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INTEGRATING FISHERY AND WATER RESOURCE MANAGEMENT: A BIOLOGICAL MODEL OF A CALIFORNIA SALMON FISHERY

by

Anthony C. Fisher, W. Michael Hanemann,
and Andrew G. Keeler

DEPARTMENT OF AGRICULTURAL AND
RESOURCE ECONOMICS

BERKELEY

CALIFORNIA AGRICULTURAL EXPERIMENT STATION

University of California

DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS
DIVISION OF AGRICULTURE AND NATURAL RESOURCES
UNIVERSITY OF CALIFORNIA

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California Agricultural Experiment Station
Giannini Foundation of Agricultural Economics

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Anthony C. Fisher
W. Michael Hanemann
Andrew G. Keeler

Department of Agricultural and Resource Economics
University of California at Berkeley

Running head: Water Flows and Fisheries

Address Correspondence to: Professor Anthony C. Fisher
Department of Agricultural and Resource Economics
207 Giannini Hall
University of California
Berkeley, CA 94720

ABSTRACT

In this paper we develop a model to simulate the impacts on the California Central Valley salmon fishery of changes in fresh water flows into and out of the San Francisco Bay Delta. The model also describes interactions among these water flow controls, hatchery operations, and harvest regulation. Traditionally, management of California's fresh water resources and anadromous fisheries have been undertaken separately, in the literature and in practice. We demonstrate the potential gains from a coordinated management approach.

INTEGRATING FISHERY AND WATER RESOURCE MANAGEMENT: A BIOLOGICAL MODEL OF A CALIFORNIA SALMON FISHERY[1]

1. INTRODUCTION

The San Francisco Bay/Delta ecosystem has become in recent years the object of intensive studies by state and federal agencies concerned with the allocation of water resources—water flows into and out of the Delta—and the management of commercial and sport fisheries. A major issue that stands out from this regulatory agenda is how to integrate the two kinds of regulation. Currently, these are addressed by separate agencies. The purpose of this paper—and of the larger project of which it is a part—is to explore the potential gains from joint, or cooperative, management. Specific objectives were (1) to determine the status of the existing fisheries, (2) to develop methods for measuring the economic value associated with preservation or enhancement of those fisheries, (3) to develop models of the relationships between water flow (and related quality) changes and the status of fisheries, and (4) to combine the economic methods with the fisheries models to determine the impacts on the value of fisheries of selected regulations.

Accordingly, we have completed an extensive review of the existing data on the status of Bay/Delta fisheries, with special emphasis on striped bass and salmon, including the abundant materials that were presented at the State Water Resources Control Board's (SWRCB) Hearings on Water Diversions from the San Francisco Bay/Delta over the period July-December, 1987. The review has enabled us to identify what is known about the fisheries, what are the main areas of dispute, and what are the competing hypotheses.[2] The present paper describes a simple model of the behavior of the California salmon fishery in relation to changes in key control variables identified in our review: water flows into and out of the Delta, hatchery operations, and fishing regulations. We note that the review has led to a shift away from an earlier focus on pollution discharges and toward fresh water flows. Since a major impact of changes in flows is on temperature and salinity and since temperature and salinity are significant elements of water quality, we remain interested in the links between water quality and fisheries. But we are approaching these through impacts of flows on quality, rather than impacts of discharges on quality. Another departure from our original intentions is an emphasis on the role of hatcheries. As we shall indicate later on, one hypothesis is that an observed decline in the population of natural or nonhatchery salmon is due primarily to the existence of the hatcheries, and the interaction between their operation and harvest regulations. This "mixed-stock hypothesis" is one focus of our modeling efforts.

The plan of the paper is as follows. Section 2 summarizes the background to the policy issues involved. In section 3 we briefly review population trends in the chinook salmon fishery. A feature of the presentation here is the construction of tables on both abundance and escapement, broken down by hatchery and nonhatchery fish, on an annual basis since 1953. Section 4 examines the causes of the trends. The emphasis is on environmental conditions (with an emphasis, in turn, on water flows), but we also look at hatchery operations and harvest regulation. Sections 3 and 4 are essentially a review of the literature, geared toward developing a framework and hypotheses for modeling. Sections 5 and 6 are the heart of the paper, a discussion of our modeling approach, with some preliminary simulations of impacts on the fishery of changes in the key control variables. A concluding section briefly summarizes major findings and indicates how they will be integrated with subsequent work on the cost of controls and the value of changes in commercial and sport harvests.

2. POLICY BACKGROUND

The San Francisco Bay/Delta consists of the San Francisco Bay, with about 300,000 acres of water surface area, and the Sacramento-San Joaquin Delta Estuary, with about 48,000 acres of water surface area and 690,000 acres of reclaimed farmland on islands protected by over 1,200 miles of levees. The delta is located where California's two major river systems, the Sacramento and San Joaquin rivers, converge to flow westward into the saltwater of San Francisco Bay. The watershed of the Bay/Delta covers about 40 percent of California's surface area, and it provides about two-thirds of all the water used in the state. In 1850, at the beginning of California's population boom, the freshwater inflow into San Francisco amounted to about 27.5 million acre-feet (MAF) per year; by 1980, this had been reduced by diversions for agricultural and urban uses inside and outside the basin to about 10.3 MAF per year. Similarly, in 1850 the Bay/Delta contained about 2.3 million acres of freshwater marsh and another 1.3 million acres of saltwater marsh; because of reclamation to create farmland in the delta and urban land and evaporation ponds for salt production in the bay, only about 207,000 acres of undiked marsh remain today.

In addition to freshwater diversions and land reclamation, the Bay/Delta ecosystem has been altered in several other ways since the time of the Gold Rush. Between 1853 and 1884, hydraulic miners in the Sierra Nevada excavated annually tens of millions of cubic meters of rock and earth which silted waterways and salmon spawning streams throughout the basin and permanently altered the bottom topography of San Francisco Bay. At the same time, many exotic species of plants and animals were being introduced into the ecosystem by newly arriving settlers, vessels visiting ports in the bay, and commercial interests. Many of the introduced species successfully established themselves, including nearly all of the common macroinvertebrates found today on the inner shallows of the bay and the striped bass, imported from the East Coast. Immediately after the Gold Rush, commercial fisheries were established for the species abundant in the estuary, including chinook salmon, sturgeon, sardines, flatfish, Dungeness crab, and shrimp. By 1900, catches in most of these fisheries were in decline, due to a combination of overfishing, elimination of essential habitat, and changes in water quality. Gradually, these commercial fisheries have been closed in order to protect the stocks for sport fishing. Today, commercial fishing in the estuary is limited to herring and anchovies; chinook salmon are fished commercially in the ocean.

Lastly, discharges from urban and agricultural activities in the Bay/Delta and upstream have affected water quality ever since the Gold Rush. Surface and subsurface return flows from irrigation both in the Delta and upstream in the Sacramento and San Joaquin Valleys have altered the composition of river water. In the 1940s the use of fertilizers, soil amendments, herbicides, and pesticides became widespread in these farming areas. In the 1950s and 1960s, water exports from the Delta led to increased irrigation of saline and mineralized soils on the west side of the San Joaquin Valley; agricultural return flows, containing salts leached from the soil, now make up more than 20 percent of the total San Joaquin River flow. As for urban wastes, point sources presently discharging into the bay include more than 30 municipal and 40 industrial waste treatment facilities and about 100 smaller industrial dischargers, in addition to urban runoff from non-point sources surrounding the bay and spills of oil and other hazardous materials from ship traffic. In 1978, the discharge from these point sources was estimated to amount to nearly 4 percent of the freshwater inflow into the bay; this ratio is expected to double by the year 2000, as waste discharges grow and freshwater inflows decline.

In short, according to a recent study by Nichols *et al.* [13], with respect to the diversity of change, San Francisco Bay is today considered the major estuary in the United States most modified by human activity.[3]

Some, but not all, of these modifications will continue to occur. Hydraulic mining has long ceased. Land reclamation and the filling of the bay are now tightly controlled by the Bay Conservation and Development Commission. The introduction of exotic species undoubtedly continues, albeit at a much slower pace. Commercial fishing is closely regulated by the California Department of Fish and Game (DFG) and the Pacific Fisheries Management Council (PFMC). The two remaining engines of change, and sources of concern, are waste discharges and reductions in freshwater inflow.

Both of these fall within the purview of the SWRCB and two of its daughter agencies, the Central Valley and San Francisco Bay Regional Water Quality Boards (RWQBs). The SWRCB has jurisdiction over both water quality and water rights in California. It shares the former—but not the latter—with nine Regional Water Quality Boards. With regard to water quality, these agencies together function as the state's equivalent of the EPA. Regional water quality plans are developed by the RWQBs with the approval of the SWRCB; since the federal Clean Water Act is involved, they also require the approval of the EPA. With regard to water use, the SWRCB administers the state's system of water rights and, under the Water Code, it has broad, but vague, powers to intervene and prevent the wasteful or unreasonable use of water within the state.

Acting in both its water quality and water rights capacities, the SWRCB initiated Hearings on Water Diversions from the San Francisco Bay/Delta in July, 1987. In them, the Board was revisiting two previous water rights decisions, decision D1485 issued in 1978 and decision D1379 issued in 1971. Both decisions concerned the water rights permits of the two projects, the federal Central Valley Project (CVP) and the State Water Project (SWP), that export water from the Bay/Delta to the San Joaquin Valley and Southern California. The CVP was originally authorized by Congress in 1937 and began operation in 1951; it exports about 3.2 MAF of water from the Delta, mainly to agricultural users in the San Joaquin Valley. The SWP was authorized in 1960 and began operation in the late 1960s; it exports about 2.4 MAF to agricultural users in the San Joaquin Valley and urban users in Southern California. In D1379 and D1485, the SWRCB had imposed restrictions on the water rights of the two projects requiring them to meet certain water quality standards in the Bay/Delta—primarily salinity standards to protect both fish and wildlife in the estuary, and municipal, industrial, and agricultural users in the Delta. The standards would be implemented by requiring the CVP and SWP to leave additional amounts of fresh water in the Delta at times of low flows.

In response to D1379, the federal government filed a lawsuit challenging the Board's authority to regulate the operation of a federal water project but that authority was upheld by the courts. In response to D1485, lawsuits were filed both by export interests claiming that they were too stringent and by environmental interests claiming that they were too lenient. The environmentalists won: In October, 1986, the Third District Court of Appeals ruled that in developing D1485 the Board had failed to strive for adequate protection of beneficial uses within the estuary (the Racanelli Decision). The Court found that the Board had an obligation to consider the actions of <u>all diverters</u> and their impacts on water quality, not just the CVP and SWP; the Board should be prepared to take enforcement action against all users throughout the watershed, upstream as well as downstream. In water quality planning, the Board should take a global perspective; it had a duty to make a policy judgment requiring a balancing of the competing public interests in the water—the needs for instream purposes and the needs of agricultural, industrial, domestic, and other users. It should aim for the highest reasonable water quality, considering all demands being made on the water and the values involved—beneficial and detrimental, economic and social, tangible and intangible. It was with this mandate that the Board organized hearings in 1987 covering instream uses for fish and wildlife in the Bay/Delta, and agricultural and urban uses, recreation and hydropower generation within the estuary, upstream, and in the export areas.

3. POPULATION TRENDS IN THE CENTRAL VALLEY SALMON FISHERY

Before 1952, no statistics were kept of salmon population size. Examination of CV salmon runs using the river gill-net catch as an indicator of population showed significant fluctuations throughout the 1864-1958 period (Skinner [21]). This was based on the total weight of gill-net catches, which was then used to estimate the number of fish caught. Peak catches occurred at 8- to 30-year intervals and tended to be followed by poor catches midway between the peaks. After 1915, the gill-net catch exhibited a lower trend, which Skinner attributes to large increases in the ocean troll fleet as well as environmental changes connected with water development projects (Dettman, Kelley, and Mitchell [4]). Researchers who have examined data on the CV commercial river catches from 1864 to 1957 have concluded that the chinook salmon population fell to low levels in the 1930s (presumably due to overfishing) and then recovered in the 1940s. Gill-net fishing was outlawed in 1957.

Following Dettman and Kelley [3], we have constructed an abundance measure for adult salmon for the years 1953-1986 as the sum of ocean catch and adult escapement (the term *escapement* refers to those salmon which have successfully returned to the CV river/delta system to spawn; both escapement and catch are estimated based on retrievals of coded, wire-tagged fish, in river system and ocean, respectively). The ocean catch estimate is based on catches reported to the PFMC by commercial and sport boats on the West Coast. The catch is then apportioned between the Sacramento and San Joaquin Rivers and other spawning sites on the basis of the location of reported catches and assumptions about how the various populations disperse in the ocean. Estimates of annual abundance are presented in

Table I. Total numbers of natural and hatchery salmon remained fairly steady at around 650,000 fish per year, with substantial year-to-year variation, until the most recent decade when the average has fallen to a bit under 600,000. Note, however, the sharp decline over this recent period in the natural population, nearly offset by a corresponding increase in the hatchery population. A map of major streams and hatcheries is shown in Fig. 1.

The data on annual escapement are shown in Table II for the fall run of the Sacramento River system which accounts for some 70 percent to 90 percent of the total. Like abundance, escapement has been more or less stable, at around 200,000 per year, with significant year-to-year fluctuation. The data for hatcheries are the estimates of hatchery-produced fish successfully returning to spawn; only a small fraction of these fish are used by the hatcheries to produce a new generation. The others spawn in the wild and enter the "natural" population which is therefore increasingly composed of fish with some hatchery ancestry. Moreover, note that hatchery production has recently increased both in absolute numbers and as a proportion of total escapement.

The composition of the CV salmon run has changed during this period. The main stem Sacramento River runs have decreased since the 1940s, but the Feather and American River runs have both increased. Both of the latter rivers have compensated for loss of habitat due to dam construction with the construction of major hatcheries; the Sacramento River runs are more dependent on natural reproduction. There are four distinct runs in the CV system, distinguished by the timing of the upstream migration of the adult salmon. Research and discussion on the effects of environmental changes in the Delta on the salmon population have focused almost exclusively on the fall run. The fall run is by far the most important, and it comprises the entire surviving San Joaquin run. The late fall, winter, and spring runs are only in the Sacramento River and have represented between 30 percent (1969) and 6 percent (1979) of total

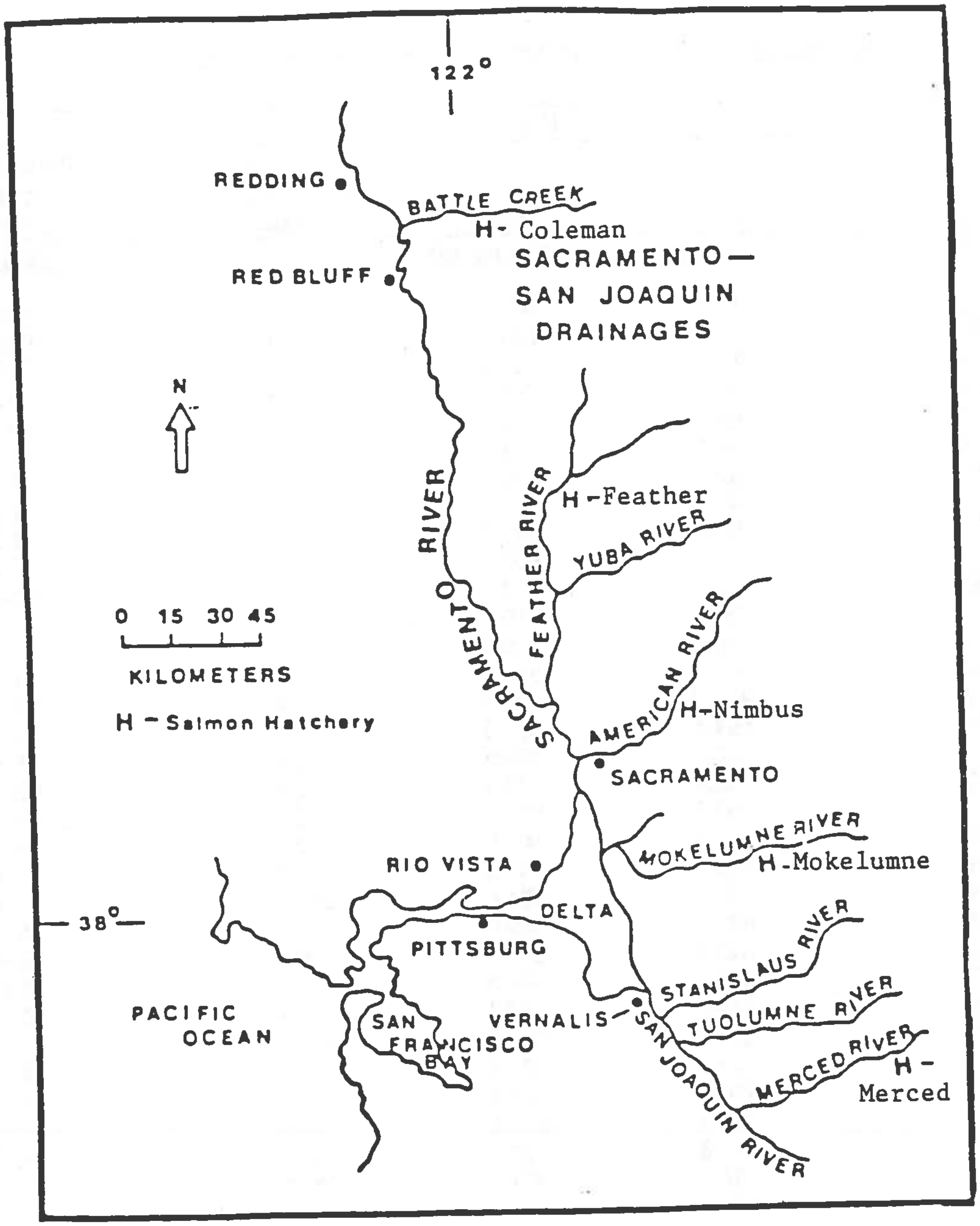

Fig. 1. Major chinook salmon spawning streams and hatcheries (H) in the Sacramento-San Joaquin River Drainages of California.

Source: U. S. Fish and Wildlife Service [25].

TABLE I

Estimated Abundance of Adult Central Valley Salmon by Year

	Population			
Year	Total	Natural[a]	Nimbus and Feather hatcheries	Natural as percentage of total
	thousands			percent
1953	983.5	983.5	0.0	100.00
1954	1,053.2	1,053.2	0.0	100.00
1955	927.0	927.0	0.0	100.00
1956	763.2	763.2	0.0	100.00
1957	396.7	396.6	0.1	99.97
1958	563.0	561.3	1.7	99.70
1959	868.1	865.7	2.4	99.72
1960	848.0	845.6	2.4	99.72
1961	741.9	729.6	12.3	98.34
1962	621.4	603.5	17.9	97.12
1963	758.3	734.5	23.8	96.86
1964	781.3	759.5	21.8	97.21
1965	666.3	646.8	19.5	97.07
1966	524.7	516.1	8.6	98.36
1967	431.9	420.5	11.4	97.36
1968	694.5	672.3	22.2	96.80
1969	917.7	888.5	29.2	96.82
1970	720.4	675.1	45.3	93.71
1971	667.9	624.1	43.8	93.44
1972	662.9	600.9	62.0	90.65
1973	992.4	757.3	235.1	76.31
1974	702.5	484.6	217.9	68.98
1975	642.6	489.0	153.6	76.10
1976	642.7	536.5	106.2	83.48
1977	687.2	548.6	248.6	79.83
1978	587.8	268.4	319.4	45.66
1979	693.9	379.4	314.5	54.68
1980	621.4	371.9	249.5	59.85
1981	760.0	385.3	374.7	50.70
1982	947.2	658.6	288.6	69.53
1983	511.8	304.1	207.7	59.42
1984	534.7	371.1	163.6	69.40
1985	b			
1986				
Average				
Total	716.1	619.4	96.7	86.50
1953-1967	728.6	720.4	8.1	98.88
1968-1977	733.1	627.7	105.4	85.62
1978-on	665.3	391.3	274.0	58.81

[a] Natural refers to salmon not from the Nimbus and Feather hatcheries and therefore includes other hatcheries for which specific data are not available.

[b] Blanks indicate no data available.

Source: David H. Dettman and Don W. Kelley [3] (Tables II-4 and III-5, based on ocean retrieval of coded wire-tagged salmon in commercial and sport fisheries).

TABLE II

Estimated Salmon Escapement for Sacramento River Fall Run by Year

	Escapement			
Year	Natural[a]	Nimbus and Feather hatcheries	Total	Natural as percentage of total
	thousands			percent
1953	500.0	0.0	500.0	100.00
1954	400.0	0.0	400.0	100.00
1955	365.0	0.0	365.0	100.00
1956	145.0	0.0	145.0	100.00
1957	101.0	0.0	101.0	100.00
1958	234.3	0.7	235.0	99.70
1959	418.0	1.0	419.0	99.76
1960	414.0	1.0	415.0	99.76
1961	243.2	4.8	248.0	98.06
1962	243.6	7.4	251.0	97.05
1963	282.5	9.5	292.0	96.75
1964	294.4	8.6	303.0	97.16
1965	181.2	7.8	189.0	95.87
1966	183.4	3.6	187.0	98.07
1967	151.9	6.1	158.0	96.14
1968	180.3	9.7	190.0	94.89
1969	253.5	14.1	267.6	94.73
1970	181.5	19.9	201.4	90.12
1971	172.5	20.8	193.3	89.24
1972	117.5	20.0	137.5	85.45
1973	190.2	72.6	262.8	72.37
1974	147.6	81.6	229.2	64.40
1975	131.0	56.1	187.1	70.02
1976	147.4	41.2	188.6	78.15
1977	150.8	44.7	195.5	77.14
1978	53.8	100.1	153.9	34.96
1979	125.4	95.6	221.0	56.74
1980	94.0	81.9	175.9	53.44
1981	99.1	131.0	230.1	43.07
1982	129.2	76.8	206.0	62.72
1983	72.3	82.0	154.3	46.86
1984	125.0	79.0	204.0	61.27
Average				
Total	204.0	33.7	237.7	85.83
1953-1967	277.2	3.4	280.5	98.80
1968-1977	167.2	38.1	205.3	81.46
1978-on	99.8	92.3	192.2	51.95

[a] Natural refers to salmon not from the Nimbus and Feather hatcheries and therefore includes other hatcheries for which specific data are not available.

Source: David H. Dettman and Don W. Kelley [3] (Table III-5, based on ocean retrieval of coded wire-tagged salmon in commercial and sport fisheries).

escapement over the past two decades (U. S. Fish and Wildlife Service (USFWS) [25]). In addition, the age structure of the population appears to have changed. Early in the century, 4- and 5-year-old fish were common in both the ocean and spawning populations; in the past 10 years, the age composition of returns to hatcheries has been mainly 3-year-olds with a significant percentage of 2-year-olds (Dettman, Kelley, and Mitchell). Less is known about the age structure of the natural returns.

4. EXPLAINING THE TRENDS: SOME TENTATIVE HYPOTHESES

The object of this section is to review the evidence on how environmental conditions, hatchery operations, and harvest regulations have affected the fishery, in order to develop a framework for modeling. We also consider the mixed-stock hypothesis, described below.

Environmental Conditions

Destruction of Upstream Habitat

Salmon spawn in shallow gravel areas (redds) upstream of the Delta. In some cases, salmon have been denied access to redds because of dams; in others, the redds have been destroyed or polluted by land development or by industrial and agricultural development. Loss of redds breaks the life cycle at the point of reproduction. Adult spawners are unable to lay their eggs in a proper environment; hence, the next generation is either nonexistent or has drastically reduced survival rates. There is wide agreement that loss of spawning habitat has been an extremely important factor in the decline in the population of wild salmon.

Water Flows

Our review of the literature suggests that the volume of water flowing in the Sacramento and San Joaquin Rivers and through the Delta is currently the environmental condition of greatest significance to the salmon. It affects abundance through a number of different mechanisms and is strongly influenced by the regulatory actions of the SWRCB.

USFWS research has examined the relationship between spring flow volumes and survival of out-migrating smolts. April-June is the time period most crucial for out-migrating smolts in the fall run. For the 1979-1986 period, there was a correlation of 0.90 between April-June Sacramento River flow at Rio Vista in the Delta and smolt abundance as measured through a midwater trawl of unmarked smolts at Chipp's Island at the western edge of the Delta. This correlation is only for smolt abundance and does not directly measure mortality and survival. In an effort to shed light on the relationship between flow and *survival*, as opposed to *abundance*, a correlation analysis was also performed for the relationship between mean daily flow at Rio Vista during the time of migration and the survival rate for tagged smolts as measured through a midwater trawl at Chipp's Island. A correlation of 0.97 was found (USFWS). Perhaps more importantly, the difference in survival rates at different flows was significant in magnitude. At Rio Vista flows below 10,000 cubic feet per second, the survival rate was generally between 0 and 20 percent. At flows in the 10,000-15,000 cubic feet per second range, the survival rate was in the 40 percent to 50 percent range. At very high flows—above 25,000 cubic feet per second—the survival rate approached 100 percent.

To go beyond the simple correlation, i.e., to explain the relationship between flow and survival in a way that can be useful for policy analysis, we need to focus on the mechanisms by which the level and timing of CV river system flows influence salmon mortality. These include water temperature, predation, diversion and pumping, food availability, and water quality.

Water Temperature

High spring water temperatures can be lethal to fry. Even at sublethal temperatures, salmonids need significantly more food to survive than at lower temperatures. In the Sacramento River, spring water temperatures above 55°F. begin to trigger undesirable effects on chinook juveniles (USFWS; Dettman and Kelley; and State Water Contractors [22]). Although there is general agreement on the importance of temperature, one source argues that there is no evidence of a causal link between flow and temperature despite the strong correlation (State Water Contractors). Research conducted for the SWRCB hearings has carefully documented Sacramento River temperatures and finds that there has been a sustained upward shift since the 1976-77 drought (Reuter and Mitchell [18]). In the Sacramento area, in particular, these increased water temperatures are not explained by climatological factors and are negatively correlated with flows. This research concluded that the major mechanism for reducing June water temperatures would appear to be increased flow.

Predation

Increased predation of young salmon by squawfish and striped bass occurs because of clearer water and greater concentration of young during low flows (Stevens and Miller [24]). It appears that greater flows may increase survival for this reason although we have found no evidence on the magnitude of this effect.

Diversion and Pumping

The water stored behind the CVP and SWP dams in the Sacramento Valley is released into the natural channel of the Sacramento River and its tributaries (the Feather and American Rivers) and flows into the Delta from the north. Export water is diverted by pumps located near Tracy, which is by the San Joaquin River in the southern part of the Delta, for transmission to users in the San Joaquin Valley and southern California through the Delta-Mendota Canal and the California Aqueduct. To facilitate the flow of freshwater through the interior channels and south across the Delta (instead of west toward the Bay), the CVP constructed the Delta Cross Channel at Walnut Grove. However, when the pumps are exporting at a high rate, this can induce a reverse flow of freshwater—and sometimes saltwater—upstream on the San Joaquin River. These operations can affect the survival of salmon.

Salmon are diverted from the main stream of the Sacramento River through the Delta Cross Channel and the Georgiana Slough in proportion to the relative volume of flows of the Sacramento River and the diversions (USFWS). Survival of salmon diverted at Walnut Grove can be expected to be decreased by longer migration routes, higher water temperatures, increased predation, greater agricultural diversions, and a more complex channel configuration, making it difficult for smolts to find their way to sea. Further, once smolts successfully traverse the Delta and reach the lower San Joaquin River, they are likely to find reverse flows on the Mokelumne River and, as already mentioned, even the San Joaquin River itself due to the operation of the pumping plants. Salmon following these reverse flows may suffer increased mortality due to entrainment at the pumping plants and to even longer migration routes. USFWS tested this relationship by releasing hatchery smolts both above and below the diversion points and then tracking their survival. They found that when the diversion rate was high, survival of smolts released upstream was 50 percent lower than for those released downstream of the diversion point when the Delta cross channel gates were open.

Food Availability

There is reduced intraspecies competition for food at high flow levels because of greater dispersal (Stevens and Miller). Also, there is some evidence that the population of neomysis, a prime food source for juvenile salmon, is affected by water flow conditions in the Delta (Williams and Hollibaugh [26]; Knutson and Orsi [11]). A long-term decline in phytoplankton, the food source for neomysis, caused by flow changes is thought to be an important causal mechanism.

Water Quality

Toxicity and other manifestations of urban and agricultural discharges presumably have negative effects on the salmon population through direct mortality and through effects on organisms at lower trophic levels such as neomysis and phytoplankton. We have, however, found no direct evidence of the effects of water quality on the salmon population.

Hatchery Operations

In addition to environmental conditions in the Delta and upstream, the operation of hatcheries has been an extremely important determinant of the size and composition of the salmon population. As noted in Tables I and II, hatchery salmon have become more important over time in the fall run on the Sacramento, accounting in some years for over 50 percent of returning adult salmon. Hatcheries have a much higher success rate in the survival of salmon eggs to fry because of their control over the condition of spawning gravels, water temperature, food supply, and predation. In recent years, the Feather, Nimbus, and Mokelumne hatcheries have increasingly been trucking smolts to the lower Delta or Suisun Bay. This increases survival still further; the escapement rate for these hatcheries is between 2 and 10 times that of hatcheries which do not truck their fish (though it is not necessarily true that trucking is the sole reason for the difference). The main negative consequence of this practice is the increased probability of straying; fish which have been trucked are much more likely to fail to return to the hatchery (USFWS).

The chief risk to hatchery populations is disease, which can do tremendous damage to a year's population because of the close proximity in which the fish are kept. Disease can also be a problem because the genetic makeup of hatchery fish is more uniform than that of natural stocks, leaving less room for resistance.

Fishery Regulations

The third factor directly affecting the salmon population is the regulation of the fishing harvest. The PFMC is charged with regulating the catch of both commercial and sport fishing. The PFMC uses a wide range of regulatory instruments, including closures of fishing grounds, catch limits, and gear regulation. The council attempts to manage the commercial and sport catches to allow sufficient spawning stock for population maintenance. The target for CV chinook salmon escapement of approximately 180,000 has been met in nearly all years since 1953 (see Table II). Note that, if regulators take account of low populations caused by adverse environmental conditions and restrict the catch, this mitigates the effect of environmental conditions on adult escapement. Escapement may also be stabilized by liberal fishing rules under favorable environmental conditions.

The ocean catch of CV salmon has ranged between a minimum of 200,800 fish in 1967 and a maximum of 684,900 in 1982 and has averaged about 420,000 fish per year (Table III). Casual examination of the data indicates that catches have been low in years with low populations. It is not clear from examination of fishing season regulations to what extent this is a result of effective regulation and to what extent it is due to more difficult fishing in years with low populations. In addition to ocean catch, perhaps 35,000 adult salmon are landed each year by the inland sport fishery (USFWS). Because there is no record-keeping system of inland sport catch, this is only a very rough estimate.

The Mixed-Stock Hypothesis

The data presented above indicate that the CV system has produced fewer and fewer salmon outside the hatcheries over the past 30 years. One explanation,

TABLE III

Estimated Ocean Catch of Adult Central Valley Salmon

	Ocean catch			
Year	Total	Nimbus and Feather hatcheries	Natural[a]	Natural as percentage of total
	thousands			percent
1953	384.5	[b]	384.5	
1954	560.2		560.2	
1955	504.6		504.6	
1956	586.7		586.7	
1957	276.7	0.1	276.6	99.96
1958	274.5	1.0	273.5	99.64
1959	390.4	1.4	389.0	99.64
1960	363.6	1.4	362.2	99.61
1961	487.2	7.5	479.7	98.46
1962	364.4	10.5	353.9	97.12
1963	457.4	14.3	443.1	96.87
1964	460.0	13.2	446.8	97.13
1965	468.3	11.7	456.6	97.50
1966	327.9	5.0	322.9	98.48
1967	200.8	5.3	195.5	97.36
1968	400.7	12.5	388.2	96.88
1969	459.4	15.1	444.3	96.72
1970	390.8	25.4	365.4	93.50
1971	349.6	23.0	326.6	93.41
1972	434.3	42.0	392.3	90.33
1973	669.2	162.5	506.7	75.72
1974	438.5	136.3	302.2	68.92
1975	396.0	97.5	298.5	75.37
1976	374.7	65.0	309.7	82.66
1977	452.4	93.9	358.5	79.25
1978	387.4	219.3	168.1	43.39
1979	452.5	218.9	233.6	51.62
1980	419.0	167.6	251.4	60.01
1981	448.3	243.7	204.6	45.64
1982	684.9	211.8	473.1	69.08
1983	274.3	125.7	148.6	54.16
1984	258.8	84.6	174.2	67.31
1985	416.3			
1986	550.6			
Average	422.5	63.0	355.7	85.09
1953-1967	407.1	4.8	402.4	98.83
1968-1977	436.6	67.3	369.2	84.58
1978-on	432.5	181.7	236.2	57.99

[a] Natural refers to salmon not from the Nimbus and Feather hatcheries and therefore includes other hatcheries for which specific data are not available.

[b] Blanks indicate no data available.

Source: David H. Dettman and Don W. Kelley [3] (Table II-4, based on ocean retrieval of coded wire-tagged salmon in comercial and sport fisheries).

suggested above, is that adverse shifts in environmental conditions have prohibited salmon spawning in the wild from producing enough offspring to maintain the population. According to this explanation, without hatchery production (and the increased survival of that production due to release near San Francisco Bay), the salmon fishery would already have experienced a precipitous decline. An alternative explanation for the decreasing numbers of natural or nonhatchery salmon is the mixed-stock hypothesis: The combined effect of hatchery operation and regulation of the salmon fishery may be acting in such a way as to steadily decrease both the proportion and the absolute numbers of nonhatchery fish (Hilborn [8]). If a greater percentage of hatchery eggs survive each year than nonhatchery eggs, the overall proportion of hatchery fish in the ocean population will rise. This is a reasonable explanation because controlled temperature conditions, food supplies, and lack of predators in the hatcheries give these eggs a higher chance of survival, and the practice of trucking smolts to the Delta increases the odds even more. If regulators base the allowable ocean catch on the goal of maintaining a reasonably steady spawning population, then increases in population due to greater survival of hatchery fish will result in larger ocean catches. The same number of spawners will return to the Central Valley, but fewer will be wild. This process will continue with the result that the total population remains more or less constant but the population of nonhatchery fish declines. Of course, it is quite possible that both shifts in environmental conditions and increased hatchery production are responsible for the observed decline in nonhatchery fish.

5. A DYNAMIC MODEL OF THE FISHERY

In this section we develop what we believe is the simplest possible model of the interactions among harvest, hatchery, and water flow controls in an age-structured salmon population. The purpose is to show how changes in one or more of the controls affect the fish population, or a relevant part of the population, or the harvest in a given year. For example, for a given target escapement and hatchery capacity, how would a decrease in water exports from the Delta affect the harvest in the year of the decrease and for (say) the next 10 years? How would these results be affected by a change in hatchery capacity, target escapement, or in precipitation over one or more years in the period? With the aid of the model, we can answer these and many other questions presumably of interest to decisionmakers in the fishery and water resource management agencies.

An advantage of the model, which we shall demonstrate as we proceed, is that it is transparent in the sense that impacts of changes in any of the controls are readily traced. Further, the model is easy and inexpensive to run, allowing the user to explore a wide variety of regulatory or policy scenarios. A corresponding disadvantage is that the model does not realistically reproduce the behavior of the fishery in the kind of detail that might be desired for some purposes. For example, it cannot show the effect on smolt survival in the Delta of additional releases of fresh water from a particular upstream dam site at a particular time of year. Similarly, it does not distinguish among the several different hatchery sites, specifying only an aggregate hatchery capacity. Thus, the model is not appropriate for studying the impacts of changes at the "micro" level. But for a quick view of interactions among key "macro" controls and population variables (the purpose for which it was designed), we feel it can be useful. We should note also that the key macro relationships are based on solid micro functions. The number of smolts reaching the Bay in a given year, for example, is a function of target escapement, hatchery intake, and fresh water flows into and out of the Delta—in reality and in our model. In the model, the aggregate functional relationships are estimated from "observations," or runs, of a very detailed micro model of the fishery as we shall explain below.

We turn now to the model. We first display the basic structure and then present and discuss the results of illustrative policy simulations. It is convenient to distinguish two sets of model equations. The first describes the relationships among natural system parameters, policy variables, and elements of the salmon population (including the harvest) in a given year. The next provides the transition from one year, or salmon age class, to the next.

The ocean population of natural (nonhatchery) salmon eligible to be caught is given by

$$\text{nat pop} = \%\ \text{nat esc}_2 \cdot \text{nat pop}_2 + \text{nat pop}_3 + \text{nat pop}_4, \qquad (1a)$$

where "nat" stands for natural; the subscripts 2, 3, and 4 are the salmon age classes; and % nat esc_2 is the exogenously given percentage of natural two-year-olds that escapes to spawn in the absence of fishing. We assume that only two-year-olds mature enough to escape are large enough to be legally retained by the ocean fishery: This is the first term on the right-hand side of equation (1a). The ocean population of hatchery salmon is similarly

$$\text{hat pop} = \%\ \text{hat esc}_2 \cdot \text{hat pop}_2 + \text{hat pop}_3 + \text{hat pop}_4, \qquad (1b)$$

where the "hat" stands for hatchery. The initial age distribution is exogenous, needed to start the model. In the absence of disturbances, it converges to an equilibrium. If the initial distribution is chosen to reflect historical averages, the convergence is very quick.

Total escapement in the absence of fishing, or potential escapement, is the sum of potential escapement of natural and hatchery fish;

$$\text{pot esc} = \text{pot nat esc} + \text{pot hat esc}$$

$$\equiv \sum_{i=2}^{4} \%\,\text{nat esc}_i \cdot \text{nat pop}_i + \sum_{i=2}^{4} \%\,\text{hat esc}_i \cdot \text{hat pop}_i . \qquad (2)$$

Thus far, we have been describing the population. Now we introduce a policy variable: target escapement (targ esc). This is the number of fish the regulatory authority wishes to allow to escape to replenish the fishery. From target escapement, the harvest is determined according to

$$\text{harv} = \text{catch factor}(\text{nat pop} + \text{hat pop}), \qquad (3)$$

where the catch factor is

$$1 - \frac{\text{t arg esc}}{\text{pot esc}} .$$

Actual escapement, with fishing, is then given for naturally reproducing fish by

$$\text{nat esc} = (1 - \text{catch factor}) \cdot \text{pot nat esc} \qquad (4a)$$

and, for hatchery fish, by

$$\text{hat esc} = (1 - \text{catch factor}) \cdot \text{pot hat esc}. \qquad (4b)$$

Since commercial fishermen have no way of distinguishing between natural and hatchery-produced fish, we assume that the same catch factor applies to both.

From fall escapement, outmigrating nonhatchery smolts in the spring and summer of the following year are determined in the model according to a pair of equations which relate smolts, as the dependent variable, to hatchery intake, water flow variables, and escapement. The observations on which the regression estimates are based are not raw data, but rather data generated from repeated runs of a highly disaggregated simulation of the fall run (Hagar, Kimmerer, and Garcia [5]; Kimmerer, Hagar, Garcia, and Williams [9]). Two equations are, in fact, estimated in this fashion—one for the number of spawning fish and one for the number of smolts reaching the Bay as a function of the number of spawners. Each equation is separately estimated for each of three precipitation year types: critical, above-normal, and wet. The California Department of Water Resources also distinguishes dry and below normal years, but data limitations have thus far prevented us from estimating spawners and smolts for these year types. In our judgment, the three year types we have are sufficient to permit useful inferences about the interaction of water flows and the fishery, especially as we are able to include a critically dry year.

The equation for spawners is, in general functional notation,

$$\text{spawners} = f(\text{targ esc}) - \text{surplus hatchery intake}, \qquad (5)$$

where surplus intake is defined as the excess of intake over a baseline level. In this formulation a positive (negative) excess intake reduces (increases) the number of naturally spawning fish.

The equation for smolts reaching the Bay is

$$\text{nat smolts} = g(\text{spawners, inflow, exports}). \qquad (6)$$

The specific functional forms and estimated coefficients are given in an Appendix. Here, we note only that the specification allows for density—dependent mortality. That is, as the number of escaping fish increases, the number of spawners increases more and more slowly. A similar sort of "diminishing returns" sets in in the relationship between spawners and smolts.

The inflow variable is based on flows (as represented in Hagar, Kimmerer, and Garcia) at three key locations: (1) above the Red Bluff Diversion Dam on the main stem Sacramento, (2) above the Thermalite Dam on the Feather River, and (3) on the American River near the Nimbus hatchery. We model flows, relative to a baseline, at all three locations in the aggregate for the April 1 to May 15 period—the most critical for outmigrating smolts. Thus, the flow variable is actual flow in cubic feet per second minus baseline flow, which varies with year type.

The exports variable represents the length of time that the Delta cross-channel gates are closed. We use dummy variables "0," "1," "2," and "3" to denote, respectively, closure for some time less than a month (depending on upstream flows), April 1 to May 1, March 15 to May 15, and March 1 to June 1.

Equation (6) describes smolts reaching the Bay. The USFWS estimates that 80 percent of these fish, in turn, reach the ocean, so the ocean population of nonhatchery salmon under two years old is given by

$$\text{nat pop}_1 = \text{nat smolts} \cdot 0.8. \tag{7a}$$

Determination of hatchery production is somewhat simpler as little is left to chance—or nature. The hatcheries function like factories: They take in 16,660 adults and produce 12,250,000 juveniles, of which the great majority are trucked to the Bay and released. These numbers are based on historical averages for the three large hatcheries operated by the state: the Nimbus, Feather, and Mokelumne hatcheries.[4] Input and output levels can be changed to simulate changes in hatchery policy. There is some evidence that hatchery smolts released in the Bay have lower survival rates to the ocean than the 80 percent used for nonhatchery fish due, perhaps, to the sudden change in temperature they experience on release. The ocean population of hatchery salmon under two years olds is then given by

$$\text{hat pop}_1 = \text{hat smolts} \cdot 0.8 \cdot \theta, \quad 0 \le \theta \le 1 \tag{7b}$$

where θ is a parameter reflecting the poorer survival prospects of trucked hatchery fish. In the absence of reliable information to the contrary, we can simply set $\theta = 1$.

We are now ready to follow an age class of salmon, natural and hatchery, from one year to the next. The transition from one- to two-year-olds is straightforward. We assume, following Hagar, Kimmerer, and Garcia, that 7.74 percent of the smolts that reach the ocean (nat pop_1 and hat pop_1 in equations 7a and 7b) survive the approximately 15 months until age two:

$$\text{nat pop}_2 = \text{nat pop}_1 \cdot .0774 \tag{8a}$$

and

$$\text{hat pop}_2 = \text{hat pop}_1 \cdot .0774. \tag{8b}$$

Recall that these immature fish cannot be harvested and do not spawn.

Survival from age two to age three is more complicated, since fishing activity and escapement come into the picture. Survival depends on three factors: (1) natural mortality, (2) escapement and fishing mortality, and (3) shaker mortality (shakers are undersize two-year-olds caught and released). With respect to (1), we follow Hagar, Kimmerer, and Garcia and assume a monthly mortality of 5 percent. Combined escapement and fishing mortality of two-year-olds is given by % nat $\text{esc}_2 \cdot$ nat pop_2, as explained following equation (1a). Shaker mortality is estimated by the PFMC as 28 for every 100 "legal" fish taken by the commercial fishery and 7 for every 100 taken by the sport fishery, with a weighted average of 24.5 (the weights based on commercial and sport catches). An expression for the surviving ocean population of three-year-olds is then given by

$$\text{nat pop}_3 = (.95)^{12} \cdot (\text{nat pop}_2 - \%\ \text{nat esc}_2 \cdot \text{nat pop}_2 - \text{harv} \cdot 0.245) \tag{9a}$$

and similarly for hatchery fish by

$$\text{hat pop}_3 = (.95)^{12}\ (\text{hat pop}_2 - \%\ \text{hat esc}_2 \cdot \text{hat pop}_2 - \text{harv} \cdot 0.245). \qquad (9b)$$

Finally, survival from age three to age four depends on natural mortality, escapement, and the harvest. Natural mortality is, again, 5 percent of the population each month. Escapement of three-year-olds is potential escapement (% nat esc$_3$ · nat pop$_3$) multiplied by the common population ratio of target to potential escapement (targ esc/pot esc) as in equation (4a). The harvest is the population of three-year-olds multiplied by the catch factor as in equation (3). An expression for the population of four-year-olds is then

$$\text{nat pop}_4 = (.95)^{12} \cdot \Big(\text{nat pop}_3 - \frac{\text{t arg esc}}{\text{pot esc}} \cdot \%\ \text{nat esc}_3 \cdot \text{nat pop}_3 - \text{nat pop}_3 \cdot \text{catch factor}\Big) \qquad (10a)$$

and, for hatchery fish,

$$\text{hat pop}_4 = (.95)^{12} \cdot \Big(\text{hat pop}_3 - \frac{\text{t arg esc}}{\text{pot esc}} \cdot \%\ \text{hat esc}_3 \cdot \text{hat pop}_3 - \text{hat pop}_3 \cdot \text{catch factor}\Big). \qquad (10b)$$

The model is now complete. With populations of natural and hatchery salmon in each age class, as given by equations (8a), (8b), (9a), (9b), (10a), and (10b), we can return to equations (1a)-(7b) and determine a new set of population, harvest, escapement, and smolt survival figures. To illustrate how the system works and how it can be used to shed light on the impacts of coordinated regulatory decisions, we present and discuss in the next section the results of several simulations.

Before proceeding with the simulations, we discuss the relationship of this model to others in the fisheries literature. The traditional approach to modeling the dynamics of a fish population was developed by Ricker [9], Shaefer [20], and Beverton and Holt [1]. In their model, the transition from one generation to the next is described by a relationship between spawning and recruitment, either exponential (Ricker) or quadratic (Shaefer; Beverton and Holt). Later work modified the traditional approach to consider multiple stocks in the same fishery with varying reproductive rates but continued to rely on the concept of an unfished equilibrium (Paulik, Hourston, and Larkin [17]). Hilborn [7] noted that salmon populations are almost never in equilibrium. As the relative sizes of the different stocks comprising the fishery change year to year, the optimal harvest rate also changes. He used stochastic dynamic programming to determine optimal harvest rules for each year as a function of stock sizes which, in turn, were stochastic outcomes. We too model a disequilibrium situation; the difference is that we explicitly represent the factors which cause the fishery to remain in disequilibrium. Our model is built around the variability in harvests, hatchery operations, and hydrological conditions caused by both natural processes and human decisions. By explicitly representing the several steps involved in the process of getting from spawning to recruitment of mature fish, we are able to more realistically introduce the decision variables. For example, increasing inflow and decreasing exports produce a dramatic effect on contemporaneous smolt survival, followed a couple of years later by an increase in the harvest of mature fish.

Another important difference is the ability of our model to treat hatchery operations differently than the naturally spawning population. As noted above, the Ricker approach depends on the concept of an unfished equilibrium—the number of salmon in the ecosystem in the absence of human intervention. Because hatchery output is to some degree independent of the carrying capacity of the ecosystem and is quite responsive to management decisions independent of any "unfished equilibrium," the usefulness of the Ricker approach to model the Central Valley chinook population is limited.

6. QUANTITATIVE ANALYSIS: THE IMPACT ON THE FISHERY OF SELECTED AND COORDINATED REGULATORY DECISIONS

A baseline simulation of the system is presented in Table IV. By baseline, we mean that hatchery intake and release are set at the levels noted in the preceding section, target escapement is similarly at an historical average (in round numbers) of 200,000 fish, and water inflow and export are set to reflect "normal" operations of the upstream dams and Delta pumping stations for a given year type. The sequence of year types for the 10-year simulation is arbitrary but exhibits two consecutive critically dry years fairly early in the sequence to reflect recent California experience. Not surprisingly, the major impact of the dry years is on natural smolts reaching the Bay, followed two years later by a steep decline in the harvest and the number and proportion of natural salmon escaping to spawn. Thus, smolt survival falls from nearly 12 million to under 4 million, the harvest from nearly 500,000 to under 250,000, and the proportion of escaping salmon not produced in hatcheries from 50 percent to 25 percent. Recovery of the system appears to be relatively rapid—by the second year following the impact in each case.

The next simulation looks at the effect of selectively increasing inflows and decreasing exports in just the dry years, all other controls remaining the same. Specifically, we increase aggregate inflows by 3,000 cubic feet per second for the April 1 to May 15 period (equivalent to about 268,000 acre-feet) and close the Delta Cross-Channel gates from March 1 to June 1. As shown in Table V, the impact on population and harvest is dramatic. Smolt survival falls only to a little over 9 million, harvest to a little under 400,000, and nonhatchery escapement to 40 percent of the total. Intermediate levels of increased inflows and decreased exports in just the dry years lead in other simulations to intermediate impacts on population and harvest, perhaps not surprisingly.

These simulations illustrate the impact of flow controls dependent on the nature of the precipitation year. Another simulation illustrates the impact of what we call "uncoordinated," i.e., not flow-dependent, controls. In this case we specify the increased inflows and decreased exports in all years, not just the dry ones. As shown in Table VI, results are very similar to those in the "coordinated" case. Providing more fresh water to the fishery in above-normal and wet years adds only a very little to smolt survival in those years and to later harvests. This is an important finding, because more fresh water for the fishery means less available to optimize dam operations upstream of the Delta and less available for export to agricultural and urban users south of the Delta.

As a final illustration of the uses of the model, we show how it can be used to simulate the workings of the mixed-stock hypothesis. Recall that this hypothesis states that, with expansion of hatcheries combined with the maintenance of a steady spawning population, a declining proportion of nonhatchery fish in the population will result. Table VII shows what happens when hatchery intake is expanded by 6,000 spawning fish, from 16,660 to 22,660, and the release of smolts to the Bay is increased by 6 million, to just over 18 million. (These increases are arbitrary, but the relationship between them is reasonable; there is evidence that a given increase in intake could produce a proportionally larger increase in smolts.) In the simulation, target escapement is kept at the baseline level of 200,000, and water flow controls are also unchanged. The harvest is substantially increased, from an average of 428,000 in the baseline case to 554,000, but the proportion of nonhatchery fish in the escaping population is down, from 43 percent to 35 percent—exactly as predicted by the mixed-stock hypothesis. We cannot conclude that a process like this is responsible for the

TABLE IV

Baseline Simulation

YEAR	LESS-THAN-2YR-OLD NATURAL	LESS-THAN-2YR-OLD HATCH	2 YR OLD NATURAL	2 YR OLD HATCH	3 YR OLD NATURAL	3 YR OLD HATCH	4 YR OLD NATURAL	4 YR OLD HATCH
1	9800000	9800000	758520	758520	304725	304725	38596	38596
2	9555862	9800000	758520	758520	302990	302990	38372	38372
3	9555862	9800000	739624	758520	303475	303475	38305	38305
4	3154308	9800000	739624	758520	294523	303707	38493	38493
5	3154308	9800000	244143	758520	295486	304669	37618	38791
6	5790666	9800000	244143	758520	63253	313240	42029	43335
7	9555862	9800000	448198	758520	87151	337138	11250	55713
8	9555862	9800000	739624	758520	180690	331507	14557	56313
9	9555862	9800000	739624	758520	306550	315734	25332	46476
10	5790666	9800000	739624	758520	293536	302720	38742	39903

YEAR	TOTAL POOL POP NATURAL	TOTAL POOL POP HATCHERY	POTENTIAL ESCAPEMENT NO FISHING	TARGET ESCAPEMENT	CATCH FACTOR	HARVEST	NATURAL ESCAPEMENT	HATCHERY ESCAPEMENT
1	419173	419173	490089	200000	0.59	496226	100000	100000
2	417214	417214	488155	200000	0.59	492558	100000	100000
3	415743	417632	486546	200000	0.59	490807	99612	100388
4	406979	418052	483185	200000	0.59	483534	98794	101206
5	357518	419312	433884	200000	0.54	418748	86967	113033
6	129697	432428	346985	200000	0.42	238119	53923	146077
7	143220	468702	369472	200000	0.46	280681	50570	149430
8	269209	463672	440198	200000	0.55	399903	75402	124598
9	405844	438062	488316	200000	0.59	498267	94477	105523
10	406241	418475	483998	200000	0.59	483923	98557	101443

AVERAGE HARVEST==> 428277

TABLE IV continued

			ENVIRONMENTAL VARIATION AND CONTROLS					
YEAR	HATCHERY INTAKE	ESCAPEMENT-% NATURAL	FLOW STATUS	X-CHANNEL OPS	YEAR TYPE	SPAWNERS	NATURAL SMOLTS AT SAN PABLO BAY	HATCHERY PLANTS AT SAN PABLO
1	16660	50%	0	0	ABOVE NRML	153583	11944827	12250000
2	16660	50%	0	0	ABOVE NRML	153583	11944827	12250000
3	16660	50%	0	0	CRITICAL	151143	3942885	12250000
4	16660	49%	0	0	CRITICAL	151143	3942885	12250000
5	16660	43%	0	0	WET	152846	7238332	12250000
6	16660	27%	0	0	ABOVE NRML	153583	11944827	12250000
7	16660	25%	0	0	ABOVE NRML	153583	11944827	12250000
8	16660	38%	0	0	ABOVE NRML	153583	11944827	12250000
9	16660	47%	0	0	WET	152846	7238332	12250000
10	16660	49%	0	0	ABOVE NRML	153583	11944827	12250000

AVERAGE NATURAL ==> 43%
ESCAPEMENT PERCENTAGE

TABLE V

Simulation of Increased Flow in Critical Years

YEAR	TOTAL POOL POP NATURAL	TOTAL POOL POP HATCHERY	POTENTIAL ESCAPEMENT NO FISHING	TARGET ESCAPEMENT	CATCH FACTOR	HARVEST	NATURAL ESCAPEMENT	HATCHERY ESCAPEMENT
1	419173	419173	490089	200000	0.59	496226	100000	100000
2	417214	417214	488155	200000	0.59	492558	100000	100000
3	415743	417632	486546	200000	0.59	490807	99612	100388
4	406979	418052	483185	200000	0.59	483534	98794	101206
5	390600	419312	466966	200000	0.57	463029	94975	105025
6	314723	423499	437904	200000	0.54	401060	86801	113199
7	301940	434752	427005	200000	0.53	391641	80835	119165
8	272690	438289	435072	200000	0.54	384146	81746	118254
9	406145	438612	486784	200000	0.59	497680	94408	105592
10	406705	418943	484841	200000	0.59	485063	98558	101442

AVERAGE HARVEST==> 458574

ENVIRONMENTAL VARIATION AND CONTROLS

YEAR	HATCHERY INTAKE	ESCAPEMENT-% NATURAL	FLOW STATUS	X-CHANNEL OPS	YEAR TYPE	SPAWNERS	NATURAL SMOLTS AT SAN PABLO BAY	HATCHERY PLANTS AT SAN PABLO
1	16660	50%	0	0	ABOVE NRML	153583	11944827	12250000
2	16660	50%	0	0	ABOVE NRML	153583	11944827	12250000
3	16660	50%	3000	3	CRITICAL	151143	9285621	12250000
4	16660	49%	3000	3	CRITICAL	151143	9285621	12250000
5	16660	47%	0	0	WET	152846	7238332	12250000
6	16660	43%	0	0	ABOVE NRML	153583	11944827	12250000
7	16660	40%	0	0	ABOVE NRML	153583	11944827	12250000
8	16660	41%	0	0	ABOVE NRML	153583	11944827	12250000
9	16660	47%	0	0	WET	152846	7238332	12250000
10	16660	49%	0	0	ABOVE NRML	153583	11944827	12250000

AVERAGE NATURAL ESCAPEMENT PERCENTAGE ==> 47%

TABLE VI

Simulation of Increased Flow in All Years

YEAR	TOTAL POOL POP NATURAL	TOTAL POOL POP HATCHERY	POTENTIAL ESCAPEMENT NO FISHING	TARGET ESCAPEMENT	CATCH FACTOR	HARVEST	NATURAL ESCAPEMENT	HATCHERY ESCAPEMENT
1	419173	419173	490089	200000	0.59	496226	100000	100000
2	417214	417214	488155	200000	0.59	492558	100000	100000
3	422852	417632	493655	200000	0.59	499969	101057	98943
4	446870	416286	502953	200000	0.60	519921	103199	96801
5	422947	412824	478585	200000	0.58	486504	99086	100914
6	314503	418795	436530	200000	0.54	397331	87786	112214
7	310494	434943	435185	200000	0.54	402853	83117	116883
8	318604	436018	457077	200000	0.56	424428	88062	111938
9	446653	430918	505947	200000	0.60	530669	100245	99755
10	446081	412402	502922	200000	0.60	517084	103815	96185

AVERAGE HARVEST==> 476754

ENVIRONMENTAL VARIATION AND CONTROLS

YEAR	HATCHERY INTAKE	ESCAPEMENT-% NATURAL	FLOW STATUS	X-CHANNEL OPS	YEAR TYPE	SPAWNERS	NATURAL SMOLTS AT SAN PABLO BAY	HATCHERY PLANTS AT SAN PABLO
1	16660	50%	3000	3	ABOVE NRML	153583	13092901	12250000
2	16660	50%	3000	3	ABOVE NRML	153583	13092901	12250000
3	16660	51%	3000	3	CRITICAL	151143	9285621	12250000
4	16660	52%	3000	3	CRITICAL	151143	9285621	12250000
5	16660	50%	3000	3	WET	152846	8595248	12250000
6	16660	44%	3000	3	ABOVE NRML	153583	13092901	12250000
7	16660	42%	3000	3	ABOVE NRML	153583	13092901	12250000
8	16660	44%	3000	3	ABOVE NRML	153583	13092901	12250000
9	16660	50%	3000	3	WET	152846	8595248	12250000
10	16660	52%	3000	3	ABOVE NRML	153583	13092901	12250000

AVERAGE NATURAL ==> 48%
ESCAPEMENT PERCENTAGE

TABLE VII

Simulation of the Mixed-Stock Hypothesis

YEAR	TOTAL POOL POP NATURAL	TOTAL POOL POP HATCHERY	POTENTIAL ESCAPEMENT NO FISHING	TARGET ESCAPEMENT	CATCH FACTOR	HARVEST	NATURAL ESCAPEMENT	HATCHERY ESCAPEMENT
1	419173	419173	490089	200000	0.59	496226	100000	100000
2	417214	417214	488155	200000	0.59	492558	100000	100000
3	415743	454784	523698	200000	0.62	538073	92545	107455
4	397995	626779	586898	200000	0.66	675557	79492	120508
5	324808	623092	530812	200000	0.62	590749	64232	135768
6	96313	637508	441512	200000	0.55	401408	33146	166854
7	116028	674939	470030	200000	0.57	454407	33433	166567
8	240275	667222	537904	200000	0.63	570077	55830	144170
9	376092	642895	585951	200000	0.66	671181	72971	127029
10	374538	623306	580094	200000	0.66	653816	75807	124193

AVERAGE HARVEST==> 554405

ENVIRONMENTAL VARIATION AND CONTROLS

YEAR	HATCHERY INTAKE	ESCAPEMENT-% NATURAL	FLOW STATUS	X-CHANNEL OPS	YEAR TYPE	SPAWNERS	NATURAL SMOLTS AT SAN PABLO BAY	HATCHERY PLANTS AT SAN PABLO
1	22660	50%	0	0	ABOVE NRML	147583	11944827	18250000
2	22660	50%	0	0	ABOVE NRML	147583	11944827	18250000
3	22660	46%	0	0	CRITICAL	145143	3942885	18250000
4	22660	40%	0	0	CRITICAL	145143	3942885	18250000
5	22660	32%	0	0	WET	146846	7238332	18250000
6	22660	17%	0	0	ABOVE NRML	147583	11944827	18250000
7	22660	17%	0	0	ABOVE NRML	147583	11944827	18250000
8	22660	28%	0	0	ABOVE NRML	147583	11944827	18250000
9	22660	36%	0	0	WET	146846	7238332	18250000
10	22660	38%	0	0	ABOVE NRML	147583	11944827	18250000

AVERAGE NATURAL ESCAPEMENT PERCENTAGE ==> 35%

observed decline in the proportion of nonhatchery fish, but our model does show that it is a possible explanation.

7. TOWARDS ECONOMIC AND POLICY ANALYSIS

We have reviewed the current status and historical trends of the Central Valley chinook salmon fishery, distinguishing between naturally reproducing and hatchery fish. The main finding is that population and harvest levels have remained fairly steady with, perhaps, a small decline in the past decade, but the small decline in total numbers has been accompanied by a dramatic decline in the natural population and a correspondingly dramatic increase in hatchery-produced salmon. The review of population trends was followed by a discussion of possible explanations of the trends and implications for policy modeling. It appears that water flows in the Delta—inflows and exports—may have a major impact on the fishery, along with hatchery operations and harvest regulations. We then developed a model of interactions among hatchery, harvest, and water flow controls in an age-structured population of natural and hatchery salmon. The model is used to show how changes in one or more of the controls can affect elements of the population or the annual harvest. Model parameters are chosen to reflect historical averages and observations in the Central Valley chinook salmon fishery so that simulation results are potentially useful to decisionmakers in the relevant fishery and water resource management agencies.

A particularly useful aspect of the model is that it is structured to permit the analysis of coordinated controls. For example, an illustrative simulation shows that increasing water inflows and decreasing exports in dry years has a substantial impact on smolt survival and subsequent harvest. Maintaining the same flow levels in other years, however, produces very little additional benefit and, presumably, carries a substantial cost.

Quantifying these benefits and costs, which is the subject of our ongoing research, is by no means simple. With regard to costs, one needs to know how a given increase in inflows and/or reduction in exports would translate into impacts on upstream hydropower generation and deliveries to farmers and cities both inside the basin and beyond, as well as the marginal economic values associated with those uses of water. Neither is readily determined.

A salient feature of the California water system is that it is closely managed and highly interconnected not only via physical facilities but also through the fact that some users of Delta water have access to water from other sources—groundwater, local surface water, or surface water imported from the Colorado River Basin—among which some substitution may be possible. Thus, reduced SWP exports from the Delta in April and May could be offset, for example, by transferring water from the CVP or other upstream diverters, by increasing exports during winter months and storing the water in aquifers or above-ground facilities south of the Delta, by using more groundwater, or by reducing agricultural or urban water use. What ultimately happens depends partly on the physical and legal constraints on the system and partly on the discretionary choices of the parties involved. As an economist, one might hope that the least-cost course of action would be adopted; but this is not well defined without reference to the given physical and legal constraints, which need to be spelled out and analyzed. At a minimum, this requires an operations model that represents the plumbing systems of the SWP and CVP and other major agricultural, urban, and hydropower users and keeps track of water flows on a monthly time scale. Furthermore, since water is a heterogeneous commodity with a different value for humans at different times and different locations—just as for fish—a spatially and temporally disaggregated analysis is required in order to obtain a credible estimate of the marginal economic costs associated with the changes in water allocation that may arise from fishery management decisions.

On the benefit side, too, there are complications. To a degree which is not yet fully quantified, protecting the chinook salmon is a joint product with protecting striped bass and protecting native freshwater fish and other components of the Bay/Delta ecosystem that are at risk and may be a source of significant use or non-use values for Californians. For species other than chinook salmon, there is limited information about use values and, for all species, there is even less information about non-use values.[5] Our current research is aimed at developing some of these pieces of information in order to permit a balanced assessment of optimal, integrated fishery and water resource management strategies.

FOOTNOTES

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[2] For a detailed report on the striped bass fishery, see Callahan, Fisher, and Templeton [2]; for salmon, see Keeler, Fisher, and Hanemann [10].

[3] We have relied on this study for much of the data presented above.

[4] There is one other large hatchery, the Coleman, on the Sacramento, which does not truck smolts to the Bay and, consequently, produces a varying output.

[5] For some initial results from a contingent valuation study related to restoring flows on the San Joaquin River, see Hanemann, Kanninen, and Loomis [6].

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APPENDIX

THE ESTIMATION OF IN-RIVER RELATIONSHIPS

In this Appendix, we describe the estimation of equations (5) and (6) in the text. We use multiple regression analysis to project the output of spawning fish as a function of target escapement and hatchery intake and then nonhatchery smolts as a function of spawners and water flows. As stated in the text, the regressions are not intended to explain the underlying relationships or test a particular theory about them but rather to simulate the output of a much more complex simulation (the "Biosystems" model as described in Hagar, Kimmerer, and Garcia and Kimmerer, Hagar, Garcia, and Williams). Accordingly, what are referred to below as "observations" are, in fact, results of separate runs of the Biosystems model. Here, a caveat is needed. The Biosystems model is still under development and has not yet been fully validated. One difficulty, in particular, is the lack of adequate data to run the different precipitation years with different water temperatures during the spring. The temperature data used were for 1975, a wet year. Since high temperatures are correlated both with low flows and with high smolt mortality, it is likely that our estimates of smolt survival are biased upward in critically dry years and, perhaps, even in above-normal years.

Regression specifications and estimations (coefficients and associated t-statistics) are presented below for spawners and smolts in critical, above-normal, and wet years. For each year type, the number of salmon spawning in the wild (both natural and hatchery strays) is estimated as a quadratic function of escapement, with a separate adjustment for hatchery intake above the baseline level of 16,660. The quadratic formulation allows for density-dependent mortality; we hypothesize that the coefficient on escapement will be positive and, on escapement squared, negative and smaller in absolute magnitude. Similarly, in the equation for smolts, the coefficients on spawners should be large and positive and, on spawners squared, small and negative. The other variables in the smolt equation are fresh water inflows and exports as described in the text.

It is important to note that the high R^2 statistics for the equations reported below indicate that our simple model does a very good job of tracking the much more complex Biosystems model for the very aggregated variables in which we are interested. The Biosystems model generates these variables through thousands of equations which track salmon of all ages in great temporal and geographical detail. The downmigration module alone consists of over 1,600 lines of FORTRAN code. This suggests why we have not simply used the Biosystems model. To elaborate, there are three reasons why we chose to develop the simple model instead of work directly with the Biosystems model. The first is the greater transparency of the simple model; it is relatively easy to see what happens from step to step and which factors are responsible for changes in the outcome variables under different scenarios. The Biosystems model, because of its very great detail, is quite difficult to follow and to present in summary. The second is the flexibility that this model offers in allowing policy variables to be dependent on stochastic environmental outcome variables—in particular rainfall—from year to year. Such flexibility would be extremely difficult in the Biosystems model and would require extensive reprogramming. The third reason is that the framework provided by this limited number of relatively simple equations can be used to find solutions to optimization problems by mathematical programming techniques. With the thousands of equations in the Biosystems model, this would be almost impossible.

A final word about data used to construct the Biosystems model: The Biosystems team drew upon all published data on the Sacramento salmon population, extensive interviews with fisheries personnel and wildlife managers, and their own micro-modeling efforts to put together a model both comprehensive in scope and exceptionally detailed in modeling time steps as short as a day and river reaches as small as a few miles. Again, this level of disaggregation is not suited to our purposes, but the equations reported below suggest that our model does track the aggregated variables satisfactorily.

1. CRITICAL YEARS

We used 1976 data to estimate relationships for critical years. Negative values for fresh water inflows (deviations from the baseline) are avoided because the Biosystems model would not run in these circumstances. The equations are

$$\begin{aligned}(\text{Thousand})\ \text{spawners} = {} & -1.275\text{E}+01 + \underset{(57.16)}{8.047\text{E}-04} \cdot \text{targ esc} \\ & \underset{(2.02)}{-7.373\text{E}-11} \cdot (\text{targ esc})^2 \\ & - (\text{hatchery intake} - 16{,}660)\end{aligned} \tag{A1}$$

$R^2 = .999$

92 observations.

$$
\begin{aligned}
\text{Smolts} = & -1.234\text{E}+03 + \underset{(11.58)}{9.425\text{E}-01} \cdot \text{inflow} - \underset{(-5.82)}{8.816\text{E}-05} \\
& \cdot (\text{inflow})^2 + \underset{(10.42)}{9.434\text{E}+02} \cdot \text{exports} - \underset{(-1.36)}{2.526\text{E}+01} \\
& \cdot (\text{exports})^2 - \underset{(-15.66)}{1.969\text{E}-01} \cdot (\text{inflow} \cdot \text{exports}) + \underset{(11.61)}{5.715\text{E}+01} \\
& \cdot \text{spawners} - \underset{(-8.96)}{1.515\text{E}-01} \cdot (\text{spawners})^2 + \underset{(3.80)}{1.764\text{E}-03} \\
& \cdot (\text{inflow} \cdot \text{spawners}) + \underset{(6.78)}{3.700} \cdot (\text{exports} \cdot \text{spawners})
\end{aligned}
\tag{A2}
$$

$R^2 = .991$

92 observations.

2. ABOVE-NORMAL YEARS

The regressions here are based on 1978 data. To get a reasonable interpretation of the quadratic term in the presence of negative deviations, we defined -4,000 cubic feet per second from the baseline as "0" and modified all other flows accordingly. The equations are

$$\begin{aligned}\text{(Thousand) spawners} = & -1.293\mathrm{E}+01 + \underset{(406.0)}{8.328\mathrm{E}-04} \cdot \text{targ esc} \\ & - \underset{(-.2903\mathrm{E}-01)}{1.431\mathrm{E}-12} \cdot (\text{targ esc})^2 \\ & - (\text{hatchery intake} - 16{,}660)\end{aligned} \tag{A3}$$

$R^2 = .999$

128 observations.

$$\begin{aligned}\text{Smolts} = & -5.021\mathrm{E}+02 + \underset{(11.31)}{6.693\mathrm{E}-01} \cdot \text{inflow} - \underset{(-6.645)}{3.574\mathrm{E}-05} \\ & \cdot (\text{inflow})^2 + \underset{(7.55)}{5.656\mathrm{E}+02} \cdot \text{exports} - \underset{(-4.109)}{5.574\mathrm{E}+01} \\ & \cdot (\text{exports})^2 - \underset{(-11.89)}{9.562\mathrm{E}-02} \cdot (\text{inflow} \cdot \text{exports}) + \underset{(25.37)}{9.288\mathrm{E}+01} \\ & \cdot \text{spawners} - \underset{(-16.17)}{1.999\mathrm{E}-01} \cdot (\text{spawners})^2 + \underset{(4.682)}{1.290\mathrm{E}-03} \\ & \cdot (\text{inflow} \cdot \text{spawners}) + \underset{(3.049)}{1.167} \cdot (\text{exports} \cdot \text{spawners})\end{aligned} \tag{A4}$$

$R^2 = .993$

128 observations.

3. WET YEARS

The regression predicting the number of spawners is based on 1975 data. The equation is

$$\begin{aligned}(\text{Thousand})\ \text{spawners} = &-9.56 + \underset{(23.91)}{7.97E-04} \cdot \text{targ esc} \\ &- \underset{(1.055)}{7.50E-11} \cdot (\text{targ esc})^2 \qquad \text{(A5)} \\ &- (\text{hatchery intake} - 16{,}660)\end{aligned}$$

$R^2 = .998$

37 observations.

With respect to the smolt equation, when flows were high, as in 1975, the level of water exports made virtually no difference to survival (in the model, at least). For this reason, we omitted exports as an explanatory variable which, in turn, permitted us to obtain a good fit with fewer observations. Also, as in the above-normal year, we subtract 5,000 cubic feet per second from the Biosystems baseline to represent "0."

$$
\begin{aligned}
\text{Smolts} = {} & -3.995\text{E}+03 + \underset{(15.29)}{1.924\text{E}+00} \cdot \text{inflow} - \underset{(-11.91)}{1.133\text{E}-04} \\
& \cdot (\text{inflow})^2 + \underset{(5.545)}{4.424\text{E}+01} \cdot \text{spawners} - \underset{(-3.959)}{9.932\text{E}-02} \\
& \cdot (\text{spawners})^2 + \underset{(2.705)}{6.652\text{E}-06} \cdot (\text{inflow} \cdot \text{spawners})
\end{aligned}
\tag{A6}
$$

$R^2 = .979$

37 observations.