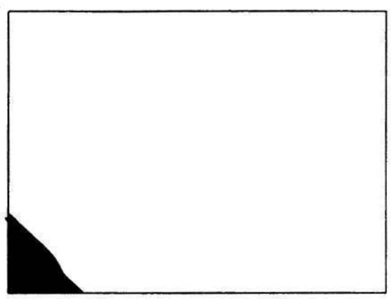
II.C. The Climatic Context

For most of its recent geological history, the watershed has exhibited a Mediterranean-type climate with a pronounced cool, moist season in the late fall and winter, and a warm, dry season from late spring through early fall. About 80% of the annual precipitation normally occurs in the months of November through March. During the summer months the lowland portion of the watershed may have no precipitation, while upland portions of the higher, eastern ranges (Sierra, Cascades) commonly have intermittent local thunderstorms.

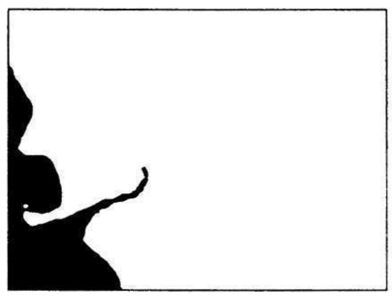
The primary source of precipitation reaching the Central Valley is the seasonal (November-March) progression of cyclonic (low-pressure) disturbances that move onshore (eastward) from the Pacific Ocean. The strength and frequency of these systems is largely determined by global oceanic/atmospheric circulation patterns. Small-scale shifts in these patterns (such as the position of the Pacific high) translate into pronounced variability in the timing and amount of annual precipitation received by the watershed (Figure II-B). In addition to the year-to-year variability (about 30% - 200% of average), there are decade-long shifts in precipitation and runoff believed directly related to the relative strength of the El Niño Southern Oscillation (ENSO) (Li and Ku, 1997).

The instrumental record in California for the past 150 years indicates that there have been periods of relative wetness (late 19th and early 20th century, and the mid-1930s to the mid-1970s), relative dryness (1917-34), and periods characterized by wet and dry extremes (1976-98). In the context of the last several millennia, the climate of the last 150 years is marked by its relative wetness and warmth, and lack of persistent extremes. Stine's (1990, 1996) and Graumlich's (1987) climate reconstruction for the Sierra indicate that the past century is the third wettest in the last thousand years. Within the last millennium California also experienced what Stine (1994, 1996) describes as two century-scale "epic" drought periods and a three century period prior to 1850 of

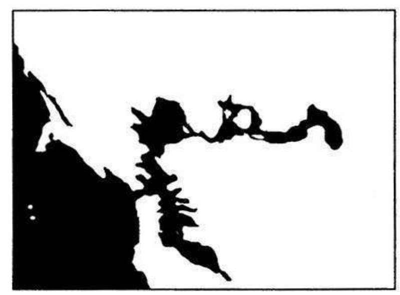
Figure II-A
The Invading Estuary



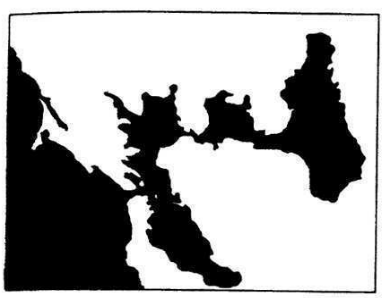
15,000 Years Ago
(End of last Ice Age--sea level approximately 400 feet below present level; rivers not shown)



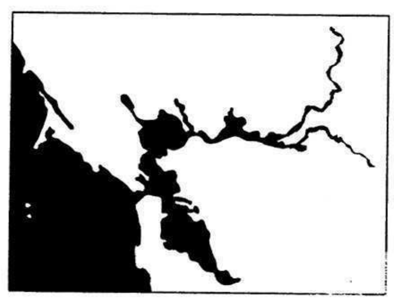
10,000 Years Ago
(Formation of Farallon Islands and intrusion into the "Golden Gate")



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



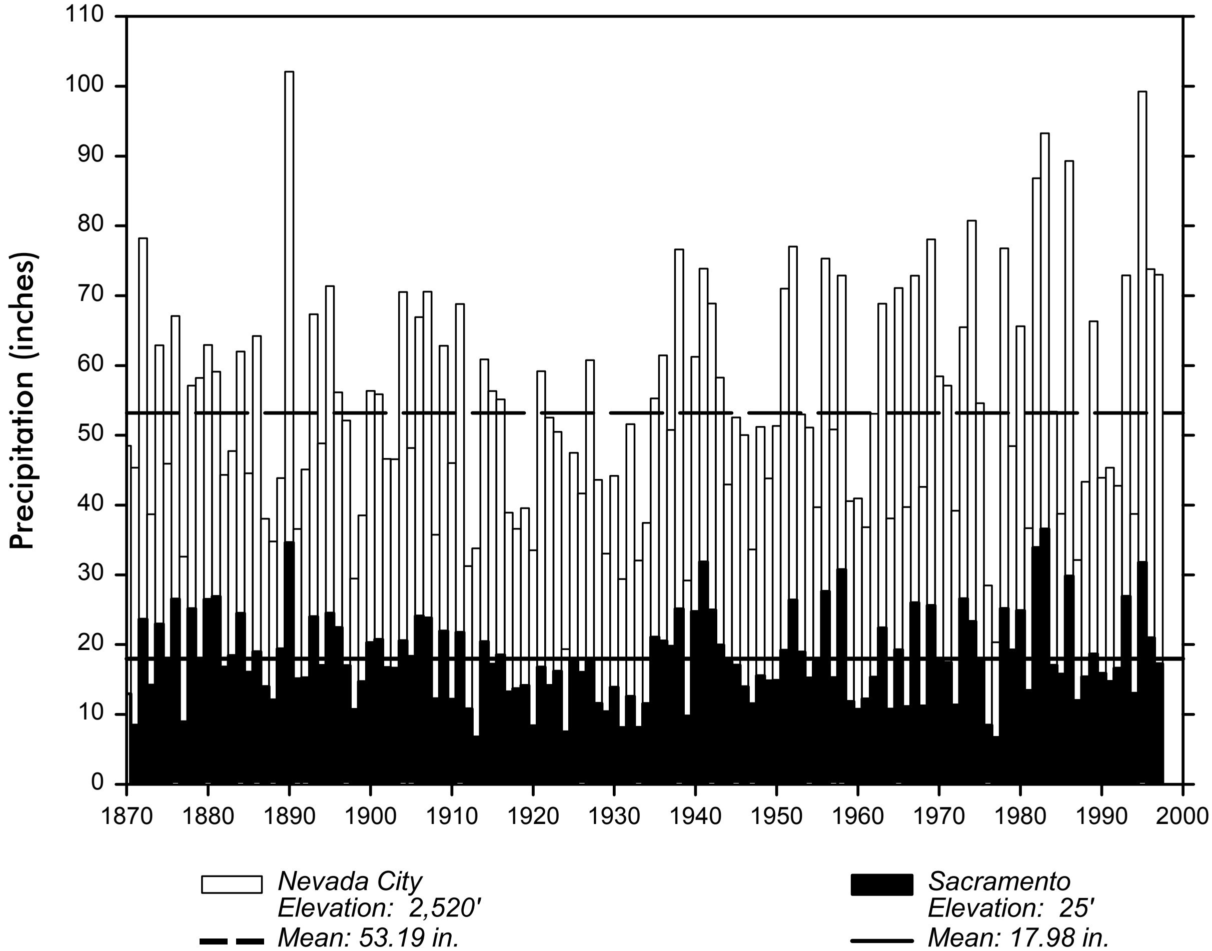
125 Years Ago
(Landward edge of undiked tidal marsh)



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

Sequential sea level rise created the Bay-Delta we know today.
Source: San Francisco Estuary Project, adapted from Atwater 1979 and Atwater et al. 1979.

Figure II-B
Annual Precipitation Variability
in the Central Valley Watershed
(1870-1997)



Annual precipitation since the mid-19th century in the upland and lowland regions of the watershed is represented by Nevada City and Sacramento, the two sites with the longest reliable records. The substantial difference in the mean precipitation between the two sites is due to the higher elevation and more northerly position of Nevada City. High inter-annual variability and large departures from the mean are typical of Central Valley watershed precipitation.
Data from compilation by J. Goodridge.

abnormally cool conditions (by 20th century standards), in which glaciers formed and advanced in the Sierra.

II.D. The Hydrologic Context

Topography, altitude and latitude are the controlling factors in the geographic distribution of precipitation and thus runoff in the watershed. Topography creates local and regional rain-shadows (an area of low precipitation on the leeward side of a mountain range). A rain shadow is located on the eastern side of the Coast Ranges and extends out over the Central Valley floor. As a result there is a general west to east increase in precipitation across the valley floor. Average annual precipitation varies from less than six inches in the Tulare Lake Basin to over 80 inches in the Cascade Range. The western slopes of the Sierra-Cascade Range receive high amounts of precipitation, and consequently contribute most of the runoff that flows into the lowlands.

Precipitation generally increases with altitude, although records suggest that it reaches a maximum somewhat below the crest, especially in the Central and Southern Sierra. High elevation precipitation averages about 40-80 inches annually, with the higher amounts in the northern part of the range and a general decline to the south (Kahrl 1979). This same trend is also evident in lowland precipitation. The Sacramento Valley averages a little more than 20 inches of precipitation annually, while the Tulare Lake Basin averages less than 8 inches. The general timing of precipitation also typically varies with latitude. The wet season commences earlier and ends later in the northern portion of the watershed, but proportionally greater amounts of precipitation fall in the southern portion of the watershed somewhat later in the rainy season.

For the watershed as a whole, about 21% of the precipitation received is retained as surface runoff and groundwater. The remainder is consumed by direct evaporation to the atmosphere, and by plant transpiration (liquid water uptake by plants and subsequent conversion into water vapor, transmitted through plant surfaces to the atmosphere). However, this is an average figure for the watershed as a whole, and does not necessarily apply to local watersheds. In some upland watersheds, for example, well over 50% of the annual precipitation becomes runoff. The total annual runoff derived from the upland zone averages about 31 million acre-feet (MAF) (CDWR 1994a). In contrast, only about 12% of the average precipitation received directly by the Central Valley lowlands (including the Delta) becomes runoff, an average of about 1.5 MAF per year (Williamson et al. 1989). In the San Francisco Bay region, about 32% of the precipitation becomes runoff, totaling on average about 1.5 MAF per year (CDWR 1994b).

III. Upland (Mountain) River-Riparian Ecosystems

Upland river-riparian systems are defined as those rivers, streams and associated riparian zones that occur above the alluvial deposits comprising the Central Valley floor, which are found near the 300 ft. elevation contour. As they descend from their headwaters towards the valley floor, smaller streams eventually join with others to form ever-larger tributary rivers that finally enter alluvial deposits of the valley floor. The upland portion of the watershed consists of a series of adjacent drainage basins whose streams, rivers and riparian zones share fundamental ecological characteristics (described below). Our purpose here is to describe those common attributes. Different workers have treated much of the region as a single “ecosystem” (e.g., SNEP 1996), or alternately a series of considerably smaller management units (i.e., ecosystems) representing particular subregions or drainages (e.g., Battle Creek, Cosumnes River, etc.). All such schemes are arbitrary, and no attempt has been made here to geographically delineate specific “ecosystems” within the upland portion of the watershed. Within the practical context of developing management and / or restoration programs for this region, it is probably most appropriate to rely on operational delineations of such boundaries most relevant to the scope and goals of particular programs.

III.A. Ecosystem Structure: Habitat Types and Biological Assemblages

River-riparian ecosystems of the upland watershed, as defined here, are characterized by two basic structural elements - the river itself, and its associated riparian zone - that define primary habitat types. The submerged portion of the channel, and the flowing waters contained therein, comprise *riverine habitat*. This is bordered by a *riparian zone* - a flanking corridor of increased soil moisture, occupied by distinctive plant assemblages. This feature is maintained through periodic flooding which transports water laterally across the floodplain, and through elevated groundwater levels. In combination, these processes result in moisture levels in surrounding soils well above those that would accrue from precipitation alone, leading to the establishment and successional development of characteristic and specialized plant assemblages that would not otherwise survive there. The two habitat types of the system are described below.

III.A.1. Riverine Habitat

a. Distribution and Extent. The rivers and streams included in the upland system (as defined herein) are distributed over a vast area, extending from southern Oregon southward to the Tehachapi Range at the southern end of the Central Valley, and occupying the western slopes of the Sierra Nevada and Cascade Ranges, and the eastern slopes of the Coast and Klamath Ranges (Figures G1, G2). The bulk of these channels are located along the Sierra Nevada and Cascade Ranges, at elevations ranging from about 300 to 12,000 ft. Together, these two ranges account for about 80% of total Central Valley runoff (Kattelman 1996).

b. Composition and Complexity. Rivers and streams of the upper watershed are naturally characterized by shallow depths, and cold, clear well-oxygenated waters low in nutrients. For the most part, these waterways consist of bedrock / boulder controlled channels surrounded by steep slopes and confined between rock outcrops. These have minimal or no floodplains, and display little sinuosity. Channels are typically steep, resulting in structurally complex mixtures of swift waterfalls and cataracts, turbulent riffles, and quiet pools. The nature of riverine habitat in this part of the watershed varies notably with slope. In the steeper reaches (slope >4%), channels are typically characterized by frequent rapids and cataracts that empty into scour pools immediately below. Where slopes are more moderate (2-4%), channels tend to be dominated by riffles, with rapids and pools common only in constricted areas or river bends (Rosgen 1994). The bedrock controlled channels along many streams are intermittently interrupted by less steep, localized accumulations of alluvial sediments that form deep glacial valleys (e.g., King's Canyon and Yosemite Valley), broad flats (e.g., Sierra Valley and Kern plateau), and scattered meadows (e.g., Tuolumne Meadows) ... "*[in which] channels may meander and form multiple channels across a broad area*" (Kattelman and Embury 1996). This creates opportunities for a more extensive riparian zone to develop than is possible in the bedrock controlled channels.

Fundamental riverine habitat characteristics reflect the flow of water (and the sediments contained therein) through this portion of the watershed. The effects of flow *per se* on local habitat structure are mediated through interactions with local topography (e.g., slope), channel morphology (e.g., cross-sectional profile, substrate composition and complexity), and the nature and extent of nearby riparian plant assemblages. In some reaches, flows may be relatively uniform, uninterrupted by irregular bottom topography or in-stream physical obstruction. In other areas, the presence and nature of in-stream structure increases the complexity of aquatic habitats by physically obstructing and diverting flow, which in turn creates backwater areas, pools, riffles, and other depth / flow variability. Some in-stream structural complexity is provided by sand bars, boulders, and other inorganic obstructions. Additional structural complexity in riverine habitat, particularly along reaches where riparian forests are well-developed, may be provided in the form of the snagged or grounded remains of tree trunks and branches that have fallen or been washed into the water. This is called *large woody debris* (LWD). Much of this material is often deposited comparatively close to its source of origin, but substantial portions are sometimes carried and deposited far downstream. LWD directly provides in-stream structure and also interacts with flow to modify fundamental characteristic of streams and rivers, including morphology and energy transport (Bilby 1988, Swanson et al. 1982). For these reasons, LWD is considered an integral link between rivers and their surrounding forests (O'Connell et al. 1993).

In their natural states, the riverine systems of higher elevations were essentially continuous, both within this zone and with waterways of lower portions of the watershed. While flows at any given site might be altered somewhat by the formation and/or dissolution of sand or gravel bars, or by accumulations of large organic debris, these represented localized, temporary, and partial obstructions. Even when landslides suddenly and completely obstructed a channel, streams eventually eroded a new channel, thereby re-establishing connectivity with lower reaches of the watershed. Thus, no physical barriers existed that were capable of completely or largely interfering, on a sustained basis, with the drainage of water (along with its loads of sediments, organic nutrients, and passively drifting organisms) or the active movement of fishes.

c. Associated Biological Assemblages. Plant life is naturally sparse in higher elevation streams, and occurs mainly in the form of benthic algae. Phytoplankton are rare in these cold, nutrient-poor waters. Benthic algae becomes more common at lower elevations, where water temperatures moderate and nutrient concentrations increase.

An array of native invertebrate animals may be found in upland rivers and streams (Erman 1996). Common aquatic invertebrates include both crustaceans (isopods, amphipods) and insects (dragonflies, damselflies, dobsonflies, and caddisflies). Some, like the caddisfly, naturally occur in high diversity (about 200 species), many of which (about 20%) are unique to the Sierra Nevada. These assemblages are known to be sensitive to changes in flow regime, water quality, temperature, predation pressure, sediment transport and deposition, and the availability of substrate such as woody debris (Erman 1996).

Some forty species of fishes are native to the Sierra Nevada. Localized differences in species distribution/abundance patterns in upland rivers and streams are generally reflective of habitat diversity and characteristics. For example, the overall species composition, distribution and diversity of temperate stream fish assemblages tend to be highly dependent upon habitat structure and complexity (e.g., substrate and flow characteristics, presence of LWD or pools/riffles, etc.). Because such factors tend to vary systematically with altitude and lead to somewhat predictable changes in fish assemblages found in different regions, it is convenient to generally characterize the fish assemblages of such systems in terms of "fish zones," typical of different elevational portions of the watershed (Moyle and Cech 1988). While such schemes are useful descriptive tools, it should be noted that "fish zones" have diffuse rather than sharp boundaries, and grade into one another as the environment gradually changes. Many species inhabit more than one zone.

The upland portion of the watershed contains two of the three basic geomorphic zones generally recognized in most stream systems, erosional and intermediate. The third type (depositional zone) is confined to the lowland rivers. The uppermost reaches of upland streams and rivers comprise an *erosional zone*, characterized by high stream gradients, abundant riffles, cold (<21°C), well-oxygenated water, a cobble-boulder-bedrock substrate, shaded and undercut banks, and few in-stream aquatic plants. In this zone, the dominant and most widely distributed salmonid is the rainbow trout *(Onchorynchus mykiss)*, which often co-occurs with less abundant salmonids, including the golden trout *(O. aguabonita)*, mountain whitefish *(Prosopium williamson)* and two cutthroat trout species. Lie-in-wait predators like sculpin, and small midwater minnows, like speckled dace, are also found here. Amphibians - frogs and salamanders - historically dominated the aquatic communities of naturally fishless areas of the Sierra Nevada, mainly above elevation 6,000 feet.

Further downslope lies an *intermediate zone*, that extends from the lower portions of the upland watershed (as defined here) into the lowland river system. This area is composed of sometimes perennial tributaries traversing open foothill woodlands of oak and pine of the Sierra and Coast ranges, and is characterized by moderate gradients, warmer (up to 30°C in summer) waters, and a balance of riffles, deep pools, and undercut banks. Native species include squawfish, large suckers, hardhead and rainbow trout. California roach are particularly adapted to the intermittent streams of this zone.

Along with resident fish populations, the upland portion of the watershed provides for part of the habitat requirements of more wide-ranging, anadromous species. Anadromous salmonids and Pacific lamprey are found in both higher and lower elevation streams, while the white sturgeon are confined to lower elevations. Chinook salmon are the most numerous and widespread of the anadromous salmonids. These highly-valued fish, which weigh up to 90 lbs (40 kg), are extremely resilient and can adapt to changing conditions such as the extended drought and flood periods typical of California, with various races ("runs") taking advantage of different flow, temperature, and habitat availability. Chinook eggs require cool (<14°C) water temperatures for optimal survival. Most spawning historically occurred in fall when the first rains increased flows and lowered water temperatures, but the runs display considerable inherent variability in terms of life-history patterns. They effectively maintained a high degree of genetic isolation through behavioral and geographic differences, although limited straying and hybridization occurred. Spring-run chinook were historically the dominant run in the watershed, and the most physically isolated, with an estimated 500,000 to one million returning each year to spawn in the upper reaches of the Sacramento and San Joaquin River watersheds (Moyle and Yoshiyama 1992).

III.A.2. Riparian Zone

The *riparian zone* in the upland ecosystem may be generally defined as an area occupied by unusually dense and distinctive assemblages of trees and associated vegetation that immediately border streams and rivers of the region. The presence and unique characteristics of these assemblages derive from elevated moisture levels (surface and/or groundwater) that result from proximity to the river. The general structure of riparian zones is that of a thickly-wooded forest, although considerable local variability is typical. Often, thickly-forested areas are interspersed with more open assemblages typical of woodlands. In general, mature riparian forests typically display a complex, multi-storied structure, with high tree density, a well-developed canopy, and several distinctive understory layers that may include a thick ground layer. Frequently, a profusion of vines is present at all layers. Riparian zones also typically display different microclimates than adjacent areas, with higher humidity, increased rates of transpiration, greater air movement (Thomas et al. 1979), and cooler air temperatures (Kattelmann and Embury 1996).

a. Distribution and Extent. Riparian forest was naturally distributed along most of the entire length of upland river and stream channels (Figure G2). Most of the riparian zone of upland systems occurs along steep, bedrock-dominated channels, where it is usually highly limited in lateral extent in comparison with lowland river systems. However, the riparian zone widens where rivers and streams traverse alluvial deposits of mountain meadows and similar landscape features, and in some places, such as along the Sacramento River above Red Bluff, extensive bands of riparian forest historically flanked upland portions of the river. Overall, it has been estimated that riparian forests generally represent between 0.1% to 1% of the total area of typical Sierran basins (Langley 1984, Kondolf et al. 1987).

b. Composition and Complexity. Riparian zones of the upland portion of the watershed naturally differ in vegetative composition and microclimate from the lands they cross (Kattelmann and Embury 1996). Upland rivers and tributaries are generally bordered by a riparian zone of large conifers, willows, cottonwoods, and other vegetation atypical of upslope forests. Cottonwood and willow grow rapidly and have a short lifespan. These species form an understory to larger coniferous forest trees. Trees typical of the riparian zone in the Sierra Nevada include white alder *(Alnus rhombifolia),* hackberry *(Celtis reticulata),* Oregon ash *(Fraxinus latifolia),* ponderosa pine *(Pinus ponderosa),* cottonwood, western birch *(Betula occidentalis),* dogwood *(Cornus stolonifera),* and willow *(Salix spp.)* among others (Kattelmann and Embury 1996).

Riparian plant associations characteristic of narrow, bedrock-dominated river channels tend to differ somewhat from those typically associated with channels traversing alluvial deposits. The former types of areas possess soils that are comparatively shallow, coarse-textured, and not generally subject to the degree of prolonged exposure to direct sunlight or strong winds endured by alluvial riparian zones (O'Connell et al. 1993), which tend to support higher plant diversity. In addition to the bordering trees, alluvial riparian areas also support a variety of sedges, rushes, grasses, and forbs. Such areas may constitute essential habitat for some specialized species of the region. For example, mountain meadows of the Sierra Nevada partially fulfill the habitat requirements of many birds that breed elsewhere (Graber 1996).

c. Associated Biological Assemblages. Riparian forests fulfill essential habitat requirements of highly diverse assemblages of insects, amphibians, reptiles, birds and mammals, some of which are obligate residents and others of which are more widely-distributed habitat generalists (O'Connell et al. 1993). The dense and diverse vegetation provides a large variety and quantity of animal living requirements including nesting and perching opportunities - food from seeds, fruits, and insects, and a shady, moist microclimate. There is little available direct information on the abundance and distribution of upland riparian animals of [150] years ago. However, it appears reasonable to infer that habitat distributions of native species evident today remain highly reflective of these species' inherent needs in this portion of the watershed, which still contains representative areas of relatively pristine habitat. Current patterns (see Kattelmann and Embury 1996) suggest that a substantial number of the birds native to the Sierra are dependent upon riparian habitat. The pivotal role of riparian zones in upland forest ecology was emphasized in a recent analysis of such relationships in the Inyo National Forest (Kondolf et al. 1996), which concluded that access to riparian zones was critical for at least one life phase of about 75% of local wildlife species.

Thirty amphibians (21 salamanders, 9 frogs or toads) are native to the Sierra Nevada. Almost all of these spend a portion of their lives in riparian areas (Jennings 1996). Both the density and diversity of birds in the upland system is highest where riparian forest and meadows co-occur. Many forest mammals, including deer, mink, beaver, raccoons, ringtail, skunks, shrews, and woodrats and such fur-bearing mammals as weasels, ermine, pine marten, and fishers are common in the riparian zone, although of the fur bearers only mink and beaver are obligate residents (Graber 1996). Historically, grizzly bears were also common visitors. Among the larger grazing herbivores, mule deer *(Odocoileus hemionus)* dominated the foothills, while mountain sheep *(Ovis canadensis)* occupied the crest and eastern slopes of the Sierra. Of the total 401 native Sierran species of mammals, birds, reptiles and amphibians combined, about 20% (84 species) depend heavily on the riparian area, and many more use it occasionally to find food, water, and shelter (Graber 1996).

III.B. Ecosystem Function: Essential Processes

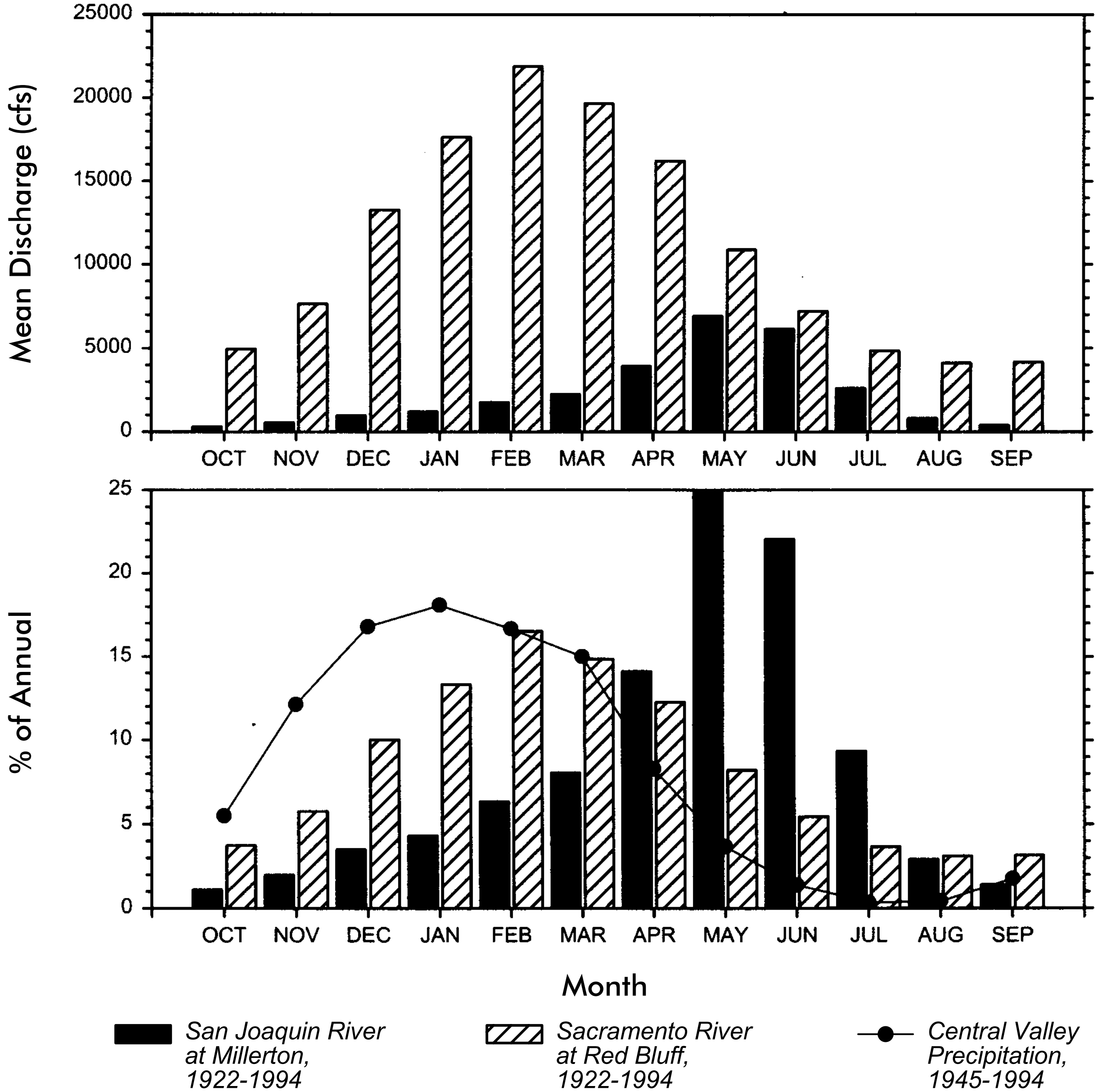
III.B.1. Hydrogeomorphic Processes

Erosion and active transport are the dominant hydrogeomorphic processes in this part of the watershed. Since the retreat of the last glaciers, the complex and dynamic topography that characterizes the upland portion of the watershed has been naturally maintained by the movement of water, derived from rainfall and melting snow and ice. This process continually erodes channels in the underlying bedrock and redeposits sediments along the way, thereby reshaping the contours of upland river-riparian ecosystems, and repositioning ecological boundaries. The natural movement of water (both as surface flows and groundwater exchange) also ecologically connects riverine and riparian habitat, allowing the vital exchange of nutrients, energy, seeds, organisms, and sediment.

The natural flows in the upland ecosystem, including the discharge into the lowland ecosystem, are characterized using modern day unimpaired runoff. Unimpaired runoff represents the flow that would occur absent any diversions or reservoir regulation and is directly derived from the measured flows. Although it is sometimes referred to as the full natural runoff, the unimpaired runoff does not reflect fully natural conditions since it does not account for changes in natural watershed runoff characteristics that have occurred in the past 150 years due to land use alterations and vegetation conversion. It is assumed, however, that the cumulative effects of those alterations on the seasonal runoff from the upland ecosystem is relatively minor and the unimpaired runoff is a satisfactory representation of natural upland runoff.

Flows throughout the upper watershed (which directly reflected runoff from rainfall and/or snowmelt) historically exhibited substantial seasonal and inter-annual variability (Figure II-C). Flows here also varied markedly on a daily, weekly, or monthly basis in response to short-term rainfall and/or snowmelt events. Throughout most of this region, such fluctuations are not dampened by notable lake or floodplain storage as they are in the lowland systems. Peak flows within different streams and rivers of the upland region varied somewhat systematically with altitude and latitude. Below about 5,000 feet, highest flows normally occurred from rainfall events during late fall and winter. At higher elevations, spring snowmelt normally produced the highest flows, particularly in the Central and Southern Sierra. Flows dropped off dramatically throughout the region once the winter precipitation season and spring snowmelt terminated. Watersheds of the Northern Coast Ranges, which are largely supplied by rainfall, at times had no surface flow in the late summer and fall months. Very low base flow also occurred during this period in the watersheds draining the Sierra Nevada. In contrast, a portion of the upper Sacramento River watershed drains spring-fed

Figure II-C
Average Monthly Unimpaired (Natural) Discharge from the Upland Sacramento and San Joaquin River Watersheds



The annnual Sacramento River runoff at Red Bluff is on average nearly four times greater than the San Joaquin River at Millerton. Temporal differences in the pattern of runoff of the two rivers is due to differences in the amount of precipitation received as rain (dominant on the Sacramento), versus snow (dominant on the San Joaquin) and differences in underlying geology. The lower graph also plots the pattern of Central Valley precipitation to illustrate how precipitation and runoff are out of phase.

Data from California Department of Water Resources.

watersheds of the Cascades and Modoc Plateau, sustaining relatively high summer base flows in the lowland Sacramento River (see Groundwater Hydrology, Section IV.B.2).

Notable differences are evident between natural seasonal flow patterns in the southern (higher elevation, more snowfall) and northern (lower elevation, more rainfall) portions of the upland region (Figure II-C). Average maximum monthly flows occur in May on the San Joaquin, versus February on the Sacramento. About 70% of the annual San Joaquin River runoff occurs in the April through July snowmelt period, while only 30% of the Sacramento River runoff occurs during this same period. Another difference in the hydrology of the two watersheds is that the volcanic terrain in the Sacramento sustains relatively high base flows in contrast to the granitic terrain in the San Joaquin that has very low base flows following snowmelt. This difference is reflected in the relative extremes of the average monthly runoff in Figure II-C, which shows the average minimum monthly runoff on the Sacramento is roughly 20% of the average maximum monthly runoff, while on the San Joaquin the average minimum monthly runoff is roughly 5% of the average maximum monthly runoff.

Sediments are derived from erosional processes in stream channels and banks, as well as from downslope transport from upland forests that occurs during heavy rain or snowmelt events. Natural erosion rates in the granitic Sierra are substantially lower than those of the sedimentary substrates of the Coast Range. Typical natural sediment yield estimates are less than 200 tons per square mile per year for the Sierra, while many portions of the Coast Range deliver sediments at ten times that rate. Highest sediment production in the Sierra originates in the foothills between the 1,000 and 3,000 ft. elevations (Kattelmann 1996).

III.B.2. Disturbance and Succession

Stream geomorphology and related habitat characteristics of upland river-riparian ecosystems may remain relatively constant in the short term, but these areas are subject to periodic disturbance in the forms of fire, earthquake, volcanic eruption, as well as from varying flow levels. Flows here have high energy, and the erosion, transport, and deposition of sediment and debris result in a constantly changing riparian community. Flow-related disturbance occurs on a continuing basis, but is accentuated by seasonal shifts in precipitation patterns. During most of the year, surface portions of the riparian areas are physically separated from their adjacent streams, and hydrologic connectivity is achieved chiefly through groundwater exchange. This process maintains the high levels of soil moisture needed to sustain the riparian plants through the drier months. Nonetheless, continual erosion regularly removes areas of mature vegetation and redeposits the resulting woody debris and sediment. This process provides a ready source of new substrate available for growth of early successional species.

During the wet season, flooding uproots plants, and transports and redistributes sediments, nutrients, and seeds downstream and across lower portions of the surrounding topography. During flood events, lower areas of the active channel and adjacent floodplain, along with their accumulations of decaying organic litter and uprooted live plants, become part of the stream (Kattelmann and Embury 1996). The seasonal expansion and contraction of stream channels is considered an essential element of river-riparian connectivity in these types of systems (O'Connell et al. 1993).

Riparian zones are particularly dynamic environments, characterized by higher levels of periodic disturbance than nearby upland habitats (O'Connell et al. 1993). Constant disruption of riparian habitat by flood, fire, wind and animal activity maintains a highly diverse and topographically complex assemblage of plants in various stages of succession at the river's edge, characteristics that often contrast markedly with the comparatively homogeneous structure of adjacent mature communities (CSLC 1993, Naiman and Rogers 1997). High levels of disturbance may partially account for the naturally high biodiversity of these ecosystems, since disturbance and subsequent successional processes not only increase habitat complexity and diversity, but also may act to prevent or inhibit community domination by a relative few superior competitors (Connell 1978).

III.B.3. Community Energetics: The Acquisition and Cycling of Organic Carbon and Nutrients

a. Sources. The ecosystem acquires energy and nutrients from internal production, and transfer from other systems. Higher-elevation (>7,000 ft) soils are sparsely vegetated and generally of low organic content. Lower elevations (1,000 to 7,000 ft) are naturally heavily forested, but nutrients here are typically bound-up in thick accumulations of litter on the forest floor. As a result, upland rivers and streams are generally clear, and contain minimal levels of organic nutrients.

Most of the organic nutrients found in riverine habitat are derived from the riparian zone, which is the major source of primary production (and the site of most decomposition) in these ecosystems. It has been estimated that dead organic matter may contribute as much as 99% of the annual energy input to headwater streams covered by a dense forest canopy (Fisher and Likens 1973). The limited in-stream primary production that does take place in the upland rivers and streams occurs mainly at lower elevations where temperatures and nutrient levels are somewhat higher. Some of the organic contribution of the riparian forest to the stream below occurs more or less continuously, as dead leaves, needles, twigs, branches, logs, bud scales, fruit, droppings of terrestrial animals, etc., fall or are carried by wind or rain into the river. Such material, along with aquatic benthic insects which fall into the water, form a source of food for aquatic organisms called *drift*. In upland rivers and streams, this may represent the predominant food source for fish, as these waterways are too deep and swift to support substantial benthic community development (McGinnis 1984 *in* CSLC 1993). Part of the forest's organic contribution to the river also occurs sporadically, as stream levels undergo seasonal shifts, or flood waters spread across the landscape and then recede back into the channel, carrying with them accumulated dissolved and particulate nutrients, as well as seeds, organisms, etc.

About two-thirds of the available food in higher elevation rivers is dissolved, half in sediments and half in the water column (Schoenherr 1992). The remaining third of the available food consists of detritus, suspended in the water or deposited on the substrate (Schoenherr 1992). Historically, large runs of 1 to 3 million chinook salmon annually transferred an estimated 20-80 million pounds of organic matter to upland rivers and streams of this watershed, representing a major nutrient source (Moyle and Yoshiyama 1992). Estimates from a comparable Pacific northwest system indicate that the annual contribution of dead salmon represents a substantial fraction of the nitrogen content of many stream insects and crustaceans, as well as about 30% of all the nitrogen and over one-third of the total carbon content of developing salmon smolts (Bilby et al. 1996).

b. Food Chains, Cycling and Exchange. Most of the biomass in these ecosystems is produced and concentrated in the riparian zone, hence most decomposition and recycling occurs on and in the soils of the forest floor. Surface fungi and microorganisms, and interstitial microorganisms within the soil and groundwater account for most decomposition and regeneration of nutrients here. Dissolved food supports algae and bacteria, which are in turn preyed upon by micrograzers such as protozoans, insects, freshwater mussels, and some fish. Detritus flushed into stream channels supports assemblages of specialized crustaceans (most common in the uppermost reaches of these systems), and aquatic insects (which tend to dominate lower reaches). Both groups play major roles in the in-stream decomposition and cycling of organic nutrients.

Fishes, birds, reptiles, amphibians, and small mammals form intermediate links in ecosystem food chains. These feed directly on plants, invertebrate animals, and one another. Fishes are the most ubiquitous consumers of riverine food chains in most of the upland part of the watershed, feeding at virtually all trophic levels. Some, such as suckers *(Catostomidae)* feed on algae, detritus, and invertebrates found in sandy substrates and on rocks. Trout are the most abundant purely aquatic predators of upland tributary and river systems, although some mammals also heavily exploit food resources here. The river otter *(Lutris canadensis)* was, and probably remains, a major predator of riverine habitat in these systems. Raccoons are also common predators on crustaceans, amphibians, and small fish. Many other mammals, birds, reptiles and amphibians that primarily reside in the neighboring upland forests regularly visit the rivers and streams to drink and avail themselves of the rich food resources found in riverine and riparian habitats (see Associated Biological Assemblages, Sections A.1.c and A.2.c, above). Some in turn become prey for riverine or riparian zone predators, thereby considerably increasing the complexity of ecosystem food webs.

c. Sinks. Downstream flow, burial, and consumption and removal by larger wide-ranging animals are major nutrient sinks for upland aquatic ecosystems. Unlike other ecosystem types of the watershed, these lack the capacity to respond quickly to sudden increases in nutrient availability by rapidly expanding phytoplankton populations. Thus, most of the sudden large influxes of nutrients to stream waters that occur during flood events is passed to downstream ecosystems.

IV. Lowland (Alluvial) River-Floodplain Ecosystems

River-floodplain systems occupied large portions of the Sacramento, San Joaquin and Tulare Lake Basins. The rivers, riparian zones, and wetlands constitute the major natural habitat types of lowland river-floodplain ecosystems. Riparian associations are naturally most common immediately adjacent to the rivers, and also along natural levees. Wetlands-dominated low-lying areas are primarily backwater areas extending laterally from the main channels and in separate floodbasins. Together, these two habitat types encompass the vast majority of frequently inundated areas of the floodplain.

Extending out upland from the margins of the forests and wetlands, or occurring sporadically in drier “pockets” within these habitats, were less frequently inundated portions of the floodplain which were occupied by two more mesic plant associations - valley oak woodlands and native grasslands. These adjacent ecosystems interacted with river-floodplain systems in several particularly notable ways. First, they provided essential habitat support to enormous populations of large, wide-ranging mammals - antelope, elk, etc. - that regularly visited the river-riparian systems, thereby forming an ecological connection among aquatic and terrestrial systems of the Central Valley through which energy and nutrients were regularly transferred. Second, because they immediately adjoined more frequently inundated habitats but were somewhat higher, they undoubtedly served as critical refuges for many ground nesting animals (reptiles, mammals, and birds) during flood events that temporarily submerged marshplains and forest floors. Interspersed within these major features of the landscape were a number of somewhat more restricted habitat features such as chaparral, wildflower fields, and vernal pools, each occupied by somewhat distinctive biological assemblages.

IV.A. Ecosystem Structure: Habitat Types and Biological Assemblages

Lowland river-floodplain ecosystems are naturally distributed among a number of somewhat different and in some ways ecologically distinctive regions of the Central Valley. The Sacramento, San Joaquin and Tulare Lake Basins all contain features that lead to systematic differences in many ecological attributes of river-floodplain ecosystems found in each region, including the nature and distribution of habitat types.

IV.A.1. Riverine Habitat

a. Distribution and Extent. Lowland rivers are distributed across a vast area covering nearly 21,000 square miles of the Central Valley (Figures G1 and G2). This does *not* include the Redding Basin, which is considered part of the "upland" system described above because it is geologically separated from the remainder of the Central Valley by the Red Bluff Arch and thus not connected to the continuous alluvial lowland.

The Sacramento Valley is drained by the Sacramento River, which enters the alluvial lowlands of the Valley near Red Bluff. Above Red Bluff, the Sacramento River collects water from the east side of the Klamath Ranges as well as drainage, via the McCloud and Pit Rivers, from the Cascade Range and the Modoc Plateau, a spring-fed area of volcanic rock east of the Cascades. From Red Bluff to its mouth near Collinsville, the lowland portion of the Sacramento River traverses about 245 miles of the Central Valley. The largest tributaries to this portion of the Sacramento are the Feather River (which is joined by the Yuba and Bear Rivers in the lowlands) and the American River, both of which mainly originate in the Sierra (except for two branches of the Feather River that collect water from the southern Cascades). A number of smaller tributaries draining the Cascades (e.g., Butte, Big Chico, Deer, Mill, and Antelope Creeks) enter the Sacramento River north of its confluence with the Feather River. Tributaries draining the Northern Coast Ranges (e.g., Elder, Stony, Cache, Putah Creeks) contribute a relatively minor portion - about 8% of the average annual inflow - of the total inflow to the Sacramento River.

On the southern (San Joaquin) side of the Central Valley, the San Joaquin River Basin is drained by the San Joaquin River. This river originates in the Sierra and enters the Central Valley in the vicinity of Fresno. From here, the river flows 267 miles to its mouth in the Delta, where its outflow joins that of the Sacramento River. The major tributaries to the San Joaquin - the Merced, Tuolumne, and Stanislaus Rivers - also originate in the Sierra Nevada. The Mokelumne, Cosumnes and Calaveras Rivers (or "eastside tributaries") are also considered part of the San Joaquin River Basin drainage because they flow into branches of the San Joaquin River in the Delta, *before* its junction with the Sacramento. Several small streams drain the Coast Ranges to the west of the

San Joaquin Basin, but these are intermittent. The larger northern westside tributaries (Ingram, Del Puerto, Orestimba Creeks) discharged directly into the San Joaquin River while the more southerly Coast Range tributaries (e.g., San Luis Creek) did not (Hall 1886b, Sheet 2).

b. Composition and Complexity. The lowland rivers of the Central Valley change in character as they emerge from the foothills of the surrounding mountain ranges and approach the main axis of the valley floor. As they first enter the lowlands, they traverse a transitional zone between the bedrock-dominated "erosional zone" of the upland systems and the comparatively flat "depositional zone" that characterizes floodplains of the valley floor. Because of its intermediate position, this region is sometimes referred to as a "zone of transport." The distinctive characteristics of this intermediate zone are derived from a unique geomorphic history. In general, the zone of transport is characterized by rivers that run swifter and deeper, and are more turbulent and complex than further downstream in the depositional zone. The river beds are composed mainly of gravel. Distinctive hydrologic and geomorphic characteristics of waterways in this zone lead to some ecologically distinctive attributes. For example, Moyle et al. (1996) ecologically distinguished streams in this region as high quality fall-run chinook salmon spawning habitat because of favorable water velocities, bed material, fall temperatures, and location.

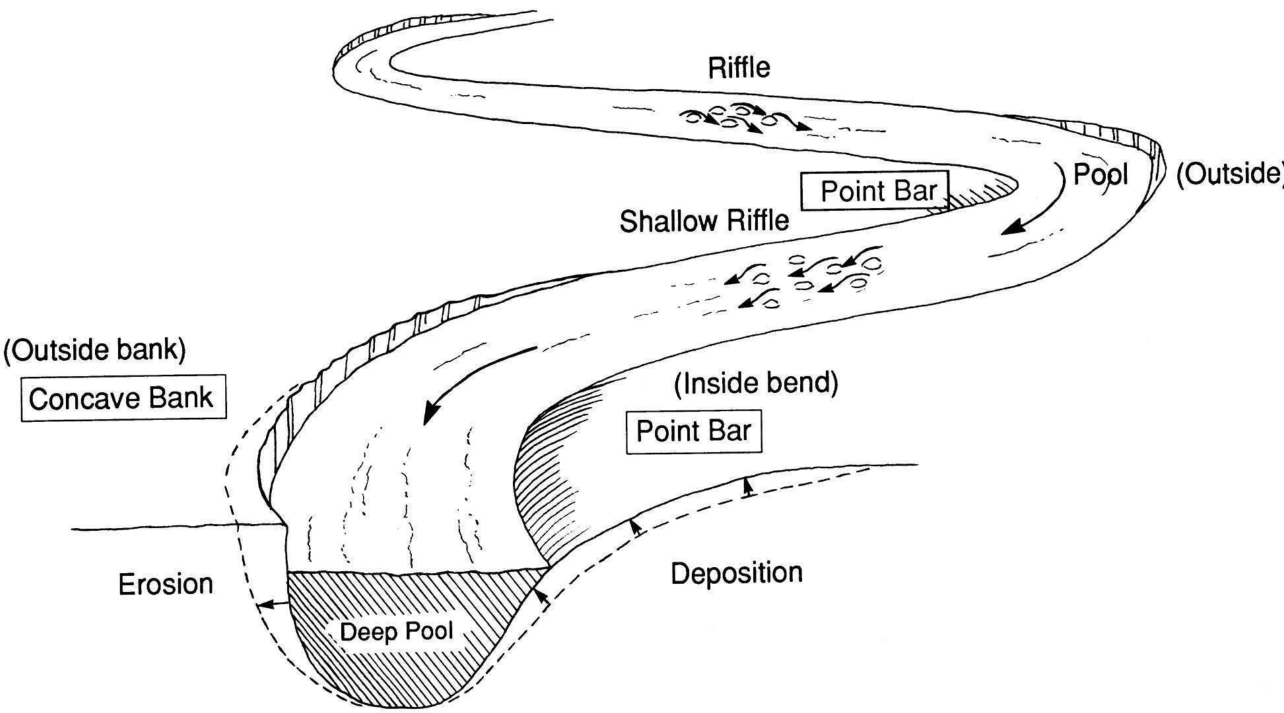
In some cases (particularly in the San Joaquin Valley), rivers and their floodplains in this zone are constricted by bluffs on each side, which rise up to a 100 feet or more above the river surface and extend up to 30 miles downstream from the foothills. On the upper San Joaquin River near Fresno, the width of the river bottom between the bluffs ranges from 1,000 to 5,000 feet (Cain 1997). In steeper reaches, branching networks of channels with sparsely vegetated banks formed (Cain 1997). In less steep reaches, the tributaries tended to form single meandering channels, with the extent of floodplain limited by the adjacent bluffs. Eventually, the bluffs gave way to the flat floodplains of the valley bottom, allowing extensive lateral development of bordering riparian forest and wetlands. In some locations the lowland rivers were entirely contained within a single channel, while in other places the flow was split into networks of secondary or overflow channels, or distributary sloughs. The presence and complexity of these ancillary channel networks was largely dependent on the gradient and depositional processes of a particular reach. Areas with particularly complex channel networks included the tributaries where they emerged from the Sierra foothills, the San Joaquin River between Firebaugh and the Merced River, the Sacramento River above Colusa, and the mouths of the Sacramento and San Joaquin Rivers.

Where vertical gradients are relatively high (1-2%), lowland river channels migrate back and forth in a sinuous pattern across their floodplains in a process called active meandering (Figure II-D). This results in comparatively high structural diversity, with "oxbow cutoffs" and backwater areas branching off from the main channel (Figure II-E). The latter encompasses side channels, distributary channels, sloughs, and other backwater areas of the main river channel. Side channels are small channels branching off the main stem. They are typically abandoned river channels or overflow channels on the floodplain or on low terraces near the main stem. Distributary channels are channels that branch off the main stem and flow through the floodplain as separate channels. Sloughs are side channels or distributary channels characterized by minimal flows. They therefore generally maintain pool or pond-like characteristics, although relatively high velocities may occur during large floods (Beechie et al. 1994).

As the rivers approach the base of the valley floor, slopes become more gentle (<1%) and a depositional zone (low-gradient floodplain) results. Rivers here have higher natural channel sinuosity, but lower rates of meander migration than those found further upstream (Fischer 1994). Here also, the main river channel beds gradually shift from mainly gravel to mostly sand, and river banks naturally take the form of laterally extensive depositional levees. As they flow downstream, lowland rivers become increasingly warmer, more turbid, lower in oxygen and richer in nutrients. In the lowest reaches, as the great rivers approach their mouths in the Delta, benthic substrates incorporate increasingly finer sediments - muds and silts - that settle out of suspension only after the river slows. In the depositional zone, only accumulations of large woody debris (LWD) provide the physical structure needed to create topographic and hydrodynamic complexity, and vary the otherwise slow (except during floods) uniform flow. In the comparatively wide channels characteristic of this region, LWD may cause local scour and channel migration, as well as trapping sediments.

Regional differences in the Central valley lowlands led to systematic differences in the nature and extent of river-floodplain systems throughout the valley. The Sacramento River enters the alluvial lowlands of the Central Valley near Red Bluff. From there to the vicinity of Colusa, the river formed a wide, active meander belt. Below Colusa (River Mile 190 to the Delta), the main river traversed a depositional, low-gradient floodplain, and took on corresponding characteristics (described above). In the lowest reaches of the Sacramento River, the valley slope decreases substantially, and large floods historically inundated the floodplains to depths exceeding 20 feet. Periodic flooding resulted in the deposition of silts and sands on the adjacent floodplain, which in time raised natural levees that were in some places several miles wide and 10-23 ft above the mean river level. Brice (1977, p. 19) observed that "*natural levees, rather than being deposited by a sheet of water flowing overbank, may be mostly deposited when water moving at high velocity through a stream channel is flanked by rather deep water on the flood plain*." Flood water occasionally breached these natural levees, but the levees tended to inhibit overflow and confine much of the sediment flow to the main channel. Because

Figure II-D
Characteristic Channel Morphology of a
Meandering Reach



Source: Reprinted from *California's Rivers, A Public Trust Report*, 1993, with permission from the California State Lands Commission.

Figure II-E
Backwater Area

Off the main river channel. Note the structural complexity of the habitat provided by overhanging branches and large wood debris in the water.

the levees along the lower Sacramento River effectively blocked the discharge of tributary streams into the main channel, an extensive parallel drainage system evolved behind many of them. The levees also greatly inhibited the lateral deposition of river-borne sediments across the adjacent floodplain, a process which in other reaches effectively counteracted natural subsidence of the valley floor. Thus, the levees here came to be flanked by a series of large, depressed *flood basins* with a combined surface area of almost 1,000 square miles (Clapp and Henshaw 1911), and a storage capacity of approximately 4.1 million acre-feet (Grunsky 1929). In this reach, the channel banks historically contained cohesive, clay basin deposits. Consequently, meander migration rates were naturally low (Fischer 1994).

The San Joaquin River Basin lacked the extensive flood basins that flanked the lower Sacramento River. In its natural state, the San Joaquin River and its main tributaries meandered across ancient alluvial fans towards the main axis of the valley floor. Where it first left the Sierra foothills and traversed the intermediate transport zone, the San Joaquin was a gravel-bed, intermediate gradient river. As it approached the main axis of the valley floor, the southwesterly flowing river emerged from confining bluffs into a lower-gradient, depositional topography. Here, the river distributed its high flows into a complex network of sloughs that branched off both sides of the river, and then, near Mendota, made an abrupt right turn to flow northwesterly (towards the Delta) along the main axis of the valley. Near this point (Mendota), the San Joaquin merged with Fresno Slough, a waterway which at that point was wider and deeper than the San Joaquin itself. Fresno Slough was part of an intricate slough system that exchanged water between the Tulare Lake Basin and the San Joaquin River (see Tulare Lake Basin, below) (Farquhar 1932b, Williamson 1853, Davis et al. 1959). Downstream of Mendota, the San Joaquin flowed through a network of large slough channels traversing extensive riparian woodland, tule marshes, and backwater ponds until it joined with the Merced River. After this, the floodplain was more confined and the river adopted a highly sinuous pattern of rapid channel meander migration. This created a rich complex of oxbow lakes, backwater sloughs, ponds, and sand bars in a mosaic of successional states. In its lower reaches just above the Delta, the river formed low natural levees approximately six feet high (Thompson 1957, Atwater and Belknap 1980).

The Tulare Lake Basin had a quite different structure. Runoff was collected in terminal lakes on the basin floor. The Kings, Kaweah, and Tule Rivers historically flowed into Tulare Lake, while the Kern River flowed into Kern and Buena Vista Lakes (which often discharged to Tulare Lake). The rivers tributary to these lakes formed broad deltaic fans near the lakes that were covered by vegetation (Williamson 1853). These fans extended completely across the valley as the Kings River and Kern River ridge (Clapp and Henshaw 1911). The lakes fluctuated from a few square miles in dry years to over

800 square miles in wet years (Grunsky 1898, Hall 1886b, Sheet 4), and supported an extensive fringing tule marsh.

Surface waters were periodically exchanged between the San Joaquin and Tulare drainage basins through a complex of slough channels. Some of the channels branching off the main stem of the San Joaquin River near Firebaugh extended southward, and eventually formed a deep slough channel about 40 miles long and 250 feet wide. This feature (Fresno Slough) eventually branched into smaller channels 8 to 10 miles from the river, which became intricate and ramified as they entered Tulare Lake, completing the surface connection (Farquhar 1932b, Williamson 1853, Hall 1886b). A large bar at the mouth of the slough (on the Tulare Lake side) prevented water exchange between Tulare Lake and the San Joaquin River except during periods of high flows.

Flow in the Fresno Slough system was generally believed to be from south to north, bringing in seasonally high water from a Kings River distributary (CDPW 1931a), groundwater (Anonymous, 1873) and the occasional overflow from Tulare Lake. Eyewitness reports exist that variously describe flows in this slough system at different times as both south from the San Joaquin towards the Tulare (Derby in Farquhar 1932b), as well as north from the Tulare into the San Joaquin (Coulter 1835, Fremont 1848). Grunsky, a well-known civil engineer who first examined this region in the 1870s, believed Derby had crossed the delta of the Kings River and that the water in the Fresno Slough was flowing from the Kings River delta north toward the San Joaquin River and that part of the Kings River was flowing south to Tulare Lake (Farquhar 1932b, note 43).

c. Associated Biological Assemblages. Current knowledge of the ecology of large rivers in this biogeographic region suggests that historically, the characteristic major components of pelagic biota in the Central Valley rivers were likely to have been the same that exist today: phytoplankton, aquatic insects, and fishes. However, this study found virtually no information regarding the species composition of phytoplankton or insect assemblages of the historical riverine system. Because of the alteration that has occurred over the last 150 years to many fundamental ecological characteristics of these rivers, the degree to which current species composition reflects historical patterns must remain speculative.

There is some rudimentary information available on the historical composition of fish assemblages of these systems. Native freshwater species identified by remains in Indian middens in the lower Sacramento Valley (Schulz and Simons 1973, Schulz 1979) consisted of a combination of freshwater and anadromous species, including the Sacramento splittail *(Pogonichthyes macrolepidotus),* Sacramento squawfish *(Ptychochei1us grandis),* hitch *(Lavinia exilicauda),* Sacramento blackfish *(Orthodon microlepidotus),* hardhead *(Mylopharodon conocephalus),* thicktail chub *(Gila crassicauda),* Sacramento sucker *(Catastomus occidentalis),* prickly sculpin *(Cottus asper),* Sacramento perch *(Archoplites interruptus),* and tule perch *(Hysterocarpus traski)* (Herbold et al. 1992). Anadromous forms included chinook salmon, sturgeon, and Pacific lamprey. Unfortunately, the native fish assemblages of this part of the watershed no longer exist as such, and not enough is known about the ecology of the native fishes nor about their precivilization habitats to make any worthwhile guesses about how the fishes subdivided the zone's space and resources (Moyle 1976a). Nonetheless, current understanding of the ecology of these native fishes indicates that many evolved behavioral and life history patterns (e.g., timing of spawning migrations, downstream migrations of young of the year, etc.) that were, and remain, keenly tuned to typical seasonal flow patterns that characterized the system prior to massive human intervention (Herbold et al. 1992). Additionally, there is reason to believe that the weedy backwaters (sloughs, marshes) of Central Valley rivers were naturally dominated by deep-bodied fishes such as Sacramento perch, hitch, thicktail chub, and tule perch, while open water was dominated by specialized minnows (blackfish and splittail) along with large suckers and squawfish (Moyle 1976b).

In general, benthic animal assemblages of Central Valley rivers tend to be dominated by aquatic invertebrates, most notably mollusks (e.g. clams and snails), crustaceans (e.g. crayfish) and several groups of worms. Substrate composition is a primary determinant of benthic community structure in aquatic environments (Sanders 1960). Thus it is not surprising that the nature of benthic invertebrate assemblages differs somewhat between the gravel/sand substrates of the zone of transport and the finer sand/silt substrates of depositional zones. Tubificid worms and midge larvae are particularly tolerant of lower oxygen and higher nutrient environments characteristic of lowland river bottoms (CSLC 1993), and may have been prominent in these environments 150 years ago as well as today.

IV.A.2. Riparian Zone

Riparian zones are distinguishable from adjacent, non-riparian plant associations by a variety of distinctive compositional and structural features (Campbell and Franklin 1979, Franklin et al. 1981, Swanson et al. 1982, Oakley et al. 1985). Some general characteristics that distinguish riparian zones from more xeric, upland plant associations were discussed previously (Upland Systems: Riparian Zones). The general structure and extent of riparian zones is highly dependent upon the size of the watercourse and topography of the surrounding landscape (Oakley et al. 1985) and also varies with other structural features of the environment, including most notably surface water, soils, and microclimate (O'Connell et al. 1993). Thus, it is not surprising that many fundamental characteristics of riparian zones of the lowland rivers of this watershed differ in many ways from those of the upland systems, particularly from those portions of the upland watershed contained in narrow, steep valleys with bedrock-dominated channels. Riparian zones of alluvial floodplains are generally characterized by a greater degree of structural complexity, and greater diversity of plant associations than are the narrow, steep-sided riparian areas typical of the upland rivers and streams (O'Connell et al. 1993).

The term "riparian" has come to be used in a number of different ways among workers describing these associations in the Central Valley lowlands, and some clarification of the use of this term in the present report is warranted. Riparian zones have been traditionally defined on the basis of topography and/or vegetation, but may also be defined functionally as a zone of interaction between aquatic (riverine) and terrestrial (upland) environments (Swanson et al. 1982). In the broadest sense, this functional definition includes *all* the vegetation that owes its presence to proximity to the river, which generally includes a "*mesoriparian*" component associated with frequently inundated portions of the floodplain, and a "*xeroriparian*" component that represents a somewhat drier (less frequently inundated) transitional zone between mesoriparian and adjacent non-riparian ecosystems.

In terms of Central Valley lowland riparian systems, the mesoriparian sub-zone may be considered the area occupied by densely vegetated, canopied plant associations ("forest"), while a xeroriparian sub-zone is characterized by more open "woodlands," in which single trees or clumps of trees (primarily valley oak) are interspersed with grass-covered, treeless patches of landscape, creating a "park-like" setting. It is particularly worth noting in this context that some Central Valley workers (e.g. Conard et al. 1977) have tended to use the term "riparian" somewhat restrictively in reference to canopied, mesoriparian associations adjacent to waterways, while others (e.g., Thompson 1961, Warner and Hendrix 1985) have used the term broadly to denote a variety of plant associations associated with high levels of groundwater, in some cases even including vegetation considerably distant from waterways and separated from them by fully terrestrial habitats. Not surprisingly, this lack of consistency in terminology has led to considerable confusion in the literature, and has made the task of summarizing available information on the pre-disturbance structural characteristics and extent of the Central Valley's riparian vegetation a challenging task. This problem is not unique to the Central Valley, and the last twenty years have witnessed a proliferation of schemes attempting to better define and classify riparian systems in other geographic regions (e.g., Cowardin et al 1979, Ratliff 1982, Youngblood et al 1985, Kovalchik 1987).

In this report, the term "riparian zone" is used to refer to the area *adjacent to a waterway* that supports either mesoriparian or xeroriparian plant assemblages, or both. This provides the major advantage of increasing the utility of both soils analyses (a primary information source which lacks the resolution to differentiate between mesoriparian and xeroriparian areas), and the historical accounts and documents (which also generally failed to distinguish the sub-zones defined above, and were additionally characterized by a general confusion of terms and scales of resolution). Where appropriate, the term "riparian forest" is used to refer to mesoriparian associations - densely-wooded, canopied areas immediately flanking the main waterways - while "riparian woodland" is used to refer to more open, xeroriparian (mainly valley oak-dominated) transitional areas.

a. Distribution and Extent. Most riparian zones of the Central Valley were decimated before the end of the 19th century. Much of what we know today of the extent of this habitat type in its natural state has been pieced together from analyses of soil types, compilations of eyewitness accounts of early explorers, and landscape reconstructions using a variety of sources (e.g., Dutzi 1979). The total acreage of riparian zones of the Central Valley was never directly mapped under natural conditions, although numerous early maps use symbols to indicate the presence of riparian vegetation (e.g., Derby 1849, Mexican Land Grant Diseños as compiled by Becker 1964). In lieu of such direct information, quantitative, valley-wide estimates of the extent of soils characteristic of Central Valley riparian zones have been generated from analysis of early soil maps (and their accompanying vegetative descriptions) of the Sacramento (Holmes et al. 1916) and San Joaquin (Nelson et al. 1918) Valleys. Lowland riparian zones are characterized by soil types that predictably differ from those of more upland areas in terms of mineral and organic content and amount of soil litter (Bilby 1988), useful attributes in this context because some of these features persist even if the forest itself no longer exists at the time the soils are surveyed.

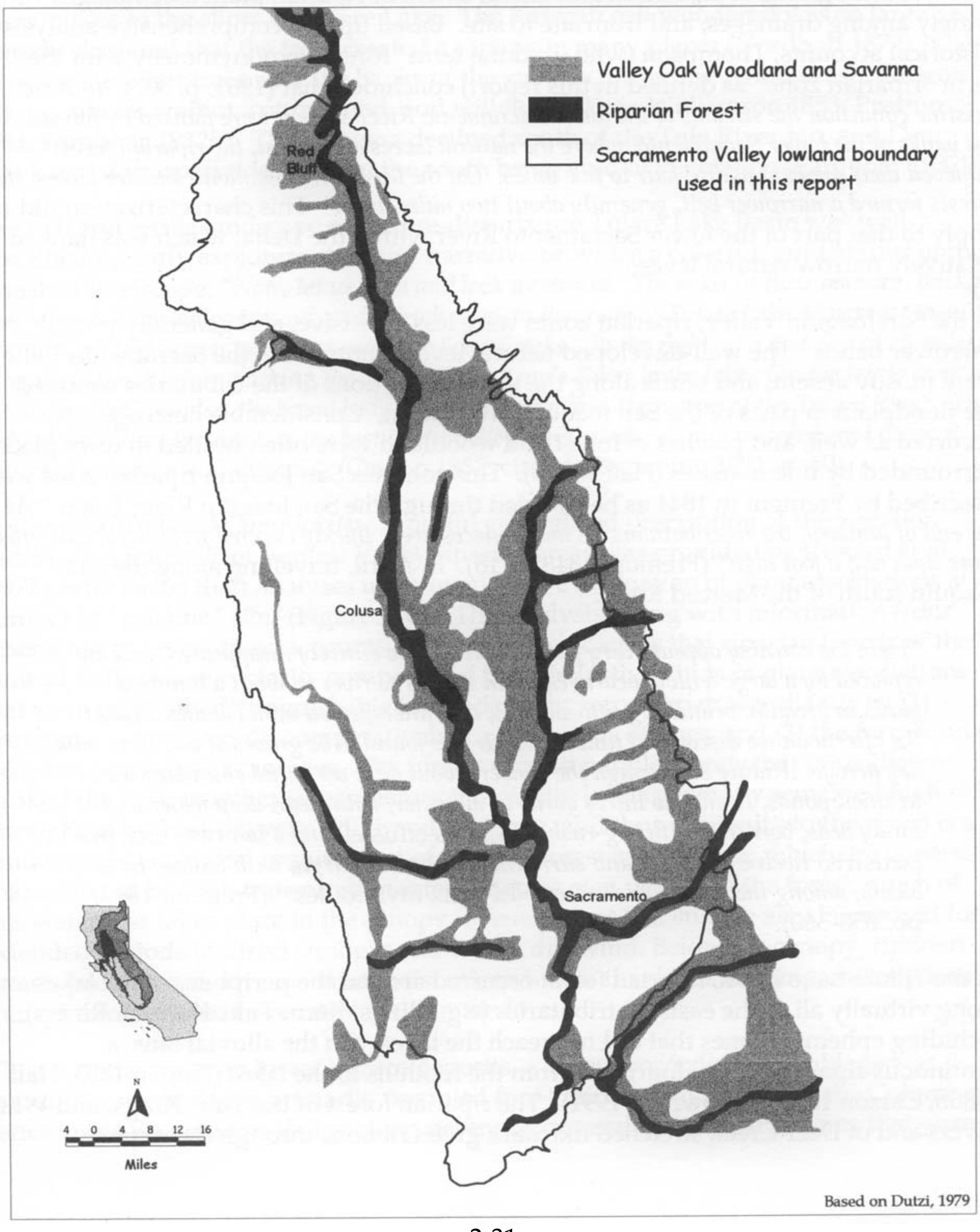
While such analyses are useful, they must be used with caution, and a clear understanding of the limitations of these techniques. As Jones and Stokes, who attempted to map riparian soils of the San Joaquin River recently pointed out (1998, pg. 3-1): "*Because riparian soils have been deposited by the river since the end of the Pleistocene, these soils represent the entire area where the river has made coarse deposits over the last 10,000 years; the actual area occupied by riparian habitats at any one time was most likely much smaller than the total area of riparian soils that is currently present.*" Thus, depictions on maps of plant or habitat distributions based upon the distribution of soils (e.g., Figures G4 and G6) must **not** be considered a "snapshot" of the riparian vegetation acreage that actually existed **at any one time.** Such estimates represent an "averaging" of what in reality were temporally variable and spatially heterogeneous environmental conditions. For the Central Valley, it is clear that in many cases the same locations were at different times occupied by either riparian or marsh vegetation, the former being indicated by soil type, while the latter was indicated by direct survey of existing vegetation in the mid-19th century. For these same reasons, the use of soil maps as a basis for estimating historical ecological parameters (e.g., primary production, population densities, transpiration losses) over large geographic areas must be considered in the light of these limitations.

Because of marked differences (discussed above) among researchers in the way the term riparian is defined, and the geographic area included as part of the "Central Valley," recent estimates of the extent of riparian zones in the Central Valley have varied substantially, ranging from about 0.9 to 1.6 million acres for the entire valley, including the Tulare Lake Basin (Katibah 1984, Warner and Hendrix 1985, Shelton 1987). The higher estimate of Warner and Hendrix includes considerable acreage (possibly up to 600,000 acres) of oak woodland in the Tulare Lake Basin. The lower estimates did not include the oak woodland and savanna in the Tulare Lake Basin. For this report, an analysis of the early soil maps and the Dutzi 1979 map generates an estimate of about 1,000,000 acres for the historical riparian zone. This zone was located primarily along the principal waterways of the Sacramento and San Joaquin Valleys, including the Delta region but excluding the Tulare Lake Basin (637,000 acres in the Sacramento Valley, 329,000 acres in the San Joaquin Valley, 42,000 acres within the Delta) (Figures G4, G6, G10). Close examination of all the different estimates indicates that they generally agree that somewhere near one million acres in the Central Valley (excluding the Tulare Lake Basin) was, at one time or another, occupied by a riparian zone.

Figure G4 shows that in the Sacramento Valley about 364,000 acres out of the 637,000 acres of the riparian zone were occupied by riparian forest. The remaining acreage of the riparian zone was occupied by wetlands, oak woodlands, and grasslands. About 87,000 acres of mapped wetlands were within the riparian zone. The forests shown on Figure G4 are confined to the principal rivers and streams of the Valley, including the mainstem Sacramento, Feather, American, Bear, and Yuba Rivers, as well as Honcutt, Butte, Stony, Cache, and Putah Creeks.

At their outer margins the riparian forests often graded into oak woodlands and savannas, which could extend a considerable distance from the river as shown on Figure II-F, which is directly derived from the map prepared by Dutzi (1979). In addition, extensive oak woodlands/savannas ringed the valley, occurring primarily on its eastern side (Dutzi 1979, Barbour and Major 1988, Griffin and Critchfield 1972, Fremont 1848) and along the Kings and Kaweah Rivers (Warner and Hendrix 1985, Preston 1981). These woodlands/savannas were frequently located on rich floodplain soils, including areas along ephemeral streams that drained into the marshes (Pavlik et al. 1991). In the greater Sacramento Valley area, oak woodland and savanna occupied 1,445,000 acres (1,109,000 acres within the Sacramento Valley boundary used in this report).

Figure II-F
Native Woodlands of the Sacramento Valley, circa 1800



Available historical documents indicate that under natural conditions, a recognizable riparian zone was present along virtually every minor and major stream in the Central Valley, although the composition and lateral extent of riparian plant assemblages varied widely among drainages, and from site to site. Based upon a comprehensive analysis of historical accounts, Thompson (who used the term "forest" synonymously with the term "riparian zone" as defined in this report) concluded that (1961, p. 307) "*in their pristine condition the streams of the lower Sacramento River system were flanked by forests...On the banks of the lower Sacramento, where the natural levees are widest, the riparian forest achieved their greatest width, four to five miles. On the lesser streams...with smaller levees, the forests formed a narrower belt, generally about two miles wide.*" This characterization did not apply to that part of the lower Sacramento River within the Delta, which was flanked by relatively narrow natural levees.

In the San Joaquin Valley, riparian zones were less extensive, and generally present in narrower bands. The well-developed natural levees common in the Sacramento Valley were mostly absent, and bluffs along the upslope portions of the tributaries confined the floodplain in parts of the San Joaquin River Basin. Considerable heterogeneity occurred as well, and patches of forest and woodland were often nestled in drier places surrounded by tule marshes (Hall 1886b). This complex San Joaquin riparian zone was described by Fremont in 1844 as he traveled through the San Joaquin River Basin: "*At the end of January, the river bottoms, in many places, were thickly covered with luxuriant grass, more than half a foot high*" (Fremont 1848, p. 18). In April, travelling along the San Joaquin south of the Merced River:

> "*Here the country appears very flat; oak-trees have entirely disappeared, and are replaced by a large willow nearly equal in size. The river is about a hundred yards in breadth, branching into sloughs, and interspersed with islands... Late in the afternoon we discovered timber, which was found to be groves of oak-tress on a dry arroyo...Riding on through the timber, about dark we found abundant water in small ponds, twenty to thirty yards in diameter, with clear, deep water and sandy beds, bordered with bog-rushes (*Juncus effusus*) and a tall rush (*Scirpus lacustris*) twelve feet high, and surrounded near the margin with willow-trees in bloom; among them one which resembled* Salix myricoides." (Fremont 1887, pp. 358-360).

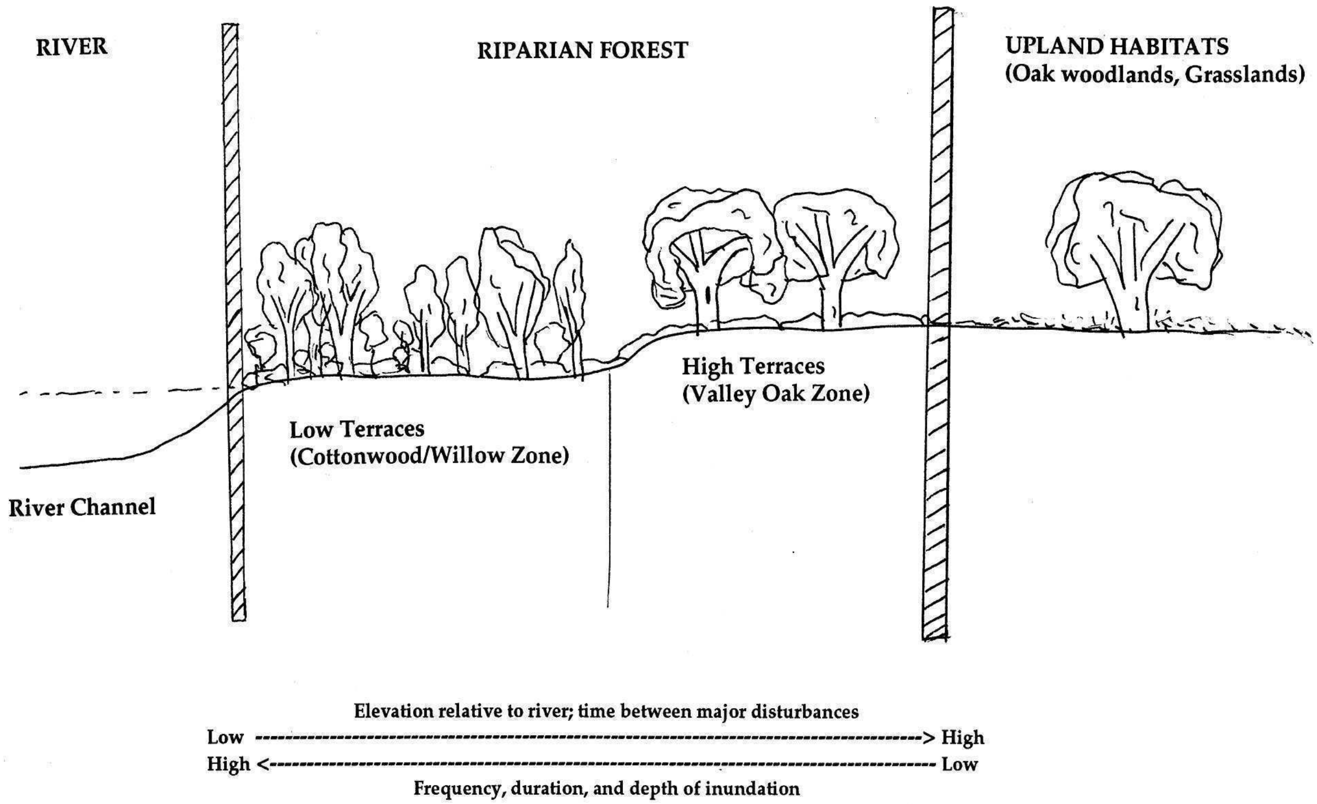
In the Tulare Lake Basin, riparian forest occurred around the periphery of the lakes and along virtually all of the eastside tributaries (e.g., Kings, Kern, Tule, Kaweah Rivers), including ephemeral ones that did not reach the lakes. On the alluvial fans, a continuous riparian forest flourished from the foothills to the lakes (Nugen 1853, Hall 1886b, Carson 1852 in Browning 1991). The riparian forest of the Tule, Kings, and White Rivers and of Deer Creek stretched like dark green ribbons through the immense surrounding oak savanna. The riparian woodlands of the Kaweah River spread to the limits of its fan, occupying some 254,000 acres (Warner and Hendrix 1985, Jepson 1910) and merging with the tree savannas to create a continuous woodland that extended in many places to the shore of Tulare Lake. The Kaweah oak woodland was so large and densely clustered that the trees created a canopy in many places (Nordhoff 1872). Oaks gave way to other trees near the banks of the streams, including Arizona ash, Oregon ash, sycamore, walnut, cottonwood, and willow (Blake in Williamson 1853, Preston 1981, Farquhar 1932b). The lushness declined south of the Tule River fan, and Deer Creek was a sharp divide, areas to the south being void of vegetation (Farquhar 1932b).

The rich and fertile landscape of the pre-disturbance Tulare Lake Basin was well-described by early explorers. An early narrative provides a colorful, guided tour of this vanished landscape: "*Now, let us turn and look westward. The oaks, in their majesty, thickly cover the plain for miles around, and stretch away to the shore of Tulare Lake. Amongst them and through high green grass, meander the Four Creeks. To the right, at a distance of 25 miles, runs the belt of timber, marking the course of the King's River to the lake. On the left is seen, at the distance of 20 miles, the broad body of timber that marks the course of the Tulare River. The body of land, thus bounded, is the best in the valley - well-timbered and watered, and covered with the best grass in California*" (Carson 1852, cited in Browning 1991, p. 60).

b. Composition and Complexity. A useful generalized description of the zonation pattern characteristic of Central Valley riparian areas was provided by Conard et al. (1977), who based their analyses upon quantitative evaluation of plant associations at a number of "pristine" sites (Figure II-G). This analysis, along with information from other sources (eyewitness accounts, soil surveys), indicates that riparian forests of the Central Valley were typically composed of two distinctive kinds of plant associations that were generally distinguishable from adjoining xeroriparian woodlands by (1) proximity to the river, (2) comparatively high densities of trees, and (3) the formation of closed or semi-closed canopies. The forests formed parallel bands that immediately flanked the river to either side, where soil moisture levels generally remained high throughout most of the year. High soil moisture (and thus proximity to the river) is a fundamental ecological requirement of riparian forest associations, which are generally characterized by high transpiration rates (Thomas et al. 1979). In the forest, much of this water loss takes place in the canopy, where a large leaf surface area is exposed for extended periods to direct sunlight and warm, dry wind. Below the canopy, riparian forests provide a shady, cool and moist microclimate that leads to comparatively low transpiration rates at lower strata within the forest.

Closest to the river, on lower terrace deposits, a *cottonwood/willow* assemblage was found. This assemblage primarily occupied fine-grained alluvial soils of the Columbia series in the Sacramento Valley along perennial or nearly perennial streams that were

Figure II-G
Riparian Vegetation Patterns



Idealized riparian vegetation along major rivers in the Sacramento Valley.
Source: after Conard, 1977.

annually inundated and which provided subsurface irrigation even when the channel was dry (Holland 1986). This assemblage was dominated by Fremont cottonwood *(Populus fremontii),* which, along with willows *(Salix spp.*) and Oregon ash *(Fraxinus latifolia)* formed a canopy that extended to about 100 ft (30 m) in height in mature stands, and ranged from about 20% to 80% in cover (Conard et al. 1977). Also contributing to this canopy were occasional California sycamore *(Platanus racemosa)* and valley oak *(Quercus lobata),* typically found rooted in high spots in this zone. Frequent shrubs and younger trees formed a layered understory. Some herbaceous species - forbs and grasses - occurred on the forest floor, while lianas were ubiquitous in all layers, and at times provided 30% to 50% of the ground cover. In all, this mixture resulted in a relatively narrow and dense zone of vegetation immediately flanking the river banks.

This cottonwood / willow association generally gave way (often somewhat abruptly) in most areas to a second, and considerably more extensive riparian forest association heavily dominated by valley oak. This form of the forest typically occurred on higher terraces slightly further from the river and above cut banks along the outside of meanders. Many of the same plants characteristic of the cottonwood / willow association, including sycamore, box elder *(Acer negundo),* Oregon ash and black walnut *(Juglans hindsii),* were also common, but in comparatively low abundance. Canopy height was somewhat lower, 50 to 65 ft (15 to 25 m), and the number of trees about half that of the cottonwood zone. Thus, at ground level, this area appeared somewhat more open than the jungle-like cottonwood zone. Nonetheless, canopy formation was comparable to that of the cottonwood zone. Cover values ranged from about 30% to 60% at sites examined by Conard et al. (1977).

In areas where disturbance from overbank flooding was both more frequent and more severe than in the valley oak riparian zone, the cottonwood / willow assemblage integrated with mixed riparian forest and at sites yet farther from the river, with valley oak riparian forest. The mixed riparian assemblage was a tall, dense, winter-deciduous, broadleafed riparian forest that was dominated by black walnut, sycamore, box elder, and willows. The tree canopy was usually fairly well closed and moderately dense with understories of shade-tolerant shrubs such as *Cephalanthus occidentalis* and *Fraxinus latifolia* (Holland 1986, CDWR / CDFG 1976).

The systematic differences in the species composition and distribution of these riparian associations is primarily attributable to different levels of disturbance experienced by each. Lower terraces immediately adjacent to the rivers naturally experience more frequent flooding and high water. These areas therefore tend to be dominated by a variety of successional stages of trees that are inherently adapted to be effective “colonizers” of recently disturbed sites - willows and cottonwoods. Higher terraces experience less frequent and intense disturbance. Hence, these are typically occupied by the more mature oak-dominated forest associations adapted to more stable soils and conditions (CDFG/CDWR 1976, Holland 1986). This basic pattern was subject to considerable local variability due to localized differences in a number of factors (e.g., water availability, soil composition, recruitment of saplings, etc.).

Even closer to the river, on the islets composed of fringing gravel and sand bars that flooded more frequently, the forest sometimes gave way to plant assemblages adapted to more extreme levels of disturbance. These are naturally dominated by shrubs and saplings considerably lower in height, 3 to 16 ft (1 to 5 m), than assemblages of the neighboring forest (Conard et al. 1977). Dense stands usually had little understory or herbaceous component and more open stands had grassy understories (Holland 1986).

The xeroriparian component (see discussion at the beginning of this section) further away from the river was dominated by oak woodlands. They consisted of widely-spaced, tall, broadleaved deciduous trees, dominated by valley oak (*Quercus lobata*). Blue oak, interior live oak, and digger pine (*Pinus sabiniana*) were occasionally present in the woodlands that were outside the riparian zone around the margins of the valley. The undergrowth was primarily grassy California prairie. Fremont described oak woodlands throughout the Central Valley on his many expeditions there between 1842 and 1854. In the northern portion of the Sacramento Valley near Red Bluff, he observed: "*Our way led through very handsome, open woods principally of oaks, mingled with a considerable quantity of the oak-shaped pine*" (Spence and Jackson 1973, p. 93). Near Cache Creek, in what is now Yolo County, a member of the 1854 railroad survey party wrote: "*The timber belt is composed of some of the most magnificent oaks I have ever seen. They are not crowded as in our forests, but grow scattered about in groups or singly, with open grass-covered glades between them.... There is no undergrowth beneath them, and as far as the eye can reach, when standing among them, an unending series of great trunks is seen rising from the lawn-like surface*" (quoted in Pavlik et al. 1991, p. 64). In the San Joaquin Valley, Fremont recorded "*open groves of oak, and a grassy sward beneath, with many plants in bloom; some varieties of which seem to love the shade of the trees, and grow there in close small fields*" (Spence and Jackson 1973). In 1850, Derby described the oak woodlands along the Kaweah floodplain as "*a beautiful, smooth, level plain, covered with clover of different kinds and high grass, and thickly shaded by one continuous grove of oaks*" (Farquhar 1932b, p. 257). At the outer margins of the woodlands, the riparian zone gave way to fully terrestrial ecosystems, mainly native grasslands only rarely punctuated by solitary or sparse stands of valley oak (Figure II-G).

The general patterns described above should be considered idealized overviews. Central Valley riparian zones displayed nearly endless spatial and temporal variability in terms of species composition and dominance, lateral extent, foliage density, etc., as they responded to local variations in topography, soils, microclimate, surface water, and disturbance and subsequent successional processes. Habitat boundaries were often diffuse rather than sharp, and in some cases, some "typical" components might be missing entirely. Nonetheless, many of the basic structural features described above appear to have persisted along much of the lowland rivers.

c. Associated Biological Assemblages. Systematic surveys of riparian fauna of the Central Valley were not conducted until well after most of the valley had been substantially modified by 19th century settlers. The following summary reconstruction of that fauna is therefore based upon fragmentary observations of early explorers, along with our knowledge of current distribution patterns of native species. As with other habitats for which we have little or no historical data, we infer that native species that use this habitat now also used it in the past. This may or may not be true for all species. Some may have been displaced from more preferred habitats because of the extensive environmental modification of the valley that has occurred during the last 150 years. Similar work has been conducted for the San Joaquin Valley and is reported elsewhere (SJVDP 1990).

Virtually all native butterflies of the Central Valley have been observed in riparian habitat. Shapiro (1974) lists 17 species, four of which are endemic to the Central Valley. The western pond turtle, along with six snakes and thirteen amphibians now constitute the native herpetofauna (Stebbins 1966). A 1973 springtime census of nine riparian sites along the Sacramento River identified 129 bird species, 51 of which were migrants and the remainder of which (78 species) nested along the river (CDWR/CDFG 1976).

Central Valley riparian zones are used by 55 of the 181 mammal species (excluding marine mammals) found in the state (Trapp et al. 1984). Most widespread river or stream dependent mammals are river otter, beaver, mink and muskrat (Mayer and Laudenslayer 1988). Grizzly bears were abundant at the time of the Spanish settlement of the valley, and were concentrated in riparian forest (Graber 1996). Many other furbearers have a strong dependency or preference for riparian habitats, including ringtail, raccoon, mink, grey fox, red fox, coyote and skunks (Brinson et al. 1981, Grinnell et al. 1937). A variety of bats, squirrels, gophers, rabbits, and others comprise a less conspicuous component of the mammalian fauna here (Ingles 1965).

IV.A.3. Wetlands

The habitat type defined here as "wetlands" consisted of a mixture of marshes heavily dominated by tules/bulrushes *(Scirpus spp.*), waterways, mudflats, extensive meadows of grasses and forbs often referred to as "wet prairie," and vernal pools (a feature which also could be found in riparian zones and more upslope areas).

a. Extent and Distribution. Under natural conditions, Central Valley lowland wetlands (non-tidal) extended in a nearly continuous band from Willows in the north to south of Bakersfield in the Tulare Lake Basin. In the lower portion of the Sacramento Basin, wetlands were predominantly located in natural flood basins between upland prairies or oak woodland / savannas and the riparian zone flanking the rivers (Dutzi 1979, Barbour and Major 1988). Under natural conditions, water remained in the basins until floods subsided, and then slowly drained back to the river. The flood basins were distinct in character and evolution from the more upstream floodplains of the transport zone. Clays, deposited during flood events, formed tight, poorly-drained soils on the basin floor. The basins were typically inundated every year from a variety of sources: runoff from local drainages, overflow from the main channel or its upstream distributary sloughs, and / or backup from the downstream drainage sloughs. This resulted in frequent and prolonged inundation - ideal conditions for the growth of extensive tule marshes. However, because the marsh plain would typically dry out by late summer, peat soils did not form here (as in the Delta marshes), and it appears that net sedimentation rates in the basins were lower than long term aggradation rates in the main river channel (Atwater 1982).

In the San Joaquin River Basin, wetlands were primarily located along sloughs connected to the main river channel rather than overflow areas (Carson 1852 in Browning 1991), and around the borders of the lakes of the Tulare Lake Basin (Figures G6, G8). The size of one of the larger such areas along the San Joaquin River was described by early explorers (Carson 1852 cited in Browning 1991): *"On the eastern side of the river and of nearly the same length, is the immense tule swamp formed by the waters of the Mariposa, Chowchilla and Fresno rivers; this swamp is from one to ten miles in width, and is of equal value as that on the opposite side of the river."* In general, the San Joaquin River flowed through a flatter, more homogeneous topography, and naturally supported a less extensive riparian forest than did the Sacramento River. Here (and also along the flood basins flanking the Sacramento River), the flat valley floor surrounding the riparian forest often took the form of extensive wetlands, dominated by tule marsh.

In 1850, Derby described the marshes between the San Joaquin River and Tulare Lake as follows: "*The whole country for forty miles in extent in a southerly direction by ten in width, between the San Joaquin river and the Tache lake (Tulare and Goose Lakes), is, during the rainy season and the succeeding months, until the middle of July, a vast swamp everywhere intersected by sloughs, which are deep, miry and dangerous*" (Farquhar 1932b, p. 261). Blake, a geologist studying the area in 1853, wrote that "*[t]he banks of this lake (Tulare) and of the others are low and marshy, and in most places are covered with a dense growth of rank grass and tule. This forms a wide green margin about a portion of the principal lake, and the growth is so luxuriant and the ground so soft that it is almost impossible to reach the water. The width of this belt of green tule is variable...and in some places it is over three miles. The plant grows* *partly in water...but grows to an enormous size, attaining a height of from 8 to 15 feet, and sometimes a diameter of three-quarters of an inch. This plant occupies the ground to the exclusion of other forms of vegetation; there are no shrubs or trees to overshadow it*" (Blake in Williamson 1853, p. 191-192).

As recently as eighty years ago, an observer (Latta 1937) described the extent and complexity of this wetland landscape, stating that: "*At all times these lakes and connecting sloughs as well as the San Joaquin River, were bounded with an almost impassable barrier of tules, willows, and mud flats. During times of high water the basin was filled to a great depth with flowing water, presenting a barrier passable with stock at probably not more than three places between the upper end of Kern Lake and San Francisco Bay*."

The location and area of lowland wetlands were systematically mapped by early, valley-wide government and private surveys. One early effort yields an estimated 1.3 million acres of marsh in the Central Valley, with about a third, or 450,000 acres of that in the Tulare Lake Basin (Mandeville 1857). A second survey, presumably conducted between 1878 and 1887, reported about 1.4 million acres of marsh in the Central Valley, with about 477,000 of that acreage in the Tulare Lake Basin (Hall 1887). Two other early maps depict "marshes" (i.e., wetlands) for the entire Central Valley, and lead to estimates of from 1.5 (Goddard 1857) to 2.1 (Baker 1855) million acres of marsh, of which 217,000 to 621,000 acres were located in the Tulare Lake Basin. Numerous more localized maps (e.g., Ord 1848, Gibbes 1850, Walthall 1869, Smith and Baker 1877, Hall 1886b) generally agree with the marsh distributions shown on these larger maps (Fox, personal communication).

For this report, the Hall (1887) map and the Board of Commissioners on Irrigation map (Alexander et al. 1874) were digitized and area of wetlands calculated. In both cases, the estimates generated correspond closely with those reported above The Hall map returns about 1.4 million acres of marsh, while the Board of Commissioners map (Alexander et al. 1874) returns about 1.3 million acres of marsh. Both of these maps also indicate that at least 300,000 acres of wetlands occurred in the Sacramento Valley north of the Delta.

The variation in wetland acreages reflected in these early maps is explained by a number of factors. The wetland acreage likely fluctuated with seasonal and longer-term variations in precipitation and runoff. The wetland area encircling Tulare Lake changed continuously as the lake margin fluctuated with climate. The Hall surveys may have additionally reflected the effects of early wetland reclamation (which would have decreased the marsh acreage) and river overflow attributable to sediment accumulation from hydraulic mining (which could have increased the marsh acreage). However, it is uncertain when the surveys that Hall's maps are based on were conducted. They may have been based on government surveys conducted prior to 1878, or, alternatively, on original surveys completed by Hall's survey teams between 1878 and 1887. Finally, the U.S. public survey maps were published annually in Surveyor General reports, and the one cited here, Mandeville (1857), was prepared before these surveys were completed.

b. Composition and Complexity. Wetlands are dynamic environments, and their composition and distribution are temporally and spatially variable. In general, Central Valley wetlands were dominated by tule (*Scirpus actus*). Distributary channels feeding and draining the tule marshes, along with occasional lakes, ponds, vernal pools, and seasonal meadows (wet prairies) were interspersed among and around the periphery of the marshes. The meadows appear to have been populated mainly with rushes that early explorers called "wire grass," along with alkali grass (Cronise 1868, Farquhar 1932b, Burcham 1957).

Tule marshes of the lowland river systems often grew in monotypic stands that formed dense mats of emergent vegetation that commonly rose from 6 to 15 feet above the marshplain (Blake in Williamson 1853). The marshplains were transected by meandering shallow channels of varying width, connecting the marsh to the river system and providing an elaborate circulatory system for the rapid exchange of water and dissolved nutrients, both within the marsh and between the marsh and river. During most years, it appears that the structure of the vegetative layer underwent cyclical seasonal variation, with higher portions of the marshes becoming sufficiently dry during the driest part of the year (fall or early winter) so as to be readily burnable (Hutchings 1860, Cone 1876). In contrast, lower lying marsh areas appear to have remained green even during prolonged droughts.

Vernal pools were common seasonal features associated with Central Valley wetlands, as well as other upland (terrestrial) ecosystems. A vernal pool, or hog wallow, is a small, hardpan-floored depression that fills with water during the winter and dries up in spring, supporting various annual plant species that flower, often in concentric rings of showy colors. These seasonal wetlands were typically small, ranging in size from 10 to 165 feet across up to several hundred acres and were typically shallow (4 to 24 inches) (SJVDP 1990). They formed a bathtub ring around the margins of overflowed areas, with an extra band through the center of the San Joaquin Valley. Soil data and photo interpretation suggest they comprised some 415,000 acres historically, of which 11% remained in the early 1970s (Holland 1978).

Vernal pools displayed highly variable and unique physical and biological characteristics (Holland 1988). Because of this, Central Valley vernal pools supported a rich and distinctive biota, with at least 100 species of plants as obligate residents of this particular habitat (Holland and Jain 1977). Additionally, these temporary bodies of standing water provided valuable nesting and foraging opportunities for migratory waterfowl (Swanson et al. 1974).

c. Associated Biological Assemblages. Tule marshes of the Central Valley provided nesting cover and rich foraging for migratory waterfowl and other avian species, and supported the highest concentrations of wintering waterfowl along the Pacific Flyway (Figure II-H). These areas also provided complex habitat for a variety of fish, amphibians, reptiles and mammals, including abundant squirrels and beaver, as well as occasional more wide-ranging predators of the Central Valley such as lynx and (for most of the system's history) grizzly bears. Tule elk, as the name suggests, regularly used these areas as favored foraging grounds. Swarms of mosquitoes and other flying insects were also a common feature of the marshes: "*The marshy region is unhealthy and infested with mosquitoes in incredible numbers and unparalleled ferocity*" (Brewer 1861) and "*[mosquitoes] [sic] were ravenous*" (Phelps 1841 in Busch 1983). Wet prairie provided foraging meadows for birds and harbored an assortment of small mammals, reptiles, and insects. These areas also served as drier refuges for animals displaced by high water from lower lying areas of the wetlands.

IV.B. Ecosystem Function: Essential Processes

Major habitat characteristics of river channels (morphology, substrate composition), water column (flow rates, depth, temperature, etc.), riparian forests and wetlands of the Central Valley reflected the natural pattern of water movement through the system, along with natural patterns of sediment transport and deposition. These processes interacted with local microclimates, soil structure, topography and biological attributes (species composition) and processes (e.g., recruitment and succession) to create nearly endless variability in the composition and distribution of the basic habitat types comprising these ecosystems. The following sections discuss the hydrology, flood characteristic, and flow of the natural system.

IV.B.1. Surface Water Hydrology and Geomorphology

a. Hydrology. Prior to 1850, parts of the Central Valley hydrologically functioned in some ways as a series of reservoirs, seasonally filling and draining every year. This had the effect of delaying the transmission of flood flows down the Sacramento and San Joaquin Rivers and reducing peak flows and velocities (Grunsky 1929). On the Sacramento River, this "reservoir" system was composed of low natural levees flanking sections of major waterways, and a series of flood basins and low depressions along parts of the main river channels. Levee development was most extensive where the

Figure II-H
Waterfowl in Flight

Freshwater emergent marshes provide habitat for millions of migratory waterfowl along the Pacific Flyway. Colusa County, California, 1930.
Source: California History Room, California State Library, Sacramento, California.

valley slope is lowest and the duration of overbank flow highest. In the Sacramento Valley, natural levees are occupied by soils of the Columbia series (Holmes et al. 1916) and in the San Joaquin Valley, by soils of the Hanford loam series (Nelson et al. 1918), which are primarily fine to coarse sediments deposited by annual flooding. Along much of their lengths, water flowed over the levees in thin sheets, until the water level on the non-river side of the levee rose and joined with the water surface in the channels. When this happened, all visible trace of a channel was lost and the area took on the countenance of a large inland sea (Rose et al. 1895).

There were seven topographically distinct flood basins in the Sacramento Valley, which together could store over 4 million acre feet (MAF) of water. In the San Joaquin Valley, flood waters spread through a multitude of floodplain sloughs, marshes and other floodplain habitats flanking the river. Historically, the east side of the Sacramento Valley was topographically subdivided into the Butte Basin (0.1 to 0.5 MAF estimated capacity), Sutter Basin (0.6 to 0.9 MAF), American Basin (0.3 to 0.6 MAF) and the Sacramento Basin. The west side was subdivided into the Colusa Basin (0.7 to 1.0 MAF) and the Yolo Basin ($\geq$1.1 MAF) (Figure G4). The basins covered somewhere between about 970 to 1,000 mi^2 (Clapp and Henshaw 1909). Low areas of the levees, which occurred periodically along their length, allowed water to escape from river channels and sloughs, and accumulate in the flood basins even when water levels were not high enough to overtop the higher portions of the levees (Rose et al. 1895, Hall 1905, Grunsky 1929). Additional (non-flood) water entered the flood basins and depressions flanking the main river channels from westside tributaries, which occurred along the entire length of the Central Valley. These had no direct connection to the Sacramento and San Joaquin Rivers but drained instead directly into the flood basins (Hall undated).

Water accumulated in the flood basins and then slowly drained back into the river or evaporated after the floods subsided. The Colusa Basin discharged through Sycamore Slough above Knights Landing, the Yolo Basin through Cache Slough at the foot of Grand Island, and the eastern basins through the Feather and American Rivers. These basins could only drain back into the river during flooding when the water elevation was higher than in the river, or in the summer, after the river fell to a stage below the water surface of the basin (Grunsky in Davidson et al. 1896). The Sacramento Flood Basin discharged into the San Joaquin River through its lower tributaries. (Heuer et al. 1905, pp. 6, 28-29). Some of these basins retained flood waters for many months, slowly disgorging their flows to the main channels, sometimes through July, or allowing them to evaporate, while others (e.g., the Yolo Basin) drained relatively rapidly at downstream points (Grunsky 1929, Rose et al. 1895). Overflow into the flood basins reduced peak flows and velocities in the bypassed reaches of the lower Sacramento River, allowing occasional sand bars to persist.

The Yolo Basin, a long narrow bypass/storage channel flanking the main river and stretching some 40 miles from Knights Landing to Cache Slough, was the largest of the seven, and drained through Cache Slough above Collinsville. When the flow at Sacramento reached about 41,000 cfs, an appreciable part entered the Yolo Basin through levee depressions between Knights Landing and Sacramento, and subsequently exited through Cache Slough into the lower Sacramento River. Flows from Cache, Putah, and other creeks also entered the Yolo Basin and exited through Cache Slough (Hall 1886a). During the high water of 1889, a year for which actual measurements permit such approximation, the discharge from this basin back into the Sacramento River was more than twice the flow in the river itself (Grunsky 1929, Rose et al. 1895). Therefore, it appears that as much as two-thirds of the flow of the Sacramento River was diverted around the main river channel during flood events, and discharged instead at the mouth of the river in the Delta.

In contrast to the extensively leveed Sacramento River, the San Joaquin River was immediately flanked by strips of relatively low land (except at a few points such as Grayson and San Joaquin City, where the high western plain sloped down to the river bank). The extensive east and west side low tracts bordering the river were subject to frequent inundation under natural conditions. The capacity of the river channel was inadequate to confine flood waters to a single channel, and flood flows spread over large areas, flowing through numerous sloughs, which sometimes formed as arms of the main channel. About 150 square miles of land above the Head of Old River were subject to frequent inundation, and the entire region became a reservoir of slowly moving waters during floods (Rose et al. 1895, Hall 1880). Where the rivers came together in the Delta, flows in the lower San Joaquin River were sometimes augmented by overflows from the Sacramento River. At all stages of the river, there was an *appreciable escape of Sacramento waters through the Georgiana and Three-Mile sloughs... into the San Joaquin. In times of high flood this is generally a very large item*" (Hall 1886a, pp. 406-407).

b. Floods. Widespread flooding along both rivers was common under natural conditions (Thompson 1960) and persisted through the turn of the century (Thompson 1996). Flooding and deposition are the primary factors that maintain the local topographic features of lowland riparian zones and allowed the natural levees and floodplains of the Central Valley to form. Almost all sediment is conveyed by rivers as fine sand, silts, and clays carried as "suspended load" in the water column during flood events. About 10% of transported sediments consist of coarser sands, gravels, and cobbles carried along the river bed as "bed load" during these higher flow periods. When flows exceeded channel capacity, floodwaters spilled out over the floodplain, water velocity decreased, and coarser sediments were deposited near the rim of the channel, forming natural levees. Finer sediments were deposited widely over the floodplain, and become particularly concentrated around obstacles to flow (such as vegetation). Most of the sediment comprising the floodplain was deposited in this manner (Leopold et al. 1964). By these mechanisms, the valley floor was gradually worked and reworked by the deposition of layers of coarse material which were deposited in the channel and in natural levees and of finer silts and clays that are dropped out of suspension onto the floodplain. The processes of erosion, transport and deposition of bed load sediments by successive floods created and maintained the patterns of meanders, riffles, pools, bars and eroding channel banks, and substrate composition characteristic of lowland alluvial rivers (Figure II-D).

Numerous accounts of flooding in the Central Valley prior to 1849 (when gold was discovered) attest to the fact that widespread flooding in the Central Valley was a common event prior to the discovery of gold in California. Some of these have been summarized by Thompson (1960) and Britton (1987a, 1987b), viz.:

> "*All the trees and roots on the banks afford unequivocal proofs of the power of the flood-streams, the mud line on a tree we measured exhibiting a rise of ten feet above the present level, and that of recent date...During the rainy season, which commences about the middle of November, and terminates about the end of February, the river is said to overflow its banks*" (Belcher 1837 in Pierce and Winslow 1979, p. 41).

> "*At the place where the survey ended, the river was two hundred feet wide, its banks being twenty feet above the river; but it was evident that its perpendicular rise exceeded this, as there was every appearance of its overflowing them; and, according to the testimony of the Indians, the whole country was annually inundated*" (Wilkes 1845, p. 189).

> "*All this country is good and has firewood, but the floods from the rivers submerge it from the beginning of the warm season until August.....Nothing we have seen today is suitable for a mission, because the land is flooded, in places for more than a league*" (Viader 1810 in Cook 1960, p. 258, describing a portion of the lands adjoining the San Joaquin River).

All areas of the Central Valley historically experienced regular flooding, but the Sacramento and San Joaquin Valleys normally did not flood at the same time. In the Sacramento Valley, rainfall induced floods (December-March) predominated, while in the San Joaquin Valley, particularly the Tulare Lake Basin, prolonged snowmelt flooding (April-June) was the norm. Large, sometimes simultaneous floods in the San Joaquin and Sacramento Valley occurred during the winter months as a result of prolonged high elevation rainfall on a saturated snowpack. By all accounts, large floods were frequent throughout most of California's colonial history. The largest on record occurred in 1862 and converted the entire valley floor into a vast inland lake (Kelley 1989). The flooding observed during the latter half of the 19th century was exacerbated due to the billions of cubic yards of mining debris which clogged stream channels at that time.

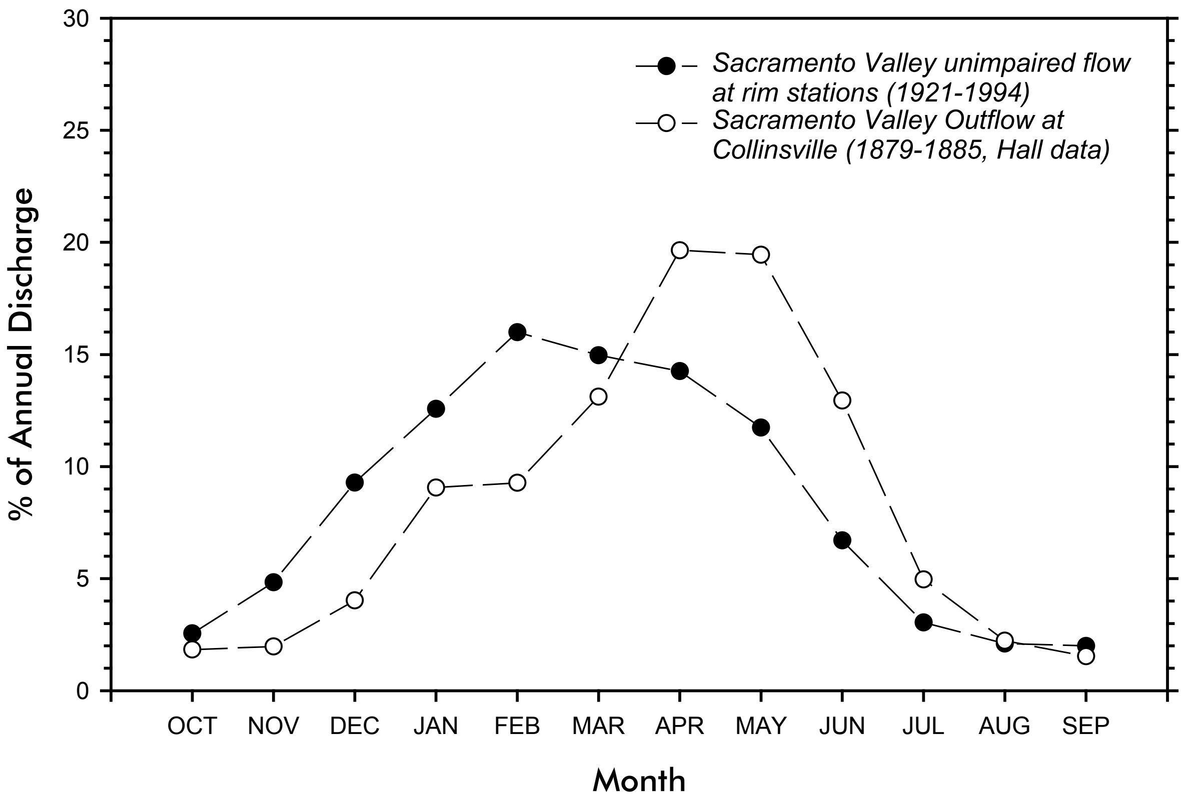
Different parts of the floodplain experienced markedly different degrees of inundation over the long term but large portions of the basins were inundated annually by regular flooding events. In the Sacramento Basin, Hall (1880) estimated that 800,000 acres (1,250 mi^2) of the valley "*as naturally constituted*" were subject to inundation from annual overflow. He estimated that an additional 288,000 acres (450 mi^2) were inundated by "*occasional temporary overflow.*" In the trough of the San Joaquin and Tulare Lake Basins including the San Joaquin portion of the Delta, Hall estimated that 624,000 acres (975 mi^2) of swamp land was subject to periodic inundation. A significant portion of the overflow lands outside the Delta were located in the Tulare Lake Basin, where the fluctuating margin of Tulare Lake could engulf hundreds of additional square miles after a series of wet years.

This report provides an estimate of the historical extent of floodplain inundation, based on historical mapping and soils classification (Figures G4, G6, and G3). For this analysis, historical flood basin and floodplain areas were identified based on descriptions of soil types in USDA soil surveys (Holmes et al. 1916, Nelson et al. 1918). The lands included in the flood basin and floodplain map were generally described as subject to "frequent," "intermittent," "periodic," or "occasional" overflow. The results proved similar to the area mapped as "overflow" lands by the California Department of Public Works (1931a, 1931b) and depicts the broad-scale pattern of inundation in the Central Valley under natural conditions. Frequency of inundation is not quantified, but probably represents a 2-10 year recurrence interval.

Under historical conditions, the combined area of the flood basins, terminal lakes, floodplains, and tidally-flooded land comprised about 2,730,000 acres (4,250 mi^2). Inundated areas not covered by wetland or riparian forest, or by standing water, were occupied by a variety of vegetation/habitat types including native perennial and annual grasslands, and oak woodlands ("other floodplain habitat" on Figures G4, G6).

c. Stream Flows. Flows were naturally dominated by runoff from the upland system. As the rivers moved toward their mouths, flows were modified by groundwater exchange, surface evaporation, riparian and marsh evapotranspiration, inflow from lowland runoff and tributaries, and, under high flow conditions, bank overflow. In the Sacramento Valley, flood basin storage and release also modified flows (Figure II-I). Thus, the resultant natural seasonal pattern of river discharge into the estuary differed from the pattern of inflow from the upland system.

Figure II-I
Estimated Differences in the Monthly Pattern of Natural Sacramento Valley Inflow versus Outflow



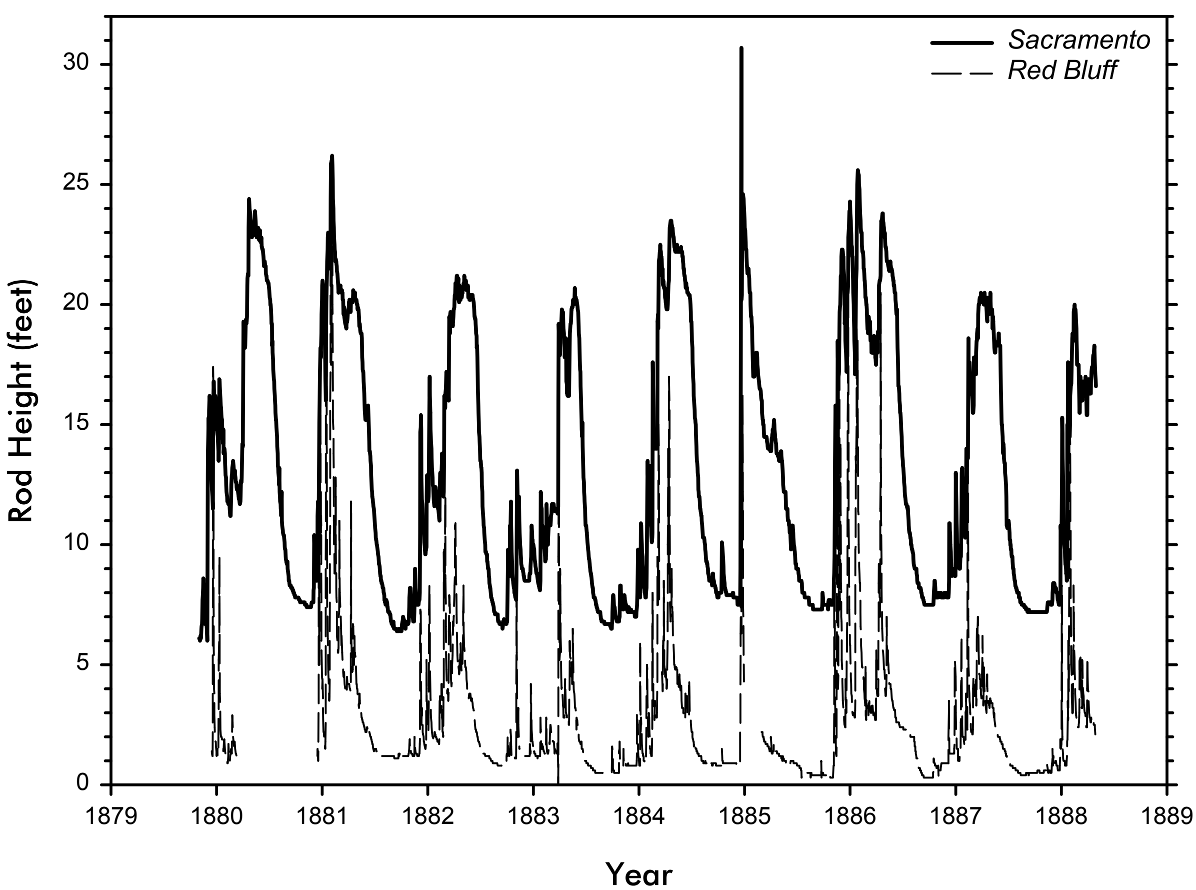
The natural inflow into the Sacramento Valley (as calculated at the rim stations of the Sacramento, Feather, American, and west-side streams) during high runoff periods was attenuated and temporarily shifted by the storage and release from the flood basins.
Data from Hall 1887 and California Department of Water Resources.

The first known quantitative estimates of streamflow within the lowland rivers were made between November 1878 and October 1885 in the Sacramento River at Freeport and other upstream sites in the Sacramento and San Joaquin Valleys, by the first State Engineer, William Ham. Hall, and his survey teams (Hall 1886a). Hall's teams focused on the Sacramento River to address the then critical issues of flooding, drainage, and debris (Hall 1880, Part I). The measurements at Freeport were later used to estimate flows at Collinsville, 57 miles downstream (Hall 1886a), in the first attempt to estimate the total discharge from the Sacramento Valley into Suisun Bay. The monthly flow distribution based on these data (Figure II-I) provides a crude approximation of the monthly pattern of discharge that was present at the mouth of the Sacramento River in the 1878-1885 period. However, the absolute magnitude of these flows in the high flow months is not accurately ascertained by Hall's measurements, because anywhere from one-half to two-thirds of flood flows bypassed Sacramento (via the flood basins, see above) and therefore were not measured by Hall's gauges, but were instead simply estimated. Low flow measurements at Freeport were affected by tides but are consistent with upstream measurements and thus are considered a more accurate estimate of the discharge.

Additionally, by the time these measurements were initiated (1878), a number of human interventions may have already altered the "natural" riverine hydrograph, particularly along lower portions of the Sacramento and Feather rivers. In these reaches, natural levees had been artificially raised, mining debris clogged river channels, portions of flood basins had been reclaimed, riparian forest had been harvested, and some diversion of river flows for irrigation and mining was under way. Despite these locally significant interventions and the questionable accuracy of Hall's high flow estimates, his estimates of proportionate monthly distribution, although crude, are probably generally reflective of the natural pattern. These values, used in conjunction with unimpaired rim inflows derived from recent (1921-94) measurements, suggest that the flood basins historically functioned as a buffer, shifting high January-May upstream flows to a March-June high river outflow period.

Flows were also directly gauged (measured on a calibrated rod) on the Sacramento River at Sacramento since September 1849, and at Red Bluff since December 1879 (Rose et al. 1895). These data are directly proportional to the flows that were actually present in the river, and therefore provide useful information on flows under natural conditions. The data shows that the discharge at Red Bluff was characterized by a large number of discrete flow pulses, corresponding to individual storms in the upper watershed. Flows entered the valley floor as pulses or spikes of relatively short duration, typically lasting 1 to 2 days to a week. The duration of these pulses was increased, and their magnitude and timing substantially reduced by the time they reached Sacramento (Figure II-J). These changes were due to the attenuating influence of the upstream flood basins and substantial additional inflows from the Yuba, Feather, and American Rivers.

Figure II-J
Modifying Effects of Flood Basin and Tributary Inflow on the Lowland Sacramento River Flow



This graph compares the daily rod records for the Sacramento River at Red Bluff and Sacramento during the 1880s, when the flood basins were still functional but some modification of the natural hydrology had occurred because of land reclamation and hydraulic mining. No adjustment was made to the Sacramento record for the shifting bed due to the influx of mining debris. The highly variable precipitation runoff at Red Bluff was attenuated by the flood basins and tributary inflow by the time it reached Sacramento. Temporal shifts also resulted from the greater snowmelt runoff from the Feather and American Rivers.
Data from Rose et al. 1895.

IV.B.2. Groundwater Hydrology

Relatively little is known about natural groundwater hydrology. The first serious attempt to rigorously examine this aspect of system hydrology was initiated by the U.S. Geological Survey at the turn of the century, when groundwater was being developed as an irrigation supply and the system was already highly modified (Bryan 1915, Mendenhall et al. 1916, Bryan 1923). Additional information has been derived from modern attempts to reconstruct the natural hydrology of this system (Williamson et al. 1985, 1989). Groundwater is believed to have originated as recharge in the low hills along the perimeter of the valley and in the upper reaches of streams, as well as from deep percolation of precipitation on the Valley floor. The water table roughly paralleled the land surface (Williamson et al. 1989), and groundwater moved toward the topographically low areas in the center of the valley. As groundwater passed through the Valley, most of it was either lost to the atmosphere through direct evaporation or plant transpiration, or ended its journey as subsurface discharge to local streams. The amount retained as subsurface flow and eventually discharging to Suisun Bay appears to have been negligible (Williamson et al. 1989).

Surface evaporation, which is seasonally high in the arid summers and falls of the Central Valley, accounted for substantial loss of groundwater to the atmosphere. Groundwater discharged at the surface over a wide area where the water table was less than about 8 feet from the surface. As it percolated to the surface and evaporated, dissolved materials remained at the point of evaporation, creating extensive deposits of alkaline surface soils scattered throughout the Valley (Bryan 1923). Alkaline soils are present throughout the Central Valley, but most are concentrated in the San Joaquin and Tulare Lake Basins (Hutchison 1946).

Much of the valley's groundwater was discharged directly into the atmosphere and standing water at the surface. It was undoubtedly an important water supply for wetlands, riparian vegetation, and oak woodland/savannas. One early 20th century estimate suggests that at that time, about 80% of the Sacramento Valley had groundwater levels of 25 ft or less. Bryan (1923) and Williamson et al. (1989) estimated that 13 million acre-ft/yr of water evaporated directly from groundwater in the central part of the Valley, where the water table was within 10 feet of the ground surface. About 40 percent of this amount was estimated to be supplied from local precipitation and most of the remainder from local stream channels. In the Tulare Lake Basin, much of the groundwater discharge was to Tulare Lake and surrounding areas, which drained into the San Joaquin River during high flows.

The Irrigation Congress, reporting on field work for canals in the San Joaquin and Tulare Lake Basins, speculated that "*the San Joaquin receives an important accession of* *volume from underground drainage - probably from the Tulare Lake drainage*" (Anonymous 1873, p. 8). However, most accounts of groundwater in this area indicate that it was "stagnant" (Mendenhall et al. 1916), discharging at the surface. Additionally, groundwater contours of the Valley (e.g., Ingerson 1941, Mendenhall et al. 1916) indicate that groundwater predominantly moved downslope toward the valley trough, rather than along the axis of the valley. Further, the suggestion is not validated by modern groundwater models (Williamson et al. 1989).

Early accounts suggest that in the pre-disturbance Central Valley, water tables were high and springs and artesian wells were common. Wells that flowed without pumps were documented as early as the 1880s over large areas throughout the Valley (Hall 1889) and were shown to cover an extensive area along the valley trough, from San Joaquin County south to Kern County, as late as 1905 (Mendenhall et al. 1916).

A large segment of the upland portion of the northern and northeastern watershed of the Sacramento River, and a portion of the Feather River watershed, is composed of porous volcanic material. Precipitation infiltrates rapidly and historically recharged an aquifer system that sustained a fairly constant and substantial year-round spring flow. This phenomenon affected summer inflow to the lowland rivers, sustaining minimum summer flows of about 4,000 cfs in the Sacramento River at Red Bluff and about 800 cfs in the Feather River as it discharged into the lowlands. It is possible that without this spring flow, which was estimated to have contributed about 3 MAF/yr of water, portions of the lowland Sacramento and Feather Rivers would have almost gone dry during most fall seasons (Grunsky 1924, 1929). The westside tributaries were also spring fed, disappearing underground in the foothills (Hall undated) to recharge local aquifers. Streams in the San Joaquin River and Tulare Lake Basins were also believed to be fed by subsurface discharge. The flow in the San Joaquin River between the railroad crossing and Firebaugh doubled even though the interval did not receive a single tributary. The flow in the Kings River doubled between Centerville and the upper ferry and again between the upper ferry and Kingston, even though there was no tributary inflow (Anonymous 1873).

IV.B.3. Disturbance and Succession

Those portions of alluvial floodplains immediately bordering river channels of the Central Valley were particularly dynamic environments, continually disturbed and rearranged by the frequent flooding documented and described above. The floodplains were also continually reshaped by depositional processes accompanying river meandering (Brice 1977). As the river migrated laterally (meandered) across the floodplain, it eroded sediment from the outer banks of riverbends and redeposited it as a series of "point bars" that formed outward from the inner bank of riverbends (Figure

II-D). In this manner, the channel maintained its full bank width while continuously redistributing and reshaping the floodplain as it moved across the valley floor. Additionally, in the lowland riparian zones, deep, finely-textured soils are exposed to direct sunlight and strong winds for extended periods.

These combined forms of disturbance created rich opportunities for riparian successional processes. The general process of succession in riparian zones is common to river systems throughout the geographic region, and still occurs today at relatively undisturbed sites. At first, common riparian plants like willows and cottonwoods disperse abundant small seeds to pioneer onto newly deposited substrates. Secondary successional species then seed on the developing terraces under the shade of the now taller willows and cottonwoods. Eventually, the terraces develop more mature plant assemblages that include shade tolerant species, such as valley oak. As with the upland systems, periodic disturbance from floods, fire, wind, and seasonal variability in instream water levels were instrumental in maintaining the diverse structural and biological characteristics of Central Valley riparian forests. The maintenance of riparian forests of the lowland rivers is also highly dependent upon adequate groundwater levels. Normally, these are sustained by absorption through the bank and channel soils during the dry season, and are seasonally augmented by lateral sheet flows during periodic flooding.

An additional form of periodic disturbance highly influential in creating and maintaining riparian habitat structural complexity was the activities of large animals, including feeding and foraging, burrowing, wallowing, building of dams, etc. The result of these activities was to increase the variety and complexity of micro-habitats within the riparian zone, along with a variety of effects on ecosystem processes such as nutrient cycling and productivity within riparian areas, and stimulating the flux of energy and materials among nearby ecosystems (Naiman and Rogers 1997).

IV.B.4. Community Energetics: The Acquisition and Cycling of Organic Carbon and Nutrients

Community energetics in river-floodplain systems of the Central Valley were not described or studied prior to massive human intervention of the last 150 years. Thus, much of the information provided here is necessarily derived from our modern understanding of fundamental aspects of the ecology of large river-riparian ecosystems in general. Because these are widespread and common features of modern examples of pristine river-riparian systems, there is good reason to believe that they are also inherent natural characteristics of Central Valley river-floodplain ecosystems.

a. Sources. River-riparian ecosystems naturally acquire energy and nutrients from internal production, and transfer from other adjacent systems, primarily through the movement and activities of large, wide-ranging animals and as inflow from the upstream portion of the watershed. Mature gallery riparian forests represent the most productive habitat in the state (CSLC 1993), and along with marshes display productivities similar to those of tropical rain forests (Major 1977). It is likely that riparian vegetation represented the largest single source of organic nutrients to riverine habitat and the ecosystem as a whole.

However, instream production plays a decidedly greater role here than in upland systems. The once bountiful salmon population, estimated at 1 to 3 million returning spawners annually (Moyle and Yoshiyama 1992, Moyle et al. 1996), was undoubtedly an important source of organic matter in natural streams throughout the Central Valley. Phelps described the Sacramento River in 1841, noting that "*in the latter part of the season the surface of the river is nearly covered with dead rotten salmon floating to the sea*" (Busch 1983, p. 200). Moyle and Yoshiyama (1992) estimated that 20 to 80 million pounds of organic matter were released into the river system, representing a major nutrient source.

As in all aquatic ecosystems, primary production in the water column is limited to that upper portion in which light levels are sufficient to support photosynthesis (photic zone). The extent of this zone varies daily and seasonally, and depends upon ambient light levels and water transparency. Production may also occur in sufficiently illuminated benthic habitats. In upstream reaches of the large Central Valley rivers, benthic algae are common and phytoplankton are rare. In downstream reaches, increased turbidity and depth limits the growth of attached algae, but increased nutrient concentrations allows for an abundant phytoplankton community (CSLC 1993). These tend to be mainly comprised of diatoms that respond to increased light, temperature and nutrient levels by rapidly increasing population levels (blooming) in the spring.

b. Cycling and Exchange. Since water is constantly transporting nutrients downstream, there is little opportunity within riverine habitats for the site-specific nutrient cycling commonly seen in terrestrial systems, except in off-channel backwaters and marshes (Hynes 1970). Instead, seasonal flooding distributes dissolved and suspended nutrients from the entire basin over the floodplain, where cycling occurs. The rich soils of both forests and marshes harbor a considerable biomass (both on and within their surfaces) in the form of decaying vegetation and other organic debris. Fungi, subsurface interstitial bacteria, and microorganisms in groundwater are the chief decomposers. These break down and assimilate detritus, thereby releasing the stored nitrogen back into the soil and water in a form readily utilizable by other forms of life.

Both insects and microorganisms recycle organic nutrients through feeding and decomposition networks. Insects are the most ubiquitous herbivores and scavengers of river and riparian habitats, and represent a primary link between trophic levels of river-riparian ecosystems, as well as among their component habitat types (Goldman and Horne 1983). Both terrestrial and purely aquatic insects depend on both riverine and riparian habitats for at least some part of their life history. They feed upon living plants and detritus (and one another), and are in turn heavily preyed upon by larger animals, including birds, bats, fishes, reptiles, amphibians, and small mammals. These small vertebrates form intermediate trophic links, and, along with insects, also feed upon plants, detritus, and one another.

Many of the larger predators of the system, along with some of the larger herbivores, were more wide-ranging species. In its natural state, the river-floodplain ecosystem as a whole provided partial support to a diverse collection of larger animals that regularly occupied territories that included this, as well as other more upland ecosystems. Together, these diverse ecosystems comprised an ecologically rich landscape that supported thriving populations of large range wildlife, including deer, tule elk, pronghorn, grizzly bears, mountain lions and bald eagles, as well as many hundreds of less conspicuous native plant and animal species. The movement and activities of these larger animals provided an avenue of exchange of energy and nutrients both among habitats (river-riparian) as well as with adjacent ecosystems. Through consumption, assimilation, death and excretion, both biomass and nutrients were exchanged.

c. Sinks. Downstream flow and burial, and consumption and removal by larger wide-ranging animals were probably major nutrient sinks for the ecosystem.

V. The Delta

The Delta is the easternmost (upstream) portion of the estuary, and today is clearly delimited by a legal boundary that includes areas that historically were intertidal, along with supra-tidal portions of the floodplains of the Sacramento and San Joaquin Rivers. It is a flat, roughly triangular area extending to the northeast and southeast from Chipps Island (the legal western boundary of the Delta - about 4 miles west of the confluence of these rivers: Figure G10). The Sacramento and San Joaquin Rivers enter the Delta from the north and south respectively, where they join and together discharge their contents to the lower estuary (San Francisco Bay). At the time of the early European explorers, this area was largely a vast, sea-level swamp, composed mostly of large tracts of intertidal wetlands (Figure II-K) transected by a complex network of waterways of varying size (Thompson 1957). Around the historical Delta's intertidal perimeter, tidal wetlands merged gradually into non-tidal wetlands, and further upland into oak woodlands and grasslands dotted with vernal pools.

Figure II-K
Early View of the Delta

A Delta marsh bordering the San Joaquin River: "*The foreground shows the dominant vegetation of the tidal marshes where the water is fresh or nearly fresh. The bushes mark the position of the natural levee, here low. An artificial levee may be faintly seen above the rushes. The work of reclamation was in progress at the date of the view: August 31, 1905*."
Source: U.S. Geological Survey, Gilbert, G.K., Photo No. 2664.

The Delta and San Francisco Bay represent contiguous components of a single estuary. However, this report treats the two areas as distinct ecosystems because of notable and systematic differences in their general physical structure, hydrology, water column characteristics, and resident biotas. Differences between the two parts of the estuary become particularly pronounced west of the Carquinez Straits. Nonetheless, some of the "average" conditions that generally serve to distinguish the Delta and the Bay (particularly those related to the nature of the water column) do not always apply. Some conditions change along gradients that vary in space and time, rather than changing abruptly at fixed geographic locations.

For most of its geologic history, the Delta was an unusually dynamic environment. To the extent possible, the summary description of the "natural" structure and function of this ecosystem provided below is based upon the system as it existed around 1850, the earliest historical period for which we have sufficient information to provide such a description. The terms "natural" or "historical" Delta are used here in that context.

V.A. Ecosystem Structure: Habitat Types and Biological Assemblages

The pre-Gold Rush Delta has sometimes been characterized as "one vast tule marsh," suggesting that this area was little more than a somewhat simple, homogeneous habitat consisting almost exclusively of monotypic stands of tule and covering a very large region. Such a perspective might in fact be readily inferred through consideration of soil maps, or from certain anecdotal accounts of early observers, most of whose view of the Delta was limited to that which could be seen from the deck of a ship travelling along its major channels, for example: "*Everything is tule swamp on each side...the banks are covered with nothing but tule, and so high that one sees nothing but sky, water and tule*" (Abella 1811 in Cook 1960, pp. 261-262).

However, from an ecological standpoint such descriptions are oversimplifications that fail to reflect the considerable habitat complexity and diversity that allowed the Delta ecosystem to support such an unusually rich and diverse native biological community. The natural Delta contained a wide variety of plant life, a fact enthusiastically reported in an early biennial report of the Fish and Game Commission: "*All the reeds, seeds, bulbs, and succulent water grasses, except rice, known to the eastern and middle states and classified by the Department of Agriculture grow in the greatest luxuriance. Many varieties of roots and grasses which I am unable to identify are also much in evidence*" (Skinner 1962, p. 139).

The picture of the historical Delta presented here is derived from a large number of historical accounts of explorers that viewed the Delta from a variety of perspectives, or who actually penetrated areas beyond the larger river channels. These early narratives are supplemented with the results of some careful modern examinations of remaining remnants of Delta habitat (e.g., Thompson 1957, Atwater 1980a) and surface geology (Atwater and Belknap 1980) to attempt to reconstruct a more comprehensive ecological perspective of the natural Delta environment than has been previously available.

Three major "depositional environments" of the historical (circa 1850) Delta distinguished by Atwater and Belknap (1980) also define the system's major habitat types: intertidal wetlands, subtidal waterways, and elevated (supratidal) landforms (mainly levees) which typically supported riparian vegetation. These are described below and mapped on Figure G10.

V.A.1. Intertidal Wetlands

This includes all areas alternately submerged and exposed by the tides. Major structural features included marshplains and their smaller drainage channels, semi-permanent bodies of standing water alternately described as "ponds," "pools" and "lakes," and mudflats. It is apparent that the Delta's wetlands were dominated by emergent vegetation (Atwater 1979, Thompson 1957). However, because this habitat type no longer exists as such, save in a few small and fragmented remnants, and because early descriptive observations were not stated in quantitative terms, the proportionate cover of the "subhabitats" (emergent vegetation, open water, mudflats) is speculative and no attempt is made here to quantify each.

a. Distribution and Extent. About 87% or 321,000 acres (502 mi^2 or 1300 km^2) of the Delta circa 1850 consisted of intertidal wetlands (Atwater and Belknap 1980). Intertidal wetlands were most prevalent and continuous in the southern and central (San Joaquin-influenced) Delta, which consisted almost exclusively of this habitat type (Thompson 1957, Atwater 1980a, Atwater and Belknap 1980). Along the Sacramento River, supra-tidal natural levees cordoned off islands (such as Merritt and Sutter) from tidal waters and left them as non-tidal tule wetlands (Atwater 1982).

b. Composition and Complexity. Intertidal wetlands of the historical Delta displayed minimal topographic relief. Most of these areas were within $\pm$ 0.7 ft ($\pm$ 0.2 m) of the average highest daily tide (Atwater and Belknap 1980). The wetlands consisted of a complex and spatially variable mosaic of marshplains (generally dominated by tule *Scirpus actus*), more diverse and complex plant assemblages, small (pools and ponds) and large (lakes) bodies of open water, and mud flats. The wetlands were periodically interrupted and transected by the other major habitat types of the ecosystem - subtidal waterways and their supratidal levees (described below) - creating a diverse and complex landscape. Wetlands of the historical Delta have also been generally referred to as "backswamp" (Thompson 1957) or frequently simply as "tule marsh." The former is a more apt descriptor since stands of tule only accounted for a portion of the area, with other plant associations and structural features also prevalent at many sites.

The appearance of the wetlands varied considerably on both a daily and seasonal basis, as the swamp was alternately inundated and exposed as a result of changes in tides, precipitation, and discharge from the lowland rivers. Most of the Delta was inundated twice daily, as high tide raised water levels above the plane of the swamps (Rose et al. 1895). Thompson (1957, p. 13) concluded that: "*In the undisturbed state of a century ago about three-fifths of the Delta was awash with an ordinary tide. Spring tides could submerge all of the backswamp. River floods were capable of overflowing the entire Delta, particularly when crests, high tides, and westerly winds created a congestion above the outlet into Suisun Bay.*" More of the wetlands became seasonally submerged during the winter and early spring, when high river discharge raised water levels. During large floods, water could rise 10 to 15 feet above the average plane of the swamp, giving the entire area the appearance of a large inland sea.

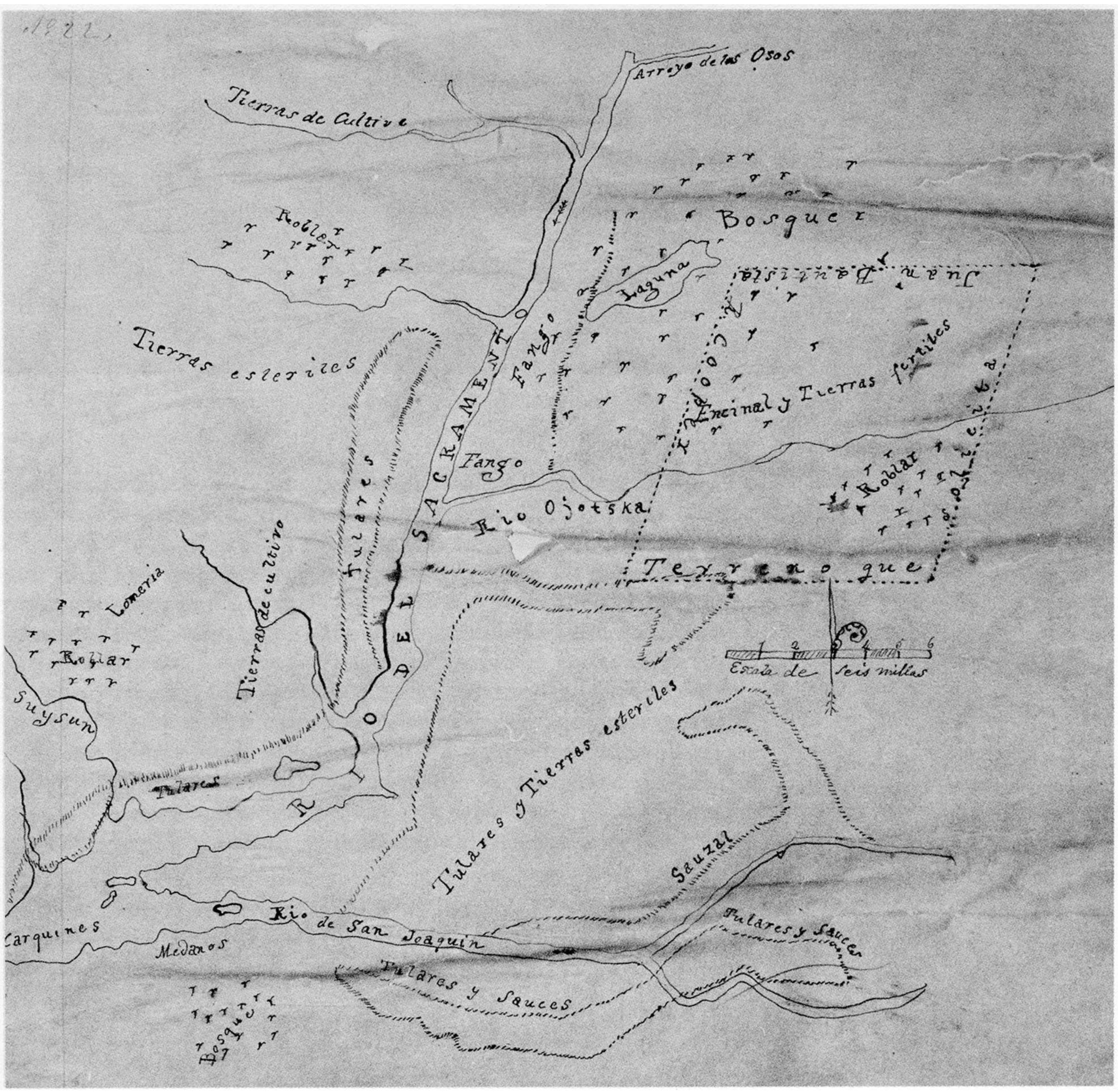
Tidal flows to and from the wetlands were alternately distributed and collected by an intricate branching network of channels that ramified from the larger subtidal waterways. The size and drainage density of these were highly variable among locations, dictated by the area and tidal prism (the volume of water between high and low tides) of the area they supplied. The complexity and variability of the Delta's channelized landscape is well described by early explorers, e.g., *"[t]hese sloughs wind through an immense timbered swamp, and constitute a terraqueous labyrinth of such intricacy that unskillful and inexperienced navigators have been lost for many days in it, and some, I have been told, have perished, never finding their way out"* (Bryant 1846, p. 343). "*We cruised to the south, but there are so many twists and windings that at times we circled the compass*" (Abella 1811 in Cook 1960, p. 262). "*The country a little way to the Westward of us is a continuation of swampy lakes of bulrushes all under water...*" (Work 1833 in Maloney 1945, p. 61). The smallest were narrow dead-end sloughs, whose nearby wetlands "*supported fewer shrubby species and more stands of common reed (*Phragmites australis)" (Atwater 1980a, p. 16).

Emergent Vegetation. Differences in the general topography and structure of the northern versus south-central Delta led to systematic differences in the distribution and character of the wetlands and emergent vegetation that typified these two regions. Atwater (1980a, p. 16) noted that "*tidal wetlands contiguous with alluvial flood basins of the ancestral Sacramento River possessed tree- and shrub-covered natural levees along major drainages and a dominance of [tule]* Scirpus actus *elsewhere,*" whereas "*wetlands along predominantly tidal tributaries of the ancestral San Joaquin River supported an irregular, overlapping patchwork of bulrushes (*Scirpus spp.*), willows, cat-tails, lady fern and many subordinate species.*" By analogy, he concludes that "*wetlands along dead-end sloughs* *supported fewer shrubby species and more stands of common reed (*Phragmites australis*). Similar conditions may have prevailed in adjacent wetlands distant from waterways*" (Atwater 1980a, p. 16). This is consistent with an 1833 hand-drawn schematic map of the Delta, which characterizes the vegetation along the San Joaquin River and its distributaries as willows (*sauces*) or willow and tules (*tulares y sauces*), while much of the rest of the Delta is simply characterized as tule marsh (Figure II-L).

The river and slough channels subdivided the swamp into a series of "islands," in which a central expanse of tidal wetlands was surrounded and "isolated" by waterways. In the south-central Delta, low and irregular banks allowed the island interiors to be flooded with each high tide. This more complex, irregular topography led to greatly increased plant diversity in comparison with the flatter, more homogeneous flood basin marshplains of the northern Delta. South-central Delta "islands" supported over 70 kinds of native plants, some of which were epiphytes (Atwater et al. 1979, Atwater 1980a). In some places, tule-dominated marshplains and the island-swamps of the south-central Delta graded into an intermediate type of wetlands that combined features of both (Atwater and Belknap 1980). An idealized diagrammatic representation of plant zonation patterns of the natural Delta is presented in Figure II-M, which has been adapted from Conard et al. (1977). As emergent vegetation died and decayed, it contributed to the rich layer of peat soil that characterizes the Delta in general.

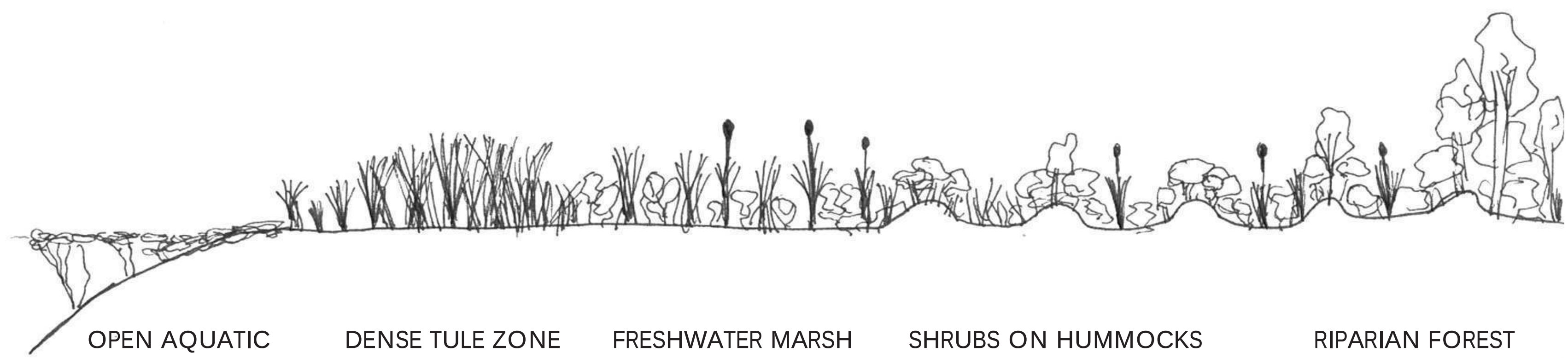
<u>Open Water Bodies (ponds/pools/lakes)</u>. Interspersed among the marshplains and other stands of emergent vegetation were frequent shallow, open water bodies largely devoid of emergent vegetation and with quite different habitat characteristics than the surrounding terrain. These were variously described by early observers as "lakes," "ponds," and "pools," and appear to have been highly variable in extent, depending upon location and water levels. Many of these areas may well have seasonally alternated between subtidal and intertidal conditions, covered by standing water throughout much of the year, but partially exposed under low water conditions. Although ecological characterization of these features is difficult due to the abbreviated and anecdotal nature of most early descriptions, numerous eyewitness accounts leave little doubt that these were common and persistent features of the natural wetland landscape: *"I have seen the water in some of them [small marshplain drainage sloughs] a foot lower than the river, and rushing in like a mill stream; these discharge into small lakes or spread out into the tule"* (Gibbes 1850a, describing exploration of a portion of the Delta above the mouth of the San Joaquin). *"This plain probably must exceed one hundred and twenty leagues in length and is in places twenty, fifteen, or fewer leagues wide. In its entirety it is a labyrinth of lakes and tulares"* (Fages/Crespi April 1772 in Treutlein, p. 355). Early maps document some of the larger lakes in the northern Delta, as well as more numerous

Figure II-L
Earliest Map of the Delta and Sacramento Region
(ca. 1833)



John R. Cooper requested land in the Sacramento Valley from Mexican officials in 1833, but never settled it. The land embraced the Rio Ojotska (now the American River). The map identifies landscape features, including oaks, oak groves, and evergreen oak groves (*robles, roblar, encinal*), forests (*bosque*), tule marshes (*tulares*), willows (*sauces*), hills (*lomeria*), sand dunes (*medanos*), a lake (*laguna*), mud (*fango*), barren land (*tierras esteriles*), and lands suitable for cultivation (*tierras de cultivo*). (Translations based on Headworth and Stines 1998 and Guinle 1981.)
Source: Cooper 1833 in Severson 1973.

Figure II-M
Delta Vegetation Patterns



Idealized vegetation patterns for the Sacramento-San Joaquin River Delta.
Source: after Conard 1977.

smaller lakes and "ponds" that were regular features throughout the south-central Delta (Gibbes 1850b).

Mudflats. In contrast to the common references to "lakes" and "ponds," references to mudflats are relatively rare in historical narratives, even though these were sometimes mapped as discrete features of the Delta (e.g., Ringgold 1852). The reason for this is open to a number of possible interpretations. It seems quite possible that mudflats are far less commonly mentioned than "lakes" and "ponds" because they were only temporarily (at low tide and at times of low river discharge) exposed, and at such times were also particularly inaccessible to early observers who traveled mainly along deeper channels. However, the fact that mud is not identified as a discrete phase in numerous borings (e.g., Atwater 1982) or in soil surveys (e.g., Cosby 1941), suggests that in fact mudflats were naturally somewhat uncommon or inconspicuous features of this part of the estuary.

Only two clear narrative references to Delta mudflats were uncovered by this study. Ringgold mapped a large expanse of mud at the mouth of Cache Slough (which drained the vast Yolo Flood Basin), and wrote: "*On the west, the waters terminate and waste themselves in swamps and mudflats*" (Ringgold 1852, p. 39). Duvall, who visited the Delta in 1846, wrote of the confluence of the Sacramento and San Joaquin Rivers at the Delta's western margin: "*The river at the entrance is about two hundred and fifty yards wide, the channel of the river being very much encroached upon by the muddy flats which extend towards it from dry land for several hundred yards*" (Rogers 1957, p.14).

V.A.2. Subtidal Waterways

This feature consisted of the main river channels and larger distributary channels that contained standing water even at the lowest of tides. Major structural subdivisions are (1) the channel bed and banks and (2) the water column contained within the channel.

a. Distribution and Extent. An estimated 25,000 acres (39 mi^2 or 100 km^2) of subtidal waterway traversed the intertidal swamps of the 1850 Delta (Atwater and Belknap 1980). The distribution of these features is presented in Figure G10.

b. Composition and Complexity. Subtidal waterways were of two main types: riverine channels, and their connected large distributary sloughs, each with differing hydrogeomorphic and ecological characteristics. Water movement in subtidal waterways (which strongly influences many other ecological characteristics) varied considerably with differences in channel width, inflow, and connection to other channels.

River channels are the primary conduits of freshwater through the Delta to Suisun Bay. The natural downstream movement of water here is at times counteracted by tidal influence, but nonetheless creates comparatively high rates of water movement (low residence times) and net downstream transport. Of the two main rivers, channels of the Sacramento generally maintained higher net downstream flows than did the San Joaquin. The San Joaquin River collected most of the tidal prism of the Delta, and was naturally scoured to a depth of about 30 feet where it joined the Sacramento River and discharged into Suisun Bay. Where these rivers joined, their mouths were obstructed by comparatively shallow sand shoals, a navigational hazard frequently noted by sailors of the mid-19th century (Ringgold 1852).

Branching off the main river channels were large distributary sloughs. Because of their configuration, water movement in slough channels was primarily controlled by the tides. Hence, it was comparatively slow and bi-directional, leading to high residence times. Thus, distributary sloughs were typically characterized by greater water transparency, finer benthic sediments, more developed benthic vegetation, and higher phytoplankton and zooplankton concentrations than are generally found in active river channels. Because of these characteristics, sloughs represented a quite different habitat than did the river channels for many fishes and other aquatic organisms.

Where water velocities were sufficient, elevated "point bars" formed in the meander bends of the larger waterways (Thompson 1957). Some of these later became isolated by branching channels to form mid-channel "islets" that support characteristic riparian assemblages - dense thickets of cottonwood, alder and willow saplings - particularly adapted to such low-profile, high-disturbance environments (Conard et al. 1977). Some of these were mapped by Ringgold in 1850. These islets were particularly prevalent in the south-central Delta (Atwater and Belknap 1980) and were reported to be frequently occupied by large beaver colonies: "*Beaver were very numerous...on the hundreds of small rush-covered islands...There is probably no spot of equal extent in the whole continent of America which contains so many of the much-sought animals*" (Thomas Farnham 1840 in Skinner 1962, p. 157). The Delta's beaver colonies probably contributed substantially to the addition of large woody debris to the waterways, creating additional habitat complexity.

Sediment characteristics at any given site were primarily determined by inflow composition and velocity. Benthic sediments of the waterways were almost entirely comprised of sand and soft mud, which were commonly stratified and had low organic carbon content (<15%). Beneath major waterways, deposits locally graded downward into gravel (Atwater and Belknap 1980, Hymanson et al. 1994). Sediment characteristics at any given site were primarily determined by inflow composition and velocity.

V.A.3. Supratidal Landforms

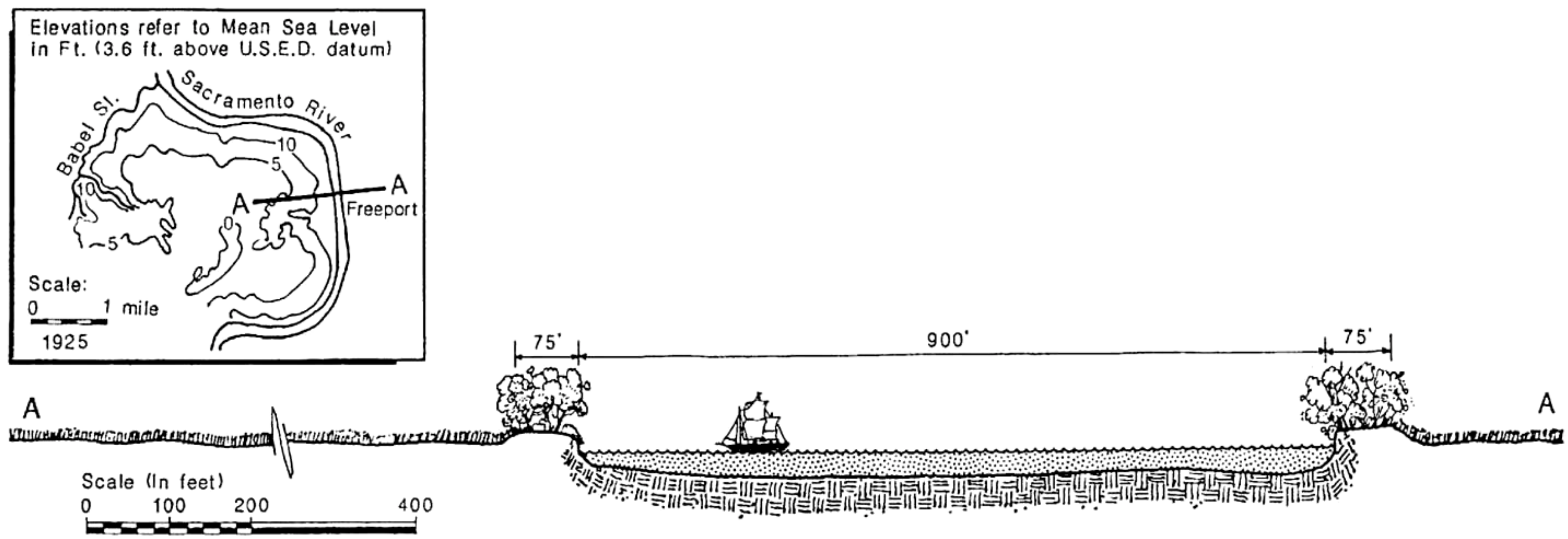
Delta landforms beyond the reach of the highest tides included natural levees and sand mounds. Mid-channel islets were also in some cases supratidal, but are considered in the previous subsection (Subtidal Waterways) as part of another habitat type.

a. Distribution and Extent. Atwater and Belknap (1980) estimated the extent of supratidal landforms to be about 25,000 acres (39 mi^2 or 100 km^2) circa 1850. The vast majority of this habitat type was in the form of natural levees bordering subtidal waterways. Thus, the distribution and extent of these two habitat types correspond quite closely. Natural levees were best developed and more extensive along the main branches and distributary sloughs of the Sacramento River in the northern Delta, but occurred in the south-central Delta as well, particularly along the major channels of the San Joaquin River (Figure G6). The comparatively rare and much smaller (in areal extent) sand mounds were most numerous in the west central Delta.

b. Composition and Complexity. The natural levees of the Delta are depositional land forms consisting primarily of sand, silt, and silty clay (Atwater 1982). They are characterized by abrupt faces towards the channels, with more gentle slopes towards the intertidal wetlands. Although natural levees somewhat isolated waterways from the wetlands at most times, large floods would periodically top the levees, which then essentially became large spillways forming a one-way connection between the subtidal waterways and backswamp (Thompson 1957).

The height and lateral extent of the Delta's natural levees varied widely. Those along the upper Sacramento River above Isleton were the widest and best-developed in the entire Delta (Thompson 1957). On western Sherman Island, Sacramento River levees appear to have been at the level of Suisun Bay at low-tide, low-water stage (Thompson 1957) and apparently supported marsh rather than riparian vegetation. This is clearly illustrated by an 1833 map of the Delta (Figure II-L), which shows tule marsh (tulares) bordering the lower Sacramento River, and is documented by numerous eyewitness accounts. In July 1841, Phelps described the confluence, viz. "*All the distance the banks were low and covered with flags or tules....*" Travelling further up the Sacramento River, "*having passed all the tule, we ran along the high banks on which were many high trees*" (Phelps 1841 in Busch 1983, p. 191) and "*[t]he banks increase in altitude, gradually, after leaving the mouth of the river, and groves of sycamore and oaks are soon reached*" (Ringgold 1852, p. 28). In the vicinity of Freeport on the Sacramento River (Figure II-N), the natural levees were about 75 ft wide and about 14 feet above low water in 1850 (McClure 1925, Ringgold 1852, CCPW 1895) and approached 24 feet near Sacramento. The banks of the Old River distributary of the San Joaquin River seem to have been fairly well developed along the present Union and Victoria islands to the latitude of

Figure II-N
Cross-section of the Sacramento River at Freeport



The Sacramento River channel bottom in 1841 was -20 ft USED (referenced to the USED datum which was 3.6 ft above mean sea level.) Water depth at low water in 1850 was 20 to 30 ft, the channel width was 900 ft, and natural levee width was about 75 ft (Ringgold 1852, CCPW 1895). Natural levee height along the left bank was +18 ft USED, and along the right bank +20 ft USED (McClure 1925). Riparian trees were 40 to 70 feet tall and tule marsh vegetation up to 15 ft tall (Jepson 1910, 1975).
Source: Fox 1987.

Rough and Ready Island (Thompson 1957), but in general, natural levees were apparently lacking in the south-central Delta (Atwater 1980a). Distributary sloughs, as well as river channels, developed natural levees, but these were generally of lower and narrower stature than those of the large river channels. Levees of the south-central Delta, particularly those of smaller river channels and distributary sloughs, were comparatively low and narrow, and in many cases topped by high tides. The natural vegetation along these channels was distinct from other Delta areas, predominately tule marsh and willows or willows alone.

The natural levees and other elevated landforms supported plant assemblages that distinctly differed from those of the backswamp, primarily described above. The majority of plants occupying the Delta's levees were adapted to drier conditions than those of the backswamp. Thompson (1957, pp. 52-53) surmises that "*[t]his natural levee cover consisted of coarse bunch grasses, willows, blackberry and wild rose thickets, and galleries of oak, sycamore, alder, walnut and cottonwood...Fine groves occupied the more southerly San Joaquin River distributary banks.*"

Early maps of the confluence of the Sacramento and San Joaquin Rivers and of the Sacramento River between the confluence and Sacramento show by way of map symbols that trees were present along nearly every major slough and channel in areas with well-developed levees (Ringgold 1852). Willows and tules were present on levees that were not well-developed. Ringgold's engravings graphically depict the riparian zone that greeted the visitor near the current junction of Steamboat Slough, Cache Slough, and the Sacramento River (Figure II-O).

The riparian zone along Delta levees was widely described by early explorers, viz., "*[e]ach branch [of the river] is covered with trees on both banks, of various kinds and very large*" (Abella 1811 in Cook 1960, p. 264). Travelling up the Sacramento River from its mouth, "*[t]he marsh land now gave way to firm ground, preserving its level in a most remarkable manner, succeeded by banks well wooded with oak, planes, ash, willow, chestnut, walnut, poplar, and brushwood. Wild grapes in great abundance overhung the lower trees, clustering to the river, at times completely overpowering the trees on which they climbed...Our course lay between banks...These were, for the most part, belted with willow, ash, oak, or plane (*plantanus occidentalis*) [sycamore], which latter, of immense size, overhung the stream*" (Belcher 1837 in Pierce and Winslow, pp. 38-46). An early resident described conditions prior to the Gold Rush, writing: "I*n passing through the narrow Steamboat Slough (then called Merritt's) the branches of the large Sycamore tree growing at the rivers edge met and formed an almost continuous arch overhead. From the Slough up, the trunks and branches of the trees protruded from the bank far out over the river on each side*" (Grimshaw 1848 in Kantor 1964).

Figure II-O
Sketch of the Lower Sacramento River in the Delta

Sketch of the Sacramento River channel and riparian zone near current day confluence with Steamboat Slough.
Source: Ringgold 1852

Single and clustered sandy mounds represented the highest feature of the Delta landscape, rising as much as 17 feet above mean swamp level. Atwater's maps suggest they were quite common and most numerous in the west-central portion of the Delta, near Old River and Knightsen-Oakley (Atwater 1982), and were identified in 1833 on an early Delta map (Figure II-L).

V.A.4. Habitat Connectivity

The natural connectivity among Delta habitats was maintained by water movement, and the movement and activities of organisms. Although somewhat isolated by high natural levees, the larger river channels were nonetheless intermittently connected to nearby intertidal wetlands by a series of distributary channels that occasionally joined the river channels. Waters were also exchanged periodically through floods. Much of the abundant wildlife of the area moved among habitats, feeding in one area and resting (or being preyed upon) in others. These processes promoted the regular exchange of nutrients and energy among major habitat types of the Delta. With the exception of some of the elevated landforms (e.g., sand mounds, alluvial ridges, point bars) and their riparian vegetation, the intertidal wetlands existed as comparatively large, continuous areas, with few natural barriers to the movement of water, sediment or organisms.

V.A.5. Associated Biological Assemblages

Our knowledge of the habitat distribution and movement patterns of the native biota of the region is fragmentary and incomplete, derived largely from anecdotal historical accounts rather than systematic scientific surveys that would allow between-habitat comparisons. Therefore, the biota of the natural Delta ecosystem is described here as a single community, rather than by habitat-specific assemblages as was done for the other ecosystem types discussed. Many, if not most, of the larger animals probably frequented all of the habitat types discussed, although there clearly are some distinctive differences in some of the characteristics of certain taxa associated with each. Where appropriate and documented, these are pointed out.

The precise nature of the historical benthic (both subtidal and intertidal) invertebrate fauna of the natural Delta remains for the most part speculative. However, as is generally typical of such areas, it is likely that the rich organic sediments of the backswamp were home to an abundant assemblage of scavengers and detrital feeders, along with filter-feeding planktivores. As is true today, animal assemblages of the water column in the natural Delta probably consisted mainly of zooplankton and fishes, and varied both spatially and temporally (daily, seasonally, and annually), depending on habitat type, depth, benthic characteristics, transparency, current velocity, and salinity. The zooplankton was naturally composed of four main groups: ciliate protozoans, rotifers, copepods, and cladocerans (Allen 1920).

Historically, the Delta's native fish fauna was composed of a mixture of freshwater, estuarine and anadromous species, which, with the exceptions of the Delta smelt *(Hypomesus transpacificus*) and longfin smelt (*Spirinchus thaleichthyes*), also commonly occur in fresh or marine waters outside the estuary. Marine species, although frequent downstream of the Carquinez Strait, seldom stray east of that location. Most native fishes of the Delta were unusually large freshwater minnows with a capacity to defer spawning under adverse environmental conditions, redirecting energy to body growth rather than reproduction. This group includes the Sacramento splittail (*Pogonichthyes macrolepidotus*), Sacramento squawfish (*Ptychocheilus grandis*), hitch (*Lavinia exilicauda*), Sacramento blackfish (*Orthodon microlepidotus*), hardhead (*Mylopharodon conocephalus*), thicktail chub (*Gila crassicauda*), and Sacramento sucker (*Catastomus occidentalis*) (Herbold et al. 1992). A second group of more advanced fishes spawn each year and tend to show a high degree of early parental care. These include the prickly sculpin (*Cottus asper*), Sacramento perch (*Archoplites interruptus*), and tule perch (*Hysterocarpus traski*). In addition to the resident species, anadromous fishes (salmon, steelhead, and sturgeon) passed through the Delta on their migrations between upstream spawning grounds and the sea.

The precise historical distribution / abundance patterns of these fishes in the Delta is unknown, but the presence of their remains in Indian middens suggests that they were common in the general region when the Delta was still a largely undisturbed intertidal swamp. A prehistoric midden, located on the south shore of Stone Lake, 2 miles east of Hood in southern Sacramento County contained remains of 12 species of fishes representing 804 individuals (Schulz and Simons 1973). Listed according to relative abundance, these are: the Sacramento perch (51%), hitch (20%), thicktail chub (12%), splittail (6%), Sacramento sucker (6%), Sacramento blackfish (1%), Tule perch, hardhead, Sacramento squawfish, chinook salmon, sculpin, and sturgeon. The Sacramento perch, the most abundant, inhabited quiet sloughs off the main channels (Turner 1966) and was once abundant (Moyle 1976b). However, it was reportedly quite rare by the turn of the century. Their decline has been attributed to the introduction of carp and catfish and the reclamation of the marshes (Rutter 1908). The hitch was the second most abundant species and predominantly inhabited sloughs and slow water. In the mid-19th century, it was reported throughout the Central Valley (Rutter 1908), but has declined since (Moyle 1976b). The thicktail chub, the third most abundant, inhabited lowland streams, overflow ponds, marshes, and lakes and is today extinct, reportedly due to land reclamation and introduced species (Miller 1963, Schulz and Simons 1973).

The abundance and diversity of game animals and birds in the Delta have been well described and documented in numerous early accounts of the region. These narratives leave little doubt that in this sense, the Delta was probably the richest ecosystem of the watershed. An early Fish and Game Commission biennial report states: "*That portion of the Sacramento and San Joaquin Delta before the era of reclamation was a veritable paradise for wild fowl, and to a great extent still furnishes a food supply for a large number of ducks, geese, swan, sandhill cranes, and other waterfowl*" (Skinner 1962, p. 139). Grizzly bears, tule elk, deer, tundra swan, ducks and geese of several types, along with a wider assortment of other waterfowl were also plentiful here, and these populations supplied bargeloads of fresh meat for San Francisco markets of the last half of the 19th century (Cohen 1991). The Delta also supported large numbers of river otter, bobcat, raccoon, mink, and skunk, as well as turtles and golden beavers (Grinnell et al. 1937, Maloney 1945). Other animals, including coyotes, badgers, skunks, ground squirrels, gophers, cottontails, and jack rabbits were reportedly observed in the tules, although these were undoubtedly more common along the drier peripheries of the Delta (Thompson 1957). Hunters of Delta animals attested to the abundance of mosquitoes throughout the wetlands (Skinner 1962).

There is no historical information available on the phytoplankton composition of the Delta. Today, these assemblages are dominated by diatoms. In the historical Delta, as today, surface plants such as duckweed often formed dense mats in areas of minimal water movement, thereby limiting the abundance and distribution of benthic macrophytes by shading.

V.B. Ecosystem Function: Supporting and Integrating Processes

V.B.1. Hydrogeomorphic Processes

The area generally referred to as "the Delta" actually represents the merging of *two* distinct river deltas which, like the rivers that formed them (Sacramento and San Joaquin), had somewhat distinctive characteristics. The Sacramento River was characterized by comparatively high flows and sediment loads. During large floods, silts and sands were deposited adjacent to the river channels forming high and wide natural levees that tended to somewhat isolate the river from the low-lying wetlands beyond. In contrast, San Joaquin River flood flows were smaller, carrying and depositing less sediment. As a result, natural levees in the south-central Delta were lower and narrower, and high water was distributed over a flatter topography. This led to many of the systematic differences in the extent and character of the wetlands in the northern versus south-central Delta described above. The soils of the Delta were formed from a combination of peat and inorganic sediments. Throughout the south-central Delta, the main natural accretionary mechanism has been peat formation. Here, peat soils up to 40 feet thick overlay layers of marine sedimentary muds, sands, shales, and rock. Soils are typically at least 90% peat by wet volume (Atwater et al. 1979, Atwater and Belknap 1980). In the northern Delta, the layer of primarily peat soils is considerably thinner, and the inorganic fraction also typically higher.

Most of the inorganic sediment delivered to the estuary as a whole was in the form of suspended alluvial deposits provided by the Sacramento River. A portion of the bed load was funneled into the northern Delta channels through distributary channels, while some of the suspended load was captured in the backswamps of the northern Delta when levees overtopped (Gilbert 1917). Lower volumes of inorganic alluvial sediments were delivered to the estuary from San Joaquin River discharge. The amount of this captured by intertidal wetlands of the southern and central Delta appears to have been minimal. Most appears to have been resuspended by wind-driven turbulence, and eventually passed through the Delta and to the lower estuary before settling out (Atwater, personal communication). Through equilibrial mechanisms not well understood, the plane of the swamps and marshes was maintained at a level closely approximating mean high tide (Atwater 1980a). This is a generally "typical" condition for such environments, and presumably represents the net results of processes that equilibrate deposition, erosion and subsidence in tidal marshes (Pestrong 1972).

Two of the most ecologically influential factors in estuarine environments - water movement and salinity gradient - are primarily determined by the complex interactions of tides, topography, and freshwater discharge from the riverine system. Under normal outflow conditions, tides exert a strong influence on water movement in the Delta. Tides affect two aspects of water movement - changes in surface level and changes in direction and volume of flow. Two high and low tides of unequal magnitude (mixed semi-diurnal) exchange water between the Delta and the Bay each day. At the Delta-Suisun Bay junction, typical summer tidal flows are on the order of 330,000 cfs. As rivers discharge into the zone of tidal influence, high flows (i.e., > 60,000 cfs) may negate changes in water surface level that would otherwise follow the change in tides, while under low outflow conditions, unidirectional flow in the large river channels may cease, becoming bi-directional in response to the tides. When high freshwater outflows block salinity incursion at Carquinez Strait and Suisun Bay, the Delta becomes further isolated from the saline conditions that typify the lower part of the estuary.

a. Delta Outflow. Although Delta outflow under natural conditions is of great interest, it is not accurately estimated given the available data. Hall's estimated flows for the Sacramento River at Collinsville for the period 1879 to 1885 ranged from 18 to 32 MAF and are probably the earliest attempt at estimating a major portion of Delta outflow (Hall 1886a). Recent estimates of Delta outflow under "natural" conditions have been derived from water balances. Estimated natural plant transpiration losses are subtracted from unimpaired runoff and precipitation estimates for the 20th century, the only period for which measured stream flows are available. This "water budget" approach estimates what the mean annual Delta outflow would have been during the 20th century in the absence of human interference in system hydrology - a value assumed to be roughly equivalent to what the natural outflow was around 1850. Using this method, Vorster (1998, in preparation) calculated an estimated mean annual outflow for this report of about 23 MAF, Fox (1987, revised by personal communication) of 12 to 25 MAF, and Williamson et al. (1989) of about 24 MAF. The variation in these different estimates is primarily attributable to values assigned to estimated areal extent of different vegetation types and their transpiration rates.

Using an unrelated approach, Ingram et al. (1996) converted paleosalinity estimates at sites in San Francisco Bay into estimated "paleo-discharge" values for the Delta. The results of that analysis are somewhat incongruous with those of the water balance approach. Analyses of cores from San Pablo Bay translate into an estimated mean annual Delta outflow value of 1250 m^3/s, or about 32 MAF, for the past 700 years. That value is higher than the water budget estimates cited above, particularly in light of the fact that the 20th century runoff period on which the water budget estimates are based is one of the wetter periods of the last 700 years (Stine 1994, 1996), but are more consistent with Hall's estimates. All of these estimates, however, are fraught with uncertainties.

b. *Salinity*. The Delta received its freshwater supply from the Sacramento, Mokelumne, Calaveras, Cosumnes and San Joaquin Rivers, whose major channels ramified into a network of distributary slough channels that fed and drained the wetlands and their marshplains. Salinity within this complex network of tidally-influenced channels and wetlands naturally varied with the tides and river discharge, the latter of which displayed substantial seasonal and inter-annual variability.

No records were found of actual salinity measurements made prior to about 1920, when the Delta had already been significantly altered (Chapter 3). Therefore, characterization of "natural" patterns of salinity distribution in the Delta are confined here to anecdotal evidence and modern reconstructions. It appears that under natural conditions, two distinct periods of peak outflow (winter rainfall and spring snowmelt) maintained essentially freshwater conditions throughout the Delta during most of the year. Nonetheless, during the warm, drier late summer and fall, greatly reduced riverine discharge allowed brackish water from San Pablo Bay (part of San Francisco Bay) to move upstream, causing upper Suisun Bay and the western Delta (Chipps Island through Sherman Island) to become seasonally brackish (about 2 ppt). This conclusion is generally supported by modern studies, some of the historical accounts, and early investigations.

Based upon examinations of soils and surface geology (along with consideration of historical accounts) Atwater and Belknap (1980) concluded that, "*Yearly minimum flows, occurring during late summer and early autumn, historically allowed slightly brackish water (about 2 ppt total dissolved solids) to spread into the western Delta*" although "*mean annual salinity has rarely exceeded 1 ppt, even in the western part of the Delta.*" Wells and Goman (1995), who examined cores from tidal marshes in this region, concluded (p. 195) that at Brown's Island (located between Chipps and Sherman islands) a little over 2,000 years ago, *"brackish conditions returned that continue to the present day.*" Under conditions of prolonged drought "*salinity (in the estuary) increases in a sawtooth manner, peaking a little higher each subsequent drought year*" (Wells and Goman 1995; p. 187), and so there is good reason to suspect that brackish water could have extended *"throughout the Delta during extreme drought*" (Atwater and Belknap 1980, p. 93). Wells and Goman (1995) also noted that *"extreme drought and salinity intrusion occurred even during periods when the mean freshwater discharge from the Sacramento/San Joaquin drainage basin was higher than modern values.*"

The salinity eyewitness accounts are difficult to interpret because they are few in number, the location of the observer is usually not known with precision, the characterization of the salinity regime is qualitative, and the hydrodynamic conditions (tides, flows) are unknown. With this caveat in mind, the accounts prior to 1850 provide somewhat different pictures of the salinity conditions of the western Delta in the late summer and fall. Canizares notes sweet water in August , 1775 and September 1776 near the confluence of the Sacramento and San Joaquin Rivers (Britton 1987a). Abella also refers to sweet water in the same area in October, 1811 (Britton 1987a). In 1796, Hermenegildo Sal (in Cook 1960) noted when the tide rises salt water was "*far upstream*" ("*muy adentro*"), but the season and location are not specified. Belcher in October 1837 and Wilkes in August 1841 are interpreted by Fox (Britton 1987a) to suggest salinity intrusion possibly as far upriver as Rio Vista (Belcher 1837 in Pierce and Winslow 1979, Wilkes 1845). After settlement of the region, it is reported that as early as the 1860s and 1870s Antioch residents required "*cisterns which they filled with fresh clear water immediately after the freshets in June, so that they would have fresh water for use in the late summer and fall months when the water supply became brackish and unfit for drinking, washing, and occasionally even garden irrigation*" (CDPW 1931c). A resident of Twitchell Island in the 1870s reported the need in dry years to go upriver to the mouth of the Mokelumne River to obtain fresh water (Grunsky 1924).

V.B.2. Disturbance and Succession

Undoubtedly, two key aspects of the maintenance of the high biodiversity that characterized the Delta ecosystem as a whole were the high level of disturbance caused by floods, and the pronounced seasonal and annual variability of fresh water supplied by river outflows. As with the riparian forests discussed elsewhere, periodic flooding not only sustained the levees as elevated landforms, but also created opportunities for successional processes to occur among riparian plant associations, thereby promoting increased biodiversity and structural complexity in this habitat type. Animal assemblages of the elevated landforms must have been catastrophically destroyed during large floods, which turned the levees into giant spillways. Similar effects would be expected to occur in the backswamp as well, with emergent vegetation destroyed and local topography rearranged as 10 feet of water or more drowned the landscape. Adding to this catastrophic form of periodic disturbance were the somewhat predictable seasonal variability and more unpredictable inter-annual variability in river outflow, which created variable and unpredictable water level and salinity conditions at any given geographic location within the Delta. To maintain viable and persistent populations within the Delta, native species either had to be highly tolerant of such variability, be capable of rather quickly relocating to a more "favorable" part of the Delta, or be capable of quickly reestablishing ravaged populations. Thus, the natural Delta might be characterized as a high-disturbance environment with considerable spatial variability in terms of biological assemblages and associations. This provided a diversity of ecological opportunities (microhabitats, food resources, etc.) that were exploited by a wide variety of plants and animals native to the region. Most of these were not obligate residents inherently dependent upon the estuarine conditions found in the Delta, but rather were facultative opportunists that also maintained populations in other ecosystems of the watershed.

V.B.3. Community Energetics: The Acquisition and Cycling of Organic Carbon and Nutrients

a. Sources. There were three major sources of organic carbon and nutrients to the historical Delta. The majority by far of the Delta's energy and nutrients was derived from autochthonous sources, namely: (1) primary production by emergent vascular plants - marshes and riparian forests and (2) primary production beneath the water surface, both by phytoplankton and macroscopic benthic plants. Organic matter entering the Delta from other ecosystems, including living organisms, detritus and dissolved material (allochthanous sources) probably represented a relatively minor contribution because it would have been consumed near its point of production. Peak allochthanous contributions occurred during flood events, times of upstream riverine plankton "blooms," and mass migrations of fish, mammal and bird populations.

Intertidal wetlands and riparian forests are characterized by unusually high production rates that at times rival those of tropical rainforests. In the natural Delta, vast quantities of organic material were produced by the bordering strips of riparian forest and large expanses of emergent wetland vegetation. This primarily fueled subtidal and intertidal assemblages, entering the aquatic food chain through both grazing and detrital links. A rough estimate developed here suggests that an annual production of nearly 915 million lbs (dry weight) of organic carbon was realized by the Delta's tidal wetlands alone (Table II-A). This level of production appears to exceed the estimated historical annual total organic contribution made to the entire Central Valley watershed (all tributaries) by returning salmon runs. However, the amount of bioavailable carbon from wetland production is debatable. Further, contributions from upstream sources (e.g., salmon carcasses, wetland product) to Delta productivity may have been small because this carbon would have been consumed near its point of production.

Table II-A
Annual In-Delta Organic Carbon Contribution to Watershed

Delta Intertidal Wetlands (circa 1850) - Net Above-Ground Primary Production:

1300 km^2 [(A)] x 800 $g / m^2 / yr$ [(B)] x 10^6 m^2 / km^2= 10.4 x 10^{11} g x 0.40 [(C)] (Carbon Content)

= 4.16 x 10^{11} g of Carbon, or **915 million lbs Organic Carbon/yr**

Sources:

(A) Atwater and Belknap 1980 (estimated area of Delta tidal marshes circa 1850)

(B) Atwater et al. 1979 (estimated average net above-ground production)

(C) Keefe 1972 (estimated carbon content of dry organic matter for wetland vegetation)

Although undoubtedly crucial to the survival of some species, the relative trophic contribution of primary production by phytoplankton and subtidal benthic plants must remain largely speculative due to a lack of quantitative historical information. The applicability of current theoretical or empirical information on primary production to historical conditions in the Delta must be considered extremely limited, due to the massive changes in numerous aspects of habitat distribution and community structure and function (including community energetics) that have occurred in the last 150 years.

b. Cycling and Exchange. Much of the primary production of the Delta's marshes and riparian forests, along with their attached assemblages of algae and the dead bodies of countless, birds, insects, mammals and other animals, entered Delta waters in the form of dead and decaying plant and animal material. Some of this rich source of nutrients was consumed in the water column by fishes and other organisms, but the bulk settled to the bottom, where it served as the trophic base for a rich assortment of benthic scavengers, detrital feeders, and decomposers (Cohen 1991), which in turn became prey to fishes, birds, and mammals. The role of microzooplankton (including bacteria) may have also been substantial in these lower levels of Delta food chains, but the historical magnitude and role of this contribution remains somewhat speculative. Zooplankton, which feed on phytoplankton, form a major food source for fishes and larger filter-feeding invertebrates. Zooplankton species were historically composed of four main groups: ciliate protozoans, rotifers, copepods, and cladocerans (Allen 1920 *in* Herbold and Moyle 1989). These generally show abundance patterns that parallel those of the phytoplankton. Many species of waterfowl, such as diving ducks, grebes, mallards, and wood ducks feed on small fishes, benthic invertebrates, zooplankton and submerged plants. The diversity of mammals common to the Delta was described above (Section V.A.5), and represents feeders that occupy a wide range of trophic levels. Some (e.g., beaver) are herbivores. Other are omnivores (raccoons, opossums, and striped skunks). Still others are carnivores (e.g., mink and river otters).

c. Sinks. Part of the primary and secondary production of the Delta is exported to the lower estuary by water movement. Some of the organic matter reaching benthic areas of the Delta is also exported downstream through sediment erosion and transport, or is lost through burial (Nichols and Pamatmat 1988, Cohen 1991). An additional fraction is lost to the ecosystem through the activities of the many large mammals that visit the area to feed, and then move to other ecosystems where energy and nutrients are redeposited through death and excretion.

VI. Greater San Francisco Bay

Greater San Francisco Bay, as defined herein, is that part of the estuary lying between Chipps Island and the Golden Gate. This includes four major embayments - Suisun Bay, San Pablo Bay, Central Bay and South Bay (Figure G12).

VI.A. Ecosystem Structure: Habitat Types and Biological Assemblages

The general structure of San Francisco Bay is that of a series of embayments, each containing a central expanse of open water overlying subtidal sediments and ringed by intertidal wetlands, mudflats, and / or rocky shores. These different kinds of areas constitute the major distinctive habitat types of the ecosystem. Hydrographically, the

Bay may be divided into two broad subdivisions with differing ecological characteristics: a *southern reach* consisting of South Bay, and a *northern reach* composed of Central, San Pablo, and Suisun Bays. The southern reach receives little freshwater discharge, leading to high salinity and poor circulation (high residence time). It also has more extreme tides. The northern reach, which directly receives Delta outflow, is characterized by less extreme tides and a pronounced horizontal salinity gradient, ranging from near full marine conditions in Central Bay to near fresh water conditions in Suisun Bay. Central and Suisun Bays contain large islands, features not present in San Pablo and South Bays.

The distribution and extent of the historical aquatic habitats of the greater San Francisco Bay are shown in Figure G12, which is based upon mapping by the San Francisco Estuary Institute for the Bay Area EcoAtlas, Version 1.50 (SFEI 1998). Habitat acreages in the following subsections are derived from the Geographic Information Systems (GIS) coverages in the EcoAtlas.

VI.A.1. Open Water (Pelagic) Habitat

This includes the entire volume of the water column contained in the four embayments and major tidal channels.

a. Distribution and Extent. It is estimated that the natural Bay and major tidal channels comprised about 274,000 acres (428 mi^2), of which 100,000 acres (156 mi^2) was deep water and 174,000 acres (273 mi^2) shallow (Figure G12). Suisun, San Pablo, and South Bays have an average depth of 10 to 13 ft (3 to 4 m), but are incised by deep, narrow channels (typically 30 to 65 ft deep) maintained by river and tidal scouring (Nichols and Pamatmat 1988, Conomos et al. 1985). Central Bay, located near the City of San Francisco, is a comparatively deep basin immediately adjacent to the ocean, with an average depth of about 36 ft (11 m), about three times that of the other embayments. Because of its greater depth, Central Bay also contains the largest water volume, even though its surface area is less than half that of South Bay.

b. Composition and Complexity Each of the four embayments that constitute San Francisco Bay historically consisted largely of the same basic habitat elements - a central expanse of open water bordered by intertidal mudflats and marshes. However, each also represents a structural subdivision with somewhat different ecological properties from the others in terms of such factors as depth and salinity characteristics, tide levels, mixing processes, distribution and extent of habitats, etc. The deepest area of the entire estuary is the heavily-scoured channel that traverses the Golden Gate. Depths here exceed 330 ft.

The water column in the Bay's northern reach is naturally characterized by complex salinity and density characteristics. The fresh waters discharged into the estuary from the watershed's major rivers are lighter (less dense) than ocean water carried in on the tides. At the interface where the two water masses meet (called the *mixing zone*) they do not readily or completely mix. Rather, the fresh water tends to form a surface layer that overrides the heavier sea water, resulting in a vertical salinity gradient that is more pronounced at times of greater river discharge. The location of the mixing zone is determined by the relative magnitude of river discharge and tidal influence. Thus, it moves back and forth twice a day a distance of about 2 to 6 miles with the advance and retreat of the semi-diurnal tide. Except during extreme high or low river discharge periods, the mixing zone is typically located in Suisun Bay, a shallow area characterized in its natural state by numerous islands and extensive wetlands along its northern shore.

On the other side of Carquinez Straits, San Pablo Bay forms an expanse of shallow open water with extensive mudflats and marshes extending along its northern borders. Due to its depth, structural characteristics, and proximity to the ocean, Central Bay maintains the most marine-like conditions of the four embayments and is largely inhabited by marine species. Historically, Central Bay was bordered by mudflats and marshes along its southeastern and western boundaries. It is the only one of the four embayments to contain substantial reef-like outcroppings of bedrock below the surface. These areas support colonies of seaweeds and intertidal invertebrates common to such habitats of the Central California coast (Ricketts and Calvin 1956).

The southern reach (South Bay) receives far less fresh water runoff, and thus, except under conditions of unusually high river discharge, does not generally exhibit the type of estuarine circulation described above for the northern reach. Salinity here is characteristically high, often close to that of the nearshore ocean, and seldom displays vertical gradients. South Bay is also characterized by a much higher residence time of water, and on average is flushed at about one-fourth the rate of the northern reach. Most of this exchange is naturally concentrated during the "wet" season of high river discharges.

c. Associated Biological Assemblages. Pelagic components of the Bay's open water biota include phytoplankton, zooplankton, fishes, birds, and marine mammals. There is little available information on the composition of the Bay's plankton prior to the development of large human populations along the Bay's margins during the 19th century. Phytoplankton blooms in the Bay, as in the coastal ocean of central California, are presently dominated by diatoms, the most common of which are *Thallassiosira spp.*, *Cyclotella spp.* and *Skeltonema costatum*. Dominant native Bay zooplankters today primarily include rotifers and crustaceans. Among the rotifers, members of the genus

Synchaeta are most common at the salinities generally found seaward of the mixing zone (Herbold et al. 1992). Among the most abundant native zooplanktonic crustaceans of the Bay are several copepods, which display a marked degree of segregation by salinity. *Acartia spp*. and *Oithona davisae* are found mainly at the higher salinities west of the Carquinez Straits, while *Eurytemora affinis* is most common in Suisun Bay, as is another crustacean, the opossum shrimp (*Neomysis mercedis*). Larvae of the ghost shrimp *(Callianassa californiensis)* are common in the Central Bay, and are occasionally joined there by sizeable numbers of oceanic krill (*Euphausid spp.*). These distribution / abundance patterns, determined over recent years, appear to correspond closely to intrinsic salinity and water movement features of the Bay, a relationship that was also probably valid historically.

The Bay was historically occupied by a diversity of marine, estuarine, and freshwater fishes. Native freshwater species of the estuary have been described above (Section V.A.5). Marine species are concentrated in the Central Bay, which maintains a marine-like environment in terms of temperature / salinity characteristics at most times. Fishes of the Bay may be divided into residents (maintaining a presence throughout the year), and visitors (present only during certain parts of the year) (Herbold et al. 1992). Many of the most abundant Bay fishes belong to the latter category, including northern anchovy (*Engraulis mordax*) and Pacific herring (*Clupea harengeus*). Native anadromous fishes that regularly pass through the estuary include chinook salmon, steelhead trout, and sturgeon (two species). Quantitative scientific information on natural Bay fish assemblages is not available, but the Bay historically supported extensive fisheries for many of the native species found today, including salmon, sturgeon, Pacific herring, northern anchovy, starry flounder, surfperches, and elasmobranchs (sharks and rays) (Skinner 1962).

A number of widely distributed birds frequently utilize open water habitat, and by all accounts these were present in large numbers at the time of the Gold Rush (Skinner 1962). These include birds that initiate their foraging dives from the water's surface (such as diving ducks, loons, grebes, and cormorants), and those that begin their dives while still in flight (such as gulls and terns). All of these birds remain common today throughout much of the nearshore ocean system (described below). The Bay also supported healthy populations of marine mammals, including sea otters which typically occurred at the numerous creek and river mouths in Napa, Sonoma, San Mateo, Santa Clara, and Alameda counties (Ogden 1941, Bonnot 1928), and harbor seals which rested along the shores and mudflats but fed in the Bay's open waters. Porpoises were also once common (Skinner 1962).

VI.A.2. Subtidal Benthic

This habitat type consists of those substrates remaining submerged during the lowest of tides.

a. Distribution and Extent. The distribution and extent of this habitat type corresponds with that of open water, described above (Section VI.A.1.a). It is estimated that about 274,000 (428 mi^2) acres of subtidal benthic areas were present in the four embayments combined circa 1850 (SFEI 1998, Figure G12).

b. Composition and Complexity. The vast majority of the subtidal substrate of the Bay consists of fine silts and clays commonly called "bay mud" (Cohen 1991). The monotony of this feature is broken only by the sand floors of deep channels, broken shell substrates found in some parts of the South Bay, and a few rock outcroppings in Central Bay. Save for limited stands of eelgrass *(Zostera marina)* currently found in Central, San Pablo, and South Bays, subtidal bay mud is unvegetated by macroscopic plants.

c. Associated Biological Assemblages. The native benthic biota of the Bay was unquestionably quite different at the time of the Gold Rush. Today, it is largely composed of non-native species. The first systematic survey of benthic invertebrates of the Bay was carried out by the *Albatross* survey in 1912-13, by which time the Bay had been substantially altered by the growing human populations along its margins. The native species composition of Bay benthic animal assemblages has been partially reconstructed from shell middens (e.g., Nelson 1910, Gifford 1916, and others), but only a fraction of the species comprising these assemblages possess lasting shells or bones, or were collected and used by Native Americans. Thus, while the results of shell midden analyses are useful in confirming the presence, and even a general abundance of certain species at a particular location or time, such analyses are of highly limited value in assessing the native biodiversity or structure of native biological assemblages.

Historical accounts document that the native Pacific oyster (*Ostrea lurida*) was once present in the Bay in prodigious quantities. Townsend (1893 *in* Skinner 1962, p. 95) notes that "*[t]here are extensive deposits of this species in the shallow water all along the western part of the Bay*," their dead shells washed ashore by seasonal high winds, forming "*a white glistening beach that extends from San Mateo for a dozen or more miles southward. So abundant are they that this constantly increasing deposit of shells covers everything along shore and forms bars extending into the Bay*." Other native mollusks that were still abundant throughout much of the Bay in 1912 included the bent-nose clam *Macoma nasuta* and the bay mussel *Mytilus edulis* (Skinner 1962, Packard 1918). All three of these mollusks were common in Native American shell mounds found around the

Bay (Gifford 1916, Nelson 1910, Uhle 1907). Harvested native benthic crustaceans included the Dungeness crab, *Cancer magister*, three epibenthic shrimp, *Crangon spp.*, and the sooty crayfish *Pacifastichus nigriscens* (Skinner 1962).

As is true today, benthic microscopic plants and blue-green algae probably occupied the upper centimeter of the Bay's mud bottom. This is a persistent and characteristic feature of benthic habitats of this type in most estuaries. As is also usual in estuaries, the subtidal muds of the Bay were (and remain) occupied by a wide diversity of smaller invertebrates, including both filter feeders and detrital feeders. However, much of this faunal component now consists of relatively recently introduced non-native species, and relatively little scientific information is available on the composition and densities of the smaller benthic infauna and epifauna of the Bay in its natural state.

A number of native fishes of the Bay are classified as either benthic or demersal and are most properly considered residents of this habitat type. These include shiner perch (*Cymatogaster aggregata*), the bay goby (*Lepidogobius lepidus*), and staghorn sculpin (*Leptocottus armatus*).

VI.A.3. Intertidal Mudflats

a. Distribution and Extent. Intertidal mudflats generally form between the subtidal portions of the Bay (described above) and the more shoreward elevated intertidal marshes. About 44,000 acres (68 mi^2) of mudflats bordered the Bay and another 6,700 acres (10.4 mi^2) line natural channels (SFEI 1998, Figure G12).

b. Composition and Complexity. In general, mudflats exhibit little vertical relief and are devoid of macroscopic plants. These areas are today (and were very likely in the historical past) composed of the same fine sediments that constitute "bay mud" of subtidal areas. However, the historical composition of the sediments that formed the mudflats is not known, and because of the many alterations in sediment delivery to the estuary due to human interventions over the last 150 years (see Chapter 4), it may well have differed from the general composition today. Composition today varies from clay/silt (80%) to sand, and includes organic debris and shell fragments (SFEP 1992, Nichols and Pamatmat 1988).

c. Associated Biological Assemblages. Mudflat vegetation is naturally dominated by microalgae (also called *microphytobenthos*), which consists of a mixture of diatoms, blue-green algae, and flagellates adapted to prolonged exposure to the full sunlight experienced in intertidal habitats (Herbold et al. 1992). The subtidal (described above) and intertidal assemblages of mud substrates of San Francisco Bay today show a considerable degree of similarity. Both are inhabited by a diversity of small deposit feeders - amphipods, isopods, snails, worms and crabs along with an assortment of native filter-feeding mollusks, including large numbers of the Baltic clam (*Macoma balthica*) (Cohen 1991). Thus, it is reasonable to suspect that much of the characterization of the Bay's historical benthic faunal assemblages (provided above: Section III.A.1.c) also may generally apply to this habitat. However, notable differences between subtidal and intertidal benthic assemblages would be expected depending upon local topography and relative exposure during low tides. These differences would be most likely in the form of correspondingly greater or lesser relative abundances and representation of species adapted to the rigors of intertidal conditions.

At high tides, a number of benthic feeding fishes, including flatfishes, gobies, rays, and sharks, are known to feed on mudflat invertebrates, but this source of predation is relatively minor compared to that of the shorebird populations that frequent Bay habitats (Cohen 1991). With probing beaks of differing lengths, a variety of species - including avocets, plovers, sandpipers, dowitchers, willets, and curlews - regularly exploit these rich food resources. At low tides, mudflats also served as haulouts for harbor seals (SFEP 1992).

VI.A.4. Intertidal ("Tidal") Marshes

San Francisco Bay contains tidal marshes existing within a range of salinities from essentially fresh water to nearly fully marine, and the biological communities inhabiting these areas vary in response. Communities change gradually rather than abruptly, and so none may be considered "typical" of the Bay (Josselyn 1983). Thus, we consider all under the general habitat type of "tidal marshes."

a. Distribution and Extent. Historically (150 years ago), San Francisco Bay was bordered by approximately 192,000 acres (300 mi^2) of tidal marshes (SFEI 1998). This habitat type was concentrated mainly in three main areas: the southern half of South Bay and the northern portions of San Pablo and Suisun Bays (Figure G12).

b. Composition and Complexity. With the exception of a relatively few introduced species, most of the major marsh plants remaining today appear to be native to this region. There is no reason to believe that most of the fundamental historical within-habitat structural characteristics of this habitat type differed substantially from those found in the relatively few pristine remnant patches of today's Bay, or in similar habitats at other locations along the California coast. The natural habitat structural features of the Bay's tidal marshes, along with their native dominant plant and animal assemblages, are described in some detail by Josselyn (1983), Atwater (1980), and Atwater et al. (1979), and therefore are only briefly summarized below.

The Bay's marshes are generally characterized by sparse and dense stands of emergent vegetation - including grasses, sedges, rushes, and succulents - varying in height from prostrate to about 6 feet (Jones and Stokes 1981). The marshplains are drained by an extensive dendritic network of tidal slough channels and a variety of microhabitats - sloughs, channels, pools, unvegetated sediments - provide additional structural complexity to the marsh. As with most intertidal habitats, the marshes exhibit a characteristic pattern of vertical zonation, with low, middle and high "zones" occupied by somewhat distinctive plant and animal assemblages. The Bay's marshes also exhibit a horizontal gradational pattern tied to average salinity conditions in each of the embayments. The marsh plant associations, such as *Scirpus actus*, adapted to the essentially fresh water or brackish water conditions usual in Suisun Bay gradually transition to associations adapted to ever higher salinities found progressively westward towards San Pablo, Central, and South Bays (Atwater 1980). Species diversity generally decreases from the Delta to the Bay, due to harsher salinity conditions.

c. Associated Biological Assemblages. By all accounts, the marshes that ringed San Francisco Bay supported unusually rich and diverse assemblages of invertebrates, fishes, birds, and mammals (Skinner 1962). There is little information available on the natural invertebrate assemblages of the Bay's tidal marshes as they existed at the time of the Gold Rush. Nonetheless, historical accounts of rich harvests of fish, birds and mammals that heavily depended upon these food resources amply attest to the historical richness of native benthic invertebrates of the Bay's tidal marshes. Josselyn (1983) divides the invertebrate fauna of tidal marshes into three major groups: benthic infauna, epifauna, and terrestrial arthropods (insects and spiders). Most investigations of benthic infauna in these environments have been conducted in the more readily accessible nearby mudflats and tidal creeks rather than in the marshes themselves, so descriptions of marshplain infaunal invertebrates tend to be more inferential than direct. Epifaunal invertebrates of tidal marshes tend to be omnivores (Montague et al. 1981), with crustaceans (crabs and amphipods) and gastropods most common. The native hornsnail *Cerithida californica* was once widely distributed through Bay marsh habitat (Race 1981, 1982). Insects and spiders, including mosquitoes, flies, gnats and midges, are common components of most tidal marsh systems (Lane 1969, Balling and Resh 1982) and were probably abundant here historically as well.

The shallow, complex and biologically productive habitat structure of marshes is well-suited to the needs of small fishes, and such habitats are commonly occupied by a diversity of species that either mature at small size, or occupy the habitat as juveniles. Native fish assemblages dwelling in today's Bay tidal marshes display considerable variability with location and salinity, a pattern that is inherently tied to the needs and adaptations of these species, and therefore also likely reflects historical distribution trends. In the saline waters of South Bay, Woods (1981) documented a primarily marine assemblage dominated by the planktivorous topsmelt (*Atherinops affinis*) and two bottom dwellers: the arrow goby (*Clevlandia ios*) and staghorn sculpin (*Leptocottus armatus*). Most of the individuals collected were juveniles. In Suisun Marsh, which is characterized by low salinities, Moyle and Daniels (1982) documented an estuarine/fresh water assemblage that included 21 native species dominated by splittail, three-spined sticklebacks, tule perch, and longfin smelt.

Tidal marshes fulfill part of the habitat requirements of a wide variety of birds. Simpkinson (1837 in Skinner 1962) noted that "*in the neighborhood of the Presidio near the sea are some extensive marshes which abound with wild fowl of all descriptions. Duck, teal, curlew, and snipe are very plentiful and often afforded us a good day's sport. The geese appear to prefer the extensive plains near the Mission where they remain feeding all day and in the evening return to their roosting places in the marshes. The numbers that one sees on these plains are really quite wonderful. When they rose they would make such a tremendous clacking as to be quite terrific.*" The vast marshlands on the east and south shores of San Francisco Bay and on the north shores of San Pablo and Suisun Bays were the most heavily used. "*From early accounts, the vicinity of Alvarado appears to have been the most fabulous, followed closely by the Suisun and Napa marshes*" (Skinner 1962).

The Bay's tidal marshes once provided winter habitat to millions of birds on their migration along the Pacific flyway. An estimated 60% of the canvasbacks (*Aythya valisineria*) and over 20% of the greater and lesser scaups (*Aythya sp.*) and surf scooters *(Melanitta perspicillata)* in the Pacific flyway utilized the Bay wetlands (CDFG 1978 in Josselyn 1983). Tundra swans were considered regular winter visitors in Suisun Marsh and in Sonoma, San Francisco and San Mateo counties (Grinnell et al. 1918 in Harvey et al. 1992). Canada geese were common winter visitors to the tidal marshes of San Pablo Bay, San Francisco and San Mateo counties (Grinnell and Wythe 1927 in Harvey et al. 1992). The California clapper rail (*Rallus longirostris*) at one time was "*exceedingly abundant, a highly prized game bird and was one of the more common species in the San Francisco markets*." (Skinner 1962). Today, the heaviest use of the Bay by shorebirds is during their spring and fall migrations, while ducks and other water-associated birds are primarily winter visitors. Recent studies indicate that the numerically most abundant group using intertidal wetlands are shorebirds, followed by ducks (Bollman et al. 1970). The bird populations of the Bay fluctuate widely with season. Most of the birds utilizing Bay tidal marshes are migratory species that breed elsewhere.

Josselyn (1983) described the historical use of Bay tidal marshes by mammals. Roosevelt elk (*Cervus canadensis roosevelti*) and tule elk (*C.c. nannodes*) were frequently observed, as were black-tailed deer (*Odocoileus hemionus columbianus*), grizzly bear (*Ursus californicus*), mountain lion (*Felis concolor californica*), mink (*Mustela vison*) and river otter (*Lutra canadensis brevipilosus*). Bryant (1915) reported that "*[t]here are said to have been weeks in 1812 in which the Russians established at Bodega killed seven or eight hundred otters in the bay of San Francisco alone.*" Other marine mammals, such as the harbor seal (*Phoca vitulina*) which utilized tidal wetlands as haul-out areas, were equally sought after. A variety of small mammals also are found in the Bay's tidal marshes.

VI.A.5. Rocky Intertidal

This habitat includes all consolidated sediments occurring between the high and low tides of the year.

a. Distribution and Extent Rocky shore naturally exists in San Francisco Bay mainly along the edges of Yerba Buena, Angel and Alcatraz Islands, along the shoreline of the Tiburon Peninsula, and along margins of the Golden Gate, a pattern likely to have changed little over the last 150 years.

b. Composition and Complexity. The general structural characteristics (and native biological assemblages) of this habitat type along the central California coast have been thoroughly described by Ricketts and Calvin (1956) and many others, and are therefore only briefly summarized here. Rocky shores exposed to waves and tides typically take on a complex topography, with numerous microhabitats - surface irregularities, cracks, crevices, etc. -that also vary in terms of suitability for organisms with wave and sunlight exposure, tidal submergence, and other factors. As shorelines erode, new substrates are created, and older substrates gradually wear away.

c. Associated Biological Assemblages. Rocky intertidal areas throughout this region of Central California are naturally home to particularly diverse and characteristic assemblages of macroscopic algae (seaweeds) and specialized invertebrates. These show pronounced characteristic vertical zonation patterns related to the tides. Green, brown, and red algae are all common, as are barnacles, crabs, isopods, amphipods, mussels, and a wide variety of other invertebrates. These characteristics are still evident today. Of the 160 species of seaweeds recorded in the Bay by Josselyn and West (1985), the majority occurred in rocky intertidal areas. Several species of shorebirds, brown pelicans, cormorants, gulls, and harbor seals are known to frequent rocky shores to rest or hunt, and the food resources here are also typically exploited by a rich assortment of subtidal invertebrates and fishes (Ricketts and Calvin 1956, Jones and Stokes 1981).

VI.B. Ecosystem Function: Supporting and Integrating Processes

VI.B.1. Hydrogeomorphic Processes

Major habitat characteristics of the Bay, including the distribution and extent of intertidal wetlands and the composition and water column characteristics of subtidal areas, are largely determined by a combination of large-scale climatic and hydrogeomorphic processes. These most notably include those affecting (1) topography, (2) the interactions between tides and river inflow, and (3) more localized processes affecting water mixing, salinity distribution, and sediment deposition within the Bay.

The gently sloping topography necessary to sustain an extensive tidal marsh system was maintained because gradual submergence of the Bay's margins (through sea level rise) was offset by deposition of river-borne sediments. During the last 150 years, sea level has risen an estimated 0.4 m (2mm / yr). However, within the estuary most of the effects of this change have been offset by a comparable sedimentation rate, resulting in minimal net change in relative sea level. River inflow is the major source of inorganic sediment naturally delivered to the Bay each year from the rivers, 80% of which originates in the Sacramento-San Joaquin River drainage (Porterfield et al. 1961, Conomos et al. 1985).

The Bay's intertidal marshes represent a natural sediment sink, trapping and accumulating sediments and building the marshplain. Unlike the freshwater tule marshes of the Delta, these are built by the accumulation of predominantly inorganic sediments. Most of the total sediment input naturally occurs during winter, greatly increasing the turbidity of the water as well as sedimentation throughout the estuary (Nichols & Pamatmat 1988). In its natural state, sediment delivery to the estuary occurred mainly during large flood discharges on the Sacramento River. Some of these sediments were subsequently resuspended by wind action and redeposited on the tidal marshes and mudflats elsewhere in the Bay, offsetting the effects of erosive processes and maintaining the topography of these habitats.

Extensive intertidal mudflats evolved and persisted between the subtidal channels and the marshplains as a net result of estuarine sedimentation and the erosive power of wave and tidal action. Most of the wave energy in the San Francisco Bay is created by wind blowing up the estuary into the Central Valley. As sea level continued to rise, the marshplain edge retreated and wind fetches and wave energy gradually increased. This accelerated erosion prevented expansion of marsh vegetation, and promoted instead the formation of extensive, gently sloping mudflats bayward of the marsh.

Salinity characteristics and distribution, mixing and circulation in San Francisco Bay are affected by interactions between a number of factors, including Delta discharge, tides, winds, and the morphology of the subtidal channels and intertidal mudflats, and thus are inherently highly variable on a daily, seasonal and longer term basis. Such variability is rarely a serious threat to estuarine organisms, which are inherently tolerant of moderate salinity fluctuations, a normal aspect of estuarine life. Mobile species often respond by simply repositioning themselves to favorable salinities. For these species, changes in salinity distribution are more likely to affect distributional patterns than survival.

Recent studies (e.g., Ingram et al 1996) have concluded that for most of the estuary's history, it has been primarily changes in river discharge that have most strongly influenced its salinity gradient. The majority of annual river discharge into the Bay (90%) comes from the Delta. The other rivers and streams entering the bay are comparatively small (the two largest are Alameda Creek and the Napa River), and most of these are intermittent with little or no flow in the summer months (Conomos et al. 1985). Average annual salinity values in the Bay have fluctuated substantially over the long term in response to variations in watershed precipitation and Delta discharge, with clear periods of lower salinity related to long-term patterns of increased precipitation (Ingram et al. 1996). Estimates of historical outflow from the river system, which is closely related to Bay inflow, were provided above (Delta Outflow, Section V.B.1.a).

The Bay experiences semi-diurnal tides, with two low and two high tides of unequal magnitude each 24.84 hours. There is usually a large differences between successive high and low tides, and variable tide-height differences within each lunar month. The tidal range is greatest at the extremity of the South Bay, and decreases progressively farther upstream. Mean tidal level is highest in the northern reach. Strong seasonal winds also may exert a strong effect on water circulation and mixing, thereby affecting water column characteristics, including temperature, oxygen, nutrient and salinity variations. Prevailing west and northwest winds, reinforced by solar heating of air masses in inland California, are strongest during the summer. Water temperature at any particular location in the Bay is primarily determined by offshore ocean temperatures, ambient air temperature, and mixing processes. These factors all interact in a complex manner to actually determine water movement, mixing, and water column characteristics of the Bay at all spatial scales.

VI.B.2. Community Energetics: The Acquisition and Cycling of Organic Carbon and Nutrients

a. Sources. The ecosystem naturally acquires organic carbon and nutrients from three main sources: (1) primary production within the system by pelagic phytoplankton, benthic microalgae (diatoms and photosynthetic bacteria), seaweeds (macroalgae and seagrasses), and marsh vegetation, (2) passive downstream transport from the Delta of dissolved organic carbon and detritus (mainly tidal marsh export), and (3) biological transport by living animals and plants entering the Bay from other ecosystems (nearshore ocean, Delta, other terrestrial and aquatic systems) (Nichols and Pamatmat 1988, Jassby 1992). The relative contribution of within-ecosystem sources is a function of production rates and areal extent of each source. Marshes have the highest natural net production rates (gross production minus respiration losses), estimated at about 800 g carbon/m^2/year (Atwater et al. 1979, Josselyn 1983). Seagrasses also have inherently high rates of net production (about 300 g/m^2/yr), while benthic microalgae and phytoplankton have relatively lower rates (120-140 g/m^2/yr) (Jassby 1992). Seagrass production, although occurring at a high rate, has probably always represented a minor contribution due to the limited extent of this vegetation type in the Bay.

The major autochthanous sources of organic carbon to the Bay in its natural state were its fringing marshes, phytoplankton, and benthic microalgae, all of which were distributed over substantial areas (Jassby 1992). It is possible to roughly estimate the comparative contribution of each of these sources to the historical system (see Jassby 1992) by applying estimates of net production rates of each source to estimates of historical habitat extent. However, such an effort would inherently involve substantial uncertainty, particularly with regard to appropriate areal extent of benthic microalgal production in the natural system, as well as unknown changes in turbidity that may have occurred over the last 200 years. In any case, because of the very high production rates of marshes and their estimated historical extent of nearly 200,000 acres, marshes were likely to have been the single greatest source of new biomass produced within the natural Bay ecosystem.

The relative contribution of external sources of organic carbon and nutrients to the Bay ecosystem is difficult to quantify, but it is reasonable to assume that some 300,000+ acres of intertidal wetlands that comprised the natural Delta, along with the lowland rivers' and Delta's extensive non-tidal marshes and riparian vegetation would have resulted in substantial allochthanous organic inputs to the Bay ecosystem.

b. Food Chains, Cycling and Exchange. Food webs of the Bay are naturally complex, involving trophic dynamics of diverse and abundant grazing and detrital chains, substantial contributions of both internal and external (to the ecosystem) sources, and large seasonal shifts in biomass of some trophic levels caused by plankton blooms and movement and activities of large migratory populations of fishes, birds, and mammals. Intermediate consumers of phytoplankton production include mainly zooplankton and benthic filter feeders (mollusks, crustaceans, worms), while a variety of clams, snails and polychaetes graze on benthic microalgae. Intermediate links in the detrital chain consist of a wide variety of benthic invertebrates and zooplankton. These in turn form the food resources of the larger predatory invertebrates, fishes, and birds of the system. Living marsh plants are eaten by animals to some extent, but most of this biomass (up to 70%) passes into the food chain as detritus (McCormick and Somes 1982 in SFEP 1991). Biological transport almost certainly played a major role in local food web dynamics and seasonal nutrient and food availability for many native species, as the reported seasonal influxes of enormous numbers of migratory fishes or birds periodically dramatically altered the availability and nature of local food / nutrient resources.

c. Sinks. Organic matter is lost to the system through passive downstream transport to the ocean, burial, and biological transport to other ecosystems. Biological transport is believed to result in a net loss to the system today (Jassby 1992), and there is no evidence that this was not also the case historically.

VII. The Nearshore Ocean

At least some interactions (e.g., activities of anadromous fishes) between the oceanic environment and the San Francisco Bay-Delta watershed span very large geographic areas, and extend far out to sea. Even so, most substantive interactions involving the regular exchange of water, nutrients, and organisms are concentrated within a comparatively restricted area near the Golden Gate. For practical purposes, discussion of oceanic interactions is confined here to a limited “nearshore ocean ecosystem.” For practical purposes, this restricted portion of the coastal sea has been delimited by some useful (but admittedly arbitrary) natural geomorphic features (Figures G1, G14), which define an area extending from the Golden Gate north to Pt. Reyes, south to the southernmost point of Half Moon Bay, and west to the edge of the continental shelf (shelf break). The continental shelf here is the most extensive to be found off Central California, reaching a maximum width of about 30 miles (54 km), and extending to an average depth of about 660 ft (200 m). Although some oceanic processes and / or events that occur beyond these boundaries may also at times influence aspects of watershed ecology, these are generally considered well beyond the scope of practical management or restoration efforts for this watershed

Included within these boundaries are the Farallon Islands (Figure G14), two comparatively large (50 to 65 acre) islands along with a number of smaller outcroppings of basement rock that also break the sea surface. These are located about 27 miles (50 km) due west of the Golden Gate, and extend as a chain paralleling the edge of the continental shelf for a distance of about 16 miles (26 km). They are the only islands north of Pt. Conception that are more than about 2 miles offshore, and have been isolated from the mainland for about 11,000 years. The islands rise from a sand / silt substrate at depths of some 490 to 660 ft (150 to 200 m) to a maximal altitude of about 360 ft (110 m) above sea level, and are primarily granitic in composition, and topographically steep, save for ancient marine terraces now located about 50 ft (16 m) above sea level.

The treatment provided below of "natural" ecological attributes of the nearshore ocean is somewhat abbreviated relative to other component ecosystems of the watershed. This was done for two main reasons. First, the geomorphology of the continental shelf, as well as many oceanographic features of the marine environment here, are generally typical of the northern portion of the Central California coast, while the marine life of this region is generally representative of the cool temperate marine biota of the west coast of North America found from Pt. Conception to southern Alaska. These features have been well-described elsewhere (e.g., Ricketts and Calvin 1956), at a scale and in a manner highly applicable to our main objective here of characterizing the major ecological attributes of the "nearshore ocean" as it probably existed prior to massive human intervention. Such information is therefore summarized rather than repeated here. Second, more in-depth analyses were considered unnecessary to the main purpose of this paper. Unlike the remainder of the watershed, management/ restoration options for the marine system are nearly non-existent in terms of practical geomorphic, hydrological or habitat manipulations.

VII.A. Ecosystem Structure: Habitat Types and Biological Assemblages

Along with the many ecological characteristics the defined area shares in common with the wider coastal region of which it is a part, the nearshore ecosystem also has some distinctive ecological and biological features, some of which clearly stem from its linkages with the watershed through San Francisco Bay, and/or the presence of the Farallon Islands. Three major structural subdivisions of the marine system are individually described below: pelagic, benthic/demersal (subtidal), and intertidal (shoreline). These are somewhat more broadly defined than the "habitat types" described above for other ecosystems of the watershed, but form appropriate ecological subdivisions for the purpose of summary description of this large and diverse environment.

VII.A.1. Pelagic Subdivision

Pelagic habitat is defined as that portion of the water column extending from the sea surface to the area immediately adjacent to the sea floor (Benthic/Demersal, Section VII.B.2).

a. Distribution and Extent. Pelagic environment covers the entire defined area of the described "ecosystem," save for the Farallon Islands, and the narrow strip of intertidal habitat lining the margins of the mainland coast.

b. Composition and Complexity. The structure of the water column in this area is unusually dynamic, with substantial current and water mass variability apparent over time scales of days to months, according to localized and seasonal weather patterns and events (Ramp et al. 1992). Surface waters are particularly variable in terms of temperature-salinity properties, as they represent a mixture of three primary water types, (1) offshore water form the California current system, (2) recently upwelled water from a source off Pt. Reyes, and (3) outflow from San Francisco Bay. Water discharged from the Bay is less dense than ocean water, and therefore confined to a thin surface layer (discharge plume) which is often clearly evident in aerial photographs. A typical summer profile reveals a relatively warm surface layer some tens of meters deep, and a cooler and more extensive layer extending to the sea floor. The two layers are separated by a narrow *thermocline,* or region of rapid temperature change. The actual depths and extent of these major features varies somewhat both temporally and spatially with the degree of mixing. During winter, the thermocline breaks down and this temperature stratification pattern disappears, although the discharge plume is generally more conspicuous. In general, turbidity throughout the water column is affected by changes in suspended particle concentrations due to fluctuations in primary production, surface currents and wind stress, subsurface currents, and Bay discharge.

Surface (0 to 820 ft or 0 to 250 m) waters here are characterized by two distinctive seasons. A "spring-summer" season extends from about March through August, and is typified by upwelling along with comparatively calm winds and surface waves. In contrast, a "winter" season extends from October through February, accompanied by frequent storms lasting 2-10 days that generate large surface waves and strong fluctuating currents. September is transitional, in some years extending the upwelling period, while in others taking on characteristics of the "winter" season. Within this generalized seasonal framework, considerable month to month variability exists.

c. Biological Assemblages. Major components of the pelagic biota include plankton, fishes, birds, and marine mammals. The Gulf of the Farallones is an area of unusually high plankton abundance and productivity due to the combined effects of seasonal upwelling, nutrient discharge from San Francisco Bay, and the Pt. Reyes upwelling jet (Noble et al. 1992, KLI 1991, Barber and Smith 1981, Owen 1974). Phytoplankton assemblages vary seasonally. Spring/summer blooms are dominated by diatoms (*Chaetocerous spp., Rhizosolenia spp.*), while non-upwelling periods are dominated by dinoflagellates, particularly *Ceratium spp.* and *Peridinium spp.* (Bollin and Abbot 1963, Welch 1967). Zooplankton assemblages here are highly diverse - more than 1500 invertebrate and ichthyoplankton species have been recorded from the California Current system (EPA 1993). Copepods and euphausids generally dominate in terms of both numbers and biomass.

Pelagic fishes of the upper (epipelagic) part of the water column are commonly dominated by small planktivores such as Pacific herring, northern anchovy, Pacific sardine, Pacific saury, and juvenile rockfishes (SAIC 1992). The latter are known to be major prey for a number of predators, including chinook salmon (Chess et al. 1988). Midwater trawls have netted about 140 species, including juvenile rockfishes, Pacific herring and northern anchovy (Bence et al. 1992). Chinook salmon and other anadromous fishes that spawn in the estuarine or fresh waters of the watershed pass through, or temporarily reside and feed in, this area as well.

The waters overlying the continental shelf here also support large numbers of foraging marine birds (Ainley and Allen 1992, Jones and Szczepaniak 1992), species defined as those that obtain most of their food from the ocean and are found over water for at least half the year (Briggs et al. 1987). This region is perhaps the most heavily used marine bird breeding area of the entire west coast of the United States (Sowels et al. 1980). Ainley and Allen (1992) documented the regular occurrence of some 63 species over these waters, including abundant year-round populations of gulls, cormorants, murres, and auklets, and seasonally abundant migratory populations of shearwaters, loons, and others (Ainley and Allen 1992).

Some 20 species of cetaceans (whales and porpoises), five pinnipeds (sea lions and seals), and one fissiped (sea otter) are frequently observed in this area (KLI 1991). Sightings of cetaceans are much more common in deeper waters than over the continental shelf here (Dohl et al. 1983). The Pacific white-sided dolphin is the most abundant of the toothed whales found in these waters. Peak numbers of pinnipeds observed at sea occur during winter and spring when the northern fur seals arrive from the Bering Sea. These and the California sea lion are the most common pinnipeds in these waters. Pinniped foraging is most heavy during the summer and fall. These animals tend to move offshore to deeper waters at other times. Summaries of the feeding habits of marine mammals common in this area indicate that anadromous fishes of the watershed are not generally considered major components of the diets of any of these marine mammals (EPA 1993), although it seems likely that some opportunistic predation, possibly heavy at times, might naturally occur as large populations of anadromous fishes move through the area.

VII.A.2. Benthic/Demersal Division

The area referred to here is comprised of the subtidal sea floor of the continental shelf, and the waters *immediately* above it (i.e., that portion of the water column regularly used by those fishes and other animals that maintain a close association with the sea floor).

a. Distribution and extent. The distribution and extent of this habitat corresponds with that of the pelagic habitat described immediately above (Section VII.A.1.a).

b. Composition and Complexity. The vast bulk of the sea floor in this region, from just beyond the surf zone to a depth of about 660 ft (200 m), consists of relatively flat, featureless plains of unconsolidated fine sand punctuated occasionally by low-relief (<½ m) rock outcroppings. To the northwest and southeast, this area is bounded by a silt-sand combination, with a band of silt extending around Pt. Reyes (Karl et al. 1996). While the predominant sediment here is fine sand, patches of medium to coarse sand are not infrequent. A corridor of such sand about 32 mi (20 km) wide extends westward from the Golden Gate to the Farallon Islands (Figure G14)., and some topographic variability (e.g. depressions with pronounced sand ripples) occur between Half Moon Bay and Pt. Reyes.

Kelp forests represent structurally complex anomalies in this generally “featureless” environment, growing sporadically just beyond the surf zone, usually where rock outcroppings of the substrate provide suitable attachment sites. The maximum depth limit of kelp growth is set by light penetration, while the minimum limits are generally related to sediment stability and wave action. In the defined area, kelp is seldom found growing at depths greater than about 50 to 65 ft (15 to 20 m). In some shallow (i.e., about 6 to 16 ft or 2 to 5 m), protected subtidal locations, seagrass meadows composed of *Zostera marina* further increase benthic habitat diversity and complexity. Such “meadows” are typically of comparatively limited extent.

c. Biological Assemblages. Animal assemblages here are generally dominated by fishes, particularly flatfishes (SAIC 1992). Most common are the Pacific sanddab (*Citharichthys sordidus),* rex sole (*Errex zachirus),* English sole (*Pleuronectes vetulus),* Dover sole (*Microstomus pacificus),* and slender sole (*Lypsetta exilis*). In addition to the flatfishes, other relatively abundant species include the plainfin midshipman (*Porichthys notatus),* pink surfperch (*Zalembius rosaceus),* white croaker (*Genyonemus lineatus),* Pacific butterfish (*Peprilus simillimus),* shortbelly rockfish (*Sebastes jordani),* striptail rockfish (*Sebastes saxicola),* and the sablefish (*Anaplopoma fimbria).* A total of 29 demersal fish species were recorded recently (SAIC 1992) from a restricted sampling site within this zone. Megafaunal invertebrates in this habitat type are typically sparse in comparison with fishes. Fewer than 15 species were recorded by a recent sampling program (SAIC

1992). The dominant groups here are echinoderms (mainly brittlestars [*Ophiuroidea*] and sea stars [*Asteroidea*]), cnidarians (mainly sea pens [*Pennatulacea*] and anemones), and molluscs including octopus (*Cephalopoda*) and gastropods. Dungeness crab *Cancer magister* is also occasionally found here, but in relatively low numbers.

On or near the sea floor, the composition of the biota often varies gradually along depth, sediment, or other gradients, with considerable overlap evident in comparative studies between different sites throughout the system. Nonetheless, some distinctive assemblages associated with particular habitat features are readily distinguished. The results of trawl samples as well as photographic sampling methods conducted both from manned submersibles and remotely-operated vehicles indicate that the continental shelf and continental slope in this region harbor quite distinctive communities, differing both in terms of population density and species composition (SAIC 1992). Additionally, the plant/animal assemblages of coastal California associated with complex rock/reef habitat and/or kelp forests typically differ substantially (and change abruptly) from those of adjacent areas of flat, unconsolidated sediment Ebeling et al (1980a, b). Kelp forests are an unusually rich habitat in terms of species diversity. More than 40 species of fish occur regularly here along with many more invertebrate animals, including spiny lobster, abalone, rock scallop, and sea urchins. Seagrass meadows also harbor distinctive assemblages of invertebrates and shore fishes, many of which live there as juveniles.

VII.A.3. Intertidal (Shoreline) Habitats

The area referred to here consists of the so-called intertidal or littoral zone, an area extending between the high and low tides of the year. The San Francisco region is particularly rich and diverse in terms of the types of shorelines present, and includes rocky shores and sand beaches with varying degrees of exposure to ocean swells and winds, factors that lead to major and distinctive differences in the resident plant and animal assemblages. Ricketts and Calvin (1956) provided a general classification of coastal types for the region that is most useful in accounting for much of the variability found in the abundance/distribution patterns of common intertidal marine life. According to this scheme, much of the shoreline north of the Golden Gate is “Open Coast,” exposed to the full force of the prevailing northwesterly swells of the Pacific Ocean. The exposed shorelines of the Farallon Islands are particularly complex, with frequent terraces, cliffs and caves. Because of relative isolation from the mainland and ready access to the rich marine food resources of the area, island shorelines represent a favored resting and breeding ground for a variety of sea birds and marine mammals common to pelagic areas of the region (see Section VII.A.1.c, above). These animals occurred in huge numbers at the time of the Gold Rush, when they were heavily hunted and otherwise exploited (Skinner 1962). Half Moon Bay and limited portions of the coast north of the Golden Gate constitute a coastal type described as "Protected Outer Coast," while the third category ("Bays and Estuaries") is represented by Bolinas Lagoon, Drake's Estero, and San Francisco Bay proper (described as a separate ecosystem above). Overall, the intertidal zone of the outer coast is generally considered only minimally interactive with the non-oceanic portion of this watershed. Nonetheless, these habitats may play a substantial role in the lives of some common species found within San Francisco Bay, particularly those of Central Bay. The location and linear extent of major shoreline features are presented in Figure G14.

VII.B. Ecosystem Function: Supporting and Integrating Processes

VII.B.1. Physical Processes

Many fundamental ecological characteristics of this system are closely tied to water movement patterns within and around the general area described. Water movement is affected by the interactions among a number of large-scale and more localized processes, including winds, currents, tides, and vertical mixing. In general, water movement over the shelf here is closely coupled to surface wind stress, with flows generally to the southeast (equatorward) when the wind is in that direction, and northward (poleward) when winds are slack or from the south. This area of the coast of California experiences mixed semidiurnal tides (two highs and lows of unequal magnitude). The strength of these tides in the Gulf of the Farallones is substantial, accounting for about half of the total variability in current records from the shelf. Tidal currents of this magnitude are sufficient to resuspend bottom sediments, and disperse materials already suspended in the water column.

Three somewhat distinct currents transect this part of the ocean. The largest by far is the California Current, a broad offshore southeasterly flow of cold, low-salinity subarctic water which forms the eastern segment of the North Pacific gyre. This feature is generally located about 160 to 1600 mi (100 to 1000 km) from shore, but may at times move further inshore. Two smaller, poleward (northward) currents regularly occur inshore of the California Current. The Coastal Countercurrent flows generally northward over the continental shelf, and is strongest at its shoreward margin. This is generally the dominant current throughout the defined area, and is typically 16 to 32 mi (10 to 20 km) wide. It flows at speeds of less than 0.3 ft/sec (10 cm/sec) during the summer season, but usually strengthens and widens to cover the entire continental shelf during the winter season, when it is also called the Davidson Current (Huyer et al. 1978). Further offshore , a deeper and stronger California Undercurrent moves subsurface water poleward above the continental slope, reaching maximum strength at depths between about 490 to 985 ft (150 to 300 m). The descriptions provided above are *average* flows. These sometimes remain stable over many months, but are also subject to considerable inter-annual variability as well as alteration by larger scale climatic and oceanographic events. For example, during the strong El Niño winter of 1982-83, the northward movement of water over the continental shelf (Davidson Current) off San Francisco was twice as strong as recorded during the more “normal” preceding and subsequent years (Huyer and Smith 1985).

A persistent and characteristic feature of oceanic circulation in this region is the regular exchange of water between the continental shelf and the deeper continental slope through the process of upwelling. Upwelled water is colder and therefore more dense than typical offshore surface water, and the two types form distinct water masses that do not mix readily. An “upwelling front” marks a sharp boundary between two such water masses, and along the central California coast long “cold filaments” of recently upwelled water may extend perpendicular to shore for distances of several hundred kilometers. Pt. Reyes and other such coastal promontories (e.g., Pt. Sur, Pt. Arena) are the primary sites of the filaments. Cross shore surface velocities along the northern edges of these filaments may reach 2 knots (100 cm / sec), a far greater speed than that generally found in surface waters of this area. Because upwelling is basically a summer season phenomenon, cold filaments are rarely seen during the winter months.

Many of the processes described above (as well as aspects of water column structure), are ultimately controlled by very large-scale oceanographic and climatological processes that extend well beyond the central California coastal region. Nonetheless, certain characteristics of the nearshore ocean here are also somewhat influenced by processes at work in the rest of the watershed, particularly with regard to surface layer salinity, temperature and turbidity characteristics, which vary with watershed outflow. Such “outflow effects” are, not surprisingly, most pronounced close to the Golden Gate. For example, discharge from the watershed has resulted in a long-term average salinity of 29.9 ppt at Fort Point on the south side of the Golden Gate, whereas at South Farallon Island salinity has averaged 33.4 ppt over the same period (EPA 1993). Surface turbidity effects are also apparent from comparisons of the results of some recent (last 25 years) hydrographic surveys. During 1991, a relatively dry year, the Bay outflow plume was observed to the north of the Golden Gate during August, and to the south and further offshore during November (Ramp et al. 1992). During peak spring flows of a “wetter” year, a plume of turbid water extended some 29 mi (46 km) offshore, almost to the edge of the continental shelf (Carlson and McCullogh 1974). Sediment discharge from the watershed, particularly during periods of high outflow, may affect benthic sediment composition in the immediate vicinity of the Golden Gate. However, benthic substrate characteristics throughout most of the defined area are mainly determined by large-scale geological features and oceanographic processes that are independent of interactions with the estuarine or fresh water components of the watershed (EPA 1993). Outflow from San Francisco Bay has the capacity to affect general circulation of water in the Gulf of the Farallones, although the nature and magnitude of such effects have not been studied, and therefore remain unknown (EPA 1993).

VII.B.2. Community Energetics: The Acquisition and Cycling of Organic Carbon and Nutrients

a. Sources. The nearshore ocean acquires organic carbon from three main sources: (1) internal (to this ecosystem) primary production by phytoplankton, kelp forests, and seagrasses, (2) outflow from the watershed, and (3) biological transport and transport by ocean currents. Phytoplankton production provides the majority of internal (autochthonous) primary production for this ecosystem, and is primarily determined by nutrient availability and light levels. Nutrient concentrations are influenced by seasonal current patterns, upwelling, and uptake by phytoplankton, which are capable of rapidly expanding populations and quickly depleting available nutrients. The naturally high productivity and planktonic activity in the pelagic habitat is in part due to the addition of nutrients from the estuary (KLI 1991). Primary production in California's coastal waters tends to be highly variable with season, and is characterized by a spring and fall period of intense production separated by summers and winters with sustained low levels of production. Kelp forest and seagrass meadows may achieve very high production rates at times, but these features are of quite limited extent in relation to the total area of the ecosystem. Kelp forests are particularly ephemeral features that undergo dramatic changes in areal coverage in response to sudden changes in sea temperatures (e.g., El Niño events) and other undetermined factors. Most kelp primary production is not consumed within the habitat, but rather "exported" as detritus to intertidal and deeper benthic areas.

b. Cycling and Exchange. Zooplankton abundance typically reflects, but lags slightly behind, patterns of phytoplankton abundance. Zooplankton forms the primary food source for most of the smaller, more abundant fishes of the coastal waters, which in turn are a major food source to many larger fishes, birds, and marine mammals of the area. The enormous populations of marine birds and mammals that once occupied the mainland coast and Farallon Islands 150 years ago represented a considerable biomass of high-level predators in this system.

In coastal seas, primary production is restricted to the upper, well-lit layer of the water column ("photic zone"). Except in very shallow inshore portions, benthic areas of the continental shelf are covered by waters too dark to support photosynthesis. Thus, food in the form of living plant tissue is largely inaccessible to deeper dwelling benthic/ demersal animals of these areas. Instead, the primary sources of nutrients here are the flux of organic debris raining down from the surface or carried downslope from the shore or inshore kelp forests (Jahnke et al. 1990, Seuss 1980), or one another. Deep benthic assemblages are therefore largely based upon detrital food chains, and it is here that decomposition converts dead organic tissue into chemical forms of organic nutrients that may be readily assimilated by phytoplankton. It is the process of upwelling, which brings this deeper, nutrient-laden water to the surface, that "fuels" the seasonal and sporadic phytoplankton blooms that to a large extent account for the unusual richness of marine life, including fisheries, found in the area.

c. Sinks. Organic carbon is lost to the system through transport by currents, downslope transport of benthic detritus and nutrients beyond the continental shelf, and biological export to other ecosystems by fishes, birds and mammals.

VIII. A Watershed-Scale Perspective

The "ecosystems" described above are by no means ecological islands. They interact with one another and with adjacent terrestrial systems to form larger ecological units, commonly referred to as landscapes. It is apparent that at this larger scale, two types of system characteristics need to be considered in restoration planning: those related to spatial extent and distribution of ecosystems (structural mosaic), and those related to interactions/exchange processes among these elements (connectivity). Prior sections of this chapter have provided documentation of the estimated pre-disturbance extent and distribution of the watersheds' ecosystems. Discussion here therefore focuses upon the nature and effects of interactive processes among ecosystems.

At landscape scales, the watershed's ecosystems are primarily connected and interactive due to two major processes: (1) water movement, and (2) active biological transport. There is little doubt that the most pronounced and far-reaching effect of inter-ecosystem interaction at the landscape scale is related to the natural movement of water and all that is carried within it - sediments, nutrients, and drifting organisms. Thus, the integrity of these ecosystems is ultimately dependent upon naturalistic patterns of flow, in terms of magnitude, timing, and variability of water received as runoff from above. Not only do flows shape system topography, they are also in themselves an integral habitat characteristic, highly influential in the lives of many aquatic organisms. For example, changes in flow serve as behavioral cues for some native fishes, triggering migrations and spawning activities (Herbold et al. 1992).

Throughout most of the watershed, water and sediment movement takes place strictly in a one-way (downstream) direction. It is only in the lower (estuarine/marine) part of the watershed that tidal influence results in bi-directional water movement. In the Delta and San Francisco Bay portion of the watershed, a number of key ecological features, such as salinity gradients, mixing processes, and nutrient exchange are directly dependent upon interactions between ocean tides and river discharge. The downstream transfer of energy among ecosystems resulting from net downstream flow appears to have been most influential, on a sustained basis, between the Delta and San Francisco Bay, and between the Bay and nearshore ocean. Net movement of nutrients in the lower estuary over the course of the year is believed to occur from the estuary to the marine environment (Jassby 1992). However, this situation may be temporarily reversed during ocean upwelling events, when tidal mixing and biological transport bring large amounts of nutrients into the nearshore ocean surface waters and consequently into the Bay. It also seems likely that substantial “pulses” of nutrient transport from upland to lowland rivers occur during flood events, when large amounts of nutrients are flushed from bordering riparian zones into stream channels, in amounts well in excess of these systems’ ability to utilize them.

It is essential to note that, although naturalistic water movement patterns among ecosystems may properly be considered the single most influential factor naturally linking them, it is also quite clear that within any particular ecosystem, many of the most fundamental ecological effects of flow received from above depend highly upon topographic and biological attributes of downstream ecosystems. Thus, the “ecological benefits” of any or all aspects of the natural watershed hydrograph may only become evident in ecosystems in which other “natural” attributes are also intact. For example, restoration or emulation of the natural lowland river hydrograph may in itself do little to restore the biological integrity of native Delta habitats or communities if “restored” flows are confined in artificially-narrowed channels lying between artificially-heightened levees; if waterways are bordered by agricultural fields or urbanized areas rather than native aquatic or upland habitat; or if native species are unavailable to recruit to the area or are otherwise inhibited from responding to enhanced conditions (whether by competition from non-native species, highly altered population genetics, or degraded water quality).

Unlike the movement of water and sediments, active biological transport takes place in both directions throughout the watershed. In general, the scope and magnitude of inter-ecosystem effects of active biological transport are poorly understood or documented. However, there is clear evidence that such processes are fundamental aspects of community ecology in some systems. For example, the inter-ecosystem migration of chinook salmon is known to be a key aspect of community energetics in some upland streams, transferring large amounts of organic tissue derived from primary production in oceanic systems to these distant waters (see Chapter 2; Section III.B.2). Regular movements of large herds of grazing mammals and migratory birds were also capable of transferring respectable quantities of energy and nutrients among ecosystems, and the activities of these large animals also strongly affected habitat structure and complexity in some systems.

Our scientific understanding of ecological integration, interaction, or biological effects at the larger scales of landscapes is highly limited. Nonetheless, such considerations remain an essential aspect of restoration planning, and effective ecological restoration of aquatic ecosystems, "*entails restoration of the target ecosystem's structure and function both locally and within its broader landscape or watershed context*" (National Research Council 1992). Failure to recognize or address ecological interaction at the broadest of spatial scales may adversely affect the success and sustainability of more localized restoration actions.

CHAPTER THREE
Transforming the Watershed: Two Centuries of Change

I. Introduction

California's native landscape has a long legacy of massive environmental change. Severe sea level and climate shifts, huge volcanic explosions, the regular burning of prairies by prehistoric peoples, and the hunting to extinction of large mammals all left their marks on the region's ecology well before the extensive settlement and development of the state that followed the Gold Rush (circa 1850). Since that time, California's natural landscape has also been purposefully and substantially altered by people in a variety of ways that have negatively affected ecological integrity and biodiversity. Some of these interventions (e.g., extensive hunting of mammals) are no longer occurring. Others (e.g., agricultural development, urbanization, water storage and diversion, pollution) are still occurring, and in some cases, increasing in magnitude. Such continuing interventions are of particular interest because unlike purely historical interventions, they will continue to interfere indefinitely with the system's inherent resilience to disturbance, and its ability to re-establish natural ecological attributes.

This chapter briefly chronicles the recent (post-European colonization) history of human activity in the watershed in terms of ecological effects and change. In this watershed a variety of human activities (e.g., excessive harvest, deliberate eradication, replacement of native species with exotics) have been responsible for *direct* species loss and population decimation. However, there is widespread agreement that it is primarily the *indirect effects* of habitat destruction and degradation that contribute to the high and alarming rates of species loss seen today (Ehrlich and Ehrlich 1981, Wilson 1985, Soule 1991).

The major types of human interventions that have, over the last 150 years, both directly and indirectly contributed to species loss and other forms of ecological change in the watershed are summarized in this chapter. For each type of intervention, the general nature of the most common and well-documented types of ecological effects is briefly discussed. The following chapter (Chapter 4) more specifically discusses the *cumulative* ecological effects these interventions, in combination, have had on each of the watershed's aquatic ecosystems.

II. Human Interventions in Watershed Ecology

The information presented below is loosely chronologically organized. Direct harvest of animals and plants began with the very first explorers, and many valuable populations had been decimated well before the end of the 19th century. The midway point of the 19th century witnessed the beginning of massive alterations of the landscape due to conversion of natural habitat by a variety of land-use practices - mining, agriculture, and urbanization - all of which continue to exert a major influence today. Finally, to meet the needs of agriculture and rapidly growing urban populations, the natural hydrology of the system became increasingly altered, with most major interventions and effects beginning during the 20th century.

Pollution and the degradation of water quality have had many documentable effects, but it is almost certain that these are far outweighed by undocumented cumulative impacts upon the watershed's biological systems. Most commonly, such effects take the form of subtle changes in survival, reproductive success, competitive ability, etc., rather than being manifested as overt mortality or externally obvious trauma. For this reason, such effects are difficult to elucidate in wild populations, even though they may have dire long-term consequences. Because distinctly different forms and degrees of pollution are associated with particular interventions, this topic is discussed in the individual contexts of each "intervention," rather than as a separate category unto itself.

II.A. Harvest

II.A.1. The Hunting of Large Mammals and Waterfowl

Large mammals were a dominant and pervasive feature of the Central Valley landscape for thousands of years, but were among the first group of species to be decimated during the 19th century. Headquartered in San Francisco, the Hudson's Bay Company extensively exploited bears, beaver, lynx, tule elk, pronghorn antelope, and river otters between Fort Vancouver and French Camp (the post on the San Joaquin) from 1829-1838. Other hunters sought out marine mammals, ducks and geese. Ranchers slaughtered grizzlies at every opportunity, so that they were extremely scarce by 1900. The last reported grizzly in California was shot in 1922, in Tulare County. Mountain lions were common, but were mercilessly hunted to eliminate their predations on deer and livestock. In 1906, legislation aimed at protecting ranchers encouraged the slaughter by placing a bounty on mountain lions.

Beaver populations of the Valley, once perhaps the richest in the entire United States, started becoming scarce on the Sacramento River as early as 1837 (Skinner 1962). By the early 20th century, hunting and the livestock industry resulted in the rapid demise of the Bay's native large mammals, including mink, river otter, and marine mammals (Josselyn 1983, SFEP 1991). Hunting drove Roosevelt elk from the Bay Area by 1870, and greatly reduced tule elk populations by 1850, although some small herds still remain. By 1870, the once bountiful fur seal and sea otter populations had been hunted to the point that it was no longer profitable to seek them out, and although the Bay remained the center of the fur trade, the animals were hunted elsewhere (Skinner 1962). Over the course of just half a century, these wildlife populations that were such an integral part of California's native ecosystems had all but disappeared, prompting the declaration in 1885 that "*the days of fur hunting, which once was a great business in California, are gone*" (Bryant 1915).

The Central Valley was also home to great numbers of waterfowl, whose populations were a favorite target of hunters. California valley quail and California clapper rail were abundant and popular game birds. By the turn of the 19th century, hundreds of thousands of ducks reached San Francisco markets each year. As population declines became increasingly evident early in the 20th century, public concern over the plight of California's waterfowl continued to grow, particularly in the San Francisco Bay area. Legislative action put an end to the open sale of waterfowl in 1915 (Skinner 1962). Decimation of bird populations also reached offshore. The heavy take of seabird eggs on the Farallon Islands proved catastrophic to these seemingly inexhaustible populations. Between 1850 and 1856 alone, the Farallon Egg Company took between 3 and 4 million seabird eggs to San Francisco markets (Figure III-A) (Skinner 1962).

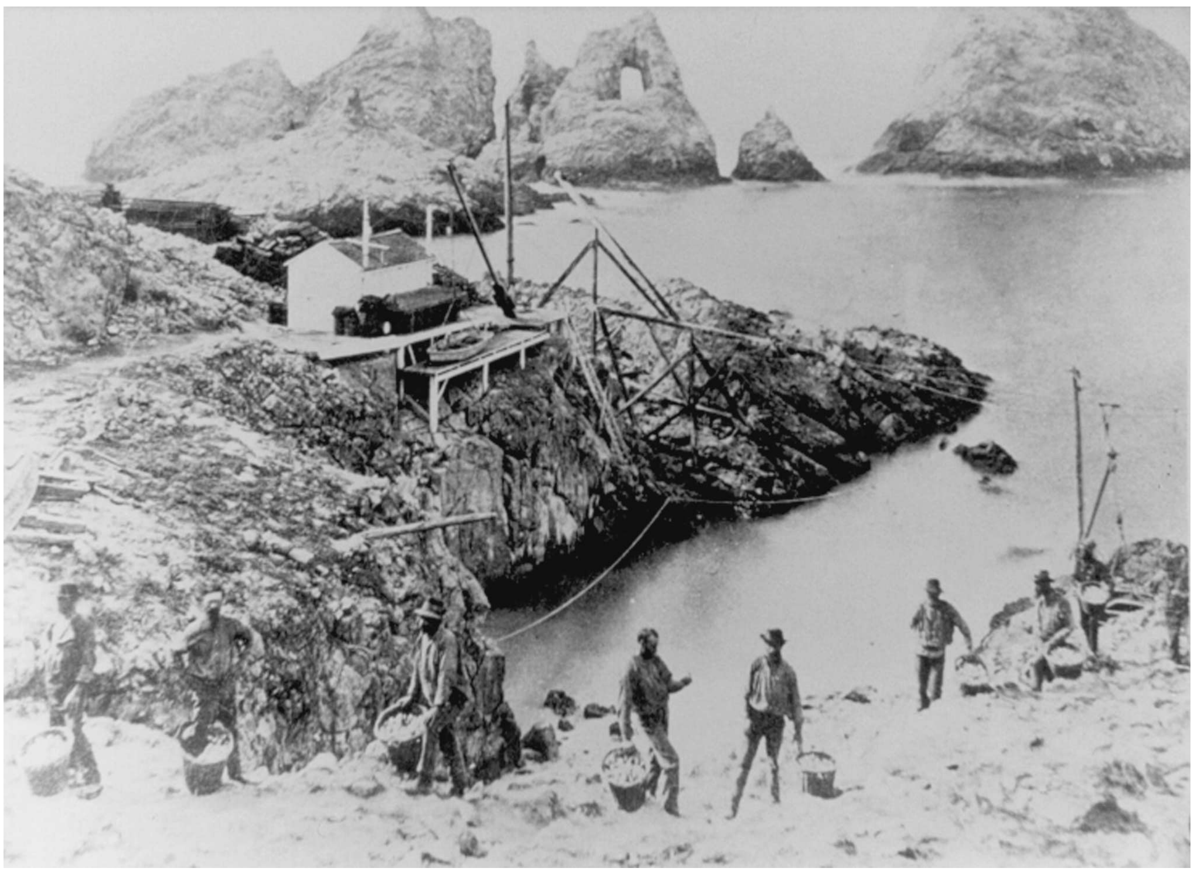
II.A.2. Fishing

The general history of fisheries exploitation in the watershed mirrors the history of many other fisheries around the world: discovery, development of demand, over-exploitation, and population crash. The watershed once supported enormous populations of salmon and other commercially valuable species. Commercial salmon fishing with gillnets and seines was initiated by settlers around 1850, mostly in the Bay and lowland rivers.

Commercial harvest in San Francisco Bay has been heavy since the time of the Gold Rush (Skinner 1962). Jordan (1887) stated that "*for many years the Bay has been systematically overfished with nets of such small mesh that probably the Bay does not contain one-twentieth the number of fish that it did twenty years ago.*" At that time, few boats ventured outside the Golden Gate, since the Bay itself provided a plentiful supply of all kinds of fish (Skinner 1962).

Overfishing in the Bay appears to have depleted certain stocks as early as 1878 (Higgens 1991). Declining profits began shutting down fish canneries in 1882, and by 1916 most had gone out of business. Other major fisheries for native species that followed this same general pattern during the late 19th and early 20th centuries include those for sturgeon, sharks and rays, bay shrimp, clams, mussels, and oysters (Skinner 1962; Smith and Kato 1979). The only major fishery of the Bay that has proved sustainable is the

Figure III-A
Egg-Hunters on the Farallon Islands



In the1850s, egg-hunters took 3-4 million murre and foolish guillemot eggs.
Source: San Francisco History Center, San Francisco Public Library.

herring fishery, perhaps because demand was low in the early years and because herring have an unusually high reproductive capacity. Intensive fishing of the nearshore ocean began in response to the rapid depletion of Bay fisheries in the late 19th and early 20th centuries (Skinner 1962).

Modern fishery management is geared towards maximizing harvest while maintaining stock viability. Take limits, many of which involve specific restrictions on size and season as well as total numbers, have now been established for virtually all harvested species in California waters. Despite these regulations, many California commercial fisheries remain in trouble, shifting from species to species as stocks become overfished and unprofitable. Recent analyses using sport and commercial fishery data and USFWS production estimates indicate that the proportional harvest (i.e., fraction of total production that is harvested) of Central Valley chinook salmon has been increasing by about 0.5% per year for the last 40 years, for a total increase of about 20% (Kimmerer, personal communication). Harvest rates have averaged about 73% of total production, about twice the levels necessary to sustain wild stocks, but acceptable for hatchery stocks (NMFS 1998).

Hatcheries have been used for many years to artificially boost production of valuable species. Unfortunately, the success of salmon hatcheries is often measured by the number of fry or smolts produced, rather than the percent that survive to adulthood. Low survival of hatchery-produced fish as well as density-dependent mortality in the ocean (Unwin 1997, Peterman 1984, 1987) limit the effectiveness of the hatchery programs. Despite enormous expenditures, the benefits of supplementation hatcheries remain unclear. Many hatcheries have continued to operate despite dramatic declines in fish returns (Washington and Koziol 1993, White et al. 1995). Additionally, negative impacts of hatcheries on fisheries management and on the genetics and ecology of native fishes have become clear in recent years. Some authors view the technical obstacles to successful hatchery supplementation as insurmountable (White et al. 1995).

California's first salmon hatchery (Baird Hatchery) was built on the McCloud River (a tributary of the Sacramento River) in 1872. By 1922, over 40 hatcheries and egg collecting stations had been built (Shebley 1922). Today, five major hatcheries release nearly 40 million young salmon every year into Central Valley streams. These appear to have successfully augmented salmon harvest (at least in the short run), although harvest opportunities are severely limited by the need to avoid endangered winter-run chinook, which at times are found mixed with fall-run fish.

Stocking refers to the transplanting of fish from a production source (natural or artificial) to a target lake or stream. It is a relatively common practice used to enhance sport fishing opportunities (see Section III.B, Exotics, below). As the negative impacts of stocking and introductions became clear in the 1970s (e.g., genetic impacts on wild populations, competition, extirpation of other animals such as amphibians), and as new goals for preserving ecological integrity were adopted, these programs have been curtailed to some extent, although stocking is still allowed in many areas. In California, fifty streams and lakes now have restrictions on harvesting and planting of fish.

II.A.3. Logging

Extensive logging began in the upland systems in conjunction with the Gold Rush, when thousands of acres of forest were cut each year to build mining structures, railroads and homes. Towards the end of the 19th century, an average of 500 million board feet was being logged each year, mostly from western foothills. In 1886, the California State Forestry Board estimated that about one third of pre-gold rush Sierra timber had been destroyed. After 1900, logging accelerated even more. Timber harvests from the Sierra averaged 650 million board feet annually from 1950 to 1994, and ranged from 227 million to over one billion board feet in a single year (SNEP 1996). Heavy logging along streams, sometimes coupled with road and railroad construction, was particularly common throughout the Pacific Northwest until the 1980s (Bilby and Ward 1991; Moyle et al. 1996). Giant sequoia and other old growth stands in riparian areas were harvested (Kondolf et al. 1996). As late as the 1970s, riparian forests were clearcut all the way to the stream bank (SNEP 1996). The major ecological effects of the logging of upland forests on aquatic ecosystems of the watershed stem from the destabilization of upland soils, leading to higher erosion rates and increased sediment loads and turbidity of streams, and the alteration of riparian habitat by the removal of larger, older trees. Logging can also increase peak streamflows, and sometimes if can increase summer flows by reducing watershed evapotranspiration (Bosch and Hewlett 1982, Rowe 1963, Pitt 1978). Exporting logs reverses the natural pattern of returning to the soil vital minerals that otherwise would have left decaying elements to nurture saplings (Johnston 1998).

Logging practices have changed substantially during the relatively recent past. Resource conservation concerns and the emerging recognition of the need to protect wildlife habitat has resulted in a two-thirds reduction in timber harvest on public lands in California. Clear-cutting has been largely replaced by selective harvest on public lands, although clear-cutting still occurs on private land. Fire management is progressing from total suppression to the inclusion of limited prescribed burns, a disturbance event crucial to ecological successional processes in forest ecosystems, and the maintenance of habitat and species diversity. There are now ongoing, vigorous efforts to protect remaining old-growth stands from logging. Recent legislation such as the Wild and Scenic Rivers Act and the Clean Water Act have mandated environmental standards for the timber industry (Ruth 1996). The Wilderness Act of 1984 set aside 1.8

million acres of national forest land in the Sierra for increased protection. Along with Yosemite, Sequoia, and Kings Canyon National Parks, this wilderness forms the largest contiguous area in the Sierra free of human intervention (with the exception of fire suppression).

The annexation of California to the United States in 1848, followed by the Gold Rush, fueled the development of the Central Valley. Riparian vegetation was among the first causalities of this rush, and its devastation was rapid. Cordua, who settled near the Yuba River in 1842 and left a decade later, bitterly disappointed at the misfortunes of the Gold Rush, noted on his departure that "*from the mouth of the Sacramento up to the Yuba, every bend of the river, almost every tree at the shore, and all the Indian villages had been known to me. Now the banks of the river, where formerly the Indians hunted bears, raccoon, and deer, were covered with growing cities, beautiful hotels, landing places, and farms of all kinds*" (Cordua in Gudde 1933, p. 303).

The riparian forests, the most accessible woody vegetation on the valley floor, were used for fencing, lumber, and fuel by early settlers. Steamships plying the Bay and upstream waters were heavy users of local fuel wood, especially oak. The wooded natural levees occurring in the Sacramento Valley and wherever river channels entered the Delta were generally high enough and broad enough to support the gardens and fields of the first settlers and their successors, and the crowns of the natural levees became the sites for artificial levees (Kelley 1989, Thompson 1961, Katibah 1984, Thompson and Dutra 1983). In September 1849, a 49er in search of more lucrative means of making a living than gold mining, wrote: "*We heard of some wood-cutters in the bottom-lands, between Suttersville and Sacramento city... we followed a small path leading through the timber, and soon found ourselves in the very midst of the wood-choppers, who were felling trees on all sides.... Oakwood was worth at this time about fifteen dollars a cord in Sacramento city... On inquiring, we learnt from the wood-cutters themselves that wood was a very good article at the present, there being not the least danger in the world of our not selling the cord for cash...*" (Gerstaecker 1853).

By the 1870s, chroniclers had documented the devastation of the riparian forests, commenting on Colusa County that "*[m]any of the water courses were originally skirted by narrow belts of trees, consisting chiefly of sycamore and cottonwood; but these having been mostly cut away the settled parts of the county are but scantily supplied with fuel and fencing timber*" (Cronise 1868, p. 297); and on Yolo County that "*[o]riginally the banks of these streams were timbered along their lower portions, after the manner common in this region.... But most of this growth has now been removed*" (Cronise 1868, p. 300). Will Green, one of the earliest settlers of Colusa County, wrote in his reminiscences in the 1890s that: "*The river is skirted on either side with a growth of timber averaging a mile in width, principally oaks, interspersed with sycamore, cottonwood, willow, and ash. Much of this along the lower end of* *the county has been cut off and sold in the shape of cordwood -- supplying the steamers on the river and the city of Sacramento; some of it, in fact, going to San Francisco"* (Green 1950). Today, less than 10% of the 930,000 acres of the riparian zone that was occupied at one time or another by riparian vegetation remains (Figs. G5, G7).

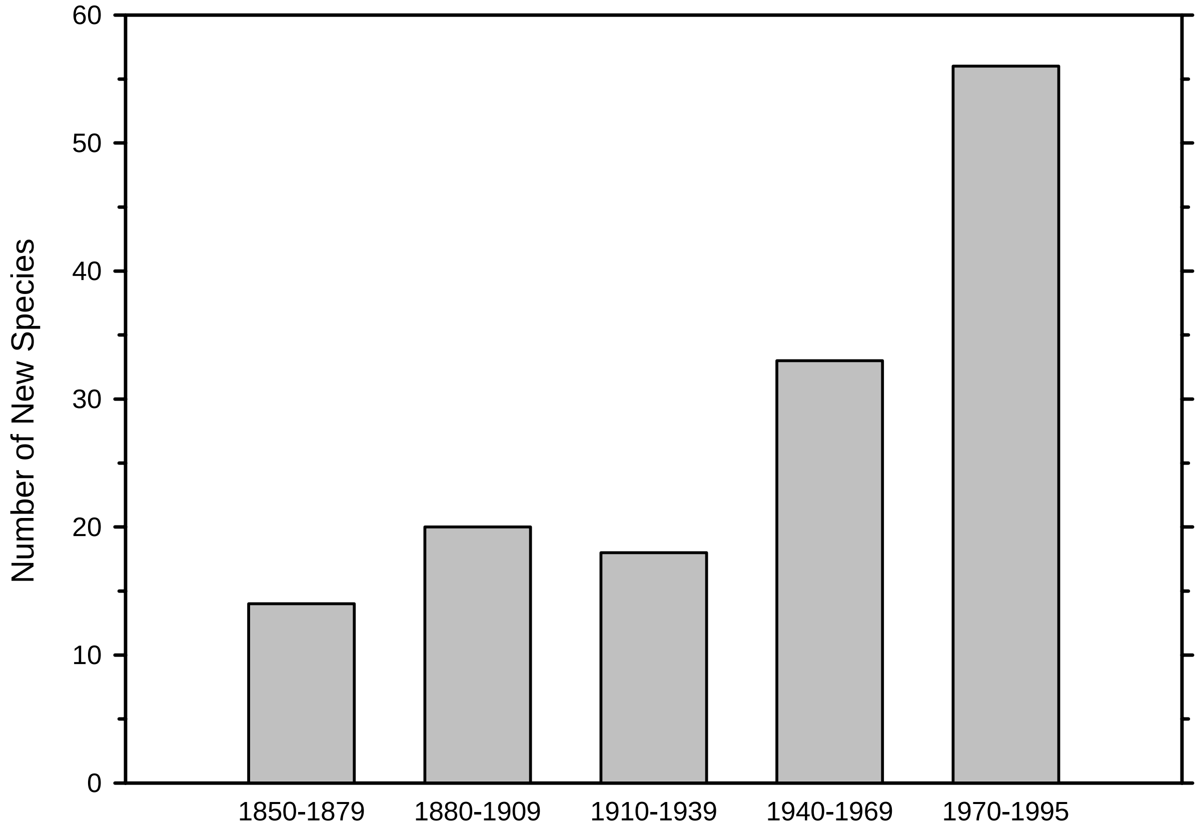
II.B. The Introduction of Exotic Species

Over the course of the last 150 years, hundreds of exotic species have been introduced to California's Central Valley watershed, some by accident and some purposefully (Figure III-B). These have in some cases wrought havoc on the native assemblages of species. Strong influxes of exotics accompanied the completion of the trans-continental railroad in 1869, the formation of the California Fish Commission in 1870 and the formation of the U. S. Fish Commission in 1871. The two commissions were dedicated to fish propagation, and were responsible for transplanting non-native fishes from the eastern United States to California (Moyle 1976a). These introductions were primarily a result of the dissatisfaction of the early settlers with the native fishes. They believed other species would prove superior as sport and commercial fish, as food supplies for these, and as biological control agents (i.e., insects, aquatic weeds). The introduction in 1871 of 10,000 American shad (*Alosa sapidissima*) fry into the Sacramento River (Nidever 1916) marked the beginning of a period of relatively intense fish stocking. The shad were followed by carp (*Cyprinus carpio*) and brook trout (*Salvelinus fontinalis*) in 1872, four species of catfish (*Ictalurus spp.*) and two species of black bass (*Micropterus spp.*) in 1874, and a steady stream of introductions from 1874 to 1891 (Moyle 1976a). This last period included the introduction of striped bass (*Morone saxatilis*), first released into Carquinez Strait in 1879 (brought by rail from a small New Jersey estuary), which subsequently flourished in the San Francisco estuary beyond all expectations (Skinner 1962, Smith and Kato 1979).

In addition to purposeful introductions of fish to the upstream reaches of the system, ships from all over the world were inadvertently bringing invertebrate invaders along for the ride in their ballast or in the form of marine borers carried in wooden ship hulls. A single introduced organism, the shipworm *Toredo navalis*, caused $615 million (in 1992 dollars) of structural damage to Bay Area maritime facilities over a three year period in the early 1900s (Cohen and Carlton 1995). Shipments of Atlantic and Pacific (Japanese) oysters also contributed major invertebrate introductions.

The recent introduction of the Asiatic clam, *Potamocorbula amurensis*, into San Francisco Bay is a good example of the far-reaching effects that an exotic species may have on an ecosystem. *Potamocorbula* appeared in the Bay in 1986, probably as a result of accidental introduction in ship ballast water (Carlton et al. 1990, Nichols et al. 1990). It spread very rapidly, becoming abundant throughout the North Bay by mid-summer 1987 and

Figure III-B
Rate of Introduction of Exotic Species by Period



Data from Cohen and Carlton 1995.

is now very common in the South Bay, where during many years it is the dominant bivalve south of the San Mateo Bridge (Thompson 1996). The introduction of this filter-feeding clam has been associated with the disappearance of the summer phytoplankton bloom in the North Bay, a sharp decline in phytoplankton biomass in late 1987 (Alpine and Cloern 1992), and declines in some species of copepods (Kimmerer et al. 1994), *Neomysis mercedis*, and other zooplankton (Kimmerer and Orsi 1996), which depend on phytoplankton for food. *Potamocorbula* also bioaccumulates more metals than other Bay bivalves, which may increase the uptake of metals by bottom-feeding fish and birds (Thompson 1996). A shift in the diet of white sturgeon, a bottom feeder, to 73% *Potamocorbula* in Suisun Bay and 67% in San Pablo Bay has been suggested as a possible source of elevated selenium body burdens and a contributor to the decline of white sturgeon since 1986 (Dunn 1996).

Today, exotic animals reach California's inland waters by several means: as invertebrates carried in ballast water of large vessels, through fish / shellfish stockings by the government to support fisheries, in seaweed packing for live bait and lobsters, as biocontrol releases, as intentional or accidental releases by individuals, for scientific research, and via canals (Cohen and Carlton 1995). The end result is that the San Francisco Bay-Delta watershed is home to a huge number of introduced species. Fifty of the 133 fish species known to occur in California are not native and many local fish assemblages are dominated by introduced species (Moyle 1976a). The estuarine portion of the watershed has been described as the most invaded aquatic ecosystem in North America, with no shallow water habitat uninvaded by exotics and, in some regions, communities consisting entirely of introduced species (Cohen and Carlton 1995). Major introductions of non-native plants are discussed in the context of land use changes (below).

II.C. Livestock Grazing and Dairies

The fertile grasslands and savannas of the Central Valley, which historically provided rich forage to native herbivores, were converted to livestock pasture in the earliest days of European colonization of California. Cattle were first introduced in 1770, and were soon joined by wild horses, goats, sheep, and burros. By 1800, livestock herds numbered in the hundreds of thousands (Hornbeck 1983). By 1860, the number of cattle alone had reached three million (Jelineck 1982). The reign of the great livestock herds was relatively short-lived, as the explosion in human population after the Gold Rush brought competing uses for land. The great flood of 1862 followed by two years of drought killed most of California's cattle, and marked the end of open range within the Central Valley (Kelley 1989). Subsequently, grazing pressure shifted to higher elevations in the Sierra, which remained the last extensive area of unfenced rangeland. Much of the area between the intensely-farmed fields of the Central Valley and the mountains of the Coast Range and Sierra Nevada is currently devoted to cattle grazing. The first regulations to limit flock size and grazing period on federal land were enacted in 1900 (Beesley 1996).

The rapid buildup of livestock resulted in the replacement of native perennial bunch grasses by annual grasses from the Mediterranean - plants already well adapted to both intense grazing and the California climate. These invading grasses died in the summer leaving soils exposed to winter rains and resulting erosion, an effect that contributed to a "desertification" process that ultimately initiated an episode of gully and arroyo formation in the Coast Range and foothills, increasing sediment delivery to the main rivers (Figure III-C).

Livestock grazing in the Central Valley watersheds affects water quality and aquatic resources in a number of ways (SWRCB 1995). Grazing removes the vegetative cover and increases soil compaction, which reduces infiltration and increases runoff. This results in greater erosion of the soil. Domestic stock have a tendency to congregate near water bodies and rivers due to the amount of forage, presence of shade, and access to water. Consumption of riparian vegetation and trampling of stream banks results in erosion and siltation of streambeds which can kill fish directly, impact fish spawning, and destroy insects that fish rely on for food. Increased animal manure in streams raises the nitrogen level and increases bacteria levels. Nitrogen leads to increased algal growth and subsequent oxygen depletion which can kill fish and other forms of aquatic life. In addition, ammonia is toxic to aquatic life at low levels. Loss of streamside vegetation as a result of cattle trampling and grazing also leads to higher water temperatures and reduces the availability of insects for salmonids.

Confined animal facilities (dairies, poultry farms, beef feeding operations) also contribute to water quality degradation and adverse impacts on aquatic organisms. There are currently 1600 dairies in the Central Valley with an average of over 500 animals per dairy (UC Davis 1994). Over the last several decades, dairies have been relocating from rapidly urbanizing Southern California into the Central Valley. Dairies in the Central Valley produce as much wastes as 30 million people (Dairy Industry Fact Sheet). Dairy wastes, consisting of a rich brine of manure, urine, and water, are typically stored in lagoons and used to irrigate crops. The lagoons are often undersized and spill into surface waters during storm events. Dairy wastes are also frequently illegally discharged directly to receiving waters because there are too many cows, not enough irrigated lands, and too few regulators (Dirringer 1997). Dairy wastes discharged to streams raises nitrogen (including ammonia) and bacterial levels and reduces oxygen concentrations, adversely affecting aquatic life, as discussed in the preceding paragraph.

II.D. The Growth of Agriculture

Agriculture has grown rapidly over the last 150 years, and today it dominates the Central Valley landscape. In 1850, 2,700 acres were under cultivation in the Central Valley. This rapidly increased to 244,300 in 1859, 1,304,000 acres in 1869, and 1,953,000 acres in 1878. Most of this acreage was dry-framed. Today, there are 7.0 million acres under cultivation in the Central Valley, of which 6.8 million acres are irrigated (CDWR 1998). Irrigation in the Central Valley annually uses about 26 MAF of water, or 61% of

Figure III-C
Impacts of Overgrazing

A field near Nevada City at one time covered by grass. *"Its present condition resulted from the extermination of grass by overgrazing."*
Source: U.S. Geological Survey, Gilbert, G.K., Photo No. 3221

the total statewide applied urban and agricultural water (CDWR 1998). Rapid expansion of irrigated acreage occurred after the turn of the century, as motor-driven groundwater pumps opened up lands not served by river diversions and transportation technology expanded markets for the agricultural products.

II.D.1. Farming the Lowland Floodplains

First initiated on the Sacramento River, dry land wheat farming replaced cattle-ranching as the state's leading agricultural industry during the latter half of the 19th century. By 1854, California was exporting surplus wheat, and by 1889 the state led the nation in wheat production, with most of the crop exported to Europe. During the peak production period, 3.75 million acres of the Central Valley were dedicated to this crop (Kelley 1989). However, wheat farming became unprofitable by the end of the century, and by 1910, less than half a million acres remained in production (Kelley 1989). During the latter part of the wheat boom, other forms of dry land farming began to develop along the Sacramento River, close to navigation and hungry markets in Sacramento and San Francisco. By 1920, the Central Valley had become the nation's "fruit belt" (Starr 1985). At first, only the higher parts of the rivers' natural levees were cultivated, but the area of these landforms was artificially expanded to allow for increased production.

Flooding along the lowland rivers made profitable farming difficult. To encourage agricultural development, in the latter half of the 19th century the federal and state governments offered low-lying lands at cheap prices to those willing to "reclaim" the land. Approximately one million acres of such land were thereby transferred to private farmers in the Central Valley (Thompson 1961). During this period, landowners and competing drainage districts constructed levees and rearranged the lowland drainage system along property lines and political boundaries (Kahrl 1979). From a hydrologic perspective, the resulting levee system made little sense and was overwhelmed by every large flood throughout the rest of the 19th century (Kelley 1989). Nonetheless, the crude system of flood control achieved the farmers' primary objective of eliminating the smaller floods, thereby allowing profitable crops to be grown in most years.

During the 19th century, land reclamation along the Sacramento River concentrated on the naturally most productive sites: natural levees and floodplains. The flood basins, with their marshes and poorly drained soils, were left relatively undisturbed until about 1910, when the construction of the Sacramento Flood Control Project allowed the initiation of a rice-growing industry. Poorly drained flood basins were perfect for rice, a semi-aquatic plant that is kept partially submerged and receives continuous irrigation during much of the growing season. Rice rapidly replaced native wetland vegetation, and a large industry was in place in Butte, Glenn, and Colusa Counties by the 1920s

(Wilson 1979), when 75,000 to 160,000 acres were reported to be under cultivation (CDPW 1931d). Today, rice growing in the former flood basins occupies 517,000 acres (CDWR 1998).

However, as the major crop in the Sacramento Valley, rice has a long legacy of water-related problems. Rice uses large amounts of water (CVWUSC 1987, Lourence and Pruitt 1971, CDWR 1978) and alters downstream flow patterns by diverting water to flood the fields, releasing some of it later in the year. Downstream effects were sufficient to cause the City of Antioch to file suit in 1920, claiming that upstream diverters (principally rice farmers) had caused the salinity of its water supply to increase to unacceptable levels.

Rice farming has also caused water quality problems from its earliest days. In the 1920s and 1930s "*[a] steady run-off of highly vegetable and more or less mineralized drainage water occurs throughout the growing months*" and during harvest in September and October, a considerable portion of the flow of the Sacramento River was rice drainage. At that time "*the principal result of rice field drainage is a considerable increase in the incrusting and corrosive properties of the water and an extremely high plankton growth in the river. These properties introduce a difficult water treatment problem at Sacramento*" (CDPW 1931d, p. 390). After the introduction of pesticides, rice drainage caused large fish kills in agricultural drainage canals and taste problems for Sacramento's water supply. Rice drainage was also alleged to cause aquatic toxicity in the lower Sacramento River and to have contributed to the decline of striped bass (Fox and Archibald 1997, Bailey et al. 1994). Since the 1980s, the rice industry has worked diligently with regulatory agencies to solve these problems. On-farm management practices, primarily holding rice waters on the fields to allow pesticides to degrade, have dramatically reduced rice pesticide loads in the Sacramento River and associated aquatic toxicity. There have been no major fish kills attributed to rice pesticides since 1983.

On the San Joaquin River, floodplain reclamation occurred later, mainly between 1915 to 1930 (USCOE 1914, revised 1930). In some reaches, the levee system was set back from the actively meandering channel leaving a fairly intact riparian corridor. However, as flood flows were eliminated by the construction of upstream dams, lands within this corridor were cleared for agriculture.

The episode of wheat farming largely completed the displacement of native vegetation on most of the Central Valley floodplain, and the 50-year era of reclamation and drainage of overflow lands completely transformed the vegetation and morphology of the lowland floodplain and flood basins.

Agricultural development and practices have historically, and continue to, adversely affect the integrity of native ecosystems in a variety of ways. Natural floodplain habitats have been largely replaced by fields of crops, with a corresponding loss of primary productivity to local ecosystems. To protect the rich agricultural lands along the larger rivers, natural levees were raised and maintained at unnatural heights, inhibiting or preventing the natural and ecologically essential periodic exchange of materials between rivers and their floodplains. Irrigation diversions reduce total flow, cause sudden flow fluctuations, redistribute flows, adversely affect water quality, and entrain aquatic organisms.

Major water quality problems caused by agriculture include increased sedimentation and salinity, elevated water temperatures, and elevated concentrations of pesticides, heavy metals, and nutrients. Pollutants are carried by surface runoff and subsurface drainage into receiving waters. The chemical era of farming was launched during the Second World War, and concentrations of pesticides in receiving waters and biota exploded after about 1950 (SWRCB 1971). Fish and bird kills attributable to pesticides became common in the 1950s and were routinely reported by 1965 (CDFG 1965-1984). Virtually all of the pesticides that caused massive fish, bird, and mammal kills were banned or phased out in the 1970s and 1980s, and new chemicals have now taken their place. However, the residues of the persistent chlorinated pesticides remain, and sediments and biota collected from throughout the watershed still contain elevated concentrations of organochlorine pesticides and their breakdown products and ingredients, including PCBs, DDT, DDE, dieldrin, toxaphene, and chlordane. Concentrations of DDT in bottom sediments of the San Joaquin River are the highest among major rivers in the United States. Concentrations in fish and other organisms frequently exceed levels established by regulatory bodies to protect public health (Gilliom and Clifton, Pereira et al. 1996, SWRCB 1990, Brown 1996, Fox and Archibald 1997, Dubrovsky et al. 1998). Recent studies have also found elevated concentrations of many of these compounds in fish captured in San Francisco Bay (SFRWQCB 1994, Pereira et al. 1994). Fish concentrations are high enough to pose a public health hazard, and the State has issued an interim consumption advisory on Bay sport fish, including striped bass, but excluding salmon, anchovies, herring, and smelt (OEHHA 1994). Many of these persistent compounds are also endocrine disrupters, which are known to cause subtle, but at present poorly understood reproductive problems (Goodbred et al. 1997, U.S. EPA 1997).

Today, pesticides are used throughout the Central Valley, where 1,250 to 4,300 pounds are applied per square mile annually in the more intensely farmed areas (Brown and Caldwell 1990). They are ubiquitous in surface waters throughout the Central Valley and concentrations frequently exceed levels that are known to be toxic to aquatic organisms. Waters are also frequently chronically and acutely toxic to sensitive fish, invertebrates, and algae. Invertebrate toxicity is primarily due to organophosphate and carbamate pesticides, including methyl parathion, carbofuran, malathion, diazinon, and chlorpyrifos (Bailey et al. 1995, Fox and Archibald 1997).

The application of irrigation waters to fields erodes soils. Over one million acres of irrigated cropland are on highly erodable soils in the Sacramento and San Joaquin Basins. Sediments carried into nearby waterways clog fish gills and cover fish spawning habitat and benthic plants, a primary food source for some waterfowl (SWRCB 1994).

Soils on the west side of the San Joaquin Valley are derived from marine shales and release more harmful inorganic substances than those elsewhere in the Central Valley. Agricultural drainage from about 90,000 acres in this area was historically discharged to channels that convey water for the management of wetlands in duck clubs and in Federal and State wildlife refuges. These waters contained elevated concentrations of toxic elements, including selenium, boron, chromium, lead, molybdenum, vanadium, and zinc. Selenium, in particular, accumulated in local biota, and in 1983 widespread deaths and deformities of waterfowl attributable to this metal were documented (Figure III-D). Currently, drainage from this area is discharged into the Grassland Bypass Channel which connects to the San Luis Drain. The drain discharges into Mud Slough and ultimately the San Joaquin River. The subsurface drainage water has thus been removed from the wetland channels. The farmers in this area are required to reduce the load of selenium discharged to the San Joaquin River to less than 8,000 pounds annually.

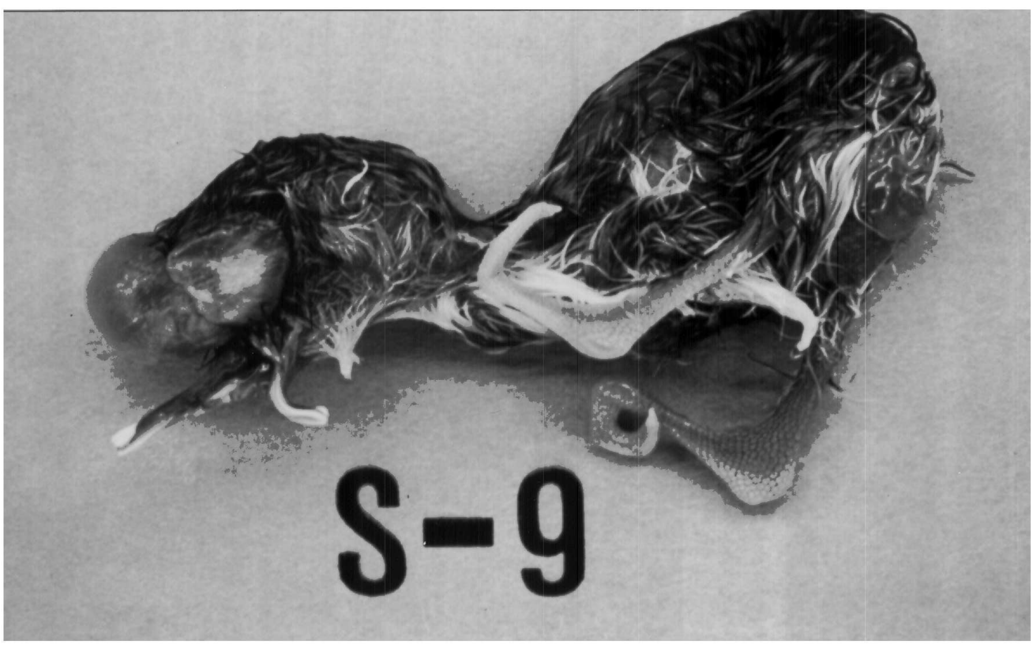
II.D.2. Farming the Delta

The Delta, endowed with rich organic peat soils and abundant fresh water, early caught the interest of immigrant farmers weary of toiling in the gold mines. However, its resources could not be exploited without draining and reclaiming the marshes and providing flood protection.

Early efforts at reclamation of Delta wetlands for agricultural production began in the 1850s, and consisted of small-scale, individual projects using hand labor. Between 1852 and 1857, portions of Grand Island, Rough and Ready Island, Andrus Island, Roberts Island, and Union Island were reclaimed in this manner (Rose et al. 1895). However, most of these early levees, with the notable exception of the Grand Island levee, were low (about 3 ft) berms constructed from tule sod (peat) built atop natural levees. Peat is a generally unsuitable building material for levees, as it is structurally unstable and readily dispersed by wind and water. These early structures were usually washed away during the first major flood. Thus, it soon became evident that large-scale efforts

Figure III-D
Effects of Pollution

(A)



(B)

Black neck stilt embryos: (A) normal embryo; (B) embryo from a Kesterson Reservoir nest (1985), which averaged 75 ppm dry weight selenium in eggs. Deformations typical of selenium exposure can be seen, such as missing eyes, deformed bills and/or malformed limbs.
Source: Joe Skorupa, U.S. Fish and Wildlife Service.

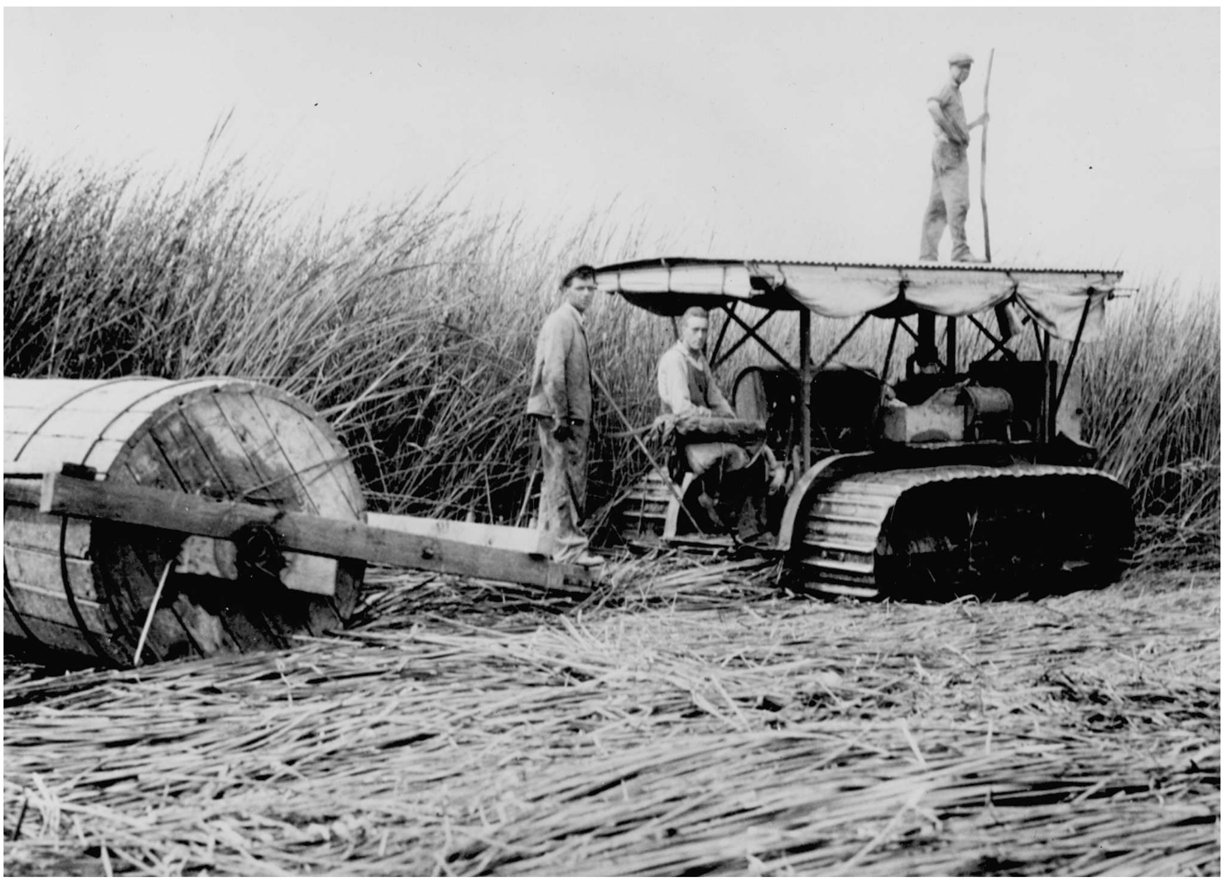
would be required to profitably reclaim Delta wetlands, and groups of individuals banded together in cooperative organizations for that purpose. Swampland or Reclamation Districts were formed in large numbers immediately after the passage of the Swampland Act in 1861. Still, the magnitude and the cost of the work was much greater than estimated by early promoters, and by 1870, only 15,000 acres had been permanently reclaimed (CDPW 1931c, Thompson 1957). With the passage of the Green Act in 1868, which removed the limits on acreage that one individual could obtain, reclamation accelerated. The way was now cleared for corporate speculators and wealthy individuals to carry out extensive reclamation.

In the late 1870s, levee-building advanced with the use of the steam-powered dredge, which allowed sand, silt, and clay to be economically dredged from the channels to create more reliable levees. By 1880, over 100,000 acres had been reclaimed, about three-quarters of which had been tidal wetlands. By 1900, the area reclaimed had increased to over half the area of the Delta (235,000 acres), including an estimated 166,000 acres of wetlands (Figure III-E) (CDPW 1931c). The process was essentially completed by 1930, with 313,000 acres of former tidal and non-tidal wetlands behind constructed levees (SFEP 1991, Atwater and Belknap 1980, CDPW 1931c). Today, most of the Delta lowlands are protected by hundreds of miles of levees to keep the land from being flooded by surrounding waters, which can be over 20 feet higher than the land surface.

A wide variety of crops have been and are grown in the Delta, including corn, asparagus, grains, alfalfa, pasture, sugar beets, fruit, safflower, nuts, and tomatoes. Water is pumped directly from Delta channels into some 1,800 irrigation diversions. Most of these are unscreened 6 to 18 inch diameter siphons and pumps, with intakes some 2 to 3 feet above the channel bottom, which intermittently supply farms during the irrigation season. During the peak summer irrigation season, diversions from these facilities collectively exceed 4,000 cfs (CDWR 1995a, Spaar 1994) and entrain large numbers of eggs, larvae, and juvenile fish, frequently more than at the CVP and SWP pumps in the southern Delta (Brown 1982, Griffin 1993, Hayes 1994, Spaar 1994).

Historically, the Delta was home to a large number of canneries that processed and packaged its bounty for shipment to market. One of the earliest pollution surveys in the Delta, between 1925 and 1930, noted that below Sacramento "*fruit wastes run without treatment to drainage canals, but the asparagus butts are dumped directly into the river... and may be seen floating there in white masses until fall or winter. In the course of a season about 14,000 tons of butts... are disposed of*" (CDPW 1931d, p. 394). Today, agricultural drainage from Delta farmlands contains elevated concentrations of organic carbon, which is converted to carcinogenic disinfection byproducts when the waters are treated for drinking water. The drainage and runoff from farmlands also contain chemical

Figure III-E
"Tule Breakers"



Reclaiming the Delta for agriculture.
Source: Phillips Library, Tiburon, California.

residues, primarily pesticides, which are toxic to phytoplankton, invertebrates, and larval fish and have caused mortality and reduced growth and reproduction in exposed organisms (Bailey et al. 1995, Fox and Archibald 1997).

In addition to agricultural pollution, subsidence and levee failure and flooding have been and remain major problems in the Delta. The elevation of the natural Delta was at about sea level. Today, much of the central lowland area occupied by peat and other organic soils has subsided at a rate of about 3 inches per year or some 10 to 21 feet on 17 separate islands. This Delta subsidence is generally believed to be caused by oxidation of organic soils, wind erosion, soil shrinkage from drying, and burning from reclamation and weed and pest control. Subsidence is currently a major concern in the Delta because it increases the water pressure on levees and, therefore, the probability of levee failure and flooding. Subsidence also depletes the organic-rich soils upon which Delta agriculture depends (CDWR 1995b, CDWR 1980).

Waterside slopes of levees are subject to erosion from wind-generated waves, boat wakes, and water flowing past them at high velocities. Levee failures are common in the Delta. Since original reclamation, each of the 70 islands or tracts has flooded at least once (CDWR 1995a). Further, because much of the Central Delta and portions of the Southern Delta are underlain with soils that have a moderate to high potential for liquefaction, Delta levees also could fail seismically in major earthquakes (CDWR 1992), with devastating consequences for landowners and others dependent on Delta water. Levee failures cause millions of dollars of property damage. The resulting flooding draws salty water into the Delta, unless offset by reservoir releases or high winter flows, adversely affecting the quality of water for agricultural and domestic uses. Many recent failures have occurred in the summer-fall low flow period and were accompanied by salinity intrusion, including Webb Tract in June 1950, Andrus-Brannan Island in June 1972, Jones Tract in September-October 1980, and MacDonald Island in August 1982 (CDWR 1995b).

II.D.3. Farming near San Francisco Bay

During the 1880s, large areas of tidal marsh adjacent to San Pablo and Suisun Bay were reclaimed for agriculture. However, it was not until the advent of affordable pumps that the draining of much of this land was made economically viable. The slightly brackish waters of Suisun Bay appeared to make the marsh soils more farmable than west of Carquinez Strait. However, continuing difficulties in farming led eventually to the reflooding of much of the reclaimed land (Van Royen and Siegel 1959) around Suisun Bay. Much of this acreage was then acquired by duck hunting clubs for waterfowl. Some of the levees have been re-built to provide better management of water levels for wetland habitat enhancement on the now-subsided lands. Today, only a portion of Grizzly Island remains in agricultural production. Much of the land bordering the South Bay, formerly devoted to farming, is today the home of Silicon Valley, the industrial heart of the late 20th century electronics revolution, and bedroom communities that house its employees.

II.E. Mining

A variety of mining practices have had severe and lasting impacts upon watershed ecology, resulting in physical alteration of habitat, alteration of hydrogeomorphic processes, and severe and continuing water quality problems. Iron, copper, cadmium, zinc, gold, silver, mercury, and other substances were mined from the early 1850s through the first half of this century, when many of the mines were shut down because they were no longer profitable. Mining of sulfide ores (pyritic ores) for iron, copper, cadmium, zinc, and other nonferrous metals occurred primarily in the Lake Shasta area and the foothills of the Sierra Nevada. Mining for gold centered in the Sierra Nevada foothills between Plumas County to the north and Madera County to the south. Mercury mining occurred primarily in the Coast Ranges, the largest being the New Almaden District south of San Jose, New Indria to the southeast, and the region around Clear Lake. The majority of the mining occurred north of Sacramento. Some asbestos mining occurred in the Coast Ranges within the San Joaquin Basin. Gold and copper mining occurred in the Sierra Nevada foothills along the Cosumnes, Mokelumne, and Calaveras Rivers, which drain into the Delta.

Large-scale mining operations were initiated by the discovery of gold at Sutter's Mill in January of 1848. Early gold mining practices were particularly destructive, as miners quickly discovered that displacing rivers from their channels provided the easiest way of gaining access to the richest (alluvial) gold deposits. Thus, during the 1850's, gold-bearing rivers of the Mother Lode region, from the Feather River to the Tuolumne River, were blocked by temporary dams and channeled out of their beds as soon as spring flows receded. In 1853, the introduction of hydraulic mining techniques allowed mining on a much greater scale (Kelley 1989). This new extraction procedure entailed directing powerful jets of water to blast away surface soils and erode gold-bearing hillside gravels (Figure III-F). Soon, the developing technology made it feasible and profitable for mining corporations to organize large-scale operations that exploited more deeply buried deposits, and operations increased throughout the Mother Lode during the 1870s and 1880s.

Water supplies for the giant hydraulic jets were obtained by diverting water from nearby rivers and conveying it through extensive systems of sluices and pipelines. This process required substantial water supplies, and completely dried out much of the middle reaches of the river channels during summer months. In 1880, it was estimated

Figure III-F
Hydraulic Gold Mine, 1908

"*The water is conveyed by pipe, under a head of several hundred feet, and delivered through a nozzle that can be turned in any direction. The jet washes the auriferous earth from the cliff and thence to a sluice, seen at left. The sluice is several hundred feet long and contains pockets of mercury by which the gold is caught*."
Source: U.S. Geological Survey, Gilbert, G.K., Photo No. 3222.

that there were nearly 6,000 miles of mining ditches and an additional 1,000 miles of branches that distributed water to gold mines. Smaller streams of the foothill region often naturally dried up by the middle of June or July. Thus, a system of storage and distributing reservoirs was required to sustain mining operations through the dry season. Many early reservoirs were created by damming the outlets of small lakes (Harding 1960, Bowie 1905). In 1880, an estimated 540,000 to 700,000 acre-feet per year ("af/yr") of water was used for hydraulic mining in the Sacramento Basin, of which up to about 150,000 af was stored in reservoirs (Bowie 1905). In the Delta and San Joaquin Basin, an estimated additional 170,000 to 200,000 af/yr was used. However mining reservoir capacity in this region is unknown (Mendell 1882, Bowie 1887, Hall 1880, Part II). In most cases, this form of reservoir storage probably had a relatively minor effect on downstream flows during the winter and spring, when flows were high. However, releases from these reservoirs probably locally increased the otherwise low downstream summer and fall flows compared to natural conditions.

In addition, enormous amounts of sediment (called "hydraulic mining debris") were washed into local rivers and streams (Figure III-G). Gilbert (1917) estimated that about 1.5 billion cubic yards, about eight times the amount of material excavated in the building of the Panama Canal, was washed from the hills by these mines. The disposal of these sediments in Central Valley streams proved highly disruptive to navigation, flood control, agriculture, and the ecology of many native species. The "*Sierra mudwave*" caused by hydraulic mining took about 100 years to work its way down river and through the estuary. At the Yuba River narrows, for example, the channel bed elevation increased by 85 feet, while the Sacramento River bed increased by 13 feet near the City of Sacramento (Gilbert 1917). At Marysville, the head of navigation for shipping on the Feather River during the 1850s, the river was as deep as 30 feet before the onset of hydraulic mining. By 1878, accumulations of sediments had elevated the river bed to the height of the surrounding floodplain (Dana 1939). In some locations, mining debris formed dams that effectively obstructed the discharge of major rivers (e.g. Feather River) into the Sacramento River. In the Sacramento Valley, mining debris deposits covered over 39,000 acres of newly established farmland (Kelley 1989), and huge amounts of debris were deposited in the natural flood basins. This substantially altered the natural hydrology of the Feather, Yuba and Sacramento rivers below the mouth of the Feather, aggravating flooding and counteracting the natural effectiveness of the flood basins to attenuate flood flows.

The Sawyer Decision (1884), now considered California's first environmental law, suspended most hydraulic mining in the Sierra. Subsequently, rivers gradually began re-establishing natural channel characteristics. As the era of hydraulic mining came to a close, the mining industry turned to the lowland, alluvial floodplains as a source of gold. By about 1910, the technology of deep dredging had been developed to exploit

Figure III-G
A Sierra Canyon Clogged by Mining Debris, 1908

"*The surface of the debris constitutes a broad plain that is covered by water only when the stream is in flood. The low-water channels traverse this plain. [At the time the photo was taken] most of the canyon deposits had been removed.*"
Source: U.S. Geological Survey, Gilbert, G.K., Photo No. 3205.

these deposits, and extraction operations were initiated on all the Sierra rivers from the Feather south to the Merced. These dredges excavated the river channels and floodplain to the depth of bedrock, processed the alluvium to extract gold and other precious metals, and redeposited their tailings in long windrows on the floodplain. This process inverted the soil profile, placing top soil on the bottom and cobble on the top, thereby preventing or inhibiting the re-establishment of natural vegetation types. On the Merced River, tailings covered about 6,000 acres (7.6 mi^2) (Vick 1995). This type of operation finally ceased by 1967 (Kattelmann 1996).

Several thousand mines have been worked and abandoned in these areas, including over 800 in the Sacramento River Basin alone. They have discharged, and in many cases continue to discharge, large amounts of sediment-laden, acidic, metal-laced drainage, which has adversely impacted streams immediately below their discharge points. Acid mine drainage, by far the greatest water quality problem, forms primarily when water and oxygen come in contact with mine tailings, waste rock piles, and underground tunnels and workings of mines that process pyritic ores. This reaction produces sulfuric acid with a pH of about 3, which dissolves metals in the surrounding rock. This drainage continues to discharge into surface waters, has low pHs, high concentrations of copper, cadmium, and zinc, and lower concentrations of other metals including nickel, lead, and chromium. Although primarily associated with sulfide ores that were processed for iron, copper, cadmium and zinc, acid mine drainage also can form in wastes from gold and mercury mines. Discharges from these mines have completely eliminated aquatic life from 54 miles of streams, caused numerous fish kills, and violations of state water quality standards on cadmium, copper, and zinc, contributing over 80% of the discharges of these metals to surface waters (Brown and Caldwell 1990, CDFG 1965-1995, Larry Walker Associates 1992).

Mercury and arsenic are a particularly pernicious legacy of gold mining. Both were widely used in the amalgamation process employed to extract metal from ores. Runoff from abandoned mines contains high concentrations of both, and today, water quality standards are locally exceeded in the Sacramento River Basin and Delta. Mercury also occurs naturally at elevated levels in the Coast Range, and high localized concentrations are present in the watersheds of the Putah and Cache Creeks, where many cinnabar mines are located. About 7.6 million pounds of mercury from cinnabar mines in the Coast Range were transported to the Sierra Nevada gold mines for use in gold amalgamation. Much of that mercury remains in the proximity of inactive gold mines or in downstream sediments, especially in the Feather, Bear, and Yuba River watersheds, where it is known to bioaccumulate in aquatic organisms.

In addition to metals, California's rivers have been (and continue to be) mined for sand and gravel (or "aggregate"), which is used for construction material (Figure III-H).

Since World War II, urbanization in California has produced an enormous demand for sand and gravel, with current annual production estimated at 130 million tons and valued at $500 million (Sandecki 1989). Until the late 1960s, aggregate operations removed sand and gravel by excavating deep pits in the river bed. In the Merced River, these were as deep as 30 feet below the natural river bed. In many rivers, pit excavation was replaced in the 1970s by bar skimming, in which sand and gravel are scraped from the surface of gravel bars without excavating deep pits. This practice still continues throughout the state in areas such as Cottonwood Creek, a tributary to the Sacramento River.

Both forms of aggregate mining have adversely impacted stream channel morphology by creating large in-channel lakes (pit mining only), and unnaturally altering channel incision, groundwater tables, and substrate composition. Concerns over the impacts of instream mining have shifted operations in some regions (e.g., Cache Creek in Yolo County) from the active channel to the adjacent floodplains or terraces. In this type of mining, the operators excavate pits in the floodplain or terrace adjacent to the active channel. However, because these pits are separated from the active river channel only by a narrow, earthen berm, they are vulnerable to capture by the river during high flows. Once captured, these pits act as sediment traps (which interrupt the downstream transport of sediment) and form lake-like zones in the channel. In the Merced River, captured terrace pits and in-channel mines form 5.6 miles of in-channel lakes in the 17-mile salmon spawning reach between Snelling and Cressey (Vick 1995). As of 1993, instream gravel mining was still taking place on a number of system creeks (e.g., Cottonwood, Cache) and rivers (e.g., Bear and Yuba) (CSLC 1993). Elsewhere, major terrace pit gravel extraction within the active floodplain of the lowland rivers continues. At present, the main constraint in permitted extraction rates is the level of sustainable yield, a quantity determined by sediment inflow estimates rather than downstream impacts.

II.F. Urbanization

The discovery of gold in 1848 sparked a shift in the distribution of human populations away from Spanish settlements in southern coastal regions to San Francisco, the gold mining regions in the Sierra Nevada, and support facilities in the Central Valley. The population of California at the end of 1848 was 15,000. By 1850, when California became a state, it had reached 93,000 and was concentrated in those three regions. By 1860, the state’s population had climbed to 380,000. At that time, over half of California’s people lived in gold-mining districts and the nearby Sacramento Valley, and another quarter in the Bay Area. Eventually, a burgeoning agriculture and vigorous manufacturing base grew out of the demise of gold and other mining activities. Much of the inhabitable land in the Central Valley was settled and cultivated

Figure III-H
Gravel Mining Pits

Aerial view of in-channel and terrace pits left by aggregate mines on the Merced River.
Source: U.S. Bureau of Reclamation, 1993.

by 1880, although less than 10 percent was irrigated. The major pattern of growth in the Central Valley from 1900 to 1950 was the conversion of flat agricultural lands to suburban and urban areas. The period from 1975 through the present has seen a growth shift from the valley to the Sierra foothills. In 1985, most land in the Central Valley was either rangeland or agricultural, with only about 2 percent classified urban.

By far the most urbanized portion of the watershed has been, and remains, the greater San Francisco Bay region. As 49ers gave up the quest for gold, mining districts began losing population by the 1860s, and towns as large as 10,000 rapidly became "ghost towns." The majority of these populations relocated in the Bay Area, which has continued to expand ever since. By 1975, about 28 percent of the state's population lived in the Bay Area and Delta. Today, over 6 million people (20% of California's population) reside in the nine counties comprising the Bay Area, while another 5 million reside in the 28 counties that make up the remainder of the Central Valley watershed.

Reclamation of tidal wetlands along the margins of Central and South Bays rapidly accelerated in response to this population boom, and marshes and mudflats around the Bay were reclaimed for urban uses. Between 1920 and 1960, most of the remaining natural tidal wetlands around San Francisco Bay had been drained and filled. This practice halted after 1965, but by then, an estimated 77% of the natural wetlands surrounding greater San Francisco Bay had been destroyed (see Section IV.D.1) (Van Royen and Siegel 1959, Nichols and Wright 1971).

The rapid expansion of human populations throughout the state has affected the watershed's resources by creating a need for additional water diversion from the system, and has been accompanied by severe impacts on water quality from domestic and industrial wastes and urban runoff. Untreated domestic sewage from household uses of water was discharged into streams adjacent to urban areas from the earliest times. These discharges contained elevated concentrations of nutrients, bacteria, and oxygen-demanding organic compounds that depleted dissolved oxygen in the receiving waters. Foul odors and floating raw sewage were common in the 19th and early 20th centuries.

Discharges of untreated sewage contributed to the decline of fish and shellfish. Lockington, who studied the fishes of the Pacific Coast in the 1870s, remarked in the Biennial Report of the State Board of Fish Commissioners, that the fishery had declined from over-fishing and boat traffic, "*but the injury from this source is small compared with that inflicted by the constant fouling of the waters and consequent destruction of life by the foetid inpourings of our sewers...into the waters to pollute them for the destruction of creatures...*" (Skinner 1962, p. 28).

By the end of the 19th century, anoxic conditions and contamination with fecal bacteria were common near points of sewage discharge, particularly in the vicinity of major population centers. Shellfish beds ringed the Bay, and commercial shellfish populations severely declined in the early part of the century due to pollution. In 1932, gross sewage pollution forced the California State Board of Public Health to establish a permanent quarantine prohibiting shellfishing in San Francisco Bay. As early as 1890, naturalists noted that discharges of domestic sewage reduced the amount of suitable habitat for water bird populations, and bacteria in the discharges caused avian botulism and cholera. Waterfowl diseases were common in the Bay (Skinner 1962, Oceanic Society 1984).

Pollution studies in the Central Valley between 1925 and 1930 documented numerous direct discharges of raw sewage directly into water courses. In Sacramento in 1930, which then had a population of 96,000 and treated its water supply (coagulation, sand filtration, chlorination), "*[t]he only treatment, if it may be so called, is passing the sewage through coarse screens to remove foreign matter that might damage the pumps*." The same study noted that "*hygienically, the reputation of the river [San Joaquin] is bad*" (CDPW 1931d, pp. 391, 410). In the Delta, about 80% of the population or some 17,000 people had "*sewers directly into the main drainage system of each island or has privies built over drain ditches*" (CDPW 1931d, p. 409). Typhoid fever was widespread in Sacramento before that city started treating its water supply. Between 1925 and 1930, 451 cases were reported in the river areas of Contra Costa, Sacramento, San Joaquin, Solano and Yolo counties (CDPW 1931d).

Studies of pollution in the Bay in the 1950s (Filice 1954-1959) and 1960s (McCarty et al. 1962) documented that toxicity and anaerobic conditions were common, particularly in the vicinity of sewage outfalls along the east and south shorelines of the Bay. Some publicly owned treatment works (POTWs) began primary treatment in the early 1950s and secondary treatment in the 1960s to remove biochemical oxygen demand, suspended sediments, and nutrients. However, large scale implementation of treatment did not occur until state (Porter-Cologne Water Quality Act of 1969) and federal (Clean Water Act of 1972) measures established minimum treatment requirements.

Today, over 22 major and many small municipal wastewater treatment plants discharge about 270 million gallons per day of treated wastewater into surface waters in the Central Valley. Over 25 major and many smaller industrial plants discharge 1.1 billion gallons per day of wastewater, including pulp and paper mills, sand and gravel mines, food processors, fish hatcheries, and power plants. Some 41 municipal wastewater treatment plants discharge over 700 million gallons per day of treated wastewater into the Bay. Six refineries and ten other major industrial facilities including chemical plants, a steel mill, C&H sugar, airports, and manufacturing facilities discharge an additional 60 million gallons/day of treated wastes. Numerous other smaller industrial facilities and power plants also discharge treated waste into the Bay.

Trace contaminants remain a concern in waters near highly urbanized areas of the watershed. In a comprehensive inventory of major discharges in the late 1980s, the most frequently detected classes of pollutants were trace elements and volatile organics. The most frequently detected toxic metals are zinc, copper, chromium and nickel, but arsenic, cadmium, lead, mercury, and silver are also frequently detected. Aquatic invertebrate toxicity, which is widespread throughout the Bay and valley, is generally attributed to organophosphate insecticides, primarily diazinon and chlorpyrifos.

Urban runoff, the other major source of pollutants from urban development, has emerged as one of the major sources of pollutants in the watershed. Urban runoff is that portion of rainfall or artificially applied water which drains from developed, urban watersheds and flows via natural or man-made drainage systems into surface waters. Most urban runoff occurs during winter and spring rainfall. However, dry season runoff from irrigation and washoff practices can also be substantial. Most urban runoff is discharged directly into receiving waters with no treatment. San Francisco and a portion of Sacramento have combined sewer systems, which collect both raw wastewater and urban runoff. During large storm events the combined wastewater and urban runoff frequently exceed the capacity of the treatment system and receive minimal or no treatment prior to discharge to receiving waters.

Urban runoff contains metals, pesticides, hydrocarbons, nutrients, pathogens, and suspended sediment. Copper, lead, and zinc are the primary metals of concern in urban runoff. Arsenic, cadmium, chromium, and nickel are also common. Synthetic organic chemicals, including pesticides, primarily from household and garden uses of chemicals, are also present, though generally at lower concentrations than metals. Hydrocarbons and polycyclic aromatic hydrocarbons, primarily from vehicle and road use, are common constituents. Urban runoff also causes elevated levels of turbidity, pathogens, and nutrients in waterways following storms.

In the Bay Area, urban runoff is the principal source of pollutants, contributing up to 13,000 tons/yr to the Bay, of which 90 percent is hydrocarbons, 3 percent is PCBs, 6 percent is metals, and the balance chlorinated hydrocarbon pesticides. In the Central Valley, urban runoff contributes up to 3,600 tons/yr of pollutants, with similar proportions of hydrocarbons, metals, PCBs, and pesticides (SFEI 1987, Montoya 1987).

The Regional Water Quality Boards have been investigating the toxicity of urban runoff to aquatic organisms. Most samples of urban runoff that have been tested are toxic to invertebrates or contain concentrations of diazinon and chlorpyrifos that exceed water quality criteria for the protection of aquatic life. Some toxicity to fish and algae has also been reported. Most of the toxicity is believed to be due to diazinon and chlorpyrifos, which are used for landscaping, gardening, and in flea dip products (Bailey et al. 1995).

II.G. Water Resource Management

II.G.1. Surface Water Diversion, Storage and Redistribution

Since the earliest days of California's colonization by European settlers, surface water diversion was used to supply the needs of mines, farms and settlements. In the early stages of Central Valley agricultural development, irrigation efforts were limited by a lack of capital to build large storage facilities (Worster 1984). A series of low diversion dams were constructed in the 1860s and 1870s on San Joaquin River tributaries to divert summer flows into simple irrigation ditches, but lack of capital precluded the construction of larger dams at this time. By 1900, only about 800,000 acres of land were irrigated in the San Joaquin Valley (CDPW 1931a).

The passage of the Irrigation District Act (Wright Act) in 1887 permitted communities to form irrigation districts, opening the door for irrigation districts to accumulate the capital necessary to build large storage reservoirs, and by the 1920s major dams were under construction on the Tuolumne, Merced, and Stanislaus rivers. By 1921, 74 irrigation districts provided water to one-third of the irrigated acreage in the state (Worster 1984).

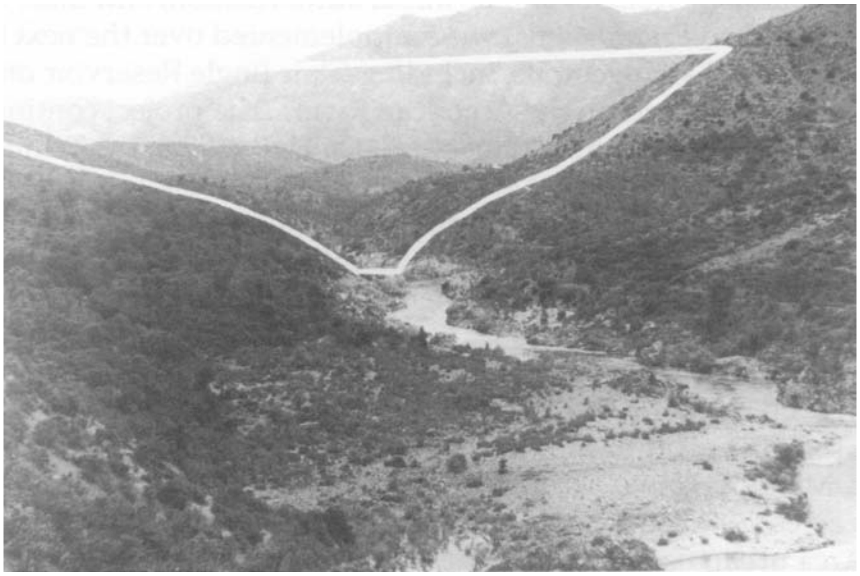
With the formation of irrigation and municipal utility districts, the construction of larger dams became feasible. By 1926 large dams (>100,000 acre-feet storage capacity) had been built on the North Fork Feather River, Stevenson Creek, the Tuolumne River, the Merced River, and the Stanislaus River. The City of San Francisco constructed O'Shaughnessy Dam on the Tuolumne River, forming Hetch Hetchy Reservoir in 1923. Currently 250,000 acre feet of water is diverted from the Tuolumne River through the Hetch Hetchy Aqueduct to provide municipal, industrial and irrigation water to the San Francisco Bay Area. East Bay Municipal Utility District completed Pardee Dam on the Mokelumne River and the Mokelumne Aqueduct in 1929. An average of 180,000 acre feet of water is diverted from the Mokelumne River and transported to East Bay communities via the Mokelumne Aqueduct.

Primarily to address the San Joaquin Valley's continually increasing agricultural demands at the time for a secure and affordable water supply, the Central Valley Project (CVP) Act was approved in 1933. This Act authorized construction of the initial features of the CVP, a system of dams and canals designed to store and divert water from the Sacramento, San Joaquin and other Central Valley rivers for agricultural uses in the San Joaquin Valley. Construction began in 1937 with the Contra Costa Canal. The first power sale from Shasta (Figure III-I), the first large dam designed to provide substantial interannual carryover storage, occurred in 1944, and the first delivery of water to irrigators in the San Joaquin Valley occurred in 1951. Shasta was designed to accommodate agricultural irrigation needs, repulse salinity intrusion in the Delta and provide flood control benefits. By drawing down the reservoir level prior to winter flood seasons, maximum flood releases below Red Bluff could be limited, thereby providing a measure of flood control. With a capacity of 4.5 MAF, equal to 23% of the total Sacramento Basin runoff, Shasta provides flood control for the entire Sacramento Valley. Power generation provided some of the electricity needed to pump water out of the Delta to the CVP irrigation units further south. Navigation was aided by maintaining minimum flows of 5,000 cfs along the Sacramento River. Water quality in the Delta could be improved through summer releases from Shasta, which counteracted somewhat increased salinity intrusion during the dry season that would otherwise be caused by removal of river waters by agricultural diversions.

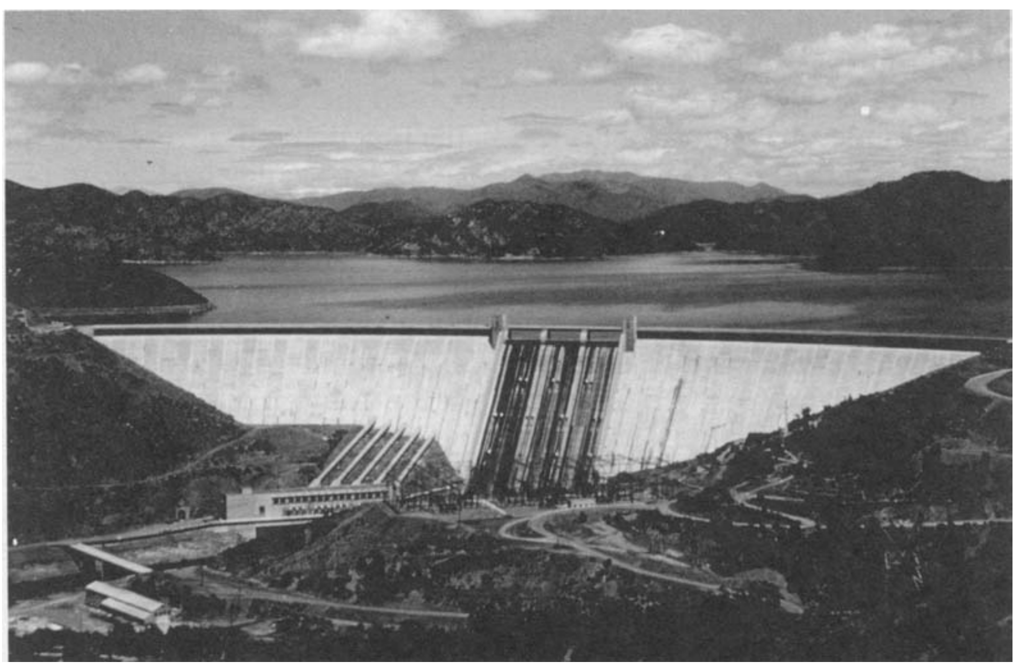
Friant Dam, completed in 1941, began to deliver water for agricultural use in 1949. Almost all water stored at Friant is diverted directly to the Friant-Kern and Madera irrigation canals, rather than being released first into natural channels for capture downstream, as with Shasta. In exchange for the water diverted at Friant, the Bureau of Reclamation built the Delta-Mendota canal in 1952 as part of the CVP to satisfy riparian water rights on the San Joaquin River below Mendota. The Delta-Mendota Canal carries water from the Delta to Mendota Pool where it is released into irrigation canals and the river for use by irrigators.

The CVP was not operated without problems for its intended beneficiaries. The temporal redistribution of “natural” flows by large upstream storage reservoirs, in combination with artificially heightened levees, caused water levels in streams to rise above the natural ground surface level. This caused unnatural seepage of water from river channels through and / or under confining levees, waterlogging soils and damaging crops. Seepage problems were first reported in 1937-38 and accelerated with the construction of upstream storage reservoirs, particularly Shasta. The most severe

Figure III-I
Shasta Dam



(A)



(B)

(A) Dam site on the Sacramento River before construction.
(B) Shasta Dam.
Source: California History Room, San Francisco Public Library.

problems of this nature occurred along the Sacramento, Feather, Yuba, and Bear Rivers (CDPW 1955, CDWR 1967).

The CVP continued expanding well beyond its initial authorization, and these major storage structures (Shasta and Friant Dams) were supplemented over the next thirty years by a series of additional storage units, including Clair Engle Reservoir on the Trinity River and Folsom Reservoir on the American River. The project continued to expand through the 1960s, adding the Sacramento Canal Unit (1950), the Trinity River Division (1955), the San Luis Unit (1960), New Melones Unit (1962), Auburn-Folsom South Unit (1965), the San Felipe Unit (1967), and New Melones Dam on the Stanislaus River, completed in 1979. As currently operated, the CVP stores winter and spring runoff on the Sacramento, Stanislaus, Trinity (which is outside the Central Valley watershed), and San Joaquin rivers. Stored water is released as needed to users in the San Joaquin Valley via the Delta-Mendota and Friant Kern Canals, while releases from Shasta Dam are conveyed down the Sacramento River, through the Delta, and then diverted south by a series of giant pumps located near the town of Tracy which redirect water into the Delta-Mendota Canal. Today, the CVP (Figure III-J) provides irrigation to about 1.2 million acres (Sandberg and Manza 1991), and also provides water to several major Bay Area urban users (Santa Clara Valley Water District and Contra Costa Water District).

The water needs of California increased rapidly with the urban population boom of the post-WWII era. The Legislature created the Water Resources Board in 1945 and directed it to develop a plan to meet California's water needs (Hundley, 1992). In 1951 the state issued the California Water Plan and proposed the Feather River Project, later renamed the State Water Project (SWP), as its first project. After numerous political skirmishes, the SWP's first deliveries were made to Plumas County and the Livermore Valley in 1962, to Santa Clara Valley by 1965, to Napa County and the San Joaquin Valley in 1968, and to Southern California in 1971. This project, built and operated by the California Department of Water Resources, consists of a system of reservoirs and canals that store water in Lake Oroville on the Feather River and release it downstream to the Delta, where it is distributed to customers in the Bay area via the North Bay and South Bay Aqueducts, and to customers in central and southern California via the California Aqueduct. The California Aqueduct, fed by the Banks Pumping Plant in the Delta, carries water southward through the San Joaquin Valley, over the Tehachapi Mountains, and to southern California (Figure III-K). Today, this system delivers an average annual total of about 2.3 million acre-feet. With full build-out the project is contracted to deliver 4.2 million acre-feet annually.

As of today, a total of 660 dams, having a capacity of 30.7 million acre-feet (which is nearly equivalent to the average annual unimpaired runoff), have been constructed in

Figure III-J
Major Central Valley Project (CVP) Facilities

Figure III-K
State Water Project Facilities

Source: California Department of Water Resources

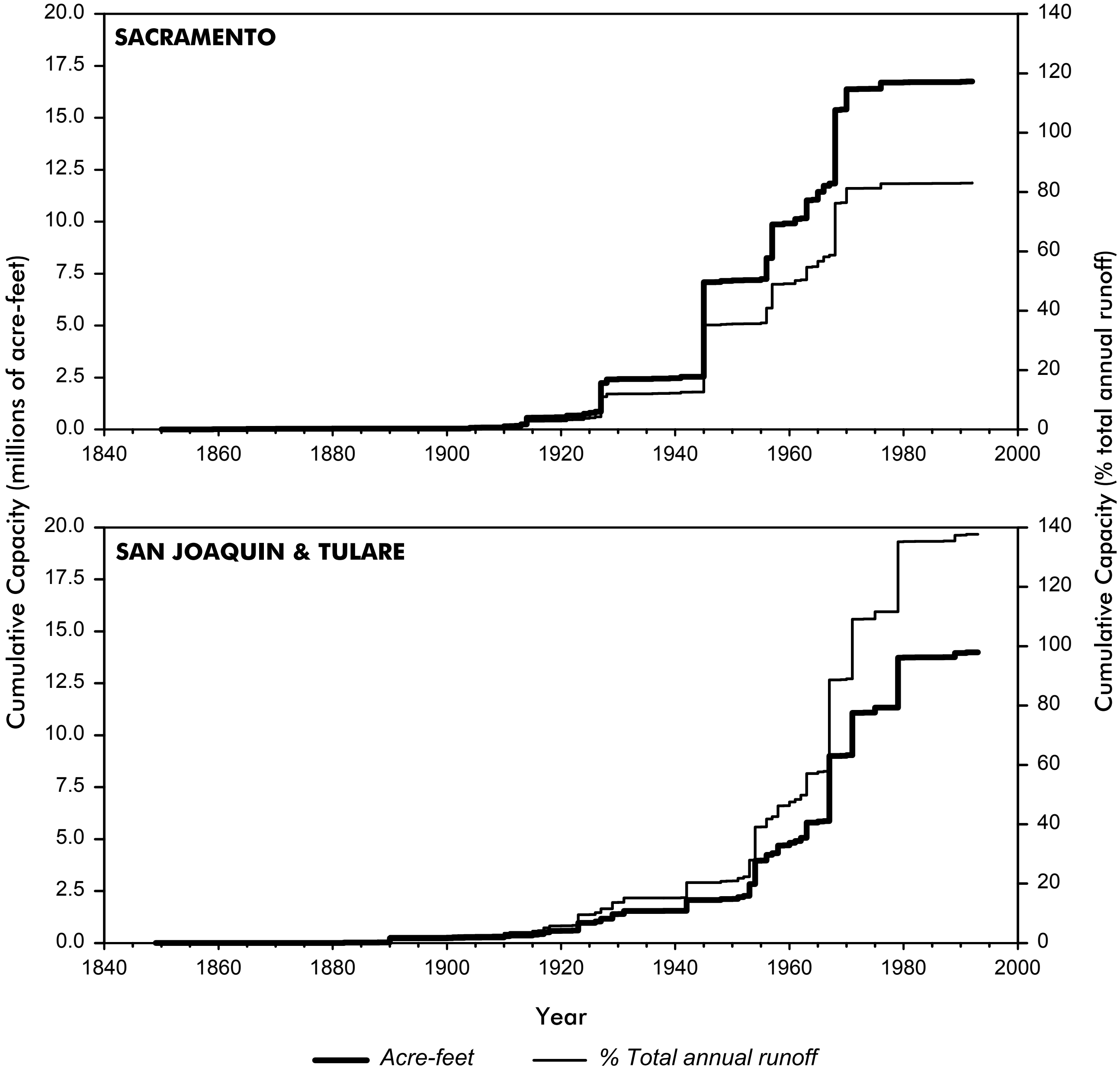
the Central Valley watersheds (CDWR, 1995a). Reservoir storage in the Sacramento River Basin is 17 MAF, or about 80% of the basin's average annual unimpaired runoff. Reservoir storage in the San Joaquin River and Tulare Lake Basins is about 13 MAF, in excess of 135% of the average annual runoff (Figure III-L). This situation, along with downstream diversions and canals in California's Central Valley, has resulted in one of the most intensively-managed river systems in the United States. Every large Sierra river, except for the Cosumnes, has a large terminal storage reservoir located near the base of the foothills. Although some major rivers (e.g., the Merced) are undammed upstream of the large terminal storage reservoir (McClure Reservoir), most (e.g., Kern, Kings, Tuolumne, American, Yuba, Feather, and Sacramento) are fragmented by numerous dams and diversions developed upstream of terminal reservoirs, mainly for hydropower purposes. In the most extreme cases, such as on the Stanislaus and San Joaquin rivers, large portions of the watershed have been impacted by a series of hydropower reservoirs on each of the main upstream forks. Thus, except during large floods, flows on the major rivers are now completely controlled and managed in a way that diverges substantially from the natural hydrologic regime.

Of the amount now captured by reservoirs, about 90% is used for irrigation, with 70% of that going to farms in the Tulare Lake Basin and San Joaquin Valley. Most of the water discharging from the San Joaquin River today is irrigation return water. In the San Joaquin Valley, almost all runoff is now captured in the foothill reservoirs for direct diversion into irrigation systems. Some of the reservoirs are subject to minimal instream flow release requirements to benefit fish and water quality in the lower San Joaquin. Today, individual irrigation districts as well as state and federal projects work together to provide water for irrigation of some 6.7 million acres, about one-half of the total Central Valley floor.

II.G.2. Groundwater Pumping

Groundwater pumping was enhanced by the invention of the gasoline or electric powered centrifugal pump, which opened additional land in the San Joaquin Valley to irrigated farming. In the San Joaquin Valley, the number of pumped wells increased from 597 in 1906 to 23,500 in 1930. Today it is estimated there are about 100,000 groundwater pumps in the Central Valley (Williamson et al. 1989). By 1940, 1.5 million acres in the San Joaquin Valley were irrigated with groundwater. Between 1921 (when the state first began monitoring groundwater levels) and 1939, average groundwater elevations in the San Joaquin Valley fell 39 feet (Worster 1984). The great drought of the 1920s and 1930s accelerated groundwater overdraft and surface water diversion. Drops in the groundwater table forced farmers to drill deeper and more expensive wells, chasing the sinking water level. In the unfavorable economic climate of the 1930s, these

Figure III-L
Reservoir Development in the Central Valley



Reservoir capacity in the Sacramento watershed increased rapidly during the 1940s through the 1960s, while in the San Joaquin and Tulare Basins reservoir development extended through the 1970s. Total reservoir capacity in the entire Central Valley is now slightly higher than the mean annual runoff from the upland system.
Data from CDWR 1995a.

increased farming costs drove many farms to foreclosure. Today as much as half of the Central Valley water supply in a dry year is derived from groundwater.

II.G.3. Flood Control

As agriculture developed on the floodplains and Delta, repeated levee failures along with obstruction of river channels by hydraulic mining debris caused increasing flood damages. To address this problem and meet other needs, a system of improved levees and bypass channels was constructed between 1911 and 1944 to convey expected major floods. In the Sacramento Valley, the first phase of the attempt to control floods was complete by the mid-1920s. Channels in the Sacramento River were realigned and deepened. Artificial levees, overflow weirs, and outfall gates on or near the Sacramento were enlarged and realigned. The weirs functioned much like the sloughs before them, conveying water from constricted channels into flood basins, where broad and massively leveed artificial floodways (e.g., Yolo and Sutter Bypasses) routed the water southward, eventually discharging into the Delta. These alterations also virtually eliminated the natural hydrologic functioning of the flood basins, which was to store large amounts of water collected during flood events of winter and spring, and release this gradually in late spring through summer. Today, only portions of the Butte Basin continue to function this way.

The design of this system reflected an attempt to accommodate several somewhat conflicting needs - flood control, navigability of major waterways, and acreage available for agriculture. Obvious economic benefits ensued from confining as much flood flow as possible to the existing Sacramento River channel, thereby flushing out hydraulic mining sediments and maintaining navigability. This necessitated maintaining and even raising levees built immediately adjacent to the river channel to protect nearby developed lands. At the same time, the plan recognized that earlier attempts to confine *all* floodwater to the river channel had been expensive failures, and it therefore utilized portions of natural nearby flood basins as flood bypasses. The weirs were constructed to control overflow into these bypasses to both maximize scouring in the natural river channel and limit maximum flood elevations. The resulting modifications allowed large areas of natural flood basin to be converted to agriculture with the protection of additional levees.

Flood control levees were built somewhat later on the San Joaquin River, with individual large landowners undertaking major floodplain reclamation efforts between 1915 and 1930. A large federal project completed in 1972 confined the San Joaquin River from the Merced River to the Delta between flood control levees. At the same time, the state constructed the Eastside Bypass, which conveys high flows around the mainstem San Joaquin River between Mendota and Bear Creek.

The multipurpose dams of the CVP and SWP, discussed above, completed the second phase of flood control in the Central Valley. These capture heavy winter runoff, thereby limiting flows downstream to the design channel capacities designated for the Sacramento and San Joaquin flood control projects, including channels and bypasses. The system is intended to limit the risk of failure of downstream levees to floods greater than the 100-year flood (floods that have a one percent chance of occurring in any year). This strategy requires elimination of smaller flood peaks and clearing of riparian vegetation to maintain the artificially elevated flood conveyance of the downstream river channel and bypass system. In addition, the system requires continued protection and maintenance of the existing levees against erosion damage from high flows and channel migration. All of these management actions greatly affect flood hydrology, sediment transport, and the structure and extent of riparian and riverine habitat.

Forty years of system operation have shown that it is difficult to fully achieve the objectives of this structural approach to flood control. This conclusion was unfortunately dramatically emphasized by the floods of early 1997, which caused extensive property damage throughout much of the Central Valley. While protection against smaller floods has proven effective, the vulnerability of some highly populated areas (e.g., Sacramento) to the inevitable large flood remains high. In the event of extreme floods (i.e., greater than the 100 year event), the current flood control system depends heavily upon upstream levee failures, which keep downstream flood flows in check by temporarily restoring functioning flood basins on the valley floor.

II.H. Waterway Navigation

The rapid expansion of commerce that followed the California Gold Rush relied almost exclusively on water-borne transport (Figure III-M). During the 1850s and 1860s, Stockton and Marysville served as the heads of navigation for ocean-going vessels, with regularly scheduled shallow-draft steamer service extending to Oroville and Red Bluff on the Sacramento River and Hill's Ferry on the San Joaquin River. Occasional trips were also available to Firebaugh (USCOE 1916, Zelinsky and Olmsted 1985). Although river steamers remained the most economical and convenient form of transport well into the 1920s, by 1856 hydraulic mining debris had begun to interfere with navigation on the Sacramento River and eventually, most commerce shifted to the newly constructed railroad system.

Maintenance of navigation on the river system had several components. Some of the upland rivers were dammed to capture mining debris, thereby preventing its transport to the navigable river reaches. Channels were dredged and deepened to 35 ft. to provide a direct waterway navigable by large vessels between the busy commercial centers of San Francisco, Stockton, and Sacramento. Authorized in 1868, the San

Figure III-M
River-borne Transport

Wheat sacks lined up on the banks of the Sacramento River, ready to be transported downstream. Before the railroads were built, rivers provided the main mode of transportation in the valley. The riparian vegetation along the river bank today would be covered with rip-rap bank.
Source: Phillips Library, Tiburon, California.

Francisco Channel was the first federal navigation project in San Francisco Bay, and has resulted in a number of habitat modifications in the Bay. For example, a submerged rock (Blossom Rock) covered by five feet of water that existed northwest of Angel Island was blown up in 1870 because it was a menace to navigation (Killinger 1934).

Maintenance of shipping channels continues to affect aquatic habitats. Between 1975 and 1985, 4.5 million cubic yards of sediment were annually dredged to maintain ports in the San Francisco Bay and Delta (SFEP 1990), a practice that continues today, although in somewhat modified form. Dredged materials are now being dumped in the ocean or used for wetland creation. Dredging of navigation channels results in increased water column turbidity due to resuspension of dredged sediment, alteration of benthic habitat characteristics (subtidal topography and sediment structure) due to sediment redistribution, and increases in the volume of the tidal prism, causing greater salinity intrusion (USEPA et al. 1996).

A more recent environmental problem, particularly in the Delta's waterways, has been the sharp increase in recreational boating seen over recent years. Pollution from engine emissions (Tjarnlund et al. 1995, 1996), leaching of bottom paint, sewage discharge, and oil and fuel spills have all added to the degradation of water quality. Additionally, boat wakes and propeller wash result in continual re-suspension of sediments and increased turbidity (Gucinsky 1982), particularly in shallow areas. This in turn leads to loss of subtidal vegetation, shoreline erosion, levee damage (Collins and Noda 1971), and harmful effects on aquatic life (Morgan et al. 1976). Department of Motor Vehicle records indicate that at present about 100,000 watercraft operating in the Bay-Delta region discharge about 4 million gallons of gasoline, 300,000 gallons of lubricating oil, and unquantified amounts of combustion by-products into the environment. Because of such effects, severe restrictions on watercraft use have been recently enacted for Lake Tahoe, yet the Bay-Delta region remains largely unrestricted in this context.

CHAPTER FOUR
The Watershed: Ecological Response

I. Introduction

This chapter summarizes the known changes to watershed ecology that have resulted from over 150 years of human intervention. It is essentially a snapshot of watershed ecology today, presented in terms of the same general conceptual framework of system structure and organization used in Chapter Two to describe the natural structure and function of the system. The same general categories of "essential ecological attributes" are also used in this chapter but in a reversed order. First, changes in the underlying geophysical processes that create and support these aquatic ecosystems and ecological opportunities - hydrology and sedimentology - are discussed and followed from the top of the watershed to the nearshore ocean. This is followed by discussions (by ecosystem type) of changes to habitats and biological assemblages that have resulted from the combined effects of hydrogeomorphic and other alterations of the environment.

The condition of the watershed today is the net outcome of numerous types of human activities, and in most cases represents the combined effects of structural and functional changes in habitat, along with more direct forms of human intervention (e.g., hunting). General trends, such as habitat degradation resulting from alterations of natural topography and/or hydrology, may be realistically linked to associated broad changes in community structure and composition. However, only in relatively few cases are the precise causes of sustained species or population declines reasonably well understood or documented.

II. Changes in Hydrogeomorphic Processes

The hydrology and geomorphology of the watershed have been altered dramatically in many ways throughout much of the system, through the combined effects of storage and diversion, land-use changes, and other factors described in the previous chapter.

II.A. Hydrology

II.A.1. Stream Flows

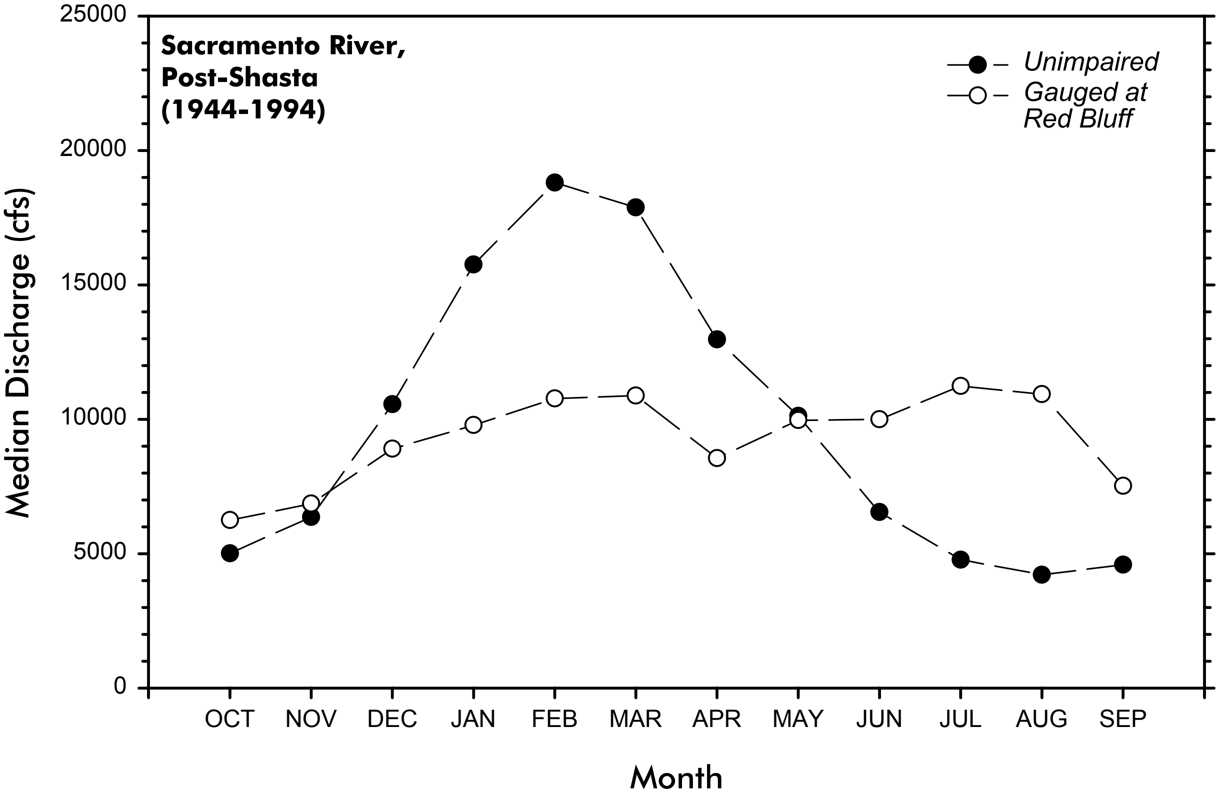
There are systematic differences in the nature and extent of changes in hydrogeomorphic processes upstream and downstream of dams. This is true on both larger waterways that have been dammed to create large terminal storage reservoirs, as well as on waterways of all sizes that have been interrupted by smaller hydroelectric dams.

In the upland part of the watershed, a large number of relatively small hydroelectric dams lie between headwaters and the large terminal storage reservoirs usually located near the "border" between the upland and lowland systems (about 300 ft. elevation). Upstream of these smaller dams, natural flow and sedimentation patterns remain relatively intact, unless locally altered by other interventions (e.g., stripping of vegetation) that have caused an increase in runoff and erosion in many parts of the upper watershed (Kattelmann 1996). Below some of these smaller dams, however, some reaches have been dewatered and/or subjected to abrupt daily flow fluctuations. The effects of the smaller hydroelectric reservoirs vary from river to river, but the general effect is to alter seasonal flow variability in much the same manner (but to a lesser degree) as the larger terminal storage reservoirs. Natural flow variability is decreased, peak flows are subdued, and, where releases are conveyed into the natural channel rather than directly diverted into aqueducts or penstocks, base flows are increased as compared with "natural" conditions.

The main changes evident below the terminal storage dams are a pronounced reduction and temporal shift in flows, and reduced monthly and inter-annual variability. In some cases (most commonly in the Sacramento River Basin), average winter/spring flows are now lower, and summer/fall flows higher than they were under natural conditions. For example, on the Sacramento River (at Red Bluff), there has been a reduction in the median monthly discharge from December through April, and an increased discharge (some of which originates as diversion from the Trinity River) from June through October (Figure IV-A). (Median flows are used wherever possible because it is more representative of the commonly-occurring flow and eliminates the bias that a few very wet years can introduce when using the mean or average.) Additionally, the magnitude of the mean difference between high and low monthly discharges within the year has been reduced by about half. In other cases, particularly in the San Joaquin River Basin, changes in river hydrographs are even more pronounced. For example, on the Tuolumne River, median monthly flows in all months have been reduced by about two-thirds, and a once dynamic annual hydrograph has been converted to a nearly uniform discharge pattern (Figure IV-B). Monthly flow variability has also been reduced to about one-fifth of its prior value. Similar changes are evident on the San Joaquin River below Friant Dam (Figure IV-B).

The seasonal pattern of outflow of the Sacramento River drainage differs considerably from its pre-disturbance state (Figure IV-C). The Hall (1887) estimates give a rough approximation of the pattern of monthly flows for the Sacramento River at Collinsville before most of the Delta and upstream wetlands were reclaimed and the upstream flood basins were cut off from the river. The changes effected may be appreciated by comparing the 1879-85 pattern with the recent period (Figure IV-C), which shows that the combined effect of reclaiming the flood basins and storing and diverting spring

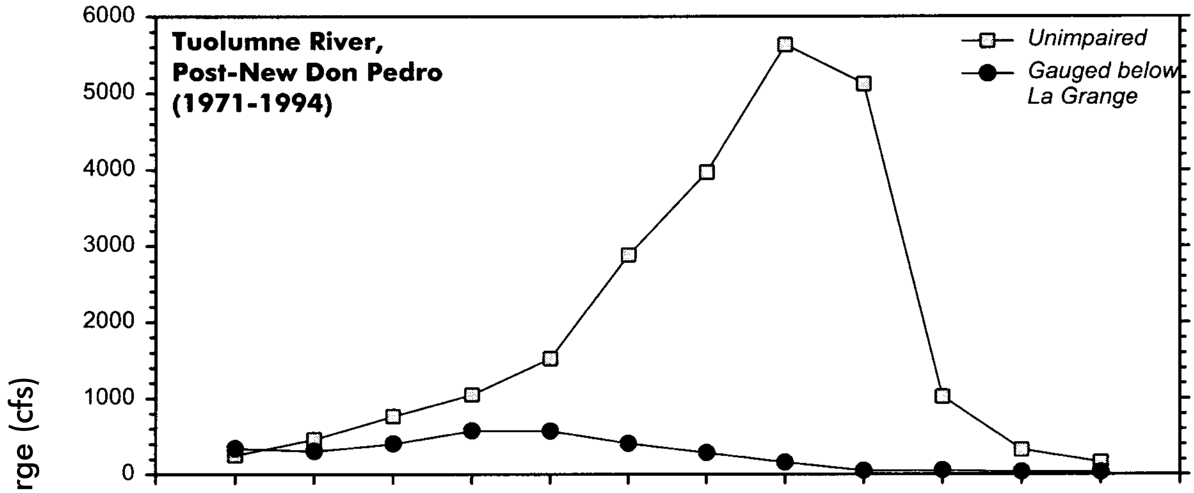
Figure IV-A
Alteration of Median Monthly Inflow
into the Lowland Sacramento River at Red Bluff



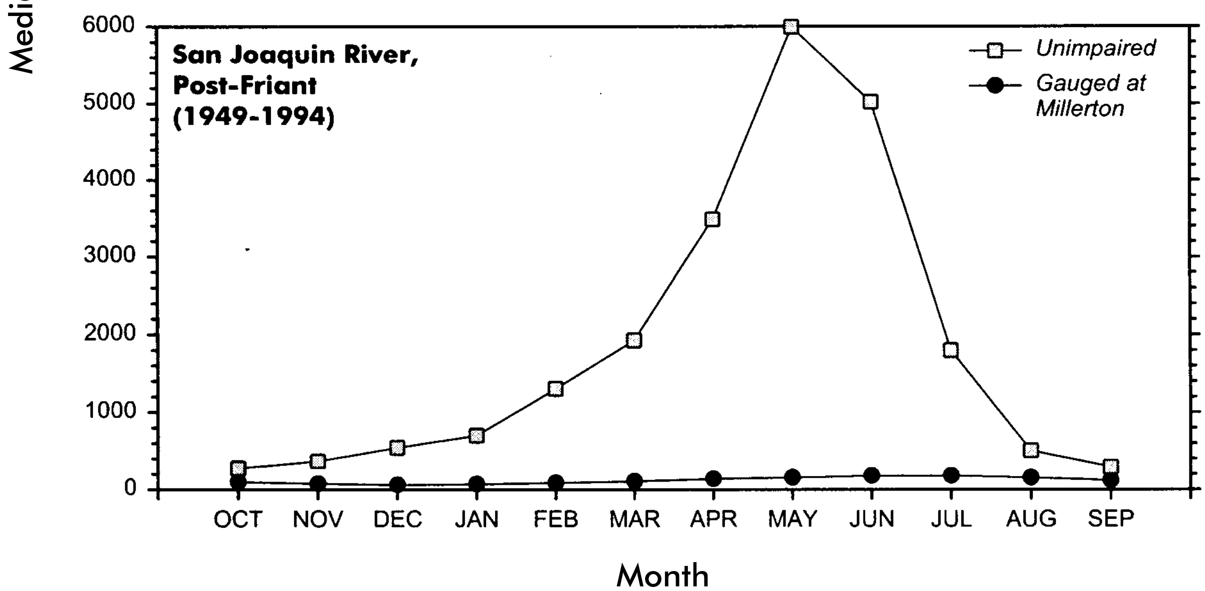
Unimpaired Data: median annual discharge, 7,278,000 acre feet.
Gauged Data: median annual discharge, 7,541,236 acre feet.
Median monthly values calculated for each month from period of record.
Median annual values calculated from annual runoff record.

Shasta Dam and associated water project operations have redistributed and dampened median monthly flows on the Sacramento River downstream of Red Bluff. The slightly greater annual median gauged value is due to the diversion of Trinity River flows into the Sacramento River.
Data from California Department of Water Resources and U.S. Geological Survey.

Figure IV-B
Alteration of Median Monthly Inflow into the Lowland Tuolumne and San Joaquin Rivers



Unimpaired median annual discharge, 1,497,500 acre feet.
Gauged median annual discharge, 318,971 acre feet.

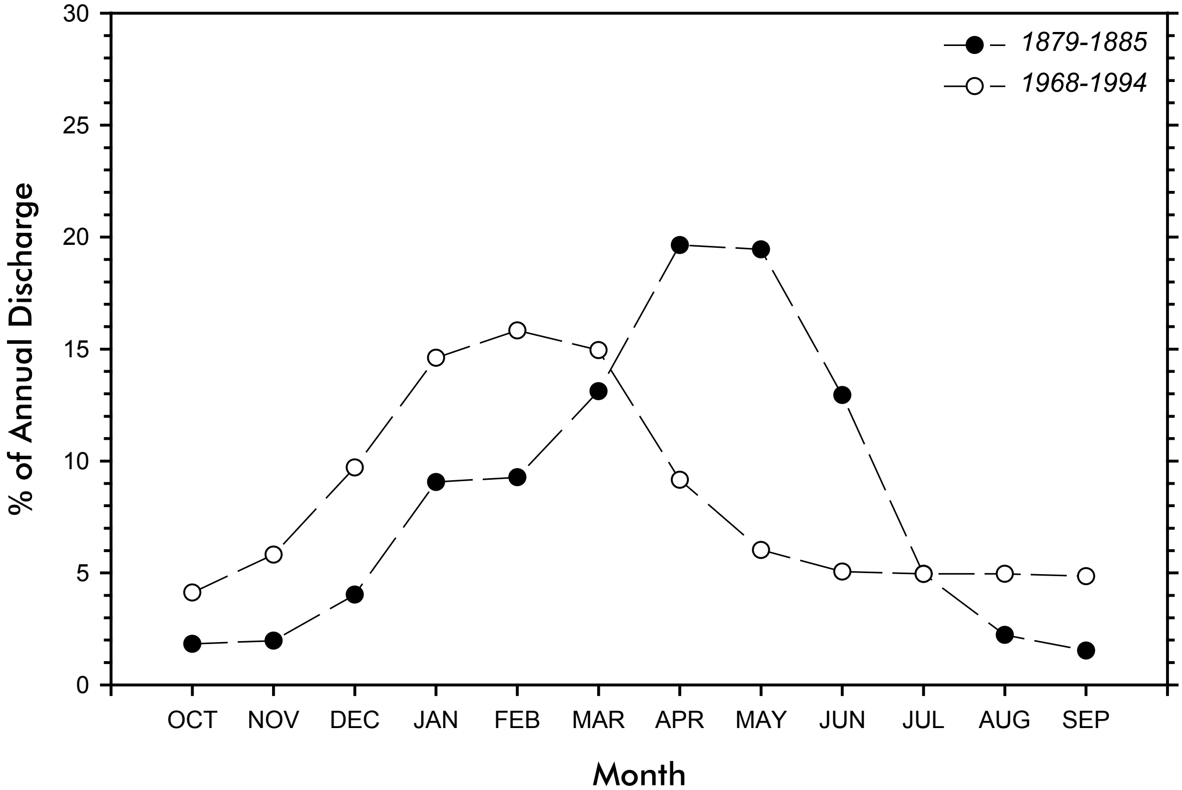


Unimpaired median annual discharge, 1,320,500 acre feet.
Gauged median annual discharge, 105,670 acre feet.

Reservoir operations, combined with canal diversions, have dramatically reduced flows and suppressed seasonal variability. Median monthly values calculated for each month from period of record. Median annual value calculated from annual runoff record.

Data from California Department of Water Resources and U.S. Geological Survey.

Figure IV-C
Estimated Alteration of Sacramento River Monthly Outflow Pattern



Water project operations and modern land use practices have resulted in substantially lower spring flows and slightly greater late summer and fall flows into the Delta from the Sacramento Valley. The higher proportion of estimated historic spring flows may be partially due to a greater proportion of the annual flow derived from snowmelt during the 19th century compared to the latter half of the 20th century, which has had a higher proportion of the annual flow derived from winter rainfall runoff.
Data from Hall 1887 and California Department of Water Resources.

runoff has had the most dramatic effect on the April-June period. Mean outflow has been reduced in that period from nearly 50% to only about 20% of the total mean annual outflow. Today the highest mean flow months are January, February, and March. In terms of timing, variability and magnitude, San Joaquin River outflow has been altered even more drastically than that of the Sacramento River. In most years, the May-June snowmelt flood peak has been eliminated, total discharge reduced, and seasonal variability nearly eliminated. Only in “wet” years is there a marked late spring outflow peak.

II.A.2. Delta Outflow

Changes in the pattern of Delta outflow are similar to what Figure IV-C shows for the Sacramento River. It is impossible to precisely quantify the magnitude of the changes in total Delta outflow from the natural condition 150 years ago because of the lack of data (see Chapter 2, Sections IV.C.1.c and V.B.1.a). By the 1920s, when the first reliable estimate of Delta outflow was made (an estimate referred to as the computed Delta outflow which is based on the measured Delta inflow and the estimated net use within the Delta), the Delta outflow hydrograph had already been somewhat modified by the combined effects of natural vegetation removal, reservoir storage, irrigation withdrawals, channel changes, and elimination of the natural flood basin storage and release. Reductions in spring and summer outflow were the biggest impact of these early interventions. Continued urban and agricultural water development over the last 70 years has had further, and in many years much more significant, impacts on the pattern and magnitude of Delta outflow. The large dams and water transfer projects further reduce spring flows and often reduce winter flows while in some year types the summer flows are higher than what they were in the early part of the 20th century. Insight into the effects of the large water transfer and dam projects can be gained by comparing computed Delta outflow in 1921-43 (pre-project) period with that of the 1968-94 (post-project) period. Estimated mean annual Delta outflow during the pre-project period was only about 14% more than the post-project period, but that number must be considered in the context of precipitation differences between the two compared periods. The net effects of water resource development were somewhat greater than a measured 14% outflow decrease would indicate, because the post-project period of comparison was about 10% wetter. Because of a general trend of increasing precipitation over the 1921-1990 period, Fox et al. (1990) concluded that there was no statistically discernible trend in Delta outflow over the entire period. Nonetheless, when all but the “wet” year types are examined, annual Delta outflow is 30% to 60% less than comparable years of the pre-project period, with even greater percent reductions in spring outflows in some year types.

II.A.3. Floods

The frequency and magnitude of flood events has been substantially altered throughout the system. Although the system had been modified in many ways by the early part of the 20th century, recorded data from that period (prior to the development of massive water management infrastructure) may be used to indicate the general nature of the differences between modern and historical conditions. First, flood frequency has been reduced. In the Sacramento Valley, the historical 2-year flood (occurring once in every 2 years on average) now occurs once every 7 to 13 years on average, and the “natural” 10-year flood every 100 years. Also, natural inter-annual variability in total flow has been suppressed. The frequency of small to moderate floods has been greatly curtailed, and heavy precipitation leads instead to uniform prolonged winter and spring flood releases with little variability. During large floods, releases are increased, but not to historical levels. On a valley-wide basis, the volumes of large floods remain largely unchanged, although only in very heavy snowpack years do flood flows approach historical levels in the San Joaquin Valley. Rather than regularly spilling out onto floodplains, flood flows today are instead confined to the river channels (or bypass channels) and quickly conveyed out of the river systems and into the lower estuary and the Pacific Ocean.

II.A.4. Estuarine Circulation

The changes in the volume and pattern of Delta outflow documented above have substantially modified estuarine hydrodynamics and ecosystems within the Bay and nearshore ocean that are dependent upon the temporal dynamics of the estuary (Cloern and Nichols 1985). Nothing is known about circulation and mixing in the natural system. However, it is evident, based on the above discussion, that significant modifications have occurred.

Changes in the volume and pattern of Delta outflow would have fundamentally altered estuarine circulation patterns, modifying biological and chemical (i.e., nutrient) exchanges between the Bay and nearshore ocean. Circulation and mixing can influence the retention or advection of young fishes and their food organisms. Fresh water inflows induce gravitational circulation in Bay waters caused by significant differences in salinities in the landward-seaward direction. Heavier saltier bottom waters move landward or toward the east and lighter surface waters move seaward at the water surface. It is generally believed that larval organisms, shrimp, and fish near the bottom in the Central Bay and nearshore ocean are transported into the northern reach of the Bay during high Delta discharges (Smith 1987), contributing to the diversity of the rich estuarine environment. In the so-called entrapment zone, bottom and surface velocities are equal, and the interaction of tidal currents with gravitational circulation retains fish in the upper estuary, allowing them to co-occur with patches of food. Estuarine circulation is dominated by tidal mixing, rather than gravitational circulation, during low flows, resulting in the loss of organisms from their optimal habitat by diffusive or advective processes (Bennett and Moyle 1996, Arthur et al. 1996).

Probably the greatest hydrodynamic modification of the Bay has been the almost total elimination of gravitational circulation in the South Bay, which today is more like a salty lagoon than an arm of a resilient estuary. Isotopic analyses of 167 fossil mussel shells suggest that South Bay salinity over the past 2,400 years was 2.1 ppt lower than at present (Ingram et al. 1996). Today, the South Bay receives negligible fresh water inflow, and circulation is controlled by the tides and winds. Gravitational circulation is only induced by very high Delta outflows (Smith 1987, McCulloch et al. 1970). These events reduce bioaccumulation of metals by benthic organisms and reduce salinity and residence times (Luoma et al. 1985), flushing out the accumulated waste products of the huge populations and numerous industries ringing the South Bay. Likewise, in the northern part of the estuary, gravitational circulation has been fundamentally altered, which has probably reduced the suitable habitat for young fish and reduced the diversity and abundance of organisms transported into the Bay from the nearshore ocean.

Systematic reductions in flood frequency and magnitude have altered the spatial and temporal distribution of the surface freshwater plume (created by riverine discharge overrunning denser seawater) that extends across the surface of the Bay and westward into the nearshore ocean. It is probably less extensive and frequent than it was historically. This feature was historically most pronounced during high winter and spring outflows and flood events, which have been curtailed by water management. Nonetheless, surface salinities at Fort Point (just beyond the Golden Gate) still average about 31 ppt or about 2 ppt less than oceanic, confirming the continued persistence of the plume. However, salinity at the ocean boundary has increased by about 12 ppm per year since 1920, or by about 3% total (Fox et al. 1991), suggesting the plume has been somewhat diminished.

Finally, oceanic conditions can also affect estuarine fish, especially anadromous forms. El Niño events, such as those which occurred in 1976-77 and 1983, can significantly reduce ocean productivity, which can reduce growth and survival of fish such as chinook salmon and pacific herring (Bennett and Moyle 1996). Frequent and prolonged periods of rising ocean temperature, associated with frequent El Niño Southern Oscillations after 1976, have been implicated as a factor contributing to the decline of older striped bass in the Bay-Delta estuary (Bennett and Howard, 1998).

II.B. Sedimentology

Today, sediment loads are generally greater than pre-mining values, which were limited by bedrock-dominated channels. Prior to mining, mountain channels had only thin patches of alluvium and were dominated by bedrock and coarse boulder material. Today, substantial amounts of mining debris remain in channels that drained gold mining regions (i.e., Feather, Yuba, Bear Rivers). These stored materials are readily reworked and entrained, resulting in sustained high transport rates that cause erosion and deposition at channel cross-sections, terrace-scarp erosion, sedimentation in deltas, erosion downstream of modern reservoirs, and lateral channel migration. In the lower Bear Basin, for example, subsurface coring indicates that about 138 million cubic yards of mining sediment remain in storage (James 1989). Reservoir sedimentation data indicate that delivery rates for the upland rivers of the heavily mined basins remain two to eight times greater the natural rates (Kattelmann 1996).

Dams, in addition to storing flows, intercept and trap the sediment eroded from the upper watershed, preventing its natural downstream transport. This affects waterway topography and morphology throughout the downstream portion of the system, frequently causing channel scouring and bank erosion (Mount 1995). Major foothill storage reservoirs typically capture most incoming sediment, including all of the bed load before discharge to the valley floor. Today, rivers below the dams have no source from which to replace sediments removed from their channels (and floodplains), save for below-dam erosion of upslope soils and channel beds and banks. Thus, sediment transport through the river system has been greatly altered. There has been a net loss of sediment delivery from the upland system to the Sacramento River, and the main local source (bank erosion) is now prevented or inhibited in many locations by levee armoring. Without the natural protection afforded by heavier sediments, rivers erode channel beds and banks to a greater degree, changing channel morphology. Sediment transport on upper river reaches has been altered even more on the San Joaquin side of the valley. In the lower part of the river, where finer sediments dominate, sediment supply and distribution does not appear to have been as dramatically altered, and net long-term sediment discharge to the estuary appears to still be above natural levels.

Almost all the sediment delivered to the Delta is transported by alluvial rivers, with about 90% of it now supplied by the Sacramento River. Today, watershed delivery rates to the estuary are higher than those believed to have occurred naturally (i.e., prior to human intervention), but it is likely that almost all sediment conveyed by the Sacramento River passes through the Delta in suspension, and is discharged instead in Suisun Bay. In San Francisco Bay, mudflats are starting to erode, while net sediment gains continue in deeper areas. Subtidal areas of the Central Bay are also showing net accretion.

III. Changes in Habitats and Biological Communities

III.A. Upland River-Riparian Ecosystems

III.A.1. Habitat Changes

While much of the mountainous region surrounding the Central Valley remains comparatively remote, over 150 years of human intervention have nonetheless taken a toll. A recent comprehensive study concluded that, "*aquatic/riparian systems are the most altered and impaired habitats of the Sierra Nevada*" (SNEP 1996). Moyle and Randall (SNEP 1996) recently evaluated 100 Sierra watersheds, and concluded that only 7 (all undammed) were in "excellent" condition, and assigned the highest scores to Deer Creek, Mill Creek, and Clavey River. Perhaps the most notable and pervasive overall changes in the structure of upland river-riparian systems have been the loss and degradation of riparian zones, and the fragmentation of once-continuous river reaches. At least 620 mi (1,000 km) of historical length of riparian zone is now covered by standing water, and of 130 watersheds studied, almost all (121) now show substantial gaps in the riparian zone (Kondolf et al. 1996). Recently, it was estimated that about 95% of 3,000 acres (1,200 ha) mapped as riparian hardwood forest had no old growth characteristics intact, with the only remaining old growth in deep, inaccessible river canyons (Franklin and Fites-Kaufmann 1996).

The removal of the riparian zone by logging has locally increased stream temperatures in upland areas, resulting in shifts in biological assemblages. Salmon (*Onchorynchus spp.*), brown trout (*Salmo trutta*), and brook trout (*Salvelinus fontinalis*), species that were either native (salmon) or introduced (trout), prosper in streams that are between 50^{o}F and 64^{o}F and may die if water temperatures exceed 75^{o}F, depending upon acclimation temperatures, pH, and dissolved oxygen (Patton 1973). Timber harvest has locally resulted in the replacement of these high-value, cold-water fish species with warm-water fish (McGurk 1989).

The once-continuous network of channels stretching from high elevations to the valley floor and beyond is now dissected by dams, dip crossings in roads, and water diversion structures, and other barriers into a series of disconnected reaches (Figure G3). It has been estimated that because of such barriers, about 82% (Yoshiyama et al. 1996) to 95% (CDFG, 1993) of historical salmon spawning and holding habitat in the Sacramento-San Joaquin system is no longer accessible to these fishes (Figures G2, G3). Construction of Shasta and Keswick dams alone blocked about 50% of the spawning and nursery habitat previously available to chinook salmon in the Sacramento River (Moffett 1949). The amount of large woody debris in streams, which normally originates in nearby forests, has declined markedly throughout much of the Sierra, simplifying in-stream habitat. Downstream of dams, altered channel morphology, turbidity, flows, and benthic sediment characteristics are widespread.

Sediment-depleted waters scour out spawning gravels below some dams, decreasing suitable salmon spawning habitat. The timing of reservoir releases are also frequently incompatible with migratory, spawning, and rearing habits of anadromous fishes. Large releases during the egg incubation period, or immediately after hatch, can scour spawning gravels, removing the eggs. Low flows during the early migration of young can interfere with their ability to reach the ocean (Mount 1995).

The water temperature distributions throughout the system have also been modified by various water storage and transfer facilities. Since the beginning of the impoundment of Sacramento River water in December 1943, maximum daily water temperature for some distance downstream from Shasta Dam became cooler than previously existed in the summer, creating new habitat where none formerly existed. However, it also resulted in temperatures somewhat warmer than those previously existing in late fall or early winter. These warmer temperatures have had detrimental effects on egg development, feeding ability, growth rate, benthic productivity, and other factors related to the survival of chinook salmon (CDWR 1988). Generally, shifts in temperature distribution adversely impact native fish assemblages, which need relatively cold water to survive and thrive. In the recent past, temperatures in the upper Sacramento River and its tributaries have often exceeded 56°F (13°C), temperatures that may have killed about 15% of the winter-run chinook produced in 1992.

Water quality problems continue to plague much of the upper watershed. Acidic, sediment-laden mine drainage, high in heavy metal concentration, continues to adversely affect nearby streams. Particularly toxic substances, including arsenic and mercury, remain in the proximity of inactive gold mines or in downstream sediments of the Feather, Bear, and Yuba River watersheds. Toxic discharges from numerous abandoned mines continue to cause violations of state standards on four metals - cadmium, copper, mercury, and zinc. Elevated concentrations of copper, cadmium, and zinc have been found in waterweed (*Elodea canadensis*), aquatic insects (midge larvae, mayfly nymphs), and fish (chinook salmon, Sacramento squawfish, Sacramento sucker, threespine stickleback) in streams receiving acid-mine drainage compared to reference streams (Saiki et al. 1995). In addition, water quality is adversely affected by increased sedimentation and erosional processes that result from overgrazing and bad forestry practices. Elevated sediment input may smother fish eggs and cause greater water column turbidity, which increases individual susceptibility to predators.

III.A.2. Changes in Biological Community Structure and Function

Invertebrate assemblages of upland streams are known to be sensitive to changes in flow regime, temperature, predation pressure, sediment transport and deposition, herbicides and pesticides, and the availability of substrate such as woody debris (Erman 1996). Although largely undocumented, the abundance, diversity, and species composition of aquatic invertebrate assemblages have probably changed in many parts of the upland riverine system as a result of changes in such factors, as well as other alterations of habitat quality and extent (see above). The most comprehensive recent report on Sierra ecosystems (SNEP 1996) concluded that "*local degradation of habitats has led to significant impacts on aquatic invertebrates, which make up the vast majority of aquatic species in the Sierra Nevada*."

Non-native fishes are now widespread and abundant throughout much of the upland system. Introduced trout, in particular, continue to affect the distribution of a wide range of native benthic macroinvertebrates, as well as of native fishes, amphibians, and zooplankton. Historically, trout were absent above approximately 6,000 feet in the Sierra Nevada. Many aquatic organisms in these reaches lack the defense mechanisms needed to cope with such predators. The decline of at least one amphibian species, the mountain yellow-legged frog (*Rana muscosa*), has been attributed to predation by introduced trout (Knapp 1996). Reservoirs, particularly low elevation reservoirs, harbor introduced species which continually invade upstream reaches disrupting native aquatic assemblages.

Changes in riparian vegetation assemblages of the Sierra Nevada have recently been documented (SNEP 1996), and it is likely that most of the changes noted in that study may be extrapolated to most of the remainder of the upland system as well. Graber (1996) estimated that as many as 25% of the species dependent upon riparian habitat of the region are now at risk of extinction. At all elevations, "*amphibian species have severely declined throughout the Sierra Nevada*," with over half of the 29 native species now at risk of extinction (Jennings 1996). Such effects are known to be commonly associated with riparian habitat fragmentation and degradation (Jennings 1996). In general, bird populations associated with riparian habitat have also declined (Ohmart 1994; Manley and Davidson 1995), and the ranges of some have become more restricted (Harris et al. 1987). The least Bell's vireo, once common in many areas, has now been extirpated from the Sierra Nevada. For a comprehensive list of threatened or endangered species of the Sierra Nevada, readers are referred to the final report of the Sierra Nevada Ecosystem Project (SNEP 1996).

Nutrient composition, concentration and distribution have been substantially altered throughout much of the upland waterways. Although definitive historical data that would allow quantitative comparison is lacking, the noted loss of riparian habitat along with a huge reduction in spawning salmon - two major sources of nutrients in upland streams - has unquestionably led to a general and seasonal decrease in nutrient availability in many cases. Another notable change has been a general reduction in both flood frequency and seasonal shifts of upland stream levels, alterations that inherently inhibit the transfer of nutrients between remaining riparian zones and their streams, thereby altering food webs and nutrient dynamics. For example, Wooten et al. (1996) concluded, from a study of Central Valley rivers, that a reduction in flood disturbance in this system routed energy away from predatory fish and into an alternate pathway of predator-resistant caddisflies. For the most part however, documentation of such effects is lacking.

III.B. Lowland River Floodplain Systems (Sacramento and San Joaquin)

III.B.1. Habitat Changes

The extent and morphology of aquatic habitat in the lowland system is considerably different than it was at the beginning of the last century. Tulare Lake is now converted to agriculture, and its tributaries are hydrologically disconnected from the San Joaquin River except in wet years. Today, many of the rivers crossing the Central Valley alluvial floodplain are generally constrained in straightened leveed sections. Over 150 miles of the Sacramento River banks are now lined with riprap, an armor layer of rocks placed on river banks or levees to control erosion. This has resulted in less complex, deeper channels contained between levees which now rise up to 15 to 20 feet above the surrounding countryside. Riprap inhibits natural erosional processes, as well as groundwater exchange by interfering with absorption. Confinement of the main channel between riprapped levees and loss of bordering riparian vegetation also greatly simplified natural habitat complexity by eliminating most meander cutoffs and oxbows, pool/riffle sequences, sunken woody debris and other irregularities. Structural characteristics of benthic (river bottom) habitat throughout the Central Valley have been substantially altered by changes in natural sediment supply from the upland system, and local transport and deposition patterns.

An extensive series of screened and unscreened agricultural diversions of varying size unnaturally connect rivers and agricultural lands. These structures siphon off unknown (in their totality) quantities of water, and on occasion eggs, larvae, and small aquatic organisms, including juvenile fish, which are sometimes discharged into farm fields.

The loss of lowland riparian forest has substantially degraded riverine habitats, altering temperature regimes, eliminating essential habitat, and increasing siltation from unprotected soil. Overhanging vegetation in near bank areas, abundantly documented in the natural system from eyewitness accounts, historically provided a rich source of food for juvenile fish in the form of terrestrial insects and important thermal refugia for fish. Shade and cool air temperatures from the deep riparian forests extended across some part of the river's surface, decreasing net heat flux at the air-water interface. Large woody debris introduced into the river from surrounding riparian forests through natural erosion and deposition provided physical cover for small fish, creating low velocity holding areas. Finally, the erosion / deposition cycle associated with riparian zones supplied gravel for successful spawning and egg incubation (Orlob and King 1997). These important habitat attributes are no longer present throughout most of the former riparian zone of the Central Valley.

The early harvesting of riparian forests undoubtedly increased river temperatures. Recent studies at two sites along the Sacramento River demonstrate that riparian zones decrease stream temperatures in nearshore areas by up to about 2°F between the hours of 0600 and 1800, compared to the main channel and unshaded nearshore areas (Orlob and King 1997). Another study conducted in the upland area reported a 10°F rise in temperature through a 1,250 foot section after clearcutting the bordering fir forest along McGill Creek in the Upper Sacramento Basin, 38 miles northeast of Redding (McGurk 1989).

Numerous studies suggest that temperatures in the lowland rivers today frequently exceed levels considered to be detrimental to juvenile native chinook salmon. Adequate temperature regimes are critical to the survival of salmon. Spawning adults are susceptible to lethal disease when temperatures reach 61°F. Juvenile salmon become more susceptible to diseases, parasites and predation when temperatures exceed 60°F. A temperature of 64°F results in a 20% reduction in growth rate for ration levels of 60% of maximum. About 50% of juvenile salmon die when temperatures reach 73°F (Baker et al. 1995; Orlob and King 1997; Mitchell 1987; CDWR 1988; Brett 1952; Seymour 1956).

Between 1978 and 1986, the temperature at four locations along the Sacramento River between Butte City and Rio Vista exceeded 64°F 14 to 16 days in May and 27 to 28 days in June (Mitchell 1987). In comparison, between September 15, 1885 and September 15, 1886, the only historical period for which temperature data are available (and after a considerable portion of the riparian forest had been harvested), the water temperature at Sacramento exceeded 64°F only 2 days in May and for the entire month of June (Buckingham et al. 1886). Since 1977, the average spring temperature of the Sacramento River has increased 2°F to 4°F (Reuter and Mitchell 1987).

Water quality remains severely degraded throughout most of the Central Valley waterways. Inactive mine discharge, and urban and agricultural runoff are still problematic, and contribute hydrocarbons, pesticides, metals, and other harmful chemicals to lowland waters, causing chronic and acute toxicity to sensitive birds, fish, invertebrates, and algae in some places. Discharges from abandoned mines in the upland system, although highly diluted by the time they reach most of the lowland system, nonetheless continue to contribute to water quality problems there (see Chapter 3, Section II.E, Mining). Urban runoff alone is estimated to annually contribute up to 3,600 tons/yr. of hydrocarbons, PCBs, metals, and chlorinated hydrocarbon pesticides to Central Valley waterways (SFEI 1987, Montoya 1987).

Floodplain habitat has also been dramatically altered. The historical 2-year floodplain along the Sacramento River channel is now a narrow terrace, while the frequently inundated portion of the floodplain is limited to the area between the levees and the flood bypass channels (Figure G5). Many miles of meandering natural backwater sloughs have been eliminated, replaced by straightened, lightly-vegetated drainage ditches whose flow levels are carefully controlled and discharged back to the river. Most of the natural flood basins are now only connected with the river system during floods, usually via the controlled flows in the bypasses. As a result, the once extensive riparian zones and wetlands that historically bordered lowland rivers and occupied much of the flood basins have been almost entirely lost, mostly converted to agricultural production.

Less than 5% of historically mapped wetlands remain (Figures G5, G7, G9), and many backwater areas previously connected to the river channel are now effectively isolated. Much of the current wetland acreage shown on Figures G5, G7, and G9 does not occur on what the 19th century surveyors mapped as permanent wetlands, but rather occurs on what is shown in Figures G4 and G6 as other floodplain habitat, which included seasonal wetlands. The current wetlands largely occur in state and federal wildlife refuges and private duck clubs and nature preserves. They are intensively-managed areas generally not naturally connected to the rivers. Instead they have artificial hydrologic regimes, the primary goal of which is the manipulation of water levels to optimize wintering waterfowl habitat, or more specifically to provide better duck hunting opportunities. Typically, these wetlands are flooded in October and drained in the early spring.

The riparian acreage that exists today in the Sacramento and San Joaquin Valleys is estimated by Katibah (1984) to be about 102,000 acres, or about 11% of the historical riparian habitat he conservatively estimated. Katibah (1984) estimated that nearly half of the remaining acreage is disturbed or degraded and most of the balance "*is heavily impacted by human activities*." The current riparian acreage shown on Figures G5 and G7, which is derived from the California Department of Fish and Game's Wetlands and Riparian Geographical Information System Database, equals about 56,000 acres or about 6% of the historical riparian zone acreage in the Sacramento and San Joaquin Valley (as discussed in Chapter 2, Section IV.A.2.a, the actual historical vegetated acreage is somewhat less than the riparian zone acreage). Most existing riparian vegetation occurs as narrow, fragmented patches less than 100 yards wide and confined to bank slopes of streams and sloughs, abandoned meanders, or on the river side of artificial levees (Thompson 1980). Remaining fragments of the riparian zone are also, in most cases, structurally simplified. The complex terraced topography and natural riparian successional processes that naturally support and maintain a diverse mixture of successional stages and plant associations have been largely eliminated by the suppression of flood flows. Channelization has effectively limited the width of the riparian zone, and continues to prevent the natural re-establishment of high terrace, mature riparian forest assemblages (see Chapter 2, Section IV.A.2.b).

III.B.2. Changes in Biological Community Structure and Function

Major changes evident in native plant associations bordering the lowland rivers were discussed above in the context of habitat changes. As with the upland river system, a general lack of historical information on the nature of most animal assemblages here makes it difficult to quantify, or in some cases even qualitatively describe many of the most notable changes that have undoubtedly occurred. This is particularly true of smaller, less conspicuous organisms such as benthic invertebrates and riparian insects.

The herds of large mammalian herbivores - deer, antelope and elk - and their mammalian predators that once depended upon the forests and marshes have been reduced to a few scattered remnant populations, a fate also endured by many of the small mammals that typically occupied these habitats. This has undoubtedly had substantial effects upon riparian and wetland habitat complexity and diversity, as well as on community structure and processes (Naiman and Rogers 1997). Some mammals, like the once-plentiful grizzly bear, are nowhere to be found in today's Central Valley. Bird populations and species diversity in these ecosystems have been particularly hard-hit, with many once-common species including the double-crested cormorant (Belding 1878), great blue heron and great egret (Cogswell 1956), Cooper's hawk (Dawson 1923), bald eagle and yellow-billed cuckoo (Grinnell 1915), now decimated or gone completely. Waterfowl that once blackened the skies above Central Valley marshes are present today in far fewer numbers.

In many cases, native fish assemblages of the lowland rivers no longer exist as such, and today "*the fish fauna of the valley floor is dominated by introduced species*" (Brown 1996; p. 13). At a number of sites examined by Saiki (1984), over 70% of the species present were non-native. The thicktail chub is now extinct, and the Sacramento perch has been displaced from the major portion of its range on the valley floor. The best remaining examples of native fish assemblages of lowland rivers now are found in the foothills, but even these are declining (Brown and Moyle 1987, 1992). Probably the best remaining example of native Central Valley fishes in the entire watershed is found in Deer Creek (Moyle and Baltz 1985).

The loss of large areas of riparian forest and marshes, along with the noted geomorphic and hydrologic alterations, has severely altered the nutrient dynamics of lowland river-floodplain ecosystems. In the minimal amounts of natural floodplain habitat remaining, it is only during extreme floods that river waters exchange materials and organisms with their riparian zones today. Rather, most nutrients that reach the rivers today are in the form of agricultural return water, livestock and industrial wastes, and municipal effluents. The natural composition, amounts, and seasonal timing of nutrient influx from the upland system, much of which was historically transported by now-extirpated large mammals, has also been disrupted. These factors, in combination, have undoubtedly led to highly modified food webs and energy/nutrient pathways (Wooten et al. 1996, Naiman and Rogers 1997).

III.C. The Delta

III.C.1. Habitat Changes

The Delta of today bears little resemblance to its historical condition (Figure G11). Today, over 95% of the original 350,000 acres (550 mi^2) of tidal wetlands and many miles of historical tidal sloughs are gone, as is most of the riparian vegetation that once bordered the larger waterways. In its place, are a patchwork of agricultural "islands," straightened and deepened channels, riprapped levees, and the flooded remnants of former wetlands now too far underwater to allow the re-establishment of emergent vegetation. Only a few isolated pockets of somewhat "pristine" tidal and non-tidal wetland habitat still exist on the interior of some Delta islands (Atwater 1979).

State and Federal pumping plants near Tracy and Banks now link the natural Delta waterways with Federal and State aqueducts. Approximately 1,800 unscreened agricultural diversions provide links to nearby farms. Pollution remains a serious and continuing concern. The combined effects of municipal and industrial dischargers along with agricultural runoff and residual contaminants continue to pose a serious threat to Delta water quality, particularly in dead-end sloughs that have poor circulation and exchange. Boating in Delta waterways has grown rapidly, and presents a relatively new major source of pollutants, as well as resulting in continual re-suspension of sediments and loss of subtidal vegetation, particularly in shallow areas.

Today, as in the past, Delta waterways generally contain fresh water. Intrusions of brackish water into the western edge of the Delta commonly occur in the late summer/early fall as they did under natural conditions. Occasional intrusions into the western Delta can also occur today during the springs and early summers of dry years when river outflow is disproportionately reduced. This differs from the 19th century pattern in which spring outflow was probably high enough in nearly every year to keep brackish water out of the Delta until the summer. Under natural conditions, however, brackish water probably spread further east into the Delta during dry periods compared to current conditions in which reservoirs are managed to maintain freshwater consumptive uses in the central and eastern Delta.

Currently, salinity in the Delta and Suisun Bay is controlled during much of the year by reservoir releases designed to protect agriculture, urban water supplies, and aquatic organisms (SWRCB 1995). Statistically significant relationships have been demonstrated between the position of the 2 ppt isohaline (X2) and the abundance of estuarine species, including striped bass, *Neomysis*, *Crangon*, starry flounder, and the base of the food chain, phytoplankton-derived particulate organic carbon (Jassby et al. 1995). Some of these relationships appear to have weakened somewhat and shifted downward since the introduction of *Potamocorbula* in 1986 (Kimmerer 1998). Aquatic organisms are now protected during February through June by requiring minimum flows at Collinsville (confluence of the Sacramento and San Joaquin Rivers), and by controlling the number of days that X2 is present at Chipps Island and Port Chicago.

One hundred and fifty years ago, detrital food webs were supported by vast amounts of organic carbon from the rich intertidal wetlands. These detrital food webs probably dominated community energetics within the upper estuary, providing widely-distributed high-quality habitat for aquatic estuarine species both upstream and downstream of Suisun Bay. With suitable habitat and food plentiful throughout the area, fishes could move about freely to rear, spawn, or adjust to salinity variations (see Chapter 3, Sections II.B.1 and 2). The modern focus on the position of the mixing zone in Suisun Bay in part reflects the loss of this formerly more widely distributed habitat.

III.C.2. Changes in Biological Community Structure and Function

The combination of habitat loss and successful invasion by a virtual army of non-native species has almost completely obliterated the natural biological community of the Delta. Benthic assemblages are dominated by non-natives, particularly five species of filter feeders. Two of the three historically dominant fish species are no longer found in the Delta: Sacramento perch (extirpated in the Delta) and thicktail chub (extinct). The historical resident fish fauna of 29 species has been replaced by a modern assemblage of 58 species, with non-natives such as threadfin shad, carp, white catfish, inland silversides, and striped bass now the most abundant species (Herbold and Moyle 1989). Waterfowl, once extremely abundant in the Delta’s tidal marshes, are now drastically reduced in numbers. Even so, at least 26 species of waterfowl (two swan, four goose, and 20 duck species), still take refuge here in high numbers during the winter months. Large members of the once diverse and abundant native mammalian fauna such as tule elk and grizzly bears, showed rapid declines following the reclamation of Delta islands. Smaller species, such as river otters, beaver and muskrat, were greatly reduced due to unrestricted fur hunting until early wildlife conservation laws were enacted. These species now occur in varying numbers at scattered locations in the Delta. Other species, such as raccoon and opossum, have altered their habits to exploit new Delta habitats.

The sources, composition, amounts, and disposition of organic carbon and nutrients within Delta food webs have been greatly modified. Today, most of the original marshes are gone, and the food web of the Delta is instead highly dependent upon primary production by Delta phytoplankton (mainly diatoms), or organic contributions from upstream rivers. Changes in the contribution of nutrients entering the Delta from upstream are difficult to document, because the comparative rates at which riverine nutrients were consumed then and now is largely unknown, as are the comparative overall residence times (i.e., the time available for consumption) in the Delta. Discharges from waste-treatment plants, urban runoff, and the transport of fertilizers from agricultural runoff also contribute to modern organic carbon sources in the Delta. Food webs have been drastically altered. Introduced copepods replaced the historically abundant *Eurytemora affinis* as a dominant element of the system's zooplankton communities. An even more ominous problem for phytoplankton communities appears to be related to the recent introduction of an Asiatic clam, *Potamocorbula amurensis*, to the western Delta and San Francisco Bay. The population has exploded, and has the capacity to consume incredible quantities of phytoplankton. The filter-feeding freshwater Asiatic clam (*Corbicula fluminea*) may also attain very high densities at times (Cohen 1991). Recent extensive discussions of modern Delta food webs and trophic dynamics are provided by IEP (1995) and Herbold et al. (1992).

III.D. San Francisco Bay

III.D.1. Habitat Changes

San Francisco Bay has undergone major habitat alterations over the course of the last 150 years (Figure G13), primarily from farming, salt production, and urbanization (Monroe and Kelly 1992). The topography of the Bay floor continues to be periodically disturbed by dredging and maintenance of shipping channels. Millions of cubic yards of sediment are dredged annually for such purposes (Cohen 1991). Changes in upstream hydrology and erosion, sediment transport and deposition rates have affected sediment types and distribution, and therefore benthic invertebrate assemblages throughout the Bay (Nichols 1979).

Bay filling and diking have decreased the open-water areas and wetlands of the Bay by raising what were naturally subtidal areas to intertidal or supratidal elevations. Pelagic (open water) habitat is perhaps the least altered, although some changes are clearly evident. Open water areas (bay and major tidal channels) have decreased by about 7%, from about 274,000 acres to 254,000 acres. Deep bay and channel (>18 ft) have decreased more (from about 100,000 acres to 83,000 acres) than shallow bay and channel (from about 174,000 acres to 172,000 acres) (SFEI 1998, Figure G13).

Intertidal habitat has been severely modified throughout the Bay's margins. Of some 51,000 acres of channel and Bay tidal mudflats that existed under natural conditions, 58% or about 29,000 acres remain today. Natural wetlands, land that was once subject to natural tidal action, historically occupied about 192,000 acres of the Bay's margin. Today, only 21% or some 40,000 acres remain and some of that is degraded. The balance has been converted to other uses, including 9,000 acres to diked wetlands and another 54,000 acres to managed wetlands, mostly in Suisun Bay; 32,000 acres to farmed and grazed baylands, mostly in the North Bay; 37,000 acres to salt ponds in the San Pablo and South Bays; and the balance (about 20,000 acres) to urban uses in the Central and South Bay (SFEI 1998).

A general lack of accurate historical information prohibits quantitative description of possible changes in the extent of rocky intertidal habitat in the Bay. However, it has been documented that the introduced boring isopod *Sphaeroma quoyanum* has altered rocky intertidal habitat topography on many Bay shores, weakening the rock and thereby facilitating its removal by wave action. At some sites the land / water margin may have retreated by a distance of at least several meters due to this isopod's boring activities (Cohen and Carlton 1995).

Habitat characteristics of the water column include vertical stratification, tides, salinity distribution and water quality, all of which have been somewhat modified by human intervention. Early observers noted changes in tides. A riverboat captain who spent his life plying the Bay and upland rivers from the 1860s to 1914, noted in his memoirs that "*the tides at the ferry landing at San Francisco (and in fact on the city front generally) are not so strong as in former years. The reason is that the by-passes on the Sacramento River -- such as the cut from Rio Vista to the lower end of Horseshoe Bend -- do not allow the winter water to accumulate in the Delta regions. All the water from the river-floods goes through Raccoon Straits or around Angel Island point out the Golden Gate to the Sea. As the young flood tide 'makes,' the river water presses it out to the city shore, and as the flood strengthens, it forces the river water toward the city, then in time -- for a short while -- the flood joins forces with the river water and this is called the bore*" (Leale 1939).

The current average annual salinity of the Bay appears to be within the range of that experienced over the last several millennia (Ingram et al. 1996, Peterson et al. 1989, Conomos et al. 1979, Fox et al. 1991). However, human interventions have unquestionably altered the temporal and spatial salinity distribution patterns within the estuary, particularly during dry years, through alteration of Delta outflow. Salinity has generally increased since 1920 from February through June and decreased at other times (Fox et al. 1991).

Water quality has been severely degraded. Some 41 municipal wastewater treatment plants, six refineries, and a number of other major and small industrial facilities discharge over 750 million gallons per day of treated wastes into the Bay, but as a result of substantial recent improvements in treatment, these discharges are far less problematic today than in the recent past. Instead, urban runoff is now the principal source of pollutants, contributing up to 13,000 tons/yr to the Bay, of which 90 percent is hydrocarbons (SFEI 1987, Montoya 1987).

III.D.2. Changes in Biological Community Structure and Function

Descriptions of the historical Bay tell of a body of water that "*stretched farther than the eye could see, abounding with game, fish and fowl of all kinds*" (Thompson 1957). Habitat alteration, overhunting and fishing, pollution, and the successful invasion of many exotic species have all contributed to sweeping changes in this picturesque description of the natural richness and diversity of the native Bay biological community.

The successful establishment of non-native species constitutes the most pronounced change of the past 140 years, an alteration frequently associated with changes in nutrient dynamics and alterations of habitat structure (Zedler, personal communication), both of which have characterized the last 150 years of the Bay's history. Benthic invertebrate assemblages are perhaps the most altered (Nichols 1979). Of all the presently common species, only the polychaete *Glycinde spp.* and the bivalve mollusks *Macoma balthica* and *Mytilus edulis* are considered natives (Nichols and Pamatmat 1988). The Asiatic clam (*Potamocorbula amurensis*) is probably the most significant introduction to the estuary. It is capable of achieving densities that allow local populations to filter the entire water column over the channels more than once per day. Dungeness crab (*Cancer magister*), which was historically abundant in the Bay (Skinner 1962), persists at low levels today (Herrgesell et al. 1983).

Plankton assemblages appear to have been substantially altered. The introduced *Acanthomysis spp.* was reportedly more abundant than the native opossum shrimp *Neomysis mercedis* by 1994 (Cohen and Carlton 1995). Phytoplankton growth rate in San Francisco Bay is currently controlled mainly by light, with nutrient concentrations having little or no effect except when they are depleted during blooms (Nichols and Pamatmat 1988). Since the appearance of *Potamocorbula*, the summer phytoplankton bloom in the North Bay has disappeared. The primary mechanism now controlling phytoplankton biomass in the South Bay during summer and fall is believed to be filter feeding by the introduced Japanese clams *Venerupis* and *Musculista* and the Atlantic clam *Gemma* (Cohen and Carlton 1995).

There is evidence suggesting that fish assemblages of the Bay west of Carquinez Strait have been substantially modified over the last 150 years. Drastic reductions in commercially harvested populations were noted by the end of the 19th century (Jordan 1887), and persist today. As in the past, Central and South Bays still harbor an assortment of marine fishes. San Pablo Bay harbors a resident assemblage of typically estuarine species which, at times of increased salinity, is augmented by upstream movement of marine species from Central Bay (Herbold et al. 1992). A major species shift occurs east of the Carquinez Strait in Suisun Bay, which today is typically occupied by a characteristic six-species assemblage (which includes the introduced striped bass (*Morone saxatilis*), although this group is subject to some temporal instability in terms of species composition (Herbold et al. 1992).

Tidal wetland plant assemblages have remained relatively intact where this habitat still exists, with few successful introductions (Josselyn 1983; Atwater 1979), although a non-native marsh grass (*Spartina alterniflora*) has become established in San Francisco Bay and is now believed to be competing with native plants. However, native animal assemblages of the remaining Bay wetlands have not fared so well; "*The distribution and abundance of invertebrates in tidal marshes [of San Francisco Bay] have been altered greatly through intended or inadvertent introductions and vector control activities...The result is a mix of species unlike any other along the west coast of North America, even in comparison to nearby embayments like Bodega and Tomales Bays*" (Josselyn 1983; pg. 57). The introduced Atlantic mudsnail *Ilyanassa* is likely playing a role in altering the diversity, abundance, size distribution, and recruitment of many species on intertidal mudflats (Cohen & Carlton 1995). Changes in the natural hydrology of the watershed have also contributed to these alterations (Hedgepeth 1979).

Bird populations have clearly declined in abundance and diversity over the last 150 years. Even with the massive reductions in population numbers of avian fauna, San Francisco Bay supports more than 57% of the total diving ducks in California (USFWS 1990 in SFEP 1991). The California clapper rail (*Rallus longirostris*) at one time was "*exceedingly abundant, a highly prized game bird and was one of the more common species in the San Francisco markets*" (Skinner 1962). Its populations have now been drastically reduced, warranting its inclusion on the federal and state lists of endangered species. Other species no longer common in the estuary which were known to be common historically include the American white pelican (*Pelecanus erythrorhynchos*), American bittern (*Botaurus lentiginosus*), white-faced ibis (*Plegadis chihi*), tundra swan (*Cygnus columbianus*), trumpeter swan (*C. buccinator*), Canada goose (*Branta canadensis*), wood duck (*Aix sponsa*), California condor (*Gymnogyps californianus*), bald eagle (*Haliaeetus leucocephalus*), mountain plover (*Charadrius montanus*), snowy plover (*C. alexandrinus*), long-billed curlew (*Numenius americanus*), sandhill crane (*Grus canadensis*), long-eared owl (*Asio otus*) and short-eared owl (*A. flammues*) (USFWS 1990 in SFEP 1991). Populations of native mammals have also suffered irreversible declines (Josselyn 1983).

Trophic dynamics and food webs of the Bay have been highly modified. Nutrient production within the Bay has been curtailed by the loss of several hundred thousand acres of highly productive tidal marsh. Because of the exceptionally high production rates of tidal marshes, and their former extent of well over half a million acres in the estuary, this source historically constituted a major form of organic input to Bay waters. Today, this contribution is estimated to be only a few percent of total annual organic production, the balance of which is now primarily attributed to phytoplankton and benthic microalgae (Herbold et al. 1992). Additionally, the large amount of detritus previously reaching the Bay in the form of Delta export is gone.

III.E. The Nearshore Ocean

III.E.1. Habitat Changes

Substantive information about the subtidal ecology of this system has become available only in the last 50 years. Thus, there is relatively little documentable evidence of habitat or community change for most of this system over the "historical" period that forms the basis of this report. Shoreline habitats throughout the region have been severely modified in many cases through extensive urbanization and development of beach areas for recreation. The natural dunes that once formed the landward margin of the area's beaches have been largely destroyed, along with their natural vegetation and animal assemblages. Many rocky intertidal communities throughout the region have been ravaged by intensive trampling of curious but careless tidepool and shore explorers, and food gathering by local residents.

Sediment characteristics are known to be a primary determinant of benthic communities in the nearshore ocean (USEPA 1993). Sediment structure, particularly near the Golden Gate, may have been altered due to changes in large-scale sediment transport processes in the watershed over the last 150 years, which have changed the natural pattern of seasonal and annual deposition of fine-grained sediments associated with outflow from San Francisco Bay (SAIC 1992). Intensive fishing of these waters began in response to the rapid depletion of Bay fisheries in the late 19th and early 20th centuries (Skinner 1962), but the nature and / or extent of benthic habitats that may well have been altered by many years of intensive bottom trawling has not been documented. Certain types of commercial fishing gear, particularly roller trawls, are capable of digging up large areas of benthic sediments and crushing outcroppings of reef-type habitat. A well-documented alteration of benthic habitat here was provided by the addition of structure to otherwise featureless sand plains in the form of hundreds of drums of radioactive waste dumped by the U. S. Navy.(Figure G14). This converted natural sand plains into reef-like habitat, two types of subhabitat that in this region (as with most inshore marine areas) are characteristically occupied by far different assemblages of benthic and demersal fishes and other forms of marine life (EPA 1993).

Documented changes in pelagic habitat of the nearshore ocean ecosystem are of two main types: gradual warming (which many now believe to be human-induced) and increased pollution. At nearby Monterey, annual mean inshore temperatures and mean summer maximum temperatures have increased during the last 60 years (Barry et al. 1995), with measurable effects on intertidal associations and vital ecological processes, such as upwelling and associated primary productivity. Such effects may also have occurred offshore of San Francisco Bay, but are undocumented. Pollution is generally not high offshore relative to inshore coastal sites of Central California (Nybakken et al. 1984; deLappe et al. 1980). Nonetheless, pelagic and intertidal habitats are occasionally affected by pollution, most of which appears to be derived from exchange with the Bay. For example, unexplained high readings of lead have been found in intertidal mussels (Nybakken et al. 1984), and elevated concentrations of dioxin have recently been reported in seabirds (and their eggs) within this region (Jarman et al. 1997).

III.E.2. Changes in Biological Community Structure and Function

Not enough is known to make all but the most cursory comments on changes due to human intervention that may have occurred over the last 150 years in the biological community of the nearshore ocean. Continued harvesting of once-plentiful abalone and other shellfish that has occurred for the last 100+ years (Skinner 1962) has undoubtedly affected rocky intertidal communities, but the precise nature of these effects is unknown. Marine mammals are now under federal protection, and many populations along the coast, particularly those of the Farallon Islands, have made substantial recoveries in recent years, as have many seabird populations ravaged during the late 19th century by egg gathering (Skinner 1962). Salmon harvest is highly regulated, but wild stocks remain at alarmingly low levels. Most commercial salmon fishing today exploits hatchery produced fish, but recent estimates suggest that as many as 50% of endangered winter-run chinook returning spawners may be unintentionally landed now by sport and commercial boats (NMFS Biological Opinion 1996).

The nearshore ocean is subject to considerable short and long-term variability in terms of annual productivity, depending upon upwelling events and large-scale weather patterns and oceanic circulation patterns - processes that have been modified over the last century due to global warming. Analysis of possible effects of altered nutrient outflow from the Bay that has likely occurred over the last century on nearshore ocean productivity or community energetics are confounded by such considerations, and are therefore difficult to assess.

IV. A Watershed-Scale Perspective

The sections of this chapter have documented the many severe and more obvious alterations in hydrogeomorphic processes as well as the habitats and biological communities of this watershed. A summary of the alterations by ecosystem type over the last 150 years is shown in Table IV-A. In its totality, the scale of habitat loss and degradation and process alteration in this watershed is truly staggering. Large and complex river systems have been functionally (and to some degree structurally) converted into a series of managed storage facilities, pumps, and concrete-lined channels. The large areas of wetlands and riparian habitat have been reconfigured into the urban and agricultural landscape of the San Francisco Bay Area and Central Valley (Figure G3).

At the landscape scale, alterations of two main types of attributes emerge that transcend the ecosystem-scale alterations discussed above - extent / distribution relationships among component ecosystems (mosaic), and connectivity among component ecosystems. Unquestionably, the single most influential factor that naturally connected and integrated these aquatic ecosystems into a larger ecological unit (i.e., watershed) was the natural downstream movement of water and sediments. The migrations and movements of a comparatively few wide-ranging species played a lesser, but not trivial, role. Thus, in terms of system integration at the watershed scale, it is the fundamental changes wrought in system hydrology (see above) by human intervention over the last 150 years - changes *not* reasonably attributable to unusual climatic trends or events during this period - that appear to have had the greatest and most pervasive effects.

Figure G3 provides a watershed-scale appreciation of the natural habitat and stream connectivity lost during the last 150 years. Natural connectivity among ecosystems has also been highly modified through the construction of permanent basins (dams), the disruption of wetland and riparian corridors, and the loss of many of the watersheds' native larger wide-ranging fishes and wildlife that formed the natural biological links among watershed ecosystems. Two of the watershed's four wild salmon runs that existed at the time of the Gold Rush (spring and winter), each once numbering in the hundreds of thousands, have been drastically reduced in number and are now federally listed. Gone also are the countless elk, antelope, and deer, and other large and small mammals and birds that regularly commuted between Central Valley waterways and the drier habitats of the woodlands and prairies, exchanging untold quantities of carbon and nutrients among ecosystems.

It is unlikely that we will ever be able to truly assess the full nature and extent of ecological change that has occurred in this vast watershed over the last 150 to 200 years. The alterations actually documented or reasonably inferred (as described above) are probably only the "tip of the iceberg" in terms of ecological change of the last 150 years. Most ecological information is collected on large-scale habitats (such as those defined here) or larger, more conspicuous plants and animals. Nonetheless, at the bases of food chains and cycling processes are a much larger biomass in the form of tiny or microscopic forms with particular micro-habitat requirements. These too have unquestionably been severely altered by the massive environmental changes of the last 150 years, yet empirical data documenting such changes is largely lacking.

Finally, it is worth noting that much of the large-scale water transfer and ecosystem protection infrastructure of the Bay-Delta system were developed in a period of relative wetness (mid-1930s to mid-1970s) without persistent periods of drought or floods. Planning and management is based upon an assumption of climatic stability because change is unpredictable. Climate change, however, is inevitable and the relative extremes of wet and dry that we have experienced in the last two decades may become the norm rather than the exception. The habitats and biota of the Bay-Delta watershed evolved with the highly variable Mediterranean climate and adapted to the seasonal and long-term swings of climate. By dramatically reducing the extent, diversity, and complexity of the natural aquatic habitats of the system, as well as inhibiting the physical processes that create and sustain those habitats, we have severely compromised the biotic system's ability to adapt to natural and human-induced climate change.

Table IV-A. Summary (by ecosystem-type) of Major Ecosystem Alterations Over the Last 150 Years (see text for discussion)

Structural Alterations	Process Alterations
UPLAND RIVERS ***Above Large Upland System Dams*** • Loss of riparian habitat; remainder highly fragmented • Fragmentation of riverine habitat due to hydroelectric dams, road crossings, and other barriers • Degradation of water quality • Loss of channel continuity to remainder of watershed; complete loss of chinook salmon spawning habitat • Biological communities altered, including: * *loss of native species* * *population losses in many taxonomic groups* * *successful establishment of exotic species* • Large sediment accumulations behind dams • Loss of instream complexity/large woody debris	• Increased sedimentation from surrounding systems • Alteration of trophic dynamics/nutrient exchange with lower watershed • Nutrient dynamics altered, including: * *supply/exchange of nutrients between riparian zone and streams altered* * *loss of nutrient contribution of spawned salmon carcasses in historic salmon streams* * *alteration of food webs* • Natural hydrologic patterns altered below smaller dams due to diversions and storage and later release of seasonal high flows
Below Large Upland System Dams *As above, but also:* • Channel morphology altered and degraded, including pool/riffle ratios, substrate composition • Water temperatures altered	*As above, but also:* • Natural hydrologic patterns altered, including: * *loss of natural seasonal and interannual flow variability* * *amount and timing of minimal/maximal flows altered; flood peaks reduced* * *spring flows lowered* * *average summer flows increased in some reaches* * *total or near-total elimination of flows in some reaches* * *groundwater/surface water exchange processes disrupted* * *increase in daily flow and temperature variability* • Sediment supply and deposition processes disrupted • Seasonal flushing of riparian nutrients/litter into streams curtailed • Upstream movement of aquatic organisms blocked

Table IV-A. Summary (by ecosystem-type) of Major Ecosystem Alterations Over the Last 150 Years (see text for discussion)

Structural Alterations	Process Alterations

LOWLAND RIVERS
 	
• 94% of riparian zone lost; remainder highly fragmented
• 95% loss of historically mapped wetlands
• 85% of inundated area lost
• Channel morphology greatly altered, including channelization, raised levees, and altered substrate composition
• Loss of "backwater" areas
• Tulare Lake converted to agriculture
• Water quality degraded
• Biological communities altered, including:
  * *loss of native species*
  * *population losses in many taxonomic groups*
  * *successful establishment of exotic species*
  * *abundance relationships shifted*
• Numerous screened and unscreened diversions connect river channels with agricultural fields
	• Natural hydrologic patterns altered, including:
	  * *loss of seasonal and interannual flow variability*
	  * *flood magnitude, frequency, duration, and area of inundation altered; small to moderate floods largely eliminated or reduced; large floods increased*
	  * *spring flows reduced and snowmelt peak largely eliminated*
	  * *summer flows augmented in some reaches*
	  * *total discharge reduced*
	• Sediment delivery and deposition reduced
	• Nutrient dynamics altered, including:
	  * *riparian/marsh contribution nearly eliminated*
	  * *exchange and cycling of nutrients between rivers and floodplains disrupted*
	  * *alteration of food webs*
	• Animal movement patterns disrupted
	• Community successional processes disrupted

DELTA
 	
• Conversion of over 95 % of tidal wetlands to agriculture or deep subtidal area; remainder fragmented in small isolated patches
• Loss of most riparian vegetation
• Gross reconfiguration of subtidal channel morphology/distribution
• Water quality degraded
• Levees armored (rip-rapped)
• Biological communities altered, including:
  * *loss of native species*
  * *successful establishment of exotic species*
  * *population losses in many taxonomic groups*
  * *abundance relationships shifted*
• Numerous unscreened diversions connect aquatic habitat to agricultural fields
• Large pumping plants connect aquatic habitat to agricultural aqueducts
• Natural pattern of seasonal salinity intrusion altered in some locations
	• Natural hydrologic patterns altered as above, including:
	  * *winter, spring, and early summer flows further reduced by export pumping*
	  * *water movement patterns altered at local and broad scales*
	• Natural soil accretion rates disrupted; soil subsidence occurring at problematic rate
	• Nutrient dynamics altered, including:
	  * *detrital inputs from marshes and riparian nearly eliminated*
	  * *alteration of food webs and trophic structure of community*

Table IV-A. Summary (by ecosystem-type) of Major Ecosystem Alterations Over the Last 150 Years (see text for discussion)

Structural Alterations	Process Alterations

SAN FRANCISCO BAY
 	
• 79% of tidal marshes lost; remainder highly fragmented and in some cases degraded
• 42% of tidal mudflats lost
• Ship channels dredged and deepened
• Intertidal mudflat habitat lost
• Rocky intertidal habitat lost
• Water quality degraded
• Subtidal sediment composition and distribution altered
• Biological community highly altered, including:
  * *loss of native species*
  * *successful establishment by exotic species*
  * *population losses in many taxonomic groups*
  * *changes in dominant species at many trophic levels*
• Natural seasonal pattern of salinity variability and distribution altered
	• Natural hydrologic patterns altered, including:
	  * *seasonal patterns of fresh water inflow altered and reduced*
	  * *tidal prism reduced*
	• Sediment delivery and deposition processes altered
	• Nutrient dynamics altered, including:
	  * *detrital inputs from Delta and Bay marshes nearly eliminated*
	  * *long-term changes in oceanic productivity*
	  * *alteration of food webs and trophic structure*
	  * *pelagic food webs altered by high filtration rates of exotic filter feeding invertebrates*

NEARSHORE OCEAN
 	
• Natural seasonal extent of freshwater plume altered
• Benthic sediment composition altered, particularly near Golden Gate
• Alteration of benthic habitat by dumping and destructive fishery harvest methods
• Alteration and loss of shoreline habitat (beaches, rocky intertidal) through multiple human-use effects
• Biological communities altered, including:
  * *population losses in many taxonomic groups*
• Increase in mean annual and summer maximum temperatures
	• Natural hydrologic patterns altered
	  * *seasonal pattern of freshwater discharge altered*
	• Long-term changes in oceanic productivity

CHAPTER FIVE

Applications: Building a Practical Framework for Ecosystem Restoration and Management

One of the greatest challenges of modern resource management is to develop the tools - both conceptual and applied - necessary to enhance the effectiveness of restoration planning at the ecosystem level, including the comparative evaluation of alternate restoration actions, and the evaluation and monitoring of the ecological condition of restored / managed systems. The preceding chapters have provided (1) a narrative overview of natural structure and function of the ecologically different kinds of areas that comprise the aquatic portion of the landscape, (2) a description of the many human activities that have in the past substantially affected these systems' ecology (and in many cases continue to do so), and (3) the net results of these interventions, in terms of the comparative states of fundamental system properties as they existed historically and exist today. This report concludes with suggested applications of that information to the challenges of planning for ecosystem-level restoration and management of the San Francisco Bay-Delta watershed.

I. Developing a Practical and Effective Strategic Approach

Restoration efforts in this highly-developed and populated watershed will necessarily reflect a compromise between conflicting needs. Ensuring the long-term protection of the full range of native biodiversity inhabiting the watershed's ecosystems and habitats requires comprehensive, ecosystem-level efforts. As Noss et al. (1994, p. 3) warned, "*A continually expanding list of endangered species seems inevitable unless trends of habitat destruction are reversed soon through a national commitment to ecosystem protection and restoration*." However, by definition true restoration involves, "*the return of an ecosystem to a close approximation of its condition prior to disturbance*" (NRC 1992). Clearly, the degree of disturbance and, in some cases, irreversible changes in the watershed, along with the extent of the system and current levels of human population and consumptive use, make it quite apparent that the pursuit of true restoration throughout the *entire* geographic range of the watershed is neither feasible nor desirable. It is incompatible with the resource and economic demands of 30 million human inhabitants of the state - demands which *also* must be met. What then might be the strategic solution to this apparent conflict? To address this question, we need to consider two fundamentally different options available, in terms of restoration projects / programs:

(1) **Rehabilitation**. Projects aimed at restoring *some limited number of particularly desirable ecological characteristics,* (e.g., increased population

levels, harvest, or production, etc.) to an area or region. This approach (also called *partial restoration*) may provide substantial "*ecological benefits even though full restoration is not attained*" (NRC 1992).

(2) **Comprehensive Restoration** (or the closest possible approximation thereof). A program designed to restore full *ecological integrity** to a defined area.

* (Note: the term "ecological integrity" is used here in the sense of the ability of a defined area to sustainably support essential ecological processes and viable populations of *all* native species, with minimal ongoing human intervention.)

Planning efforts to date suggest that only *a combination of both* approaches - a program that seeks to protect the full range of native biodiversity through comprehensive restoration of representative portions of the region's aquatic ecosystems, along with more broadly dispersed rehabilitative efforts directed at more narrowly focused objectives - will achieve the diverse long and short-term biological conservation / resource enhancement goals encompassed by the CALFED program in a manner compatible with current and projected human population levels and their resource needs. While a species-oriented, rehabilitative approach to restoration / management may address particular economic objectives (e.g., enhanced commercial harvest or recreational opportunities), and also serve as a useful and complementary conservation tool addressing the short-term needs of species in immediate danger, such an approach is, in and of itself, neither efficient or effective as a comprehensive strategy for long-term protection of overall biodiversity (Kohm 1991). Additionally, it must be re-emphasized that simply spreading out species-focused actions over a large portion of the landscape does not constitute a form of "ecosystem"-level restoration or management, which is by definition guided by the states of a comprehensive suite of attributes of a particular **area**, rather than the states of the perceived "limiting factors" of particular species.

The approach recommended above - the concept of complementing such species-focused efforts with a systematic program of comprehensive restoration and / or protection of limited areas that represent the full gamut of native biological communities / assemblages - is a relatively recent development. Called "*ecosystem representation*," the establishment of such a network has recently been called "*one of the most widely accepted goals of conservation*" (Ecological Society of America, 1995). Integrated with other uses of the surrounding landscapes, this approach has the capacity to simultaneously address the needs of entire biological communities as well as ensure the sustainable use of natural resources for the benefit of society. Such a strategy has already been adopted as a proactive national conservation policy in Canada, in the form of the Endangered Spaces Campaign (Hummel 1989), with wide support at the popular level, as well as top levels of government and some 260 environmental organizations. Here, the entire country is being inventoried to identify the diversity of ecosystems that need to be represented, with protection slated to be in place *prior to* the need for species listing. To a large degree, addressing species concerns at these broader levels of communities and ecosystems preempts the need to individually analyze or address the ecological requirements of each and every resident species.

An ecosystem representation approach is particularly appropriate to the goal of protecting overall biodiversity in the Bay-Delta-River watershed, since that goal includes conservation of many species about whose ecology little or nothing is known. The comprehensive restoration and subsequent long-term protection of sizeable areas of any landscape, is in many cases an inherently costly endeavor. Nonetheless, it has been pointed out that such efforts would, "*almost certainly be less costly in terms of time and money than an uncoordinated series of recovery plans and habitat-conservation plans for each individual species*" (Noss et al 1994, p. 8). It has been estimated that comprehensive "community-level" conservation strategies may be able to protect 85-90% of the species in an area without the need for assessment of any particular species requirements (Noss et al. 1994).

It might be argued that such a program is largely unnecessary, since a number of areas that might be considered "representative" of the watershed's aquatic ecosystems are already under some sort of protective management. These include a number of national parks (Yosemite, Kings Canyon, and Sequoia), national forests (Shasta-Trinity, Lassen, Plumas, El Dorado, Tahoe, Stanislaus, Toiyabe, Sierra, and Sequoia), many state and county parks (e.g. Mt. Diablo, Calaveras Big Trees), state recreation areas (e.g. Brannan Island, Kettlemen), national wildlife refuges (e.g. Kern, Pixley, Merced, Kesterson, San Luis), and a number of smaller, less well-known areas. The Wild and Scenic Rivers Act of 1968 provided protection for many rivers across the country. "Wild and Scenic" means that a river must remain undammed and allowed to follow its natural course. In California, these are the only rivers in the state that still have reasonable runs of salmon and steelhead trout (Schoenherr 1992). A number of large-scale restoration projects on former tidal marshes are now in the planning stages, including projects to create managed seasonal wetlands and projects to restore natural tidal wetland processes. The California Department of Fish and Game has recently acquired 7,000 acres slated for future restoration as functional wetlands.

While the current network of protected areas is unquestionably of some conservation value in terms of protecting some relatively rare habitats and species, in general the current network consists of areas that are too small, fragmented, and primarily managed for other purposes (e.g., recreation) to achieve full species protection or system integrity. In this context, Noss (1991, p. 229-230) concluded that "*because parks are generally too small for viable populations of many species and their legal boundaries do not conform to ecological boundaries, disruption of processes (such as fire regimes) and species composition is almost inevitable. Scenery is a hollow virtue when ecological integrity has been lost.*" Unlike national parks and forests, which are primarily managed for other purposes, the ecosystem representation strategy employs protected areas carefully selected on the basis of natural ecological boundaries and features, and managed with the *primary* purpose of ecosystem and species protection.

While the basic concept is relatively simple and straightforward, its practical application is not. The idea that we might just rope off an area, stand aside, and let nature "do her thing" is not a realistic approach to conservation in the 21st century. Today, there are relatively few landscapes left in America that might be considered sufficiently "pristine" to adequately address conservation needs in their present condition. Even activities far distant from a protected area may continue to have substantial effects on local ecology. The situation is even more complicated in the Bay-Delta-River watershed, which has been extensively colonized by exotic species. Thus, to be effective, most protected areas nestled within highly developed landscapes will require active restoration and dedicated management, both of which must be integrated with resource and land use over a much larger geographic scale than the refuge itself. Restored ecosystems may be reasonably expected to *approximate* rather than *duplicate* past conditions, and thus require continual monitoring and flexible, adaptive management provisions to address unexpected or unwanted eventualities.

The basic design of protected areas has received considerable attention in recent years, and substantial progress has been made. The size, shape, and connectivity (with other natural systems) will affect the conservation success of protected areas, and the optimal combination of these must be determined individually for each area, in conjunction with consideration of other societal needs and resource uses within the region. The most widely recognized general approach is to use a centrally located and highly regulated "core area" as the focus of species protection, surrounded by a "buffer zone" which is more open to other compatible uses, but still under active management as part of the refuge. The buffer zone serves several key purposes. It isolates the core area from nearby human activity, provides an area in which to safely "experiment" with adaptive management options (including the effects of different types of human activity), and provides pre-acquired additional area that, if necessary, might be added to the "core" with minimum additional expenditure or disruption of nearby human activity. In complex landscapes (such as the Central Valley watershed) consisting of a number of ecosystem types, protected representations of different systems should be linked by a protected corridor, ensuring adequate connectivity and integrity at the landscape scale.

The total exclusion of people from conservation areas is *not* a necessary pre-requisite to successful conservation, but strict control of the amount and types of activity unquestionably is. It is an undeniable fact that indigenous peoples throughout the world have lived amidst, and been sustained by, native plants and animals for many millennia without destruction of species or habitats. Here, the magnitude and nature of resource exploitation were compatible with ecological integrity of these natural systems. Reasonable levels of hunting, fishing or other uses of the natural resources of protected areas are not necessarily inherently harmful; many ecosystems thrive on regular “disturbances” - floods, fire, etc. - that periodically kill, injure, or displace thousands of resident animals and plants. Adaptive management and the use of the core / buffer zone concept provides a means to empirically determine the levels and types of human activities that are compatible with conservation objectives within protected areas.

II. Developing Practical Tools for Restoration and Management at the Ecosystem Level

This report does not, and was never intended to, provide a detailed blueprint for restoration in this watershed. Rather, it was designed to provide a coherent and defensible *ecological framework* for restoration, defining appropriate management units and essential ecosystem characteristics that comprise the most useful and practical focus of restoration actions and planning. Development of a comprehensive and detailed restoration plan for the watershed will require considerable additional effort. Below, the translation of the information base developed in this report into practical restoration / management tools is demonstrated.

Among the most useful and essential of tools needed by ecosystem restoration / management programs are *ecological indicators* - practical measures of system characteristics that provide a direct means to objectively evaluate and monitor the status and “health” of the system as a whole, or of individual aspects of the system of particular interest. Essentially, indicators are the means by which restoration / management success may be objectively measured, or alternate restoration management options evaluated. Because of these pivotal roles, the development of ecological indicators has received a great deal of attention in recent years, although there remains little consensus on just how to best go about developing such tools. To illustrate how the kind of historical information base developed here might be applied to such tasks, the narrative overview of Delta ecology presented above was used to develop a provisional suite of indicators that could be used to practically plan, evaluate and monitor a conservation program seeking to restore and sustainably protect a representative portion of the historical Delta ecosystem.

A large number of broadly stated ecological attributes, such as "variable flows" or "complex topography," might be identified as ecologically influential. Each of these may in turn have numerous aspects warranting consideration, and each aspect might be measured in a number of ways. Thus, the process of selecting indicators involves choosing, from a far larger number of variables that might be measured, a manageable and appropriate set. A rational approach to the problem of selecting indicators was illustrated by Keddy and Drummond (1996), who focused upon (p. 748-749) "*essential properties*" that "*indicate higher levels of health or integrity*" and are additionally, "*(1) easy to measure and monitor and (2) compare macro-rather than micro-scale properties.*"

To illustrate these applications of the developed historical data base, the above criteria were applied to the conceptual framework of ecological structure and function of both the Delta and upland river-floodplain ecosystems developed in Chapter 2 to derive a suite of system attributes (Tables V-A and V-B) that reflect each of the major categories used to analyze these systems: habitat structure, biological community composition, and essential hydrogeomorphic and ecological processes. The attributes selected are believed essential to biodiversity support and ecological integrity in this system; thus, they might well serve as a basis for evaluating and monitoring overall system integrity. Based upon the understanding of natural system structure, function, and organization developed here, it would seem reasonable to conclude that if all these attributes were intact, the system could be judged as doing "well." Conversely, serious biological/ ecological repercussions might reasonably be expected to accompany the finding that any one or combination of these attributes was not intact. The next task was to select, for each attribute, a tentative list of indicators (practical measures) that could be used to quantitatively evaluate and monitor the attribute (Tables V-A and V-B).

Finally, it is clear that practical application of ecological indicators requires the development of "reference values" - a quantitative framework with which to evaluate measured values and/or establish target values for indicators. Keddy and Drummond (1996) used empirical measurements from a number of modern representative temperate deciduous forest ecosystems to establish high-to-low ranges for indicators. Such an approach is not an option in the present case, because comparable modern systems are not available. However, historical conditions may also be used to establish an analogous quantitative framework that, while not particularly precise, may nonetheless provide an invaluable guide to emulation of a suite of environmental conditions that approximate "natural" conditions closely enough to achieve desired restoration goals and objectives. For example, the natural topography, proportionate extent of major habitat types, typical organic content of soils, etc. all are reasonably quantified through the historical analysis provided, and might be compared with current values for the same parameters to provide a quantitative framework for the selected indicators (Table V-C). While attempting precise definition of "healthy" or “unhealthy” values for these indicators may not particularly productive, the range provided (natural versus current) nonetheless quantitatively defines and compares conditions known to have at one time sustainably supported “desirable” biological assemblages with conditions deemed “unacceptable” from that same standpoint.

It is emphasized that the preliminary tools presented in V-A to V-C are intended as “demonstration” products. The choice of attributes is admittedly somewhat arbitrary - perhaps others should be added, or perhaps all are not necessary. Nonetheless, the list provided would appear to represent a rational starting point in this regard. These suggestions are unquestionably in need of further refinement, and will continue to be modified according to the results of a planned adaptive management approach to watershed restoration. It is also emphasized that application of attributes (and indicators) will require careful consideration of the unique properties and environmental conditions found at particular restoration sites, as well as the specific goals and objectives of the particular projects / programs. Nonetheless, it is clear that restoration / management efforts at *any and all scales* at least require consideration of a comprehensive suite of essential attributes; interactions among seemingly “irrelevant” factors (from the standpoint of more narrowly focused management programs) may in fact eventually prohibit or inhibit project success.

III. Concluding Recommendations

This report has examined the ecological history of the Bay-Delta-River watershed, and considered practical alternative strategic approaches to ecological restoration that might lead to long-term protection of the system’s native species and ecological structure and function. Based upon these analyses, we make the following broad recommendations:

> (1) An ecosystem approach to natural resource restoration and management is the most efficient and effective available means to meet the need for long-term protection of ecological integrity and biodiversity within the watershed. This must be complemented by more focused efforts that address the immediate needs of threatened and endangered species. The granting of protected status and preparation of recovery plans for individual species must remain a viable tool in our comprehensive species protection strategies.
>
> (2) A guiding and overarching long-term restoration strategy should be clearly articulated and adopted that seeks to achieve and integrate a geographically broad program of ecological rehabilitation with a focused, ecosystem representation program aimed at full restoration of ecological

structure and function of a connected network of representative areas of each of the ecosystem and habitat types defined herein.

(3) In general, ecosystems should replace populations and species as the fundamental planning units of long-term, comprehensive restoration efforts. Specific long-term restoration actions should be primarily, although not exclusively, aimed at the enhancement and protection of essential ecosystem processes and structural features, rather than particular taxa or species. Although protection of individual species, biodiversity or ecological integrity may not be the primary goal of resource use in non-protected areas, such considerations should be accommodated to the full extent compatible with other (higher priority) resource use objectives.

(4) Hydrogeophysical support (flows and sediments) must be adequate to support essential ecosystem functions and restore and maintain essential structural attributes within designated restoration sites, and to provide sufficient connectivity among restored sites to allow the natural migration and movement of wide-ranging species.

(5) In all cases, care must be taken to ensure that program elements - "new" restoration / management actions - do not inadvertently displace or threaten surviving remnant populations of native species now restricted to locations likely to be highly altered by such actions, or create conditions that favor exotic species rather than natives.

Adopting the recommendations of this report will not resurrect the rich, complex, undisturbed ecosystems of the San Francisco Bay-Delta-River system of 150 years ago. Nonetheless, applying an understanding of "natural" watershed ecology will serve as an invaluable guide to comprehensive restoration in particular representative segments of the watershed, and to a general program of rehabilitation throughout much of the region. Initiating a restoration program based on good intentions alone is not sufficient. The most successful restoration program for this watershed will ultimately be that which most effectively and efficiently applies the precepts of modern restoration ecology within the practical limits of resources available and within the practical constraints set by other legitimate societal needs. Such efforts - properly designed and executed - have the capacity to protect, restore and sustain native ecosystems, and the full range of remaining native plants and animals that depend on them; reduce conflicts over protection of endangered species; provide for more economically and environmentally sound flood management; enhance recreational opportunities; ensure high water quality for urban and industrial uses; and create an aesthetically more pleasing environment. It is our best opportunity to preserve the unique ecological heritage of California's Bay-Delta-River watershed for ourselves and future generations.

Table V-A. Delta Ecosystem: Proposed Essential Attributes and Their Indicators

	Ecosystem Attribute	Corresponding Indicator
1.	Flat topography, near sea level	% of area within ± 5 ft MHHW
2.	High organic content of wetland soils	% organic content (wet weight)
3.	Variable wetland water levels (daily / seasonally)	(a) difference in % area awash at MHHW versus MLLW (b) mean flood frequency / year
4.	Natural water movement patterns (river channels only)	days of bi-directional flows: *Sacramento channels* Winter (December-March) Spring (April-July) Summer / Fall (August-November) *San Joaquin channels* Winter (December-March) Spring (April-July) Summer / Fall (August-November)
5.	Characteristic salinity distribution	mean monthly salinity *western Delta* December-July August-October *central Delta* December-July August-October *eastern Delta* December-July August-October
6.	Natural habitat mosaic	Proportionate extent of: intertidal wetlands subtidal waterways supratidal landforms other (urban, ag)

Table V-A. Delta Ecosystem: Proposed Essential Attributes and Their Indicators

	Ecosystem Attribute	Corresponding Indicator
7.	Good water / soil / sediment quality	toxicity measure water soils benthic sediments
8.	Naturalistic plant assemblages	(a) Marshplains # native species present % native biomass (b) Willow fern swamps # native species present % native biomass (c) Riparian # native species present % native biomass
9.	Naturalistic animal assemblages	For each of the following: fishes, birds, insects, mammals -- # native species / genera present # exotics established last 3 years % biomass native species
10.	Sources of Primary Production	% ecosystem primary production by: native emergent plants riparian plants phytoplankton benthic macrophytes

Table V-B. Upland River-Floodplain Ecosystem: Proposed Essential Attributes and Their Indicators

(Indicator reference values will predictably differ at different sites, and in different geomorphic zones)

	Ecosystem Attribute	Corresponding Indicator
1.	Balanced sediment budget	net change in depth of unconsolidated sediments
2.	Dynamic channel substrates	inter-annual comparison of sand-bar distribution
3.	Continuous channels	# of barriers blocking / diverting flows and / or movement of fishes
4.	Seasonal shifts in stream level	mean % change in depth (cm): February vs. September
5.	Periodic flooding	mean frequency overbank flows
6.	Naturalistic hydrograph	mean monthly flows
7.	Continuous riparian corridor	mean length unbroken riparian zone / 10 km
8.	Instream habitat complexity	(a) pool / riffle ratio / linear mile (b) frequency of LWD
9.	Good water / soil / sediment quality	toxicity measure water soils benthic sediments
10.	Naturalistic plant assemblages	(a) Riparian # native species present % native biomass (b) Phytoplankton # native species present % native biomass (c) benthic macrophytes # native species present % native biomass
11.	Naturalistic animal assemblages	For <u>each</u> of the following: fishes, birds, insects, mammals -- # native species / genera present # exotics established last 3 years % biomass native species

Table V-B. Upland River-Floodplain Ecosystem: Proposed Essential Attributes and Their Indicators
(Indicator reference values will predictably differ at different sites, and in different geomorphic zones)

	Ecosystem Attribute	Corresponding Indicator
12.	Nutrient / energy sources	(a) Primary production / unit stream length by: riparian plants phytoplankton benthic macrophytes (b) Annual weight of returning salmon (natural spawning streams only)

Table V-C. Delta Ecosystem: Sample Reference Values for Selected Indicators[1]

	Ecosystem Attribute	Corresponding Indicator	Reference Values	
			Natural[2]	**Current**
1.	Topography	% of area within ± 5 ft MHHW	>85%	<25%
2.	Soil composition	% organic content (wet weight)	>80%	<20%
3.	Habitat mosaic	Proportionate extent of:		
		intertidal wetlands	85%	<5%
		subtidal waterways	7.5%	7.5%
		riparian vegetation (supratidal)	7.5%	<1%
		other (urban, agriculture)	0%	>90%

1 These reference values are presented primarily for demonstration purposes. Values given represent best estimates.

2 “Natural” values are derived from historic reconstruction and refer to estimated values circa 1850.

REFERENCES

Ainley, D. G. and S. G. Allen. 1992. Abundance and Distribution of Seabirds and Marine Mammals in the Gulf of the Farallones: Final Report to the Environmental Protection Agency (Region IX) LTMS Study Group, submitted July 30, 1992. Point Reyes Bird Observatory, Stinson Beach, CA.

Alexander, Lieut. Col. B. S., Maj. G. H. Mendell, and Prof. G. Davidson. 1874. Report of the Board of Commissioners on The Irrigation of The San Joaquin, Tulare, and Sacramento Valleys of the State of California. Government Printing Office, Washington D.C.

Allen, W. E. 1920. A quantitative and statistical study of the plankton of the San Joaquin River and its tributaries in and near Stockton, California, in 1913. University of California Publications in Zoology 22:1-31.

Alpine, A. E. and J. E. Cloern. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. Limnology and Oceanography 37:946-955.

Angermeier, P. L. and J. R. Karr. 1994. Biological integrity versus biological diversity as policy directives: protecting biotic resources. BioScience 44:690-697.

Anonymous. 1873. Irrigation in California, The San Joaquin and Tulare Plains. A Review of the Whole Field. Record Steam Book and Job Printing House, Sacramento, CA.

Arthur, J. F., M. D. Ball, and S. Y. Baughman. 1996. Summary of Federal and State water project environmental impacts in the San Francisco Bay-Delta Estuary, California. Pages 445-495 *in* J. T. Hollibaugh, ed. San Francisco Bay The Ecosystem: Further Investigations into the Natural History of the San Francisco Bay and Delta with Reference to the Influence of Man. Proceedings of the 75th Annual Meeting of the Pacific Division / American Association for the Advancement of Science, Golden Gate Park, San Francisco, CA.

Association of Bay Area Governments (ABAG). 1991. Status and Trends Report on Land Use and Population. The Geomorphology, Climate, Land Use and Population Patterns in the San Francisco Bay, Delta and Central Valley Drainage Basins. February 1991.

Atwater, B. F. 1979. Ancient processes at the site of southern San Francisco Bay: movement of the crust and changes in sea level. Pages 143-174 *in* T. J. Conomos, ed. San Francisco: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science., San Francisco, CA.

Atwater, B. F. 1980. Attempts to correlate late quaternary climatic records between San Francisco Bay, the Sacramento-San Joaquin Delta, and the Mokelumne River, California. Ph.D. Dissertation. University of Delaware, Newark.

Atwater, B. F. 1980a. Distribution of Vascular-Plant Species in Six Remnants of Intertidal Wetland of the Sacramento-San Joaquin Delta, California. U.S. Geological Survey Open-File Report 80-883.

Atwater, B. F. 1982. Geologic Maps of the Sacramento-San Joaquin Delta, California. U.S. Geological Survey MF-1401, Menlo Park, CA.

Atwater, B. F., S. C. Conard, I. N. Dowden, C. W. Hedel, R. L. MacDonald, and W. Savage. 1979. History, landforms, and vegetation of the estuary's tidal marshes. Pages 347-385 *in* T.J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Proceedings of the 58th Annual Meeting of the Pacific Division of the American Association for the Advancement of Science, Golden Gate Park, San Francisco, CA.

Atwater, B. F. and D. F. Belknap. 1980. Tidal-wetland deposits of the Sacramento-San Joaquin Delta, California. *In* M. E. Field, A. H. Bouma, I. P. Colburn, R. G. Douglas, and J. C. Ingle, eds. Quaternary Depositional Environments of the Pacific Coast: Pacific Coast Paleogeography Symposium 4. Proceedings of the Society of Economic Paleontologists and Mineralogists, Los Angeles, CA.

Bailey, H. C., C. Alexander, C. Digiorgio, M. Miller, S. T. Doroshov, and D. E. Hinton. 1994. The effect of agricultural discharge on striped bass (*Morone saxatilis*) in California's Sacramento-San Joaquin drainage. Ecotoxicology 3:123-142.

Bailey, H. C., S. Clark, J. Davis, and L. Wiborg. 1995. The Effects of Toxic Contaminants in Waters of the San Francisco Bay and Delta. Final Report Prepared for Bay / Delta Oversight Council.

Bailey, H. C., L. Deanovic, K. Luhman, T. Shed, and D. Hinton. 1996. Pesticides in Urban Stormwater from the Sacramento Valley and San Francisco Bay Area. Poster, State of the Estuary. October 1996.

Baker, G. H. 1855. Map of the mining region of California. Drawn and compiled by George H. Baker. Fishbourne's Lithography, San Francisco. Barbor and Baker, Sacramento, CA.

Baker, P. F., T. P. Speed, and F. K. Ligon. 1995. Estimating the influence of temperature on the survival of chinook salmon smolts (*Oncorhynchus tshawytscha*) migrating through the Sacramento-San Joaquin River Delta of California. Canadian Journal of Fisheries and Aquatic Sciences 52(4):855-863.

Balling, S. S. and V. H. Resh. 1982. Arthropod community responses to mosquito control recirculation ditches in San Francisco Bay salt marshes. Environmental Entomology 11:801-808.

Barber, R. T. and R. L. Smith. 1981. Coastal upwelling ecosystems. Pages 31-68 *in* A. R. Longhurst, ed. Analysis of Marine Ecosystems. Academic Press, London.

Barbour, M. G. and J. Major, eds. 1988. Terrestrial Vegetation of California. California Native Plant Society, Special Publication Number 9. University of California, Davis, CA.

Barry, J. P., C. H. Baxter, R. D. Sagarin and S. E. Gilman. 1995. Climate-related, long-term faunal changes in a California rocky intertidal community. Science 267:672-675.

Becker, R. H. 1964. Diseño of California ranchos maps of thirty-seven land grants (1822-1846) from the Records of the United States District Court, San Francisco. The Book Club of California.

Beechie, T., E. Beamer, and L. Wasserman. 1994. Estimating coho salmon rearing habitat and smolt production losses in a large river basin, and implications for habitat restoration. North American Journal of Fisheries Management 14:797-811.

Beesley, D. 1996. Reconstructing the landscape: an environmental history, 1820-1960. *In* Sierra Nevada Ecosystem Project: Final Report to Congress. Vol.11: Assessments and Scientific Basis for Management Options.Wildland Resources Center Report 37. University of California, Davis, CA. 1528 pp.

Belding, L. 1878. A partial list of the birds of central California. Proc. U.S. Natl. Mus. 1: 88-449.

Bence, J. R., D. Roberts, and W. H. Lenarz. 1992. An Evaluation of the Spatial Distribution of Fishes and Invertebrates off Central California in Relation to EPA

Study Areas with Emphasis on Midwater Ichthyofauna. Report to U.S. EPA Region IX. National Marine Fisheries Service, Tiburon Laboratory, Southwest Fisheries Science Center, Tiburon, CA. 234 pp.

Bennett, W. A. and P. B. Moyle. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. Pages 519-542 *in* J. T. Hollibaugh, ed. San Francisco Bay The Ecosystem: Further Investigations into the Natural History of the San Francisco Bay and Delta with Reference to the Influence of Man. Proceedings of the 75th Annual Meeting of the Pacific Division / American Association for the Advancement of Science, Golden Gate Park, San Francisco, CA.

Bennett, W. A. and E. Howard. 1998. Climate change and the decline of an estuarine fishery. Submitted to Ecological Applications, January 8.

Berger, J. J., ed. 1990. Environmental Restoration: Science & Strategies for Restoring the Earth. Island Press, Washington, D.C.

Bilby, R. E. 1988. Interactions between aquatic and terrestrial systems. Pages 13-29 *in* K.J. Raedeke, ed. Streamside Management: Riparian Wildlife and Forestry Interactions. University of Washington Press, Seattle, WA.

Bilby, R. E. and J. W. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests. *In* Southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences. 48:2499-2508.

Bilby R. E., B. R. Fransen and P. A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 53:164-173.

Bollin, R. L. and D. P. Abbott. 1963. Studies on the marine climate and phytoplankton of the central coastal area of California, 1954-1960. CalCOFI Report 9:23-45.

Bollman, F. H., P. K. Thelin, and R. T. Forester. 1970. Bimonthly bird counts at selected observation points around San Francisco Bay, February 1964 to January 1966. California Fish and Game 56:224-239.

Bonnot, P. 1928. Report on the Seals and Sea Lions of California. California Division of Fish and Game. Fish Bulletin 14. 61 pp.

Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55:3-23.

Bowie, A. J. 1887. Mining Debris in California Rivers. Transactions of the Technical Society of the Pacific Coast, February and March, 1887.

Bowie, A. J., Jr. 1905. Practical Treatise on Hydraulic Mining in California. Van Nostrand Company, 10th Ed., New York, NY.

Brandenburg, B. 1995-96. Central San's experience with diazonin and chlorpyrifos. Regional Monitoring News. Winter 1995-96, p. 10.

Brett, J. R. 1952. Temperature tolerance in young Pacific salmon, *Genus Oncorhynchus*. Journal of the Fisheries Research Board of Canada 9(6):265-323.

Brewer, W. H. 1861. Up and Down California in 1860-1864. F. P. Farquhar, ed. University of California Press, Berkeley, CA. 3rd edition, 1974.

Brice, J. 1977. Lateral Migration of the Middle Sacramento River, California. U.S. Geological Survey Water-Resources Investigations 77-43.

Briggs, K. T., D. G. Ainley, D. R. Carlson, D. B. Lewis, W. B. Tyler, L. B. Spear, and L. A. Ferris. 1987. California Seabird Ecology Study. Vol. 1: Feeding Ecology of California Nesting Seabirds. Final Report to the U.S. Minerals Management Service by the Institute of Marine Sciences. University of California, Santa Cruz, CA. 153 pp.

Brinson, M. M., B. L. Swift, R. C. Plantico and J. S. Barclay. 1981. Riparian Ecosystems: Their Ecology and Status. U.S. Fish and Wildlife Service Biol. Serv. Prog. FWS/OBS-81/17. Washington, D.C. 151 pp.

Britton, A. S. 1987a. Eye-Witness Accounts of the Central Valley, 1772 to 1876 *in* P. Fox, Rebuttal to David R. Dawdy Exhibit 3 in Regard to Freshwater Inflow to San Francisco Bay Under Natural Conditions, SWC Exhibit No. 276.

Britton, A. S. 1987b. Eye Witness Accounts of Riparian Forest in the Central Valley, 1776 to 1862 *in* P. Fox, Additional Evidence in Regard to Freshwater Inflow to San Francisco Bay Under Natural Conditions, SWC Exhibit No. 281.

Brown, L. R. 1996. Aquatic Biology of the San Joaquin Tulare Basins, California: Analysis of Available Data Through 1992. USGS Water Supply Paper 2471.

Brown and Caldwell. 1990. Sanitary Survey of the State Water Project. Brown and Caldwell Consultants. October 1990.

Brown, R. L. 1982. Screening Agricultural Diversions in the Sacramento-San Joaquin Delta. Internal Department of Water Resources Report.

Brown, R. L. and P. B. Moyle. 1987. Survey of the Fishes of the Mid-Elevation Streams of the San Joaquin Valley: California Department of Fish and Game, Final Report, Contract C-20607, 222 pp.

Brown, R. L. and P. B. Moyle. 1992. Native fishes of the San Joaquin drainage: status of a remnant fauna. Pages 89-98 *in* Williams, D. F., Byrne, S., and Rado, T. A., eds. Endangered and Sensitive Species of the San Joaquin Valley: Sacramento, California, The California Energy Commission.

Browning, P., ed. 1991. Bright Gem of the Western Seas: California 1846-1852. Great West Books, Lafayette, CA.

Bryan, K. 1915. Ground Water for Irrigation in the Sacramento Valley, California. USGS Water-Supply Paper 375-A.

Bryan, K. 1923. Geology and Ground-Water Resources of Sacramento Valley, California. USGS Water-Supply Paper 495.

Bryant, E. 1846. What I Saw in California: Being the Journal of a Tour, in the Years 1846, 1847. Ross and Haines, Inc., Minneapolis, MN. 1967.

Bryant, H. C. 1915. California's Fur-Bearing Mammals. California Fish and Game.

Buckingham, R. H., A. B. Dibble, and T. J. Sherwood (Commissioners). 1886. Biennial report of the Commissioners of Fisheries of the State of California for 1885-1886. Pages 17-19 *in* Appendix to the Journals of State Assembly of the 27th Session of the Legislature of State of California v. 1.

Buer, K., D. Forwalter, M. Kissel and B. Stolhert. 1989. The middle Sacramento River: human impacts on the physical and ecological processes along a meandering river. *In* Proceedings of the California Riparian Systems Conference, U. S. Forest Service Pacific Southwest Forest and Range Experiment Station. General Technical Report PW-110, Berkeley, CA.

Burcham, L. T. 1957. California Range Land. An Historico-Ecological Study of the Range Resource of California. California Department of Natural Resources, Division of Forestry, Sacramento, CA.

Busch, B. C., ed. 1983. Alta California 1840 - 1842. The Journal and Observations of William Dane Phelps, Master of the Ship "Alert," The Arthur H. Clark Company, Glendale, CA. 364 pp.

Cain, J. 1997. Hydrologic and geomorphic change to the San Joaquin River between Friant Dam and Gravelly Ford and implications for restoration of chinook salmon (*Oncorhynchus tshawytscha*). Masters Thesis. Center of Environmental Design Research, University of California, Berkeley, CA.

California Commissioner of Public Works (CCPW). 1895. Report to the Governor of California, 1983-1894. *In* Appendix to Journal of Senate and Assembly of the 31st Session of the Legislature, Sacramento, CA.

California Department of Fish and Game (CDFG). 1993. Restoring Central Valley Streams: A Plan for Action. Compiled by F. L. Reynolds, T. J. Mills, R. Benthin and A. Low. Report for public distribution, November 10, 1993. Inland Fisheries Division, Sacramento, CA. 129 pp.

CDFG. 1965-1995. Fish and Wildlife Losses in California. Environmental Services Branch, Water Pollution Control Lab.

California Department of Public Works (CDPW). 1931a. San Joaquin River Basin. Bulletin 29.

CDPW. 1931b. Sacramento River Basin. Bulletin 26.

CDPW. 1931c. Variation and Control of Salinity in Sacramento-San Joaquin Delta and Upper San Francisco Bay. Bulletin 27.

CDPW. 1931d. Economic Aspects of a Salt Water Barrie Below Confluence of Sacramento and San Joaquin Rivers. 445 pp.

CDPW. 1955. Report to the Water Project Authority of the State of California on Seepage Conditions in Sacramento Valley. June 1955

California Department of Water Resources (CDWR). 1967. Sacramento Valley Seepage Investigation. Bulletin 125. August 1967.

CDWR. 1978. Sacramento Valley Water Use Survey 1977. Bulletin 168. October 1978.

CDWR. 1980. Subsidence of Organice Soils in the Sacramento-San Joaquin Delta, Central District. 15 pp plus Appendices A & B.

CDWR. 1987. California Water: Looking to the Future. Bulletin 160-87. November 1987.

CDWR. 1988. Water Temperature Effects on Chinook Salmon (*Oncorhynchus tshawytscha*) With Emphasis on the Sacramento River. A Literature Review. January 1998. 42 pp.

CDWR. 1992. Seismic Stability Evaluation of the Sacramento-San Joaquin Delta Levees. August 1992.

CDWR. 1994a. California Central Valley Unimpaired Flow Data (October 1920 through September 1992). Third Edition.

CDWR. 1994b. California Water Plan Update, Vol 1. Bulletin 160-93.

CDWR. 1995a. Dams Within the Jurisdiction of the State of California. Digital Database Provided by the CDWR.

CDWR. 1995b. Sacramento San Joaquin Delta Atlas. 121 pp.

CDWR/CDFG. 1976. Birds in Riparian Habitat of the Upper Sacramento River. Memorandum Report. State of California, Department of Water Resources/Department of Fish and Game. Regional Studies, Northern California Investigation.

California State Board of Fish Commissioners (CSBFC). 1885-1886. Biennial Report 1885-1886. Appendix to Journal of Senate & Assembly, 27th Session, VI, 1887.

California State Lands Commission (CSLC). 1993. California's Rivers: A Public Trust Report. Report prepared for the California State Lands Commission.

Campbell, A. G. and J. F. Franklin. 1979. Riparian vegetation in Oregon's western Cascade Mountains: composition, biomass and autumn phenology. Coniferous Forest Biome Ecosystem Analysis Studies Bulletin 14:1-90.

Carlson, P. R., and D. S. McCulloch. 1974. Aerial observations of suspended-sediment plumes in San Francisco Bay and the adjacent Pacific Ocean. Journal Res. U.S. Geological Survey 2:519-526.

Carlton, J. T., J. K. Thompson, L. E. Schemel, and F. H. Nichols. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the asian clam *Potamocorbula amurensis*. 1: introduction and dispersal. Marine Ecological Progress Series 66:81-94.

Central Valley Water Use Study Committee (CVWUSC). 1987. Irrigation Water Use in the Central Valley of California.

Chess, J. R., S. E. Smith, and P. C. Fischer. 1988. Trophic relationships of the shortbelly rockfish, *Sebastes Jordani*, off central California. CALCOFI Report 29:129-136.

Clapp, W. B. and F. F. Henshaw. 1911. Surface Water Supply of the United States. 1909. Department of the Interior, United States Geological Survey. Water Supply Paper 271. Government Printing Office, Washington, D.C.

Cloern, J. E. and F. H. Nichols, eds. 1985. Temporal dynamics of an estuary: San Francisco Bay. Dr W. Junk Publishers, Dordrecht (Reprinted from Hydrobiologia, v. 129, 1985).

Cogswell, H. L. 1956. Middle Pacific Coast Region Report. Aud. Field Notes 10:359.

Cohen, A. N. 1991. An Introduction to the Ecology of the San Francisco Estuary. Produced by the Save San Francisco Bay Association for the San Francisco Estuary Project. Second Edition. June 1991.

Cohen, A. N. and J. T. Carlton. 1995. Nonindigenous Aquatic Species in a United States Estuary: A Case Study of the Biological Invasions of the San Francisco Bay and Delta. A Report for the U.S. Fish and Wildlife Service and National Sea Grant College Program Connecticut Sea Grant. December 1995. 246 pp.

Collins, I. J. and E. K. Noda. 1971. Causes of Levee Damage in the Sacramento-San Joaquin Delta. Report P-218-1. Tetra Tech, Pasadena, CA.

Conard, S. G., R. L. MacDonald, and R. F. Holland. 1977. Riparian vegetation and flora of the Sacramento Valley. Pages 47-55 *in* A. Sands, ed. Riparian Forests of California: Their Ecology and Conservation. Institute of Ecology, Publication No. 15, University of California, Davis, CA.

Cone, M. 1876. Two Years in California. S.C. Griggs and Company, Chicago, IL.

Connell, J. H. 1978. Diversity in tropical rain forests and coral reefs. Science 119:1302-1310.

Conomos, T. J., R. E. Smith, D. H. Peterson, S. W. Hager, and L. E. Schemel. 1979. Processes affecting seasonal distributions of water properties in the San Francisco Bay estuarine system. Pages 115-142 *in* T. J. Conomos, ed. San Francisco: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco, CA.

Conomos, T. J., R. E. Smith, and J. W. Gartner. 1985. Environmental setting of San Francisco Bay. Hydrobiologia 129:1-12.

Cook, S. F. 1960. Colonial Expedition to the Interior of California, Central Valley, 1800-1820. Anthropological Records 16:6. University of California Press, Berkeley and Los Angeles.

Cooke, R. U. and R.W. Reeves. 1976. Arroyos and Environmental Change in the American South-West. Clarendon Press, Oxford. 213 pp.

Cooper, C. F. 1969. Ecosystem models in watershed management. *In* G.M. Van Dyne, ed. The Ecosystem Concept in Natural Resource Management. Academic Press, N.Y.

Cosby, S. W. 1941. Soil Survey of the Sacramento-San Joaquin Delta Area, California. U.S. Department of Agriculture. Bureau of Chemistry and Soils. Series 1935, no. 21.

Coulter, T. 1835. Notes on upper California. Journal of the Royal Geographical Society of London 5:59-70.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of Wetlands and Deep Water Habitats of the United States. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C.

Cronise, T. F. 1868. The Natural Wealth of California. H.H. Bancroft & Company, San Francisco, CA.

Cronise, T. F. 1870. The Agricultural and Other Resources of California. A. Roman & Company, San Francisco, CA.

Dana, J. 1939. The Sacramento: River of Gold. Farrar & Rinehart, Inc., New York, NY. 294 pp.

Davidson, G., Col. G. H. Mendell, and Col. W. C. Alberger. 1896. Report of Board of Consulting Engineers to the Landowners of Reclamation District No. 108. Accompanied by Report of C.E. Grunsky.

Davis, G. H., J. H. Green, F. H. Olmsted and D.W. Brown. 1959. Ground-Water Conditions and Storage Capacity in the San Joaquin Valley, California. U.S. Geological Survey Water-Supply Paper 1469.

Davis, J. A., A. J. Gunther, and J. M. O'Connor. 1992. Priority pollutant loads from effluent discharges to the San Francisco Estuary. Water Environment Research 64(2):134-140.

Dawson, W. L. 1923. The Birds of California. Four volumes. South Moulton Co., San Diego, CA. 2121 pp.

deLappe, B. W., W. R. Sistek, E. F. Letterman, M. Firestone-Gillis, and R.W. Risebrough. 1980. Pre-Discharge Studies, San Francisco South-West Ocean Outfall Project: The Distribution of Higher-Molecular Weight Hydrocarbons in the Coastal Environment. Report of the Bodega Marine Laboratory and the Bodega Bay Institute of Pollution Ecology to the CH2MHill Co., San Francisco, CA. 100 pp with Four Data Supplements.

Derby, Lieutenant. 1849. The Sacramento Valley from the American River to Butte Creek (map). Mexican Land Grant Diseños.

Diringer, E. 1997. In Central Valley, defiant dairies foul the water. San Francisco Chronicle, July 7, 1997.

Dohl, T. P., R. C. Guess, M. L. Dunman and R. C. Helm. 1983. Cetaceans of Central and Northern California, 1980-83: Status, Abundance, and Distrubition. MMS Contract # 14-12-0001-29090. University of California, Santa Cruz, CA. 153 pp.

Dubrovsky, N. M., C. R. Kratzer, L. R. Brown, J. M. Gronberg, and K. R. Burow. 1998. Water quality in the San Joaquin-Tulare Basins, California, 1992-95. USGS Circular 1159. 38 pp.

Dunn, M. 1996. Selenium in White Sturgeon (*Acipenser transmontanus*) from the San Francisco Bay and Estuary. Presentation to IEP Contaminants Project Work Team. California Department of Fish and Game. Delta and Special Water Projects Division, Stockton (209-942-6075). October 8, 1996.

Dutzi, E. J. 1979. Valley oaks in the Sacramento Valley: past and present distribution. M.S. Thesis, Dept. of Geography, University of California at Davis, CA.

Ebeling, A. W., R. Larson, W. Alevizon. 1980a. Habitat groups and mainland-island distributions of kelp-bed fishes off Santa Barbara, California. Pages 403-411 *in* D.M. Power, ed. Multi-disciplinary Symposium on the California Islands. Santa Barbara Museum of Natural History.

Ebeling, A. W., R. Larson, W. Alevizon, and R. Bray. 1980b. Annual variability of reef fish assemblages in kelp forest of Santa Barbara, California. Fish Bulletin 78:361-377.

Ecological Society of America (ESA). 1995. The Scientific Basis of Ecosystem Management: An Assessment by the Ecological Society of America. Ad hoc committee on Ecosystem Management, Ecological Society of America, Washington, D.C.

Ehrlich, P. R. and A. H. Ehrlich. 1981. Extinction: The Causes and Consequences of the Disappearance of Species. Random House, New York, NY.

Emlen, J. M., R. R. Reisenbichler, A. M. McGie, and T. E. Nickelson. 1990. Density-dependence at sea for coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences 47:1765-1772.

Erman, N. A. 1996. Status of aquatic invertebrates. Sierra Nevada Ecosystem Project: Final Report to Congress. Vol. II: Assessments and Scientific Basis for Management Options, Chapter 35. Wildland Resources Center Report No. 37. University of California, Davis, CA.

Farquhar, F. P. 1932a. The topographical reports of Lieutenant George H. Derby. Quarterly of the California Historical Society XI(2):99-123.

Farquhar, F. P. 1932b. The Topographical Reports of Lieutenant George H. Derby, Part II. Report on the Tulare Valley of California, April and May 1850. California Historical Society XI(2):247-265.

Federal Register. 1993. Endangered and threatened species: screening of water diversions to protect Sacramento River winter-run chinook salmon 58(199):53703-53704.

Filice, F. P. 1954a. An ecological survey of the Castro Creek area in San Pablo Bay: Wasmann. Journal of Biology 12:1-24.

Filice, F. P. 1954b. A study of some factors affecting the bottom fauna of a portion of the San Francisco Bay Estuary. Wassman Journal of Biology 12:257-292.

Filice, F. P. 1958. Invertebrates from the estuarine portion of San Francisco Bay and some factors influencing their distribution. Wassman Journal of Biology 16:159-211.

Filice, F. P. 1959. The effect of wastes on the distributionof bottom invertebrates in San Francisco Bay Estuary. Wassman Journal of Biology 17:1-17.

Fischer, K. J. 1994. Fluvial geomorphology and flood control strategies: Sacramento River, California. *In* Schumm, S. A. and B. R Winkley, eds. The Variability of Large Alluvial Rivers. ASCE Press, New York, NY.

Fisher, S. G. and G. E. Likens. 1973. Energy flow in Bear Brook, New Hampshire: an integrative approach to stream ecosystem metabolism. Ecological Monographs 43:421-439.

Foe, C. and V. Connor. 1991. San Joaquin Watershed Bioassay Results 1988-90. CVRWQCB Staff Report. July 1991.

Fox, J. P. 1987. Freshwater Inflow to San Francisco Bay Under Natural Conditions. State Water Contractors Exhibit Number 262. Bay Delta Hearings, Sacramento, CA.

Fox, J. P. and E. Archibald. 1997. Aquatic Toxicity and Pesticides in Surface Water of the Central Valley. Final Report Prepared for Caifornia Urban Water Agencies. September 15, 1997.

Fox, J. P., T. R. Mongan, and W. J. Miller. 1990. Trends in freshwater inflow to San Francisco Bay from the Sacramento-San Joaquin Delta. Water Resources Bulletin, American Water Resources Association 26:1. February 1990.

Fox, J. P., T. R. Mongan, and W. J. Miller. 1991. Long term annual and seasonal trends and surface salinity of San Francisco Bay. Journal of Hydrology 122:93-117.

Franklin, J. F. and J. A. Fites-Kaufmann. 1996. Assessment of late successional forests of the Sierra Nevada. Pages 627-662 *in* Sierra Nevada Ecosystem Project, Vol. II: Assessments and Scientific Basis for Management Options. Final Report to Congress. Wildland Resources Center Report No. 37. University of California, Davis, CA.

Franklin, J. F., K. Cromack Jr., W. Denison, A. McKee, C. Maser, J. Sedell, F. Swanson, and G. Juday. 1981. Ecological Characteristics of Old-Growth Douglas-Fir Forests. USDA General Technical Report PNW-GTR-118.

Fremont, J. C. 1848. Geographical Memoir upon Upper California in Illustration of his Map of Oregon and California by John Charles Fremont, Newly Reprinted from the Edition of 1848 with Introductions by Allan Nevins and Dale L. Morgan and a Reproduction of the Map. The Book Club of California, San Francisco, CA 1964.

Fremont, J. C. 1887. Memoirs of My Life, Including in the Narrative Five Journeys of Western Exploration, During the Years 1842, 1843-44, 1845-6-7, 1848-49, 1853-54. Together with a Sketch of the Life of Senator Benton, In Connection with Western Expansion. Belford, Clarke & Co., Chicago, IL.

Fritts, H. C., G. R. Lofgren, and G. A. Gordon. 1979. Variations in climate since 1602 as reconstructed from tree rings. Quarternary Research 12:18-46.

Gerstaecker, F. 1853. Narrative of a Journey Round the World. Comprising a Winters-Passage Across the Andes to Chile: With a Visit to the Gold Regions of California and Australia. Harpers & Bros. 624 pp.

Gibbes, C. D. 1850a. Letter to Stockton Times, June 8, 1850.

Gibbes, C. D. 1850b. Map of the San Joaquin River. Bancroft Library, University of California, Berkeley, CA.

Gifford, E.W. 1916. Composition of California shellmounds. University of California Publications in American Archaeology and Ethnology 12:1-29.

Gilbert, G. K. 1917. Hydraulic-Mining in the Sierra Nevada. U.S. Geological Survey Professional Paper 105. Government Printing Office, Washington, D.C.

Gilliom, R. J. and D. G. Clifton. 1990. Organochlorine pesticide residues in bed sediments of the San Joaquin River, California. Water Resources Bulletin 26, 1:11-14.

Goddard, G. H. Undated. C. E. Britton and Rey's Map of the State of California, Compiled from the U.S. Land and Coast Surveys, the Several Military, Scientific and Railroad Explorations, the State and County Boundary Surveys Made Under the Order of the Surveyor General of California, and From Private Surveys with Britton and Rey. San Francisco, CA.

Goldman and Horne. 1983. Limnology. McGraw-Hill. New York, NY. 464 pp.

Goodbred, S. L., R. J. Gilliom, T. S. Gross, N. P. Denslow, W. L. Bryant, and T. R. Schoeb. 1997. Reconnaissance of 17B-Estradiol, 11-Ketotestosterone, Vitellogenin, and Gonad Histopathology in Common Carp of United States Streams: Potential for Contaminant-Induced Endocrine Disruption. USGS Open-File Report 96-626.

Graber, D. M. 1996. Status of terrestrial vertebrates. Pages 709-734 *in* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Volume II: Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No.37. University of California, Davis, CA. July 1996.

Graumlich, L. J. 1987. Precipitation variation in the Pacific Northwest (1675-1975) as reconstructed from tree rings. Annals of the Association of American Geographers 77:19-29.

Green, W. S. 1950. The History of Colusa County, California and General History of the State. The Sacramento Lithograph Company, Sacramento, CA.

Griffin, J. R. and W. B. Critchfield. 1972. The Distribution of Forest Trees in California. USDA Forest Service Research Paper PSW-82/1972.

Griffin, S. 1993. Monitoring of an Unscreened Agricultural Diversion on the San Joaquin River at McMullin Tract. Public Notice 199200393. San Joaquin County, CA. May-July.

Grinnell, J. 1915. A distributional list of the birds of California. Pacific Coast Avifauna 11.

Grinnell, J., J. S. Dixon, and J. M. Linsdale. 1937. Fur Bearing Mammals of California, Their Natural History, Systematic Status, and Relations to Man, Vol I and II. University of California Press, Berkeley, CA.

Grunsky, C. E. 1898. Irrigation near Bakersfield, California: U.S. Geological Survey Water Supply Paper 17. 96 pp.

Grunsky, C. E. 1924. Salinity in the Delta. *In* Proceedings of the Sacramento River Problems Conference. Sacramento Chamber of Commerce and Division of Water Rights, Sacramento, CA.

Grunsky, C. E. 1927. Hydrographic Section. *In* Marine Borers and their Relation to Marine Construction on the Pacific Coast. Final Report of the San Francisco Bay Marine Piling Committee, C.L. Hill and C.A. Kofoid eds.

Grunsky, C. E. 1929. The relief outlets and by-passes of the Sacramento Valley Flood-Control Project. Transactions of the American Society of Civil Engineers 93:791-811.

Gucinsky, H. 1982. Sediment Suspension & Resuspension from Small Craft Induced Turbulence. U.S. EPA Report EPA 600/3-82--084.

Gudde, E. G. 1933. Memoirs of Theodore Cordua, the pioneer of New Mecklenburg in the Sacramento Valley. California Historical Society Quarterly 12:279-311.

Guinle, R. L. 1981. A Modern Spanish-English and English-Spanish Technical and Engineering Dictionary. Compania Editorial Continental, S.A., Mexico. 311 pp.

Hall, W. H. Undated. The Great Valley of California is Admirably Adapted for Irrigation. Handwritten undated manuscript in CDWR files catalogued as 800.91, No. 201.

Hall, W. H. 1880. Drainage of the Valleys and the Improvement of the Navigation of River. Report of the State Engineer to the Legislature of the State of California, Session of 1880, in three parts.

Hall, W. H. 1886a. Physical Data and Statistics of California: Tables and Memoranda. State Engineering Department of California, Sacramento, CA. 451pp.

Hall, W. H. 1886b. Topographical and Irrigation Map of the San Joaquin Valley. (Scale: 1" = 3 mi.)

Hall, W. H. 1887. Topographical and Irrigation Map of the Great Central Valley of California: Embracing the Sacramento, San Joaquin, Tulare and Kern Valleys and the Bordering Foothills. California State Engineering Department, Sacramento. The Dept., 1887. San Francisco, CA. Lithographers: Britton & Rey, Scale not given.

Hall, W. H. 1889. Irrigation in California: National Geographic Magazine 1(4):281.

Hall, W. H. 1905. Sacramento Valley River Improvement. Government Policy and Works. Addressed to Board of Engineers for Improvement of the Sacramento and Tributary Rivers. September 14, 1905.

Hamilton, S. J. and R. H. Wiedmeyer. 1990. Concentrations of boron, molybdenum, and selenium in chinook salmon. Transactions of the American Fisheries Society 119:500-510.

Harding, S. T. 1960. Water in California, n-p publications, Palo Alto CA.

Harris, R. R., C. A. Fox, and R. Risser. 1987. Impacts of hydroelectric development on riparian vegetation in the Sierra Nevada Region, California, USA. Environmental Management 11(4):519-27.

Harvey, T. E., K. J. Miller, R. L. Hothem, M. J. Rauzon, G. W. Page, and R. A. Keck. 1992. Status and Trends Report on Wildlife of the San Francisco Estuary. Prepared by the U.S. Fish & Wildlife Service for the San Francisco Estuary Project. U.S. Environmental Protection Agency. San Francisco, CA. 279 pp. and appendices. January 1992.

Hayes, D. 1994. Screening Agricultural Diversions in the Sacramento-San Joaquin Delta. Draft Internal DWR Report.

Headworth, H. and S. Steines. 1998 English / Spanish & Spanish / English Dictionary of Environmental Science and Engineering. John Wiley & Sons, New York, NY. 310 pp.

Hedgepeth, J. W. 1979. San Francisco Bay: the unsuspected estuary. Pages 9-29 *in* T. J. Conomos, ed. San Francisco: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco, CA.

Herbold, B. and P. B. Moyle. 1989. The Ecology of the Sacramento-San Joaquin Delta: A Community Profile. U.S. Fish and Wildlife Service Report 85(7.22). Washington, D.C. 106 pp.

Herbold, B., A. D. Jassby, and P. B. Moyle. 1992. Status and Trends Report on Aquatic Resources in the San Francisco Estuary: Public Report. San Francisco Estuary Project, Oakland, CA.

Herrgesell, P. L., R. G. Schaffter, and C. J. Larsen. 1983. Effects of Freshwater Outflow on San Francisco Bay Biological Resources. Interagency Ecological Study Program for the Sacramento-San Joaquin Estuary Technical Report 7. July 1983.

Heuer, W. H., T. H. Handbury, and W. W. Harts. 1905. Report of a Board of Engineers Upon Examination of Sacramento, San Joaquin, and Feather Rivers, California, and their Tributaries, with the View of Considering What, if Anything, the United States Can or Should do, In Conjunction with the State of California, to Improve the Navigation of Said Streams. House of Representatives, 59th Congress, 1st Session. Document No. 262.

Higgens, P. T. 1991. Habitat types of the Eel River Estuary and their associated fishes and invertebrates. *In* C. Roberts, ed. Report on Fish and Wildlife Species of the Eel Delta. Eel River RCD, USDA Soil Conservation Service, Eureka, CA.

Hittell, T. H. 1885. History of California. Pacific Press Publishing House and Occidental Publishing Co., San Francisco, CA.

Holland, R. F. 1978. The geographic and edaphic distribution of vernal pools in the Great Central Valley, California. California Native Plant Society, Special Publication No. 3.

Holland, R. F. 1986. Preliminary Descriptions of the Terrestrial Natural Communities of California. California Department of Fish and Game.

Holland, R. F. 1988. Vernal pools. Pages 1013-1014 *in* M.G. Barbour and J. Major, eds. Terrestrial Vegetation of California. California Nature Plant Society, Supplement.

Holland, R. F. and S. K. Jain. 1977. Vernal pools. Chapter 15 *in* M.G. Barbour and J. Major, eds. Terrestrial Vegetation of California. Wiley, New York, NY.

Holmes, L. C., J. W. Nelson and Party. 1916. Reconnaissance soil survey of the Sacramento Valley, California. Pages 2297-2438 *in* Field Operations of the Bureau of Soils, 1913. U.S. Department of Agriculture, Bureau of Soils, Washington, D.C.

Hornbeck, D. 1983. California Patterns: A Geographical and Historical Atlas. Mayfield Publishing Company, Mountain View, CA.

Hummel, M., ed. 1989. Endangered Spaces: The Future of Canada's Wilderness. Key Porter, Toronto, ON.

Hundley, N., Jr. 1992. The Great Thirst: Californians and Water, 1770s – 1990s. University of California Press, Berkeley and Los Angeles, CA. 551 pp.

Hutchings, J. H. 1860. Scenes of Wonder and Curiosity in California. Hutchings & Rosenfield, San Francisco, CA.

Hutchison, C. B., ed. 1946. California Agriculture. By Members of the Faculty of the College of Agriculture, University of California. University of California Press, Berkeley and Los Angeles, CA.

Huyer, A., R. L. Smith, and E. J. C. Sobey. 1978. Seasonal differences in low-frequency current fluctuations over the Oregon continental shelf. Journal of Geophysical Research 83:5077-5089.

Huyer, A. and R. L. Smith. 1985. The signature of El Niño off Oregon 1982-1983. Journal of Geophysical Research 90:7133-7142.

Hymanson, Z., D. Mayer, and J. Steinbeck. 1994. Long-term Trends in Benthos Abundance and Persistence in the Upper Sacramento-San Joaquin Estuary. Summary Report 1980-1990. Prepared for the Interagency Ecological Program for the San Francisco Bay/Delta Estuary. Technical Report 38, May 1994.

Hynes, H. B. N. 1970. The Ecology of Running Waters. University of Toronto Press, Toronto, ON. 555 pp.

Ingerson, I. M. 1941. The hydrology of the Southern San Joaquin Valley, California, and its relation to imported water supplies. Pages 20-45 *in* American Geophysical Union Transactions, Part I, Reports and Papers (A). Section of Hydrology, National Research Council, Washington, D.C.

Ingles, L. G. 1965. Mammals of the Pacific States. Stanford University Press, Stanford, CA.

Ingram, L., J. C. Ingle, and M. E. Conrad. 1996. Isotopic records of prehistoric salinity and river inflow in San Francisco Bay Estuary. *In* J.T. Hollibaugh, ed. San Francisco Bay The Ecosystem: Further Investigations into the Natural History of the San Francisco Bay and Delta with Reference to the Influence of Man. Proceedings of the 75th Annual Meeting of the Pacific Division/American Association for the Advancement of Science, Golden Gate Park, San Francisco, CA.

Interagency Ecological Program for the San Francisco Bay / Delta Estuary (IEP). 1995. Working Conceptual Model for the Food Web of the San Francisco Bay / Delta Estuary. Interagency Technical Report.

Jahnke, R. A., C. E. Reimers, and D. B. Crave. 1990. Intensification of recycling of organic matter on the sea floor near continental margins. Nature 348:50-54.

James, L. A. 1989. Sustained storage and transport of hydraulic gold mining sediment in the Bear River, California. Annals of the Association of American Geographers 79(4):570-592.

Jarman, W. M., W. J. Sydeman, K. A. Hobson and P. A. Bergqvist. 1997. Relationship of polychlorinated dibenzo-p-dioxin and polychlorinated debenzofuran levels to stable nitrogen isotope abundance in marine birds and mammals in coastal California. Environmental Toxicology and Chemistry 16:5:1010-1013.

Jassby, A. D. 1992. Organic carbon sources for the food web of San Francisco Bay. *In* B. Herbold, A. D. Jassby, and P. B. Moyle Status and Trends Report on Aquatic Resources in the San Francisco Estuary: Public Report. San Francisco Estuary Project, Oakland, CA.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecological Applications 5(1):272-289.

Jelineck, L. J. 1982. Harvest Empire, A History of California Agriculture.

Jennings, M. R. 1996. In Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Vol II: Assessments and Scientific Basis for Management Options. University of California, Davis, CA. Wildland Resources Center Report No. 37. University of California, Davis, CA.

Jepson, W. L. 1910. The Silva of California. Memoirs of the University of California, Vol. 2. The University Press, Berkeley, CA.

Jepson, W. L. 1975. A Manual of the Flowering Plants of California. University of California Press, Berkeley, CA.

Johnston, V. R. 1998. Sierra Nevada. The Naturalist's Companion. University of California Press, Berkeley, CA. 207 pp.

Jones & Stokes Associates, Inc. 1979. Protection and Restoration of San Francisco Bay Fish and Wildlife Habitat. Prepared for the U.S. Fish and Wildlife Service and California Department of Fish and Game, Sacramento, CA.

Jones and Stokes Associates. 1981. An Ecological Characterization of the Central and Northern California Coastal Region. FWS/OBS-80/46.1. October, 1981.

Jones and Stokes Associates. 1998. Historical Riparian Conditions of the San Joaquin River - Draft.

Jones, P. A. and I. D. Szczepaniak. 1992. Report on the Seabird and Marine Mammal Censuses Conducted for the Long-Term Management Strategy (LTMS) August 1990 Through November 1991. Prepared for the U.S. EPA, Region IX, San Francisco, CA. July 1992.

Jordan, D. S. 1887. The Fisheries of the Pacific Coast. Part XVI *in* G. B. Goode, ed. The Fisheries and Fishery Industries of the United States. Section II, U.S. Commission of Fish and Fisheries. Government Printing Office, Washington, D.C.

Josselyn, M. 1983. The Ecology of San Francisco Bay Tidal Marshes: A Community Profile. U.S. Fish and Wildlife Service, Division of Biological Services, FWS/OBS-83/23, Washington, D.C. 102 pp.

Josselyn, M. N. and J. A. West. 1985. The distribution and temporal dynamics of the estuarine macroalgal community of San Francisco Bay. Hydrobiologia 129:139-152.

Kahrl, W. L., ed. 1979. California Water Atlas. California Governor's Office of Planning and Research and Department of Water Resources, Sacramento, CA.

Kantor, J. R. K. 1964. Grimshaw's Narrative. Sacramento Book Collectors Club.

Karl, H. A., W. C. Schwab and J. L. Chin. 1996. Gulf of the Farallones geological inventory investigations: a prototype for environmental studies on continental margins off major urban areas. *In* S. Kelly, ed. Proceedings from Marine Technology Society.

Katibah, E. F. 1984. A brief history of riparian forests in the Central Valley of California. Pages 23-29 *in* R. E. Warner and K. M. Hendrix, eds. California Riparian Systems: Ecology, Conservation, and Productive Management. University of California Press, Berkeley, CA.

Kattelmann, R. 1996. Hydrology and water resources. Pages 855-920 *in* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Vol. II: Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. University of California, Davis, CA.

Kattelmann, R. and M. Embury. 1996. Riparian areas and wetlands. Pages 201-273 *in* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Volume II: Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. University of California, Davis, CA.

Keefe, C. W. 1972. Marsh production - a summary of the literature. Contributions in Marine Science 16:163-181. University of Texas, TX.

Keddy, P. A. and C. G. Drummond. 1996. Ecological properties for the evaluation, management, and restoration of temperate deciduous forest ecosystems. Ecological Applications 6(3):748-762.

Kelley, R. 1989. Battling the Inland Sea: American Political Culture, Public Policy, and the Sacramento Valley, 1850-1986. University of California Press, Berkeley, CA. 395 pp.

Killinger, E. T. 1934. The Islands of San Francisco Bay. National Society of the Colonial Dames of America, California. Publications No. 6. San Francisco, CA.

Kimmerer, W. J. 1992. An Evaluation of Existing Data in the Entrapment Zone of the San Francisco Bay Estuary. Technical Report 33. Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary.

Kimmerer, W. J. 1995. Update on Studies of the Biology of the Entrapment Zone. Interagency Ecological Program Newsletter. Spring 1995.

Kimmerer, W. J. 1998a. A Discussion of Technical Issued Raised in the August 1997 CUWA/SLDMWA Review. Draft. Prepared for USFWS, June 1, 1998. 13 pp.

Kimmerer, W. J. 1998b. The Fish-X2 Relationships: Update. Presented at X2 Workshop, Contra Costa Water District. March 11, 1998.

Kimmerer, W. J. and J. J. Orsi. 1996. Changes in the zooplankton of the San Francisco Bay Estuary since the introduction of the clam *Potamocorbula amurensis*. *In* J. T. Hollibaugh (ed.) San Francisco Bay The Ecosystem: Further Investigations into the Natural History of the San Francisco Bay and Delta with Reference to the Influence of Man. Proceedings of the 75th Annual Meeting of the Pacific Division / American Association for the Advancement of Science, Golden Gate Park, San Francisco, CA.

Kimmerer, W. J., E. Gartside, and J. J. Orsi. 1994. Predation by an introduced clam as the probable cause of substantial declines in zooplankton in San Francisco Bay. Marine Ecological Progress Series 113:81-93.

Kinetic Laboratories, Tetra Tech, and Environmental Science Associates, Inc. (KLI). 1991. Ocean Disposal Site Evaluation Report. Prepared for the U.S. Army Corps of Engineers, San Francisco District.

Knapp, R. A. 1996. Non-native trout in natural lakes of the Sierra Nevada: an analysis of their distribution and impacts on native aquatic biota. Pages 363-407 *in* Sierra Nevada Ecosystem Project Final Report to Congress. Volume III: Assessments, Commissioned Reports, and Background Information. Wildland Resources Center Report No. 38. University of California, Davis, CA. July 1996.

Kohm, K. A., ed. 1991. Balancing on the Brink of Extinction: The Endangered Species Act and Lessons for the Future. Island Press, Washington, D.C.

Kovalchik, B. L. 1987. Riparian Zone Associations of the Deschutes, Ochoco, Fremont and Winema National Forests. USDA Forest Service, Pacific Northwest Region 6 R6 ECOL TP-279-87.

Kondolf, G. M., J. W. Webb, M. J. Sale, and T. Felando. 1987. Basic hydrologic studies for assessing impacts of flow diversions on riparian vegetation: examples from streams of the eastern Sierra Nevada, California, USA. Environmental Management 11(6):757-770.

Kondolf, G. M., R. Kattelmann, M. Embury, and D. C. Erman. 1996. Status of riparian habitat. Chapter 36 *in* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Vol. II: Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. University of California, Davis, CA. July 1996.

Kope, R. G. and L. W. Botsford. 1990. Determination of factors affecting recruitment of chinook salmon, *Oncorhynchus tshawytscha*, in Central California. Fishery Bulletin 88:257-269.

Lamarche, V. C. 1973. Holocene climate variations inferred from treeline fluctuations in the White Mountains, California. Quarternary Research 3:632-660.

Lane, R. S. 1969. The insect fauna of a coastal salt marsh. M.A. Thesis. San Francisco State University, San Francisco, CA. 78 pp.

Langley, R. D. 1984. SOFAR: A small-town water diversion project on the South Fork, American River. Pages 505-14 *in* R. E. Warner and K. M. Hendrix, eds. California Riparian Systems: Ecology, Conservation, and Productive Management. University of California Press, Berkeley, CA.

Larry Walker Associates. 1992. A White Paper on Pollution Problems Associated with Inactive Mines in the Sacramento river Basin. Prepared for the County of Sacramento and the City of Sacramento, CA.

Latta, F. F. 1937. Little Journeys in the San Joaquin. Copyrighted by F. F. Latta. 37 pp.

Leale, Captain J. 1939. Recollections of a Tule Sailor by John Leale (1850-1932) Master Mariner San Francisco Bay, with Interpolations by Marion Leale. George Fields, San Francisco, CA. 311 pp.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial Processes in Geomorphology. W. H. Freeman and Company, San Francisco, CA. 522 pp.

Li, Hong-Chun and Ku, Teh-Lung. 1997. Decadal hydroclimatic variability in the western coastal United States: temporal and spatial variations in precipitation, streamflow, and lake level. *In* C.M Isaacs and V.I. Tharp, eds. Proceedings of the Thirteenth Annual Pacific Climate (PACLIM) Workshop April 15-18, 1996. Interagency Ecological Program. Technical Report 53. California Department of Water Resources.

Lourence, F. J. and W. O. Pruitt. 1971. Energy balance and water use of rice grown in the Central Valley of California. Agronomy Journal 63(5):827-32.

Luoma, S., N. D. Cain, and C. Johansson. 1985. Temporal fluctuations of silver, copper, and zinc in the bivalve *Macoma Balthica* at five station in South San Francisco Bay. Pages 109-120 *in* J. E. Cloern and F. H. Nichols, eds. Temporal Dynamics of an Estuary: San Francisco Bay. Hydrobiologia v. 129.

Major, J. 1977. California climate in relation to vegetation. Pages 11-74 *in* M. G. Barbour and J. Major, eds. Terrestrial Vegetation of California. University of California Press, Berkeley, CA.

Maloney, A. B. 1945. Fur Brigade to Bonaventura: John Work's California Expedition, 1832-1833, for the Hudson's Bay Company. California Historical Society, San Francisco, CA.

Mandeville, J. W. 1857. Map of Public Surveys in California to accompany report of Surveyor General. Surveyor General's Office, San Francisco, CA.

Manley, P. N. and C. Davidson. 1995. Assessing Risks and Setting Priorities for Neotropical Migratory birds in California. Draft manuscript on file, San Francisco: U. S. Forest Service, Pacific Southwest Region.

Matthew, R., J. A. Chase, and D. R. Warren. 1931. Variation and Control of Salinity in the Sacramento-San Joaquin Delta and Upper San Francisco Bay. California Department of Water Resources Bulletin No. 27. Sacramento, CA. 440 pp.

Mayer, K. E. and W. F. Laudenslayer, Jr., eds. 1988. A Guide to Wildlife Habitats of California. California Department of Forestry and Fire Protection. Sacramento, CA. 166 pp.

McCarty, J. C., R. A. Wagner, M. Macomber, H. S. Harris, M. Stephenson, E. A. Pearson. 1962. An Investigation of Water and Sediment Quality and Pollutional Characteristics of Three Areas in San Francisco Bay. Sanitary Engineering Research Laboratory, College of Engineering and School of Public Health, University of California, Berkeley, CA.

McClure, W. F. 1925. Maps and Profiles to Accompany Sacramento Flood Control Project. Revised Plans. Submitted to the Reclamation Board.

McCulloch, D. S., D. H. Peterson, P. R. Carlson, and T. J. Conomos. 1970. A preliminary study of the effects of water circulation in the San Francisco Bay Estuary: some effects of fresh-water inflow on the flushing of South San Francisco Bay. Pages A1-A27 *in* USGS Circular 637-A.

McGie, A. M. 1983. Commentary: evidence for density dependence among coho salmon stocks in the Oregon production index area. *In* W. G. Pearcy (ed.) The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific.

McGurk, B. J. 1989. Predicting stream temperature after riparian vegetation removal. Pages 157-164 *in* Proceedings of the California Riparian Systems Conference. Protection, Management, and Restoration for the 1990s. USDA Forest Service General Technical Report PSW-110.

Mendell, G. H. 1882. Protection of the navigable waters of California from injury from the debris of mines. *In* Annual Report of the Chief of Engineers, United States Army, to the Secretary of War, for the Year 1882, Part III, Appendix MM.

Mendenhall, W. C., R. B. Dole, and H. Stabler. 1916. Ground Water in San Joaquin Valley, California. USGS Water Supply Paper 398.

Miller, R. R. 1963. Synonymy, characters, and variation of *Gila crassicauda*, a rare California minnow, with an account of its hydridization with *Lavinia exilicauda*. California Fish and Game 49(1):20-29.

Miller, J., G. Miller, and P. Fox. 1997. Identification of the Causes of Fathead Minnow Toxicity in the Sacramento River Watershed - Role of Metallodithiocarbamate Fungicides.

Miller, W. H., T. C. Coley, H. L. Burge, and T. T. Kisanuki. 1990. Analysis of Salmon and Steelhead Supplementation: Emphasis on Unpublished Reports and Present Programs. Bonneville Power Administration. DOE/BP-9263-1.

Mitchell, W. T. 1987. Evaluation of the Frequency and Duration of Exposure of Downstream Migrant Chinook Salmon to High Water Temperatures in the Sacramento River. Report Prepared for K.W. Kelley & Associates for CDWR. July 1987. 10 pp.

Moffett, J. W. 1949. The first four years of king salmon maintenance below Shasta Dam, Sacramento River, California. California Fish and Game 35:77-102.

Montague, C. L., S. M. Bunker, E. B. Haines, A. L. Pace, and R. L. Wetzel. 1981. Aquatic macroconsumers. Pages 69-86 *in* L. R. Pomeroy and R. G. Wiegert, eds. Springer-Verlag. New York, NY.

Montoya, B. L. 1987. Urban Runoff Discharges from Sacramento, California, 1984-1985. Report #87-1SPSS. Central Valley Regional Water Quality Control Board, Sacramento, CA.

Monroe, M. W. and J. Kelly. 1992. State of the Estuary. A Report on Conditions and Problems in the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. Prepared by the Association of Bay Area Governments for the San Francisco Estuary Project. U.S. Environmental Protection Agency, June. San Francisco, CA. 269 pp & figures.

Morgan II, R. P., R. E. Ulanowicz, V. J. Rasin, Jr., L. A. Noe, and G. B. Gray. 1976. Effects of shear on eggs and larvae of striped bass, *Morone saxatilis*, and white perch, *M. americana*. Transactions of the American Fisheries Society 1:149-154.

Mount, J. F. 1995. California Rivers and Streams. The Conflict Between Fluvial Process and Land Use. University of California Press, Berkeley, CA. 359 pp.

Moyle, P. B. 1976a. Fish introductions in California: history and impact on native fishes. Biological Conservation 9:101-118.

Moyle, P. B. 1976b. Inland Fishes of California. University of California Press, Berkeley CA. 405 pp.

Moyle, P. B. and D. M. Baltz. 1985. Microhabitat use by an assemblage of California stream fishes: developing criteria for instream flow determinations. Transactions of the American Fisheries Society 114:695-704.

Moyle, P. B. and J. J. Cech, Jr. 1988. Fishes, an Introduction to Ichthyology. Prentice Hall, Englewood Cliffs, NJ. 559 pp.

Moyle, P. B. and J. E. Williams. 1990. Biodiversity loss in the temperate zone: Decline of the native fish fauna of California. Conservation Biology 4:475-484.

Moyle, P. B., B. and R. A. Daniels. 1982. Resources partitioning in a non-coevolved assemblage of estuarine fishes. Pages 178-184 *in* G. M. Caillet and C. A. Simenstad, eds. Gutshop 1981. Washington Sea Grant Publishing, Seattle, WA.

Moyle, P. B. and R. M. Yoshiyama. 1992. Fishes, Aquatic Diversity Management Areas, and Endangered Species: A Plan to Protect California's Native Aquatic Species. The California Policy Seminar, University of California.

Moyle, P. B., R. Kattelmann, R. Zomer, and P. J. Randall. 1996. Management of riparian areas in the Sierra Nevada. Pages 1-38 *in* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Volume III: Status of the Sierra Nevada. Wildland Resources Center Report No. 38. University of California, Davis, CA.

Moyle, P. B., P. J. Randall, and R. M. Yoshiyama. 1996. Potential aquatic diversity management areas in the Sierra Nevada. Pages 409-478 *in* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Volume III: Status of the Sierra Nevada. Wildland Resources Center Report No. 38. University of California, Davis, CA.

Moyle, P. B., R. M. Yoshiyama, and R. A. Knapp. 1996. Status of fish and fisheries. Chapter 33 *in* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Volume II: Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. University of California, Davis, CA.

Naiman, R. J. and K. H. Rogers. 1997. Large animals and system-level characteristics in river corridors. BioScience 47:521-529.

National Marine Fisheries Service (NMFS) Biological Opinion. 1993. Letter from Rolland A. Schmitten, Assistant Administrator for Fisheries, National Oceanic and Atmospheric Administration to Mr. Roger Patterson, Regional Director, U.S. Bureau of Reclamation, dated May 17, 1995, amending the Biological Opinion issued for the CVP-OCAP originally issued on February 12, 1993.

NMFS. 1998. Federal Register 63(45):11481-11520. March 9, 1998.

National Research Council (NRC). 1992. Restoration of Aquatic Ecosystems. National Academy Press. Washington, D.C.

Nelson, N. C. 1910. The Ellis Island shellmound. *In* American Archeology and Ethnology 7:1-35. University of California Publications.

Nelson, J. W., J. E. Guernsey, L. C. Holmes, E. C. Eckmann and M. H. Lapham. 1918. Reconnaissance soil survey of the lower San Joaquin Valley, California. Pages 2583-2733 *in* Field Operations of the Bureau of Soils 1915. U.S. Department of Agriculture, Bureau of Soils, Washington, D.C.

Nichols, D. R. and N. A. Wright. 1971. Preliminary Map of Historic Margins of Marshland, San Francisco Bay, California. U.S. Geological Survey Open File Map, Menlo Park, CA.

Nichols, F. H. 1979. Natural and anthropogenic influences on benthic community structure in San Francisco Bay. Pages 409-426 *in* T. J. Conomos, ed. San Francisco: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco, CA.

Nichols, F. H. and M. M. Pamatmat. 1988. The Ecology of the Soft-Bottom Benthos of San Francisco Bay: A Community Profile. U.S. Fish and Wildlife Service Biological Report 85 (7.19). 73 pp.

Nichols, F. H., J. K. Thompson, and L. E. Schemel. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the asian clam *Potamocorbula amurensis.*

2: displacement of a former community. Marine Ecological Progress Series 66:95-101.

Nidever, H. B. 1916. Shad in California. California Fish and Game 2(2):59-64.

Noble, M. A., S. R. Ramp, and K. Kinoshita. 1992. Current Patterns Over the Shelf and Slope Adjacent to the Gulf of the Farallones. Executive Summary. Prepared for the U.S. Environmental Protection Agency, Region IX, San Francisco, CA.

Nordhoff, C. 1872. California for Health, Pleasure, and Residence: A Book for Travelers and Settlers. Harper and Brothers, New York, NY.

Noss, R. F. 1991. From endangered species to biodiversity. *In* K. A. Kohn, ed. Balancing on the Brink of Extinction: The Endangered Species Act and Lessons for the Future. Island Press, Washington, D.C.

Noss, R. F., E. T. LaRoe III, and J. M. Scott. 1994. Endangered ecosystems of the United States: a preliminary assessment of loss and degradation. Biological Reports 28:1-28.

Nugen, J. A. 1853. Topographical Sketch of the Tulare Valley. Bancroft Library, University of California, Berkeley, CA.

Nybakken, J., W. Broenkow, M. Silberstein, P. Slattery, A. R. Flegal, G. Knauer, R. Risebrough, and B. Antrim. 1984. Baseline Survey and Site Selection for Ocean Disposal, Gulf of the Farallones. Report prepared for the U.S. Army Corps of Engineers, San Francisco District. 241 pp.

Oakley, A. L., J. A. Collins, L. B. Everson, D. A. Heller, J. C. Howerton, and R. E. Vincent. 1985. Riparian zones and freshwater wetlands. Pages 57-80 *in* E. R. Brown, ed. Management of Wildlife and Fish Habitats in Forests of Western Oregon and Washington. USDA Forest Service R6-F&WL-1992-1985.

O'Connell, M. A., J. G. Hallet, and S. D. West. 1993. Wildlife use of riparian habitats: a literature review. Timber, Fish & Wildlife. Publication TFW-WLI-93-00 1.

Oceanic Society. 1984. The Changing Bay. Map Series and Information Sheets.

Office of Environmental Health Hazard Assessment (OEHHA). 1994. Health Advisory on Catching and Eating Fish. Interim Sport Fish Advisory for San Francisco Bay. December 1994.

Ogden, A. 1941. The California Sea Otter Trace 1784-1848. University of California Press, Berkeley, CA. 251 pp.

Ohmart, R. D. 1994. The effects of human-induced changes on the avifuana of western riparian habitats. Pages 273-85 *in* J. R. Jehl, Jr. and N. K. Johnson, eds. A Century of Avifaunal Change in Western North America. Studies in Avian Biology No. 15.

Ord, E. O. C. 1848. Topographical Sketch of the Gold and Quicksilver District of California, July 23, 1848. P.S. Duval's Lithographic Steam Press, Philadelphia, PA.

Orlob, G. T. and I. P. King. 1997. Sacramento River Temperature Modeling Project, Center for Environmental and Water Resources Engineering. University of California, Davis, CA. Report 97-01, January 1997.

Owen, R. W., Jr. 1974. Distribution of Primary Production, Plant Pigments, and Secchi Depth in the California Current Region, 1969. CalCOFI Atlas No.20.

Packard, E. L. 1918. The molluscan fauna from San Francisco Bay. University of California Publications in Zoology 14(2). University of California Press, Berkeley, CA.

Page, R. W. 1986. Geology of the Fresh Ground-Water Basin of the Central Valley, California, with Texture Maps and Sections. U.S. Geological Survey Professional Paper 1401-C. U.S. Geological Survey, Washington, D.C. 54 pp.

Parr, T., K. Kutchins, M. Stevenson, and F. C. Newton. 1987. Baseline Physical Analysis of Potential Ocean Disposal Sites Offshore San Francisco, Site B1, B1A, and B2. Report to the U.S. Army Corps of Engineers, San Francisco District, San Francisco, CA.

Patton, D. R. 1973. A Literature Review of Timber Harvesting Effects on Stream Temperature. Research Note RM-249. Rocky Mountain Forest and Range Experiment Station. Forest Service, USDA, Ft. Collins, CO. 4 pp.

Pavlik, B. M., P. C. Muick, S. G. Johnson, and M. Popper. 1991. Oaks of California. Cachuma Press and the California Oak Foundation.

Pereira, W. E., F. D. Hostettler, J. R. Cashman, and R. S. Nishioka. 1994. Occurrence and distribution of organochlorine compounds in sediments and livers of striped bass (*Morone saxatilis*) from the San Francisco Bay-Delta Estuary. Marine Pollution Bulletin 28(7):434-441.

Pereira, W. E., J. L. Domagalski, F. D. Hostettler, L. R. Brown, and J. B. Rapp. 1996. Occurrence and accumulation of pesticides and organic contaminants in river sediment, water and clam tissues from the San Joaquin River and tributaries, California. Environmental Toxicology and Chemistry 15(2):172-180.

Pestrong, R. 1972. San Francisco Bay Tidelands. California Geology 25:27-40.

Peterman, R. M. 1984. Density dependent growth in early ocean life of sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences 41:1825-1829.

Peterman, R. M. 1987. Review of the components of recruitment of Pacific salmon. Pages 417-429 *in* Common Strategies of Anadromous and Catadromous Fishes. American Fisheries Society Symposium 1.

Peterman, R. M. 1989. Application of statistical power analysis to the Oregon coho salmon (*Oncorhynchus kisutch*) problem. Canadian Journal of Fisheries and Aquatic Sciences 46:1183-1187.

Peterson, D. H., D. R.Cayan, J. F. Festa, F. H. Nichols, R. A. Walters, J. V. Slack, S. E. Hager, and L. E. Schemel. 1989. Climate variability in an estuary: effects of riverflow on San Francisco Bay. Pages 419-442 *in* D. H. Peterson, ed. Aspects of Climate Variability in the Pacific and the Western Americas. American Geophysical Union, Geophysical Monograph 55.

Pierce, R. A., and J. H. Winslow, eds. 1979. H.M.S. Sulphur on the Northwest and California Coasts, 1837 and 1839. *In* Materials for the Study of Alaska History, No. 12. The Limestone Press, ON.

Pitt, M. D. 1978. Influences of brush conversion and weather patterns on runoff from a Northern California watershed. Journal of Range Management 31(1):23-27.

Porterfield, G., N. L. Hawley, and C. A. Dunnam. 1961. Fluvial Sediments Transported by Streams Tributary to the San Francisco Bay Area. U.S. Geological Survey, Open-File Report. 70 pp.

Preston, W. L. 1981. Vanishing Landscapes. Land and Life in the Tulare Lake Basin. University of California Press, Berkeley, CA.

Race, M. S. 1981. Field ecology and natural history of Cerithidea Californica (*Gastropoda: Prosobranchia*) in San Francisco Bay. Veliger 24(1):18-27.

Race, M. S. 1982. Competitive displacement and predation between introduced and native mud snails. Oecologia 54:337-347.

Ramp, S. R., N. Garfield, C. A. Collins, L. K. Rosenfeld, and F. B. Schwing. 1992. Circulation Studies Over the Continental Shelf and Slope Near the Farallon Islands, CA. Executive Summary, Report to the U.S. Environmental Protection Agency, Region IX, San Francisco, CA.

Ratliff, R. D. 1982. A meadow site classification for the Sierra Nevada, California. USDA Forest Service General Technical Report GTR-PSW-60.

Reisenbichler, R. R. 1986. Use of spawner-recruit relations to evaluate the effect of degraded environment and increased fishing on the abundance of fall-run chinook salmon, *Oncorhynchus tshawytscha*, in several California streams. Ph.D. Dissertation. University of Washington, WA.

Reuter, J. E. and W. T. Mitchell. 1987. Spring Water Temperatures of the Sacramento River. Report Prepared by D. W. Kelley & Associates for CDWR. July 1987. 65 pp.

Ricketts, E. F. and J. Calvin. 1956. Between Pacific Tides. Stanford University Press, Palo Alto, CA.

Ringgold, C. 1852. A series of charts, with sailing directions, embracing surveys of the Farallones, the entrance to the bay of San Francisco, bays of San Francisco and San Pablo, straits of Carquines [sic] and Suisun Bay, confluence of the deltic branches of the Sacramento and San Joaquin rivers, and the Sacramento River (with the middle fork) to the American River, including the cities of Sacramento and Boston, state of California. J. T. Towers, Washington, D.C. 48 pp.

Roberts, W. G., J. G. Howe, and J. Major. 1977. A survey of riparian forest flora and fauna in California. Pages 3-19 *in* A. Sands, ed. Riparian Forests in California: Their Ecology and Conservation. Symposium May 14, 1977, Davis, CA.

Rogers, F. B. 1957. A Navy Surgeon in California 1846-1847: The Journal of Marius Duvall. John Howell, San Francisco, CA.

Rose, A. H., M. Manson and C. E. Grunsky. 1895. Report of the Commissioner of Public Works to the Governor of California. State Printing Office, Sacramento, CA.

Rosgen, D. 1994. A classification of natural rivers. Catena 22:169-198.

Rowe, P. B. 1963. Streamflow increases after removing woodland-riparian vegetation from a Southern California watershed. Pages 365-370 *in* Journal of Forestry. May 1963.

Ruth, L. 1996. Conservation and controversy: national forest management 1960-1995. Chapter 7 *in* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Volume II: Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. University of California, Davis, CA.

Rutter, C. 1908. The Fishes of the Sacramento-San Joaquin Basin, with a Study of their Distribution and Variation. U.S. Bureau of Fisheries, Document No. 637.

SAIC. 1992. Trawl and Remotely Operated Vehicle Ocean Studies Report for Detailed Physical and Biological Oceanographic Studies for an Ocean Site Designation Effort Under the Marine Protection, Research, and Sanctuaries Act of 1972. Prepared for U.S. EPA under Contract No. 68-C8-0062, June 1992.

Saiki, M. K. 1984. Environmental conditions and fish faunas in low elevation rivers on the irrigated San Joaquin Valley floor, California: California Fish and Game 70:145-157.

Saiki, M. K. and D. U. Palawski. 1990. Selenium and other elements in juvenile striped bass from the San Joaquin Valley and San Francisco Estuary, California. Archives of Environmental Contamination and Toxicology 19:717-730.

Saiki, M. K and R. S. Ogle. 1995. Evidence of impaired reproduction by western mosquito fish inhabiting seleniferous agricultural drainwater. Transactions of the American Fisheries Society 124:578-587.

Saiki, M. K., M. K. Jennings, and T. W. May. 1992. Selenium and other elements in freshwater fishes from irrigated San Joaquin Valley, California. The Science of the Total Environment 126:109-137.

Saiki, M. K., M. R. Jennings, and W. G. Brumbaugh. 1993. Boron, molybdenum, and selenium in aquatic food chains from the lower San Joaquin River and its tributaries, California. Archives of Environmental Contamination and Toxicology 24:307-319.

Saiki, M. K., D. T. Castleberry, T. W. May, B. A. Martin, and F. N. Bullard. 1995. Copper, cadmium, and zinc concentrations in aquatic food chains from the Upper Sacramento River (California) and selected tributaries. Archives of Environmental Contamination and Toxicology 29:484-491.

Sandberg, J. and P. Manza. 1991. Global Climate Change Response Program: Evaluation of Central Valley Project Water Supply and Delivery Systems. U.S. Bureau of Reclamation, Sacramento, CA.

Sandecki, M. 1989. Aggregate mining in river systems. California Geology. 42(4):88-94.

Sanders, H. L. 1960. Benthic studies in Buzzards Bay III. Limnology and Oceanography 5:138-153

San Francisco Estuary Institute (SFEI). 1987. An Assessment of the Loading of Toxic Contaminants to the San Francisco Bay-Delta. August 26, 1987.

SFEI. 1998. Bay Area EcoAtlas. Version 1.50.

San Francisco Estuary Project (SFEP). 1990. Status and Trends Report on Dredging and Waterway Modification in the San Francisco Estuary. Prepared under EPA Cooperative Agreement CE-009496-01 by the Aquatic Habitat Institute and Philip Williams & Associates Ltd.

SFEP. 1991. Status and Trends Report on Wetlands and Related Habitats in the San Francisco Estuary. Prepared by the Association of Bay Area Governments, Oakland, CA. December 1991.

SFEP. 1992. State of the Estuary: A Report on Conditions and Problems in the San Francisco Bay / Sacramento-San Joaquin Delta Estuary. June 1992.

San Francisco Regional Water Quality Control Board (SFRWQCB), State Water Resources Control Board, and California Department of Game. 1994. Contaminant Levels in Fish Tissue from San Francisco Bay.

San Joaquin Valley Drainage Program (SJVDP). 1990. Fish and Wildlife Resources and Agricultural Drainage in the San Joaquin Valley, California, Volume I.

Sawyer, J. O. and T. Keeler-Wolf. 1995. A Manual of California Vegetation. California Native Plant Society.

Schoenherr, A. A. 1992. A Natural History of California. University of California Press, Berkeley, CA.

Schulz, P. D. 1979. Fish remains from a historic central California Indian village. California Fish and Game 65(4):273-276.

Schulz, P. D., and D. D. Simons. 1973. Fish species diversity in a prehistoric central California indian midden. California Fish and Game 59(2):107-118.

Seuss, E. 1980. Particulate organic carbon flux in the oceans: surface productivity and oxygen utilization. Nature 288:260-263.

Severson, T. 1973. Sacramento, An Illustrated History: 1839 to 1874. From Sutter's Fort to Capital City. California Historical Society. 207 pp.

Seymour, A. H. 1956. Effects of temperature upon young chinook salmon. Ph.D. Dissertation. University of Washington, WA. 127 pp.

Shapiro, A. M. 1974. The butterfly fauna of the Sacramento Valley, California. J. Res. Lepidoptera 13:73.

Shebley, W. H. 1922. A history of fishcultural operations in California. California Fish and Game 8(2):61-99.

Shelton, M. L. 1987. Irrigation induced changes in vegetation and evapotranspiration in the Central Valley of California. Landscape Ecology 1:95-105.

Sierra Nevada Ecosystem Project (SNEP). 1996. Status of the Sierra Nevada. Ecosystem Project Final Report to Congress. Wildland Resources Center Reports, University of California, Davis, CA.

Skinner, J. E. 1962. An Historical Review of the Fish and Wildlife Resources of the San Francisco Bay Area. Water Projects Branch Report No.1. California Department of Fish and Game Water Projects Branch.

Smith, G. W. and P. Y. Baker. 1877. Map of the County of Stanislaus, California. Compiled from U.S. and County Surveys and Public Records. Lithographers Britton & Rey & Co., San Francisco, CA. January 15, 1877.

Smith, L. H. 1987. A Review of Circulation and Mixing Studies of San Francisco Bay, California. USGS Circular 1015. 38 pp.

Smith, S. E. and S. Kato. 1979. The fisheries of San Francisco Bay: past, present and future. Pages 445-468 *in* T. J. Conomos, ed. San Francisco: The Urbanized Estuary. Pacific Division of the American Association for the Advancement of Science, San Francisco, CA.

Smith, I. W. 1879. Relief Canal and the Cut Through the Montezuma Hills, Sacramento River Drainage District, November 28, 1879. Appearing in Record-Union, Supplement. Sacramento, December 2, 1879.

Soule, M. E., ed. 1991. Conservation: tactics for a constant crisis. Science 253: 744-750.

Sowels, A. L., A. R. DeGange, J. W. Nelson, and G. S. Lester. 1980. Catalog of California Sea Bird Colonies. FWS/OBS-80/37. U.S. Fish and Wildlife Service, Biological Services Program.

Spaar, S. 1994. Delta Agricultural Diversion Evaluation 1992 Pilot Study. Interagency Ecological Program. Technical Report 37.

Spence, M. L. and D. Jackson. 1973. The Expeditions of John Carles Fremont, Vol. 2. University of Illinois Press, Chicago, IL.

Starr, K. 1985. Inventing the Dream: California through the Progressive Era, as cited in Kelley, 1989. Oxford University Press, New York, NY.

State Water Resources Control Board (SWRCB). 1971. A Review of Pesticide Monitoring Programs in California. February 1971.

SWRCB. Toxic Substances Monitoring Program. Ten Year Summary Report 1978-1987. Report 90-1WQ. August 1990.

SWRCB. 1994. Irrigated Agriculture. Technical Advisory Committee Report. December 1994.

SWRCB. 1995. California's Rivers and Streams. Working Toward Solutions. January 1995.

Stebbins, A.C. 1966. A Field Guide to Western Reptiles and Amphibians. Houghton Mifflin Co., Boston, MA.

Stine, S. 1990. Late holocene fluctuations of Mono Lake, eastern California. Palaeogeography, Palaeoclimatology, Palaeoecology 78:333-381.

Stine, S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. Letters to Nature, Department of Geography and Environmental Studies, California State University, Hayward, California, v. 369.

Stine, S. 1996. Climate, 1650-1850. *In* Sierra Nevada Ecosystem Project (SNEP): Final Report to Congress. Vol. II: Assessments and Scientific Basis for

Management Options. University of California. Wildland Resources Center Report No. 37. University of California, Davis, CA. 1528 pp.

Swanson, G. A., M. I. Meyer and J. R. Serie. 1974. Feeding ecology of breeding blue-wing teals. Journal of Wilderness Management 38:396-407.

Swanson, F. J., S. V. Gregory, J. R. Sedell, and A. G. Campbell. 1982. Land-water interactions: the riparian zone. Pages 267-291 *in* R. L. Edmonds, ed. Analysis of Coniferous Ecosystems in the Western United States. Hutchinson Ross Publishing Company, Stroudsburg, PA.

Tanji, K., A. Lauchli, and J. Meyer. 1986. Selenium in the San Joaquin Valley, Environment 28 (6).

Thomas, J. W., H. Black Jr., R. J. Scherziner, and R. J. Pedersen. 1979. Deer and elk. Pages 104-127 *in* J. W. Thomas, ed. Wildlife Habitats in Managed Forests; the Blue Mountains of Oregon and Washington. USDA Forest Service Agriculture Handbook No. 553.

Thompson, J. 1957. The settlement geography of the Sacramento-San Joaquin Delta, California. Dissertation. Stanford University, Stanford, CA.

Thompson, J. 1996. Flood Chronologies and Aftermaths Affecting the Lower Sacramento River, 1878-1909. California Department of Water Resources.

Thompson, J. and E. A. Dutra. 1983. The Tule Breakers. The Story of the California Dredge. The Stockton Corral of Westerners. University of the Pacific, Stockton, CA. 368 pp.

Thompson, J. K. 1996. The Asian Clam: Trends and Impacts. Abstract Book, 3rd Biennial State of the Estuary Conference. Officers Club, Presidio of San Francisco, October 10-12.

Thompson, K. 1960. Historic flooding in the Sacramento Valley. Pacific Historical Review 29:349-360.

Thompson, K. 1961. Riparian forests of the Sacramento Valley. Annals of the Association of American Geographers 51(3):294-315.

Thompson, K. 1980. Riparian forests of the Sacramento Valley, California. Chapter 4 *in* A. Sands, ed. Proceedings of the Symposium: Riparian Forests in California - Their Ecology and Conservation. Originally published as Institute of

Ecology Publication No.15. (Originally published in Annals of the Association of American Geographers, 1961, v. 51.)

Tjarnlund, U., G. Ericson, E. Lindesjoo, I. Petterson and L. Balk. 1995. Investigation of the biological effects of two cycle outboard engine exhaust on fish. Marine Environ. Res. 39:313-316.

Tjarnlund, U., G. Ericson, E. Lindesjoo, I. Petterson, G. Akerman and L. Balk. 1996. Further studies of the effects of exhaust from two-stroke outboard motors on fish. Marine Environ. Res. 42:267-271.

Trapp, G. R., G. L. Linck, and E. D. Whisler. 1984. The status of ecological research on the mammalian fauna of California's Central Valley riparian communities. Pages 942-949 *in* R. E. Warner and K. Hendrix, eds. California Riparian Systems. University of California Press, Berkeley, CA.

Treutlein, T. E. 1972. Fages as explorer, 1769-1772. Pages 338-356 *in* California Historical Quarterly, Winter 1972.

Turner, J. L. 1966. Distribution and food habits of centrarchid fishes in the Sacramento-San Joaquin Delta. Pages 144-153 *in* J. L. Turner and D.W. Kelley (compilers) Ecological Studies of the Sacramento-San Joaquin Delta, Part II. California Department of Fish and Game. Fish Bulletin 136.

Uhle, M. 1907. The Emeryville shellmound. University of California Publications in American Archeology and Ethnology 7:1-35.

United States Army Corps of Engineers (USCOE). 1914. San Joaquin River, California, Herndon to Head of Delta (survey). USCOE, San Francisco, CA. 108 sheets (revised 1930 by California Division of Water Resources).

USCOE. 1916. Control of Floods on the Mississippi and Sacramento Rivers: Supplemental Report on Flood Control of the Sacramento River. Extract from House Report 616. Government Printing Office, Washington, D.C. 167 pp.

United States Environmental Protection Agency (U.S. E.P.A). 1993. EIS for Designation of a Deep Water Ocean Dredge Material Disposal Site off San Francsicso. California EPA, Region IX. San Francisco, CA.

U.S. E.P.A, USCOE, San Francisco Bay Conservation and Development Commission (BCDC), San Francisco Bay Regional Water Quality Control Board, and State Water Resources Control Board (SWRCB). 1996. Long-term Management Strategy (LTMS) for Placement of Dredged Material in the San

Francisco Bay Region (Draft) Policy Environmental Impact Statement/Programmatic Environmental Impact Report, USEPA, San Francisco, CA.

U.S. E.P.A. 1997. Special Report on Environmental Endocrine Disruption: An Effects Assessment and Analysis. Report EPA/630/R-96/012.

University of California, Davis. 1994. Proceedings of a Conference on Animal Agriculture. Impacts on Water Quality in California.

Unwin, M. J. 1997. Fry-to-adult survival of natural and hatchery produced chinook salmon (*Oncorhynchus tshawytscha*) from a common origin. Canadian Journal of Fisheries and Aquatic Sciences 54:1246-1254.

Van Royen, W. and C. O. Siegel. 1959. Future Development of the San Francisco Bay Area 1960-2020. Prepared for the U.S. Army Corps of Engineers, San Francisco, CA.

Vick, J. C. 1995. Habitat Rehabilitation in the Lower Merced River: A Geomorphological Perspective. University of California Center for Environmental Design Research Report Nos. CEDR-03-95 and CEDR-04-95, Berkeley, CA. 192 pp.

Vorster, P. 1998 (in preparation). A Monthly Water Balance for the Sacramento and San Joaquin Valleys Under Natural Conditions. The Bay Institute, San Rafael, CA.

Walthall, M. 1869. Map of the San Joaquin Valley from the Latest and Most Authentic Sources and from Actual Surveys, Land Surveying & General Land Business, Stockton, CA. Lithographers Britton & Rey, San Francisco, CA. August, 1869.

Warner, R. F. and K. Hendrix. 1985. Riparian Resources of the Central Valley and California Desert, A Report On Their Nature, History and Status with Recommendation For Their Revitalization and Management. Final Draft, California Department of Fish and Game.

Washington, P. M. and A. M. Koziol. 1993. Overview of the interactions and environmental impacts of hatchery practices on natural and artificial stocks of salmonids. Fisheries Research 18:105-122.

Welch, R. H. 1967. A study of the stratification of phytoplankton at selected locations in Monterey Bay, California. Masters Thesis. Naval Postgraduate School, Monterey, CA. 70 pp.

Wells, L. E. and M. Goman. 1995. Late holocene environmental variability in the upper San Francisco Estuary as reconstructed from tidal marsh sediments. *In* Proceedings of the Eleventh Annual Pacific Climate (PACLIM) Workshop. Interagency Ecological Program Technical Report 40, California Department of Water Resources, Sacramento, CA.

White, R. J., J. R. Karr and W. Nehlsen. 1995. Better roles for fish stocking in aquatic resources management. American Fisheries Society Symposium 15:527-547.

Wilkes, C. 1845. Narrative of the United States Exploring Expedition, During the Years 1838, 1839, 1840, 1841, 1842, Vol V. Lea & Blanchard, Philadelphia, PA 1842.

Williamson, Lieutenant R. S. 1853. Corps of Topographical Engineers Report of Explorations in California for Railroad Routes, to connect with the routes near the 35th and 32nd parallels of north latitude. War Department: Washington, D.C. 1855.

Williamson, A. K., D. E. Prudic, and L. A. Swain. 1985. Ground-Water Flow in the Central Valley, California. USGS Open-File Report 85-345.

Williamson, A. K., D. E. Prudic, and L. A. Swain. 1989. Ground-Water Flow in the Central Valley, California. USGS Professional Paper 1401-D.

Wilson, E. O. 1985. The biological diversity crisis. BioScience 35:700-706.

Wilson, J. H., ed. 1979. Rice in California. Published by Butte County Rice Growers Association, Richvale, CA.

Woods, E. 1981. Fish utilization. Pages 35-46 *in* T. Niesen and M. Josselyn, eds. The Hayward Regional Shoreline Marsh Restoration: Biological Succession During the First Year Following Dike Removal. Technical Report 1. Tiburon Center for Environmental Studies, Tiburon, CA. 178 pp.

Wooten, J. T., M. S. Parker and M. E. Power. 1996. Effects of disturbance on river food-webs. Science 273:1558-1560.

Worster, D. 1984. Rivers of Empire: Water, Aridity, and the Growth of the American West. Oxford University Press, New York, NY. 402 pp.

Youngblood, A. P., W. G. Padgett, and A. H. Winward. 1985. Riparian Community Type Classification for Eastern Idaho-Western Wyoming. USDA Forest Service Intermountain Forest Range Experimental Station, Ogden, UT.

Yoshiyama, R. M., E. R. Gerstung, F. W. Fisher, and P. B. Moyle. 1996. Historical and present distribution of chinook salmon in the Central Valley drainage of California. *In* Sierra Nevada Ecosystem Project. Final report to Congress, Vol. II: Assessments, Commissioned Reports, and Background Information. Wildland Resources Center Report No. 37. University of California, Davis, CA.

Zelinsky, E. G. and N. L. Olmsted. 1985. Upriver boats - when Red Bluff was the head of navigation. California History LXIV(2):86-117.