California's Yolo Bypass:
Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture

ABSTRACT

Unlike conventional flood control systems that frequently isolate rivers from ecologically-essential floodplain habitat, California's Yolo Bypass has been engineered to allow Sacramento Valley floodwaters to inundate a broad floodplain. From a flood control standpoint, the 24,000 ha leveed floodplain has been exceptionally successful based on its ability to convey up to 80% of the flow of the Sacramento River basin during high water events. Agricultural lands and seasonal and permanent wetlands within the bypass provide key habitat for waterfowl migrating through the Pacific Flyway. Our field studies demonstrate that the bypass seasonally supports 42 fish species, 15 of which are native. The floodplain appears to be particularly valuable spawning and rearing habitat for the splittail (*Pogonichthys macrolepidotus*), a federally-listed cyprinid, and for young chinook salmon (*Oncorhynchus tshawytscha*), which use the Yolo Bypass as a nursery area. The system may also be an important source to the downstream food web of the San Francisco Estuary as a result of enhanced production of phytoplankton and detrital material. These results suggest that alternative flood control systems can be designed without eliminating floodplain function and processes, key goals of the 1996 Draft AFS Floodplain Management Position Statement.

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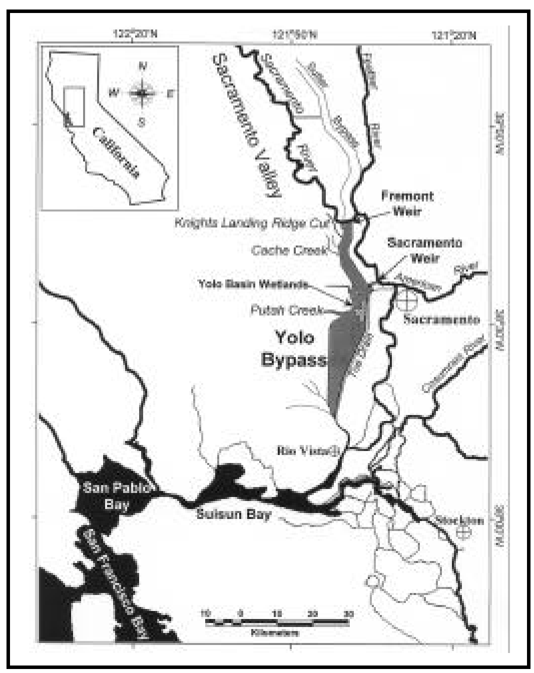
Introduction

The adverse environmental effects of conventional flood control techniques such as levee and dam construction, river channelization, and riprapping are well-documented (Bayley 1991; Toth et al. 1993; Galat et al. 1998). Additional criticisms have come from geologists, who note that dams face long-term limitations from sedimentation and levees are particularly sensitive to tectonic activity and global climate change (Mount 1995). These concerns led to the draft AFS Position Statement for Floodplain Management (Rasmussen 1996), which recommended the use of non-structural flood control methods to the extent possible. When structural measures are used, setback levees, gated levees, and levees with spillways were suggested as environmentally superior techniques. This guidance was based on substantial evidence demonstrating that natural floodplains have exceptional habitat values for numerous species at different trophic levels (Junk et al. 1989; Bayley 1991). Unfortunately, there is little information about the ecological performance of some of the structural alternatives.

In the present article we report on the Yolo Bypass, a unique large-scale engineered floodplain with many of the features cited as desirable alternatives in the draft AFS Position Statement. The flood control system has been regularly operated since the early 1930s, providing an excellent opportunity to evaluate the effectiveness of an established engineered floodplain. In this paper we summarize some of the major attributes of the Yolo Bypass and its associated benefits to fisheries, wildlife, and wetlands. We believe that the Yolo Bypass provides an instructive example of how flood control projects can be designed and operated without eliminating processes needed to sustain aquatic and wetlands systems.

Figure 1. Location of Yolo Bypass (shaded area) relative to the Central Valley, the San Francisco Bay and its tributaries.



History

The historical Sacramento Valley floodplain above Sacramento, California occupied much of the valley floor (Figure 1), when periodic floods filled a large part of the alluvial valley.

One of the most dramatic of these events occurred in 1862, when the valley was essentially converted into an inland sea. This legendary event helped fuel a 50-year debate on the best flood control approach to protect the valley's rapidly-growing communities (Kelley 1989). Initial recommendations in 1905 for high river levees were based on a relatively short hydrologic record. Coincidentally, the release of the flood engineering report was followed immediately by the extreme flood of 1907 in which an estimated 120,000 ha of the valley were inundated by Sacramento River flows of about 17,000 m^3/sec^{-1}. An additional large flood in 1909 convinced flood managers that other alternatives were needed. The solution had its roots in an 1860s proposal by newspaper editor Will Green to construct a broad bypass system that would more closely mimic the Sacramento River's natural floodplain functions. Based in part on Green's concept, the U.S. Army Corps of Engineers eventually developed a network of weirs and bypasses, which became the Sacramento Flood Control Project. Central features of the plan included the development of two engineered floodplains, the Yolo and Sutter bypasses, to safely convey floodwaters around Sacramento and other valley communities. Much of the system was in place by the early 1930s, although there were several additions over the next several decades, including the development of upstream reservoirs.

Hydrology

Inundation of the Yolo Bypass (Figure 1) is one of the most dramatic seasonal events in California's Sacramento Valley. The Yolo Bypass presently floods in more than half of water years, creating a large expanse of shallow water habitat (Photograph 1).

This has a major physical effect on the San Francisco Estuary and its two component regions: 1) the Sacramento-San Joaquin Delta, a network of channels bordered by the cities of Sacramento, Stockton, and a point 20 km downstream of Rio Vista; and 2) the chain of downstream bays including Suisun, San Pablo, and San Francisco bays. At Yolo Bypass flows greater than about 2,100 m^3/sec^{-1} the partially leveed 24,000 ha floodplain is fully inundated; this level of inundation approximately doubles the wetted area of the delta and is equivalent to about one-third the area of San Francisco and San Pablo bays. Besides Yolo Bypass, the only other delta region with substantial connectivity to portions of the historical floodplain is Cosumnes River, a small undammed watershed. The floodplain has historically been inundated as early as October and as late as June, with a typical peak period of inundation during January–March (Figure 2).

The hydrology of the system is complex, with inundation possible from several different sources (Figure 1). The primary input to the Yolo Bypass is through Fremont Weir in the north, which conveys floodwaters from the Sacramento and Feather rivers. The typical sequence of inundation is as follows. Flow pulses in the Sacramento River are first diverted into Sutter Bypass, a 7,300 ha agricultural floodplain with many similarities to Yolo Bypass. The Sacramento River immediately upstream of

Photograph 1. Seasonally flooded shallow water habitat in the Yolo Bypass, a 24,000 ha engineered floodplain of the San Francisco Bay-Delta Estuary.

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Fremont Weir has a relatively low channel capacity (800 m^3/sec^{-1}), so Sutter Bypass flooding is often initiated in modest flow pulses. When the combined flow of Sutter Bypass and Sacramento and Feather rivers raises stage at Fremont Weir to a level of 9.2 m (NGVD datum QUERY:SPELL OUT), water subsequently enters Yolo Bypass. The relative distribution of flow from different tributaries affects the timing that this stage threshold is reached; however, Yolo Bypass flooding typically occurs when total flow from the Sutter Bypass and two rivers surpasses 1,600 m^3/sec^{-1}. Floodwater through Fremont Weir initially flows through the "Toe Drain," a perennial riparian channel on the eastern edge of the bypass before spilling onto the floodplain when discharge in this small channel exceeds 100 m^3/sec^{-1}. The floodplain is considered inundated when the stage of the Toe Drain at Lisbon Weir exceeds 2.5 m (NGVD datum). In major storm events (e.g. >5,000 m^3/sec^{-1}), additional water enters from the east via Sacramento Weir, adding flow from the American and Sacramento rivers.

Flow also enters the Yolo Bypass from several small west side streams: Knight's Landing Ridge Cut, Cache Creek, Willow Slough Bypass, and Putah Creek. These tributaries can substantially augment the Sacramento basin floodwaters or cause localized floodplain inundation before Fremont Weir spills. Interestingly, the diverse inputs from the Sacramento Basin and west side streams create distinct water masses that are visible across much of the length of the 64-km long bypass (Photograph 2).

Examination of archived aerial photographs indicate that water mass banding is a regular phenomenon, occurring during both low flow and extreme high flow events. Presumably this

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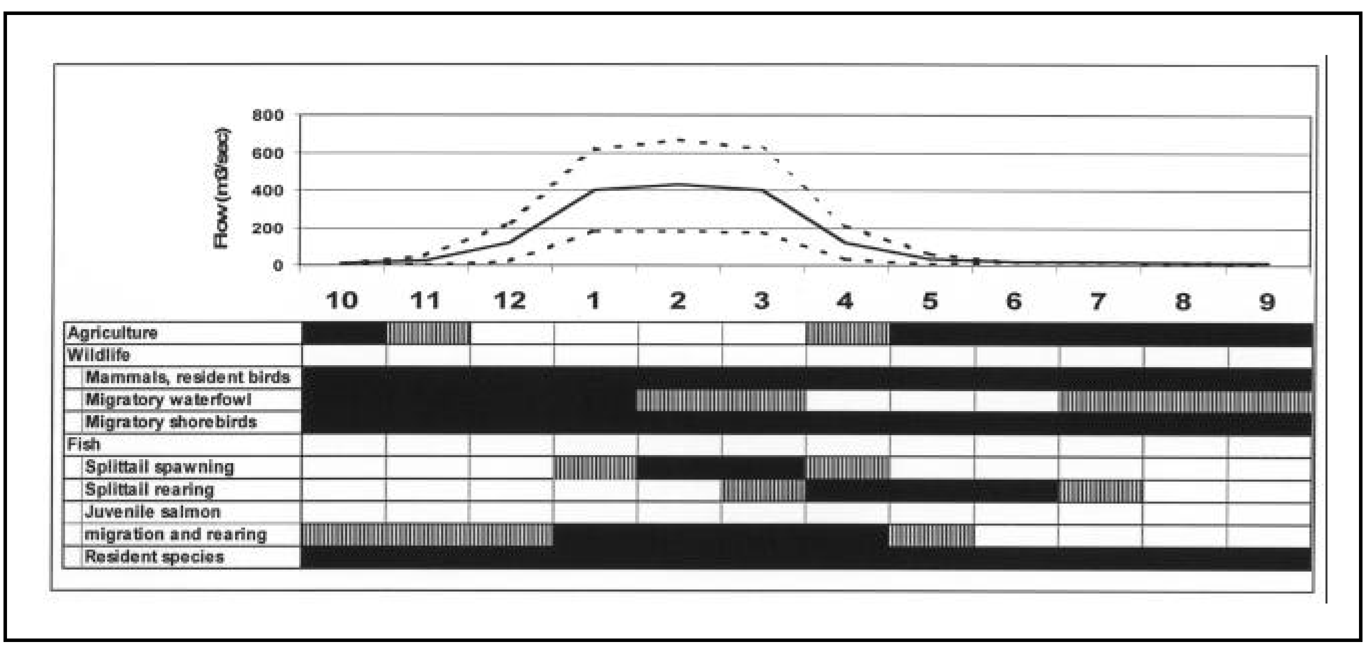
Photograph 2. Natural color aerial photographs of a portion of the Yolo Bypass. The color bands are formed by flow from tributaries, which remain hydrologically separated throughout its 64 km length.

Figure 2. Yolo Bypass hydrograph relative to agricultural and environmental activity in the floodplain by month (x-axis). The mean (solid line) and standard error (dashed line) of total daily Yolo Bypass flow is shown for October 1967–September 1996, the period when all major dams were completed in the Sacramento Valley. For agricultural and environmental uses of the floodplain, the primary (solid bars) and marginal (dashed bars) periods are shown. During dry periods (e.g. flows <100 m^3/sec^{-1}), resident fishes are confined to the perennial waters which occupy less than 5 percent of the total floodplain area.



occurs because the size of the turbulent eddies that would mix these water masses is limited by the shallow depth. The mean depth of the floodplain does not exceed 3 m, except in the most extreme flood events.

After floodwaters recede, the basin empties through the Toe Drain. The floodplain is relatively well-drained as a result of land-grading for agriculture; there are no major topographic features to impede the drainage of flood flows to the lower Sacramento-San Joaquin Delta. During drier months the tidally-influenced Toe Drain channel is the primary source of perennial water in the Yolo Bypass, feeding a complex network of canals and ditches.

From a flood control standpoint, the Yolo Bypass has saved valley communities numerous times. The maximum design flow for the Sacramento River channel below the Sacramento metropolitan area is 3,100 m^3/sec^{-1}. By contrast, the adjacent Yolo Bypass floodplain is engineered to convey approximately 14,000 m^3/sec^{-1}. To illustrate this point, in 1999 flow in the Sacramento River was maintained below 3,000 m^3/sec^{-1} during high flow events by diverting up to 1,350 m^3/sec^{-1} excess flow to the Yolo Bypass floodplain (Figure 3a). As an indication of the frequency that the Yolo Bypass has been needed, total Sacramento River basin flow exceeded the design capacity of the river below Sacramento in 58% of years during 1956–1998 (Figure 4). During these wetter years, the design flow was exceeded an average of 23 days. The design capacity of the Yolo Bypass has not yet been exceeded, despite major floods such as 1997, estimated to be a 70-year recurrence interval event.

Agriculture and Wetlands

Land use in the Yolo Bypass is dominated by seasonal agriculture, but approximately one third of the area is a mosaic of more "natural" habitat types on the floodplain including wetlands, riparian, upland, and pond areas. By contrast, the adjacent Sacramento River has little habitat diversity. Like most other delta channels, the Sacramento River is bounded by steep levees covered with riprap or thin corridors of riparian vegetation (Photograph 3). The deep (typically >5 m mean depth) channel has minimal shallow water habitat, essentially no submerged vegetation and only minor strips of emergent vegetation.

The primary agricultural crops in Yolo Bypass are sugar beets, rice, wild rice, safflower, tomatoes, corn, and other grains. Farming activity is concentrated in late spring and summer, when flooding is uncommon (Figure 2). The state government has flood easements during all months, which can delay spring planting in the event of unusual late season storms. Crop yield data are not available specifically for the Yolo Bypass, but yields are generally lower than other nearby regions as a result of high clay content in the soils of the eastern half of the floodplain and by occasional late-season flooding. Nonetheless, the Yolo Bypass remains a key crop production area for Yolo County, where agriculture is the major source of revenue (Robert Crowder, California Farm Bureau, pers. comm.). The current wholesale market value of

Figure 3 (a-e). Results of floodplain and river sampling for 1999 adapted from Sommer et al (2001). a. Mean daily flow (m^3/sec^{-1}) in Yolo Bypass (solid line) and Sacramento River (dashed line). b. Mean daily water temperature (°C) at Yolo Bypass (solid line) and Sacramento River (dashed line); c. Mean daily chinook salmon fork length for Yolo Bypass (solid symbols) and Sacramento River (open symbols) beach seine stations. For presentation purposes, only the daily mean fork lengths are shown; d. Weekly density of zooplankton in Yolo Bypass (solid symbols) and Sacramento River (open symbols); e. Density of dipterans in weekly drift samples in Yolo Bypass (solid symbols) and Sacramento River (open symbols).

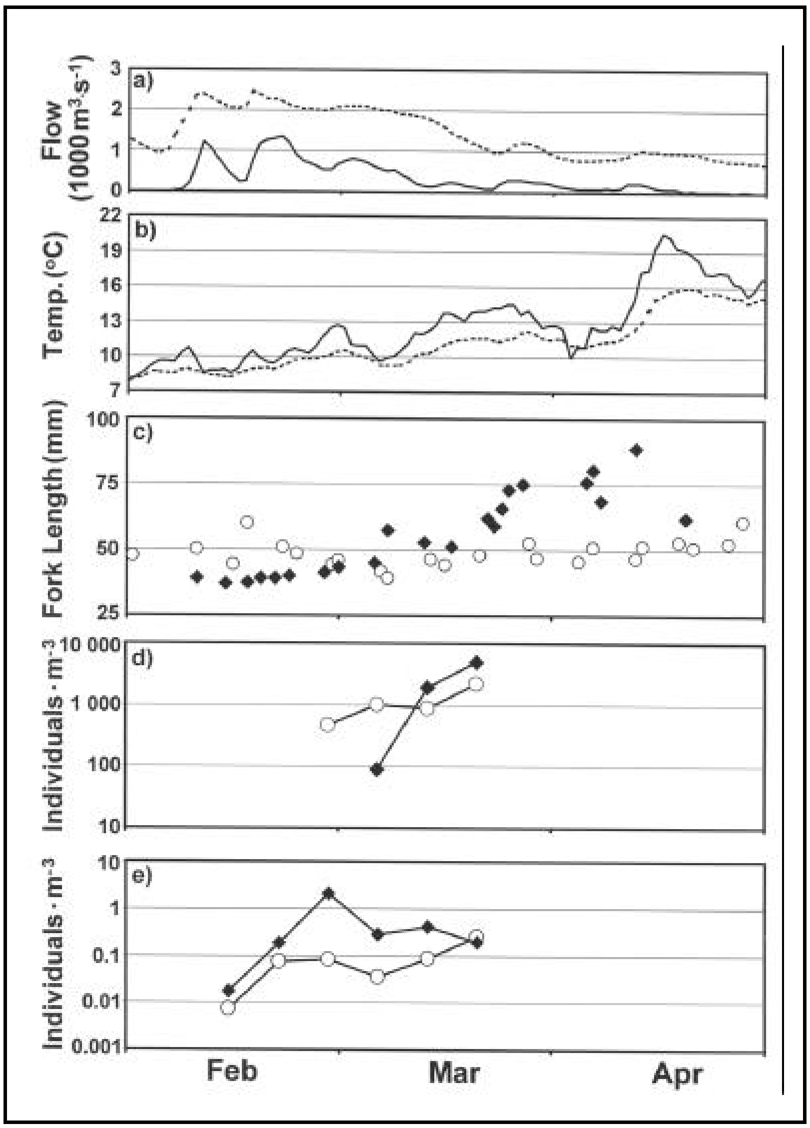
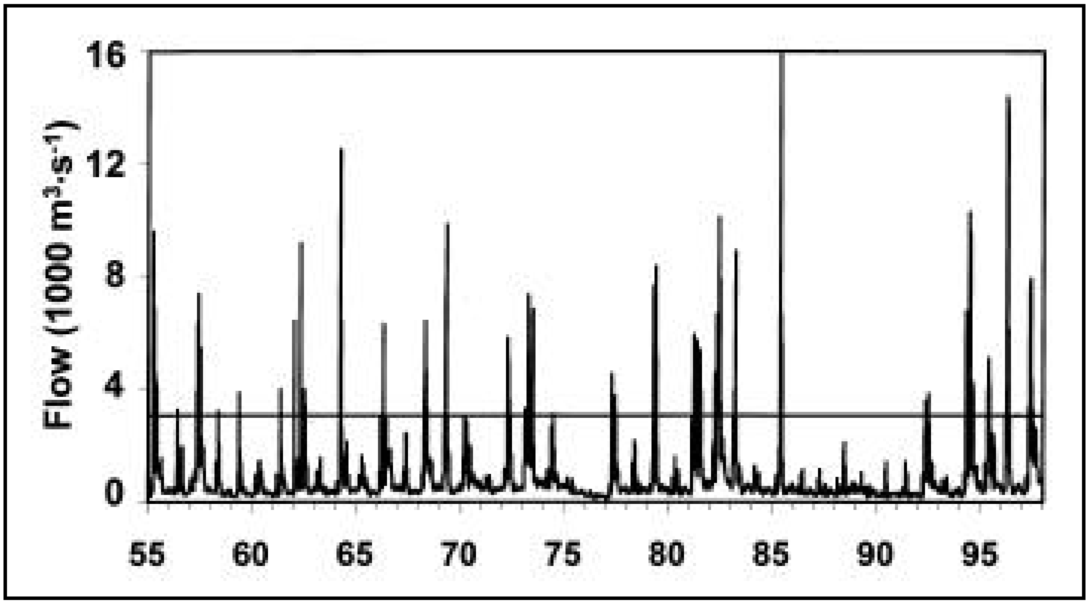


Figure 4. Total daily Sacramento Basin flow (m^3/sec^{-1}) during 1956–1998. The horizontal line at 3,100 m^3/s^{-1}



agricultural crops from Yolo County is approximately $300 million each year.

The floodplain also has large areas of wetlands, many of which are managed for waterfowl. The best example is the Yolo Basin Wetlands, a 1,250 ha project (Figure 1), reported to be one of the largest wetlands restoration projects in the western United States. Land for the project was purchased in 1991 and wetlands were constructed through the cooperative efforts of the U.S. Army Corp of Engineers, California Department of Fish and Game, Yolo Basin Foundation, U.S. Fish and Wildlife Service, California Department of Water Resources, California Wildlife Conservation Board, and Ducks Unlimited. The project was officially dedicated in 1997 by President Clinton. Habitat types in the Yolo Basin Wetlands include seasonal wetlands (940 ha), uplands (196 ha), perennial wetlands (75 ha) and riparian forest (11 ha).

The Yolo Bypass occupies a critical part of the Pacific Flyway, a migration route traveled by vast numbers of waterfowl. Examples of species that use the newly-created Yolo Basin Wetlands wildlife area include mallards, northern pintails, American wigeon, green-winged teal, northern shovelers, ruddy ducks, snow geese, Ross's geese, and Canada geese (Table 1).

Wildlife managers seasonally flood the area in October and maintain ponds for migratory waterfowl through January (Figure 2). The region also supports numerous species of shorebirds (e.g., sandpipers, curlews, and avocets), raptors (e.g., northern harriers, red-tailed hawks, and kestrels), songbirds (e.g., orioles, towhees, and bluebirds), and mammals (e.g., raccoons, skunks, and grey foxes). Yolo Bypass appears to be especially important to the Swainson's hawk, a state-listed

Photograph 3. A typical reach of the Sacramento River showing heavy channelization and minimal shallow water habitat.

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threatened species which uses the floodplain as foraging habitat. In recent years, up to 70 individuals have been observed foraging on the floodplain at the same time during dry periods. (Dave Feliz, Calif. Department of Fish and Game, pers. comm.).

Fish

Since 1997 we have conducted fish sampling in the Yolo Bypass, with emphasis on juvenile chinook salmon (*Oncorhynchus tschawytsch)* and other native species. Our major research questions have included: 1) what fish species use floodplain habitat; 2) what functions does floodplain habitat provide for fish; 3) is habitat quality better on floodplain than river channels; 4) is invertebrate species composition and biomass different on floodplain habitat than river channels; and 5) what is the effect of the floodplain on the downstream San Francisco estuary? The area presents formidable sampling challenges due to its large size and hydrologic variability, requiring diverse methods to address different biological questions. Our sampling program has included: egg and larval tows (1998-2001), screw trap, drift and zooplankton nets (1998–2001), beach seine (1997–2001), and purse seine (1998). Comparative data were also collected by U.S. Fish and Wildlife Service in the Sacramento River using beach seine and trawling methods (Sommer et al. 2001).

Our results show that the Yolo Bypass provides valuable aquatic habitat to 42 fish species, 15 of which are native (Table 2).

Many of these species are year-round residents in perennial waters in the floodplain. The bypass seasonally supports several state and federally-listed species: delta smelt (*Hypomesus transpacificus*), splittail, steelhead trout (*Oncorhyncus mykiss*), and spring-run and winter-run chinook salmon. Popular game fish are also present including white sturgeon (*Acipenser transmontanus*), striped bass (*Morone saxatilis*), largemouth bass (*Micropterus salmoides*), and white crappie (*Pomoxis annularis*). Like other parts of the Sacramento-San Joaquin Delta, there are more exotic than native fish species in the Yolo Bypass. Exotic species are one of the major environmental problems in the delta, where they frequently dominate the fish fauna on a year-round basis (Bennett and Moyle 1996). We hypothesize that floodplain may provide special benefits to native fish because of the seasonal hydrology of the floodplain. As illustrated in Figure 2, the majority of the floodplain habitat is seasonally dewatered and therefore cannot be dominated by exotic fish except in perennial waters. In other words, the Yolo Bypass is largely a "clean slate" at the beginning of each winter. Moreover, the typical winter and spring spawning and rearing period for native delta fishes (Moyle 2001) coincides with the timing of the flood pulse. By contrast, most of the introduced species shown in Table 2 spawn in late spring or summer, when the floodplain is drained. The hypothesis that the timing of the flood cycle may provide a competitive advantage to native fish (or at least helps to maintain coexistence with introduced species) is difficult to test because the floodplain-river system is too large and variable for adequate hypothesis testing. However, we can at least demonstrate that floodplain habitat itself has direct benefits to native fish. To illustrate the importance of the Yolo Bypass to fish we discuss observations on two native species, splittail and juvenile chinook salmon.

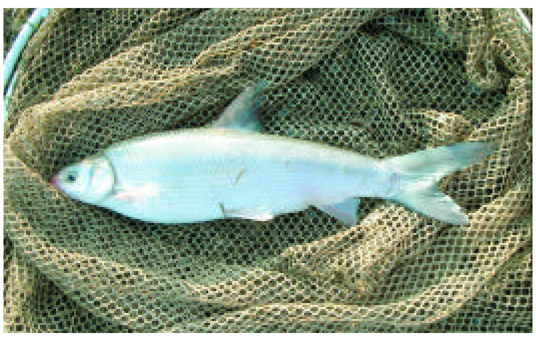
Splittail, a large native cyprinid (Photograph 4), is perhaps the most floodplain-dependent species in the Sacramento-San Joaquin Delta. In 1999 the species was listed as threatened under the federal Endangered Species Act as a result of concerns about reduced abundance and distribution (USFWS 1999). The legal status of splittail is currently being reviewed as part of court proceedings; however, the species remains a major focus of water management and restoration activities in the Delta. Splittail reside in the San Francisco Estuary, but seasonally migrate upstream through the Sacramento-San Joaquin Delta and its tributaries to spawn (Sommer et al. 1997). The Yolo bypass represents key habitat for the species and year-class strength is strongly correlated with the duration of floodplain inundation. Sommer et al. (1997) found that adults move onto the floodplain in winter and early spring to forage and spawn on flooded vegetation. Splittail rear on the floodplain and emigrate to the river channels and estuary as floodwaters recede. These results are consistent with more "natural" floodplains such as the Cosumnes River, a nearby undammed watershed that was recently identified as a major spawning and

Table 1. Counts of several major bird groups from 12 monthly surveys at Yolo Basin Wildlife Area during 1998 and 1999. The total number of individuals is shown for each year with the total number of species (in parentheses). Note that the observations represent the results of one survey day each month and therefore do not represent annual population estimates. Source: Dave Feliz, California Department of Fish and Game, unpublished data.

Bird Group	1998 Total	1999 Total	Dominant Species (top three)
Diving ducks	4,631 (7)	6,281 (7)	Ruddy, canvasback, scaup
Puddle ducks	44,493 (7)	173,323 (7)	Wigeon, mallard, shoveler
Geese and swans	136 (5)	192 (4)	Canada goose, white-front goose, snow goose
Raptors	224 (11)	269 (13)	Northern harrier, red-tailed hawk, Swainson's hawk
Shorebirds	3,485 (14)	18,530 (11)	Western sandpiper, dowitcher spp., dunlin
Wading birds	452 (2)	1,222 (2)	Black-necked stilt, American avocet

rearing area for splittail (Moyle, unpublished data). Sommer et al. (1997) concluded that the decline in numbers of splittail during the 1987–1992 drought was likely due to the lack of access to floodplain spawning habitat, although the relatively long life span of the fish (frequently > 5 years) allows it to survive periods without access to this habitat. Results from 1998–2000 also indicate that another native minnow, Sacramento blackfish (*Orthodon microlepidotus*) uses the bypass for spawning and rearing (T. Sommer, unpublished data).

Juvenile chinook salmon represent another good example of the value of the Yolo Bypass for native fish. Most young chinook salmon emigrate from the Sacramento River and its tributaries during winter and spring and enter the Sacramento-San Joaquin Delta (Fisher 1994). In low flow periods, the Sacramento River and similar delta channels are the only migratory paths, but during flood pulses the Yolo Bypass floodplain provides an alternative migration corridor. The results of Sommer et al. (2001) suggest that inundation of the Yolo Bypass may provide better rearing conditions than the adjacent Sacramento River. Chinook salmon rearing has been well-documented in river channels and estuaries (Kjelson et al. 1982; Healey 1991; Levings et al. 1995) and in off-channel habitats in small Pacific Northwest rivers and streams (Swayles et al. 1986; Swales and Levings 1988; Richards et al. 1992). However, our studies of the Yolo Bypass described in part below present the first solid evidence that we are aware of demonstrating that seasonal floodplains in large, low elevation rivers represent major areas for rearing. Like splittail, initial results from the Cosumnes River suggest that more "natural" floodplains also provide good habitat for young salmon (Moyle, unpublished data).



Photograph 4. Sacramento splittail (*Pogonichthys macrolepidotus*), a federally-listed minnow which uses the Yolo Bypass as key spawning, rearing, and foraging habitat.

We have collected juvenile salmon in all inundated regions of the floodplain and in all habitat types including agriculture, riparian, and wild vegetation. However, salmon are most abundant in areas with velocity refuges such as trees, shoals, and the downstream portions of levees. This observation is not surprising given the preference of chinook salmon fry for low velocity areas (Everest and Chapman 1972). The Yolo Bypass has substantially more of this habitat than the Sacramento River, which has little habitat complexity as a result of channelization and riprapping. As one indicator of the amount of low velocity habitat, we examined the amount of "edge" habitat in March 1998 aerial photographs (Photograph 1). For this analysis, we calculated the measured shoreline length for adjacent reaches of the Yolo Bypass and Sacramento River that each had a total linear distance of 55,500 m. The Yolo Bypass shoreline estimate was primarily based on the levee margins of the floodplain, but also included perimeters of internal islands and inundated riparian patches. Yolo Bypass had a total of 320,500 m of shoreline (5.8 m shoreline/m linear distance) compared to the Sacramento River, which had 95,200 m of shoreline (1.7 m shoreline/m linear distance). In other words, the Yolo Bypass had over three times as much shoreline habitat than the Sacramento River. However, edge habitat is a gross underestimate of the total amount of low velocity rearing habitat because it does not include the broad shoals that cover most of the western bypass. We are presently working on a physical model to estimate this additional shallow inundated area.

As evidence of better habitat quality for juvenile salmon in Yolo Bypass compared to the river, Sommer et al. (2001) found that mean salmon size increased significantly faster in the seasonally-inundated Yolo Bypass floodplain than in the Sacramento River, suggesting better growth rates. Their results for 1999 are shown in Figure 3c; however, we have observed the same trend each winter during 1997–2000. There are several habitat characteristics that could account for faster growth of young salmon. First, Yolo Bypass was significantly warmer than adjacent Sacramento River channels (Figure 3b) as result of the shallower depth and greater surface area of the floodplain. Higher water temperatures up to a point can enhance salmon growth, provided that there is sufficient energy to offset increased metabolic requirements (Brett 1995). Salmon diet analyses showed that the two major prey items for river and floodplain salmon are dipterans and zooplankton (Sommer et al. 2001). In 1999, there was little difference in zooplankton abundance between the Yolo Bypass and Sacramento River (Figure 3d) during the main period of flooding; however, dipterans were up to an order of magnitude more abundant in the floodplain drift net samples than the river due to high densities of chironomids (Figure 3e). Hence, food resources are substantially better in Yolo Bypass. Sommer et al. (2001) found that these differences led to significantly higher feeding success of young salmon on the floodplain than in the adjacent Sacramento River. Differences in water velocity between the river and floodplain could also potentially influence bioenergetics. For example, during the primary period of inundation in 1999 (February–March), we estimate that mean channel velocity in Yolo Bypass was approximately 0.1–0.3 m/sec^{-1}, compared to Sacramento River that exceeded 1.0 m/sec^{-1}. The lower velocity Yolo

Bypass habitat is closer to the velocity preferences of young salmon (Everest and Chapman 1972) and may result in lower energy expenditure. The benefits of floodplain habitat are consistent with Pacific Northwest studies by Swales et al. (1986) and Swales et al. (1989 QUERY: NOT IN REFERENCES), who found that coho salmon grew faster in off-channel ponds than main river channels.

Although our results suggest that several measures of habitat quality may be better for young salmon in the Yolo Bypass, floodplain habitat carries risks from avian predation and stranding when water levels drop. Some predation occurs as a result of wading birds such as egrets and herons; however we believe that these birds are unlikely to have a major population effect as the densities of wading birds are typically low (e.g., Table 1) relative to the thousands of hectares of available fish rearing habitat. The relative importance of stranding mortality is difficult to evaluate because the number of salmon emigrating from the Sacramento River and its tributaries is unknown, despite substantial monitoring efforts by several agencies. The floodplain is exceptionally well-drained because of grading for agriculture, which likely helps promote successful emigration of young salmon. Moreover, water stage decreases are relatively gradual; for example, the maximum stage decreases in 1998 were 1 cm/hr^{-1} (Figure 4), well below levels that have been found to result in high stranding rates in experimental systems (Bradford 1997). Sommer et al. (2001) examined the survival issue by doing paired releases of juvenile coded-wire-tagged salmon in Yolo Bypass and Sacramento River to obtain comparative data. They found that the Yolo Bypass release groups had somewhat higher survival indices than Sacramento River fish in both 1998 and 1999, but the sample size (n=2 paired releases) was too low to demonstrate statistical significance.

Importance of the Yolo Bypass to the San Francisco Estuary

High flow years are known to enhance populations of a variety of fish and invertebrates of the San Francisco Estuary (Jassby et al. 1995). However, the exact mechanisms for these relationships remain largely unknown. Possible reasons for the positive effects of higher flow on fish include increased habitat availability, food supply and larval transport and reduced predation or competition (Bennett and Moyle 1996). Floodplain inundation is one of the unique characteristics of above normal flow years and may be responsible for some of the positive effects. The previously-described fish studies demonstrate that floodplain is important habitat for many fish. However, we also have evidence that floodplain inundation may also affect organisms downstream in the brackish portion of the estuary. Studies by Schemel et al. (1996) indi-

Table 2. Yolo Bypass fish species documented during 1997–2001. Federally-listed species are identified as threatened (FT) or endangered (FE) and state-listed species are identified as threatened (ST) or endangered (SE). Species names are listed in alphabetical order.

NATIVE SPECIES	
white sturgeon	*Acipenser transmontanus*
Sacramento sucker	*Catostomus occidentalis*
prickly sculpin	*Cottus asper*
threespine stickleback	*Gasterosteus aculeatus*
delta smelt (FT,ST)	*Hypomesus transpacificus*
tule perch	*Hysterocarpus traski*
river lamprey	*Lampetra ayresi*
Pacific lamprey	*Lampetra tridentata*
hitch	*Lavinia exilicauda*
Pacific staghorn sculpin	*Leptocottus armatus*
steelhead trout (FT)	*Oncorhyncus mykiss*
chinook salmon	*Oncorhynchus tschawytscha*
fall-run	
sprint-run (ST)	
winter-run (FE,SE)	
Sacramento blackfish	*Orthodon microlepidotus*
splittail (FT)	*Pogonichthys macrolepidotus*
Sacramento pikeminnow	*Ptychocheilus grandis*
INTRODUCED SPECIES	
yellowfin goby	*Acanthogobius flavimanus*
American shad	*Alosa sapidissima*
white catfish	*Ameiurus catus*
black bullhead	*Ameiurus melas*
brown bullhead	*Ameiurus nebulosus*
goldfish	*Carassius auratus*
common carp	*Cyprinus carpio*
red shiner	*Cyprinella lutrensis*
threadfin shad	*Dorosoma petenense*
western mosquitofish	*Gambusia affinis*
wakasagi	*Hypomesus nipponensis*
channel catfish	*Ictalurus punctatus*
green sunfish	*Lepomis cyanellus*
warmouth	*Lepomis gulosus*
bluegill	*Lepomis macrochirus*
redear sunfish	*Lepomis microlophus*
inland silverside	*Menidia beryllina*
smallmouth bass	*Micropterus dolomieu*
spotted bass	*Micropterus punctulatus*
largemouth bass	*Micropterus salmoides*
striped bass	*Morone saxatilis*
golden shiner	*Notemigonus crysoleucas*
bigscale logperch	*Percina macrolepida*
fathead minnow	*Pimephales promelas*
white crappie	*Pomoxis annularis*
black crappie	*Pomoxis nigromaculatus*
shimofuri goby	*Tridentiger bifasciatus*

cate that the Yolo Bypass is the major pathway for sediment into the estuary in wet years. They also found that the floodplain is the dominant source of organic carbon in wet years, when estuarine production of aquatic organisms is enhanced (Jassby et al. 1995). Although much of the carbon from river-floodplain sources may not be bioavailable (Jassby et al. 1996), floodplain organic carbon still remains a potentially major contribution to the estuary. As evidence, our results demonstrate that the Yolo Bypass can be a modest exporter of phytoplankton, a high quality source of organic carbon for the food web. In 1998 chlorophyll *a* (an indicator of phytoplankton biomass) trends downstream of the Yolo Bypass closely followed the floodplain hydrograph, with a peak as floodwaters receded (Figure 5), presumably caused by shallower water, increased residence time, and warmer temperature in the floodplain. As noted by Sommer et al. (2001), enhanced primary productivity is unlikely to be a result of agricultural fertilizer use in the bypass because nutrients are rarely limiting to phytoplankton in the San Francisco estuary. Modeling studies by Jassby and Cloern (2000) also confirm that Yolo Bypass is an important local source of phytoplankton. Post-flood blooms of phytoplankton have been reported for tropical (Schmidt 1973; Garcia de Emiliani 1997) and temperate locations (Heiler et al. 1995; Hein et al. 1999).

Higher floodplain production of phytoplankton may be relatively brief in Yolo Bypass; however, it still probably represents an important carbon subsidy to the downstream estuarine food web. Phytoplankton are responsible for most of the primary production in the estuary (Jassby et al. 1996), but there has been a major long-term decline in biomass (Lehman 1992). Reasons for reduced phytoplankton biomass include the effects grazing by introduced bivalves (Alpine and Cloern 1992), water exports and outflow (Jassby et al. 1995), and climate change (Lehman 2000). To illustrate the magnitude of this decline, Alpine and Cloern (1992) found that mean annual chlorophyll *a* concentrations decreased from >10 $\mu g/L^{-1}$ in 1980 to less than 1 $\mu g/L^{-1}$ by 1990 in Suisun Bay, a major rearing area for estuarine fish and invertebrates.

The degree to which the floodplain contributes invertebrate biomass to the estuary remains to be determined. As noted previously, sampling to date shows that Yolo Bypass zooplankton biomass is not higher than the adjacent Sacramento River during floodplain inundation (Figure 3d). The drift invertebrate results (Figure 3e) suggest that invertebrate production within the floodplain is substantial; however, we have not determined how much of this biomass is used by downstream consumers.

Summary

Yolo Bypass was originally constructed based on engineering considerations. At the turn of the century, a passive floodplain system was the most reasonable approach given the extreme seasonal and annual variability in California hydrology. Its economic effectiveness versus conventional levees and dams has not yet been evaluated, but the fact that the system has not failed after many decades of operation suggests a high degree of success. Moreover, the Yolo Bypass appears to provide substantial benefits to aquatic, terrestrial, and wetland species, while still being compatible with agriculture. Although the system is an engineered basin rather than a natural floodplain, it shares some ecological characteristics with the natural large river-floodplain systems described by Junk et al. (1989). Like natural floodplains, habitat diversity

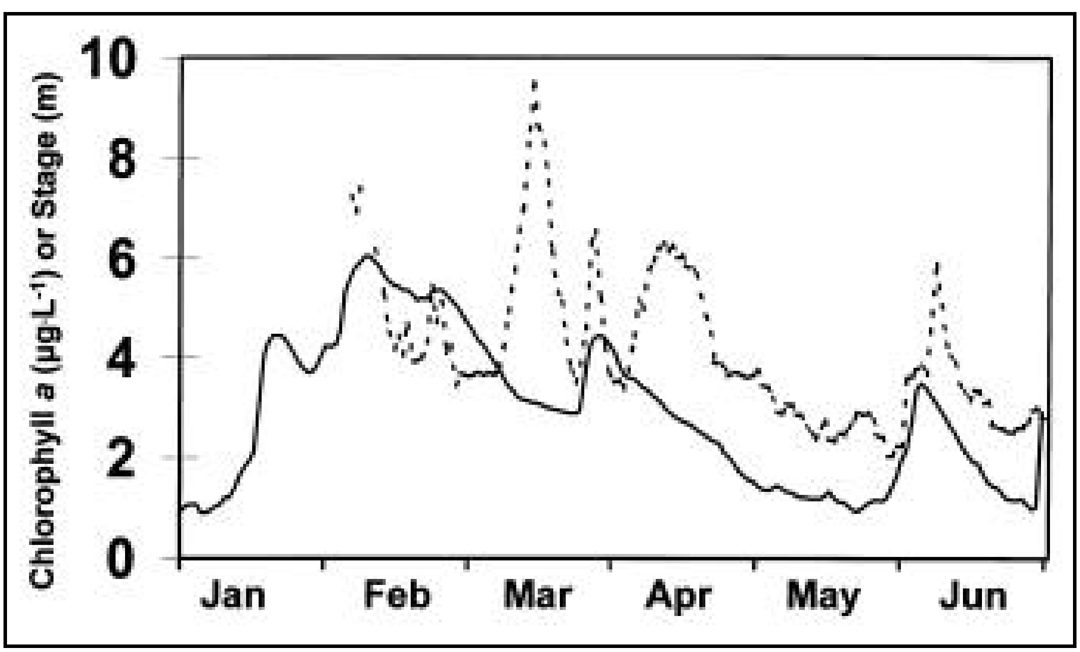


Figure 5. Chlorophyll *a* ($\mu g/L^{-1}$; solid line) trends as measured using a fluorometer (Turner Designs) at Rio Vista and Yolo Bypass floodplain stage (m, NGVD datum; solid line) versus date during January–June 1998. Rio Vista is located at the confluence of the Sacramento River and the outflow from the Yolo Bypass.

in the Yolo Bypass is much higher than adjacent river channels. Yolo Bypass has a mosaic of habitats including wetlands, ponds, riparian corridors, and upland areas, whereas the adjacent Sacramento River is a relatively homogenous channel bordered by steep levees covered with riprap or some vegetation. Junk et al. (1989) note that natural floodplain production from lower trophic levels is a major input to channels, which is consistent with Yolo Bypass drift insects and phytoplankton exports to downstream areas. Finally, our data on splittail and salmon growth support the observations of Junk et al. (1989) that more natural river-floodplain systems can result in higher fish production on the floodplain than in the river channels.

On the whole, we believe that the Yolo Bypass example discussed here provides strong support for the use of a carefully designed and engineered floodplain as an alternative to conventional flood control techniques. This is not to say, however, that the Yolo Bypass is optimally designed. Examples of possible improvements to the Yolo Bypass include the construction of more wetlands for wildlife, fixing fish passage and stranding problems at the floodplain weirs, and increasing the frequency of floodplain inundation in drier years. These and other actions are being considered as part of the CALFED (2000) program, an ambitious state, federal, and local effort to resolve long-standing problems in the San Francisco Estuary and its tributaries. We acknowledge that the Yolo Bypass model is not wholly applicable to many areas. For example, the Missouri River shows bimodal flood pulses in March–April and June (Galat et al. 1998), making crop production before July less feasible in that region's floodplain. While large areas of Missouri River floodplain are also managed to promote fall and spring use by migratory waterfowl, overwintering is not a primary habitat function as in the Yolo Bypass. As a consequence, regional analyses are needed to determine the compatibility of different land uses in potential engineered floodplain projects.

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