Summary of data and analyses indicating that exotic species have impaired the beneficial uses of certain California waters

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Dr. Cohen directs SFEI's Biological Invasions research program, which he founded in 1997. His research topics have included: invasions in San Francisco Bay, Puget Sound and southern California; invasion vectors including ships' ballast water and the baitworm trade; the spread and potential distribution of exotic species; species and environmental characteristics that affect invasion success; the treatment of ballast water; and the impacts of introduced plants in Pacific Coast salt marshes. In 1998 he was awarded a Pew Fellowship in Marine Conservation to investigate biological invasions in tropical marine waters, and in 1999 he received the San Francisco BayKeeper's Environmental Achievement Award in recognition of the his research and its contribution to policy development. He has served on the Executive Committee of the Western Regional Panel on Aquatic Nuisance Species, and on the Advisory Board of the National Aquatic Nuisance Species Clearinghouse. He also has authored several general-interest publications on the environment, including a guide to the natural history of San Francisco Bay.

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(1) Introduction

We summarize here the scientific data and analyses that support a conclusion that beneficial uses have been impaired in selected water bodies in California. The list of water bodies treated here is far from comprehensive. We do not include the waters of San Francisco Bay and its various subembayments, because these have already been listed as impaired by the State Board. More significantly, we do not include at this time a large number of other water bodies where we believe there is information to support a conclusion that they have been impaired by exotic species, but where we have not yet compiled the relevant data and analyses.

We first define some terms that we will use (Section 2). To avoid repetition, we then discuss the general data and analyses that relate to certain types and aspects of impacts from exotic species that are common to all the water bodies discussed herein and contribute to the impairment of their beneficial uses (Section 3). These deal with impacts on species composition, habitat and biological diversity; and with the generally long-term, increasing, spreading, and often irreversible nature of exotic species' impacts. We then present the data and analyses regarding impairment of beneficial uses for several water systems in California (Sections 4-10).

(2) Terminology

We use the following terminology in these comments:

- *Exotic*, to refer to an organism that is not native to California but has arrived in California waters as a result of human activities, without any implication regarding it population status (*i.e.* whether it is established or not), behavior or impact.
- *Established exotic*, to refer to an exotic organism that is present and reproducing in California waters in sufficient numbers, over a sufficient area and for a sufficient time that it is unlikely to go extinct due to the stochastic and demographic effects that threaten small populations (called Allee effects).
- *Introduction*, to refer to the anthropogenic transport of an exotic organism into California and its release into the environment, including both intentional releases and releases that are by-products of human activity.
- *Interbasin exotic*, to refer to an organism that is native to some California waters but has been introduced into others; and *interbasin introduction*, to refer to the anthropogenic transport and release of a species that is native to some California waters into California waters where it is not native.
- *Vector*, the mechanism, pathway or activity through which an exotic organism is transported to the new area and/or released into the environment.

- *Native*, to refer to organisms whose presence in the area in question is not due to arrival via human activities, as described above. These include both organisms that were present in the area prior to human occupation, and organisms that have since spread there by natural means.
- *Cryptogenic*, to refer to species for which the evidence of native or exotic status is unclear.

(3) <u>Impacts of exotic species that are common to all California water systems discussed herein</u>

(3a) <u>Impacts on native species composition</u>

Beneficial uses for various water bodies in California can include the following (CVRWQCB 1998, and basin plans for other regions):

> Freshwater Habitat (Warm or Cold) - Uses of water that support warm (cold) water ecosystems, including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish, or wildlife, including invertebrates.
>
> Estuarine Habitat - Uses of water that support estuarine ecosystems, including, but not limited to, preservation or enhancement of estuarine habitats, vegetation, fish, shellfish, or wildlife (*e.g.*, estuarine mammals, waterfowl, shorebirds).
>
> Wildlife Habitat - Uses of water that support terrestrial or wetland ecosystems, including, but not limited to, preservation and enhancement of terrestrial habitats or wetlands, vegetation, wildlife (*e.g.*, mammals, birds, reptiles, amphibians, invertebrates), or wildlife water and food sources.

These definitions suggest that the following types of phenomena could constitute an impairment of a beneficial use:

A. To the extent that the preservation of vegetation, fish, invertebrates, shellfish or wildlife in a water body means *preventing the extirpation* of native plant, fish, invertebrate or wildlife species from that water body, any exotic species introduction that caused or contributed to the local extirpation of a native species would constitute an impairment of a beneficial use.

B. To the extent that the preservation of these types of organisms means *preventing substantial declines* in native populations within a water body, any exotic species introduction that caused or contributed to substantial declines in native populations within a water body would constitute an impairment of a beneficial use.

C. To the extent that the preservation of these types of organisms means preventing the extirpation or substantial declines of *pre-existing species* (including both native and established exotic species) within a water body, any exotic species introduction that caused or contributed to the extirpation or substantial declines in pre-existing populations within a water body would constitute an impairment of a beneficial use.

There are many examples of each of these types of phenomena in California waters, and several are described in the sections below. In addition, there are a number of cases where several exotic species have been introduced and become abundant in a water body, sometimes coming to constitute the majority of the species, the number of individuals, or the biomass present in the water body or in a community component within the water body; with this increase in exotic species occurring concomitant with the decline in many or most of the native species and the local extirpation of some of the natives. In these cases there can be little doubt that the type of Habitat beneficial use applicable to the water body has been impaired.

(3b) Impacts on native habitat

The Freshwater, Estuarine and Wildlife Habitat beneficial uses involve not only the preservation of individual biota, but also the preservation of freshwater, estuarine, terrestrial or wetlands habitats. An organism's habitat is of two types. On the one hand, the physical structure and the physical/chemical parameters in which it lives constitute its physical habitat, including organisms that provide that structure (such as the dominant plants). On the other hand, the web of biological interactions in which it is enmeshed constitutes its biological habitat.

Introductions of exotic species that substantially alter the physical habitat—for example, by burrowing activities, by destroying vegetation or other organisms that provide physical structure in the habitat, by replacing these with organisms that provide a different type of structure, by shading, covering, or otherwise altering physical or chemical parameters, etc.—impair the Habitat beneficial uses. Introductions of exotic species that substantially alter the species composition and populations in a water body—especially where one exotic species or a suite of exotic species come to dominate a community within an ecosystem—change the biological habitat of the organisms that live there, thereby also impair the Habitat beneficial uses.

(3c) Impacts on biological diversity

Recent assessments of imperiled, endangered and extinct species concluded that exotic species are a leading threat to biodiversity (Cohen 2002). Wilcove *et al.* (1998) found that competition with or predation by exotic species constituted the second greatest threat to imperiled plants and animals in the United States, second to habitat loss or degradation, but affecting more than twice as many imperiled species as pollution, and nearly three times as many species as over-exploitation. Miller *et al.* (1989) found that exotic species were a contributing or causal factor in 68% of the extinctions of North American fish in the preceding century. Richter *et al.* (1997) found in a survey of leading biologists that "interactions with exotic species is the leading threat reported [to freshwater fauna in the Western U.S.] under both historic and current conditions." In 1998, the World Conservation Union ranked exotic species as the second greatest threat to biodiversity, after habitat loss (Raven 1999); and in 2000, the Director of the U.S. Geological Survey predicted that the spread of invasive organisms would be the second most serious ecological problem facing the United States in the 21st century (Groat 2000).

Biological diversity is most often measured simply as species diversity, the number of species present. In cases where introductions of exotic species ultimately exterminate native species, even to the point of reducing raw species diversity (*i.e.* species diversity counted without regard to whether the species are native or exotic), the introductions initially increase species diversity. Thus the brown tree snake (*Boiga irregularis*) initially increased Guam's species diversity by one, before eating its way through and eliminating many of the island's bird and amphibian species. Similarly, the Nile perch (*Lates nilotica*) increased the number of fish species in Lake Victoria by one before proceeding to extirpate an estimated 200 cichlid species that were endemic to the lake. Therefore, the impact of exotic species on species diversity must be considered over the long term, and the prospect is often bleak. Data from collections made over three-quarters of a century on the San Joaquin River provide an example (Moyle & Nichols 1974; Moyle 2000):

Year of collection:	1898	1934	1940-41	1970
Estimated number of native species:	14	13	13	6
Estimated number of total species:	14	17	21	13

As exotic species invaded, the number of native species steadily declined, but the total number of species (raw species diversity) increased dramatically through at least the first 43 years. It wasn't until after that time that native species number dropped sufficiently to offset the influx of exotics; so that by 1970 total diversity (13 species, including a majority of exotics) had dropped *below* the initial diversity (14 species).

Evolutionary considerations suggest that a decline in native species is the likely if not inevitable general result of exotic species introductions. Ecosystems—and water basins—that are isolated from one another over evolutionary time scales develop unique biotas, which are often similar in composition at the family and genus level but differ at the species and subspecies levels. It is the isolation of the ecosystems that allows these difference to evolve. Mix the biotas together—as species introductions do—and some of the unique taxa will not survive, even though it make take a considerable time for them to die out. Species-area curves—an empirical relationship between area and species number that has been found to be remarkably consistent across "island" ecosystems (MacArthur & Wilson 1967 pp. 8-18)—tell us much the same thing. Two areas separated as "islands" are capable of supporting a larger number of distinct species than when the two are joined together in one interconnected ecosystem.

Finally, it is important to remember that species diversity (or any other quantitative diversity measure) at a single site is not the whole diversity story. Diversity between sites is also an important component of biological diversity. So, even if some exotic species should be "harmless" in the sense that they don't eliminate any native species by competition, by predation, by the introduction of parasites or diseases, or by other means, so that their introduction would tend to permanently increase species diversity at a site, they would at the same time make the site more similar in species composition to the other site or sites where they are present. Thus, by homogenizing between sites their introduction would tend to decrease global biodiversity even if it were to increase species diversity locally.

(3d) Long-term, increasing, spreading, and often irreversible nature of impacts

Exotic species can and do reproduce. Thus, unlike a discharge of a chemical pollutant, a discharge of an exotic species "biological pollutant" can become more potent (*i.e*. achieve a greater density or concentration than its initial concentration at the point of discharge) over time; it can spread for much greater distances (over 1,000s of km in some cases) without dissipating or attenuating its potency; and it can last for long periods (for centuries at least) also without attenuating its impact. Discharges of exotic species are also very difficult to clean up, perhaps even impossible in most cases in estuarine or ocean environments. These points should be borne in mind when assessing the impacts of species introductions.

(4) Impacts of exotic species in the Sacramento-San Joaquin Delta (in Region 5: Solano, Sacramento, San Joaquin and Contra Costa counties)

At least 94 exotic species are found in Delta waters (Attachment A, updated from Cohen & Carlton 1995; Cohen 1996 pp. 225-229, 241 & 270-271; and other sources), including seven aquatic plants that are commonly considered weed species; twelve fish parasites (including parasitic flatworms, nematodes, copepods and leeches); a clam, crab and several fish that are widely considered to be harmful pests; and other plants, copepods, fish, frogs and turtles that are reported to have harmful impacts on native species through competition, predation or the transmission of diseases and parasites.

These exotic species have dramatically altered species composition and habitat in the Delta, with exotic species now accounting for a majority of the biological diversity in many habitats, whether counted as number of species, number of individuals or biomass (Attachment B). The Asian clam *Corbicula* is the dominant mollusk and one of the most abundant benthic organisms in the Delta, and can account for most of the benthic biomass in many areas. Juvenile *Corbicula* often settle at densities of 2,000/m^2 sometimes reach 50,000/m^2 (Herbold & Moyle 1989 pp. 41-49; Cohen & Carlton 1995). The eastern American worm *Manayunkia speciosa* is also one of the most abundant benthic organism in the Delta, occurring in densities of 2,000 to 5,000/m^2 (Cohen & Carlton 1995). Exotic fish dominate south Delta waters numerically and by biomass, and all crayfish and crabs in the Delta are exotic. Meadows of floating or rooted aquatic plants can cover areas of formerly open water. These overall changes would seem to be an impairment of the Freshwater Habitat beneficial use, which is defined to include the "preservation or enhancement of aquatic habitats, vegetation, fish or wildlife, including invertebrates " (CVRWQCB 1998).

In addition to the overall impact of these exotic species on biodiversity and habitat, there are direct impacts from particular exotic species on fisheries and fishing activities (thus impairing the listed beneficial use of Water Contact Recreation), on navigation (impairing Non-contact Water Recreation), and on the operations of water withdrawal facilities (impairing the beneficial uses of Municipal and Domestic, Agricultural and Industrial Water Supply). Exotic species have also harmed populations of rare or endangered species, and by continually altering the ecosystem have undermined the accumulation of sufficient knowledge to effectively manage the Delta. This, in turn, increases the pressure for greater restrictions on water withdrawals, to avoid further losses of fish populations.

Writing in 1995, Cohen and Carlton (1995) provided the following summaries of impacts from exotic species in the Delta:

> Eastern and central American fish -- carp, mosquitofish, catfish, green sunfish, bluegills, inland silverside, largemouth and smallmouth bass, and striped bass -- are among the most significant predators, competitors, and habitat disturbers throughout the brackish and freshwater reaches of the Delta, with often concomitant impacts on native fish communities. The introduced crayfish *Procambarus* and *Pacifastacus* may play an important role, when dense, in regulating their prey plant and animal populations. (p. 4)
>
> Introduced freshwater and anadromous fish have been directly implicated in the regional reduction and extinction, and the global extinction, of four native California fish. The bluegill, green sunfish, largemouth bass, striped bass, and black bass, through predation and through competition for food and breeding sites, have all been associated with the regional elimination of the native Sacramento perch from the Delta. The introduced

> inland silversides may be a significant predator on the larvae and eggs of the native Delta smelt. Expansion of the introduced smallmouth bass has been associated with the decline in the native hardhead. Predation by largemouth bass, smallmouth black bass and striped bass may have been a major factor in the global extinction of the thicktail chub in California. (p. 5)
>
> Government introductions of organisms for sport fishing, as forage fish and for biocontrol have frequently not produced the intended benefits, and have sometimes had harmful "side effects," such as reducing the populations of economically important species. (p. 5)
>
> Waterway fouling by introduced water hyacinth has become a problem in the Delta over the last fifteen years, with other introduced plants beginning to add to the problem in recent years. Hyacinth fouling has had significant economic impacts, including interference with navigation. (p. 6)
>
> Perhaps the greatest economic impacts may derive from the destabilizing of the Estuary's biota due to the introduction and establishment of an average of one new species every 24 weeks. This phenomenal rate of species additions has contributed to the failure of water users and regulatory agencies to manage the Estuary so as to sustain healthy populations of anadromous and native fish, resulting in increasing limitations and threats of limitations on water diversions, wastewater discharges, channel dredging, levee maintenance, construction and other economic activities in and near the Estuary. (p. 6)
>
> The greatest impact from introductions to the Estuary may be restrictions on the operation of the California water system. In recent years a combination of litigation, new legislation, and regulatory realignment has placed increasing environmental demands on the water agencies that store and divert water from the Estuary's watershed...Specifically, the agencies' ability to withdraw water increasingly depends on whether they can restore and sustain healthy populations of anadromous and native fish. This in turn will depend on the water agencies' and regulators' level of understanding of the ecosystem and their ability to figure out the necessary habitat conditions, including the amount and timing of instream flows needed, to maintain the fish...A constantly changing species composition may make the ecosystem even less stable, and major functional shifts more common. Under such conditions, the reliable management of the Estuary required of (and promised by) the water agencies may be impossible. (p. 201)

Exotic plants in the Delta that are commonly considered weeds include water hyacinth (*Eichhornia crassipes*), Brazilian waterweed (*Egeria densa*), Eurasian watermilfoil (*Myriophyllum spicatum*), parrot's feather (*Myriophyllum aquaticum*), purple loosestrife (*Lythrum salicaria*), perennial peppergrass (*Lepidium latifolium*) and curly pondweed (*Potamogeton crispus*) (Anderson 1990). Water hyacinth, "perhaps the world's most troublesome aquatic weed" (Hickman 1993 p. 1303) is a South American native that has spread to more than 50 countries on five continents. It reproduces by fragmentation and has the highest reported growth rate for any vascular plant, doubling its biomass in favorable conditions in 6-18 days (Schmitz *et al.* 1993). It is capable of covering the water surface with mats of living and decaying plant tissue that are up to two meters thick (Barrett 1989). Reported impacts include water loss due to evapotranspiration at 3.2 to 6.0 times the rate on adjacent open water; increases in dissolved carbon dioxide, acidity, and turbidity; increased deposition of plant detritus (to 404 to 1,886 metric tons wet-weight per hectare); decreases in dissolved oxygen sometimes leading to anoxic bottom conditions and fish kills; decreases in phytoplankton concentrations; removal of heavy metal ions from the water column and possible cycling into the food web; alterations in fish fauna; and the smothering of submersed and emergent vegetation that is of value to waterfowl (Schmitz *et al*. 1993).

Water hyacinth, Brazilian waterweed, and to a lesser extent Eurasian watermilfoil and parrot's feather have caused serious problems with waterway fouling in the Delta. Eurasian watermilfoil and Brazilian waterweed foul boat propellers and the water intakes of boat engines, and clog channels and boat berths. Water hyacinth has blocked boat passage through navigable waterways and boat access to marinas and berths, and has blocked canals and fouled water system intakes and pumps. Around 1957 the U.S. Bureau of Reclamation began using herbicides to try and control water hyacinth in the Delta (Thomas & Anderson 1983). Water hyacinth fouling became serious enough by the early 1980s to block ferry boats from reaching Bacon Island and prevent the island's produce from reaching the market (CDBW 1994). At the Central Valley Project pumps in Tracy, each day tons of water hyacinth had to be mechanically harvested, trucked away and disposed off, at a cost of several hundred thousand dollars a year (Anderson 1990). Invasion by water hyacinth would thus appear to impair the beneficial uses of Navigation; Municipal and Domestic, Agricultural and Industrial Water Supply; and Non-contact Water Recreation; and to violate the Floating Material water quality objective for inland surface waters ("Water shall not contain floating material in amounts that cause nuisance or adversely affect beneficial uses") (CVRWQCB 1998).

In 1982 the California Legislature passed Senate Bill 1344 ordering the control of water hyacinth in the Delta. Control efforts included setting up barriers to keep masses of hyacinth out of navigation channels, spraying herbicides (including Weedar (2,4-D), Diquat and Rodeo (glyphosphate)), and releasing biocontrol agents, at a cost that reached $400,000/year, though it only partly alleviated the problems (Cohen & Carlton 1995). Control efforts for Brazilian waterweed included the use of an aquatic weed killer on 35 acres of Delta waterways in 1991 (Holt 1992). Field tests of another herbicide were conducted on 600 acres in Clifton Court Forebay in 1995, and biocontrol agents were investigated (Rubissow 1994; BDOC 1994). The USDA has investigated the use of herbicides and biocontrol to manage parrot's feather (BDOC 1994). These plants also alter shade and cover and, in the case of water hyacinth, may become dense enough in places to interfere with salmon migration (CDBW 1994). In many places, Brazilian waterweed forms dense walls of vegetation that deny migrating native species (*e.g*. salmon, splittail) access to shallow water habitat while increasing habitat for predatory largemouth bass. These effects would in particular appear to constitute an impairment of the "migration of aquatic organisms" beneficial use (CVRWQCB 1998). Water hyacinth and parrot's feather are reported to provide good mosquito-breeding habitat (Johnson 1920; BDOC 1994).

Purple loosestrife (*Lythrum salicaria*) is listed as a noxious weed in California (Hickman 1993 p. 746). It is a highly invasive wetland weed, often growing in monospecific stands and outcompeting cattails and other marsh plants, thereby degrading waterfowl habitat (Mills *et al*. 1993 p. 30; Hight 1993). Perennial peppergrass (*Lepidium latifolium*) is classified as a "B"-level plant pest by CDFA, and CDFG has tested burning, discing and herbicide treatments as control measures. Peppergrass may compete with and displace rare native marsh plants such as *Lillaeopsis masoni* and *Cordylanthus mollis mollis* (BDOC 1994).

The Asian freshwater clam *Corbicula fluminea* has plugged condenser tubes at the Central Valley Project pumps in Tracy (Ingram 1959). The *Corbicula* larvae that passed through the pumps settled in the Delta-Mendota Canal at typical densities of 10,000 to 20,000/m^2 with a maximum of 131,200/m^2. They trapped sediment and formed bars, with one bar described as filling the bottom of the canal from 0.3-1.0 meter deep for 3 kilometers. The reduction in delivery capacity required the dewatering of the canal and the dredging of over 50,000 cubic yards of clam-bearing material (Eng 1979). Ingram (1959) described *Corbicula* as a pest of water delivery systems elsewhere in California, clogging underground pipes, turnout valves, laterals and sprinkler systems. Dense settlement of *Corbicula* makes river sand and gravels unfit for use in aggregate, and *Corbicula* is reported to outcompete native clams (McMahon 1982). Efforts to control Corbicula in some California waters by the introduction of blue catfish were unsuccessful (Gleason 1984).

Much of the Delta's zooplankton fauna has become dominated by exotic species. Five species of Asian copepods (*Sinocalanus doerrii*, *Limnoithona sinensis*, *Pseudodiaptomus marinus*, *Pseudodiaptomus forbesi*, *Limnoithona tetraspina*) were discovered in 1978-1993. *S. doerrii* dominated the Delta copepod fauna in 1979 to the early 1980s, *P. forbesi* in 1988-89 and *L. tetraspina* in 1994. Herbold *et al*. (1992 pp. 46-61) reported that the "invasions of the western Delta and Suisun Bay by *Sinocalanus doerrii* in 1978 and by *Pseudodiaptomus forbesi* in 1987 were followed by declines in abundance of *Eurytemora affinis* and the almost complete elimination of *Diaptomus* spp." Studies indicated that *P. forbesi* and *S. doerri* were less useful as prey items for fish and shellfish than were the copepods that had been common prior to their arrival (Orsi 1989; Meng & Orsi 1991; Kimmerer 1991; Kimmerer *et al*. 1994); and this differential predation may have contributed to the dramatic shift in copepod fauna, though competition may also have been a factor (Orsi *et al*. 1983, Orsi 1995). Other exotic zooplankton include (1) the copepod *Eurytemora affinis*, which was long considered a native but that a recent molecular genetic study shows is probably introduction from the East Coast (Orsi 2001); (2) the mysid shrimp *Deltamysis holmquistae*, which appeared in the Delta in 1977 but has not become common (Bowman & Orsi 1992); and (3) the Asian cladoceran *Daphnia lumholtzi*, which showed up in 1999 (Mueller-Solger 2001; Orsi 2002). The newest invader is the Siberian prawn, *Exopalaemon modestus*, a large (to 50 mm carapace length) shrimp that occurs in dense aggregations in many areas (Souza 2001; Hieb 2002; Zeung 2002).

The exotic crayfish *Orconectes virilis*, *Procambarus clarki* and *Pacifastacus leniusculus*, the Chinese mitten crab *Eriocheir sinensis* and the eastern American muskrat *Ondatra zibethicus* are all burrowers that are capable, when dense, of extensive local habitat alteration, causing local bank collapse that affects shallow water and riparian habitat. *Procambarus clarkii* excavates burrows 5 cm in diameter and half a meter deep into levees and banks; and mitten crabs can dig burrows up to 12 cm in diameter and 80 cm deep, sometimes digging their burrows beneath riprap (Peters 1933; Elton 1936). Muskrats similarly create extensive burrow systems in the Delta, and in Great Britain the destruction of banks and ditches by introduced muskrat led to an intensive trapping program that eradicated them (Lever 1994).In the Delta the most important impact may be the incremental threat that this suite of exotic burrowing animals pose to levee stability, given the fragile nature of many Delta levees and the potential for levee failures to be initiated by water "piping." The prospect of damage from mitten crab burrowing in particular has been a major concern of federal and state resource managers and researchers (CDFG 1986; USFWS 1988; Cohen & Carlton 1997; Veldhuizen & Stanish 1999 pp. 17-18). Levee failure can negatively affect all beneficial uses in the Delta.

The mitten crab is listed as a pest species by both California and the federal government because of potential damage from its burrowing and because it can serve as an intermediate host for a human parasite, the oriental lung fluke *Paragonimus westermani*, which can also affect other mammal species such as river otter (CDFG 1986; USFWS 1988; Cohen 2003). In addition, in the late 1990s large numbers of downstream migrating mitten crabs arrived at the state and federal fish salvage facilities in the south Delta, where they clogged fish screens, entered fish bypass channels, collection devices and holding tanks, and were transferred into fish transport trucks in large numbers along with salvage fish (Scott Siegfried, USBR, pers. comm. 1998; Lloyd Hess, USBR, pers. comm. 1998; Siegfried 1999;

Veldhuizen & Stanish 1999 pp. 19-20). Salvage activities were hampered, requiring overtime work by salvage crews and other costs. High fish mortality occurred due to crabs interfering with the flushing of fish from holding tanks to the transfer bucket, into the transport truck, and out of the truck into the river. Experiments indicated that large numbers of crabs in confined spaces could also reduce dissolved oxygen to harmful levels (Parker & Arnold 1999). Contact by fish with the sharp edges of crab carapaces in confined spaces probably also removed scales and caused abrasions, leading to delayed mortality. As a result of this experience, there are concerns about impacts on fish ladders and other fish passage facilities designed for anadromous salmonids. Mitten crabs or their shells have clogged intake screens, pipes, condensers or valves at one wastewater treatment plant and two power plants in California, reducing power plant cooling flows on at least one occasion (Lew Bauman, San Jose/Santa Clara Water Pollution Control Plant, pers. comm. 1996; Kathy Hieb, CDFG, pers. comm. 1997; Sam Fagindo, Pacific Gas & Electric Company, pers. comm. 1998; Veldhuizen & Stanish 1999 pp. 19-20). On one occasion an accumulation of mitten crabs and vegetative debris clogged the intake screens at the USBR's Tracy Fish Collection Facility raising a potentially destructive 3-4 foot head across them (Brown 1998; Lloyd Hess, USBR, pers. comm. 2001). In addition to the above impacts on domestic, industrial and agricultural water supply systems, mitten crabs have been a pest of commercial and recreational fisheries including commercial shrimp trawlers in San Francisco Bay (by clogging nets and possibly damaging the nets and catch), commercial crayfish trappers in the Delta (by filling traps and possibly by competing with crayfish) and recreational hook-and-line anglers in the Bay and Delta (by persistently stealing bait) (Veldhuizen & Stanish 1999 pp. 18-19). Substantial harm has been reported to trap and set-net fisheries in Europe, by clogging traps, clogging and sometimes damaging nets, and eating or damaging fish caught in traps and nets (*e.g*. Panning 1939; Ingle & Andrews 1976; Veldhuizen & Stanish 1999 pp. 18-19).

Like the exotic burrowing animals discussed above, the common carp (*Cyprinus carpio*) is capable of structurally altering habitats. It feeds by "grubbing" in bottom sediments in shallow water, which digs up the bottom, destroys rooted vegetation, and muddies the water, rendering potentially productive areas unsuitable for use as spawning or nursery areas by other fish species. This appears to constitute an impairment of the "spawning, reproduction and/or early development" beneficial use (CVRWQCB 1998). Carp are abundant in the Delta (Herbold & Moyle 1989 pp. 51-59). Shebley (1917) reported that carp "probably have been the principal cause of destruction of the California [Sacramento] perch, by eating the eggs and digging up the nests." By 1942, Curtis reported that carp "had become the most unpopular fish ever brought into California. It stands as Public Enemy No. 1 on the fisherman's books" for preying on the spawn of other fish, muddying the water and destroying plants. BDOC (1994) reported that considerable effort is expended on controlling carp in some waters and that their spread to areas where they are now absent (such as the Klamath basin) should be prevented

Several exotic centrarchids are abundant in the Delta, including redear sunfish, bluegill, largemouth bass and black crappie (Turner 1966; Herbold & Moyle 1989 pp. 51-59). Competition with exotic sunfish for food and breeding sites (Moyle 1976; Vanicek 1980; BDOC 1994), predation by largemouth bass (Cohen & Carlton 1995), and possibly the introduction of exotic parasites likely contributed to the loss of Sacramento perch (*Archoplites interruptus*) from its native waters in the Delta (Moyle 2002). Predation by largemouth bass and striped bass was also probably a factor in the extinction of the thicktail chub (*Gila crassicauda*) (Cohen & Carlton 1995). It is interesting to note that even as they made the initial plantings, fishery agents were aware of "black" bass' potential to reduce native fish populations. As Smith (1896 pp. 442-446) reported, "State fish commissioners have refrained from depositing fry or yearling bass in waters already stocked with salmon or trout, but have restricted the distribution to lakes, reservoirs, ponds, and rivers in which the predaceous bass could do no damage. It seems only a question of time, however, when the bass will naturally find their way into and become abundant in all those rivers in which they have not already been planted." Predation by green sunfish, bluegill and largemouth bass, perhaps along with predation or competition by bullfrogs, probably contributed to the extirpation of native red-legged frogs in the Delta (Herbold & Moyle 1989 pp. 60-61; BDOC 1994). In recent years, both spotted bass (*Micropterus punctulatus*) and redeye bass (*M. coosae*) have invaded the Delta. While their impact in the Delta has not yet been determined, the redeye bass has devastated the native fish fauna of the Cosumnes River basin, a Delta tributary (Moyle *et al*. 2003). The next new predator is the northern pike (*Esox lucius*). If it is not eradicated from Davis Reservoir on the Feather River soon, it will wind up in the Delta where it will surely thrive and potentially prey on salmon, splittail and other native fishes.

Threadfin shad and inland silverside are abundant in the Delta (Herbold & Moyle 1989 pp. 51-59; Moyle 2002). Several workers have concluded that threadfin shad compete with the fry of gamefish, including black bass, crappie and striped bass (McConnell & Gerdes 1961; Von Geldern & Mitchill 1975). Inland silverside may prey on the eggs and fry of the endangered Delta smelt (BDOC 1994; Moyle 2002). In 1959, wakasagi were introduced into California from Japan as a forage fish. By 1994 they had reached the Delta through a combination of human transport and natural spread, and began hybridizing with Delta smelt, which are listed as threatened under both state and federal law (Trenham *et al*. 1998).

The striped bass has been reported as a major predator of salmon fingerlings in the Delta (US Bureau of Reclamation 1983), and is the most abundant predator at sampled locations in the Delta (Pickard *et al*. 1982). In 1992 the stocking of striped bass in the Delta was curtailed due to concern over predation on the endangered winter-run chinook salmon (BDOC 1994). BDOC (1994) noted that while few young salmon are eaten by striped bass in the Estuary except at salmon stocking sites and in Clifton Court Forebay, salmon sometimes form a substantial part of the diet of striped bass upstream in the Sacramento River; and concluded that striped bass predation reduces salmon abundance by an unquantified amount. Predation by striped bass may also have been a factor in the extinction of the thicktail chub (*Gila crassicauda*) and the elimination of Sacramento perch (*Archoplites interruptus*) from its native waters in the Delta (Cohen & Carlton 1995).

Exotic fish parasites in the Delta include 4 trematodes, 5 tapeworms, a nematode, a leech and a copepod (Edwards & Nahhas 1968; Hensley & Nahhas 1975; Cohen 1996 pp. 225-229, 241 & 270-271). In the Delta these parasites mainly infest exotic warmwater gamefish, but a few have also been reported there and elsewhere on native California fish. For example, the anchor worm (*Lernaea cyprinacea*), an Asian species that has spread to Africa, Europe, Australia and North America, is described as a "dangerous" and "devastating" parasite that infests a wide variety of freshwater fish as well as frog and salamander tadpoles (Haderlie 1950; Hoffman 1970). The native California species that it has parasitized include hitch, hardhead, Sacramento blackfish, splittail, Sacramento squawfish, Sacramento sucker, Sacramento perch, rainbow trout and chinook salmon (Haderlie 1950, 1953; Hensley & Nahhas 1975; Love & Moser 1983).

(5) <u>Impacts of exotic species in the mainstem, valley-floor reach and associated waters of the San Joaquin River (in Region 5: San Joaquin, Stanislaus, Merced and Madera counties)</u>

The native fish communities of the valley floor, which the aboriginal populations relied on as a source of food, have been almost completely replaced by assemblages dominated by exotic species. Sacramento perch (*Archoplites interruptus*), tule perch (*Hysterocarpus traski*), thicktail chub (*Gila crassicauda*), splittail (*Pogonichthys macrolepidus*), roach (*Hesperleucus symmetricus*), hardhead (*Mylopharodon *conocephalus*), squawfish (*Ptylocheilus grandis*), and Sacramento sucker (*Catostomus occidentalis*) are uncommon, rare or absent from the valley floor waters where they were once common or abundant (Moyle & Nichols 1974; Brown & Moyle 1993). Instead, valley-floor waters are occupied by exotic fish. Seventy-seven percent of the fish species collected in 1986 were exotic, including the four most abundant species, threadfin shad (*Dorosoma petenense*), mosquitofish (*Gambusia affinis*), inland silverside (*Menidia beryllina*) and red shiner (*Notropis lutrensis*) (Jennings & Saiki 1990). Based on similarities in ecological requirements, the California roach may be displaced by red shiner (Jennings & Saiki 1990). This apparently constitutes an impairment of the "freshwater habitat" beneficial use (CVRWQCB 1998).

The red-legged frog (*Rana aurora*) disappeared from the San Joaquin Valley floor concomitant with the spread of the eastern American bullfrog (*Rana catesbeiana*). There appears to be plenty of suitable habitat for the red-legged frog, but it is occupied by large populations of bullfrogs. Predation or competition by the bullfrog is probably the single most important factor in eliminating red-legged frog from the floor of the San Joaquin Valley (Moyle 1973). This constitutes an impairment of the "wildlife habitat" beneficial use, which is defined to include the preservation of wildlife, including amphibians (CVRWQCB 1998).

(6) <u>Impacts of exotic species in the Sierra foothill reaches of the Cosumnes, Stanislaus, Tuolomne, Merced, Chowchilla, Fresno, upper San Joaquin, Kings, Kaweah, Tule and Kern river systems (in Region 5: Sacramento, El Dorado, Amador, San Joaquin, Stanislaus, Merced, Madera, Fresno, Kings, Tulare and Kern counties)</u>

Throughout the Sierra foothill region of the San Joaquin Valley, native fish species—including California roach (*Lavinia symmetricus*), hardhead (*Mylopharodon conocephalus*) and hitch (*Lavinia exilicauda*)—have declined as exotic fish have taken over, with at least part of the decline due to competition with or predation by the exotic fish (Moyle & Nichols 1974). Half of the fish species present are now exotic. Native fish remain only as isolated populations on different streams in a narrow, mid-elevation band, in danger of going extinct one by one, with little chance of recolonization from the remaining populations (Moyle & Nichols 1974; Brown & Moyle 1993). A particularly striking change was the absence of roach in the upper San Joaquin and Fresno rivers by 1970 and its rarity in the Chowchilla River, despite the presence of ample suitable habitat. Roach populations were negatively correlated with the presence of exotic green sunfish, a predaceous and possibly competing exotic species (Moyle & Nichols 1974), and roach were most abundant where exotic species were absent or rare (Moyle & Nichols 1973). Similarly, in the mid-1980s hitch and hardhead were absent from drainages where they had been collected in 1970, with hardhead being absent or scarce in otherwise suitable habitat that contained smallmouth bass. In the upper Kings River drainage, smallmouth expanded their range and hardhead declined between 1970 and 1986 (Brown & Moyle 1993). On the Tuolumne River, smallmouth and largemouth bass are impacting salmon populations by preying on young salmon. A control effort is being undertaken by CALFED, at a cost of millions of dollars, that involves filling instream gravel pits to reduce habitat for bass. In the Cosumnes River, redeye bass (*Micropterus coosae*) have eliminated or reduced most of the native fish fauna (Moyle *et al*. 2003). As a result of such invasions, the inland fish fauna of the San Joaquin Valley and of California is becoming increasingly homogenized (Marchetti *et al*. 2001).

In general, there are strong negative correlations between native and exotic fish species in this region (Moyle & Nichols 1973, Table 4: 77% of exotic-native correlations are negative, but only 38% of native-native and exotic-exotic correlations). Studies conducted on the San Joaquin River at Friant over a 72-year period show an increase in exotic species accompanied by a loss of natives (Moyle & Nichols 1974; Moyle 2000):

Year of study:	1898	1934	1940-41	1970
Estimated number of exotic species:	0	4	8	7
Estimated number of native species:	14	13	13	6

The replacement of native fish by exotic species would appear to constitute an impairment of the "freshwater habitat" beneficial use.

Throughout this region, the red-legged frog (*Rana aurora*) has largely disappeared and the foothill yellow-legged frog (*Rana boylii)* has declined as the bullfrog has invaded and become the dominant frog. In 1970, yellow-legged frog occurred in intermittent streams only where bullfrog were absent (Moyle 1973). The replacement of native frogs by an exotic frog would appear to constitute an impairment of the "wildlife habitat" beneficial use.

Recent studies have shown that foothill yellow-legged frogs have been largely eliminated from the San Joaquin watershed as the result of air pollution to which bullfrogs are more resistant. Attempts to restore foothill yellow-legged frogs once air pollution has abated are likely to be frustrated by bullfrog invasions in many areas. In higher elevation areas, mountain yellowlegged frogs have declined in good part due to stocking of exotic trout (mainly brook trout and brown trout) into mountain lakes (Knapp 2000; Knapp *et al*. 2001).

(7) Impacts of exotic species in the Truckee River Hydrologic Unit, Little Truckee River Hydrologic Unit, West Fork Carson River Hydrologic Unit, Susanville Hydrologic Unit and Eagle Drainage Hydrologic Unit (in Region 6: Lassen, Sierra, Nevada, Placer and Alpine counties)

All of these drainages except Eagle Lake have been invaded by exotic salmonids (including brook, brown, lake, and rainbow trout and kokanee salmon) which have eliminated native cutthroat trout, and by signal crayfish (*Pacifastacus leniusculus*). The Truckee and Little Truckee rivers have recently been invaded by smallmouth bass. The Truckee River has largemouth bass and green sunfish as well. Brook trout have invaded Pine Creek in the Eagle Lake drainage, which is otherwise free of exotic fish.

Each of these water bodies has a Species Composition water quality objective, which states that "the species composition of aquatic organisms shall not be altered to the extent that such alterations are discernible at the 10 percent significance level" (LRWQCB 1994). The introduction of numerous exotic species and the associated reduction or elimination of native species clearly alter the species composition of the Truckee River Little Truckee River, West Fork Carson River and Susanville Hydrologic Units to a degree that violates this water quality objective, and possibly does so in Pine Creek in the Eagle Drainage Hydrologic Unit as well.

(8) Impacts of exotic species in Clear Lake (in Region 5: Lake County)

Inland silverside were stocked in Clear Lake in 1967 to control gnats. The population exploded, so that silverside were the most abundant species taken in seine hauls by the fall of 1968, one year after the introduction of less than 3,000 fish, with up to 2,500 silversides in a single haul (Cook & Moore 1970). Silverside became the dominant inshore fish in the lake and eliminated the native Clear Lake splittail. Li *et al*. (1976) discuss data showing that silverside also compete with and caused a decline in the growth rate of black and white crappie in Clear Lake. Exotic species now dominate the fish fauna in Clear Lake.

(9) Impacts of exotic species in Lake Tahoe (in Region 6: El Dorado County)

Problems with exotic aquatic plants including hydrilla have resulted in costly control programs involving both herbicide applications and mechanical removal. Introduced lake trout eliminated the endangered Lahontan cutthroat trout from the lake. Kokanee probably compete with native tui chub. Both largemouth and smallmouth bass are now widespread in lake, and threaten native minnows. The mysid shrimp *Mysis relicta* was introduced in the 1950s as forage for juvenile lake trout, but instead eats the copepods that young trout feed on.

(10) Impacts of exotic species in southern California nearshore waters (in Regions 3, 4, 8 and 9: Santa Barbara, Ventura, Los Angeles, Orange and San Diego counties)

Two exotic shellfish parasites that can infect all California abalone species (all of which are in decline and one of which is endangered) have been released into this region, the South African shell parasite *Terebrasabella heterouncinata*, and the exotic Rickettsia parasite tentatively named *Xenohaliotis californiensis* (Bower 2004).

Terebrasabella was apparently imported accidentally by one southern California abalone farm and subsequently spread by transfer of stock to virtually all California abalone culture facilities by the mid-1990s. It became established in native intertidal snails in at least one southern California site around the water outlet from an abalone farm, where it has since been eradicated (Culver & Kuris 2000). It is possibly present in other sites, especially in some of the many unknown subtidal locations where tens of thousands of red abalone, many of them undoubtedly carrying *Terebrasabella*, were outplanted in southern California waters in the 1980s and 1990s. Intense infestations in abalone produce shells that are easily broken, that are disproportionately tall relative to the size of the aperture and foot, and that frequently lacking respiratory holes. In addition the growth of soft tissue was slowed or halted. Overall, such infestations produced abalone with reduced reproductive potential and, were they to occur in the natural environment, greater vulnerability to predators and to dislodging or damage by waves or rock movement in the surf zone. Kuris and Culver (1999) found that these worms can infest not just Red Abalone but probably all species of California abalone—all of which are in decline and one of which, the White Abalone (*Haliotis sorenseni*) is thought to be near extinction (Tegner *et al.* 1996)—and a wide variety of native California marine snails (Cohen 2002b).

Xenohaliotis californiensis produces a condition in abalone known as withering syndrome, withering disease, foot withering syndrome or abalone wasting disease—a lethal disease that causes lethargy, retracted visceral tissues and atrophy of the foot, and the progression of the disease is accelerated and intensified by warm temperatures. (Bower 2004). It appeared first in black abalone in the Channel Islands, and has subsequently spread to sites from the west coast of Baja California to Point Conception and northward, possibly as far as San Francisco; and to other abalone species including red, pink, green and the endangered white abalone. Similar organisms have been detected, with no associated pathology, in the South African abalone *Haliotis midae*, which could possibly be the source. It has caused mass mortalities of black abalone, involving population crashes on 6 of the 8 Channel Islands by 1992.

These two diseases have impaired several beneficial uses in southern California waters, including Aquaculture; Marine Habitat; Commercial and Sport Fishing; Shellfish Harvesting; Contact Water Recreation; Rare, Threatened or Endangered Species; and Preservation of Biological Habitats of Special Significance.

Literature Cited

Aldrich, F. A. 1961. Seasonal variations in the benthic invertebrate fauna of the San Joaquin River estuary of California, with emphasis on the amphipod *Corophium spinicorne* Stimpson. *Proc. Acad. Nat. Sci. Phila.* 113: 21-28.

Anderson, L. W. J. 1990. Aquatic weed problems and management in the western United States and Canada. Pages 371-391 in: Pieterse, A. H. and K. J. Murphy (eds.), Aquatic Weeds: The Ecology and Management of Nuisance Aquatic Vegetation, Oxford Univ. Press, 593 pp.

Arthington, A. H. 1991. Ecological and genetic impacts of introduced and translocated freshwater fishes in Australia. *Can. J. Fish. Aquat. Sci.* 48(Suppl. 1): 33-43.

Barrett, S. 1989. Waterweed invasions. *Scientific American* 261: 90-97.

BDOC. 1994. Draft Briefing Paper on Introduced Fish, Wildlife, and Plants in the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. Bay-Delta Oversight Council, Calif. Resources Agency, Sacramento, 33 pp.

Bower, S.M. 2004. Synopsis of Infectious Diseases and Parasites of Commercially Exploited Shellfish: Withering Syndrome of Abalone. URL: http://www-sci.pac.dfo-mpo.gc.ca/shelldis/pages/fwsab_e.htm

Bowman, T. E. and J. J. Orsi. 1992. *Deltamysis holmquistae*, a new genus and species of Mysidacea from the Sacramento-San Joaquin Estuary of California (Mysidae: Mysinae: Heteromysini). *Proc. Biol. Soc. Wash.* 105(4): 733-742.

Brown, L. R. and P. B. Moyle. 1993. Distribution, ecology, and status of the fishes of the San Joaquin River drainage, California. *Calif. Fish and Game* 79(3): 96-114.

Brown, R. 1998. Mitten crabs. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 11(4): 4.

CDBW. 1994. 1993 Summary of Operations: Water Hyacinth Chemical Control Program. Calif. Dept. of Boating and Waterways, 51 pp.

CDFG. 1986. Pre-publication of Notice Supporting Placement of the Genus *Eriocheir* on the Department of Fish and Game Commission's List of Prohibited Species (June 12, 1986). California Department of Fish and Game, Sacramento, CA.

Cohen, A. N. 1996. *Biological Invasions in the San Francisco Estuary: A Comprehensive Regional Analysis*. Ph. D. dissertation, Energy and Resources, University of California, Berkeley CA.

Cohen, A. N. 2002. Success factors in the establishment of human-dispersed organisms. Pages 374-394 in: *Dispersal Ecology*. J.M. Bullock, R.E. Kenward and R.S. Hails (eds.). Blackwell Publishing, Oxford, for the British Ecological Society, London.

Cohen, A.N. 2002b. The release of pest species by marine aquaculture: lessons from a South African parasite introduced into California waters. Pages 9-13 in: *Invasions in Aquatic Ecosystems: Impacts on Restoration and Potential for Control*, Proceedings of a Workshop, April 25, 1998, Sacramento, California, A.N. Cohen, and S.K. Webb (eds.). San Francisco Estuary Institute, Oakland, California.

Cohen, A.N. 2003. On mitten crabs and lung flukes. *IEP Newsletter* 16(2): 48-51.

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*. U. S. Fish and Wildlife Service, Washington DC.

Cohen, A.N. and J.T. Carlton. 1997. Transoceanic transport mechanisms: The introduction of the Chinese mitten crab *Eriocheir sinensis* to California. *Pac. Sci.* 51(1): 1-11.

Cook, S. F., Jr. and R. L. Moore. 1970. Mississippi silversides, *Menidia audens* (Atherinidae), established in California. *Trans. Am. Fish. Soc.* 99: 70-73.

Culver, C. S. and A. M. Kuris. 2000. The apparent eradication of a locally established introduced marine pest. *Biological Invasions* 2: 245-253.

Curtis, B. 1942. The general situation and the biological effects of the introduction of alien fishes into California waters. *Calif. Fish and Game* 28: 2-8.

CVRWQCB. 1998. Water Quality Control Plan (Basin Plan) for the California Regional Water Quality Control Board Central Valley Region, Fourth Edition.

Elton, C.S. 1936. A new invader (review of Peters & Panning, 1933) *J. Anim. Ecol.* 5: 188-192

Eng, L. L. 1979. Population dynamics of the Asiatic clam, *Corbicula fluminea* (Müller), in the concrete-lined Delta-Mendota canal of central California. Pages 40-48 in: Britton, J. C. (ed.), Proc. 1st Int'l *Corbicula* Symp., Texas Christian Univ., Fort Worth, Texas, Oct. 13-15, 1977.

Gleason, E. 1984. The Freshwater Clam, *Corbicula fluminea*, in California. Calif. Dept. of Fish and Game, Inland Fisheries—Informational Leaflet No. 37, 9 pp.

Groat, C. 2000. Statement of Charles Groat, Director US Geological Survey, from *People, Land & Water* (US Department of the Interior) July/August 2000, at http://www.usgs.gov/invasive_species/plw/usgsdirector01.html, accessed 26 January 2001.

Herbold, B. and P. B. Moyle. 1989. The Ecology of the Sacramento-San Joaquin Delta: A Community Profile. U. S. Fish and Wildlife Service (Biol. Rep. 85(7.22)), 106 pp.

Herbold, B., Jassby, A. D. and P. B. Moyle. 1992. Status and Trends Report on Aquatic Resources in the San Francisco Estuary. San Francisco Estuary Project, Oakland, 257 pp.

Hickman, J. C. (ed.) 1993. The Jepson Manual: Higher Plants of California. Univ. California Press, Berkeley, 1400 pp.

Hieb, K. 2002. San Francisco Bay Fisheries Monitoring. Interagency Ecological Program Newsletter (California Department of Water Resources, Sacramento, CA) 15(1): 4

Hight, S. D. 1993. Control of the ornamental purple loostrife (*Lythrum salicaria*) by exotic organisms. Pages 147-148 in: McKnight, B. N. (ed.), Biological Pollution: The Control and Impact of Invasive Exotic Species. Indiana Acad. Sci., Indianapolis, 261 pp.

Holt, S. 1992. Delta faces new weedy situation. *Brentwood News* (Brentwood CA) 30 June 1992: 1, 8.

Hymanson, Z., Mayer, D. and J. Steinbeck. 1994. Long-term Trends in Benthos Abundance and Persistence in the Upper Sacramento-San Joaquin Estuary, Summary Report: 1980-1990. Interagency Ecological Program for the San Francisco Bay/Delta Estuary, Tech. Rep. 38 (FWQ/BIO/IATR/94-38), Calif. Dept. Water Resources, Sacramento, 66 pp.

Ingle, R.W. and M.J. Andrews. 1976. Chinese Mitten Crab reappears in Britain. *Nature* 263: 638.

Ingram, W. M. 1959. Asiatic clams as potential pests in California water supplies. *J. Amer. Water Works Assoc.* 51(3): 363-370.

Jennings, M. R. and M. K. Saiki. 1990. Establishment of red shiner, *Notropis lutrensis*, in the San Joaquin Valley, California. *Calif. Fish and Game* 76(1): 46-57.

Johnson, E. 1920. Water hyacinth. A menace to navigation in the south. *Monthly Bull.* (Calif. Dept. Agric.) 9: 76-80.

Kimmerer, W. 1991. Tests on effects of food limitation on reproduction in two copepod species important in the diet of larval striped bass. Pages 7-17 in: Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, 1990 Working Papers of the Food Chain Group, No. 2 (FCG-90-2), Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, Calif. Dept. Water Resources, Sacramento, 71 pp.

Kimmerer, W. J., Gartside, E. and J. J. Orsi. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. *Mar. Ecol. Prog. Ser.* 113: 81-93.

Knapp R. A. 2000. Non-native fish introductions and the decline of the mountain yellow-legged frog from within protected areas. *Cons. Biol.* 14:428ˆ438.

Knapp, R. A., P. S. Corn, and D. E. Schindler. 2001. The introduction of non-native fish into wilderness lakes: good intentions, conflicting mandates, and unintended consequences. *Ecosystems* 4:275-278.

Kuris, A. M. and C. S. Culver (1999) An introduced sabellid polychaete pest infesting cultured abalones and its potential spread to other California gastropods. *Invertebrate Biology* 118(4): 391-403.

LRWQCB. 1994. Water Quality Control Plan for the Lahontan Region—North and South Basins. California Regional Water Quality Control Board Lahontan Region, South Lake Tahoe, CA.

Lever, C. 1994. Naturalized Animals: The Ecology of Successfully Introduced Species. T. & A. D. Poyser Ltd., London, 354 pp.

Li, H. W., Moyle, P. B. and R. L. Garrett. 1976. Effect of the introduction of the Mississippi silverside (*Menidia audens*) on the growth of black crappie (*Pomoxis nigromaculatus*) and white crappie (*P. annilaris*) in Clear Lake, California. *Trans. Am. Fish. Soc.* 105: 404-408.

Lloyd, L. N., Arthington, A. H. and D. A. Milton. 1986. The mosquitofish—a valuable mosquito-control agent or a pest? Pages 6-15 in: Kitching, R. L. (ed.), The Ecology of Exotic Animals and Plants: Some Australian Case Histories. John Wiley & Sons, Brisbane.

MacArthur, R. H. and E. O. Wilson. 1967. The Theory of Island Biogeography. Princeton University Press, princeton, NJ.

Marchetti M. P., Moyle P. B. and Levine R. 2004. Invasive species profiling? Exploring the characteristics of non-native fishes across invasion stages in California. F*reshwater Biology* 49: 646–661.

Markmann, C. 1986. Benthic Monitoring in the Sacramento-San Joaquin Delta: Results from 1975 through 1981. Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, Tech. Rep. 12 (WQ/BIO-4ATR/87-12), Calif. Dept. Water Resources, Sacramento, 51 pp.

McConnell, W. J. and J. H. Gerdes. 1961. Threadfin shad, *Dorosoma petenense*, as food of yearling Centrarchids. *Calif. Fish and Game* 50: 70-175.

McKay, R. J. 1984. Introductions of exotic fishes in Australia. Pages 177-199 in: Courtenay, W. R., Jr. and J. R. Stauffer, Jr. (eds.), Distribution, Biology and Management of Exotic Fishes, Johns Hopkins Univ. Press, Baltimore, 430 pp.

McKechnie, R. J. 1966. Golden shiner. Pages 488-491 in: Calhoun, A. (ed.), Inland Fisheries Management, Calif. Dept. of Fish and Game, 535 pp.

McMahon, R. F. 1982. The occurrence and spread of the introduced Asiatic freshwater clam, *Corbicula fluminea* (Müller), in North America: 1924-1982. *Nautilus* 96(4): 134-141.

Meng, L. and J. J. Orsi. 1991. Selective predation by larval striped bass on native and introduced copepods. *Trans. Am. Fish. Soc.* 120: 187-192.

Miller, R.R., Williams, J.D. & Williams, J.E. (1989) Extinctions of North American fishes during the past century. *Fisheries* 14(6), 22-38.

Mills, E. L., Leach, J. H., Carlton, J. T. and C. L. Secor. 1993. Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. *J. Great Lakes Res.* 19(1): 1-54.

Moyle, P. B. 1973. Effects of introduced bullfrogs, *Rana catesbeiana*, on the native frogs of the San Joaquin Valley, California. *Copeia* 1: 18-22.

Moyle, P. B. 1976. Fish introductions in California: history and impact on native fishes. *Biol. Conserv.* 9: 101-118.Pickard *et al.* 1982

Moyle, P. B. 2002. Inland Fishes of California, revised and expanded. U.C. Press, Berkeley, CA, 502 pp.

Moyle, P. B. and R. D. Nichols. 1973. Ecology of some native and introduced fishes in the Sierra Nevada foothills in Central California. *Copeia* 3: 478-490.

Moyle, P. B. and R. D. Nichols. 1974. Decline of the native fish fauna of the Sierra Nevada foothills, Central California. *Amer. Midl. Nat.* 92(1): 72-83.

Moyle P. B., Craina P. K., Whitener K. and Mount J. F. 2003. Alien fishes in natural streams: fish distribution, assemblage structure, and conservation in the Cosumnes River, California, U.S.A. *Environmental Biology of Fishes* 68: 143–162.

Mueller-Solger, A. 2001. First Observation of an Exotic Water Flea, *Daphnia lumholtzi*, in the Delta. Interagency Ecological Program Newsletter (California Department of Water Resources, Sacramento, CA). 14(3): 12-14

Orsi, J. 2001. *Eurytemora affinis* is Introduced. Interagency Ecological Program Newsletter (California Department of Water Resources, Sacramento, CA).14(4):12

Orsi, J. 2002. *Daphnia lumholtzi* Detected Again. Interagency Ecological Program Newsletter (California Department of Water Resources, Sacramento, CA). 15(1): 15

Orsi, J. J. 1989. Another new copepod. Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, *Newsletter* (June 1989) 1(1): 4.

Orsi, J. J. 1995. Radical changes in the estuary's zooplankton caused by introductions from ballast water. Interagency Ecological Studies Program for the Sacramento-San Joaquin Estuary, *Newsletter*, Summer 1995: 16-17.

Orsi, J. J., Bowman, T. E., Marelli, D. C. and A. Hutchinson. 1983. Recent introduction of the planktonic calanoid copepod *Sinolanus doerri* (Centropagidae) from mainland China to the Sacramento-San Joaquin Estuary of California. *J. Plankton Res.* 5(3): 357-375.

Panning, A. 1939. The Chinese mitten crab. *Ann. Rep. Smithsonian Inst.* 1938: 361-375.

Parker, G. and J. Arnold. 1999. Mitten crab (*Eriocheir sinensis*) depletion of dissolved oxygen in a confined space. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 12(1): 9-10.

Peters, N. 1933. Lebenskundlicher Teil ["Natural history section"]. Pages 59-156 in: Die Chinesische Wollhandkrabbe (*Eriocheir sinensis* H. Milne-Edwards) in Deutschland ["The Chinese Mitten Crab (*Eriocheir sinensis* H. Milne-Edwards) in Germany"], Peters, N. and A. Panning (eds.), Akademische Verlagsgesellschaft M.B.H., Leipzig. [in German; translation by M. Myers provided]

Raver, A. 1999. What's eating America? Weeds. *New York Times* Oct. 18, 1999.

Richter, B.D., Braun, D.P., Mendelson, M.A. & Master, L.L. (1997) Threats to imperiled freshwater fauna. *Conservation Biology* 11, 1081-1093.

Rubissow, A. 1994. Water weed. *Estuary* (San Francisco Estuary Project, Oakland) 3(4): 2.

Schmitz, D. C., Schardt, J. D., Leslie, A. J., Dray, F. A., Jr., Osborne, J. A. and B. V. Nelson. 1993. The ecological impact and management history of thre invasive alien plant species in Florida. Pages 173-194 in: McKnight, B. N. (ed.), Biological Pollution: The Control and Impact of Invasive Exotic Species. Indiana Acad. Sci., Indianapolis, 261 pp.Shebley, W. H. 1917. History of the introduction of food and game fishes into the waters of California. *Calif. Fish and Game* 3(1): 2-12.

Shebley, W. H. 1917. History of the introduction of food and game fishes into the waters of California. *Calif. Fish and Game* 3(1): 2-12.

Siegfried, C. A., Kopache, M. E. and A. W. Knight. 1980. The benthos of a portion of the Sacramento River (San Francisco Bay Estuary) during a dry year. *Estuaries* 3(4): 296-307.

Siegfried, S. 1999. Notes on the invasion of the Chinese mitten crab (Eriocheir sinensis) and their entrainment at the Tracy fish collection facility. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 12(2): 24-25.

Smith, H. M. 1896. A review of the history and results of the attempts to acclimatize fish and other water animals in the Pacific states. *Bull. U. S. Fish Comm.* 15 (1895): 379-475.

Smith, H. M. 1896. A review of the history and results of the attempts to acclimatize fish and other water animals in the Pacific states. *Bull. U. S. Fish Comm.* 15 (1895): 379-475.

Souza, Kelly. 2001. Spring Midwater Trawl Survey. Interagency Ecological Program Newsletter (California Department of Water Resources, Sacramento, CA). 14(2): 8

Tegner, M. J., L. V. Basch and P. K. Dayton (1996) Near extinction of an exploited marine invertebrate. *Trends in Evolution and Ecology* 11(7): 278-279.

Thomas, L. and L. Anderson. 1983. Water hyacinth control in California (unpublished ms.).

Trenham, P. C., H. B. Shaffer and P. B. Moyle. 1998. Biochemical identification and assessment of population subdivision in morphologically similar native and invading smelt species (*Hypomesus*) in the Sacramento-San Joaquin Estuary, California. Transactions, *American Fisheries Society* 127: 417-424.

Turner, J. L. 1966. Distribution and food habits of centrarchid fishes in the Sacramento-San Joaquin Delta. Pages 144-153 in: Turner, J. L. and D. W. Kelley (eds.), Ecological Studies of the Sacramento-San Joaquin Delta. Part II: Fishes of the Delta, Calif. Dept. of Fish and Game, *Fish Bull.* 136, 168 pp.

USBR. 1983. Central Valley Fish and Wildlife Management Study: Predation of Anadromous Fish in the Sacramento River, California. U. S. Bureau of Reclamation, 71 pp.

USFWS. 1988. Proposed Rule: Injurious Wildlife: Mitten Crabs. *U. S. Federal Register* 53(219): 45784-45788 (Nov. 14, 1988).

Veldhuizen, T. and K. Hieb. 1998. What's new on the mitten crabs front? *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 11(3): 43.

Von Geldern, C. E. and D. F. Mitchill. 1975. Largemouth bass and threadfin shad in California. Pages 436–449 in: Black Bass Biology and Management, H. Clepper (ed.), Sport Fishing Institute, Washington, DC.

Wilcove, D.S., Rothstein, D., Dubrow, J., Phillips, A. & Losos, E. (1998) Quantifying threats to imperiled species in the United States. *BioScience* 48, 607-615.

Zeug, S. 2002. Introduced Palaemonid Shrimp Invades the Yolo Bypass Floodplain. Interagency Ecological Program Newsletter (California Department of Water Resources, Sacramento, CA). 15(1): 13-15

Attachment A. Exotic Species in the Sacramento-San Joaquin Delta

Plants
- Chenopodium macrospermum
- Cotula coronopifolia
- Egeria densa
- Eichhornia crassipes
- Iris pseudacorus
- Lepidium latifolium
- Limosella subulata
- Lythrum hyssopifolium
- Lythrum salicaria
- Myriophyllum aquaticum
- Myriophyllum spicatum
- Polygonum patulum
- Potamogeton crispus
- Rorippa nasturtium-aquaticum

Cnidarians
- Cordylophora caspia

Platyhelminthes
- Alloglossidium corti
- Atractolytocestus huronensis
- Bothriocephalus claviceps
- Cleidodiscus pricei
- Corallobothrium fimbriatum
- Corallobothrium giganteum
- Dactylogyrus extensus
- Khawia iowensis
- Pisciamphistoma stunkardi

Nematodes
- Philometroides sanguinea

Annelids
- Boccardiella ligerica
- Branchiura sowerbyi
- Manayunkia speciosa
- Marenzelleria viridis
- Myzobdella moorei
- Paranais frici
- Potamilla sp.
- Potamothrix bavaricus

Mollusks
- Cipangopaludina chinensis
- Corbicula fluminea
- Melanoides tuberculata

Crustaceans
- Asellus sp.
- Balanus improvisus
- Caecidotea racovitzai
- Crangonyx floridanus
- Daphnia lumholtzi
- Eriocheir sinensis
- Eurytemora affinis
- Exopalaemon modestus
- Lernaea cyprinacea
- Limnoithona sinensis
- Limnoithona tetraspina
- Melita nitida
- Munna sp.
- Orconectes virilis
- Pacifastacus leniusculus
- Procambarus clarkii
- Pseudodiaptomus forbesi
- Rhithropanopeus harrisii
- Sinocalanus doerrii

Insects
- Neochetina bruchi
- Neochetina eichhorniae

Kamptozoans
- Urnatella gracilis

Fish
- Acanthogobius flavimanus
- Alosa sapidissima
- Ameiurus catus
- Ameiurus melas
- Ameiurus nebulosus
- Carassius auratus
- Cyprinus carpio
- Dorosoma petenense
- Gambusia affinis
- Hypomesus nipponensis
- Ictalurus furcatus
- Ictalurus punctatus
- Lepomis cyanellus
- Lepomis gibbosus
- Lepomis gulosus
- Lepomis macrochirus
- Lepomis microlophus
- Lucania parva
- Menidia beryllina
- Micropterus coosae
- Micropterus dolomieu
- Micropterus punctulatus
- Micropterus salmoides
- Morone saxatilis
- Notemigonus crysoleucas
- Percina macrolepida
- Pimephales promelas
- Pomoxis annularis
- Pomoxis nigromaculatus
- Tridentiger barbulatus
- Tridentiger bifasciatus

Amphibians
- Rana catesbeiana

Reptiles
- Pseudemys scripta

Mammals
- Ondatra zibethicus

Attachment B. Fraction of Species that are Exotic in the Sacramento-San Joaquin Delta region

Adapted from Cohen & Carlton 1995, Table 4.

Location	Number and percent of species that are exotic	Reference [date of collection]
At Antioch and Bradford	6 out of 7 epibenthic/fouling species (86%)	Aldrich 1961
Decker Island to Chipps Island	3 out of 5 dominant benthic species (60%)	Siegfried *et al*. 1980 [1976]
Delta to Grizzly Bay	2 out of 4 dominant benthic species (50%)	Markmann 1986 [1975-81]
Old River to Grizzly Bay	2 out of 5 dominant benthic species (40%)	Herbold & Moyle 1989 [1983-84]
Delta	26 out of 52 fish present (50%) 25 out of 36 resident fish (69%)	Herbold & Moyle 1989
Frank's Tract and Sherman Lake	6 out of 22 (27%) benthic invertebrate species	Hymanson *et al*. 1994 [1980-90]
At Sherman Island	10 out of 17 (59%) benthic invertebrate species	Hymanson et al. 1994 [1980-90]