Multi-Objective Analysis for Ecosystem Reconciliation on an Engineered Floodplain: The Yolo Bypass in California's Central Valley

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Using Multi-Objective Analysis for Ecosystem Reconciliation on an Engineered Floodplain: the Yolo Bypass in California's Central Valley

Abstract

Floodplains in California and elsewhere are extremely productive habitats with high levels of biodiversity, yet they are often permanently disconnected from rivers by urban or agricultural development. This poses a potential threat to the many native fish, bird and other species that evolved to take advantage of seasonal floodplain inundation. The traditional restoration approach to this problem would recreate historical floodplain in some places by restoring natural hydrologic and successional processes. However levees, dams, and development prevent this approach in much of California. Reconciliation ecology recognizes this limitation, and encourages instead the re-engineering of human dominated landscapes so that native species and human uses can sustainably co-exist. Flood control bypasses are a particularly promising location for reconciling historical fish and bird uses of floodplain habitats with human uses. However the reconciliation approach requires nuanced management of a complex multi-purpose system. This study proposes the use of formal multi-objective optimization to help planners choose management options that best improve habitat quality for fish and birds with minimal costs to farmers or wetland managers. Models like the one developed here can integrate large amounts of data and knowledge, and explicitly account for the relationships and tradeoffs among different objectives. This is especially useful in reconciliation planning where many uses and variables interact on a landscape, and deliberate re-engineering requires considering many decisions simultaneously. Results suggest several land use changes and inundation management strategies on the Yolo Bypass that can significantly improve seasonal bird and fish habitat at very little cost to farmers and other human uses. The model applications herein demonstrate the usefulness of multi-objective optimization in reconciling managed floodplains, and provide a framework for integrating new knowledge and testing varying assumptions to improve management over time.

Chapter 1

The Yolo Bypass as a Case for Floodplain Reconciliation

INTRODUCTION

This study presents a multi-objective analysis for balancing ecological goals with human uses on the Yolo Bypass: a highly engineered floodplain in the Central Valley of California. Floodplains are widely known to provide extensive ecosystem and societal values. Despite this, most temperate climate, mid-latitutde floodplains are disconnected from their rivers or severely downsized and altered, with a rate of disappearance much higher than that of most other landscape types. (Bayley 1995, Sparks 1995, Ward, Tockner and Schiemer 1999, Tockner and Stanford 2002, Keddy et al. 2009, Opperman et al. 2010, Tockner et al. 2010). Recognition of the ecological importance of floodplains has spurred growing global interest in floodplain conservation and restoration (Keddy et al. 2009, Bayley 1995, Welcomme 2008). On the west coast of the United States, and California in particular, studies have noted the special roles of floodplains in the life history strategies of native fish and birds, their importance as sources of primary productivity for downstream estuaries, and their roles in water quality improvement and flood attenuation for urban areas (Jones & Stokes 2001, Sommer et al. 2004, Sommer et al. 2002, Ahearn et al. 2006, Feyrer, Sommer and Harrell 2006a, Trowbridge 2007, Jeffres, Opperman and Moyle 2008, Opperman et al. 2010, Cloern 2007, CVJV 2006).

Today over 90% of California's floodplains are disconnected and inactive, following over a century of land development and flood control efforts (Mount 1995, Kelley 1989). Once a vast seasonal "inland sea" that was inundated almost every year, California's Central Valley floodplains have been developed for urban and agricultural uses and disconnected from most of its major rivers by a vast network of levees (Kelley 1989). This disconnection and conversion of the landscape has filled permanent water bodies, drained most marshes, removed riparian forests, eliminated vast networks of distributary channels, and prevented the exchange of water, sediment and nutrients between river channel and floodplain (Welcomme 2008, Florsheim and Mount 2003).

The end result has been a more than 90 percent reduction in California's wetland habitat and resources for the diverse set of species adapted to seasonal floodplain inundation (CVJV 2006, Ahearn et al. 2006). This has contributed to large population declines in an increasing number of floodplain-dependent fish and bird species, spurring a growing regional interest in restoring and conserving remaining floodplain landscapes to help recover these species (U.S. Department of the Interior et al. 2013, CVJV 2006).

In doing so, policy-makers have two options: 1) traditional restoration, and 2) reconciliation. Traditional restoration typically aims to restore habitat to a pristine state similar to what existed before human development. Reconciliation ecologists recognize that opportunities for this kind of restoration are limited, and so instead promote the re-engineering of human-dominated landscapes in a way that also serves the habitat needs of native or other desired species (Rosenzweig 2003). For floodplains, traditional restoration relies on reconnecting large areas of the historical floodplain to a river with a naturally varied hydrology, to reinstate the dynamic processes that make floodplains so productive (Tockner and Stanford 2002, Opperman et al. 2010). The idea behind these restorations is that the river itself does the work of conserving and restoring floodplain habitats through restored physical and successional processes (Tockner and Stanford 2002). Success depends on the ability to reproduce the magnitude, frequency, duration, timing and predictability of floods, and to recreate a diversity of flooding processes (Tockner, Malard and Ward 2000). An example is the restored Cosumnes River floodplain in California. The Cosumnes River has no significant upstream dams and thus a naturally varying hydrograph (except for direct and groundwater diversions). A coalition of non-profit organizations and state and federal agencies purchased agricultural land adjacent to the river and breached levees to reconnect the river to the floodplain. This re-established the physical and biological process needed to restore floodplain functions. The successful ecosystem restoration project improved wetland and successional riparian communities, restored access to high quality floodplain habitat for foraging salmon, and led to the successful reproduction of several native fishes (Florsheim and Mount 2003, Jeffres et al. 2008, Ahearn et al. 2006).

While a success on the Cosumnes, this kind of restoration is not feasible in much of California. Upstream dams (removing natural flow variability) and vast human settlements and development of floodplains make most of the state’s historical floodplains unavailable for full re-connection to a natural flow regime. However, in places like the Sacramento Valley, large portions of the river’s historical floodplain remain partially connected to the river by seasonal flood bypasses. These bypasses provide opportunities for an important potential alternative (reconciliation), and locations where ecosystem functions might be maintained on some of the state’s already multi-use floodplains.

The following sections provide more detail on the state's historical, natural floodplains, and compares them to modern flood bypasses. This is followed by a discussion of reconciliation ecology and ways in which managed floodplains (bypasses and others) are still beneficial for floodplain-dependent species, even without all natural processes and habitats fully restored. Finally, focus is given to the Yolo Bypass itself, and its role as a case study for the reconciliation approach to floodplain management.

THE HISTORICAL FLOODPLAIN

In its broadest definition, a floodplain is land that is periodically inundated by flows from a nearby river channel (Opperman et al., 2010). A floodplain can be delineated in three ways: 1) Hydrologically as the area inundated with a given probability or recurrence interval; 2) Geomorphologically as the area with soils from recent alluvial depositon, or 3) Ecologically as the area colonized by flood-adapted organisms (Tockner and Stanford 2002). No matter the delineation used, floodplains are highly productive ecosystems characterized by fluctuation and mixing between terrestrial and aquatic communities, and dynamic physical and biotic processes that accompany variously sized and timed flood pulses (Junk 1996, Tockner et al. 2010, Vilizzi et al. 2013).

Opperman et al. (2010) suggest three different types of floods that support a naturally functioning floodplain: (1) The Floodplain Activation Flood is a small and relatively frequent flood pulse large enough in size and duration to activate significant ecological processes on the floodplain (Williams et al. 2009). These floods provide habitat for those aquatic and wetland species who’s life history strategies depend upon the near-annual availability of foraging, spawning and shelter opportunities on the floodplain, and promote nutrient and organic matter exchanges between the river and floodplain (Opperman et al. 2010). (2) The Floodplain Maintenance Flood is large enough to perform the geomorphic work that maintains topographic complexity on the floodplain, including erosion and sediment deposition. And finally: (3) The Floodplain Resetting Flood is a large, infrequent flood causing widespread scour and potentially even channel relocation. These large floods create topographic and vegetative heterogeneity and open spaces, while also resetting the successional processes of riparian forests. This creates a mosaic of diverse habitat patches that become available to organisms during more common activation floods. These temporally and spatially varying floods work together to create high levels of hydrological and structural complexity on the floodplain, and encourage the transport of nutrients and foods to flooded habitats and ecosystems, making floodplains supportive of high levels of biodiversity. (Cloern 2007, Vilizzi et al. 2013, Ahearn et al. 2006, Tockner and Stanford 2002, Opperman et al. 2010, Bellmore et al. 2013)

A diversity of habitats and exchange of nutrients also help to make floodplains highly productive. Several studies show that primary productivity on the floodplain greatly outpaces that of the adjacent river channel (Junk, Bayley and Sparks 1989, Ahearn et al. 2006). In a study of the Cosumnes floodplain in California, Ahearn et al. (2006) demonstrated that phytoplankton production is correlated with residence time and depth. During the drain phase of a flood, water turbidity, depth and velocities are low, and nutrients concentrated. Sunlight penetrates and warms the shallow, slow-moving floodwaters, creating a favorable environment for primary productivity (Opperman et al. 2010). These periods of high residence time support the accumulation of phytoplankton, which take advantage of the nutrient-rich flood waters (Henning, Gresswell and Fleming 2006, Bayley 1995, Lehman, Sommer and Rivard 2008).

With abundant food resources, warmer water temperatures, and slower water velocities, native fish species in California (and around the world) evolved to take advantage of floodplain habitats (Jeffres et al. 2008, Moyle, Crain and Whitener 2007). Most importantly, these species often spawn just before or at the beginning of a flood season, so juveniles can use inundated floodplains for foraging and shelter (Junk et al. 1989, Bayley 1995, Halls and Welcomme 2004). Floodplain productivity supports a high invertebrate biomass, which eventually translates into high growth rates for floodplain fishes (Bayley 1995) that can far outpace the growth of fish in the main river channel (Jeffres et al. 2008). Fish that utilize the high growth conditions on floodplains can grow larger and reduce predation losses once they leave for the larger river channel or ocean (Katz et al. 2013) Floodplains also increase survival by providing more room for juvenile fish, with fewer competitors and a refuge from predators (Thorpe 2008).

Waterbirds also take advantage of the vast resources available on floodplain wetlands, using inundated habitats for rearing and foraging. Plant species and invertebrates available on floodplain wetlands are high in protein, providing an important fuel source for adult birds in the middle of winter or spring migrations, and for ducklings that, like juvenile fish, need to grow quickly to increase their liklihood of survival (CVJV 2006, Smith, Rollins and Shinn 1994). Many other species (vegetation, invertebrates, and some terrestrial) also evolved to these diverse, dynamic, and seasonal habitats. Kelley (1989) provides a vivid description of the diversity and density of life in California's historical Central Valley floodplains:

> *"Thousands of antelope, tule elk, and deer grazed the Valley floor in drifting bands… and the Valley's many small and larger watercourses were full of fish… birds of all descriptions swept overhead in flocks that could darken the sky…The river's channel could never contain within its natural banks the huge flows of water that almost annually poured out of the canyons of the northern Sierra Nevada. Signs of yearly flooding were everywhere apparent… Together, the ponds in the basins annually created a vast inland sea a hundred miles long occupying the centerline of the Sacramento Valley which slowly drained back into the river channels and down through the delta during the spring months."*

Because floodplain productivity and biodiversity are so closely tied to variable hydrologic and geomorphic processes as described above, engineered bypasses can seem a questionable replacement for the floodplains of pre-development past. The following paragraphs describe the development of flood bypasses in California, and compares them with their historical floodplain counterparts.

FLOOD BYPASSES

Directly following the Gold Rush in California, hydraulic mining contributed so much sediment to river channels that rivers often aggraded above the surrounding floodplain (Mount 1995). The U.S. Army Corp of Engineers responded to this flood risk by re-aligning and channelizing the rivers. Tall levees were constructed directly along the main channel, causing higher flow velocities to scour the excess sediment (Mount 1995, Kelley 1989). While largely successful in transporting hydraulic mining debris downstream, a problem with relying purely on levees built close to the main channel is that large storm events must be contained within a relatively narrow river channel. This causes river stages to rise much higher than before, and increases pressure on the levee systems.

Conversely, connected floodplains provide greater conveyance capacity and storage for overbank flows, attenuating floods as they move downstream and reducing pressure and scour on flood control structures (Mount 1995). It is estimated that levee failures have been responsible for about a third of all flood disasters in the United States, many of which could have been avoided if the river was given an outlet to flow onto a part of its historical floodplain (Pinter 2005). For this reason, the last century has seen a growing interest in providing more "room for the river" in flood-prone areas worldwide (Klijn, Buuren and Rooij 2004). A bypass is one way to do this: Engineers direct high flows onto the floodplain using carefully placed weirs and training levees, so that uncertainties are minimized, urban centers protected, and river levees are less likely to breach in large floods.

Bypasses are especially important in the Sacramento Valley flood control system, where the historical river channel only carried a small percentage of almost annual winter peak flood flows and relied on adjacent low-lying basins to carry most of the discharge (James and Singer 2008). After several decades of severe flooding in the Sacramento Valley, engineers in the early 1900s realized that the river's levee system would need to be accompanied by a series of bypasses with much higher flow capacities than the river channel itself (James and Singer 2008, Kelley 1989, Stutler 1973). This eventually resulted in the Sacramento River Flood Control Project (Figure 1.1), which contains approximately 1760 km of levees (James and Singer 2008) and 3 major bypasses, including the Yolo Bypass, connected to the river by a series of weirs and smaller bypasses (DWR 2010). These bypasses can convey up to four times the flow of the

Sacramento River (Mount 1995), transforming them into the main river channel during the valley's largest floods. In this way, the bypasses act as the natural floodplain once did, conveying most of the river's flood flows over parts of the valley floor.

However, flood bypasses differ from natural floodplains in many ways. They are engineered systems, limited in size by encompassing levees, only spatially connected to the adjacent river by a few weirs, temporally connected during less frequent high flows that are moderated by upstream dams, and dominated by surfaces leveled for agriculture and flood carrying capacity rather than by successional riparian forests and varied topography. Because connectivity and flows are moderated by levees, weirs and upstream dams, the floodplain maintenance and floodplain resetting floods described by Opperman et al. (2010) do not occur or function on flood bypasses as they do on more natural floodplains. Sediment deposition, erosion, and successional vegetation are largely limited to areas just downstream of the few weirs that connect the bypass to the river. Any other sediment deposition is typically removed to maintain human uses like agriculture and flood control. Also, distributary channels and floodplain water bodies are nonexistent. Overall, bypasses engineered for flood control lack the hydrologic, vegetative, and topographic variability that define a naturally functioning floodplain (Opperman et al. 2010).

Notes:

The American River has two capacities for the reach from Carmichael Bluffs to the State Exposition: 115,000 cfs with a freeboard of 5 feet, or 152,000 cfs with a freeboard of 3 feet

The capacities depicted on this map are from the 1957 Design Profile and Operations and Maintenance Manuals and do not represent existing system capacities. The capacities shown on this map represent only those pertaining to leveed channel systems.

These capacities represent an estimate made at a specific time with limited resources. The existing system capacitites, in some cases, may differ substantially.

Figure 1.1. Map of State Plan of Flood Control Facilities in the Sacramento River Basin. Source: California Department of Water Resources, State Plan of Flood Control Descriptive Document. Available at: http://www.cvfpb.ca.

However, such bypasses do connect to the river at least once every two to three years. The persistence of these more moderate floods, similar in some ways to floodplain activation floods in more natural systems, creates the opportunity for reconciliation on flood bypasses. As discussed in more detail below, many invertebrate, fird, and fish species can still take advantage of flooded bypass habitat. Reconciliation on these bypasses becomes largely a matter of optimizing the land use, timing, and duration of flows to better accommodate native species, without eliminating human uses like flood control, agriculture, and wetland management.

RECONCILIATION

> *"Our task is epic and dramatic, monumental and clear. People have already engineered the Earth's habitats. The time has come to learn how to do that without endangering most of the world's species. Then we must merely re-engineer the entire Earth, but this time, responsibly."* (Rosenzweig 2005)

Reconciliation is a relatively recent strategy in conservation biology. It is based on several ideas. First, one of the few generally accepted laws in ecology is the species-area relationship, which states that large areas contain more species than small ones (Rosenzweig 2003). Further, desireable ecosystems typically have high levels of native biodiversity, often indicated in aquatic systems by the abundance and diversity of native fish species (Hanak et al. 2011). Finally, reconciliation ecology recognizes that almost all of the earth's surfaces and ecosystems are forever changed by human use and activities, that many inevitably contain alien species, and that restoration is therefore not viable as a stand-alone strategy (Rosenzweig 2005, Moyle

2013). Planners, engineers, economists, ecologists, and other experts will have to work together to find ways to modify anthropogenic landscapes so they also can sustain a variety of wild species, thereby giving some species back their geographical ranges without eliminating human uses or occupation (Rosenzweig 2003).

Floodplains are a good example of the need for and promise of a reconciliation approach. While being important sources of biodiversity, floodplains also benefit human societies. As discussed above, floodplains are important to many urban flood control systems. They also provide aquifer recharge, operational flexibility for water supply, aesthetic value, recreational opportunities, educational opportunities, water quality improvements, and food via agricultural production and fishing (Tockner and Stanford 2002, Bennett and Goulter 1989, Tockner et al. 2010, Junk 1996, Hanak et al. 2011). Finally, when disconnected from their rivers by levees, floodplains provide land to develop adjacent to, and sometimes on top of, one of the most important basic needs of the world's urban and agricultural centers: water. These reasons have caused over 90% of California's Central Valley wetlands to disappear, a large percentage of which was seasonally inundated floodplain or permanent floodplain waterbodies (Shuford, Page and Kjelmyr 1998, Ahearn et al. 2006, Whipple et al. 2012). Of the remaining floodplains, most are engineered bypasses or designated overflow basins rather than naturally connected wild landscapes.

Humans will probably never completely disengage from their interaction with and use of floodplains, or reverse their effects on natural floodplain ecosystems. Therefore, if some remnants of prior floodplain function are to be preserved in California and elsewhere, then rare instances of full restoration will need to be supplemented and supported by much more extensive reconciliation of floodplains within modified systems. Even downsized and altered floodplains can be important reserves of ecosystem functionality. Because so few opportunities exist for full-scale restoration, reconciliation of managed floodplains (like bypasses) is an important complimentary strategy for recovering floodplain-dependent species.

Tockner and Stanford (2002) come to a similar conclusion about the status of European floodplain management, asserting that with over 90% of floodplains already cultivated, those developed floodplains that retain even some semblance of natural functions are worthy of protection. And in his famous paper describing the ecology of floodplains, Junk (1996) suggests that management strategies be developed that maintain principle floodplain functions while being economically viable in the long term, inherently recognizing the need for ecosystem planning to be consistent with human needs.

Managed floodplains are already showing significant promise for reconciliation. Many years of waterfowl management in California's Central Valley, and studies of productivity and fish use on California's bypasses, suggest bypasses can retain substantial ecosystem functions that significantly benefit at least the fish and birds that evolved to take advantage of historical floodplain inundation in the valley (Feyrer, Sommer and Harrell 2006b, Feyrer et al. 2006a, Lehman et al. 2008, Sommer et al. 2001, Benigno and Sommer 2008, CVJV 2006, Duffy and Sharon 2011, Fleskes et al. 2007, Earl 1950). As an example, Elphick (2000) showed that flooded rice fields can function in much the same way as seasonal wetlands for many waterbird species. Sommer et al. (2001) concluded that highly modified floodplains might maintain important functional characteristics for Chinook salmon when connected to adjacent rivers. These studies (and many others) suggest an alternative to full, process-based floodplain restoration for the recovery of at-risk, flood-dependent species.

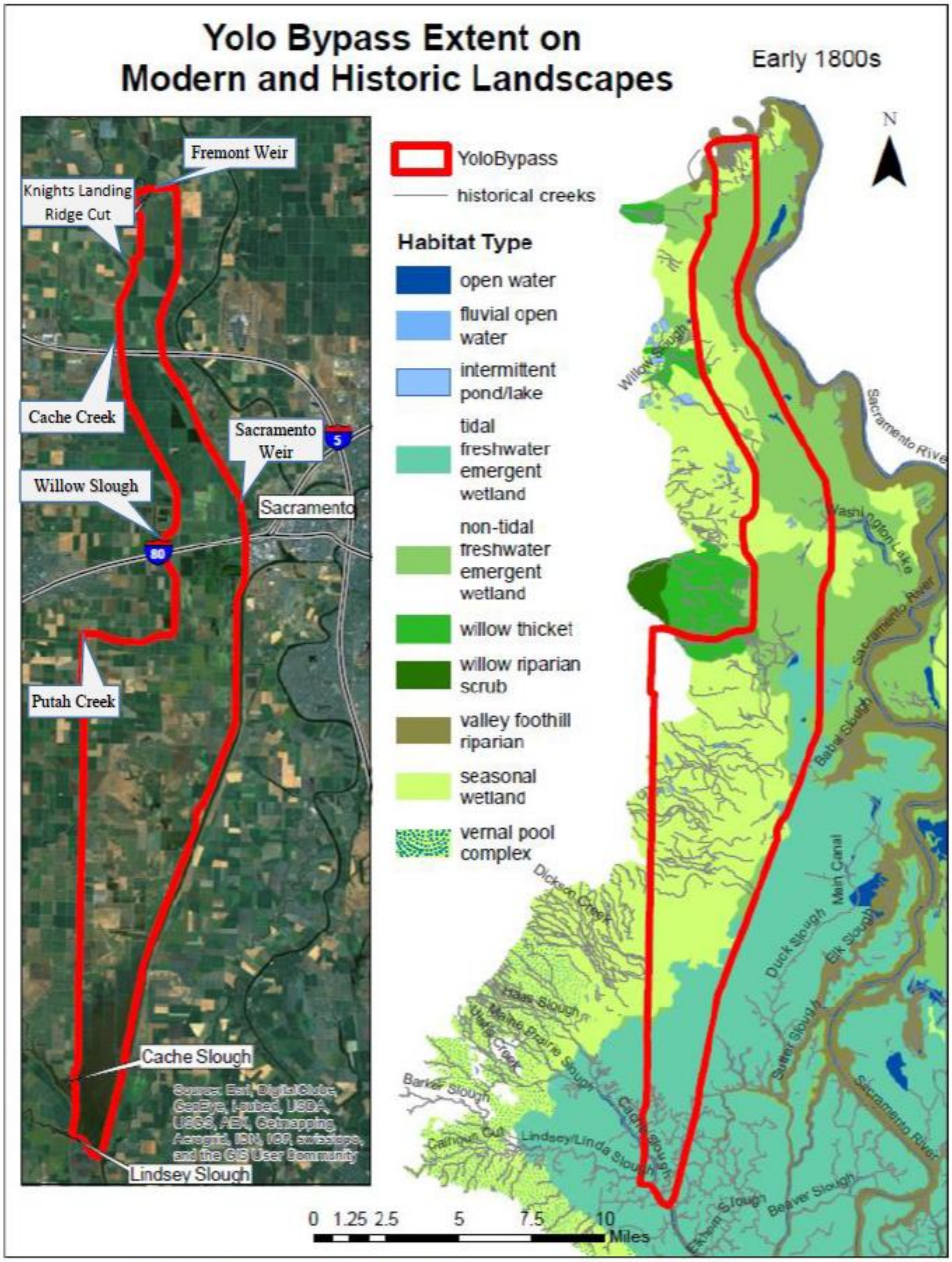
The Yolo Bypass (the Bypass) is particularly promising for ecosystem reconciliation for four reasons: 1) It already provides significant benefits to native fish and bird species, while remaining a vital component of the Sacramento area's flood control system, of Yolo County's agricultural economy, and of the Central Valley Joint Venture management plan for native waterfowl and shorebirds. 2) The Bypass is a large area – full inundation of its 59,000 acres doubles the wetted area for the Sacramento-San Joaquin Delta (U.S. Department of the Interior et al. 2013). 3) It's existing water supply and drainage infrastructure provide opportunities for purpose-specific management of varied flows and land uses, and, most importantly: 4) Lessons learned on the Bypass are applicable to similar flood bypasses elsewhere in the state and world. The following sections describe the history, current land uses, and management of the Yolo Bypass, and identify the opportunity for systems analysis tools to identify promising opportunities for better reconciling ecological and human goals.

THE YOLO BYPASS

Like other flood bypasses in the San Joaquin and Sacramento River watersheds, the Yolo Bypass serves multiple functions that vary in prominence with location and time of year. When water flows over its main upstream weir (the Fremont Weir) or otherwise enters the Bypass in winter and spring, inundated areas can serve an ecological function as foraging, spawning and rearing ground for the Sacramento splittail and Chinook salmon. Managed wetlands (both public and private) scattered throughout the Bypass require water and dry land at specific times for pond and mudflat habitat creation, and management of moist soil plants. Farmers grow rice, tomatoes, grain, pasture and other crops, with planting and harvesting times (and thus water and dry land needs) that vary depending on the crop and conditions in the current and previous year. Several landowners in the Bypass have created private duck clubs for hunting, and bird watchers visit the publicly managed wildlife area to watch migrations in spring and fall. Finally, the Bypass's primary purpose is for flood control when the Sacramento River exceeds channel capacity (usually in January or February). This flood purpose requires that all other land uses not reduce the floodplain's ability to convey the design flood flow.

Before flood control and agricultural development of California's Central Valley, the Sacramento River's lower reaches would almost annually inundate large parts of its vast floodplain, as well as migrate laterally within its valley confines. The floodplain in some places stretched as wide as 30 miles, and was predominantly covered in dense stands of tules (Kelley 1989). As discussed in previous sections, the first half of the 20th Century saw an almost complete disappearance of that floodplain, as cities and agricultural landowners dammed the river, leveed its channels, and drained the floodplains. Now, the Sacramento's lower effective floodplain is usually reduced to a system of bypasses only a mile or two wide, with fixed locations relative to the main channel. The Yolo Bypass is the lowest bypass, just above the Sacramento-San Joaquin Delta. It occupies what was once the seasonally flooded edge of historically perennial wetlands (Whipple et al. 2012), a landscape of extensive seasonal marshes and some permanent water bodies (Stutler 1973). It is thought that this habitat was extremely productive and exported large quantities of organic matter to the Delta (Ahearn et al. 2006).

Figure 1.2 outlines the Bypass's position within the valley's current landscape, compared with the historical landscape.



Sources: San Francisco Estuary Institute-Aquatic Science Center and The California Department of Fish and Game

Figure 1.2. The modern Yolo Bypass (left) with western tributaries, weirs, and connections to the Delta (Cache and Lindsey Slough), compared to the location of the Yolo Bypass wtihin the historical floodplain (right).

The Yolo Bypass was named and engineered by the California Debris Commission as a part of the "Jackson Plan" of 1910, eventually adopted within the State Flood Control Act of 1911 (Kelley 1989). It is 42 miles long, from 1.25 to 2.5 miles wide, with a flood carrying capacity that grows from 343,000 cfs at its upstream end where water flows over the Fremont Weir, to 490,000 cfs where the Bypass discharges its floodwaters into the mouth of Cache Slough at the southern end (Stutler 1973). Aside from the Fremont Weir, other inflows include the Sacramento Weir (just upstream of the confluence between the Sacramento and American Rivers), and four western tributaries: Knights Landing Ridge Cut, Cache Creek, Willow Slough, and Putah Creek (Figure 1.2).

Chapter 3 of the Bay Delta Conservation Plan (U.S. Department of the Interior et al. 2013) provides a nice overview of flood frequency on the Bypass: During the heart of winter (December 1st – February 15th), when large storms are more common, the Bypass floods in 61% of water years. The frequency of inundation decreases into the late winter, with flooding in less than 50% of years between February 16th and March 23rd. Some years also have flooding from a large snowmelt event in April or May. Some Bypass inundation has occurred in approximately 70% of water years between 1968 and 2003, with a wide range of durations from 0 to 135 days (Jones & Stokes 2001).

Many ecologists and biologists agree that these flood events provide essential spawning and rearing habitat for the native Sacramento splittail and also increase growth rates and survival of native juvenile Chinook salmon that take advantage of the Bypass's extensive food supplies (YBMS 2001, Sommer et al. 2001, 2004, 2005; Feyrer et al. 2006, Williams et al. 2009). Feyrer et al. (2006b) found that annual system-wide production of splittail is positively related to production on the Bypass, following on a study by Sommer et al. (2002) which found that splittail used several different habitat types during Bypass inundation. Early life stages were found in shallow habitat near sources of flow and emergent vegetation. Larger fish used deeper water in open and vegetated areas. The study concluded that it would be prudent to provide a mosaic of floodplain habitat types in the design of any restoration project.

Similarly, young migrating Chinook salmon benefit greatly from Bypass inundation. Sommer et al. (2001) found that Chinook salmon that rear in the Bypass floodplain have higher apparent growth rates than those remaining in the Sacramento River, especially during longer duration flood pulses. A more recent study involving experimental rearing of salmon in designated rice fields on the Bypass suggests that rice stubble can be particularly good rearing habitat (Katz et al. 2013).

Several studies have also reported higher rates of primary productivity on the Bypass due to longer residence times, high surface to volume ratio, and high temperatures (Sommer et al. 2004). Schemel et al. (2004) found that chlorophyll a concentrations reach levels beneficial to primary consumers as the floodplain drains, and that average chlorophyll concentration on the lower Bypass during late March 2000 was higher than in the Delta. This productivity increases invertebrate availability for fish, as evidenced by a study comparing fish diets in the Bypass versus the Sacramento River (Sommer et al. 2001). High productivity may also act as a source of organic carbon to organisms downstream in the Delta, similar to the role historical floodplains once played (California DFG, Yolo Basin Foundation and EDAW 2008).

These ecological benefits of Bypass inundation suggest that Yolo Bypass flooding parallels historical floodplain functioning within the aquatic ecosystem in significant ways, even without the same variation in hydrology and other physical and biological processes. Sommer et al. (2001) point out some ecological characteristics that the Bypass shares with the natural large river-floodplain systems described by Junk et al (1989): (1) Higher habitat diversity relative to the Sacramento River; (2) Drift insects and phytoplankton exports to downstream areas, and (3) Higher fish production than in the river.

Inundation serves another ecological purpose on the Bypass as managed and agricultural wetlands for waterbirds. The state-run wildlife area provides seasonal and permanent wetland for hundreds of species, including various dabbling ducks, geese, shorebirds, and hawks (California DFG et al. 2008). Some agricultural crops also provide usable habitat (Elphick 2000, Shuford et al. 1998). This wildlife area is so vital to waterbirds that the National Audubon Society has classified it as a Globally Important Bird Area (California DFG et al. 2008). Private landowners in the Bypass also have the option of entering into one of several available government programs that incentivize development and maintenance of waterfowl and bird habitat. The Partners for Fish and Wildlife, Conservation Reserve Enhancement, and Presley programs provide a few examples (California DFG et al. 2008). These programs offer payment to landowners in exchange for habitat creation and maintenance for waterfowl and other birds.

Bird activity in the Bypass in late winter and early spring varies by species. Many, like the cinnamon teal and gadwall, are in the midst of their migration to wintering grounds further south, and require food supplies from December through February to fuel the remainder of their long flights to Mexico and/or Central America (Ducks Unlimited 2013). Some birds, including the northern pintail, white fronted geese, and shorebirds like the snowy plover, overwinter in the Bypass itself or elsewhere in Califorina's Central Valley, remaining longer (and thus foraging longer) before migrating back towards Alaska or the Canadian Arctic (Ducks Unlimited 2013, CVJV 2006). Another class of birds resides in the Bypass year-round, breeding during the late spring and summer (California DFG et al. 2008, Earl 1950). In general, dark geese populations are highest in January, duck and white geese populations are highest in February, and shorebird populations peak in March and April (CVJV 2006).

Timing, however, is not the only factor affecting foraging habitat for waterbirds. Access to food supplies also requires that water not be too deep for various species to eat the seeds or invertebrates that are plentiful near the ground. Dabbling ducks, for instance, cannot forage in water deeper than 18 inches, and prefer water depths of less than 10 inches (Petrik et al. 2012, Taft et al. 2002). Shorebirds need even shallower habitats, preferring water 2 to 6 inches deep, the availability of which is potentially limiting in winter (Taft et al. 2002).

Regardless of the exact timing and depth of foraging, all of these birds depend on moist soil management for wetland plants in the spring to ensure nutritious food supplies in the following fall and winter. Management of these plants is an attempt to recreate some of the habitat and food supplies that were available in the historical Yolo Basin. An example is swamp timothy, an important food source for pintails and green winged teal as they arrive in the fall: Birds eat the seeds of the plant, which "facilitate the accumulation of fat reserves and the restoration of nutrients expended during molt and migration" (Smith et al. 1994). The branch structure of swamp timothy also provides a good substrate for invertebrate production (California DFG et al. 2008), which becomes an important food in the late winter and early spring. Optimal swamp timothy growth in the Sacramento Valley requires that wetlands be drained between April 15th and 30th, before other less nutritious vegetation takes over or the growing season becomes too short for necessary summer irrigations (Smith et al. 1994). The other moist-soil plant commonly grown in the Central Valley is watergrass (Naylor 1999), requiring a later drawdown of May 1st through 31st (Smith et al. 1994, Naylor 1999).

In addition to these managed moist-soil plants, waterfowl and shorebirds also depend on flooded rice and other agricultural crops for winter and spring food supplies (Elphick and Oring 2003, CVJV 2006, Shuford et al. 1998). Agricultural habitats in the Yolo Basin actually provide 79% of the "food energy" available to ducks, making it an extremely important addition to managed wetlands as foraging habitat (CVJV 2006). Similar to moist soil environments, when the seeds and other plant material of these agricultural food sources have all been consumed, fields continue providing a protien source from invertebrates.

Agriculture is the dominant land use on the Bypass, and compliments the system's flood control mission in that the land remains well-graded with good drainage to the Toe Drain (the Bypass's main internal channel along its eastern border) (Howitt et al. 2013, Stutler 1973). Bypass agriculture also provides significant benefits to the local economy (Howitt et al. 2013). Soils and climate are most condusive to agriculture in the north, where the predominant crops are rice, corn, tomatos, melons, and safflower (Jones & Stokes 2001). Further south, and especially below Putah Creek, grazing becomes dominant as a cooler climate makes rice and other farming more expensive and/or difficult (Howitt et al. 2013, Jones & Stokes 2001, Stutler 1973).

RECONCILIATION IN THE YOLO BYPASS

Because such a diverse array of fish, invertebrates, and waterbirds all already benefit from and function within this largely agricultural landscape, the Yolo Bypass might already be considered a reconciled ecosystem. In many ways this is true, especially considering how many agricultural land uses and vegetation seem to provide reasonable substrate and food supplies for both fish and birds. However there remains room for improvement.

Although the Bypass still experiences floodplain activation floods that clearly facilitate the exchange of nutrients and organic matter between the river and floodplain, there is a major difference between the current and historical Yolo Bypass in the timing and duration of those flows. While water still enters the floodplain in most years, it does not necessarily stay as long as it used to, arrive at the same time, nor pulse on and off as often. Williams et al. (2009) define the Floodplain Activation Flow (FAF) for historical Sacramento River lowlands as the river stage that is exceeded in at least two out of three years and sustained for at least seven days between March 15 and May 15. Analysis of hydrologic data found that overflow from Fremont Weir into the Bypass during this FAF interval only occurs an average of 6.5 days once in every 4 years (Williams et al. 2009). This implies that Bypass inundation does not currently occur frequently or long enough during the appropriate months to be most useful for native fish species and the food web they depend on.

Current planning efforts reflect this. Chapter 3 of the Bay Delta Conservation Plan (BDCP) calls increased inundation in the Yolo Bypass the most promising opportunity for enhancing seasonally inundated floodplain for covered species in the Central Valley (U.S.

Department of the Interior et al. 2013). The BDCP proposes notching the Fremont Weir to increase flood frequency (and duration) in the winter and spring, with largest potential gains in March and April. Figure 1.3 shows how this might allow Bypass managers to more closely mirror historical flooding in the Central Valley. The Bypass could also be improved in other ways for native fish, including improved passage at Fremont Wier between the river and floodplain (U.S. Department of the Interior et al. 2013).

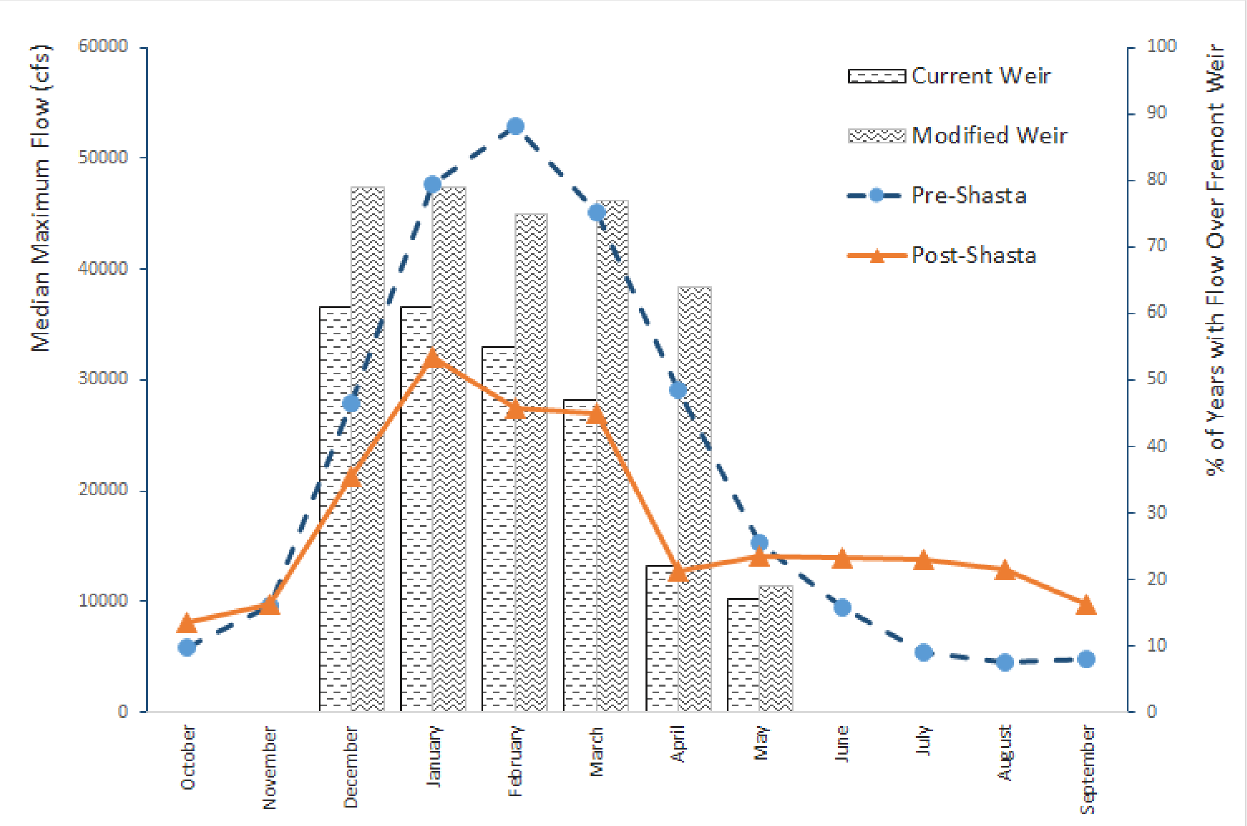


Figure 1.3. Median monthly high flows in the Sacramento River at Red Bluff, before and after the construction of Shasta Dam (Source: waterdata.usgs.gov), and proposed monthly increases in flood frequency on hte Yolo Bypass (U.S.D.O.I., 2013). Reservoir operations flatten out the flow distribution through time, decreasing the liklihodd of flooding in the winter and especially in the spring. Proposed modifications to the Fremont Weir seek to increase availability of flows during these months to more closely resemble historical flooding.

However additional inundation in the bypass is a controversial idea. While farmers receive cheaper land rents for Bypass leases because of flood easement obligations, inundation too late in the spring is nevertheless costly (Howitt et al. 2013). Timing depends on the particular crop, but some fields need to be prepared as early as March to maximize growing season and yields (Howitt et al. 2013). Similarly, waterfowl biologists and wetland managers worry that drawdown dates for moist-soil plants might be delayed with extended flooding, reducing food supplies for the next years' bird populations, or that deep inundation may make lands unavailable as foraging habitat for dabbling ducks and shorebirds (Petrik et al. 2012).

MULTI-OBJECTIVE ANALYSIS FOR A RECONCILED YOLO BYPASS

As planners move towards an engineered solution to bring more water onto the Bypass, there is a need to develop creative management alternatives that place and control these flows. Ideally, these alternatives would consider ways to reorganize the landscape or manage the timing and placement of added water so that aquatic ecosystem functioning is best reconciled with human economic interests and waterbird management.

However, the Bypass is a complex system, and ecological and economic goals interact with each other and the landscape in different ways. Traditional restoration efforts focus mostly on restoring natural processes to a landscape, so those processes can work to re-create preferred habitats for targeted native species. However within reconciled landscapes, natural processes are forever modified by human activity. Creating habitat for native species within these new landscapes requires very deliberate and strategic engineering on the part of land and water managers, so useable habitats exist in a landscape without the purely natural processes that once created them. This is certainly true for the Yolo Bypass, where human uses prevent full restoration of floodplain processes, vegetation, and topography.

This study proposes formal multi-objective optimization as a tool to help further integrate land and water management on the Bypass and develop alternatives that account for tradeoffs among fish habitat, bird habitat and human uses. Models like this one can help in reconciliation efforts by integrating large amounts of data and knowledge into one place, and providing a formal representation of decision variables, objectives, and the relationships among them (Loucks, Stedinger and Haith 1981). This allows decision-makers to choose management options with a more transparent and holistic understanding of how each choice effects the major objectives.

This study uses the constraint method to generate a set of non-inferior solutions that estimate tradeoffs among three management objectives for the Yolo Bypass: 1) economic revenues from agriculture, hunting and recreation, 2) habitat quality for waterfowl and shorebirds, and 3) habitat quality for Chinook salmon and Sacramento splittail. A solution is considered non-inferior (or Pareto-optimal) if no other solution exists that can better performance towards one objective without decreasing performance towards another objective (Cohon 1978). Solutions focus on the land use mosaic and the timing, placement and duration of flows, with implications for how flow management and land use might change with varied priorities.

Chapter 2 describes the construction and parameterization of a Yolo Bypass Multi-objective Optimization Model (YBMOM) for designing managed floods in the winter and spring of otherwise dry years, and provides a few small proof of concept applications. Chapter 3 describes sensitivity analysis and further develops the non-inferior solution set, with conclusions focusing on the tradeoffs among birds, fish and fowl on the bypass, and detailed land and water management implications for various prioritizations of those objectives. Finally, some thought is given to the policy implications of this work, and ways it could be applied to future management of the Bypass and other similar systems.

Chapter 2

Building a Multi-Objective Optimization Model for Economic and Ecosystem Uses on an Engineered Floodplain

"A measure of the success of any systems study resides in the answer to the following questions: (1) Did the study have a beneficial impact in the planning and decision-making process? (2) Did the results make the debate over the proper choice of alternatives more informed? And (3) Did it introduce competitive alternatives which otherwise could not have been considered?" (Loucks et al. 1981)

INTRODUCTION

Floodplains are some of the most biodiverse ecosystems on the planet, and also among the fastest disappearing (Bayley 1995, Opperman et al. 2009, Sparks 1995, Tockner and Stanford 2002). Prior to reclamation, the Sacramento River in California flooded almost every year, forming riparian forests and vast expanses of permanent and seasonal wetlands. Today, over 90% of those wetlands are gone, disconnected from rivers by a vast system of levees and replaced by agricultural and urban development. This translates to a loss of seasonal habitat for native bird, fish, and other species that evolved to take advantage of the floodplains' seasonal inundation. However some floodplains remain episodically connected in the form of flood control bypasses. These bypasses (Figure 1.1) are important for urban and rural flood protection because they allow strategic diversion of large amounts of floodwaters onto a portion of the historical floodplain, taking pressure off the mainstem levee system and greatly increasing the system's capacity for carrying large floods without flooding urban areas.

While located on the historical floodplain, bypasses differ greatly from their historical counterparts – they are graded for agricultural drainage or to reduce roughness during flood events, are connected to the river in only one or two locations via concrete weirs, and are not inundated with the frequency, duration, timing, or volume that occurred before levees and dams were developed. This moderated form of connection to the river means that bypasses lack the topographic, vegetative and hydrologic heterogeneity so important for floodplain ecosystems (Figures 1.2 and 1.3). Despite this shortcoming, bypasses are the largest expanse of episodically connected floodplain remaining in the Sacramento watershed, and there is some evidence that they still provide important habitat for fish, bird and invertebrate species.

This makes these bypasses excellent cases for a reconciliation ecology approach to habitat management for native species in California's Central Valley. Reconciliation ecology recognizes that traditional restoration, which restores natural processes to bring a landscape back to pre-development conditions, is no longer possible in most places (Hanak et al. 2011, Rosenzweig 2005). Species survival depends instead on the ability to re-engineer human dominated landscapes in ways that also support desired (usually native) species (Rosenzweig 2003, Moyle 2013).

Re-engineering a landscape for multiple human and ecological purposes can sometimes be very complicated. Tools like the computer model developed here can help to integrate large amounts of data, explicitly define objectives, constraints, and possible management decisions, and describe the relationships among decisions and objectives. This study uses the lowest bypass on the Sacramento River, the Yolo Bypass, as a case study for the application of multi-objective optimization to ecosystem reconciliation of an engineered floodplain. Results suggest that such tools are extremely helpful in describing and integrating important aspects of floodplain management in a holistic and consistent way, and can help guide reconciliation so ecological goals are met with less significant cost to human uses.

THE YOLO BYPASS

The Yolo Bypass (the Bypass), when flooded, serves as the transition between the Sacramento River watershed and the tidal sloughs of the Sacramento-San Joaquin Delta (Figures 1.1 and 1.2). The main source of inflow to the Bypass is its upstream Fremont weir, which begins overtopping when Sacramento River stage exceeds 33.5 feet. Other inflows include the Sacramento weir, and four smaller western tributaries: Knights Landing Ridge Cut, Cache Creek, Willow Slough, and Putah Creek. These western tributaries typically only add significant flows to the Bypass in wetter years when the Fremont weir is also overtopped, but can sometimes cause smaller localized flooding in other years (California DFG et al. 2008). The Bypass has the capacity for up to four times the flow of the main stem Sacramento River, making it an important component in the area's urban flood control system.

The Bypass also has proven especially important for Chinook salmon and Sacramento splittail as spawning and rearing habitat, with higher rates of productivity and growth than in the main-stem river (Feyrer et al. 2006b, Sommer et al. 2001, Schemel et al. 2004). However, longer, more frequent, and more strategically timed inundation on the Bypass could better mimic the historical floodplain, making it even more productive and accessible to the fish that still depend on it (Williams et al. 2009, U.S.D.O.I. 2013). Because of this and its size, California's

Bay Delta Conservation Plan (BDCP) hails the Bypass as the best opportunity for enhancing seasonally inundated floodplain for covered fish species in the Central Valley (U.S.D.O.I. 2013). The plan proposes building a gated notch in the Fremont weir (Figure 1.2) to introduce and manage additional flows. Frequency and duration of flooding is expected to especially increase in late February through early April (Figure 1.3, Table 2.1).

Table 2.1: ***Summary of BDCP's list of potential operations for a gated notch in the Fremont Weir.***
Data Source: BDCP Chapter 3, Tables 3.4.2-1 and 3.4.2-2 (U.S.D.O.I. 2013)

	Dec 1 – Feb 15	**Feb 16 – Feb 28**	**March 1 – March 23**	**Mar 24 – April 10**	**April 11 – May 15**
Current % of Years with Fremont Weir Overflow	61	50	47	22	17
Potential Frequency of Inundation w/ Modified Weir (% of Years)	69 - 89	67 - 75	72 - 81	61 - 67	19
Proposed Volume (cfs)	Up to 6,000	Up to 6,000	Up to 6,000	Up to 6,000 **only in years with natural overflow (currently 22% of yrs)*	Up to 6,000 **only in years with natural overflow*
Targeted Flood Extent (acres)	17,000	17,000	7,000 – 10,000	7,000 – 10,000	7,000 – 10,000
Proposed Duration	30 – 45 days or longer	30 – 45 days or longer	30 days	30 days	30 days
Targeted Species for Floodplain Habitat (does not include passage)	Winter-run & Spring-run Chinook salmon, and Sacramento splittail	Fall, Winter & Spring-run Chinook salmon, and Sacramento splittail	Fall, Spring and Butte Creek Spring-run Chinook salmon, and steelhead		Late Fall-run Chinook salmon, and steelhead

However the Bypass is also home to a robust agricultural economy and managed wetlands that serve ducks, geese, and shorebirds (many of which migrate along the Pacific

Flyway), and recreational hunters and bird watchers (Jones & Stokes 2001, Howitt et al. 2013, California DFG et al. 2008). And while the BDCP provides some detail on the volume and timing of added flows to maximize potential use by targeted fish species, it does not make an attempt at nuanced management of those flows to achieve balance among the system's multiple uses (Salcido 2012). The challenge is to find a way to manage land and added flows on the Bypass in ways that reconcile fish and bird use without serious economic losses for farming or other human users. This type of reconciliation planning is especially important for places like the Sacramento watershed, where few opportunities remain for true restoration of historical habitats, and human interaction is a permanent feature of the environment (Hanak et al. 2011, Rosenzweig 2003, Salcido 2012).

Because the Bypass is already managed for flood control, farming, and waterfowl, it offers many ways to re-engineer the system for multi-objective management that includes new fish habitat. Countless gates, canals, and other control structures allow for the strategic movement and retention of water across varied land uses. A precedence already exists of leveraging this infrastructure for ecological use in managed wetlands, where gates and carefully constructed ponds provide strategically timed foraging, nesting, and/or loafing habitat for targeted bird species (Salcido 2012, California DFG et al. 2008). There is no physical reason this functionality cannot be extended to fish habitats, but there is some concern that varying depth and other habitat preferences make fish and bird habitat mutually exclusive.

While the system's complexity is advantageous in that is allows for nuanced management of land and water, it also presents a challenge in that there are many intricate combinations of potential decisions. It is difficult to know which land use changes and flooding decisions provide the most gains, or whether there are ways to engineer other modifications that further optimize the system. This study develops and applies a multi-objective systems model to better define the Bypass's most important management objectives and decision variables, quantify tradeoffs, and suggest promising land and management changes. The model focuses mostly on managed flooding in those weeks for which frequency of inundation is likely to increase the most, and for which the highest number of water bird and fish species are most dependent upon flooded habitat: February through April (Table 2.1 and Appendix A). Results will provide decision-makers with a more robust understanding of how to best leverage various Bypass characteristics for birds, fish, farmers, and recreational users.

BRIEF INTRODUCTION TO MULTI-OBJECTIVE OPTIMIZATION

Many studies have pointed out the difficulty of applying traditional net present value or benefit-cost methods to complex water issues like flood protection infrastructure or wetland management; such issues have diverse implications for different groups which are often difficult to represent in a single index of evaluation (Woodward et al. 2013, Bennett and Goulter 1989, Loucks et al. 1981). The Yolo Bypass is a good example of such difficult multi-objective problems, with economic and flood protection values to human users and habitat values to fish and birds. Multi-objective optimization is well-suited to problems with diverse objectives that are difficult to evaluate solely with dollar values. One study specifically recommends the use of multi-objective programming for wetlands-related questions, concluding that some wetland functions are often impossible to measure in purely economic terms, including the provision of habitat for many of the world's threatened or endangered species (Bennett and Goulter 1989).

Unlike benefit-cost or net present value analysis, multi-objective optimization does not identify a single optimal solution. Instead, it provides an explicit consideration of the relative value of varied decisions by defining and evaluating alternatives that represent different compromises among conflicting groups or management objectives (Loucks et al. 1981, Cohon 1978). More formally, multi-objective methods seek to identify a set of non-inferior alternatives that should be considered given the system's goals, variables, and constraints. A solution is non-inferior (or Pareto-optimal) if no other solution exists that can improve one objective without decreasing performance towards any of the other objectives (Cohon 1978). Another way to look at the set of non-inferior solutions is as a representation of the trade-offs among different objectives (Woodward et al. 2013).

The use of formal mathematical models in multi-objective analysis further helps decision-makers by providing an explicit description of important aspects of the system (objectives, constraints, manageable variables, and relationships between those variables and the system's objectives) and providing a record of all data and assumptions (Loucks et al. 1981, Cohon 1978). This is especially true if the mathematical model is built within widely-accessible software. The following sections describe the formulation and construction of an MS Excel spreadsheet model for enhanced flows on the Yolo Bypass and highlight some important lessons learned in quantifying those objectives and their relationship to decision variables. Finally, the model is tested against several years of land use data from Yolo County, and applied to the question of added benefit for fish and birds that could have been achieved had additional, managed flows been available in those years. This application of the model allows some insights about the tradeoffs among fish, birds, and economic returns on the bypass, and the value extra water could bring.

MODEL FORMULATION

If more water becomes available in drier years on the Bypass from a modified Fremont Weir, managers will have four decisions they can make to alter bird habitat, fish habitat, and economic performance: 1) Land use mosaic, 2) flooded acreage by land use type, 3) depth of flooding, and 4) time of year (and duration) of flooding. All together, these four land and water management decisions for different parts of the Bypass create 3,168 variables that take the form A_{jtid}: acres of land use j in zone i, flooded to depth d in week t.

There are three main objectives for land and water management on the Yolo Bypass in the late winter and early spring: profit (or net revenues), fish habitat, and bird habitat. These objectives are each constrained by the requirement that the Bypass continue to function well for conveying large floods from the Sacramento River, and by other realities like climate, soil, available acreage, crop rotations, and other habitat and wetland conservation requirements. Net economic returns on the Bypass come primarily from agricultural returns from rice, wild rice, corn, tomato, safflower, and pasture. Managed wetlands sometimes also provide revenue from hunting permits, leases or memberships. Farmers and hunters only obtain profits if the annual cost of business is less than annual gross revenues. Increased inundation could decrease revenues for farmers by reducing the growing season, and could increase or decrease hunting revenues depending on the depth, timing, and extent of increased flows. Net economic returns on the Bypass therefore not only depend on the total acreage of each land use type (and associated per acre revenues), but also upon the depth, timing, and duration of the water applied to those lands.

Mathematically, the economic objective for the Bypass can be written as:

$$Max\ P = \sum_i \left[\left(\sum_j \sum_{\substack{t=start\\date}} \left(A_{jti,d=0} - A_{j(t-1)i,d=0}\right) * R_{jti} \right) - \sum_j \emptyset_{ij} e^{\gamma_{ij} * A_j} \right]$$

[Eqn 1]

where

i = zone (explained in following sections)

j = land use type

d = depth

t = week

$A_{jti,\, d=0}$ = Acres of land use type j in zone i at time t that are no longer flooded.

R_{jti} = the annual gross revenues from land use j in zone i, available for use by time step t.

and $\emptyset_{ij}$ and γ_{ij} are cost parameters for farming A acres of land use j in zone i, taken from an agronomic model of the Yolo Bypass developed for a separate study (Howitt et al. 2013)

The quality of bird and fish habitat on the Bypass (when water is available) depends on similar factors: the availability (extent) and type of land use flooded, depth of flooding, and the timing and duration of flows. All these factors affect the quality of habitat and the abundance of productive food sources like phytoplankton and invertebrates. Forty biologists and ecologists were interviewed and surveyed to develop the weighted "Habitat Quality" objective functions for Yolo Bypass inundation presented below, along with an extensive literature review. Survey results are discussed in detail in Appendix A and reviewed in following sections. The mathematical form is summarized here:

$$Max\ HQ = \sum_{s} \sum_{\substack{t=start\\date}} \omega_{ts}\, \delta_{ts} \sum_{d} \delta_{ds} \sum_{j} \beta_{sA} \left(\frac{A_{jtid} * \alpha_{sj}}{Max\left(A_{jtid} * \alpha_{sj}\right)} \right) + \beta_{sC} \left(\frac{Entropy\left(A_{jtid}\right)}{Max\ Entropy} \right)$$

[Eqn 2]

where

HQ = habitat quality

ω_{ts} = marginal benefit of each additional week of flooding for species s

δ_{ts} = relative importance (weight)of flooding in week t for species s

δ_{ds} = relative benefit (weight)of flooding in depth zone d for species s

B_{sA} and β_{sC} = relative importance of total area and land use types flooded (A) versus complexity (C)for species s, where complexity is expressed with an entropy function.

α_{sj} = the relative weight of land use j for species s

Some Caveats and Importance of Sensitivity Analysis

A famous statistician once said "All models are wrong. Some are useful" (Box and Draper 1987). This is especially true when the model must mathematically express one or more environmental objectives. In reality, the cost or benefit of any flooding scenario to various fish and bird species on the bypass is likely non-linear, and dependent on variable conditions of weather, climate, access to the bypass, health of that year's populations, conditions in other habitats used in other life stages away from the bypass, and one's preferred metric for defining "costs" and "benefits." The habitat quality objective functions presented above are similar to traditional habitat suitability indices, which have been criticized for not considering the potential relationships and correlation structure of the habitat variables (Ahmadi-Nedushan et al. 2006). Multiplying each individual suitability index together for a composite HSI (much like weighted scores are multiplied together in Equation 2) inherently assumes that the organism selects each variable independently of others (Ahmadi-Nedushan et al. 2006).

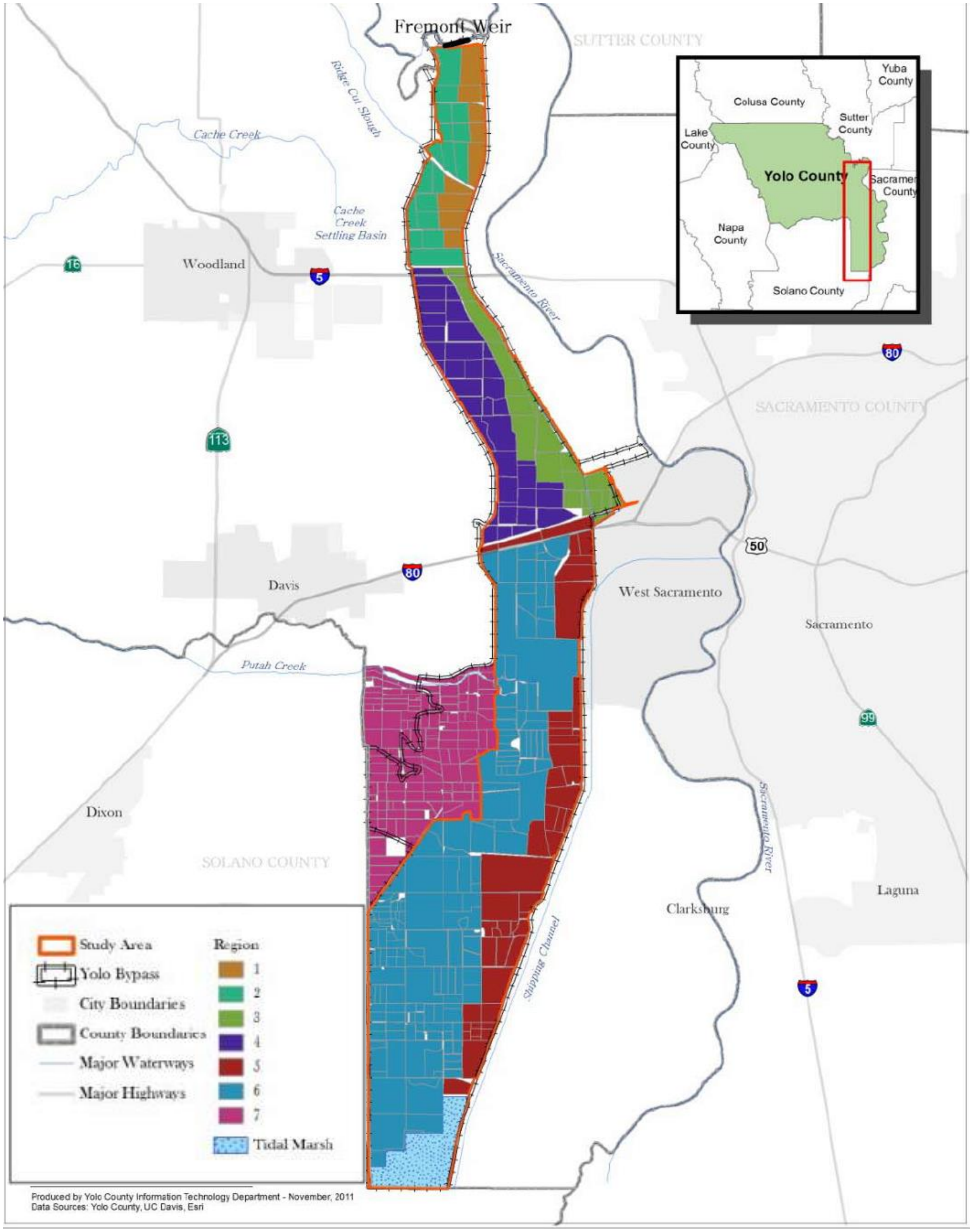
Equation 2 is not meant to be an exact simulation of fish or bird population responses to flooding. It is rather an attempt to characterize, based on currently available understanding, how one would optimally design flooded habitat on the Bypass for a single group of species. The actual response of these species to any set of flood characteristics would need to be evaluated over time. One advantages of having a model available for a system is that the parameters can be adjusted to incorporate new knowledge, and with additional work the underlying functional form of the objective also can be changed, while all other objectives (economic, other species) are still represented. In this way the model can help decision-makers adaptively manage the system by providing a framework for testing the implications of changed assumptions.

The extent to which current inaccuracies in any objective function might change the preferred management strategy on the Bypass can more immediately be tested with sensitivity analysis. The model runs presented here use only the base case parameters and weights in order to provide a proof of concept, leaving broader sensitivity analyses to future applications.

Developing the Economic Objective Function – Agricultural Economics

The profit objective was developed by quantifying the annual per acre revenues and costs of each land use type, and the relationship (if any) those revenues and costs have to the timing and depth of bypass inundation. Agricultural gross revenues per unit area (R_{jti} in Eqn 1) are calculated as price times crop yield for each crop type. Prices are an average of observed 2005 – 2007 prices, taken from the Yolo County Agricultural Commissioner Reports and the National Agricultural Statistics Service. Crop yields depend on the length and timing of growing season, and therefore on the planting date. These time-dependent yield functions were developed using the DAYCENT model, which estimates crop yield on a given field with considerations for production conditions like climate and date the crop was planted (Howitt et al. 2013).

The agricultural cost functions ($\sum_j \emptyset_{ij} e^{\gamma_{ij} * A_j}$) by crop were developed for a model specific to the Bypass using positive mathematical programming (PMP) to simulate farming decisions (Howitt et al. 2013). The model assumes that farmers are profit-maximizers, and thus incorporates marginal production and cost conditions, allowing it to replicate a base year of observed input and output data (Howitt et al. 2013). These marginal conditions can vary by region in the Bypass due to colder climates in the south and varied soil conditions, as well as proximity to processing facilities and management skills (Howitt et al. 2013). Colder temperatures and strong winds across the southern bypass, for example, make it difficult to grow rice (Stutler 1973). The effects of flooding on these regions also varies from east to west, with longer times to drain on the east side, and therefore a further delayed plant date for eastern fields following the last day of flooding from Fremont Weir. Given these variables, the Bypass was split into seven distinct zones for the PMP-based Bypass Production Model (Howitt et al. 2013), shown in Figure 2.1. Only zones 1 – 6 are considered in this study as those that might be inundated by added flooding from a new notch in the Fremont Weir (U.S.D.O.I. 2013, Howitt et al. 2013).



Produced by Yolo County Information Technology Department - November, 2011
Data Sources: Yolo County, UC Davis, Esri

Figure 2.1. Agricultural Zones on the Yolo Bypass. Source: Howitt et al., 2013

Calibrating the Bypass Production Model to a set of given land use data (crop acreage) results in exponential cost functions specific for each zone (*i*) and land use (*j*) (Howitt et al. 2013). For this study, all zones in the model were calibrated to the maximum observed acreage of each crop type (per zone) for the years 2005 through 2009. This acreage was assumed to represent the point at which farmers acted as if marginal costs become larger than marginal revenues, and additional planting no longer increases economic returns. This calibration resulted in crop and zone specific values for $\emptyset_{ij}$ and γ_{ij} applied in the cost term of Eqn 1.

Together, these revenue and cost functions represent total agricultural net returns on the Bypass. Figure 2.2 displays the resultant per acre profits for the Bypass's primary crop types in zone 1, assuming no delay in plant date (i.e. no flooding). In the northern part of the Bypass, rice remains profitable at a much higher total acreage than any other crop, but higher net returns are possible with tomatoes (Figure 2.2). These results have been verified by field data, with rice the dominant crop type in the northern Bypass, and tomato often following.

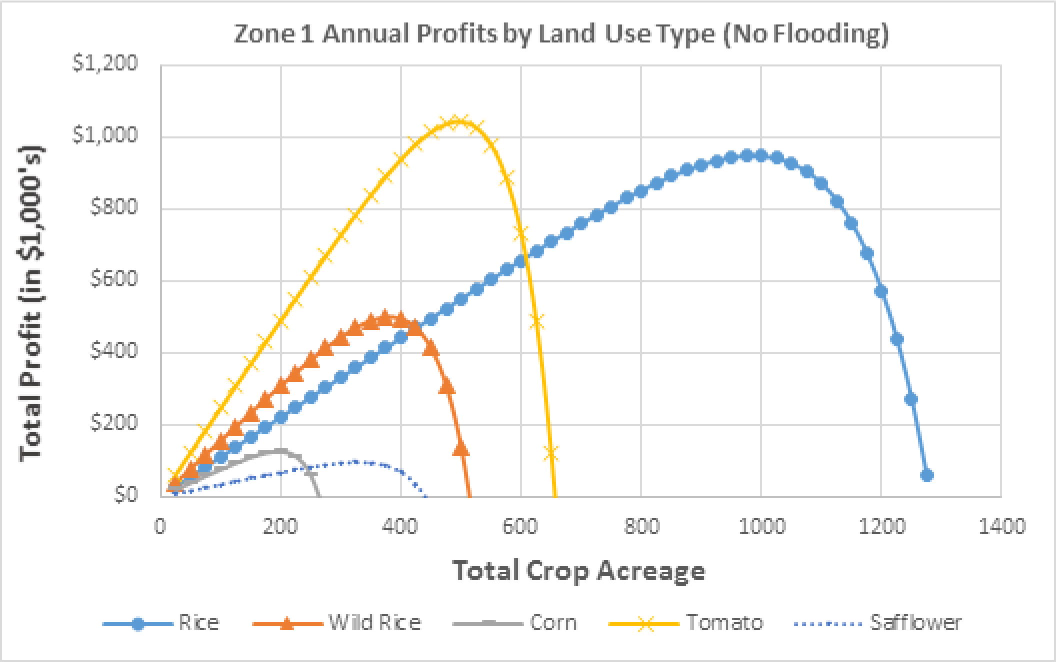


Figure 2.2. Average annual per acre profits for major crop types in Zone 1 on the Yolo Bypass in a dry year.

Developing the Economic Objective Function – Wetland Economics

The above profit functions only capture agricultural land uses. Agricultural land use is currently dominant on the Bypass, with over 30,000 acres of mixed crop and pasture lands compared to about 9,500 acres of managed wetlands. But changing priorities could encourage (and compensate) some landowners to reduce agricultural production and increase wetland services (supporting birds and fish). Although some statewide surveys have captured data on annual wetland management costs (Brown 2013), local costs and revenues can vary widely depending on factors like water supply, mosquito abatement, and land values. Eight local wetland and duck club managers were surveyed about costs and net returns specific to the Bypass (Appendix A).

Annual Costs of Private Wetlands

The average reported annual costs of private seasonal wetland was $160 per acre, ranging from $80/acre to $300/acre. Follow-up interviews with some wetland managers indicated that this variance (even within the bypass itself) is possibly due to differences in management intensity, or varied interpretations of the question: Some respondents only considered the cost of managing the wetlands themselves, whereas others included basic costs of ownership (e.g. for the land, infrastructure, and salaries for paid managers). The higher estimates are probably closer to the true total annualized costs of owning and running a private wetland.

Annual Net Returns from Private Wetlands

Follow-up interviews with survey respondents also provided a better understanding of how private duck clubs cover costs. Duck club revenues come in two forms: a one-time, upfront buy-in, and annual assessments. Interviewees provided data for three clubs on the Bypass, and data was available for a fourth from an online membership listing (Channel Ranch, listed on www.duckclubsrus.com in November, 2013). Annual assessments ranged from $0 to $6000 depending on club size, buy-in value, and provisions (e.g. club house, blinds, etc…), with an average of $1600. Buy-ins ranged from $95,000 to $275,000, with an average of about $143,000, or $7200 when annualized at a 5% discount rate. Taken together, per-member annual revenues average around $8775, which translates to average annual revenues of around $200 per acre. When compared to the annual costs of seasonal wetlands ($160/acre average up to a high-end estimate of $300/acre), these revenues suggest that most private clubs are not netting substantial annual profits. This conclusion is consistent with what some owners and managers reported in interviews.

The spread in these estimates indicates how difficult it is to accurately apply average measurements to truly represent wetland fiscal realities. Owners and managers make many yearly choices that can dramatically change the cost of management. However, the broader story on the Bypass seems fairly consistent in that the per acre profits (if any) from wetland management are very small relative to agriculture. In general, private wetland owners are not running a business in the same way as farmers. Instead, members generally pay the price needed to produce enough waterfowl on the property so that they can pursue recreational activities. When prompted about profitability of existing clubs being affected by increasing wetland area, interviewed managers responded there is a small possibility of declining profits as waterfowl populations on the Bypass may not grow at the rate of newly opened wetland areas. Because of this and annualized net returns close to break-even, our base case model runs assume zero net revenues per unit area for any newly added wetlands.

Other Costs for Public and Private Wetlands

For existing wetlands, there may be some costs of added flooding on the Bypass for moist soil management, or lost access to wetlands during the hunting season from deep flooding. If floodwaters cannot be drained by the prescribed drawdown periods, less desirable vegetation is encouraged in seasonal wetlands and actions are needed to mitigate this invasion (Smith et al. 1994). These actions include mowing, spraying, and extra irrigations, which all require extra labor and potentially some equipment rental. However these costs are small relative to the parallel per acre losses faced by farmers from a similarly delayed growing season (between $24 and $70 per acre for wetlands as opposed to as much as $1500 per acre for some delayed crops). Because they would therefore not significantly decrease the Bypass's overall economic performance, they are ignored. Lost hunting opportunity also is not considered in this early model application because the model does not consider flooding before January 24th.

Developing the Habitat Objective Function

Quantifying the costs and benefits of various flooding scenarios is more complicated for fish and birds than for farmers and hunters. First, there is the question of which metric is most appropriate. Because salmon and splittail have other habitats and many birds are migratory, only spending part of their lives on the Bypass, this study does not attempt the complicated task of relating various flooding scenarios to population-level responses that also depend on conditions elsewhere. Instead, increases and decreases in habitat quality are used as a proxy for the potential benefits or losses for species from flooding. Habitat quality is described in terms of the extent, depth, land use type (or substrate), timing, and duration of a given solution, with some of those variables implying further components of habitat quality like the heterogeneity or complexity of available land uses. Connectivity is ignored; connectivity is assumed with a well-planned notch in Fremont Weir and strategic land and water placement. This assumption will require testing with a 2-D hydrodynamic model of the Bypass in further applications.

This approach is similar to the use of habitat suitability indices (HSI), which seek to quantify an organism's requirements for survival in a particular setting by using various components of habitat (Roloff and Kernohan 1999). Cioffi and Gallerano (2012), for example, use habitat suitability to quantify the ecosystem objective in a multi-objective reservoir operations study. The index typically ranges from 0 to 1, with 0 indicating no habitat preference and 1 indicating maximum habitat preference (Ahmadi-Nedushan et al. 2006). Suitability indices for each habitat characteristic are multiplied together to form a complete HSI. The habitat characteristics relevant for inclusion in the formulation are dependent upon species and life stage (Zheng, Hobbs and Koonce 2009). Most habitat suitability indices for stream fishes are based on some combination of water velocity, depth, area, cover, and substratum conditions (Ahmadi-Nedushan et al. 2006).

A very similar combination of "indices" are applied here in Equation 2, with depth (d) represented as one of six possible weighted (δ_d) zones (0 inches, 2 – 4 inches, 5 – 7", 8 – 12", 13 – 18", and greater than 18"), and area as a percent of the maximum flooded area ($\frac{A_{jtid}*\alpha_{sj}}{Max(A_{jtid}*\alpha_{sj})}$). However Eqn 2 differs from a typical HSI in several ways:

a. The objective function attempts to maximize habitat quality within the Bypass itself, and not across all habitats available to these species. It is focused on added benefit within a constrained reality, rather than overall suitability.
b. Velocity during a managed low-flow event (like those prescribed by the BDCP) is assumed to be relatively low and uniform across most of the bypass, and velocity is therefore not considered.
c. Cover and substrate are described in this study by land use type (j). Substrate is especially important for splittail spawning, and for all bird and fish species as a source of seed or invertebrate food.

d. The timing (t) of flooding is added as an important factor, since species migrate to or through the bypass only during some weeks and months of the year, and weather conditions in different weeks can affect primary productivity.

e. Duration is also considered. Both fish species, for example, require a minimum of 2 weeks inundation for the development of sufficient zooplankton and invertebrate food supplies (U.S.D.O.I. 2013). A marginal added benefit (ω_{ts}) is applied to each additional week of flooding (up to 8 weeks) that transforms the non-linear relationship between duration and fish benefits into a stepwise linear function. Because fish require at least three weeks of inundation but probably see decreasing returns towards the end of a long flood (Appendix A), it is assumed that the third, fourth, and fifth weeks deliver much higher returns than the first and second weeks, and also more than any additional weeks thereafter (Figure 2.3). Detailed information on the relationship between flood duration and bird benefits is discussed in a later section.

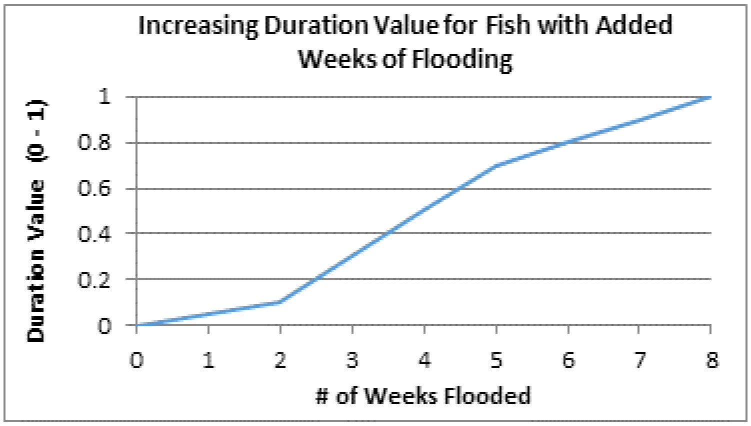


Figure 2.3. ***The duration value for salmon and splittail of any given flooding scenario or solution increases at varied rates with each added week.***

f. Complexity is simplified in this study to mean the variety of different land use types available as habitat, and is generally assumed to be a beneficial attribute of floodplain habitat mosaics for fish and birds. Complexity is measured with an entropy function $\left(\frac{Entropy(A_{jtid})}{Max\ Entropy}\right)$in Eqn 2, where Entropy is typically calculated as $E_t = \sum_j \left[\left(\frac{A_{jt,d>0}}{\sum A_j}\right) * -ln\left(\frac{A_{jt,d>0}}{\sum A_j}\right)\right]$ (Loke et al. 2014). To make the model more efficient, this function is linearlized with new decision variables $A_{j1},\ A_{j2},\ A_{j3}\ and\ A_{j4}$ as follows:

$$E_{jt} = 2.3 * A_{j1} + 0.9 * A_{j2} + 0.4 * A_{j3} + 0.12 * A_{j4}$$

$$\text{Where } A_{j1} + A_{j2} + A_{j3} + A_{j4} \leq \frac{A_{jt,d>0}}{\sum A_j}$$

$$\text{And } A_{j1}, A_{j2}, and\ A_{j3} \leq 0.1,\ \ A_{j4} \leq 0.05$$

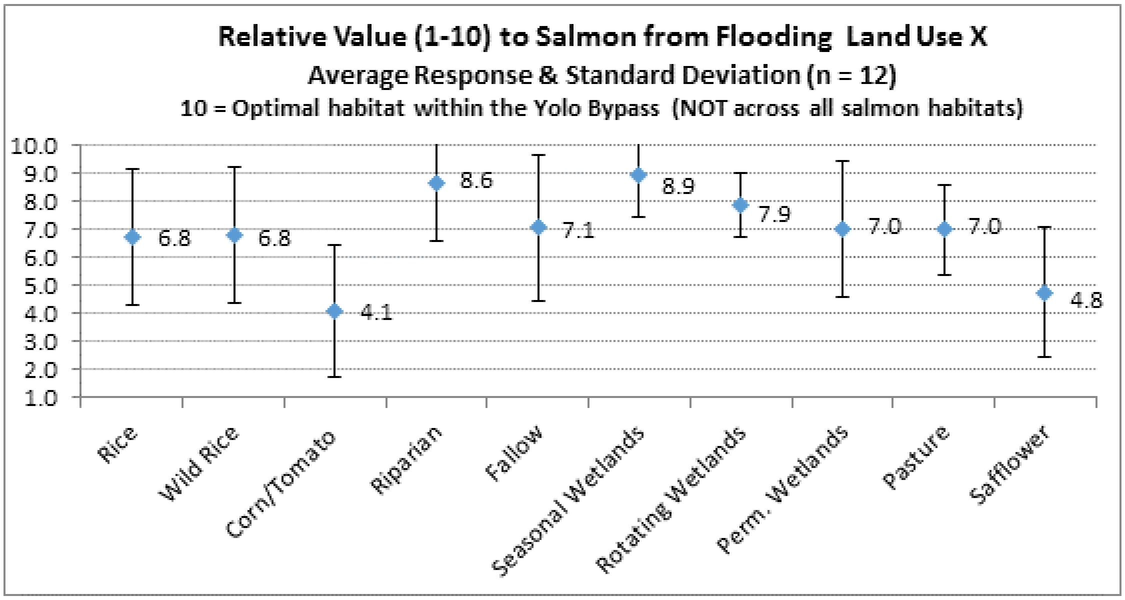
g. Complexity is not multiplied together with other weighted characteristics. It is instead added to a separate term that encompasses area, land uses, and depths of flooding. (It is this second term that more closely resembles typical HSIs.) The sum of these two factors results in total habitat quality for any given week of inundation. Because complexity is represented by the entropy function above, habitat quality can only equal 1 if all land use types are equally valuable. Since some land uses are better habitat for fish and birds than others, the maximum achievable habitat quality is less than 1.

While much is known about the general benefits to fish and bird species of floodplain habitat, less is currently understood about their preferences while on the floodplain itself, especially one like the Yolo Bypass that is almost entirely managed agricultural or wetland land uses not found on historical or more natural floodplains. As such, the weights applied in Equation 2 depend largely on expert judgment to augment the information available in literature. The use of expert judgment in developing ecosystem or habitat-based functions within multi-objective studies is not new (Ahmadi-Nedushan et al. 2006); similar methods were employed for a study of dam removal alternatives on Lake Erie, and to help managers maximize benefits for fish on floodplains in the Murray-Darling basin in Australia (Vilizzi et al. 2013, Zheng et al. 2009).

A full description of the interview and survey process is provided in Appendix A, with questions on species preferences for time of year (on a bi-weekly time-step), area, depth, flooded land use, duration, and the relative value of total area and land use flooded versus the complexity or variability of land uses flooded. Experts were asked to judge each habitat characteristic relative to the best habitat available within the Bypass itself. This exercise helped inform the model and also highlighted questions which merit further research and discussion. There also tended to be very strong agreement about the superiority of some characteristics. These areas of strong agreement may help inform the types of habitat that managers can first look to create, as better understanding is gained about others.

Quantifying Habitat Quality for Salmon and Splittail

Figures 2.4 through 2.6 summarize average expert opinion on salmon and splittail preferences within an inundated Yolo Bypass for land use, depth, and timing. When asked about physical habitat structure and soil-emergent invertebrate food availability for juvenile salmon, experts were in highest agreement about the relative value of seasonal wetlands and pasture (standard deviations of 1.5 and 1.6, respectively), but varied significantly in their opinion on almost all other land uses, with scores for example ranging from 5 (moderate quality) to 9 (very high quality) for rice, fallow, and permanent wetlands (Figure 2.4). Similar responses were given for splittail, although with more agreement about the preferability of wetland and riparian land uses.



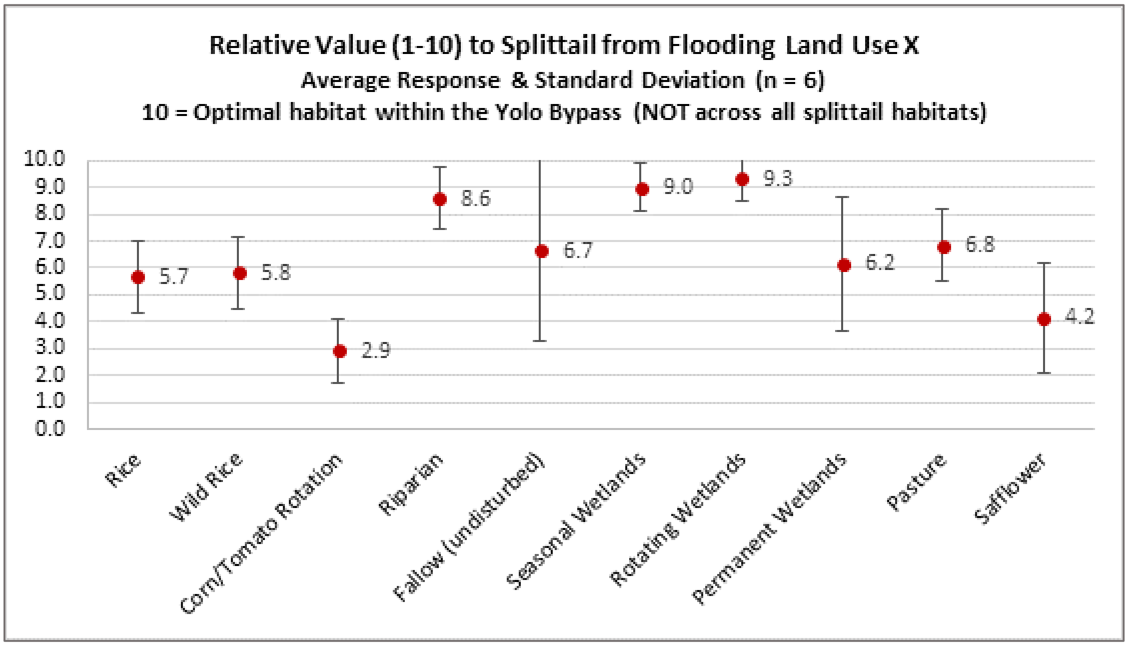


Figure 2.4. Summary of expert responses about the relative value to salmon and splittail of different land use types as substrate and cover. Experts were asked to only consider values relative to the best land use for fish within the Yolo Bypass, and not across all habitat types ever available to either species.

Almost identical responses were given for depth preferences for the two species (Figure 2.5), although again there was less deviation around the splittail responses. In both cases, flooding greater than 13 inches was thought to be good or ideal for both species, and 2-4 inches was either bad or useless. (Note that experts were asked to imagine low flow scenarios, in which the greater than 18 inches range would usually extend no deeper than 3 feet.)

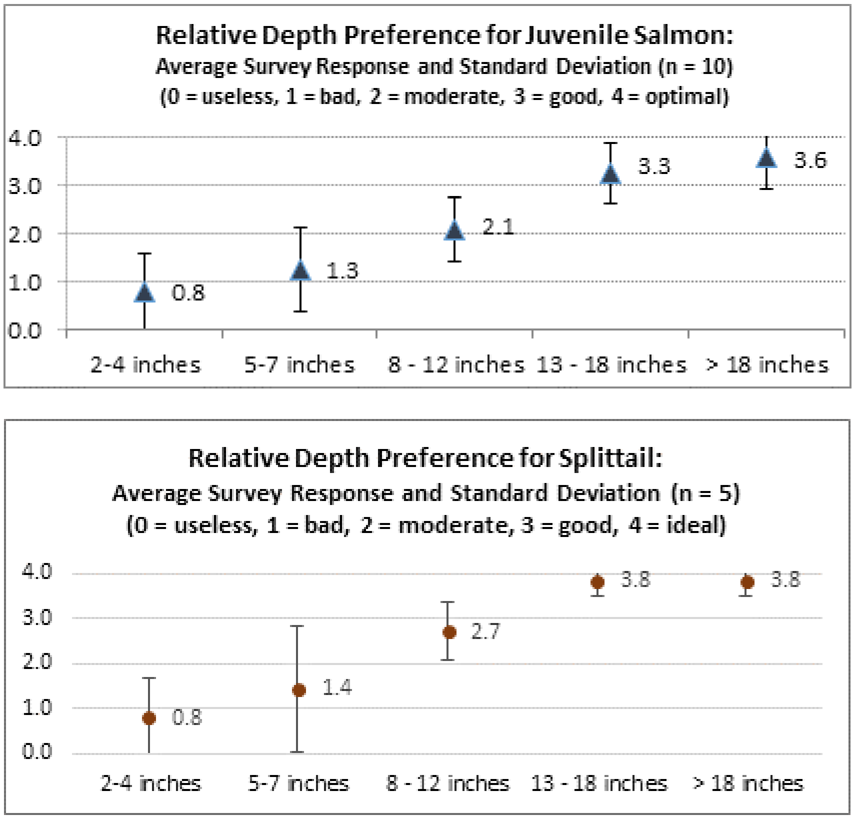
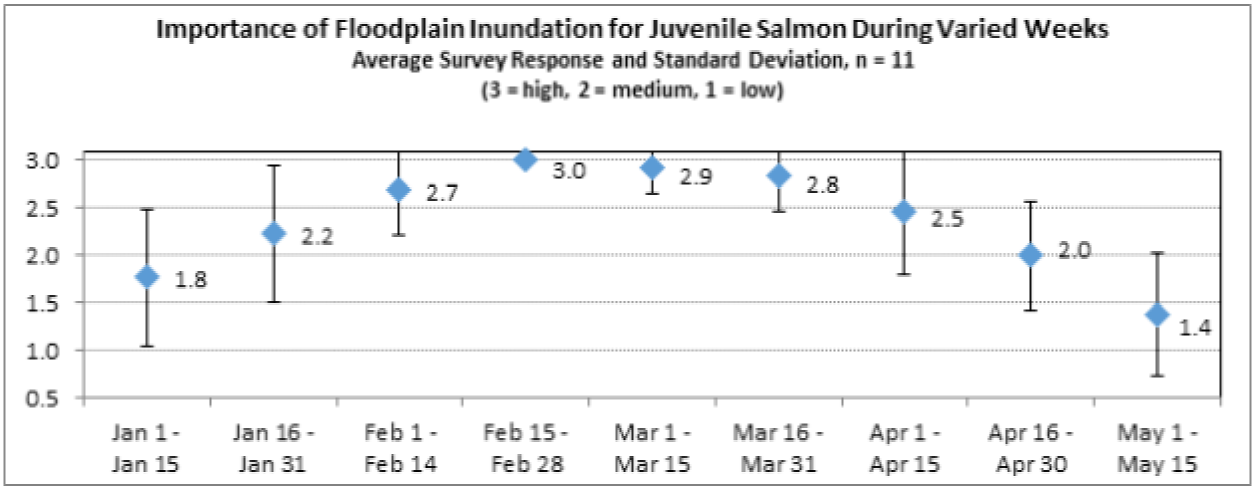


Figure 2.5. Summary of expert responses on the relative usefulness of varied depth ranges for salmon and splittail on an inundated floodplain.

Finally, most experts seem to agree that floodplain habitat is of highest priority to fall-run salmon from February 15 through the end of March and to splittail from March 1st through April 15th, but opinion begins to vary as one moves further away from those dates (Figure 2.6). This is fairly consistent with data presented in the BDCP, which reports that juvenile fall-run Chinook salmon densities are highest in the adjacent Sacramento River between January and April, and splittail are present between March 1 and May 15 (U.S.D.O.I. 2013).



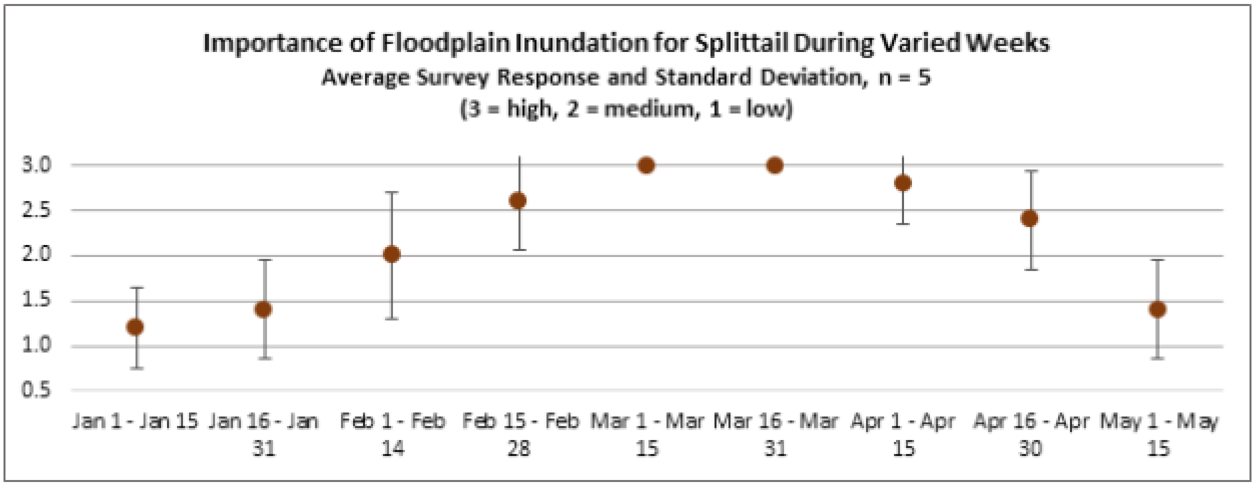


Figure 2.6. Summary of expert responses on the importance of floodplain inundation for salmon and splittail during varied weeks in the winter and spring.

The first model applications presented in this paper use average responses, with one exception in the land use category for rice and wild rice. After the surveys were completed, fieldwork in the northern Bypass found rice to be excellent rearing habitat for juvenile salmon (Katz et al. 2013), and very productive in terms of soil-derived invertebrates that can serve as fish food (Appendix B). Therefore rice and wild rice are both assumed to represent one of the best land uses for juvenile salmon. Because this represents inconsistent methodology, the original survey responses are used in sensitivity analysis to test the importance of this assumption. Results are presented in a later section.

Weights for habitat characteristics were developed by dividing the average response for each characteristic (e.g. depth, land use type) by the highest average score in that category. For example, seasonal wetland received the highest average score (8.9 out of 10) within the land use category for salmon, so each average land use type score was divided by 8.9, for a final value between 0 and 1. This process resulted in the following sets of weights (comparable to individual indices in an HSI):

Table 2.2: ***Relative fish habitat preferences (weights) for varied land use types and time of year.***
Source: Expert Survey, Appendix A

Land Use Type (j)	**Weights (α_{sj})**		**Timing (t)**	**Weights (δ_{ts})**	
	Splittail	**Fall-Run Chinook Salmon**		**Splittail**	**Fall-Run Chinook Salmon**
Rice	0.61	1.00*	Jan 1 - Jan 15	0.40	0.59
Wild Rice	0.63	1.00*	Jan 16 - Jan 31	0.47	0.74
Corn	0.31	0.46	Feb 1 - Feb 14	0.67	0.90
Tomato	0.31	0.46	Feb 15 - Feb 28	0.87	1.00
Pasture	0.73	0.78	Mar 1 - Mar 15	1.00	0.97
Fallow	0.71	0.79	Mar 16 - Mar 31	1.00	0.95
Riparian	0.92	0.97	Apr 1 - Apr 15	0.93	0.82
Seasonal Wetlands	1.00	1.00	Apr 16 - Apr 30	0.80	0.67
Permanent Wetlands	0.66	0.78	May 1 - May 15	0.47	0.46
Safflower	0.45	0.53			

**Rice and wild rice have been proven to be excellent salmon habitat since the administration of the survey. These weights reflect those findings, rather than average survey response.*

Table 2.3: ***Relative fish habitat preference for varied flood depths. Source: Expert Survey, Appendix A***

Depth **(d)**	**Splittail Weights ($\delta_{splittail,\ d}$)**	**Salmon Weights ($\delta_{salmon,\ d}$)**
Zone 1: 2 – 4″	0.21	0.22
Zone 2: 5 – 7″	0.38	0.35
Zone 3: 8 – 12″	0.71	0.58
Zone 4: 13 – 18″	1.00	0.91
Zone 5: > 18″	1.00	1.00

Experts were also asked to distribute "benefit points" (Appendix A) between the two main factors of: (1) Complexity or heterogeneity of flooded land uses, and (2) The total acres flooded, with considerations of depth and land use type. Their answers resulted in the following weights:

Table 2.4: Relative importance of the area and particular land use types flooded versus the overall heterogeneity, or "complexity" of flooded land uses. Source: Expert Survey, Appendix A

Flood Characteristics	**Weight (β_{sA} and β_{sC})**
Total area, depth, and land use types flooded	0.7
Complexity (entropy) of flooded land uses	0.3

Finally, Equation 2 assumes a linear relationship between the number of acres flooded and benefits to fish. Experts were asked if this was a realistic assumption. Many said no, citing a likely carrying capacity after which added acreage does not achieve much added benefit for the fish. However, experts were also asked to choose a range that best represents the minimum acreage needed for inundation to have potential population-scale benefits for salmon and splittail (assuming a good year for each species with passage into the bypass available to them). The average range was 4500 to 9800 acres for salmon and 4300 to 7700 acres for splittail, but standard deviations were very high. Almost half the respondents, for example, thought that at least 10 – 20,000 acres would be required for juvenile salmon. These higher responses agree with BDCP targets (summarized in Table 1) for 17,000 acres of inundation (U.S.D.O.I. 2013). Finally, the amount of added water likely to be available from a notched weir (up to 6000 cfs) is insufficient to flood more than approximately 20,000 acres according to previous hydrodynamic modeling efforts (CBEC 2010). The work here assumes that the model's maximum flooded acreage of 20,000 is below the point of diminishing returns for fish, meaning the assumption of a linear relationship between added acreage and fish benefit is a reasonable simplification. Because this analysis is focused on the optimal use of lower flows brought in through a notched weir, the benefit of added aquatic habitat beyond 20,000 acres is not considered.

Because the weights for each habitat characteristic differ for salmon and splittail, habitat quality for each is calculated separately. Total fish habitat quality is then calculated as an evenly weighted sum: $HQ_{Fish} = 0.5(HQ_{salmon}) + 0.5(HQ_{splittail})$. However, these species-specific weights (0.5 for each) are adjustable and can be tested in future sensitivity analyses.

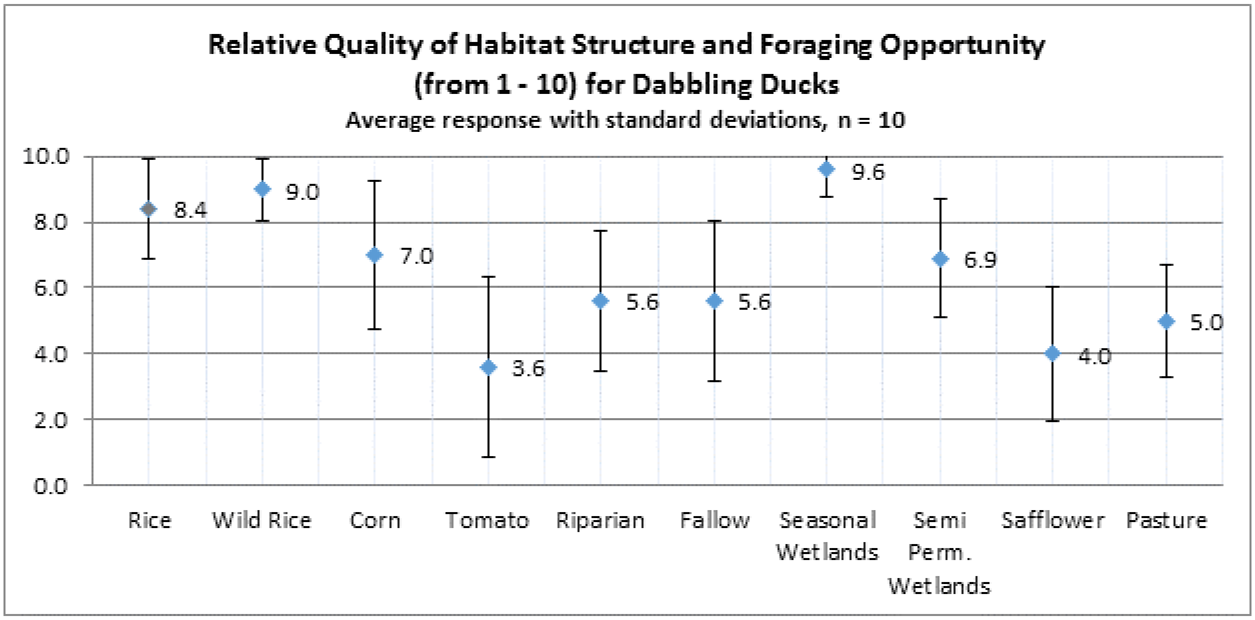
Quantifying Habitat Quality for Dabbling Ducks and Shorebirds

The habitat objective for birds on the Bypass takes the same functional form as for fish (Eqn 2) and was developed with a similar method, but the specific objective and weights are different. Many bird species use wetland and agricultural areas on the Bypass for multiple life stages and functions throughout the year (California DFG et al. 2008). Interviews with biologists and wetland managers helped narrow focus to two groups of birds that most depend on or are likely affected by the additional application of water on the Bypass in late winter through early spring: dabbling ducks and shorebirds.

California's Central Valley supports up to 60% of the total Pacific Flyway population, and at least 200,000 shorebirds winter in the valley, with food availability the key limiting factor during migration and winter (CVJV 2006, Elphick and Oring 2003, Naylor 1999). The Bypass is home to one of several large wetland areas in the Central Valley managed specifically for these birds, with flooding on seasonal wetland, permanent wetland, and some rice fields timed to create optimal foraging opportunities (California DFG et al. 2008). Because food is a limiting factor for birds during the time period of interest, expert surveys were focused primarily on the implications of various inundation characteristics for foraging habitat.

The quality of foraging habitat for birds depends on the same variables that more generally describe fish habitat. The type of land use flooded determines the quantity and quality of food available as seed, and also has a relationship to the abundance of soil-emergent invertebrates. Depth determines the ease with which each species can access that food, with an upper threshold beyond which the habitat becomes too deep for foraging (CVJV 2006). Timing is important as bird densities increase in some months, putting greater strain on the valley's overall food supplies (Shuford et al. 1998). Timing is also important for seasonal wetland habitat. Wetlands are typically drained during March or April to encourage growth of plants like swamp timothy and watergrass to grow over the summer; these plants provide a protein-rich source of food for birds the following winter (Smith et al. 1994). When drawdown is delayed, the growing season is limited and other less valuable plants tend to displace plants which provide better food sources, both of which may reduce the following year food supply (Naylor 1999).

As with salmon and splittail, expert surveys were used to improve understanding of the nuanced preferences of dabbling ducks and shorebirds for manageable flood characteristics on the Bypass (Appendix A). Figures 2.7 through 2.9 summarize responses for land use type, timing, and depth. As was the case for fish, variance in expert opinion was much higher for some habitat characteristics. Experts generally agreed that rice, wild rice, and seasonal wetlands provide the best foraging habitat for dabblers and shorebirds alike, but all other land uses received scores that varied by up to 4 points out of a total of only 10. The inclusion of rice as good foraging habitat follows from past research confirming its value as a good food source and habitat for various water birds (Elphick 2000, CVJV 2006). Other agricultural land uses on the Bypass have not been studied in as much detail (regarding bird usage), which likely explains the greater variance in expert opinion. However average responses suggest that corn and semi-permanent wetlands also might provide decent foraging habitat for dabblers, as could pasture and fallow lands for shorebirds.



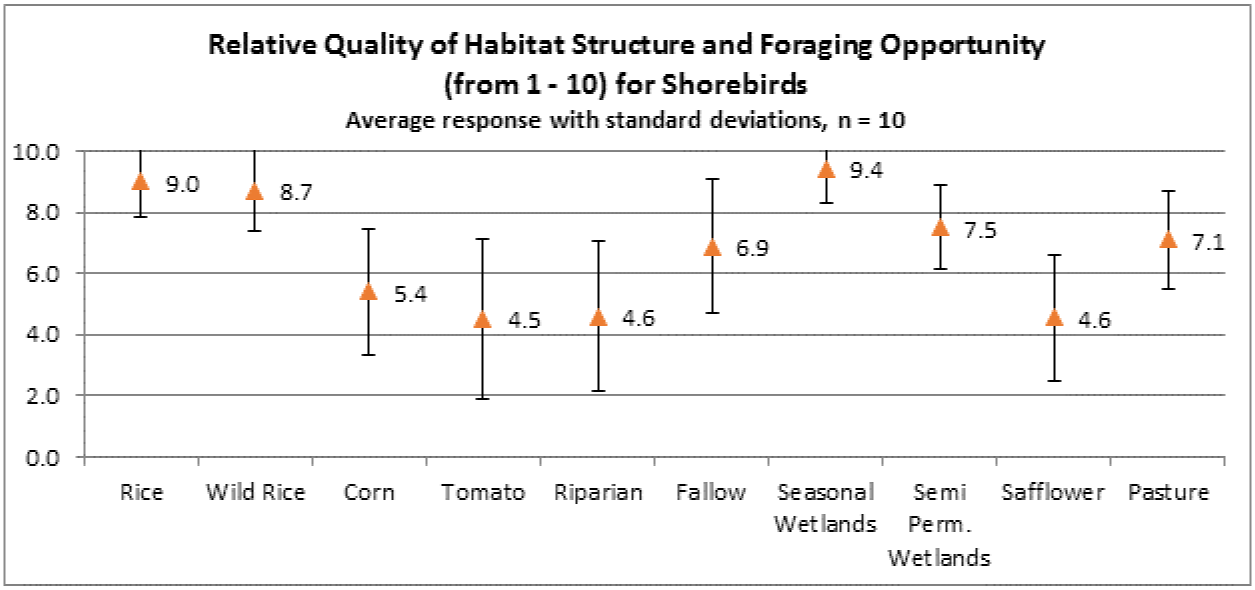


Figure 2.7. Summary of expert responses on the relative quality of different land use types on the Yolo Bypass as winter foraging habitat for dabbling ducks and shorebirds

Regarding the preferred timing of inundation (Figure 2.8), most respondents agreed that earlier foraging habitat (shallow flooding) is preferable to late flooding for dabbling ducks, with highest scores in January and February, and the opposite for shorebirds. This again reflects data available in the literature: the Central Valley Joint Venture tracks food supplies and bird densities through the winter and spring, showing for example that dabbling duck populations generally peak in February in the Yolo Basin, around the same time that food supplies currently become more sparse (CVJV 2006).

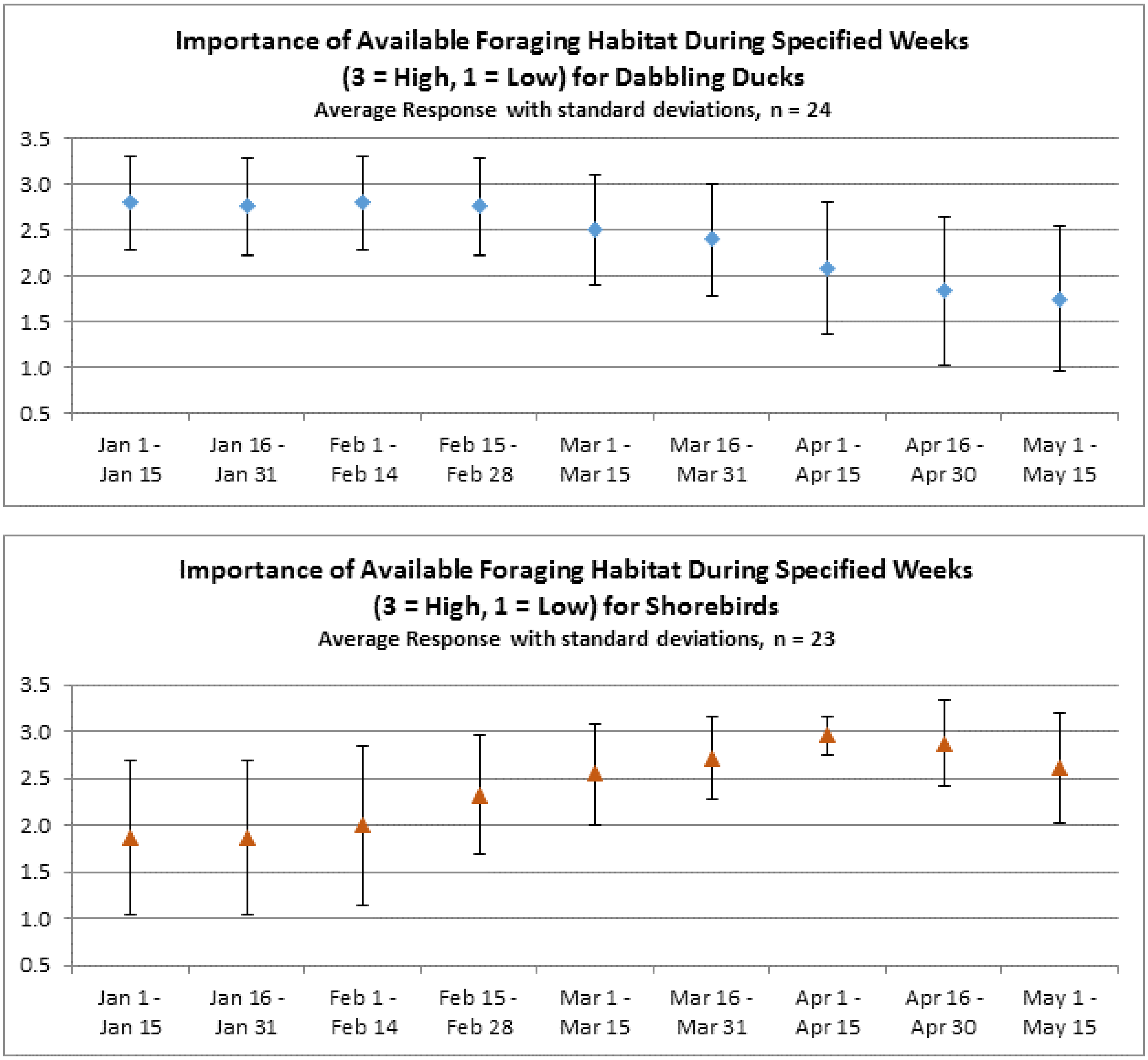


Figure 2.8. Summary of expert responses on the importance of available foraging habitat for dabbling ducks and shorebirds during specified weeks in the winter and spring.

Most experts identified 5-7 inches as the optimal foraging depth for dabbling ducks (when asked to average across the preferences of all species that use the bypass) and 2-4 inches as optimal for shorebirds (Figure 2.9). These responses generally agree with past research on depth preferences for the two species groups (Petrik et al. 2012, Taft et al. 2002).

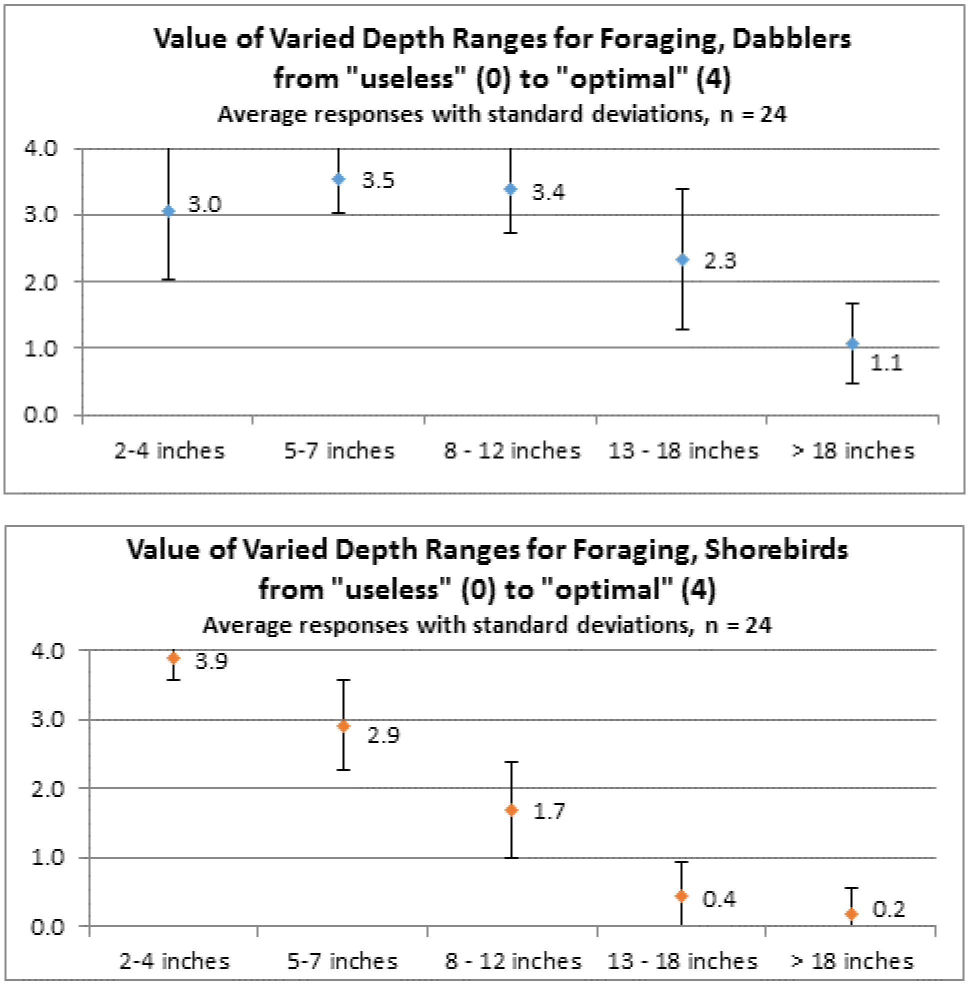


Figure 2.9. Summary of expert responses on the value of varied depth ranges for dabbling duck and shorebird foraging habitat.

Weights were derived from survey responses the same way they were for salmon and splittail – by dividing the average response for each habitat characteristic by the highest average score for the entire category. Tables 2.5 and 2.6 summarize the resultant weights for land use type, timing, and depth:

Table 2.5: Relative dabbling duck and shorebird foraging habitat preferences (weights) for land use types and time of year. Source: Expert Surveys, Appendix A

Land Use Type (j)	**Weights (α_{sj})**		**Timing (t)**	**Weights (δ_{ts})**	
	Dabbling Ducks	**Shore-birds**		**Dabbling Ducks**	**Shore-birds**
Rice	0.88	0.96	Jan 1 - Jan 15	1.00	0.63
Wild Rice	0.94	0.93	Jan 16 - Jan 31	0.99	0.63
Corn	0.73	0.57	Feb 1 - Feb 14	1.00	0.68
Tomato	0.38	0.48	Feb 15 - Feb 28	0.99	0.79
Pasture	0.52	0.76	Mar 1 - Mar 15	0.90	0.86
Fallow	0.58	0.73	Mar 16 - Mar 31	0.86	0.92
Riparian	0.58	0.49	Apr 1 - Apr 15	0.75	1.00
Seasonal Wetlands	1.00	1.00	Apr 16 - Apr 30	0.66	0.97
Permanent Wetlands	0.72	0.80	May 1 - May 15	0.63	0.89
Safflower	0.42	0.48			

Table 2.6: Relative value (weights) to dabbling ducks and shorebirds for specified flood depths in foraging habitat

Depth (d)	**$\delta_{dabbler}$**	**$\delta_{shorebird}$**
Zone 1: 2 – 4″	0.86	1.00
Zone 2: 5 – 7″	1.00	0.75
Zone 3: 8 – 12″	0.95	0.44
Zone 4: 13 – 18″	0.66	0.11
Zone 5: > 18″	0.30	0.04

As discussed above, the preference for foraging habitat during various time periods is more complex for birds – flooding into late April and May might provide some marginal benefits at the time, but can reduce foraging capacity in the following year, especially for dabbling ducks that depend on seeds as much as on invertebrates. Wetland managers were asked to describe the effect of a late drawdown date for seasonal plants like swamp timothy and watergrass on the bypass. While the literature provides some data on moist soil management practices (Naylor 1999), results are likely to vary by area due to differences in soils and climate; managers were asked about best practices specific to the Bypass. Responses suggest that, on average, watergrass will still grow well even with a drawdown as late as May 1st, but swamp timothy will lose approximately 10% of its fall biomass with each week that drawdown is delayed past early April.

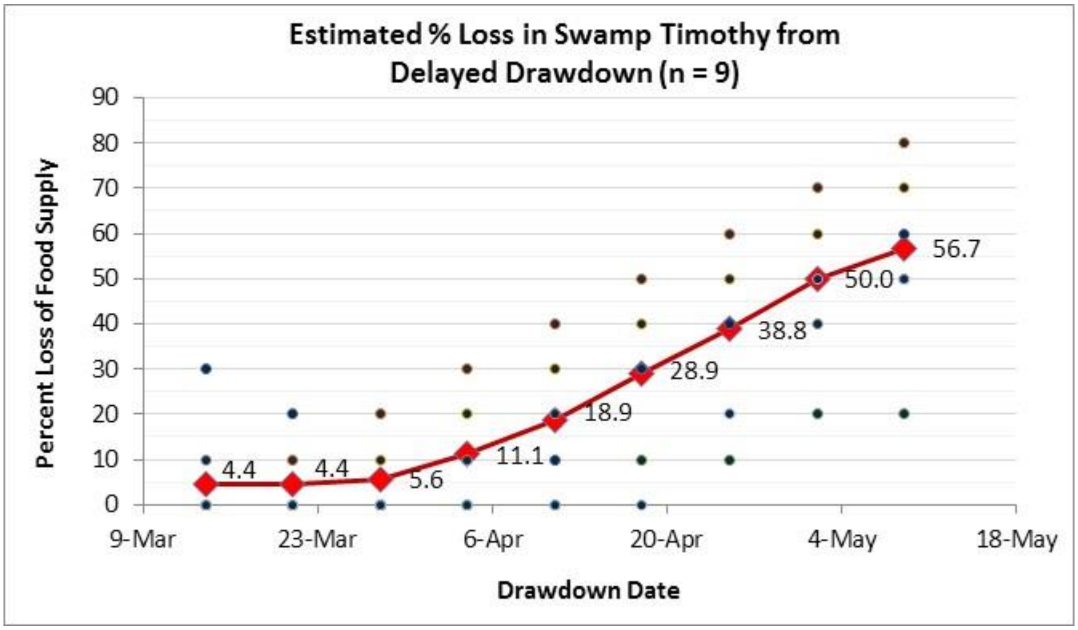


*Figure 2.10. **Estimated percent loss in fall and winter swamp timothy biomass on the Yolo Bypass from delayed drawdown in spring. Individual responses are all plotted with red line showing the mean response (of 9 total).***

To adjust for this loss in the next season's foraging opportunity from a delayed drawdown, a factor $(100 - l_t)$ is added to Equation 2 when calculating the habitat benefit for dabbling ducks (shorebirds do not suffer the same losses because they are more dependent on invertebrates than seeds):

$$Max\ HB = \sum_{s=dabbler} \sum_{\substack{t=start\\ date}} (100 - l_{t)} \omega_{ts}\, \delta_{ts} \sum_{d>0} \delta_{ds} \sum_{j} \beta_{sA} \left(\frac{A_{jtid} * \alpha_{sj}}{Max\left(A_{jtid} * \alpha_{sj}\right)} \right) + \beta_{sC} \left(\frac{Entropy\left(A_{jtid}\right)}{Max\ Entropy} \right)$$

Such that $l_t = 0$ for all weeks up to April 2nd, and 10 for all weeks thereafter.

The final time-related characteristic of flooding is duration. Experts were asked if it was a reasonable simplification to assume that bird benefits increase linearly with each additional week of inundation. Only 42% of respondents said "yes" or "maybe" for dabbling ducks, while 68% thought this might be reasonable for shorebirds. Some respondents commented that a flooded field is most valuable to dabbling ducks in the first two weeks of inundation when there is abundant seed availability. This period is followed by a lull in food supply during which the birds will often find other resources, only to return again to the same field several weeks later as invertebrate populations begin to grow (Appendix A). Some survey participants further explained this is not true for shorebirds, which depend mostly on invertebrates for food; their food supplies generally increase with additional weeks of flooding. It was therefore assumed that ω_{ts} is constant over time for shorebirds, but greater in the first few weeks for dabblers. Figure 2.11 shows the estimation of total duration benefit for dabbling ducks over time (with marginal increases for each time step t $=\omega_{ts}$). It is assumed that 60% of the value of a flooded field is obtained in the first two weeks of flooding (ω_{ts} = 0.3 for weeks 1 and 2). The marginal return on additional weeks of flooding increases slightly again after week 5, to account for the likely increase in invertebrate food sources.

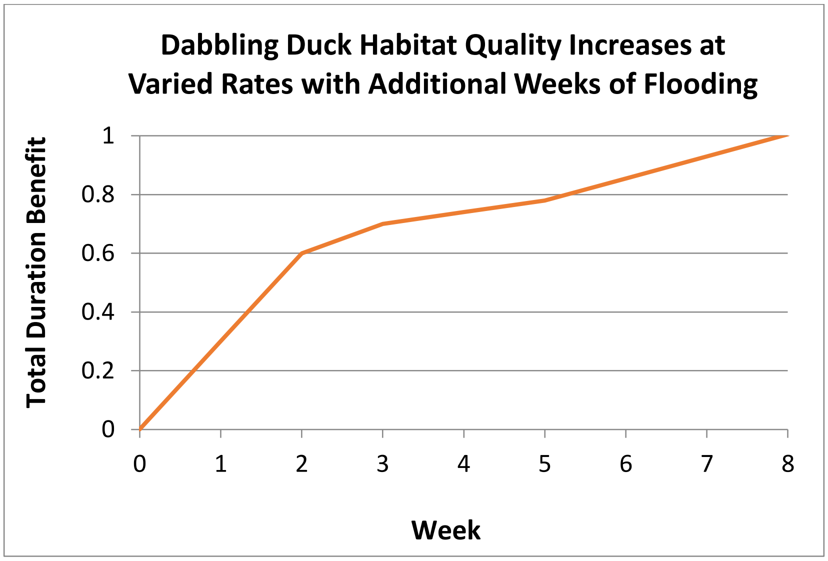


Figure 2.11. Duration Benefit for Dabbling Ducks increases at varied rates with each additional week of flooding. The majority of total benefit of any flooded foraging habitat is received within weeks 1 and 2, with decreasing returns thereafter.

In addition to describing the relative benefits of certain depths, land uses, and weeks, experts were asked to distribute "benefit points" between the two main factors of: (1) complexity or heterogeneity of flooded land uses, and (2) total acres flooded, with considerations of depth and land use type. Their answers resulted in the following weights:

Table 2.7: Relative importance to dabbling ducks and shorebirds of the area and particular land use types flooded versus the overall heterogeneity, or "complexity" of flooded land uses. Source: Expert Survey, Appendix A

Flood Characteristics	Weight (β_{sA} and β_{sC})
Total area, depth, and land use types flooded	0.68
Complexity (entropy) of flooded land uses	0.32

Finally, as discussed in the above section on developing weights for the fish objective, Equation 2 assumes a linear relationship between acres flooded and habitat benefits, such that 200 acres is twice as beneficial as 100. When experts were asked if this was a reasonable simplification for birds as long as some minimum amount of habitat was available, 70% said yes for dabbling ducks, and 60% for shorebirds. Most respondents pointed out that there is likely an upper threshold beyond which this is no longer true, but also indicated that this maximum would be larger than the maximum flooded acreage to which added managed flows on the Bypass are constrained.

Because the weights for each habitat characteristic are different for dabbling ducks and shorebirds, habitat quality for each is calculated separately. Total bird habitat quality is then calculated as an evenly weighted sum: $HQ_{Birds} = 0.5(HQ_{dabbling\ ducks}) + 0.5(HQ_{shorebirds})$. However, as with salmon and splittail, these species-specific weights (0.5 for each) are adjustable and can be tested in future sensitivity analyses.

Developing the Constraint Set

Decision variables can only be manipulated within their physical limits, or constraints. The model presented here assigns the acreage for each zone, land use type, depth, and week within an 8 week period of varying start dates, for a total of 3168 total decision variables in the form A_{jtid} (acres of land use *j* in zone *i*, flooded to depth *d* in time step *t*). Almost all constraints on these decision variables can be categorized as being related to land use or water management.

LAND USE CONSTRAINTS

The Bypass's primary societal function as a flood carrying channel requires that its surface roughness not be substantially increased by trees or topographic changes. For this reason, riparian vegetation is constrained to only 5% of total available acreage (an estimate based on bypass land use maps available from Yolo County), and the model otherwise assumes that the Bypass's current major land uses will continue in any future scenario. Therefore the model is limited in its land use decisions to assigning the acreage of rice, wild rice, tomatoes, corn, safflower, pasture, seasonal and permanent wetlands, riparian, and/or fallow land. Geographic data for each of these land uses on the Bypass is available from Yolo County for years 2005 through 2009, separated by agricultural zone as defined earlier and shown in Figure 3. This data was used to develop all other land use constraints discussed in the following paragraphs.

While there is an upper limit on some land use types like riparian vegetation, others require a minimum presence. Soil management necessitates, for instance, that some portion of each zone be fallowed every year, with crops rotating through on 3 or 4 year cycles. For this constraint, the minimum number of acres fallowed in each zone for years 2005 through 2009 is used. Mathematically, the constraints for riparian and fallow acreage can be written as follows:

$$\sum_i \sum_d A_{riparian} \leq 2400\ acre, \quad \forall\ t$$

[Eqn 3]

where i = zone, $A_{riparian}$ is the total acreage of riparian land in zone i flooded to depth d, and t is week. (2400 is approximately 5% of total bypass area for zones 1 – 6 on the bypass).

And

$$\sum_{d,zone\ i} A_{fallow} \geq F_{min,i} \quad \forall t$$

[Eqn 4]

where $F_{min,i}$ is the minimum observed acreage of fallow land in zone i for the years 2005 through 2009, or, more specifically,

Zone	$F_{min,i}$
1	629
2	1040
3	581
4	241
5	520
6	440

The Bypass is also home to several public and private wetlands, particularly in the central and southern zones (3 through 6). Many private wetlands are protected under US Fish and Wildlife Service habitat conservation programs (California DFG et al. 2008). Because most of these wetlands exist by public mandate, the model is constrained to assign at least 75% as many acres of wetland as are already in existence. This allows some flexibility in the land use mosaic while recognizing the political and legal preference for maintaining wetland habitat on the Bypass. Mathematically:

$$\sum_{d,zone\ i} A_{seasonal\ wetland} + A_{permanent\ wetland} \geq W_{min,i} \qquad \forall t$$

[Eqn 5]

where $W_{min,i}$ is the minimum observed wetland acreage in zone *i* for the years 2005 through 2009, or, more specifically,

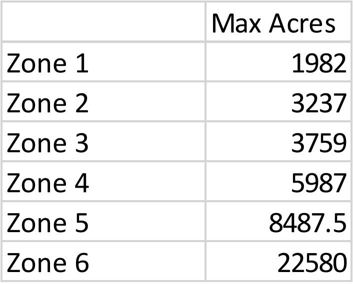
Zone (i)	$W_{min,i}$
3	499.2
4	663.5
5	2695.9
6	3212.1

Finally, there are some obvious land use constraints that more generally define the system, including maximum total acreage per zone and across the entire bypass, non-negativity, and continuity across all time steps:

Total acreage utilized in each zone is less than or equal to the area of that zone:

$$\sum_d \sum_j A_{jtid} \leq MaxA_i \qquad \forall t, i$$ [Eqn 6]

where $MaxA_i$ is the maximum total acreage of zone *i*:



	Max Acres
Zone 1	1982
Zone 2	3237
Zone 3	3759
Zone 4	5987
Zone 5	8487.5
Zone 6	22580

All assigned acreage must be greater than or equal to zero:

$$A_{jtid} \geq 0 \qquad \forall j, t, i, d \qquad \text{[Eqn 7]}$$

And finally, the acreage of any land use type in each zone cannot decrease throughout the season (a rice field cannot become a corn field in the middle of the winter):

$$\sum_d A_{jtid} \leq A_{j(t+1)id} \qquad \forall i, j \qquad \text{[Eqn 8]}$$

WATER MANAGEMENT CONSTRAINTS

As mentioned earlier, the Bypass has an abundance of manageable canals, gates, pumps, drainage systems, and other infrastructure that could be used to strategically design multi-purpose inundation with additional flows in the winter and spring. The model inherently constrains these floods to be 8 weeks in duration (by only containing 8 time steps). This decision is based on expert interviews and survey results indicating diminishing returns for fish and bird species after fields or wetlands are flooded for longer than 4 to 6 weeks, and because BDCP targets don't extend beyond 6 weeks of added flooding in any given year (Table 2.1).

An attempt is also made to make the solution feasible for water managers on the Bypass. For simplicity, the model assumes that the acreage devoted to flooding or habitat does not increase significantly from week to week (it remains steady or decreases). This is to reflect that more water is typically available earlier in the season than later, although this constraint could be changed to test years for which this assumption is not true. It also assumes that any land that becomes dry in week t remains dry in all weeks thereafter. This is so that fields dedicated to agriculture after being drained are not flooded again in later weeks. Finally, total flooded area is constrained to 20,000 acres. This maximum flood extent is based on hydrodynamic modeling of the Bypass and on BDCP targets, both of which suggest that the volume of water likely to be available through a gated notch in Fremont Weir during January - May will not inundate more than approximately 20,000 acres, except for during less frequent major floods (CBEC 2010, U.S.D.O.I. 2013)). Mathematically:

$$\sum_j \sum_{d>0} \sum_i A_{jtid} \geq A_{j(t+1)id} \qquad \forall t \qquad \text{[Eqn 9]}$$

$$A_{jti(d=0)} \leq A_{j(t+1)i(d=0)} \qquad \forall j, t, i \qquad \text{[Eqn 10]}$$

$$\sum_j \sum_{d>0} \sum_i A_{jtid} \leq 20{,}000 \qquad \forall t \qquad \text{[Eqn 11]}$$

SOLUTION METHODS

Constraint Method

A typical single-objective optimization problem is fully defined and can be solved once all decision variables, constraints, and the objective are mathematically represented. However because multi-objective problems contain tradeoffs, and objectives are often expressed in different units, further mathematical manipulation is required. The solution to a multi-objective problem is a trade-off curve, or a set of non-inferior alternatives, each representing a different prioritization of the objectives.

Many methods can generate this solution set, all of which essentially convert the multi-objective problem into a single-objective problem. This is most often done by applying weights to each objective and combining them into one function (the weighting method) or by converting some objectives into constraints (the constraint method) (Cohon 1978, Louie, Yeh and Hsu 1984, de Neufville 1990). Both methods have been successfully applied in similar problems. The weighting method was used to explore tradeoffs between salmon passage and hydropower generation in the Willamette basin ((Kuby et al. 2005). The constraint method has been applied to a multi-dam removal problem with fish benefits, minimized cost, and public safety objectives, and a basin-wide management study with water quality, water supply, and groundwater recharge objectives (Zheng and Hobbs 2012, Louie et al. 1984)

Of these two, only the constraint method allows the objective functions to be expressed in varying units, and is therefore the method used here. Known for being computationally efficient (Louie et al. 1984, Cioffi and Gallerano 2012), the constraint method operates by converting all but one objective into constraints, and solving multiple times for that objective with varying performance required of the others (de Neufville 1990). Because the fish and bird objectives for the Bypass are both expressed in "habitat quality" units, and the economic objective in dollars, the natural formulation for this problem converts the fish and bird objectives into constraints on an economic optimization. Mathematically, maximize profit (Eqn 1) such that:

$$\frac{HQ_{Birds}}{MAX(HQ_{Birds})} \geq x \quad and \quad \frac{HQ_{Fish}}{MAX(HQ_{Fish})} \geq y$$

(And all other physical constraints presented above are also satisfied.)

where x and y are re-set for consecutive optimization runs, increased by an interval of 0.01 to 0.1

Branch and Bound Algorithm and the What's Best Global Solver for Excel

Solving the converted single-objective profit maximization requires a numerical algorithm. This study employs a solver add-on to Excel called What's Best, developed by Lindo Systems Inc. (available online at http://www.lindo.com), that contains several options for nonlinear problems like the profit maximizing objective in Eqn 1. The "global solver" was chosen for this model because it operates using a branch and bound scheme that efficiently finds a global optima to the mathematical problem (Gau and Schrage 2004).

Branch and bound techniques have been compared to dynamic programming as an efficient, structured search of the entire feasible solution space (Lawler and Wood 1966). They generally work by first finding infeasible subsets of decision values and using these to then eliminate many broader combinations of all decision values, or by similarly eliminating entire "branches" of decision values that lead to inferior solutions (Nakamura and Riley 1981, Lawler and Wood 1966). In this way, a branch and bound scheme quickly and significantly decreases the solution space over which it continues searching to find a global optimum.

MODEL TESTING AND APPLICATION TO PAST LAND USE MOSAICS

Land use data for years 2005 through 2009 were used to assess whether the model reasonably estimates farming decisions on the Bypass with the bird and fish constraints left inactive (i.e. when the only objective is net revenues). The acreage for each crop in each zone was manually entered into the model so it could simulate the economic performance of that year (with no flooding except in wetlands). The model was then allowed to change land use decisions as necessary so as to maximize profits; this run was titled "Optimal Econ". Finally, a second optimization run was completed titled Fish and Bird Optimal which re-introduced fish and bird constraints, optimizing habitat benefits for each to the maximum extent possible before tradeoffs were needed between them, and allowing economic performance to decrease as necessary. After several iterations, a balanced optimization of fish and bird habitat quality was found for a January 24th start date with the following habitat constraints:

$$\frac{HQ_{Birds}}{MAX(HQ_{Birds})} \geq .75 \qquad and \qquad \frac{HQ_{Fish}}{MAX(HQ_{Fish})} \geq .75$$

This and the purely economic optimization were used to compare past land use mosaics with optimized land use decisions (Figure 2.12).

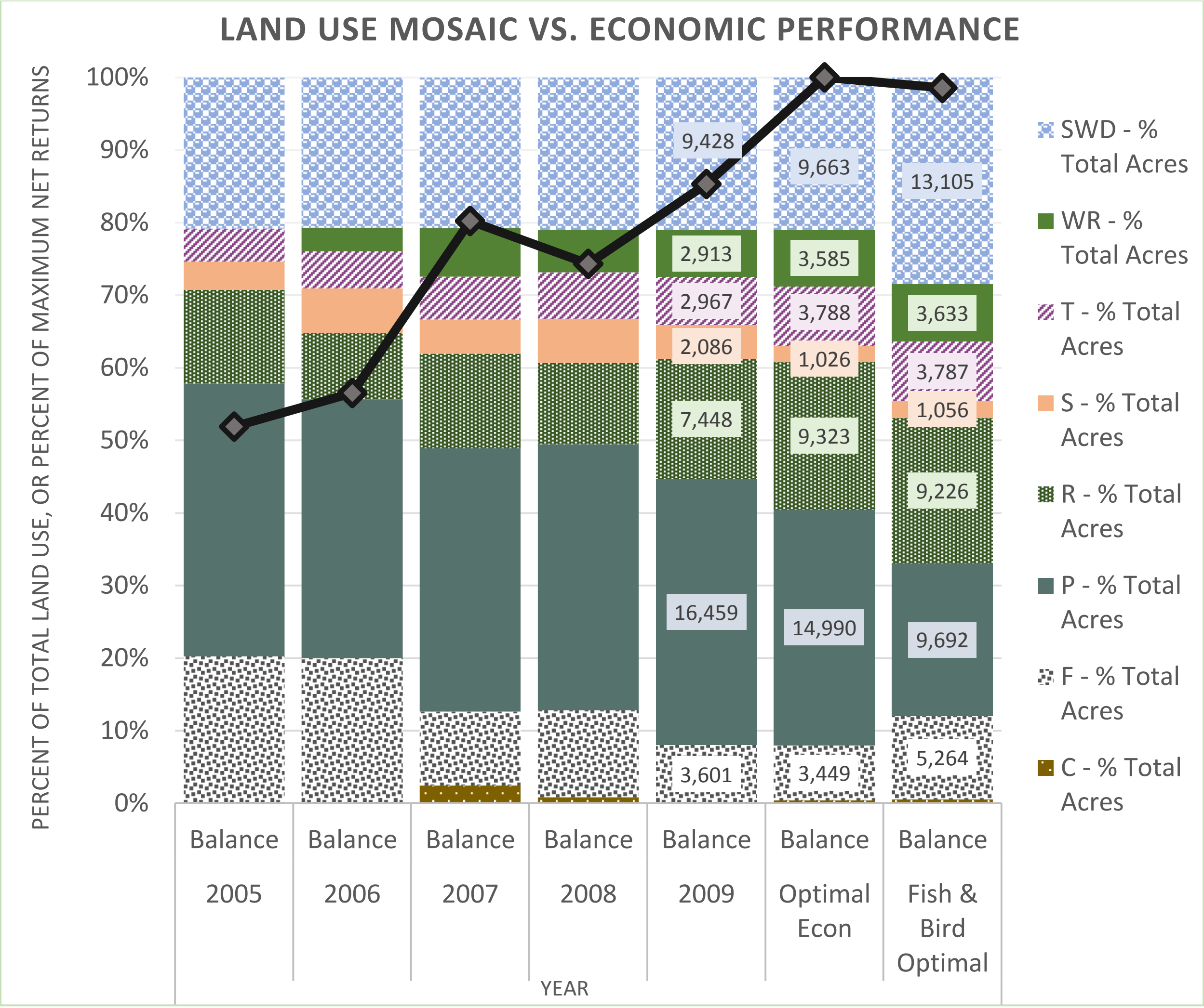


Figure 2.12. Percent of total area represented by each land use type, per year, and the percent of maximum profit netted in each year (black line). SWD = seasonal wetland, WR = wild rice, T = tomatoes, S = safflower, R = rice, P = pasture, F = fallow, and C = corn. NOTE: Total area can vary from year to year. 100 percent applies to a different base in 2005 than in 2009. This graph displays only the relative prominence of different land use types through time and in modeled decisions. Acreage of each land use type is displayed for year 2009 and for the modeled land use decisions for more direct comparison. Source for years 2005 - 2009: Yolo County GIS land use layers..

Modeled land use decisions for the economic optimization are shown above as “Optimal Econ,” just to the right of true cropping patterns for 2009, the most profitable year for Bypass farmers between 2005 and 2009 (assuming average crop prices). Actual acreage is displayed for each land use type for these two years for a more direct comparison, and economic performance is displayed as a black line showing the percent of optimally achievable profits. Modeled land use decisions in the economic optimization closely resemble the relative prominence of different land uses in 2009, suggesting that the economic objective function (Eqn 1) is a fairly good estimate of marginal realities for Bypass farmers. However the optimized decisions suggest that, absent fish and bird objectives, approximately 15% improvement in net returns might be possible on the Bypass with increases in overall tomato and rice production, and a corresponding decrease in pasture.

Alternatively, the run that maximized fish and bird habitat quality in exchange for economic performance suggests that a more habitat friendly land use mosaic might trade much of the southern Bypass's pasture for seasonal wetlands, with a resultant drop in net economic returns to about 66% of optimal. Rice acreage is also decreased (although not relative to 2006), while corn, safflower, tomato and wild rice acreage all grow slightly. The growth in wild rice, fallow, and wetland land uses responds to their are all being weighted highly as potential habitat for several bird and fish species. Added acreage for the remaining agricultural crops may offset the economic costs of lost pasture and delayed plant dates for inundated rice. Because this run only explores one set of constraints for fish and bird habitat, it only represents one point on a much larger trade-off surface that needs broader exploration before any final conclusions can be drawn about promising changes to land management on the Bypass. However, these results show that the model is making logical changes in land use as bird and fish habitat are increasingly prioritized.

The increases in tomato acreage for both model runs and increase in rice for the economic optimization are consistent with the general trend in the data from 2005 through 2009, but a caution is in order. To maximize profit in "Optimal Econ," the model planted the largest observed zone-specific acreage of rice and tomatoes for years 2005 through 2009, across all zones at once and in one year. (In reality, for example, zone 1 planted its greatest acreage of tomatoes in a different year than zone 5.) This increase in total Bypass acreage for these two crops might not actually be possible due to crop rotations, processing limitations, or other logistical considerations. Crop prices may also change from year to year, which affects relative profits for different land use types. Later applications of the model could test sensitivity to added constraints on rice and tomato acreage and the effect of different market prices for Bypass crops.

The model was also run with varied weights in the salmon habitat quality objective for rice and wild rice preferences, to test the importance of a changes in those weights with new information from recent field work in the northern Bypass. These weights were the only ones not derived from expert survey results. The original survey-derived weights (0.76 for rice and wild rice) were tested against the newer assumption that rice is ideal habitat for salmon on the Bypass (or equal in value to wetlands with a weight of 1). Figure 2.13 shows results for the balanced habitat quality case for fish and birds. Only very slight changes occured in the amount of rice flooded in later weeks, and in resultant economic performance. These results suggest that the modified rice weights for salmon habitat do not significantly change modeled decisions or outputs when improving habitat quality for fish and birds.

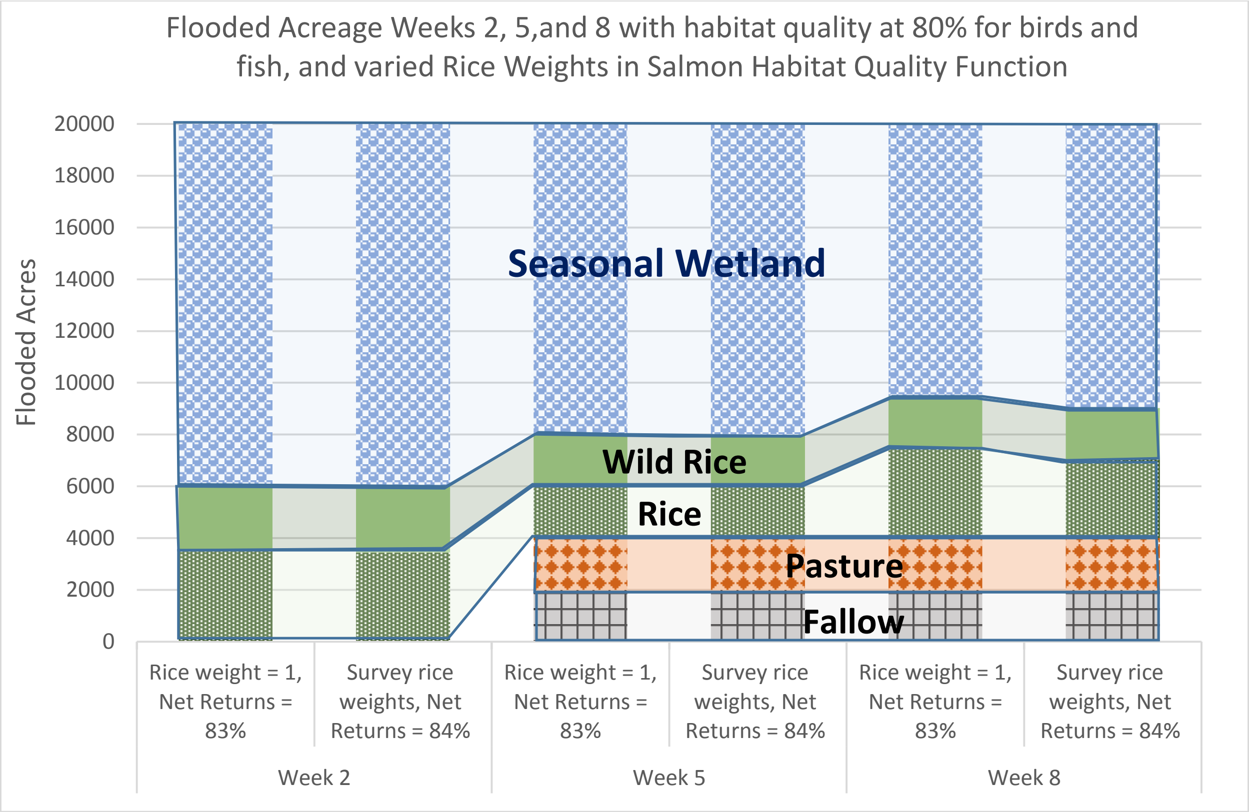


Figure 2.13. Test of model sensitivity to varied rice weights for the salmon quality objective. Only flooded lands are shown.

APPLYING ADDED WATER TO PAST LAND USE MOSAICS

Once compared against 2005 – 2009 data, the model was used to explore the value that added water alone could provide to the Bypass for fish and birds, without any changes in land use mosaic or net returns. More specifically, the model estimated how much improvement would have been possible for fish and bird habitat in the winters of 2007, 2008, 2009, and 2010 at no cost to Bypass farmers, if extra water had been available via a modified Fremont weir or other means.

To answer this question an understanding was first developed of current habitat quality for fish and birds on the Bypass. Simulations evaluated the habitat benefits already achieved in a dry year (from seasonal and semi-permanent wetlands) compared to a year of natural Fremont weir overflow (when almost the entire bypass is inundated). Flood depth and extent was simulated for the 2006 March through May flood using data from previous hydrodynamic modeling efforts for the Bypass, including detailed simulation results on the depth of flooding as a percent of total area flooded bypass-wide (CBEC 2010). It was assumed this depth distribution would be similar for each individual land use type in each zone (e.g. based on data available from CBEC, for every A_{jti}, 16% is less than 6 inches deep, 19% between 6 and 12 inches, etc…). Two dry years (winters of 2007 and 2009) were simulated assuming all wetlands were flooded to depths needed to maximize bird benefits, but that no other land uses were inundated (wetlands currently constitute approximately 9500 acres). Results are reported as a small range of potential bird habitat quality in those years to account for uncertainty in the true management decisions that were made for flood depths across the landscape in either scenario. Fish habitat quality is assumed near zero in current dry years because salmon and splittail typically lack access to managed wetlands when Fremont Weir is not overtopping.

After current habitat quality was simulated, the model was used to calculate the improvement in habitat quality possible with a modified weir and added water in the winter. Decision variables were re-introduced to the 2006, 2007, 2008 and 2009 land use mosaics so that modeled inundation could occur in late January (starting January 24th) and early February of the following winters (2007 – 2010). However only some decision variables were made adjustable: the acreage of each land use type was held constant, while the depth of flooding was allowed to vary during weeks 1 through 3 when inundation would not affect yields or agricultural profits (dependent on crop type and zone).

Within this subset of possible decisions for those years, depth and placement of inundation was optimized for fish habitat, then for bird habitat, and finally for a balance of habitat quality, whereby each habitat constraint was tightened until any further adjustment in one objective decreased performance for the other. This provides a very rough estimation of trade-offs among fish and bird habitat quality in the context of real land use mosaics and set economic performance. These runs were finally compared to a fully profit-optimized bypass in which fish, bird, and balanced fish and bird habitat objectives were all maximized within the constraint that net revenues must remain optimal.

RESULTS

The habitat quality trade-off curves for managed flooding (available via a modified weir or some other means) on 2007 and 2009 land use mosaics appear in Figure 2.14, with boxes showing the habitat quality actually available on those dry land uses and during the very large March – May flood of 2006.

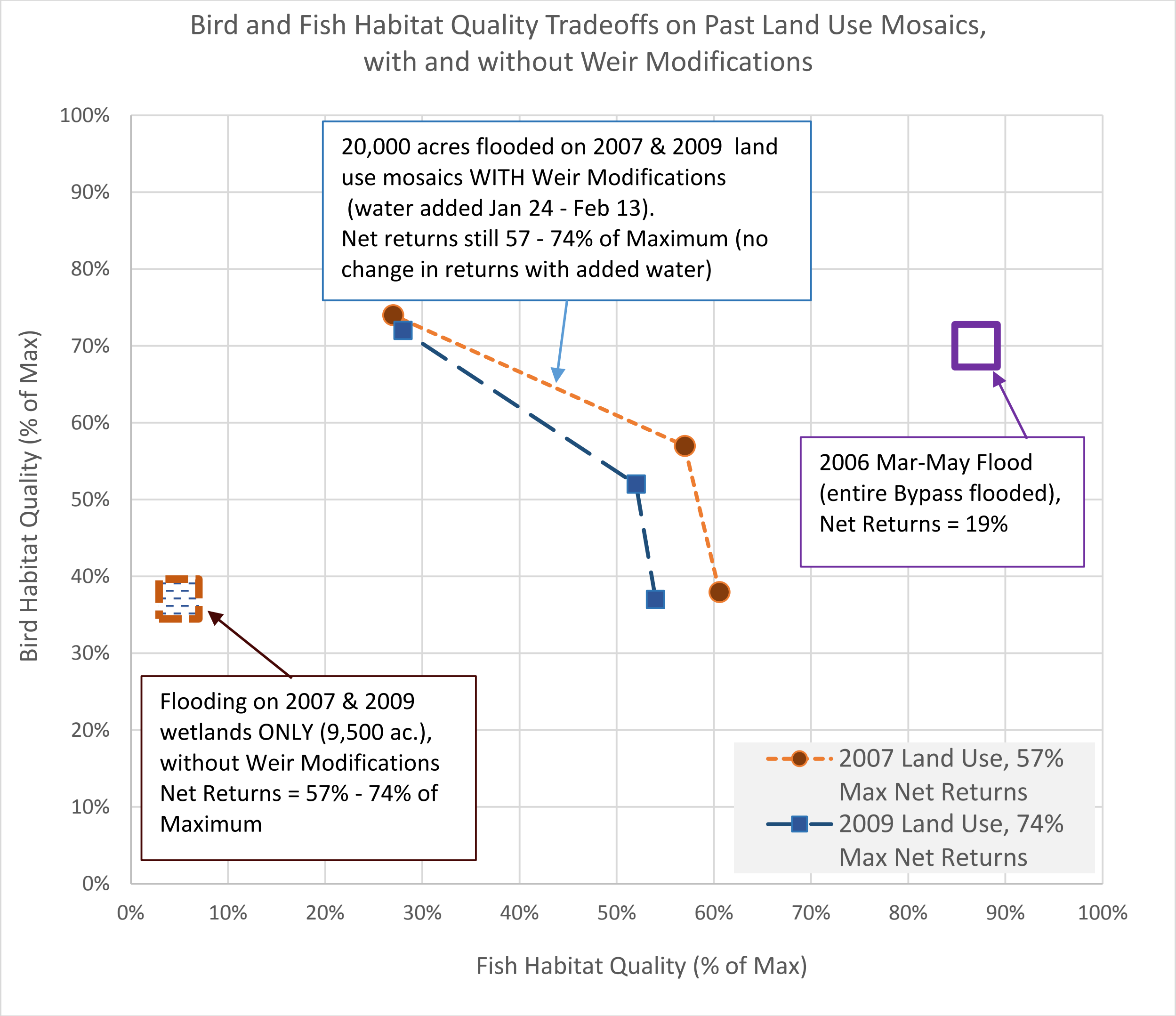


Figure 2.14: Comparison of bird and fish habitat quality tradeoffs for past land use mosaics without any added water or weir modifications (actual) and with weir modifications (hypothetical). The graph also shows habitat quality during the March – May flood in 2006, simulated on the land use mosaic that was planted in the spring of 2005. NOTE: The 2007 and 2009 land use mosaics were planted in the springs of 2006 and 2008.

The curves show that a substantial habitat quality improvement would have been available for fish with just 3 or 4 weeks of added flooding in February with no effect on net economic returns in those years. Bird habitat quality can improve by 5 to 25 percentage points compared to current wetland management, and fish habitat quality can improve by as much as 55 percentage points. This improvement is without reduction to agricultural profits or land use other than the costs of water management and, of course, initial construction costs of weir and any other infrastructure modifications needed to obtain and move the added flows.

What might a balanced approach between fish and bird habitat quality (middle point on the curves) imply? As shown in Figure 2.12, balanced habitat management for fish and birds in the winters of 2007 and 2009 could have achieved 52 to 57% of optimal habitat quality for both species groups had additional water been available in those years. This is slightly better performance than currently achieved for birds, and a substantial increase in the bypass's habitat potential for fish.

These simulations also indicate that fish and bird habitat benefits are very high for years in which the Bypass is almost completed inundated as it was in the spring of 2006, with bird habitat 65 to 75% of optimal, and fish habitat 82 to 92% of optimal. Fish fare slightly better than birds in this case because of the prevalence of deeper water (approximately 54% of inundation was deeper than 18 inches) (CBEC 2010), with foraging bird habitat only available on the edges of inundation. However these large floods incur great cost to farmers, especially when they occur late in the spring; simulated net revenues for that year were only 19% of optimal. Compared to simulated net revenues of 52% for that same land use mosaic without flooding, this is a 63% loss for that year. Late flooding is also potentially harmful to wetland managers and bird habitat for the following year, with fewer nutritional plants likely to be available because of a shortened growing season. The runs with added water on 2007 and 2009 land uses, by contrast, suggest that the Bypass can provide more than half the habitat quality for birds and fish that is available during such a large flood, but without economic losses if the added water is timed and placed strategically.

We also explored whether all three objectives could further improve with a modified Fremont weir (and added flows) if the land use mosaic was also allowed to change. Figure 2.15 shows the potential performance of each real year's land use mosaic if bird and fish habitat quality was prioritized equally in managing added flows, compared to performance within an economically optimized Bypass ("Optimal Econ" in Figure 2.15) where all land use is assigned by the model. These results suggest that fish habitat, bird habitat, and profits can all be improved on the Bypass with some small changes to the land use mosaic in addition to added flows.

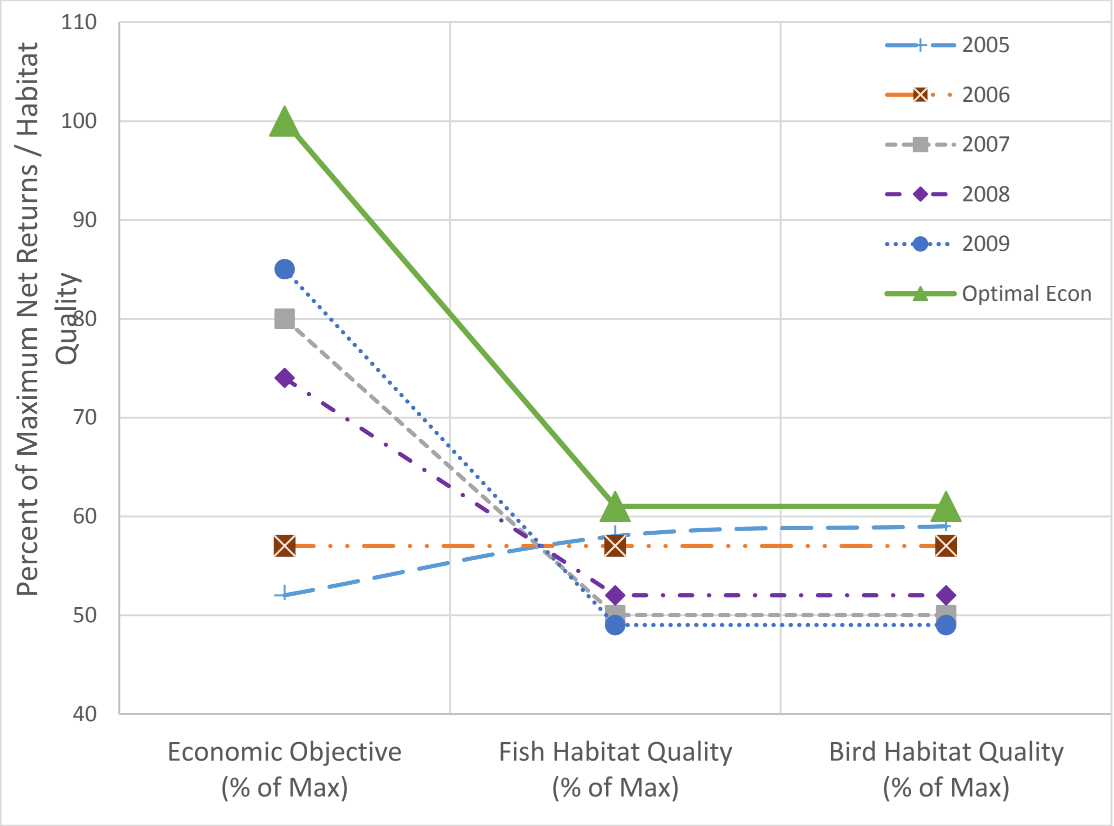
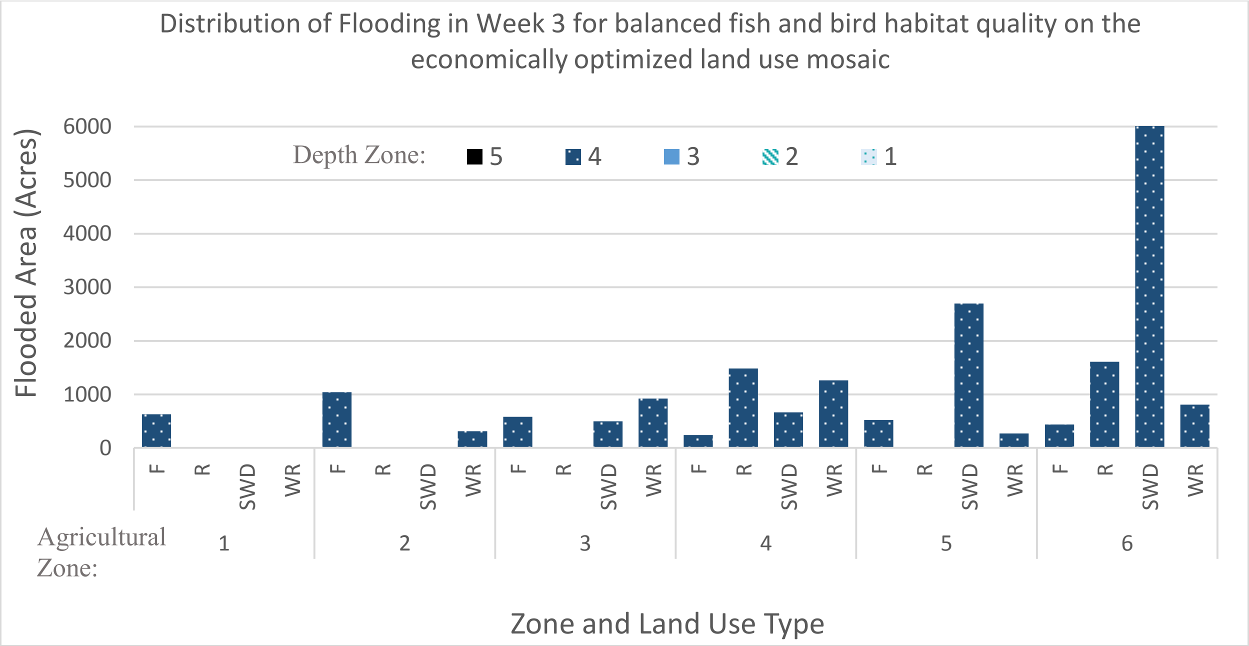


Figure 2.15. Performance Profile showing modeled net returns and habitat quality on real land use mosaics versus an economically optimal land use mosaic.

Figure 2.16 provides more detail on how these improvements in all three objectives might be possible. Flooding in week 3 (February 7th – 13th) for observed land use planted in the spring of 2006 is compared against flooding on the economically optimal land use mosaic, with balanced fish and bird habitat quality constraints. (Fish and bird habitat can be managed at 57% of optimal quality on 2006 land uses, and 61% on economically optimal land uses.) Only flooded land uses are shown for each zone, with area of flooding by depth.



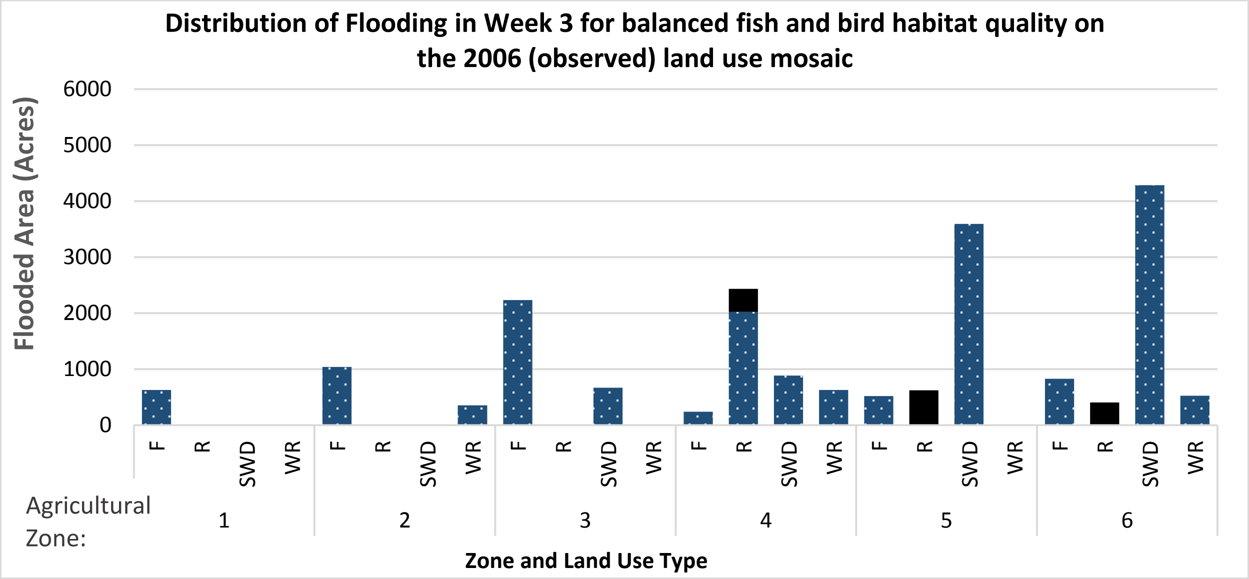


Figure 2.16. Flood distributions during Week 3 of the Optimal Econ run with the maximum balanced habitat quality for both birds and fish, and for balanced fish and bird habitat quality on the 2006 land use mosaic. In either run, habitat quality was only improved insofar as it did not reduce profits for that year. Only flooded land uses are shown. F = Fallow, R = Rice, SWD = Seasonal Wetland, and WR = Wild Rice. Depth zone 5 = >18 inches, 4 = 13 – 18 inches, 3 = 8 – 12 inches, 2 = 5 – 7 inches, and 1 = 2 – 4 inches

These flood distributions show that added wild rice acreage in the economically optimized land use mosaic serves a dual purpose as additional fish and bird habitat. Added seasonal wetlands and rice in the south-western Bypass also add habitat to that which was available on 2006 land uses. There are similarities between the two distributions, with the same land use types generally serving as inundated habitat - fallow, rice, seasonal wetland, and wild rice – and more habitat concentrated in the southern bypass.

As the weeks go by in the season, flooding becomes deeper to adjust for different species' preferences. Figure 2.17 compares flood distributions in weeks 1 and 3 for the 2006 land use mosaic and the economically optimized run:

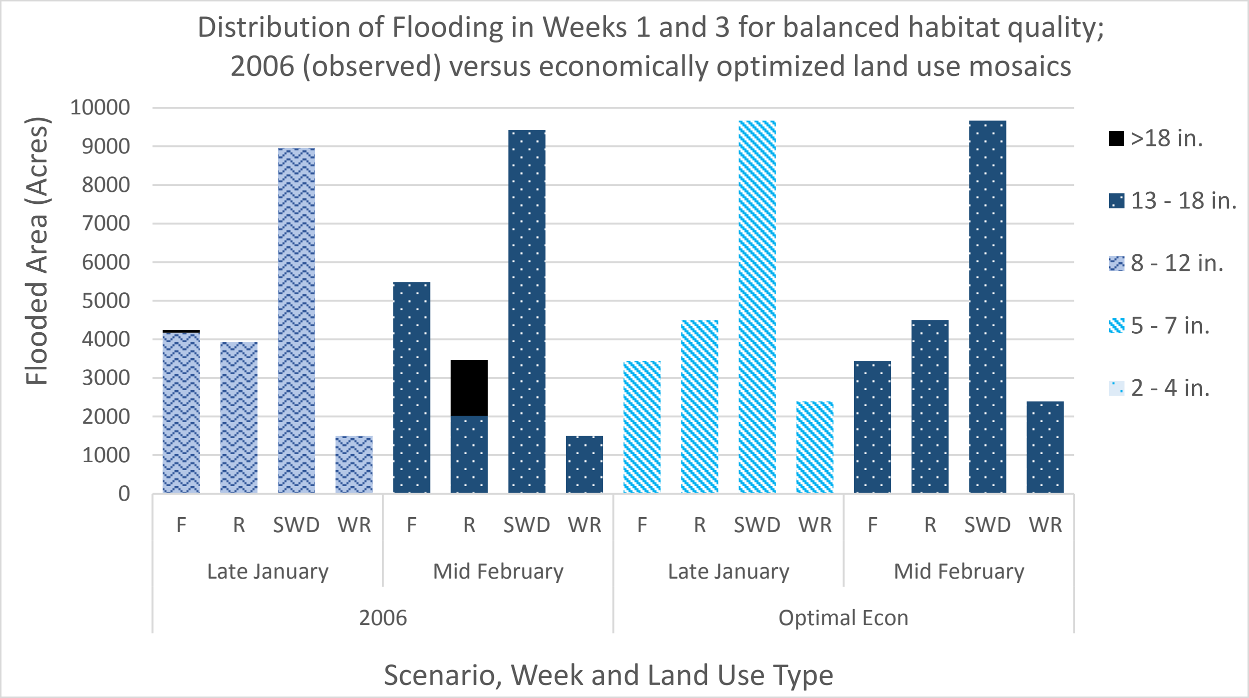


Figure 2.17: Flood distribution for the 2006 land use mosaic and economically optimized land use mosaic in weeks 1 and 3, summed across all zones in the bypass. Only flooded land uses are shown. F = Fallow, R = Rice, SWD = Seasonal Wetland, and WR = Wild Rice.

Both modeled solutions create shallower habitat in late January and early February, when dabbling duck densities are high and fish are usually not yet abundant in the system, and switch to deeper water as inundation moves into mid-February, the most preferable timing for fish (Tables 2.2 and 2.5). This switch to deeper water is also partly because the marginal benefit of a third and fourth week of flooding for fish is much higher than for the first two weeks, while the opposite is true for dabbling ducks.

CONCLUSIONS

The model application and results presented above lead to several conclusions about reconciled fish, bird and anthropogenic objectives on the Bypass and similar systems. These conclusions can be separated into two categories: 1) Trade-offs between fish habitat, bird habitat, and economic performance in a modified Bypass, and 2) Land use implications.

Trade-offs Between Habitat and Economic Objectives

Fish habitat, bird habitat, and economic performance probably can all be improved on the Bypass if additional water is available by way of a modified weir or some other means, and some small changes are made to the current land use mosaic. Optimization of early-season flooding on past land use mosaics (2005 – 2010) also suggests that just 3 weeks of flooding in late January and early February can increase habitat quality for fish and birds from what is currently available in dry years at no cost to farmers. However longer-duration and later flooding would likely further increase habitat quality for fish and shorebirds, and should be tested in later applications of this model. Still more habitat improvement is possible if economic performance is allowed to decrease, but these tradeoffs were not thoroughly explored in this initial application.

Land Use Implications:

Rice and wild rice are both economically and ecologically beneficial. Decision-makers might want to develop incentives for farmers to plant more acres of habitat-friendly rice (in addition to what is already grown). Fallow lands also can be a good source of added habitat at no economic cost, if these fields are easily inundated and accessible to fish and/or birds. This implies that farmers and land managers would have to incorporate fish and bird habitat considerations into crop placements and rotations; this is another area for which economic incentives might be necessary. Finally, seasonal wetland acreage is also likely to increase slightly in a more fish and wildlife friendly bypass. All of these added rice and wetland acres are most likely to replace pasture and safflower in the southern Bypass (the two least valuable agricultural land uses).

NEXT STEPS

The large disparity between habitat quality and economic performance on a mostly dry Bypass versus one undergoing a large flood event highlights the potential for a 'meet in the middle' solution in current dry years; such a solution would provide added habitat benefits for fish and birds with minimal impacts on farming revenues and wetland operations. By keeping economic performance constant, modeling mostly pre-determined land use mosaics, and only experimenting with one start date, this model application did not explore the entire solution space to reveal the full range of trade-offs among economic and habitat goals. Future applications would more thoroughly use the constraint method to develop a more exhaustive set of non-inferior solutions for the reconciliation of fish and bird habitat provision with human uses on the bypass.

These more thoroughly-developed solution sets should be accompanied by more thorough post-processing of the results. Because the results presented in this paper are limited in scope, the conclusions are not as detailed as they perhaps could be for a model with so many decision variables. Implications for land and water management can be explored in much greater depth once trade-offs are better understood and a set of most promising solutions is identified. These might include, for example, zone specific breakdowns of weekly flood depths across all land uses, and associated economic costs for that zone.

This model also is based on many assumptions about fish and bird preferences, agricultural economics, and land use restrictions. Future applications would benefit from sensitivity analyses performed on many of these parameters so that results are developed that are robust within a range of possible realities. Sensitivity analysis could also guide further Yolo Bypass or more general floodplain research that can reduce uncertainties which most matter to future planning decisions.

Finally, results from these initial runs suggest some areas of potential refinement for the model. First, more research is needed to find out if the economically preferable increases in wild rice and tomato acreage are actually possible. Crop rotation, equipment, or other constraints may limit the total acreage that can physically be grown across the bypass at one time. The model also spreads flooding across all zones in the bypass when it is hydrodynamically easiest to instead concentrate flooding in the lower, eastern zones. Future runs could limit flooding to zones 1, 3, 5 and 6 so that solutions are more easily applicable in real system management.

Next steps aside, these preliminary runs have shown that the model assigns acreage and water in a way that makes sense relative to past land use decisions and what is currently understood about fish and bird preferences. It is likely to be a powerful tool in future decision-making for the Yolo Bypass and serves as a good example for the use of multi-objective programming in reconciliation planning.

Chapter 3

Reconciling fish and bird habitat with agricultural uses on an engineered floodplain: Central Valley, California

INTRODUCTION

This chapter uses a multi-objective spreadsheet model to explore tradeoffs among fish, bird, and human uses on an engineered floodplain in California's Central Valley. Floodplains are ecologically productive and important landscapes that encourage high levels of biodiversity (Bayley 1995, Junk et al. 1989, Ward et al. 1999). They also provide societal benefits from flood attenuation, water quality improvements, food production, fiber, and recreation (IWMI et al. 2014, Keddy et al. 2009). Floodplains in California and elsewhere have been disconnected from their rivers and reclaimed for land development and flood management, with a rate of disappearance higher than that of almost any other type of landscape (Bayley 1995, Sparks 1995, Tockner and Stanford 2002, Kelley 1989, Opperman et al. 2010, Tockner et al. 2010, Mount 1995).

However, in places like California's Yolo Bypass (the Bypass) (Figure 3.1), remnants of historical floodplain remain, mostly as agricultural land or as managed wetlands. Research over the last decades suggest that these remnants are places where human uses can be reconciled with the habitat needs of native fish and waterfowl (Feyrer et al. 2006b, Sommer et al. 2001, California DFG et al. 2008, Salcido 2012). In particular, the Bypass, because of its size and location, is an excellent case study for a reconciliation approach to managing floodplain ecosystems. This approach calls for efforts that

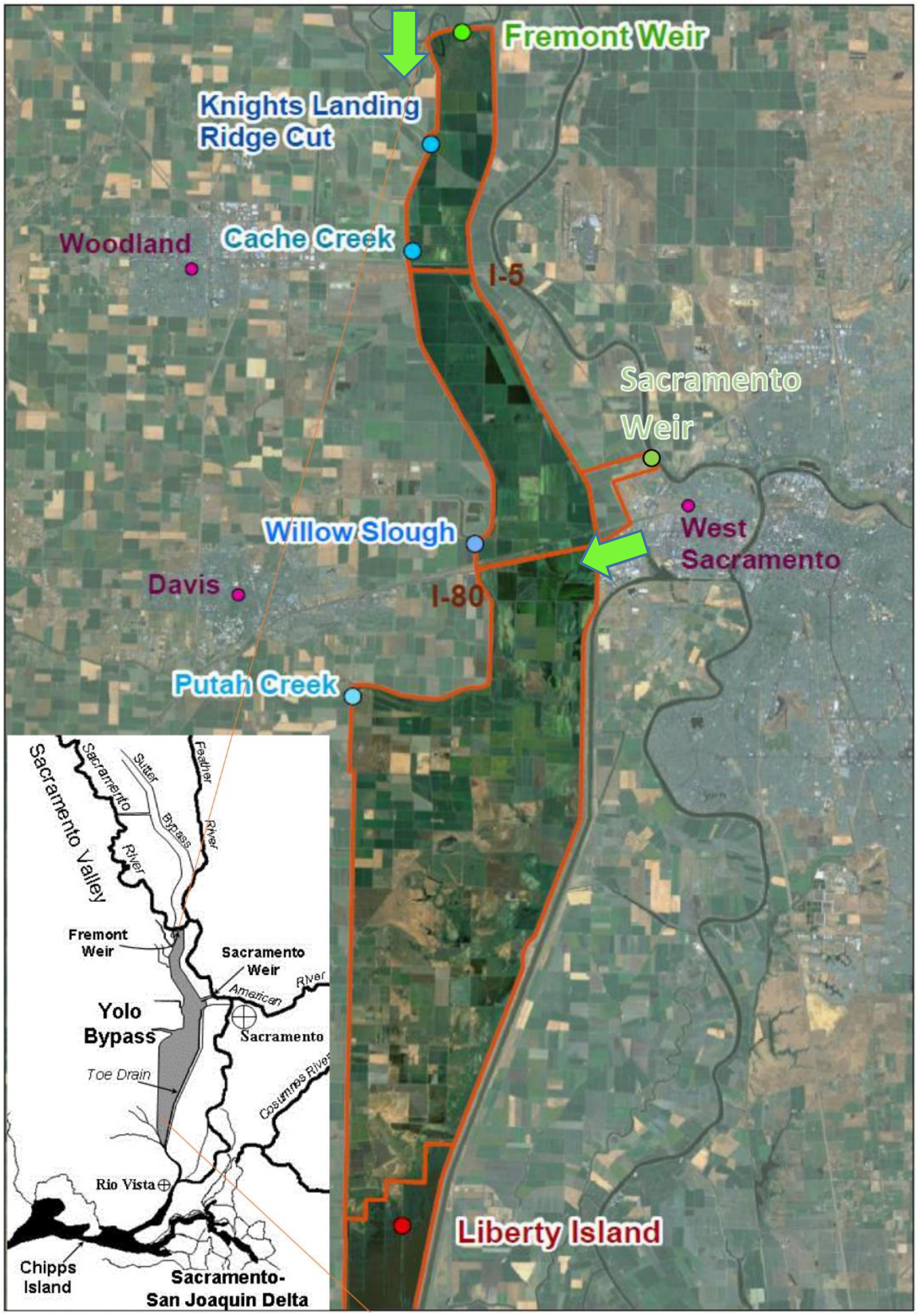


Figure 3.1. Map of the Yolo Bypass and Inflows to the Bypass. Western tributaries are marked with blue circles, and Sacramento River inflows (weirs) with green arrows.

encourage the sustainable co-existence of humans and native species (Rosenzweig 2005). Reconciliation ecologists recognize that preserving or restoring landscapes to pristine (pre-development) conditions is, for the most part, not possible (Rosenzweig 2003, Hanak et al. 2011), and that most landscapes must therefore be managed or even re-engineered in ways that support biodiversity while accommodating human activities (Rosenzweig 2005, Moyle 2013). On the Bypass, this means improving bird and fish habitat within a largely agricultural landscape that also serves for flood control.

Ecosystem reconciliation can benefit from quantitative analysis, like the multi-objective model used here, to guide initial efforts and provide a framework for incorporating new knowledge as it becomes available. Multi-objective analyses are especially important when integrated land and water management must serve a variety of human uses and ecological goals. Computer models can integrate vast amounts of data and describe complex relationships between decisions and system objectives, even when those objectives are measured differently. They help planners account for tradeoffs, make decisions, and appropriately mitigate for losses based on a transparent and consistent consideration of the entire system.

However, these tools often require some formal representation of the relationship of management decisions to ecological goals (like improved fish habitat quality). Because species' interactions with habitats are usually more dynamic and variable than what can be easily simplified into mathematical form, it is important that analyses like this one explore a broad range of ecological assumptions before prescribing solutions or describing tradeoffs.

This study performs a sensitivity analysis on the habitat quality objective functions for the Yolo Bypass Multi-Objective Model (YBMOM) (Chapter 2) to find solutions that are effective under diverse ecological assumptions, and bring attention to important uncertainties. The methods and conclusions herein can be applied to similarly engineered floodplains in California and elsewhere, and demonstrate the usefulness of trade-off analysis in multi-objective floodplain planning. Results imply that well-timed and strategically placed flows can vastly improve habitat quality for multiple fish and bird species on a landscape like the Bypass, with very little cost to farmers or other human uses.

THE YOLO BYPASS

The Yolo Bypass is the lowest in a series of large flood conveyance bypasses on the Sacramento River, situated just above the Sacramento-San Joaquin Delta (Figure 1). These bypasses can carry up to four times the flow of the neighboring leveed river channel (Mount 1995). Sacramento River flows primarily enter the Bypass over the Fremont Weir at its northern end (Figure 3.1). Other inflows to the bypass include the Sacramento Weir (just upstream of the confluence between the Sacramento and American Rivers), and 4 western tributaries: Knights Landing Ridge Cut, Cache Creek, Willow Slough, and Putah Creek (Figure 3.1). Water from the Sacramento river or other tributaries inundates all or part of the bypass in approximately 70% of water years, with durations ranging from 1 to 135 days (Jones & Stokes 2001) usually between December 1st and February 15th (U.S. Department of the Interior et al. 2013).

Human uses of the bypass – primarily agriculture and hunting – are adapted to this periodic flooding. The most common agricultural crops are rice and pasture, but tomato, corn, and safflower are also grown. These crops are mostly unaffected by flooding from December through February, with a growing season that generally begins in March and ends in the fall. However, floods can harm farming activities when they occur in late winter or during the spring (March or April depending on crop), as this delays planting dates and may reduce crop yields and revenues (Howitt et al. 2013).

Most other land on the Bypass is managed as wetlands for a variety of birds, with some private duck clubs more specifically targeted at dabbling duck habitat for recreational hunting. The state-run Yolo Bypass Wildlife Area provides seasonal and permanent wetland for hundreds of species, including various dabbling ducks, geese, shorebirds, and hawks (California DFG et al. 2008), with some agricultural crops also providing useful habitat (Shuford et al. 1998). Many of these birds use the Bypass as over-wintering habitat in the midst of larger migrations along the Pacific Flyway. Duck and white geese populations tend to peak in February, and shorebird populations peak in March and April (CVJV 2006).

Almost all of these birds depend on the availability of some relatively shallow habitat (12 inches deep or less) during winter and early spring for foraging (Taft et al. 2002, Petrik et al. 2012). Flooding that is too deep can limit access to food supplies at the bottom of the water column. Birds are also particular to certain types of seeds that best help them accumulate fat reserves and nutrients used during migration (Smith et al. 1994). In the Bypass, these come primarily from swamp timothy and watergrass, with optimal growing seasons beginning in late April or early May, respectively (Smith et al. 1994, Naylor 1999). Flooding that lasts too long can reduce productivity for these wetland plants, effectively reducing bird food supplies the following fall and winter.

Finally, inundation on the Bypass benefits several native fish species that use flooded fields and wetlands for spawning and rearing. Floodplain habitat is extremely productive for out-migrating juvenile Chinook salmon, which exhibit much higher growth rates on the bypass than they do in the main river channel (Sommer et al. 2001, Williams et al. 2009, Schemel et al. 2004), and grow especially well on flooded rice stubble (Katz et al. 2013). Sacramento splittail, as obligate floodplain spawners, also use several habitats on the Bypass for spawning and rearing (Feyrer et al. 2006b, Sommer et al. 2002).

Because such a diverse array of fish and birds all benefit from and function within this largely agricultural landscape, the Bypass is in some ways already a reconciled system. However flood timing and duration is very different from the historical floodplain. Fish and birds can only use aquatic habitat if it exists at the appropriate time, and lasts long enough so that invertebrate and other food resources become significantly abundant. The most prevalent run of Chinook salmon, for example, typically doesn't migrate through the lower Sacramento watershed until sometime in early to mid-February (U.S. Department of the Interior et al. 2013), and splittail spawn sometime between February and May (Williams et al. 2009, Moyle et al. 2004). Shorebirds similarly depend on shallow mudflat habitat in March and April.

Some biologists have suggested that Bypass inundation could be more beneficial for native fish species if it occurred more frequently, with increased variability in timing and duration (U.S. Department of the Interior et al. 2013, Williams et al. 2009). Because of this and its proximity to the Sacramento-San Joaquin Delta, the Bypass is targeted for floodplain habitat restoration in current state planning efforts (U.S. Department of the Interior et al. 2013) with plans to create a gated notch in the Fremont Weir so water can more frequently enter the Bypass at times that maximize its benefits for fish and other floodplain species. If such a notch were built, those flows could be managed for a variety of characteristics, including placement, depth, and, to the extent that water is available, area, timing and duration.

However, this idea of added flows on the Bypass is not without conflict. Inundation too late into the spring can be costly for farmers and wetland managers, and even decrease food supplies for some bird species. Wetland managers are also concerned that deep flooding may make some lands unavailable as foraging habitat for dabbling ducks and shorebirds (Petrik et al. 2012). In this study, The Yolo Bypass Multi-Objective Optimization Model (YBMOM) is used to examine the tradeoffs present amongst three objectives for Bypass management: fish habitat quality, bird habitat quality, and annual economic revenues from agriculture, within the context of an ongoing flood protection function.

REVIEW OF MODEL FORMULATION

A thorough description of YBMOM is available in Chapter 2. This section provides a brief overview. The performance of all Bypass objectives in the model share a dependence upon three decisions: overall land use mosaic (extent and location of different land use types), flood extent on each land use type, and the timing (and duration) of inundation in the winter and spring. Fish and bird habitat also depends on the depth of flooding. A combination of agricultural economic modeling, interviews, and expert surveys were used to develop the set of objective functions that describe these relationships (Chapter 2 and Appendix A).

The economic objective is driven primarily by agricultural costs and revenues. Because agricultural crops vary in prominence with location and climate on the Bypass, Howitt et al. (2013) defines seven different zones to better reflect location-specific economic realities. These zones are pictured in figure 2.1, and described in better detail in Chapters 1 and 2.

The economic objective for the Bypass is to maximize annual net revenues, or profits (P). Mathematically,

$$Max\ P = \sum_{i}\left[\left(\sum_{j}\sum_{\substack{t=start\\date}}\left(A_{jti,d=0} - A_{j(t-1)i,d=0}\right) * R_{jti}\right) - \sum_{j}\emptyset_{ij}e^{\gamma_{ij}*A_j}\right]$$

[Eqn 1]

where

i = agricultural zone, as defined in Howitt et al. (2013)

j = land use type

d = depth

t = week

$A_{jti,\ d=0}$ = Acres of land use type j in zone i at time t that are no longer flooded.

R_{jti} = the annual revenues from land use j in zone i, available for use by time step t.

and $\emptyset_{ij}$ and γ_{ij} are cost parameters for farming A acres of land use j in zone i, taken from an agronomic model of the Yolo Bypass developed for a separate study (Howitt et al. 2013)

Habitat quality for fish and/or birds on the Bypass is described in terms of habitat preferences for the fish and bird species groups that most depend on flooding during the winter and spring: Chinook salmon, Sacramento splittail, dabbling ducks (dabblers), and shorebirds (Appendix A). Habitat quality for each can be expressed with the same equation, using varied weighting schemes for each group. The objective is to maximize habitat quality (HQ). Mathematically,

$$Max\ HQ_{fish\ or\ birds} = \sum_{s} P_s \sum_{\substack{t=start\\ date}} \omega_{ts}\ \delta_{ts} \sum_{d} \delta_{ds} \sum_{j} \beta_{sA} \left(\frac{A_{jtid} * \alpha_{sj}}{Max\left(A_{jtid} * \alpha_{sj}\right)} \right) + \beta_{sC} \left(\frac{Entropy\left(A_{jtid}\right)}{Max\ Entropy} \right)$$

[Eqn 2]

where

P_s= the amount that species s habitat quality contributes towards total fish or bird habitat quality (set at 0.5 initially so that salmon and splittail are equally prioritized for the total fish habitat quality score, and dabblers and shorebirds are equally prioritized for the total bird habitat quality score.)

ω_{ts} = marginal benefit of each additional week of flooding for species s

δ_{ts} = relative importance (weight) of flooding at time t for species s

δ_{d} = relative benefit (weight) of flooding in depth zone d for species s

α_{sj} = the relative benefit (weight) of land use j as habitat for species s

B_{sA} and β_{sC} =
relative importance of total area and land use types flooded (A) versus complexity (C)for species s, where complexity is expressed with an entropy function.

A_{jtid} = the acreage of land use j in week t

Entropy is calculated as $E = \left(\frac{A_{jt,d>0}}{\sum A_j}\right) * -ln\left(\frac{A_{jt,d>0}}{\sum A_j}\right)$

The weighting schemes for the habitat objective function are developed in Chapter 2 and Appendix A, and are reproduced here in Tables 3.1 through 3.4.

Table 3.1: ***Relative fish habitat preferences (weights) for varied land use types and time of year. Source: Chapter 2 and Appendix A***

Land Use Type (j)	**Weights (α_{sj})**		**Timing (t)**	**Weights (δ_{ts})**	
	Splittail	**Fall-Run Chinook Salmon**		**Splittail**	**Fall-Run Chinook Salmon**
Rice	0.61	1.00*	Jan 1 - Jan 15	0.40	0.59
Wild Rice	0.63	1.00*	Jan 16 - Jan 31	0.47	0.74
Corn	0.31	0.46	Feb 1 - Feb 14	0.67	0.90
Tomato	0.31	0.46	Feb 15 - Feb 28	0.87	1.00
Pasture	0.73	0.78	Mar 1 - Mar 15	1.00	0.97
Fallow	0.71	0.79	Mar 16 - Mar 31	1.00	0.95
Riparian	0.92	0.97	Apr 1 - Apr 15	0.93	0.82
Seasonal Wetlands	1.00	1.00	Apr 16 - Apr 30	0.80	0.67
Permanent Wetlands	0.66	0.78	May 1 - May 15	0.47	0.46
Safflower	0.45	0.53			

Table 3.2: Relative dabbling duck and shorebird foraging habitat preferences (weights) for land use types and time of year. Source: Chapter 2 and Appendix A

Land Use Type (j)	Weights (α_{sj})		Timing (t)	Weights (δ_{ts})	
	Dabbling Ducks	Shore-birds		Dabbling Ducks	Shore-birds
Rice	0.88	0.96	Jan 1 - Jan 15	1.00	0.63
Wild Rice	0.94	0.93	Jan 16 - Jan 31	0.99	0.63
Corn	0.73	0.57	Feb 1 - Feb 14	1.00	0.68
Tomato	0.38	0.48	Feb 15 - Feb 28	0.99	0.79
Pasture	0.52	0.76	Mar 1 - Mar 15	0.90	0.86
Fallow	0.58	0.73	Mar 16 - Mar 31	0.86	0.92
Riparian	0.58	0.49	Apr 1 - Apr 15	0.75	1.00
Seasonal Wetlands	1.00	1.00	Apr 16 - Apr 30	0.66	0.97
Permanent Wetlands	0.72	0.80	May 1 - May 15	0.63	0.89
Safflower	0.42	0.48			

Table 3.3: **Relative fish habitat preference for varied flood depths. Source: Chapter 2 and Appendix A**

Depth (d)	Splittail Weights ($\delta_{splittail,\ d}$)	Salmon Weights ($\delta_{salmon,\ d}$)	Dabbler Weights ($\delta_{dabbler,d}$)	Shorebird Weights ($\delta_{shorebird,d}$)
Zone 1: 2 – 4″	0.21	0.22	0.86	1.00
Zone 2: 5 – 7″	0.38	0.35	1.00	0.75
Zone 3: 8 – 12″	0.71	0.58	0.95	0.44
Zone 4: 13 – 18″	1.00	0.91	0.66	0.11
Zone 5: > 18″	1.00	1.00	0.30	0.04

Table 3.4. Relative importance of the area and particular land use types flooded versus the overall heterogeneity, or "complexity" of flooded land uses. Source: Chapter 2 and Appendix A

	Weight (β_{sA} and β_{sC})	
Flood Characteristics	**Fish**	**Birds**
Total area, depth, and land use types flooded	0.7	0.68
Complexity (entropy) of flooded land uses	0.3	0.32

In trying to maximize the economic or ecological objectives presented above, decisions on the Bypass are also bound by a set of constraints that fall into one of two categories: land use or water management. These are summarized qualitatively in Table 3.5 and described in more detail in Chapter 2.

Table 3.5: YBMOM Constraint Set.

Land Use Constraints	**Water Management Constraints**
Total acreage used in each zone is limited.	Total duration cannot exceed 8 weeks.
Non-negativity: Assigned acreage cannot be less than zero.	Total inundation area cannot exceed 20,000 acres.
Total acreage of any land use in each zone must remain steady through the season.	Total flooded acreage cannot increase through the season.
Total fallow acreage in any zone must equal or exceed the minimum observed fallow acreage in that zone for the years 2005 – 2009.	Any land use that becomes dry any week must remain dry all later weeks.
Wetland acreage in any zone cannot be less than 75% of the observed wetland acreage in that zone for the years 2005 - 2009.	Flooding in the northern bypass can only occur in the eastern zones (1 and 3) along the Toe Drain.
Total riparian acreage cannot exceed 5% of total bypass area.	

There are many solutions to the above system of objective and constraint equations. Multi-objective analyses identify a set of efficient trade-off solutions, known as Pareto optimal or non-inferior, for which no other solutions exist that can better one objective without decreasing performance towards other objectives (Cohon 1978). This solution set is accompanied by trade-off tables or curves that report how performance towards one objective impacts the others. Individual solutions along these curves represent different preferences for particular objectives. The YBMOM finds a non-inferior (Pareto-optimal) solution set by employing the constraint method (Cohon and Marks 1975, Cioffi and Gallerano 2012), which converts all but one objective into constraints, then solves multiple times for that objective with varying levels of performance required towards the others. More specifically:

$$Maximize\ Profit\ (Eqn\ 1)\ such\ that$$

$$\frac{HQ_{Birds}}{MAX(HQ_{Birds})} \geq x \quad and \quad \frac{HQ_{Fish}}{MAX(HQ_{Fish})} \geq y$$

(And all other physical constraints presented above are also satisfied.)

Where x and y are re-set for consecutive optimization runs

In Chapter 2, the model was only tested for the original objective functions without any changes to parameters. In this application, several different habitat quality functions are created for fish and birds based on varied assumptions about species' preferences, resulting in four sets of objective functions. The constraint method is employed for each of these, so that multiple non-inferior solution sets are created with varying tradeoff implications. The following section describes some of the complexities and uncertainties inherent in quantifying habitat quality on the Bypass and other systems, and how these are represented in the modified habitat objective functions.

VARYING THE HABITAT FUNCTIONS

The habitat quality objective functions in the YBMOM are focused on some of the native migratory bird and fish species adapted to seasonal floodplain inundation in the Sacramento Valley. In the model, habitat quality depends mathematically on various weighting schemes that attempt to relate floodplain and flood characteristics to the preferences of specific fish and bird species (Tables 3.1 through 3.4 and Appendix A). However these preferences evolved in a floodplain system much different from today's Bypass, and depend on dynamic physical and biological interactions that are sometimes difficult to quantify.

Historically, the valley flooded almost annually, with significant variation in the timing, volume, and duration of inundation, and flows often extending across vast expanses of low-lying riparian forests, floodplain lakes, permanent wetlands, and tule marsh (Kelley 1989). Because of the frequency and variability in flood events and the heterogeneous inundation of floodplain habitat, a variety of native bird and fish species evolved life history strategies that take advantage of such seasonal floods. However, the frequency, variability, and extent of flooding have all diminished on the Bypass, and the landscape itself has transitioned from successional floodplain vegetation and varied topography to a graded patchwork of agricultural crops and managed wetlands. The resultant reduction in availability and complexity of floodplain habitat makes it more difficult to manage for a broad mix of species and life history strategies, and makes prioritization of particular birds or fish an important management or policy question. These changes also make it difficult for biologists and planners to estimate species' preferences for various floodplain characteristics in new habitats that differ so much from their natural counterparts.

Finally, inter-annual uncertainties make static mathematical descriptions of habitat quality more difficult. Year-to-year variability in precipitation, temperature and flows can affect species' habitat preferences on the Bypass in space and time during any given year. Chinook salmon, for example, leave floodplain habitats as floodwaters recede or when water temperatures get too warm. In years when water temperatures remain cool through the early spring, juvenile salmon may benefit from longer and later floodplain inundation than otherwise (pers. comm. C. Jeffres).

To more fully explore and capture this natural variability and uncertainty, four changes were made to the base weighting schemes for fish and bird habitat quality objectives.

1. **Weighting 1: Land Uses Equal.** The base case applies weights to the relative value that different bypass land use types provide as habitat in terms of foraging opportunities and structure (α_{sj} in Eqn 2). These weights differ for each species or species group. However, dabbler and shorebird preferences for agricultural and wetland units on the bypass have been more widely observed and studied than those of Chinook salmon or splittail, and expert opinion on the value of some agricultural land use types as fish habitat vary greatly. Also, these current land uses are very different from those available on the historical floodplain, making it difficult for experts to ascribe fish preferences for one type over the other. To test whether or not fish land use preferences are important, a fish habitat quality objective function was created that assumed fish are indifferent to land use type (all land use weights equal 1).

2. **Weighting 2: More Linear Timing and Duration.** This represents the largest deviation in functional form from the base case habitat functions. The base case made two important assumptions about flood duration and timing. First, weights are applied to specific weeks of flooding (i.e. February 7th – 13th or March 20th – 27th) that describe the value of habitat availability in that week for a given species. Second, the marginal benefits assigned to each added week of flooding generally reflect diminishing marginal returns, so later weeks are less valuable than earlier weeks (Chapter 2). These assumptions may be true on average, but ignore years in which weather or other factors change optimal timing for some species, or make it so fish can stay on the floodplain for a longer time. To find out how such years might change management decisions for the Bypass, the weights for any week after mid-February or late-February for salmon and splittail (respectively) were all set to 1 (the maximum weight). Additionally, the marginal benefit for added weeks of flooding for birds was linearized. Because food resources for fish (zooplankton and other macroinvertebrates) require approximately two weeks to develop significant biomass, only the marginal benefit of weeks 3 – 8 were linearized in the fish functions (with the marginal value of weeks 1 and 2 remaining relatively low).
3. **Weighting 3: Complexity Weight Reduced.** Expert interviews and surveys suggest that both fish and birds on the Bypass value some amount of variability in the types of land use available to them as inundated habitat (Appendix A). Experts were asked to distribute benefit points between two factors: (1) Complexity or heterogeneity of flooded land uses, and (2) The total acres flooded, with considerations of depth and land use

type. Their answers resulted in complexity contributing 30% and 32% to the total habitat quality score for fish and birds, respectively (Table 3.4). This incentivizes the optimization to spread inundation across multiple land use types rather than concentrating it all on the one or two land uses with the highest habitat value. However, some experts believe that complexity of land use types is much less important than other floodplain characteristics (Appendix A). To test the implications of such a reality, new habitat quality functions were developed for fish and birds in which complexity contributes only 10% to the total habitat quality value for any given species.

4. **Weighting 4: Salmon and Dabblers Prioritized.** Weighting schemes 1 through 3, above, are all based on variability or uncertainties in species' preferences for different habitat characteristics on the Bypass. This weighting scheme focuses instead on uncertainty about human, or societal preferences. The base case equally prioritizes salmon and splittail in the fish habitat objective, and dabblers and shorebirds in the bird habitat objective. However, because some runs of Chinook salmon are listed as endangered, and more wetlands are managed for dabbling ducks than for shorebirds on the Bypass, managers might prefer more targeted habitat. This weighting scheme prioritizes fall-run salmon and dabblers over splittail and shorebirds by assigning the following weights for P_s in Eqn 2:

   $P_{salmon} = 0.9$, $P_{splittail} = 0.1$, $P_{dabblers} = 0.9$, and $P_{shorebirds} = 0.1$

The above and original weightings result in five varied descriptions of habitat quality and species preferences on the Bypass, with unique YBMOM objective functions for each. However, while weighting 4 addresses the potential for targeting salmon and dabblers above other species, it does not address the different ways birds or fish in general might be prioritized on the Bypass. Using the constraint method described above, all five weighting schemes were applied to two trade-off scenarios:

1. **Scenario A– Balanced Habitat Quality.** This scenario balances improvements in fish and bird habitat to the maximum extent possible so that neither can be further improved without reducing habitat quality for the other. For the base case, this threshold occurs when habitat quality for fish and birds is approximately 75% of maximum. To compare consistently across all weighting schemes, all were set to 75% habitat quality, or as high as possible if 75% was infeasible.
2. **Scenario B – Fish Prioritized.** This scenario maintains bird habitat quality at approximately 50% of optimal, a level only slightly higher than what is being achieved with current wetland management (Chapter 2). It then improves fish habitat quality as much as possible. Depending on weighting scheme and start date, this translates to fish habitat quality between 90 and 99% of optimal.

A more complete solution space was also explored for weighting schemes 1 and 4 (Land Uses Equal and Salmon and Dabblers Prioritized) with habitat quality for fish and birds varied between 40 and 100 % of optimal at intervals of 5 to 10%. This allowed for comparison across a broader spectrum of tradeoffs. Finally, the model was changed in a set of runs to reflect years in which lower Sacramento river flows might only provide 6 weeks and no more than 15,000 acres of inundation.

LIMITATIONS

While models can be useful in describing and navigating the management of complex systems, they are also subject to simplifications and data limitations. A few problems are highlighted here as they relate to this application of the YBMOM.

First, the only sensitivity analysis in this application involves habitat weights and flood constraints. Many other inputs influence optimized model decisions and results, including agricultural economic parameters like crop price. These are based only on 2005 through 2009 records from Yolo County, and may not reflect more recent trends in the local agricultural economy. Future applications would benefit from testing model sensitivity against varied agricultural parameters.

Second, habitat suitability indices, which closely resemble the habitat quality functions in the YBMOM, have been criticized for ignoring correlations among different habitat variables (Ahmadi-Nedushan et al. 2006), and are only one way of measuring benefits for native species. While the study presented here varies weights to test model sensitivity to changes in habitat preferences, the inherent functional form is unchanged. Future applications might benefit from exploring different formulations that otherwise describe habitat quality or ecological benefits, especially as more research refines our knowledge of how fish and bird species use this new floodplain habitat.

Another mathematical limitation is that the agricultural cost functions dis-incentivize planting any added acres of a crop beyond those for which marginal benefits equal marginal cost (assumed to occur at the maximum number of acres historically grown for years 2005 –

2009). Growing beyond this point means less profit as the added revenues do not make up for added costs. However the model punishes such decisions with unrealistic exponential functions over some ranges for which costs grow very quickly for each acre added. While accurate in reporting a decrease in profits from such decisions, the model greatly exaggerates these losses.

Finally, the economic objective in the YBMOM is to maximize annual profits. The tradeoffs presented here only show this annual perspective, and do not consider the original sunk costs of notching the Fremont weir or any other infrastructure necessary to bring in the added flows. The model assumes that this particular cost-benefit analysis and decision has already been made, and is instead focused on decisions within the new system.

RESULTS

Tradeoffs for the Base Case, Salmon and Dabblers Prioritized, and All Land Uses Equal

Figure 3.2 shows habitat quality tradeoffs for given annual economic losses with a February 7th start date. For comparison it also plots simulated habitat benefits that are currently achieved on the Bypass in dry years without a notch in the upstream Fremont Weir, and possible habitat gains with added flows on past land use mosaics (years 2006 and 2008). Figure 3.3 shows similar tradeoff curves with varied weightings in the fish and bird habitat objectives (all land uses equal, and salmon and dabblers prioritized).

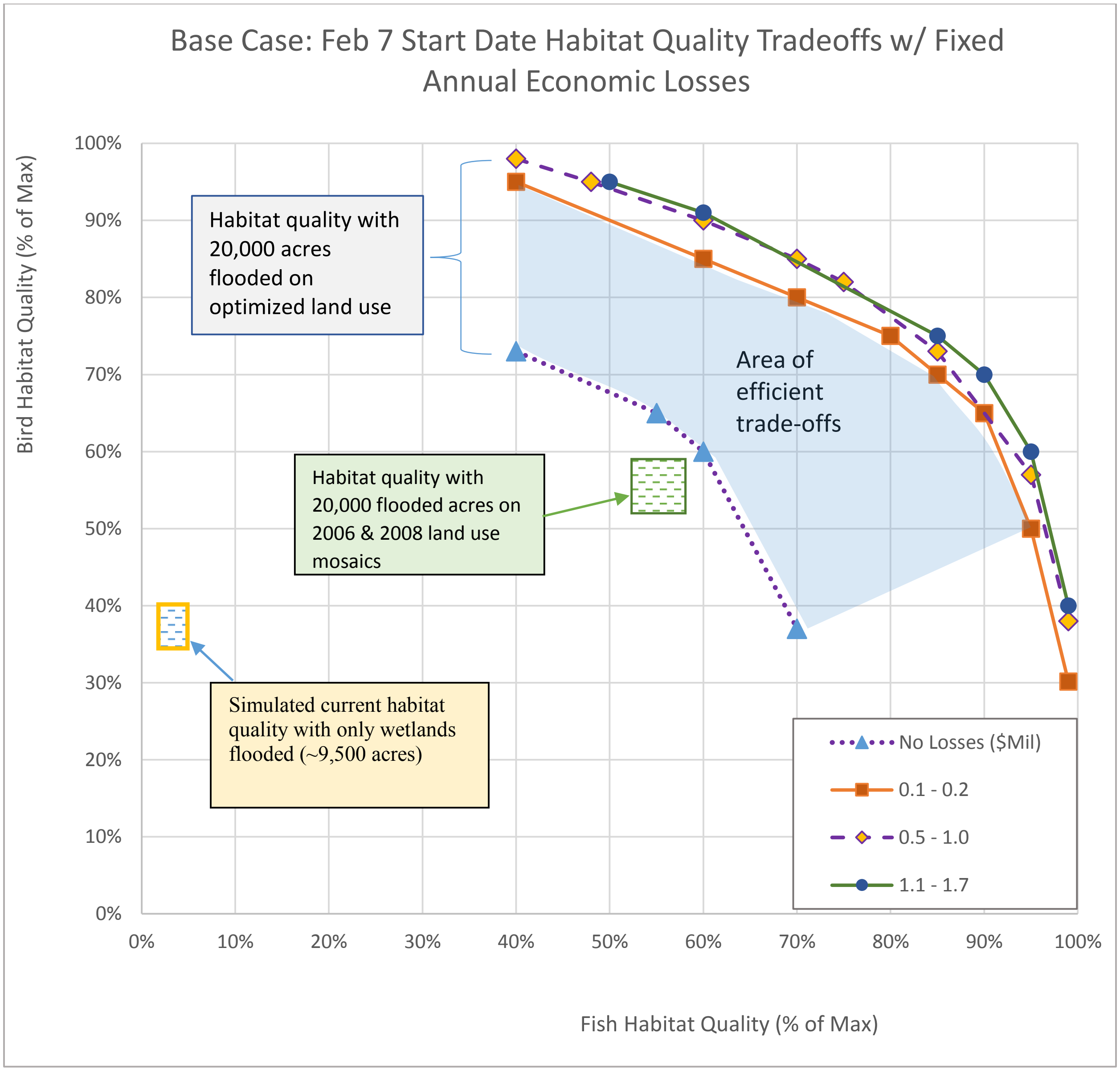


Figure 3.2. Feb 7 Habitat Quality Tradeoffs with Fixed Annual Economic Losses (Base Case Weighting Scheme). The yellow square shows current habitat quality available (mainly for birds) in current wetlands. Only depths were optimized – all other decision variables (land use, acres flooded, etc) were simulated. The green square shows increases in habitat quality that would be possible on historic land use mosaics with added water and an extra 10,500 acres of flooded acreage (for a total of 20,000 acres). Land use was simulated for years 2006 and 2008; only flow placement was optimized. Finally, the set of 4 curves display bird and fish habitat quality tradeoffs for fully-optimized runs in which the model made all decisions (land use, timing of flows, water placement, and depth) and a total of 20,000 acres were inundated. The blue area shows significant habitat gains are possible for zero or small losses in annual revenues.

Perhaps the most important result is that added water from a notched weir could create fish habitat and improve bird habitat quality relative to current dry years with no annual revenue losses for farmers or duck club owners (the move from the yellow to the green box in Figure 3.2). Also, some land use changes would further optimize the application of that water for habitat without any losses in annual agricultural revenues (the move from the green box to the "no losses" curve in Figure 3.2). Finally, significant improvements in habitat quality are achievable with additional land use changes and $100,000 - $200,000 in annual net revenue losses, with minimal habitat quality gains for relatively large economic losses thereafter.

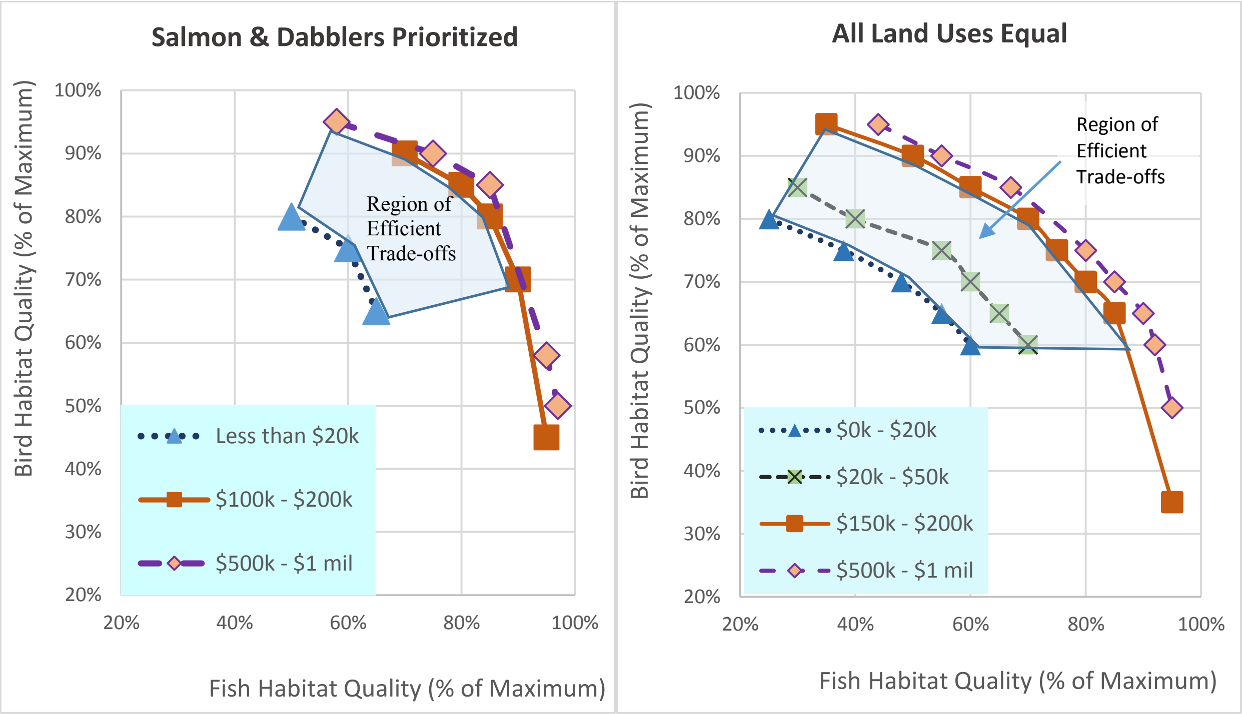


Figure 3.3. Habitat quality tradeoffs for given losses in annual revenues with a February 7th start date, and varied habitat assumptions and priorities (salmon and dabblers prioritized on the left, and all land uses weighted equally for fish on the right). Blue shaded area shows the regions where tradeoffs among fish, birds, and annual revenues are low for significant gains in habitat quality objectives.

Feasible habitat quality for the base case (Figure 3.2) ranges from 30% to 98% for fish and birds. Once fish habitat quality is improved beyond 90 or 95% of optimal, bird habitat quality begins decreasing at a much higher rate per percentage point increase in fish habitat quality. Similar curves result with different weighting schemes (Figure 3.3). In all cases, minimal sacrifices in fish habitat quality (shifting from 95% of optimal back to 85% or 90% of optimal) result in significant gains for bird habitat quality, suggesting that a holistic consideration of all species is much more efficient than targeting fish alone. Figure 3.3 also shows that it is easier to improve overall fish and bird habitat quality when prioritizing salmon and dabblers because the model is no longer forced to balance the needs of 2 species for each objective (i.e. habitat quality is higher for the same level of foregone annual revenues).

In all cases, it seems possible to manage land and water on the Bypass to achieve 70 to 80% of the maximum attainable habitat quality for fish and birds for $100,000 - $200,000 in annual costs. This loss in annual revenues represents less than a 1% loss of total annual crop revenues on an economically optimized (modeled) bypass, and a loss of 1 – 5% of annual historical revenues in real years 2005 – 2009.

Land Use Changes Inside and Out of the Region of Efficient Tradeoffs

The improvements in habitat quality shown in Figures 3.2 and 3.3 are achieved in two ways: (1) Permanent changes in the land use mosaic to increase availability of habitat-friendly land uses, and (2) Flooding decisions that strategically direct and move added flows across that land use mosaic, with depths and placement that vary in space and time to optimize habitat availability for different species while minimizing costs to agriculture. The following results focus on the first of these two decision groups: permanent land use changes. Figure 3.4 shows permanent land use changes that occur within and outside of the region of efficient trade-offs (shown in Figures 3.2 and 3.3) for different points along the base case tradeoff curves.

The most efficient land use change is an exchange of pasture for wetlands. This happens regardless of whether fish and birds are balanced or one is prioritized over the other. Other lands begin increasing or decreasing in acreage as habitat quality is further improved (beyond the region of efficient tradeoffs). In this case, wild rice, rice, and fallow land is added while tomato and some additional pasture acreage decreases.

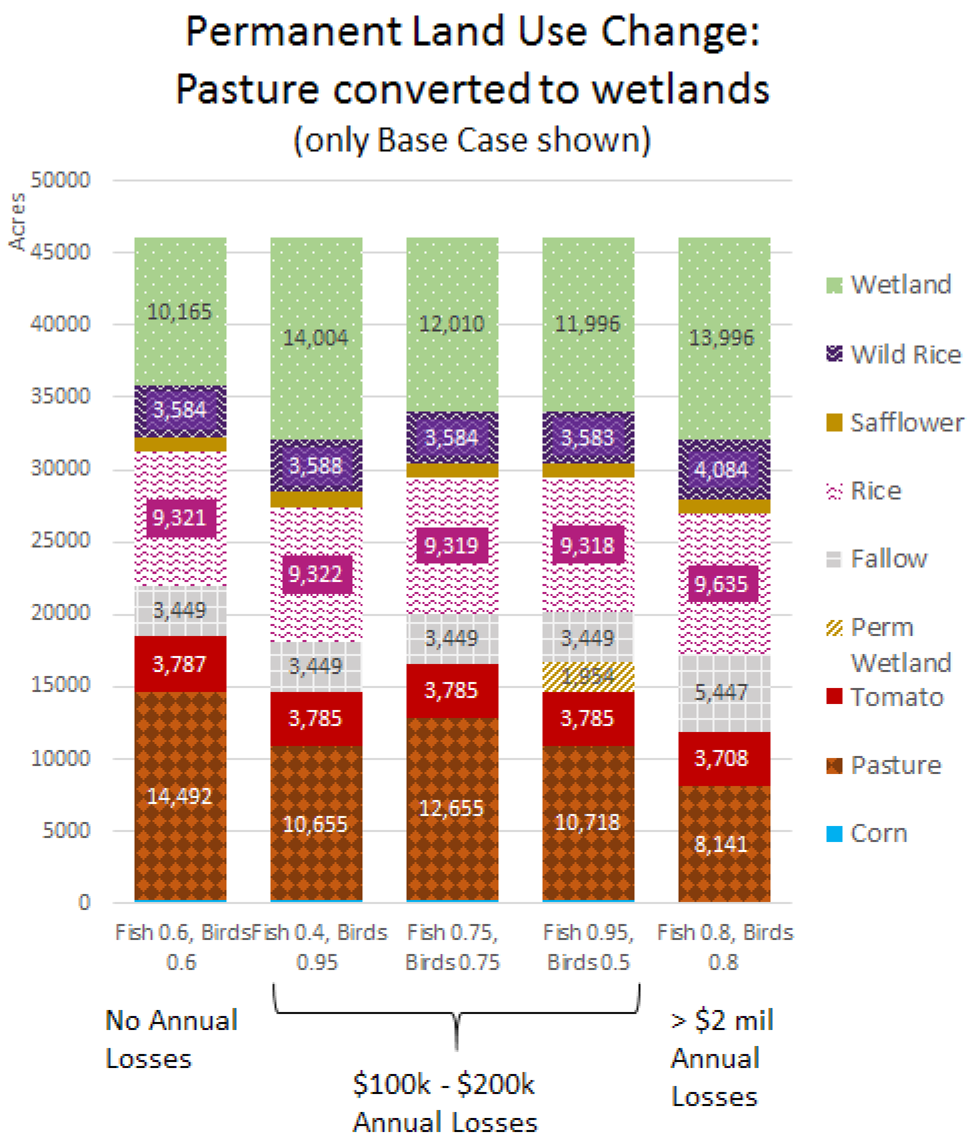
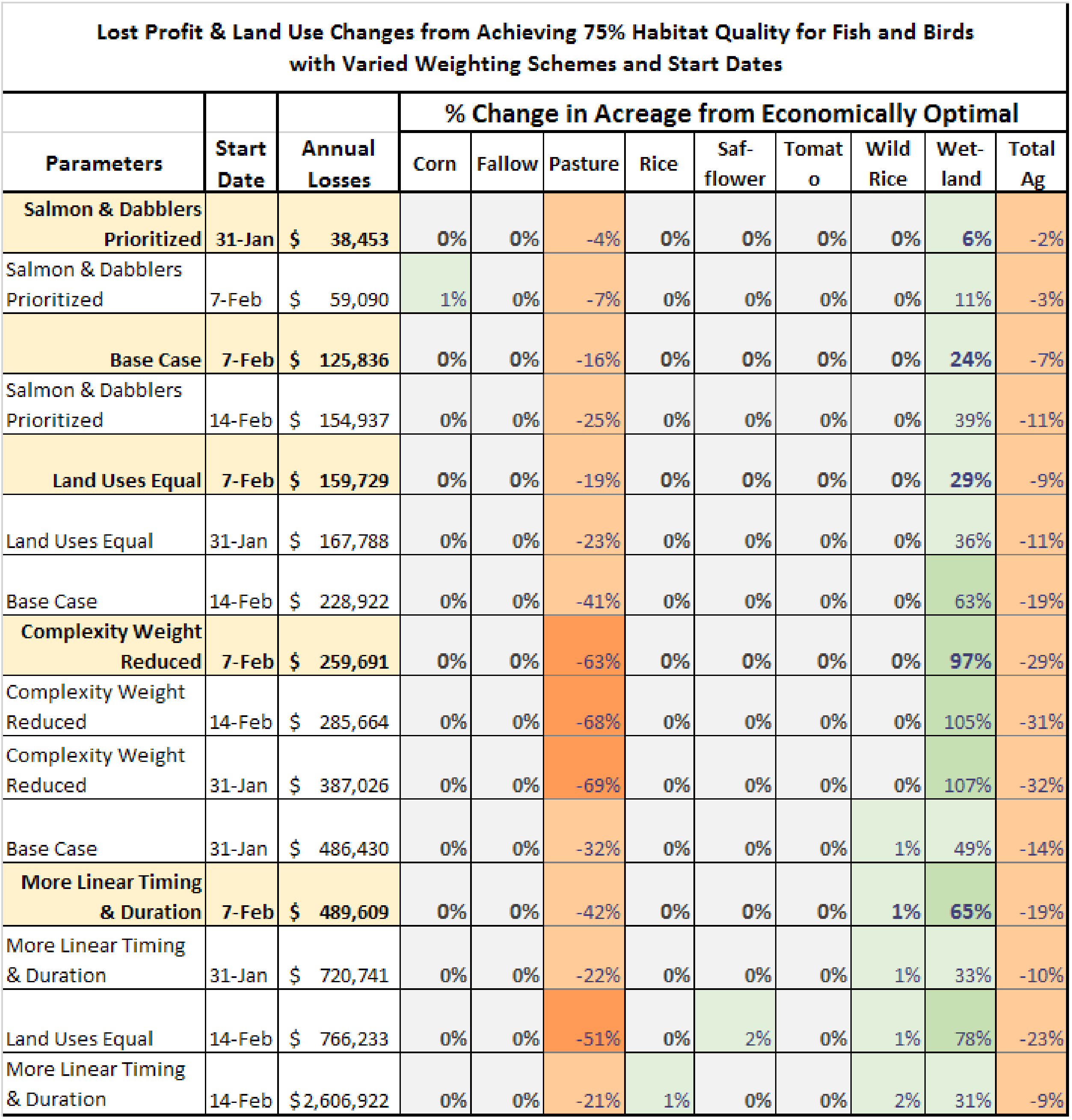


Figure 3.4. Base case land use changes in the area of efficient trade-offs (first four bars). Each bar represents a different point in the trade-off space. Numbers show acreage for each land use type. The last bar (Fish 0.8, Birds 0.8) is the only point outside the area of efficient tradeoffs, and shows additional changes to rice, wild rice, fallow, and tomato acreage as habitat quality is further improved. Habitat quality is reported on a scale from zero to one, where fish 0.6 means that fish habitat quality is at 60% of optimal. In all cases, wetland acreage is increased at the expense of pasture.

Similar land use changes are made with varied habitat quality assumptions (weightings 1 through 4) and fish and bird priorities. Tables 3.6 and 3.7 show annual net revenue losses and land use changes summed for the entire bypass for three start dates, first with balanced habitat quality for birds and fish at 75% of optimal (Table 3.6) and then with fish prioritized (Table 3.7).

Table 3.6: Variations in cost and land use with different weighting schemes and start dates, and bird and fish habitat quality balanced at 75%.



Lost Profit & Land Use Changes from Achieving 75% Habitat Quality for Fish and Birds with Varied Weighting Schemes and Start Dates

			% Change in Acreage from Economically Optimal								
Parameters	**Start Date**	**Annual Losses**	Corn	Fallow	Pasture	Rice	Saf-flower	Tomato	Wild Rice	Wet-land	Total Ag
Salmon & Dabblers Prioritized	**31-Jan**	**$ 38,453**	0%	0%	-4%	0%	0%	0%	0%	6%	-2%
Salmon & Dabblers Prioritized	7-Feb	$ 59,090	1%	0%	-7%	0%	0%	0%	0%	11%	-3%
Base Case	**7-Feb**	**$ 125,836**	0%	0%	-16%	0%	0%	0%	0%	24%	-7%
Salmon & Dabblers Prioritized	14-Feb	$ 154,937	0%	0%	-25%	0%	0%	0%	0%	39%	-11%
Land Uses Equal	**7-Feb**	**$ 159,729**	0%	0%	-19%	0%	0%	0%	0%	29%	-9%
Land Uses Equal	31-Jan	$ 167,788	0%	0%	-23%	0%	0%	0%	0%	36%	-11%
Base Case	14-Feb	$ 228,922	0%	0%	-41%	0%	0%	0%	0%	63%	-19%
Complexity Weight Reduced	**7-Feb**	**$ 259,691**	0%	0%	-63%	0%	0%	0%	0%	97%	-29%
Complexity Weight Reduced	14-Feb	$ 285,664	0%	0%	-68%	0%	0%	0%	0%	105%	-31%
Complexity Weight Reduced	31-Jan	$ 387,026	0%	0%	-69%	0%	0%	0%	0%	107%	-32%
Base Case	31-Jan	$ 486,430	0%	0%	-32%	0%	0%	0%	1%	49%	-14%
More Linear Timing & Duration	**7-Feb**	**$ 489,609**	0%	0%	-42%	0%	0%	0%	1%	65%	-19%
More Linear Timing & Duration	31-Jan	$ 720,741	0%	0%	-22%	0%	0%	0%	1%	33%	-10%
Land Uses Equal	14-Feb	$ 766,233	0%	0%	-51%	0%	2%	0%	1%	78%	-23%
More Linear Timing & Duration	14-Feb	$2,606,922	0%	0%	-21%	1%	0%	0%	2%	31%	-9%

Table 3.7: Variations in cost and land use with different weighting schemes and start dates, and fish habitat quality prioritized.

Annual Cost of Achieving 90 - 95% of the Maximum Habitat Quality for Fish and 50% for Birds with Varied Habitat Quality Functions and Start Dates

			% Change in Acreage from Economically Optimal								
Parameters	**Start Date**	**Annual Losses**	**Corn**	**Fallow**	**Pasture**	**Rice**	**Saf-flower**	**Tomato**	**Wild Rice**	**Wet-land**	**Total Ag**
Salmon & Dabblers Prioritized	**31-Jan**	**$ 177,298**	-88%	0%	-25%	0%	0%	0%	0%	36%	-10%
Base Case	**7-Feb**	**$ 185,697**	-88%	0%	-27%	0%	0%	0%	0%	39%	-11%
Salmon & Dabblers Prioritized	7-Feb	$ 207,068	-88%	0%	-28%	0%	0%	0%	0%	41%	-11%
Complexity Weight Reduced	**7-Feb**	**$ 273,303**	-88%	0%	-64%	0%	0%	0%	0%	94%	-26%
Complexity Weight Reduced	14-Feb	$ 279,439	-88%	0%	-65%	0%	0%	0%	0%	96%	-27%
Complexity Weight Reduced	31-Jan	$ 289,753	-88%	0%	-68%	0%	0%	0%	0%	99%	-27%
Base Case	14-Feb	$ 541,091	-87%	0%	-42%	0%	-1%	0%	1%	61%	-17%
Base Case	31-Jan	$ 786,873	-88%	0%	-19%	0%	0%	0%	1%	27%	-7%
Land Uses Equal	**7-Feb**	**$ 835,440**	-100%	53%	-18%	0%	37%	0%	1%	6%	-2%
More Linear Timing & Duration Weights	**31-Jan**	**$ 859,771**	-88%	0%	-18%	0%	0%	0%	1%	26%	-7%
More Linear Timing & Duration Weights	7-Feb	$ 1,394,448	-88%	0%	-22%	0%	0%	0%	2%	32%	-9%
Land Uses Equal	14-Feb	$ 1,441,170	-100%	53%	-14%	-3%	78%	-1%	0%	0%	0%
Fish 100%	7-Feb	$ 1,538,966	-88%	0%	-18%	1%	0%	0%	2%	26%	-7%
Land Uses Equal	31-Jan	$ 1,912,695	-100%	0%	-2%	-5%	95%	-1%	0%	0%	0%
More Linear Timing & Duration Weights	14-Feb	$ 2,204,107	-88%	0%	-24%	1%	0%	0%	2%	34%	-9%
Salmon & Dabblers Prioritized	14-Feb	$ 2,775,586	-88%	0%	-36%	1%	-1%	0%	2%	51%	-14%

The main difference between less and more expensive scenarios in Tables 3.6 and 3.7 is in land use changes. Costs increase slowly as pasture and/or corn acreage decreases. When crops like rice, safflower, or wild rice are added as habitat, however, costs can increase significantly with very small changes. These more expensive land use changes occur when depth or land use decisions aren't enough to improve habitat to desired levels, so the model improves quality by increasing complexity of the flooded land use mosaic with habitat-friendly agriculture. This is why the complexity reduced weighting scenario has a very narrow and small range of revenue losses; there is no incentive for the model to use a broader mix of land use types as flooded habitat.

There are some differences in land use changes when fish are prioritized compared to the balanced case – corn is also eliminated in favor of wetlands, and safflower acreage sometimes increases along with rice and wild rice. However, all results suggest two basic permanent land use changes for improved habitat quality on the Bypass, with varying economic implications depending on the magnitude of change and combination of approaches:

i. Replace some corn and/or pasture with new wetlands. This happens with every weighting scheme and for both prioritization scenarios, and is relatively inexpensive.
ii. Increase crop acreage for rice and wild rice beyond the extent that is economically optimal (where marginal costs are potentially greater than marginal revenues). The model assigns very high revenue losses to this decision with a cost function intended to dis-incentivize poor economic decisions (discussed in Model Limitations). The losses are therefore not representative of the actual difference between marginal costs and revenues with added acres. However these calculated losses correctly

represent that growing additional agricultural crops as habitat may not make immediate economic sense unless some incentive is available for farmers and/or landowners.

Managing Added Flows on the Improved Land Use Mosaic – Start Date

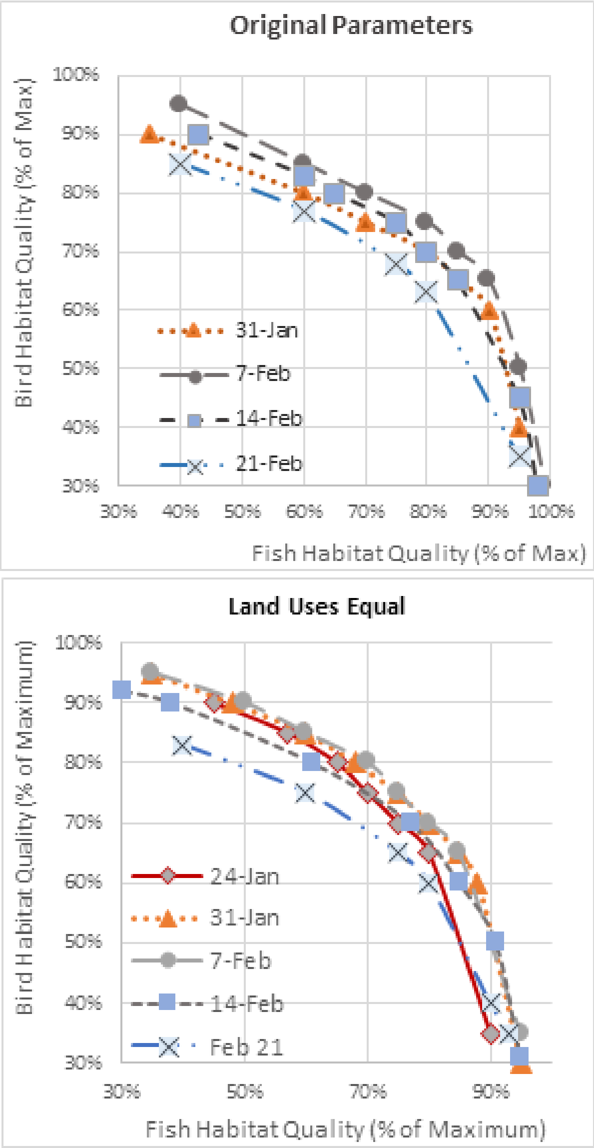


Figure 3.5. Habitat quality tradeoffs for varied start dates and annual revenue losses no greater than $200,000. Curves for the base case (top) and land uses equal (bottom) weightings are shown.

Once land uses have been reconciled for fish, bird and human purposes, decisions also must be made about how best to manage added flows in space and time. These decisions have important implications for habitat quality and annual revenues. This study initially assumed an 8-week inundation extending across 20,000 acres. The first flooding decision concerns timing; in years that Sacramento river stage is high enough to provide flow through a notched weir at any time throughout the winter and spring season, when should the gates first be opened to initiate an 8-week inundation?

Start dates were tested on a weekly time step from late January through February. Figure 3.5 compares habitat quality trade-off curves for varied dates when annual revenue losses are no greater than $200,000. Almost all starts between January 24th and February 7th or 14th achieve very similar habitat quality at this given level of revenue losses. However, in late February the same improvements can no longer be attained, as it becomes more difficult to achieve habitat goals without flooding several weeks into the growing season. This is problematic economically and for wetland plants and bird food supplies. The later start dates also create flooded habitat after the optimal time in the season for dabblers or fall run Chinook salmon, making it more difficult to achieve a given level of performance for these species groups.

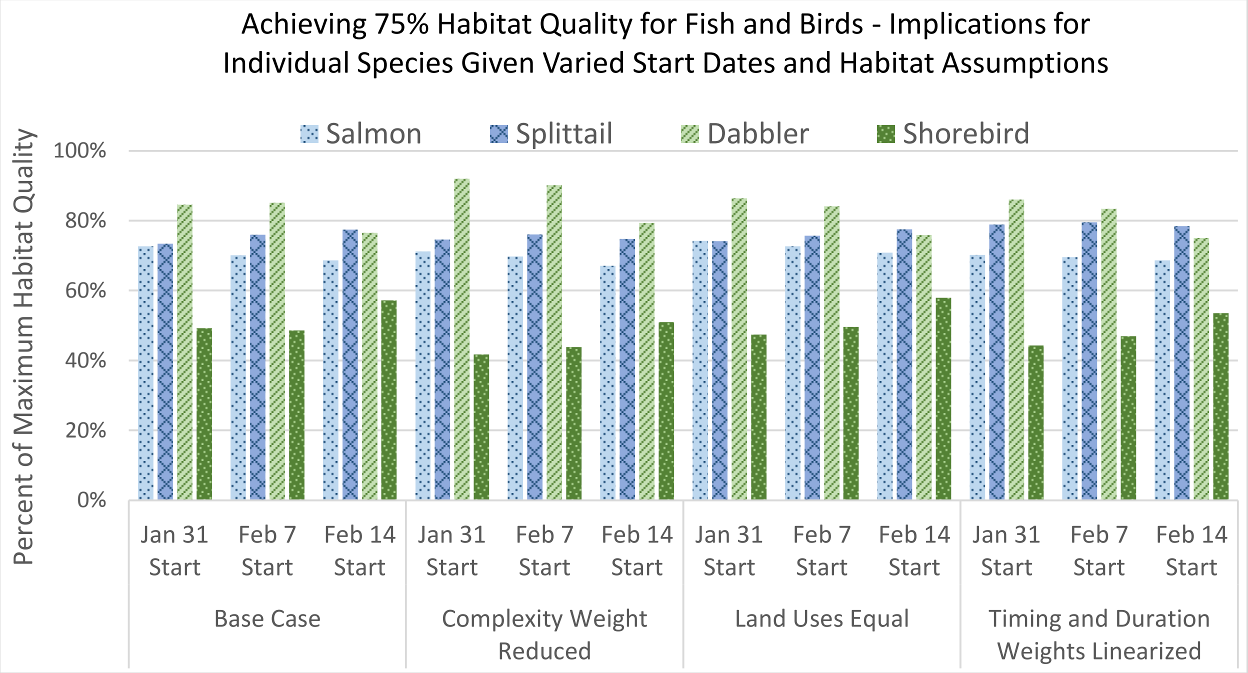


Figure 3.6. Habitat quality for individual species or species groups with varied habitat assumptions and start dates. Birds and fish are equally prioritized at 75% of optimal. Later start dates better balance habitat quality and availability for all four species groups considered in the study.

Within the optimal range of start dates, however, mid-February generally achieve more balanced habitat quality when looking across all species groups. Figure 3.6 shows individual species group habitat quality for varied start dates and different habitat assumptions. In all cases, February 14th is the only start date that achieves at least 50% (moderate) habitat quality for all four groups, partly because that start date better allows for focused shorebird habitat in early April, when shorebirds compete less with the other species groups. However, as shown in Tables 3.6 and 3.7, this later start date has a cost from flooding added agricultural lands into their growing season.

Interestingly, splittail, because they can better utilize shallow habitats, do better than salmon as long as some priority is given to bird habitat quality. This is because they are better able to take advantage of the entire flood depth mosaic (discussed more below). However while there are management strategies in which various habitats can be beneficial to more than one species, results also highlight the inherent difficulty of managing for a variety of native species in a limited landscape. This is especially true for birds. Achieving 75% bird and fish habitat quality usually means a focus on dabbler rather than shorebird habitat because dabblers share more preferences with fish.

Managing Added Flows on the Improved Land Use Mosaic – Depth

Depth is an extremely important habitat quality indicator for all four species groups considered in this study. Figure 3.7 shows expert opinion of the relative value (where 1 is optimal) of different depth zones for fish and birds on the Bypass. Any water below 8 inches is optimal for birds but bad for both fish species, whereas the opposite is true for water greater than 18 inches. Water depths between 13 and 18 inches are good for fish and moderate for dabbling ducks, but almost useless for shorebirds. Only water 8 to 12 inches deep approaches a compromise between the four species groups, but is still much less than ideal for shorebirds. Splittail are also better able to use these shallower depths than salmon.

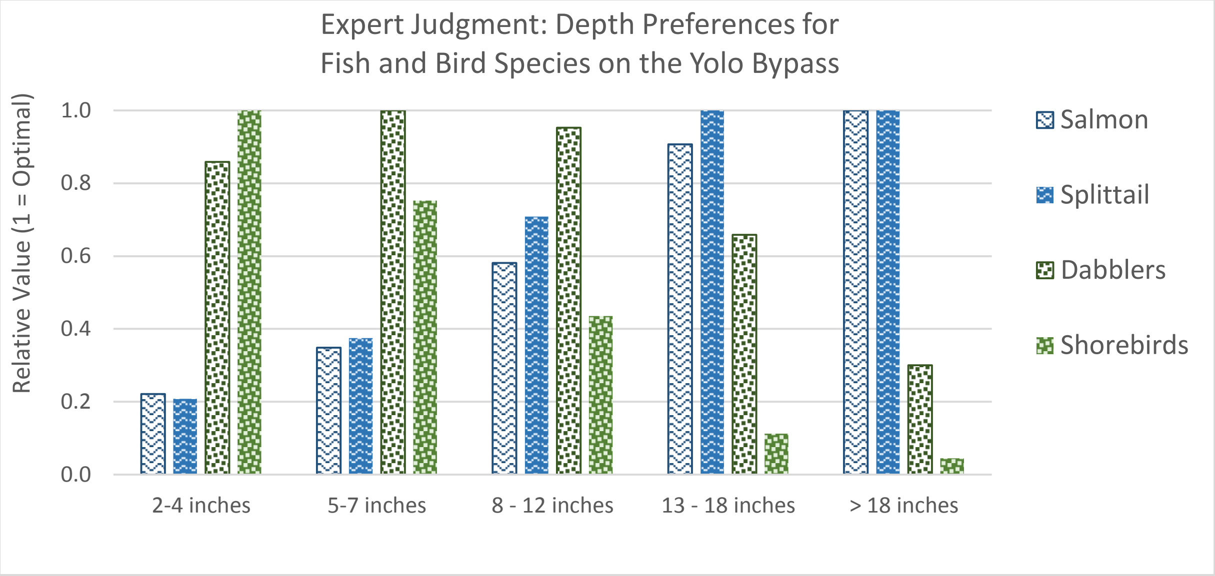


Figure 3.7. Expert judgment about depth preferences for different bird and fish species groups. 1 = optimal, 0.75 = good, 0.5 = moderate, 0.25 = bad, and 0 = useless. Source – Appendix A.

With these species preferences in mind, the decision to flood to different depths in space or time can be thought of in terms of creating one of four habitat types: (1) Bird habitat (2 – 7 inches), (2) Compromise habitat that is not great for any species but best for splittail and dabbling ducks (8 – 12 inches), (3) Fish and dabbling duck habitat (13 – 18 inches), and (4) Fish habitat (> 18 inches).

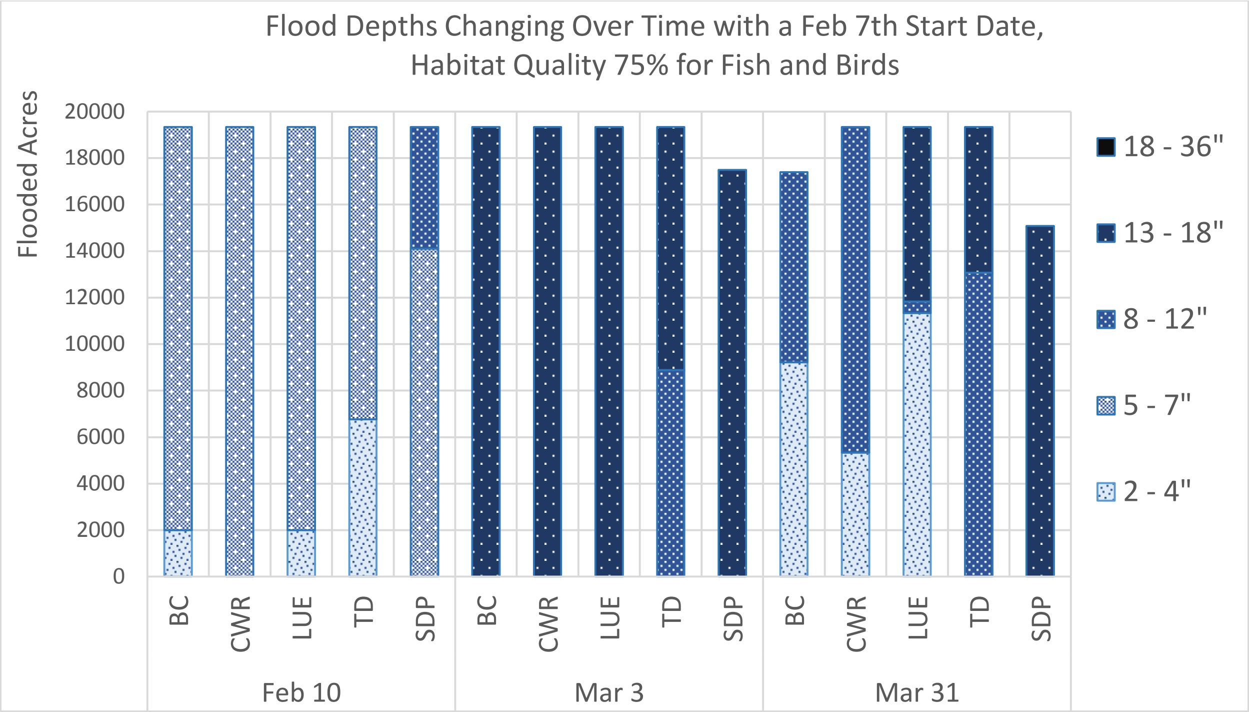


Figure 3.8. Changing flood depths over time with a February 7th start, and fish and bird habitat quality balanced at 75% of optimal. BC = base case, CWR = complexity weight reduced, LUE = land uses equal, TD = timing & duration more linear, and SDP = salmon & dabblers prioritized.

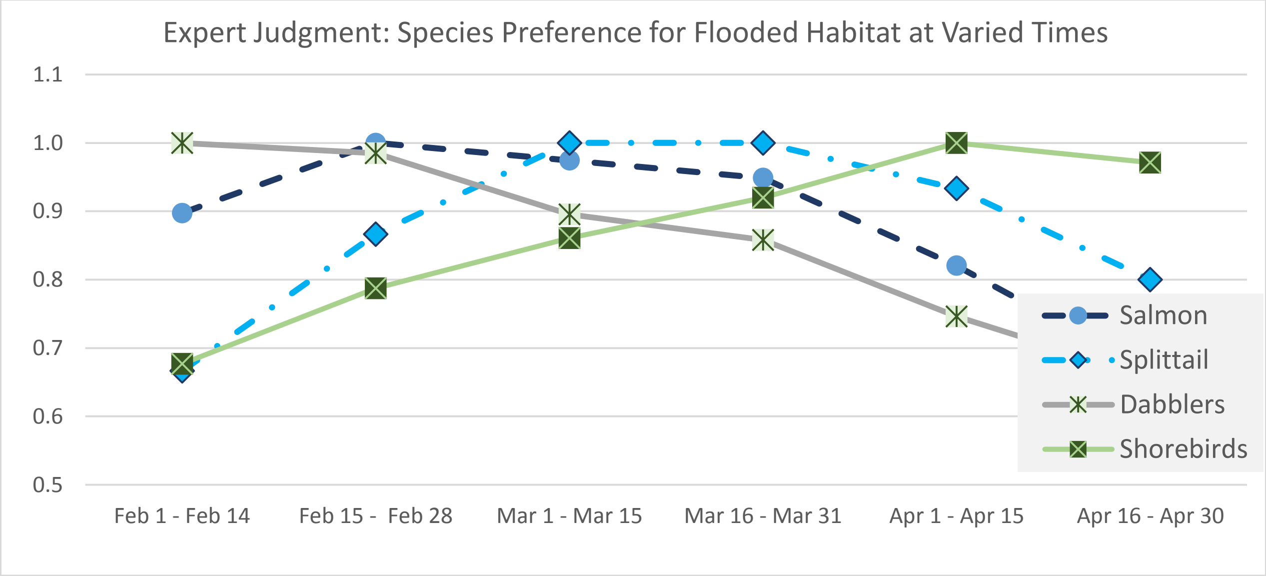


Figure 3.9. Importance of floodplain habitat for fish and bird species during varied weeks in the winter and spring. 1 = highly important, and 0.5 = moderately important. Source: Appendix A.

Figure 3.8 shows flood depth changing over the course of an 8-week inundation starting on February 7th, and Figure 3.9 shows the importance to fish and bird species of habitat availability during different weeks in the same timeframe. Depth is managed the same way in the first month of inundation regardless of habitat assumptions or species priorities: most inundated acres are flooded to between 5 and 7 inches in weeks 1 and 2, then to between 13 and 18 inches in weeks 3 and 4. Several factors contribute to this decision. First, for any start date in late January or early February, dabbling ducks value flooded habitat more than any other species (Figure 3.9). Habitat becomes more important to both fish species during late February and into the month of March. Depth is therefore partially driven by providing habitat for whatever species groups most values it at a given point in time.

The marginal habitat value of added weeks of flooding for fish and birds is another important factor. Flooded land is more immediately valuable to dabblers, who forage on seeds at the bottom of the water column, than to fish that rely on an accumulation of invertebrate biomass for food. (Chapters 1 and 2). Under most assumptions, fish gain the most substantial benefits from flooding in weeks 3 through 5, whereas dabbling ducks extract more than half of the value of inundation on a given field during weeks 1 and 2 (Appendix A and Chapter 2). Therefore, this change in depth from shallow to deeper water at the end of week 2 persists for almost all start dates and habitat quality weights.

Also consistent across almost all habitat assumptions is the provision of at least some shorebird habitat during the last weeks of inundation, and some compromise habitat focused mostly on splittail and dabblers. Water is deepest in later weeks when both fish species are assumed to still highly value added habitat at that time (as when timing and duration benefits are more linear with each added week), or when shorebird and splittail habitats are less important (when salmon and dabblers are prioritized).

Managing Added Flows on the Improved Land Use Mosaic – Shifts in Water Placement with Time (during an 8-week inundation)

The YBMOM not only manages for depth, but can also direct water to flood specific land uses from week to week. While nuanced depth management has significant habitat quality implications, flow placement decisions have both habitat quality and economic consequences. Figure 3.10 shows changes in flooded land uses over an 8 week inundation period that starts on February 7th, with varied habitat assumptions and priorities. Five major land use types are used initially as flooded habitat in almost all cases: wetlands, pasture, wild rice, rice, and fallow. However these results suggest that the flood footprint should not be static over time.

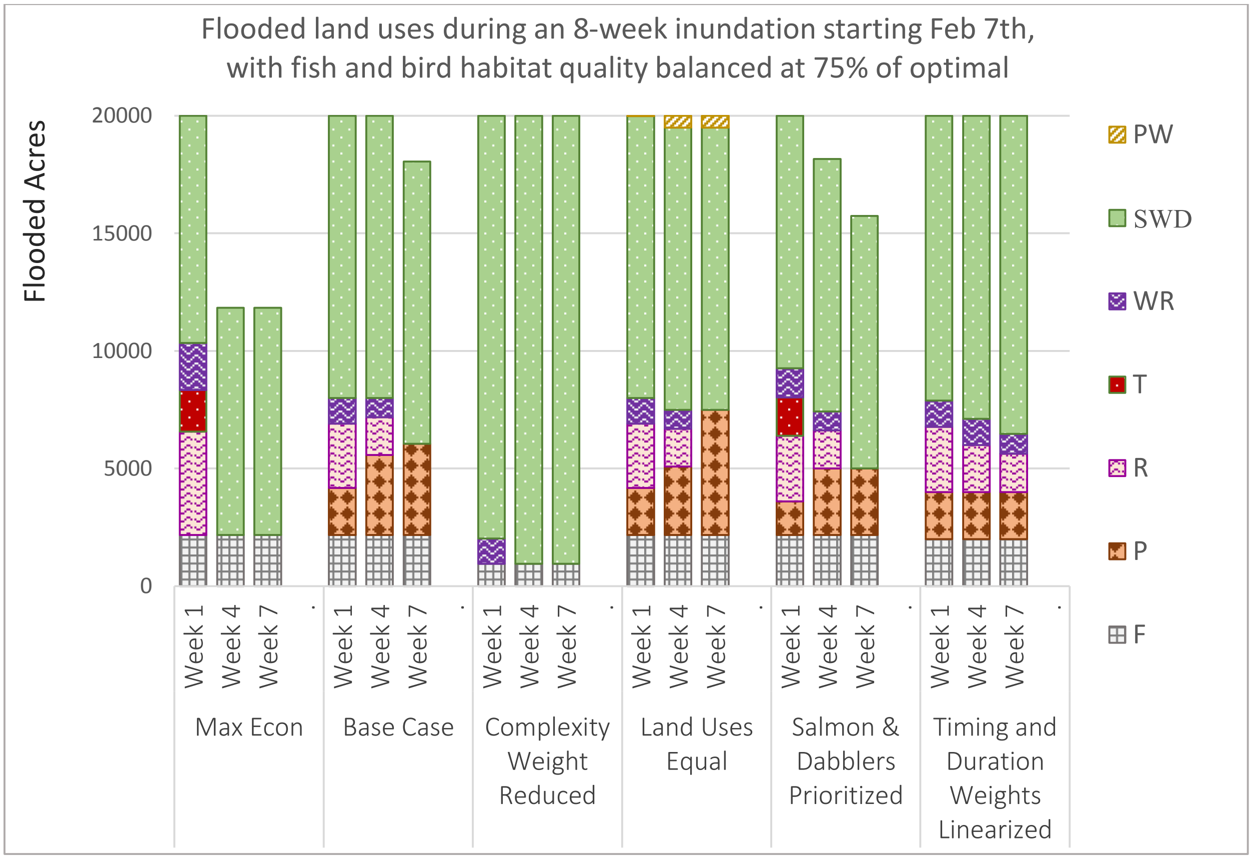


Figure 3.10. Changes in the flooded land use mosaic during an 8-week flood event that starts on February 7th. Results are compared against an economically optimal run in which habitat quality is only 60% (Max Econ). For all other runs, habitat quality = 75% of optimal. PW = permanent wetland, SWD = seasonal wetland, WR = wild rice, T = tomato, R = rice, P = pasture, and F = fallow.

Instead, highly managed inundations in which water is strategically moved across the landscape from week to week would allow managers to leverage high value, habitat-friendly agriculture (usually rice and wild rice) as flooded habitat until the growing season, and then shift water off of those fields when they need to be readied for planting. Typically water is shifted to pasture or added wetlands. In this way, fish and birds could take advantage of the food and added complexity value of those agricultural lands without stripping them of their economic value. This makes sense from a food resources standpoint as well – once water has been on the Bypass for several weeks, invertebrate productivity may be high enough within the water column that soil-derived or seed food sources are no longer as important. Because of this, it would not matter as much which land use types are flooded, as long as enough habitat remains within useable depth ranges.

The Importance of Different Habitat Assumptions – Where is more research most useful?

Although many flooding decisions are consistent regardless of habitat quality assumptions, some important decisions change with the weighting schemes. The economically consequential decisions of how much pasture to convert to wetland, and of how long to keep water on higher value agricultural lands before draining or shifting to pasture and wetland, largely depends on whether variety (or complexity) of land uses is important enough for habitat quality. More important complexity leads to increased flooding on more valuable crops like rice and pasture.

For example, the model floods more agricultural lands into the growing season when all land uses are assumed to be of equal value for fish (Figure 3.10). This is somewhat counterintuitive as one would expect all flooding in this case to occur on less costly, non-agricultural lands. However, reducing the role of one factor in the habitat objective functions increases the importance of others. If land use is not important, start date (timing) is given, and complexity is a valuable habitat characteristic, then the only ways to improve habitat quality are to increase duration and flood a greater variety of land use types. Results suggest that it is more economical to do so by accepting lost yields from a delayed plant date for high-value agricultural lands that are also valued bird habitat, rather than eliminating those crops in favor of some other habitat friendly land use type.

This contrasts to the complexity weight reduced case (3rd histogram from the left in Figure 3.10) for which habitat quality is most economically improved by converting as much pasture to wetland as possible and applying water almost exclusively to wetland and fallow lands. This is more expensive (in terms of forgone revenues) than extending flooding onto rice for just a week or two into the growing season, but less expensive than adding un-economical acres of rice, wild rice, or safflower as habitat and flooding those until late March (Tables 3.6 and 3.7).

By far the most expensive case is the one in which timing and duration benefits are assumed linear for fish and bird species into the second month of flooding (Timing and Duration Weights Linearized, Figure 3.10). Annual revenue losses for this case are shown in Tables 3.6 and 3.7, and are consistently higher than any other weighting for a given start date. This happens because a higher percentage of total habitat quality for all four species groups depends on habitat quality in weeks 6 through 8, so more rice and wild rice remain flooded into late March (Figure 3.10). This, again, is to increase the variability of flooded land use types (or complexity) in those later weeks by flooding agricultural lands with the highest habitat value.

Because complexity interacts so much with other habitat quality assumptions, and drives decisions with real economic consequences, it seems warranted to support further research about the added value that increased variability in flooded land use types can really bring for fish and birds on the Bypass.

Land and Water Management Decisions with Lower Flow Conditions

An eight-week-long, 20,000-acre flood on the Bypass will not be feasible every year. Because of this, the Base Case and Salmon and Dabblers Prioritized weighting schemes were re-optimized with tightened flood constraints (6 weeks duration and less than 15,000 flooded acres). Flooding also was constricted in zone 6 to be less than or equal to the acres flooded in zone 5. Figure 3.11 shows the resultant changes in March flooding. Base Case results are shown for two levels of habitat quality under low flow conditions – 51% (the maximum achievable), and a slightly relaxed 50%.

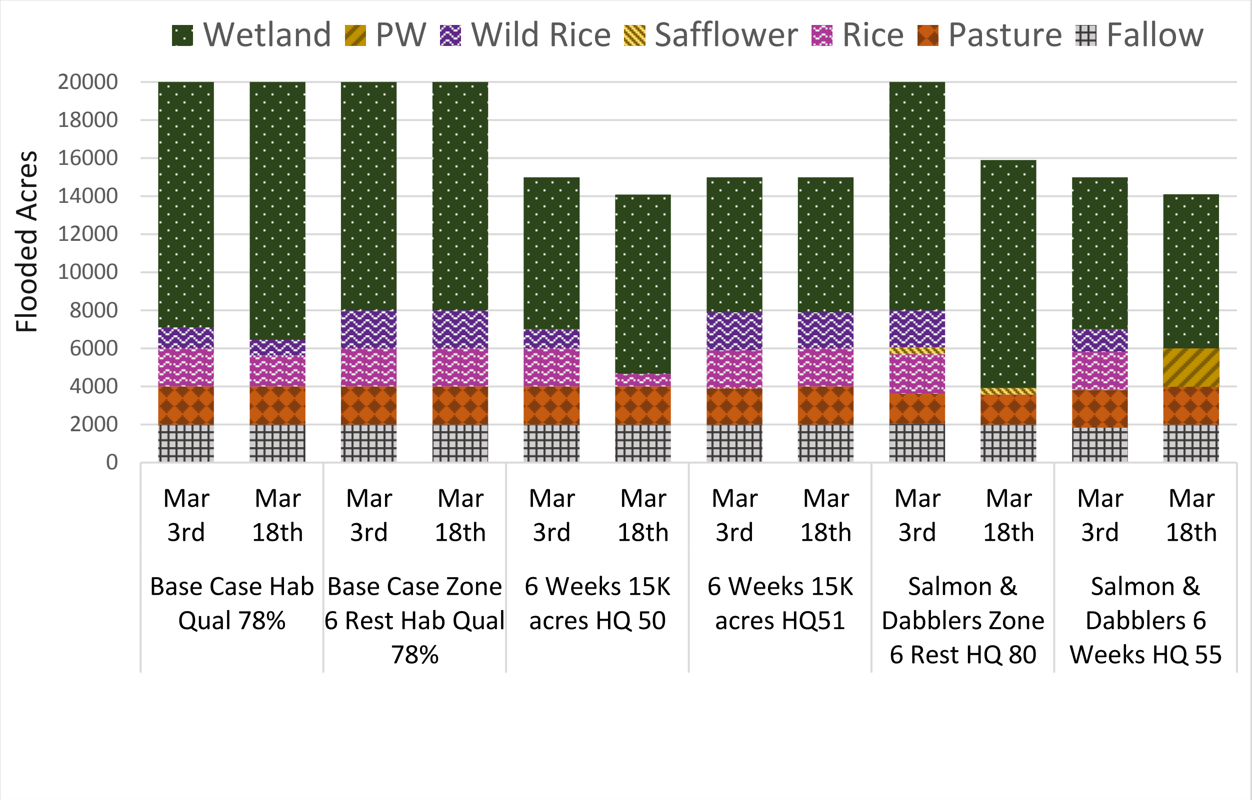


Figure 3.11- March flooding for the Base Case and Salmon and Dabblers Prioritized weighting schemes with increasing flood restrictions. Lower flow scenarios are compared to higher flow scenarios to show how the flooded land use mosaic changes when constricted to a smaller footprint. Base case = 8 weeks inundation, 20,000 acres, no restrictions. Base Case Zone 6 Restricted = 8 weeks inundation, 20,000 acres, zone 6 restricted to flood fewer acres than zone 5. Base Case Low Flows = 6 weeks inundation, 15,000 acres, and zone 6 restricted to flood fewer acres than zone 5.

Costs increase with restricted flooding in zone 6 because zone 5 is limited in the amount of pasture that can be traded for wetlands, forcing the model to use other agricultural lands as flooded habitat. Nevertheless, the model can still achieve 78% balanced habitat quality for fish and birds. Lower flows that further restrict the duration and extent of flooding lead to a minimum 25% loss in attainable habitat quality for both species groups.

Rice, wild rice, and pasture are all still components of flooded habitat even when flooding is limited, driven by the assumed preference for variability or complexity within the flooded habitat mosaic. The largest decrease in flooded acreage is instead for seasonal wetlands. However, as was the case for many of the higher flow scenarios, the amount of rice and wild rice that is flooded into the growing season can significantly decrease with just slight relaxation of ecological objectives, leading to significant annual economic savings.

Zone-Specific Flooding and Land Use Changes

As was reiterated in the low flow case, every flow or habitat scenario within the area of most efficient tradeoffs manages water movement through time in a similar way: Water is initially placed on a broader mix of land use types, including pasture, rice, wild rice, wetlands, and fallow land. Water is shifted off of rice and wild rice and onto additional pasture or wetlands sometime in early March. More specifically, between one and three thousand acres of flooded rice and wild rice are drained at that time, and between one and three thousand acres of previously dry pasture and wetlands become flooded.

Figure 3.12 explores variations in the flood footprint through time by comparing total acres flooded in each agricultural zone over the course of a 4, 6 and 8 week inundation, and for some varied habitat assumptions. In all cases (and during all weeks of inundation), most flooded habitat is concentrated in the southern bypass (zones 5 and 6). The total acres flooded in each zone does not significantly change through time. This implies that water shifted from rice and wild rice to pasture and wetlands does so within a given zone, rather than moving significant distances from north to south or west to east.

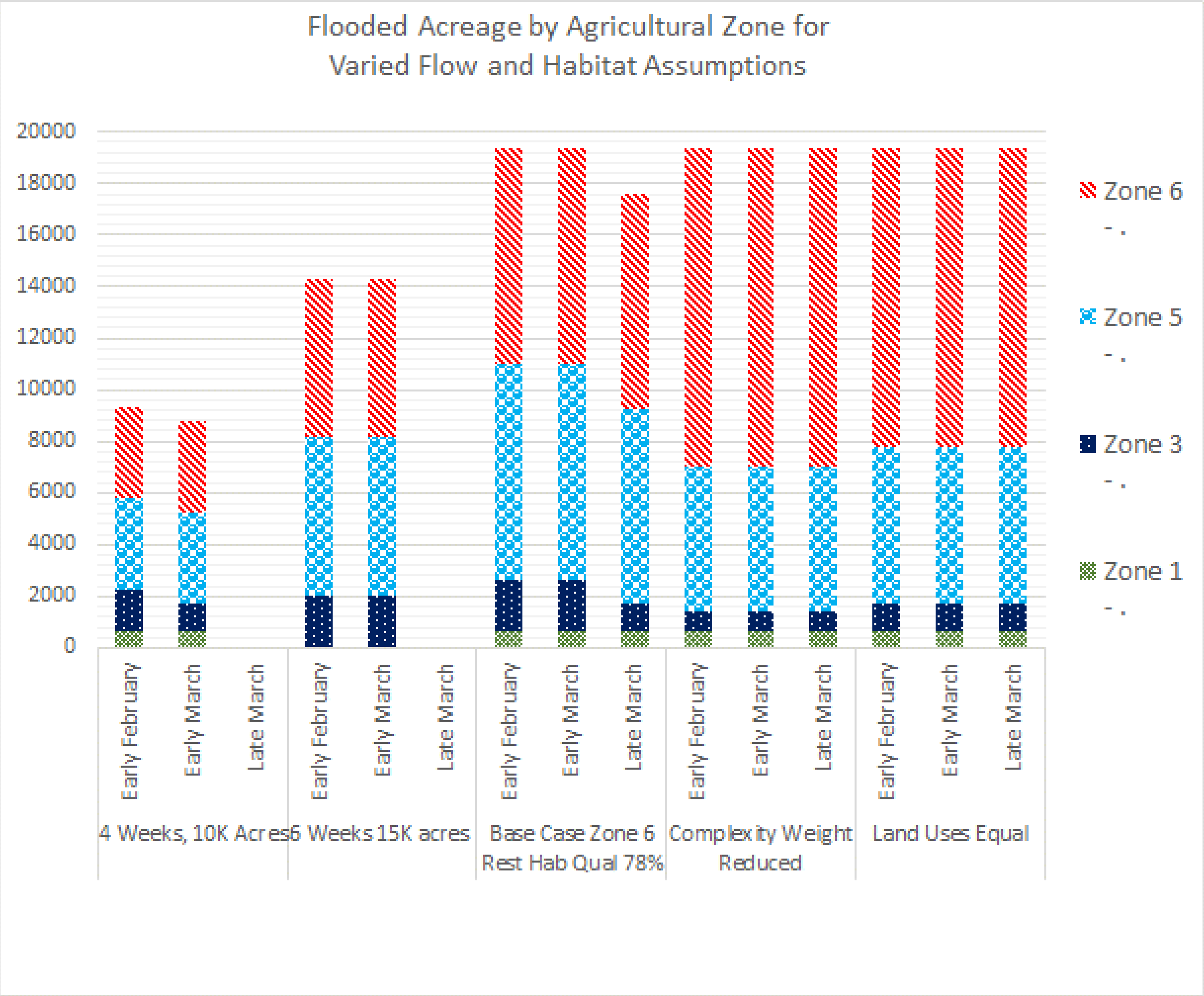
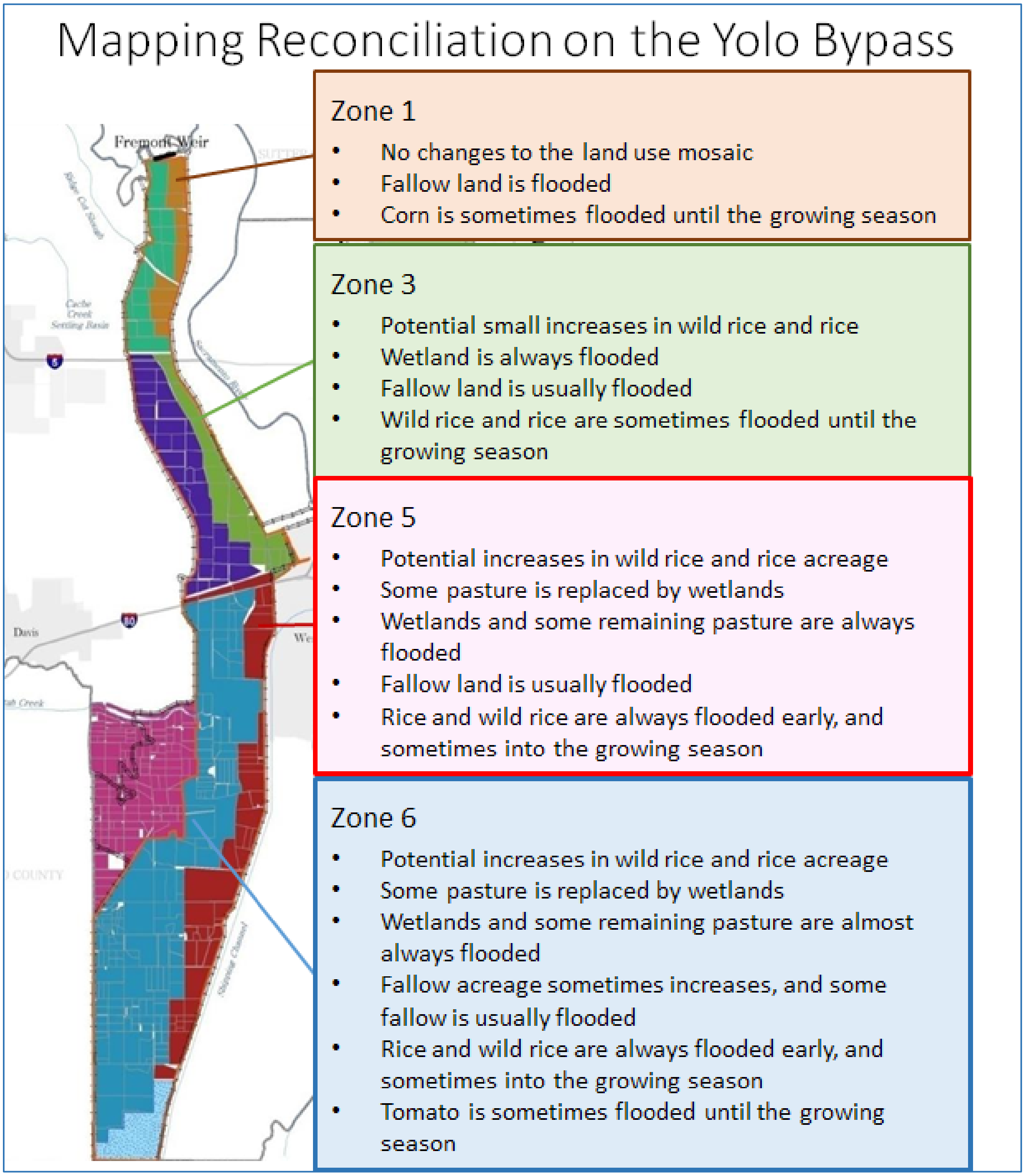


Figure 3.12. Flooding by agricultural zone with varied flow scenarios and habitat assumptions. The majority of water is applied in the southern bypass (zones 5 and 6). NOTE: There are ~600 acres of wetland already existent in zone 4 that are also flooded, and not pictured in the above graph. Base Case Zone 6 Rest shows that flooded acreage increases for all other zones when zone 6 cannot flood more than zone 5.

For more detail, Figure 3.13 summarizes land use change and flooding management by zone. With flooding concentrated in the southern bypass, this is also where the majority of land use change occurs, and a wider array of land use types are used as flooded habitat. Flooding such a higher proportion of lands in the south when water will enter the Bypass in the north is not necessarily easy, and might require the construction of several strategically placed berms that run from north to south in the northern bypass, and/or other innovative engineering.

Future applications could constrain the model to flood more evenly in the north, to test the value of considering these kinds of engineered solutions.



Mapping Reconciliation on the Yolo Bypass

Zone 1

- No changes to the land use mosaic
- Fallow land is flooded
- Corn is sometimes flooded until the growing season

Zone 3

- Potential small increases in wild rice and rice
- Wetland is always flooded
- Fallow land is usually flooded
- Wild rice and rice are sometimes flooded until the growing season

Zone 5

- Potential increases in wild rice and rice acreage
- Some pasture is replaced by wetlands
- Wetlands and some remaining pasture are always flooded
- Fallow land is usually flooded
- Rice and wild rice are always flooded early, and sometimes into the growing season

Zone 6

- Potential increases in wild rice and rice acreage
- Some pasture is replaced by wetlands
- Wetlands and some remaining pasture are almost always flooded
- Fallow acreage sometimes increases, and some fallow is usually flooded
- Rice and wild rice are always flooded early, and sometimes into the growing season
- Tomato is sometimes flooded until the growing season

Figure 3.13. Land use changes and flooding management by agricultural zone on the Yolo Bypass. YBMOM results suggest that the majority of flooded habitat should be concentrated in the southern bypass.

CONCLUSIONS

This study examined ecological and economic tradeoffs and management decisions on a human-engineered floodplain in California's Central Valley, under a variety of habitat quality assumptions and priorities. Some results persisted under almost all assumptions, while others depend more on particular parameter values. The following paragraphs highlight conclusions that seem to persist under a wide range of assumptions about bird, fish, and human preferences, and areas for which more research could better refine future management.

Economic and Ecological Tradeoffs

A surprising outcome of this work is that, under all assumptions, significant improvements in habitat quality for native species on the Yolo Bypass are possible with little loss in annual revenue for landowners or farmers, costs which seem economical for compensation. This is feasible on engineered agricultural floodplains with management that takes advantage of land uses high in economic and habitat value when those two objectives are least in conflict, and shifts water to less profitable land uses for additional flooded habitat when the growing season begins.

Even greater habitat improvements are possible with some relatively low-cost, permanent shifts of land from agriculture to seasonal wetlands. On the bypass, the least expensive way to do this is to trade pasture for wetlands in the southern bypass. Trading 10 to 40% of the bypass's pasture acreage causes 1-5% declines in farming revenues for a 15 – 20%

improvement in fish and bird habitat quality. This result persisted for every habitat function tested.

Economic costs and habitat tradeoffs increase when optimizing only for habitat quality for either fish or birds. This is shown by the generally higher costs of the Fish Prioritized scenario (Table 3.7), and by the trade-off curves in figures 3.2 and 3.3. The balanced approach is likely more cost effective in terms of economic and ecologic tradeoffs, than focusing management on birds or fish alone. Slightly later inundation (starting in the second half of February) additionally allows for more balanced management across individual species of fish and birds, but is also more costly in terms of lost farming revenues.

Depending on the combination of land use change and flooding decisions, a compensation package of $100,000 - $500,000 per year to farmers or bypass landowners should be adequate for a reconciliation program.

Land Management Implications

Agricultural land uses can contribute to fish and bird habitat quality at very little cost, as long as flooding is optimized in space and time. The cheapest way to improve habitat quality on the Bypass is to exchange some pasture in the southern bypass for added wetlands. However some other agricultural crops could add habitat value by increasing, rather than decreasing, their acreage. Wild rice acreage was increased in over 40% of the scenarios tested here, with rice and safflower following. Because the cost functions in the YBMOM exaggerate the marginal costs of these decisions, exact economic losses are difficult to quantify within this analysis. However these results suggest that if costs are small enough or incentives large enough, adding rice, wild rice, and sometimes safflower acreage would be very effective at improving the flood habitat mosaic and further integrate economic activities with species management. There is also already a precedent for a mixture of flooded rice and wetland habitats for birds within the Yolo Bypass Wildlife Area. This conclusion warrants a better understanding of the point where marginal costs exceed benefits for some of those habitat-friendly crops, and of the economic incentives needed to entice farmers to plant additional habitat-friendly acres.

Flood and Water Management Implications

The above discussion focused on long-term land use decisions. In years when managed flows are brought in via a notched Fremont Weir, decisions also must be made about where, when, and for how long to apply water. These decisions fall into the following categories:

1. **Timing** – under almost all habitat quality assumptions, the best start date for a 6 or 8 week inundation lies somewhere in the last week of January or first few weeks of February. This is not just because of the economics of a longer growing season, but is also the best balance of the needs of all four species groupings. However, the best start date also depends on duration of flooding; an early February start date will only have significant benefits for shorebirds, for instance, if it lasts at least 6 weeks. The shorter the duration, the more important timing becomes for each individual species and the harder it is to strike a balance with just one flood event.

2. **Depth** – Inundation depth varies in space and time over the course of a 6 or 8 week flood, and is the one management decision for which general conclusions are difficult. Depth controls exactly when and where a particular species will have viable habitat within the larger flood mosaic, so small changes in weightings or system preferences can make a large difference in the optimal pattern. In general, a Bypass balanced for fish and birds will benefit most from an inundation that starts sometime in late January or early February with shallow flooding during the first few weeks (usually less than 8 inches deep for birds), then deeper for a few weeks (13 - 18 inches) to provide better fish habitat, then a mixture of mudflat to moderately deep habitats as waters recede and shorebirds begin to share the system with fish and dabblers. This is even the case for floods that last only for 6 weeks if they start in February.

3. **Duration** – If flooding begins before the end of February, then it is always valuable (and not necessarily costly) to keep at least some water on wetlands and other lower-value land uses for a full 8 weeks (if possible). When flooding duration was decreased by 2 weeks, attainable habitat quality decreased by about 25%. Long-duration floods optimize the availability of flooded habitat in time and space and make it possible to satisfy a wider variety of species preferences.

4. **Hydraulic Management –** The ability to move and control the flood footprint throughout a 6 to 8 week inundation event can significantly increase the cost-effectiveness of flooded habitat quality improvements on the Bypass. Hydraulic

management could direct most flooding to the southern bypass, where agricultural losses are not as high, and phase rice, wild rice, and sometimes safflower out of the flood footprint by mid-March, when lost yields from a delayed plant date begin to more significantly reduce crop revenues. Hydraulic control of flows also could move water that drains from these fields to wetlands and pasture for the remaining weeks of inundation, so fish and birds can still take advantage of food resources built up in the water column. Finally, it might help managers control for different depth targets, although natural topographic variability in the landscape will also always play a role.

NEXT STEPS

This work makes several recommendations for land use changes with varied implications for different stakeholders on the Yolo Bypass (summarized by agricultural zone in Figure 3.13). Trading pasture for wetlands or adding acres of rice and wild rice will have tax implications for Yolo County, and obvious financial implications for local farmers and landowners. None of these changes can occur without first deciphering how to finance them, or more specifically, designating who pays for changes in management. The YBMOM can help provide detailed and zone-specific information about the economic implications of management decisions, and a rough estimate of ecological gains or losses resulting from any changes.

Another potentially required land use change will be the creation of new wetlands and fields devoted to habitat-friendly crops; strategically locating these land uses close together and near the water source will allow applied water to be more easily managed for depth and duration. It is more difficult to flood x acres of rice and y acres of pasture if they are several miles apart and far from the eastern channel that delivers water down the length of the Bypass. The model makes zone-specific recommendations that were not studied in detail here, but would warrant closer examination once water is actually available. This would also help in developing more location specific mitigation or incentive programs for landowners.

Actual hydraulic outcomes of applying specific volumes of water to the landscape need closer examination. Habitat-friendly lands cannot be placed into the flood footprint without first knowing what that flooding footprint is. 2-D hydrodynamic modeling can help with this effort, and test different internal modifications to Bypass infrastructure that might make optimal flood management easier. The YBMOM could then iterate with the 2-D flow model and solve for more realistic flood footprints for each zone, and under a range of potential low and high flow scenarios.

Regardless of these needed steps, the conclusions presented above are robust: even under a wide variety of assumptions on habitat and species preferences, there is much promise for a reconciliation approach to management of the Yolo Bypass that is not extremely costly from the landowners' and farmers' perspective. This study highlights the ability for birds and fish to both benefit from management of a mixed agricultural and wetland landscape, without large tradeoffs among them. Importantly, agricultural crops are a vital component of the overall habitat mosaic, a sign that even heavily modified floodplains can be improved for native species without eliminating human use. The YBMOM and similar quantitative analysis can serve as a useful tool in providing detailed suggestions for managing the system when infrastructure modifications allow for more controlled and more frequent inundation.

REFERENCES

Aguilar-Alberola, J. A. & F. Mesquita-Joanes (2011) Population dynamics and tolerance to desiccation in a crustacean ostracod adapted to life in small ephemeral water bodies. *Limnologica,* 41**,** 348-355.

Ahearn, D. S., J. H. Viers, J. F. Mount & R. A. Dahlgren (2006) Priming the productivity pump: flood pulse driven trends in suspended algal biomass distribution across a restored floodplain. *Freshwater Biology,* 51**,** 1417-1433.

Ahmadi-Nedushan, B., A. St-Hilaire, M. Berube, E. Robichaud, N. Thiemonge & B. Bobee (2006) A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. *River Research and Applications,* 22**,** 503-523.

Anderson, T. 2007. Contributions to the Systematic and Ecology of Aquatic Diptera: A tribute to Ole Saether. Columbus, OH: The Caddis Press.

Bayley, P. B. (1995) Understanding Large River-Floodplain Ecosystems. *BioScience,* 45**,** 153-158.

Bellmore, J. R., C. V. Baxter, K. Martens & P. J. Connolly (2013) The floodplain food web mosaic: a study of its importance to salmon and steelhead with implications for their recovery. *Ecological Applications,* 23**,** 189-207.

Belsky, A. J., A. Matzke & S. Uselman (1999) Survey of livestock influences on stream and riparian ecosystems in the western United States. *Journal of Soil and Water Conservation,* 54**,** 419-431.

Benigno, G. M. & T. R. Sommer (2008) Just add water: sources of chironomid drift in a large river floodplain. *Hydrobiologia,* 600**,** 297-305.

Bennett, J. & I. Goulter (1989) The Use of Multiobjective Analysis for Comparing and Evaluating Environmental and Economic Goals in Wetlands Managements. *GeoJournal,* 18**,** 213-220.

Berg, M. B. & R. A. Hellenthal (1992) The Role of Chironomidae in the Energy Flow of a Lotic Ecosytem. *Netherlands Journal of Aquatic Ecology,* 26**,** 471-476.

Box, G. & N. Draper. 1987. *Empirical Model-Building and Response Surfaces*. Wiley.

Brown, M. 2013. Assessing California's Wetlands: A Comprehensive Survey of Management Techniques and A New Rapid Assessment Method. In *Avian Science*. Davis, CA: University of California, Davis.

California DFG, Yolo Basin Foundation & EDAW. 2008. Yolo Bypass Wildlife Area Land Management Plan. ed. C. D. o. F. a. Game. Sacramento, CA.

CBEC. 2010. BDCP Effects Analysis: 2D Hydrodynamic Modeling of the Fremont Weir Diversion Structure. Sacramento, CA: Prepared for the SAIC and the California Department of Water Resources.

Chittapun, S. (2011) Fire and recovery of resting egg bank: an experimental study in paddy fields in Pathum Thani province, Thailand. *Hydrobiologia,* 662**,** 163-170.

Cioffi, F. & F. Gallerano (2012) Multi-objective analysis of dam release flows in rivers downstream from hydropower reservoirs. *Applied Mathematical Modelling,* 36**,** 2868-2887.

Cloern, James E. (2007) Habitat Connectivity and Ecosystem Productivity: Implications from a Simple Model. *The American Naturalist,* 169**,** E21-E33.

Cohon, J. L. 1978. *Multiobjective Programming and Planning*. San Diego, California: Academic Press, Inc.

Cohon, J. L. & D. H. Marks (1975) A review and evaluation of multiobjective programing techniques. *Water Resources Research,* 11**,** 208-220.

CVJV. 2006. Central Valley Joint Venture Implementation Plan - Conserving Bird Habitat. Sacramento, CA: U.S. Fish and Wildlife Service.

Dahms, H. U. (1995) Dormancy in the Copepoda - an Overview. *Hydrobiologia,* 306**,** 199-211.

de Neufville, R. 1990. *Applied Systems Analysis*. New York: McGraw-Hill, Inc.

Ducks Unlimited. 2013. Waterfowl Identification. Ducks Unlimited.

Duffy, W. G. & N. K. Sharon (2011) Wetland ecosystem services in California's Central Valley and implications for the Wetland Reserve Program. *Ecological Applications,* 21**,** S18-S30.

DWR. 2010. Fact Sheet: Sacramento River Flood Control Project Weirs and Flood Relief Structures. Sacramento, CA: State of California, the Resources Agency, Department of Water Resources, Division of Flood Management.

Earl, J. P. (1950) Production of Mallards on Irrigated Land in the Sacramento Valley, California. *The Journal of Wildlife Management,* 14**,** 332-342.

Elphick, C. S. (2000) Functional equivalency between rice fields and seminatural wetland habitats. *Conservation Biology,* 14**,** 181-191.

Elphick, C. S. & L. W. Oring (2003) Conservation implications of flooding rice fields on winter waterbird communities. *Agriculture Ecosystems & Environment,* 94**,** 17-29.

Feyrer, F., T. Sommer & W. Harrell (2006a) Importance of flood dynamics versus intrinsic physical habitat in structuring fish communities: Evidence from two adjacent engineered floodplains on the Sacramento River, California. *North American Journal of Fisheries Management,* 26**,** 408-417.

--- (2006b) Managing floodplain inundation for native fish: production dynamics of age-0 splittail (Pogonichthys macrolepidotus) in California's Yolo Bypass. *Hydrobiologia,* 573**,** 213-226.

Fleskes, J. P., J. L. Yee, G. S. Yarris, M. R. Miller & M. L. Casazza (2007) Pintail and Mallard Survival in California Relative to Habitat, Abundance, and Hunting. *The Journal of Wildlife Management,* 71**,** 2238-2248.

Florsheim, J. L. & J. F. Mount (2003) Changes in lowland floodplain sedimentation processes: pre-disturbance to post-rehabilitation, Cosumnes River, CA. *Geomorphology,* 56**,** 305-323.

Gau, C.-Y. & L. Schrage. 2004. Implementation and Testing of a Branch-and-Bound Based Method for Deterministic Global Optimization: Operations Research Applications. In *Frontiers in Global Optimization,* eds. C. A. Floudas & P. Pardalos, 145-164. Springer US.

Gleason, R. A., N. H. Euliss, D. E. Hubbard & W. G. Duffy (2003) Effects of sediment load on emergence of aquatic invertebrates and plants from wetland soil egg and seed banks. *Wetlands,* 23**,** 26-34.

Halls, A. S. & R. L. Welcomme (2004) Dynamics of river fish populations in response to hydrological conditions: a simulation study. *River Research and Applications,* 20**,** 985-1000.

Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle & B. Thompson. 2011. *Managing California's Water: From Conflict to Reconciliation*. San Francisco, CA: Public Policy Institute of California.

Henning, J. A., R. E. Gresswell & I. A. Fleming (2006) Juvenile salmonid use of freshwater emergent wetlands in the floodplain and its implications for conservation management. *North American Journal of Fisheries Management,* 26**,** 367-376.

Howitt, R., D. MacEwan, C. Garnache, J. Medellin Azuara, P. Marchand, D. Brown, J. Six & J. Lee. 2013. Agricultural and Economic Impacts of Proposed Fish Conservation Measures in the Yolo Bypass. Prepared For Yolo County.

IWMI, I. W. M. I., M. McCartney, S. De Silva, L.-M. Rebelo, E. Geatrix, E. Mapedze, S. Morardet, C. Murgue & A. Noble. 2014. Wetlands and People. 32. Colombo, Sri Lanka: International Water Management Institute.

James, L. A. & M. Singer (2008) Development of the Lower Sacramento Valley Flood-Control System: Historical Perspective. *Natural Hazards Review,* 9**,** 125-135.

Jeffres, C. A., J. J. Opperman & P. B. Moyle (2008) Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. *Environmental Biology of Fishes,* 83**,** 449-458.

Jones & Stokes. 2001. A Framework for the Future: Yolo Bypass Management Strategy. Sacramento, CA: CALFED Bay-Delta Program.

Junk, W., P. Bayley & R. Sparks (1989) The flood pulse concept in river-floodplain systems. *Can J Fish Aquat Sci,* Special Publication**,** 110 - 127.

Junk, W. J. 1996. Ecology of floodplains - a challenge for tropical limnology. In *Perspectives in Tropical Limnology,* ed. F. S. K. T. Boland, 255-265. Amsterdam, The Netherlands: SPB Academic Publishing.

Karanovic, I. 2012. *Recent Freshwater Ostracods of the World; Crustacea, Ostracoda, Podocopida*. New York, New York: Springer.

Katz, J., C. Jeffres, L. Conrad, T. Sommer, N. Corline, J. Martinez, S. Brumbaugh, L. Takata, N. Ikemiyagi, J. Kiernan & P. Moyle. 2013. Experimental Agricultural Floodplain Habitat Investigation at Knaggs Ranch on Yolo Bypass, 2012-2013. US Bureau of Reclamation.

Keddy, P. A., L. H. Fraser, A. I. Solomeshch, W. J. Junk, D. R. Campbell, M. T. K. Arroyo & C. J. R. Alho (2009) Wet and Wonderful: The World's Largest Wetlands are Conservation Priorities. *BioScience,* 59**,** 39-51.

Kelley, R. 1989. *Battling the Inland Sea: Floods, public policy, and the Sacramento Valley, 1850 - 1986*. Berkeley and Los Angeles, California: University of California Press.

King, J. L., M. A. Simovich & R. C. Brusca (1996) Species richness, endemism and ecology of crustacean assemblages in northern California vernal pools. *Hydrobiologia,* 328**,** 85-116.

Klijn, F., M. v. Buuren & S. A. M. v. Rooij (2004) Flood-Risk Management Strategies for an Uncertain Future: Living with Rhine River Floods in the Netherlands? *Ambio,* 33**,** 141-147.

Kuby, M. J., W. F. Fagan, C. S. ReVelle & W. L. Graf (2005) A multiobjective optimization model for dam removal: an example trading off salmon passage with hydropower and water storage in the Willamette basin. *Advances in Water Resources,* 28**,** 845-855.

Lawler, E. L. & D. E. Wood (1966) Branch-And-Bound Methods: A Survey. *Operations Research,* 14**,** 699-719.

Lehman, P. W., T. Sommer & L. Rivard (2008) The influence of floodplain habitat on the quantity and quality of riverine phytoplankton carbon produced during the flood season in San Francisco Estuary. *Aquatic Ecology,* 42**,** 363-378.

Lemke, A. M. & A. C. Benke (2009) Spatial and temporal patterns of microcrustacean assemblage structure and secondary production in a wetland ecosystem. *Freshwater Biology,* 54**,** 1406-1426.

Loucks, D. P., J. R. Stedinger & D. A. Haith. 1981. *Water Resource Systems Planning and Analysis*. Englewood Cliffs, N.J.: Prentice-Hall, Inc.

Louie, P., W. Yeh & N. Hsu (1984) Multiobjective Water Resources Management Planning. *Journal of Water Resources Planning and Management,* 110**,** 39-56.

Merritt, R. W., K. W. Cummins & M. B. Berg. 2008. An Introduction to the AQUATIC INSECTS of NORTH AMERICA. Dubuque, Iowa: Kendall/Hunt Publishing Company

Mount, J. F. 1995. *California Rivers and Streams: The Conflict Between Fluvial Process and Land Use*. California: University of California Press.

Moyle, P. B. (2013) NOVEL AQUATIC ECOSYSTEMS: THE NEW REALITY FOR STREAMS IN CALIFORNIA AND OTHER MEDITERRANEAN CLIMATE REGIONS. *River Research and Applications***,** n/a-n/a.

Moyle, P. B., R. D. Baxter, T. Sommer, T. C. Foin & S. A. Matern (2004) Biology and population dynamics of Sacramento Splittail (Pogonichthys macrolepidotus) in the San Francisco Estuary: A Review. *San Francisco Estuary and Watershed Science,* 2.

Moyle, P. B., P. K. Crain & K. Whitener (2007) Patterns in the Use of a Restored California Floodplain by Native and Alien Fishes. *San Francisco Estuary and Watershed Science,* 5.

Nakamura, M. & J. M. Riley (1981) A MULTIOBJECTIVE BRANCH AND BOUND METHOD FOR NETWORK-STRUCTURED WATER-RESOURCES PLANNING PROBLEMS. *Water Resources Research,* 17**,** 1349-1359.

Naylor, L. W. 1999. Evaluating Moist-Soil Seed Production and Management in Central Valley Wetlands to Determine Habitat Needs for Waterfowl. In *Ecology*. Davis, CA: University of California, Davis.

Opperman, J. J., G. E. Galloway, J. Fargione, J. F. Mount, B. D. Richter & S. Secchi (2009) Sustainable Floodplains Through Large-Scale Reconnection to Rivers. *Science,* 326**,** 1487-1488.

Opperman, J. J., R. Luster, B. A. McKenney, M. Roberts & A. W. Meadows (2010) Ecologically Functional Floodplains: Connectivity, Flow Regime, and Scale. *Journal of the American Water Resources Association,* 46**,** 211-226.

Petrik, K., M. Petrie, A. Will & J. McCreary. 2012. Waterfowl Impacts of the Proposed Conservation Measure 2 for the Yolo Bypass - An effects analysis tool. ed. B. D. C. P.-Y. B. F. E. P. Team. Sacramento, CA: Ducks Unlimited.

Pinter, N. (2005) One Step Forward, Two Steps Back on U.S. Floodplains. *Science,* 308**,** 207-208.

Ripley, B. J. & M. A. Simovich (2009) Species richness on islands in time: variation in ephemeral pond crustacean communities in relation to habitat duration and size. *Hydrobiologia,* 617**,** 181-196.

Roloff, G. J. & B. J. Kernohan (1999) Evaluating reliability of habitat suitability index models. *Wildlife Society Bulletin,* 27**,** 973-985.

Rosenzweig, M. L. (2003) Reconciliation ecology and the future of species diversity. *Oryx,* 37**,** 194-205.

--- (2005) Avoiding mass extinction: Basic and applied challenges. *American Midland Naturalist,* 153**,** 195-208.

Salcido, R. E. (2012) The success and continued challenges of the Yolo Bypass Wildlife Area: A grassroots restoration. *Ecology Law Quarterly, Boalt School of Law,* 39, 1085 - 1134.

Schemel, L. E., T. R. Sommer, A. B. Muller-Solger & W. C. Harrell (2004) Hydrologic variability, water chemistry, and phytoplankton biomass in a large floodplain of the Sacramento River, CA, USA. *Hydrobiologia,* 513**,** 129-139.

Shuford, W. D., G. W. Page & J. E. Kjelmyr (1998) Patterns and Dynamics of Shorebird Use of California's Central Valley. *The Condor,* 100**,** 227-244.

Simpson, I. C., P. A. Roger, R. Oficial & I. F. Grant (1994) Effects of Nitrogen-Fertilizer and Pesticide Management on Floodwater Ecology in a Wetland Ricefield .3. Dynamics of Benthic Mollusks. *Biology and Fertility of Soils,* 18**,** 219-227.

Smith, D., G. Rollins & R. Shinn. 1994. A Guide to Wetland Habitat Management in the Central Valley. Sacramento, CA: California Waterfowl Association and the California Department of Fish and Game.

Sommer, T., B. Harrell, M. Nobriga, R. Brown, P. Moyle, W. Kimmerer & L. Schemel (2001) California's Yollo Bypass: Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries,* 26**,** 6-16.

Sommer, T. R., L. Conrad, G. O'Leary, F. Feyrer & W. C. Harrell (2002) Spawning and rearing of splittail in a model floodplain wetland. *Transactions of the American Fisheries Society,* 131**,** 966-974.

Sommer, T. R., W. C. Harrell, A. M. Solger, B. Tom & W. Kimmerer (2004) Effects of flow variation on channel and floodplain biota and habitats of the Sacramento River, California, USA. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 14**,** 247-261.

Sparks, R. E. (1995) Need for Ecosystem Management of Large Rivers and Their Floodplains. *BioScience,* 45**,** 168-182.

Stenert, C., R. C. Bacca, A. C. Avila, L. Maltchik & O. Rocha (2010) Do Hydrologic Regimes Used in Rice Fields Compromise the Viability of Resting Stages of Aquatic Invertebrates? *Wetlands,* 30**,** 989-996.

Stutler, L. L. 1973. An Historical Geography of the Yolo By-pass. In *Geography*, 308. Berkeley, CA: University of California, Berkeley.

Taft, O. W., M. A. Colwell, C. R. Isola & R. J. Safran (2002) Waterbird Responses to Experimental Drawdown: Implications for the Multispecies Management of Wetland Mosaics. *Journal of Applied Ecology,* 39**,** 987-1001.

Thorp, J. H. & A. P. Covich. 2010. Ecology and Classification of North American Freshwater Invertebrates. San Diego, CA: Academic Press.

Thorpe, J. E. (2008) Influence of restricted access to floodplains on life-history patterns in fish: implications for conservation. *Ecohydrology & Hydrobiology,* 8**,** 159-167.

Tockner, K., F. Malard & J. V. Ward (2000) An extension of the flood pulse concept. *Hydrological Processes,* 14**,** 2861-2883.

Tockner, K., M. Pusch, D. Borchardt & M. S. Lorang (2010) Multiple stressors in coupled river–floodplain ecosystems. *Freshwater Biology,* 55**,** 135-151.

Tockner, K. & J. A. Stanford (2002) Riverine flood plains: present state and future trends. *Environmental Conservation,* 29**,** 308-330.

Tronstad, L. M., B. P. Tronstad & A. C. Benke (2005) Invertebrate seedbanks: rehydration of soil from an unregulated river floodplain in the south-eastern US. *Freshwater Biology,* 50**,** 646-655.

Trowbridge, W. B. (2007) The role of stochasticity and priority effects in floodplain restoration. *Ecological Applications,* 17**,** 1312-1324.

U.S. Department of the Interior, U.S. Bureau of Reclamation, California Natural Resources Agency & California Department of Water Resources. 2013. Chapter 3: Conservation Strategy. Sacramento, CA.

U.S.D.O.I. 2013. Chapter 3: Conservation Strategy. ed. U. S. B. o. R. U.S. Department of the Interior, California Natural Resources Agency, California Department of Water Resources. Sacramento, CA.

Vanschoenwinkel, B., S. Gielen, M. Seaman & L. Brendonck (2009) Wind mediated dispersal of freshwater invertebrates in a rock pool metacommunity: differences in dispersal capacities and modes. *Hydrobiologia,* 635**,** 363-372.

Vilizzi, L., B. J. McCarthy, O. Scholz, C. P. Sharpe & D. B. Wood (2013) Managed and natural inundation: benefits for conservation of native fish in a semi-arid wetland system. *Aquatic Conservation-Marine and Freshwater Ecosystems,* 23**,** 37-50.

Ward, J. V., K. Tockner & F. Schiemer (1999) Biodiversity of floodplain river ecosystems: Ecotones and connectivity. *Regulated Rivers-Research & Management,* 15**,** 125-139.

Welcomme, R. (2008) World prospects for floodplain fisheries. *Ecohydrology & Hydrobiology,* 8**,** 169-182.

Whipple, A., R. M. Grossinger, D. Rankin, B. Stanford & R. Askevold. 2012. Sacramento-San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process. Richmond, CA: SFEI.

Willaims, D. D. (1998) The role of dormancy in the evolution and structure of temporary water invertebrate communities. *Arch. Hydrobiol. Spec. Issues Advanc. Limnol. ,* 52**,** 109-124.

Williams, P. B., E. Andrews, J. J. Opperman, S. Bozkurt & P. B. Moyle (2009) Quantifying activated floodplains on a lowland regulated river: its application to floodplain restoration in the Sacramento Valley. *San Francisco Estuary and Watershed Science,* 7.

Woodward, M., B. Gouldby, Z. Kapelan & D. Hames (2013) Multiobjective Optimisation for Improved Management of Flood Risk. *Journal of Water Resources Planning and Management*.

Zheng, P. & B. Hobbs (2012) Multiobjective Portfolio Analysis of Dam Removals Addressing Dam Safety, Fish Populations, and Cost. *Journal of Water Resources Planning and Management,* 139**,** 65-75.

Zheng, P. Q., B. F. Hobbs & J. F. Koonce (2009) Optimizing multiple dam removals under multiple objectives: Linking tributary habitat and the Lake Erie ecosystem. *Water Resources Research,* 45.

Appendix A

Quantifying habitat quality for fish and birds on an engineered, human-dominated floodplain using expert surveys

The Yolo Bypass (the Bypass) represents a relatively new type of ecosystem reconciliation effort – combining fish habitat, bird habitat, and agricultural production on an engineered flood control bypass. The landscape is largely agricultural, with some managed wetlands for waterfowl and other bird species, and is graded to ensure drainage to a canal that runs along its eastern levee. While it is understood that fish and birds both benefit from inundated habitats on the Bypass, their preferences for varied characteristics are not as well documented, especially during times of lower and smaller flood events when choices may be more limited.

The Bypass flooded in approximately 1 of every 3 years over the past several decades, most often between December and early February. Current state planning efforts propose bringing additional managed flows into the Bypass through a notch in its upstream Fremont Weir (Chapters 1 and 2), especially to increase annual flood frequency in late February through early April. There may be a way to strategically place, move, and time those flows that creates optimal habitat for a broad group of fish and bird species, without significant cost to human uses. However such nuanced management requires technical tools and analysis to guide initial decisions.

The modeling effort presented in Chapters 2 and 3 provides this analysis, but requires a quantification of habitat quality on the Bypass with varied land and flooding characteristics. This appendix describes interview and expert survey efforts conducted to fill gaps in recorded knowledge about fish and bird habitat quality on inundated lands in the Bypass, and to help form and parameterize the habitat quality objective functions utilized in the Yolo Bypass Multi-Objective Model. Responses indicate surprising areas of potential compromise between fish and bird habitats.

DEVELOPING THE FISH HABITAT SURVEY: EXPERT INTERVIEWS JULY - AUGUST 2011

A series of meetings and interviews were held with 6 fish biologists familiar with the Yolo Bypass in the summer of 2011. These meetings were intended to begin formulating the terms of the habitat quality objective, and to help develop the formal online expert fish habitat surveys that were eventually conducted in March 2013. Experts identified important aspects of floodplain habitat quality for fish: connectivity, timing of inundation (and, related to this, water temperature), duration, velocity, depth, area, complexity, structure (substrate and vegetation), and food availability or productivity. Experts also indicated that the last two characteristics, structure and food availability, are linked to agricultural or wetland land use type on the Bypass, with some food taking the form of soil-emergent invertebrates.

Because this study assumes that managed low flows (and fish) are brought in via a notched Fremont Weir (Chapter 2), connectivity and velocity are ignored. (Experts generally agreed that velocity differentials in managed low-flow events would be insignificant for fish.)

Because area and duration of inundation is additive, experts were also asked in these early interviews whether they thought the relationship between fish habitat quality and these two factors was likely to be somewhat linear. Most agreed that more area was generally better (each added acre beneficial) up until a point of decreasing returns, but that the benefits of added weeks of flooding are likely more complicated. The first week isn't as beneficial as weeks 2 and 3 when zooplankton and invertebrate food supplies have had time to develop. Experts also indicated that flooding after 5 or 6 weeks likely isn't as valuable as those 2nd through 4th weeks of inundation, although still beneficial as long as the water isn't too warm for some species. Finally, several experts also mentioned that duration is likely one of the most important factors in determining floodplain habitat quality, largely because of its relationship to zooplankton and invertebrate productivity.

There are several fish species that use the bypass when it is flooded. To simplify the analysis, experts were asked to identify those that are most prevalent and dependent upon the bypass in the winter and spring. Most answered Fall-run Chinook salmon, and Sacramento Splittail. For this reason, those species became the representative fish species for the fish habitat quality objective.

EXPERT FISH SURVEYS AND SUMMARIZED RESPONSES

Follow-up interviews over the next year (2012) led to the eventual development of a Yolo Bypass salmon and splittail habitat survey that was sent to 25 fish biologists from academia, government agencies, and/or non-profits in March 2013. 15 experts responded to questions focused on Fall-run Chinook salmon, and 6 of those 15 experts also responded to questions focused on Sacramento splittail. Respondents had between 4 and 43 years of experience working with California's Central Valley fish, with average experience at 13 years. Questions and responses are presented below.

Question 1:

> *There are many different land uses on the Yolo Bypass. During the time period of interest (January through May), most agricultural lands are in the process of being harvested or have already been plowed / disked in preparation for next season's planting. The bypass is also home to numerous managed wetlands. All of these manageable units (fields, ponds, wetlands, mudflats, and grazing plots) provide differently structured aquatic habitat during inundation events. As well as being influenced by vegetation and topography, the structure and complexity of available habitats depends on the depth and velocity of water flowing across each unit. For the purpose of this first exercise (question 1), please assume a low-flow event in which average depth and velocity are equal across all land use types, with water flowing over and through each one.*
>
> *In terms only of physical habitat structure and soil-emergent invertebrate food availability (ignoring the over-riding needs for complexity at the landscape scale, other food requirements, temperature, connectivity, duration, and passage for the time being), please fill out the table below with your expert judgment of the likely relative "value" of each land use type (on a scale of 0 to 10) during a shallow flooding event (<1 m). This scale is relative within the bypass only. In other words, 10 = best possible substrate / habitat structure WITHIN the Yolo Bypass, NOT over all habitats ever available to salmon or splittail. 0 = no habitat value whatsoever, and 5 = moderate habitat value relative to other bypass land uses. Each land use need not have a unique*

> *value. All could be assigned the same score. As an example, if you thought riparian and rice landscapes were equally the most beneficial types of land cover for salmon / splittail on the Yolo Bypass, you would give them both a value of 10. If you further thought that fallow land was half as good as those, you'd give fallow a value of 5.*

Figure A.1 summarizes average responses to this first question for salmon and splittail, with bars indicating standard deviation for each land use type:

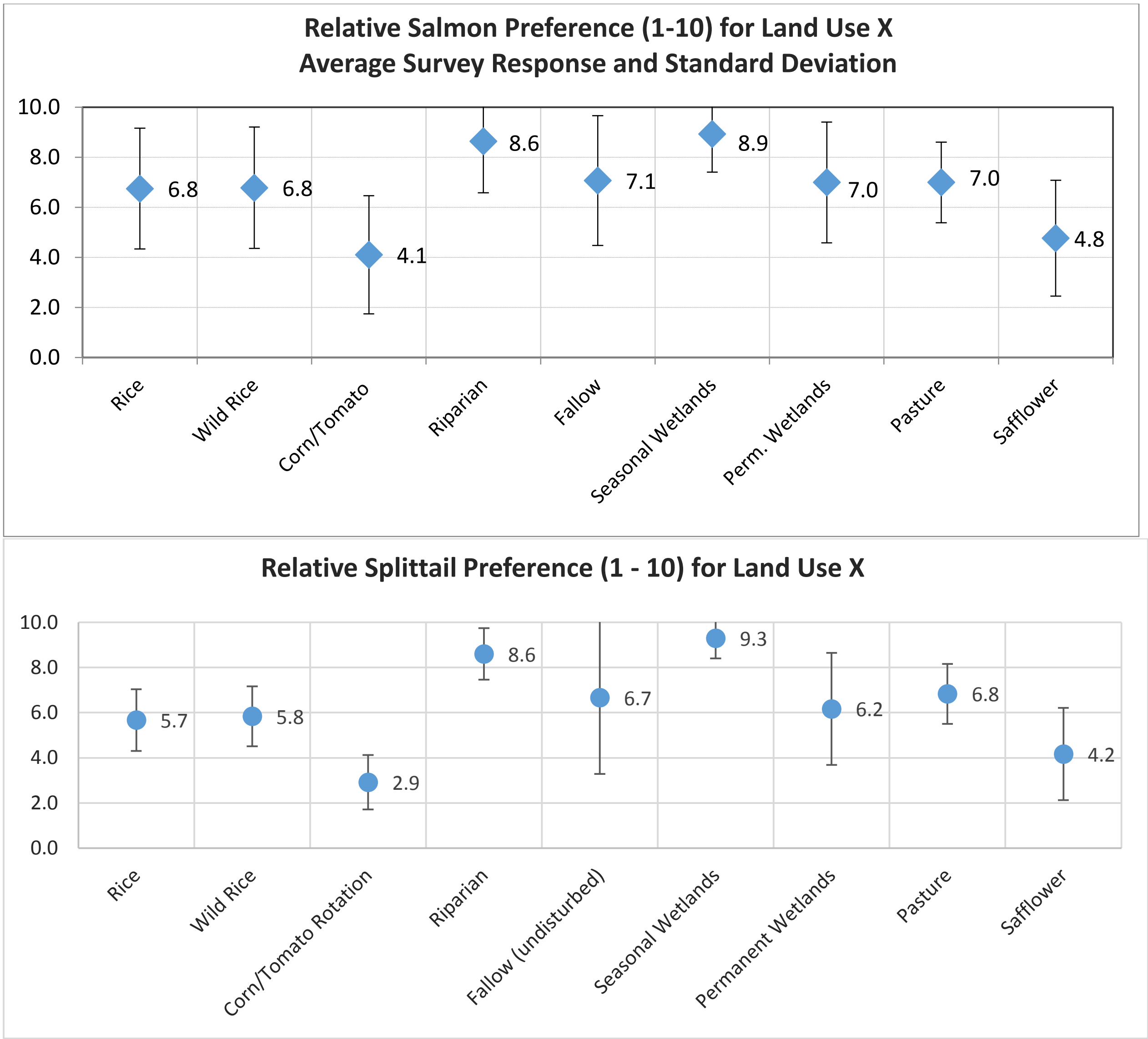


Figure A.4. Fish preferences for different agricultural and wetland land use types on the Yolo Bypass. (Expert Opinion Survey, 2013)

Biologists generally believed seasonal wetland and riparian land use types on the Bypass to be most beneficial for salmon and splittail, and that rice, wild rice, fallow, permanent wetlands, and pastureland are all also potentially moderately useful. However standard deviation is very high, reflecting a general lack of research (at the time of the survey) about fish preferences in agricultural floodplains. Corn, tomato, and safflower fields are ranked lowest for both fish species.

Questions 2 through 6 of the fish habitat surveys were introduced as follows:

> *The table you filled out in part one will go towards creating a weighted metric to describe the quality of different flooded land use types in terms of habitat structure and soil-emergent invertebrate food bank. This metric will be used as one factor in a larger equation that describes the value of various physical aspects of flooding for salmon / splittail. Physical habitat quality, as you know, is just one part of the relative benefit of a given flooding scenario. Other factors to be included in this study are total acreage flooded, average depth, duration, and timing.*
>
> *The following questions will help us more accurately quantify how different factors might improve the potential for fish usage of a bypass flooding event. Feel free to add comments below, and please answer just to the best of your knowledge. (Remember this is a survey of expert opinion, necessary due to a lack of known research pertaining to fish habitat usage within engineered floodplains.)*

Question 2:

> *Given a scenario in which flooding depths never exceed 3 feet, please rate the usefulness of each depth range below to salmon / splittail by selecting optimal, good, moderate, bad, or useless. Answers need not be distinct. (For example, you might say that all depths listed are "good.")*

Figure A.2 shows average responses and standard deviation. Both species prefer deeper water, but experts seem to believe that splittail have a higher tolerance (or use?) for water between 8 and 18 inches than salmon do.

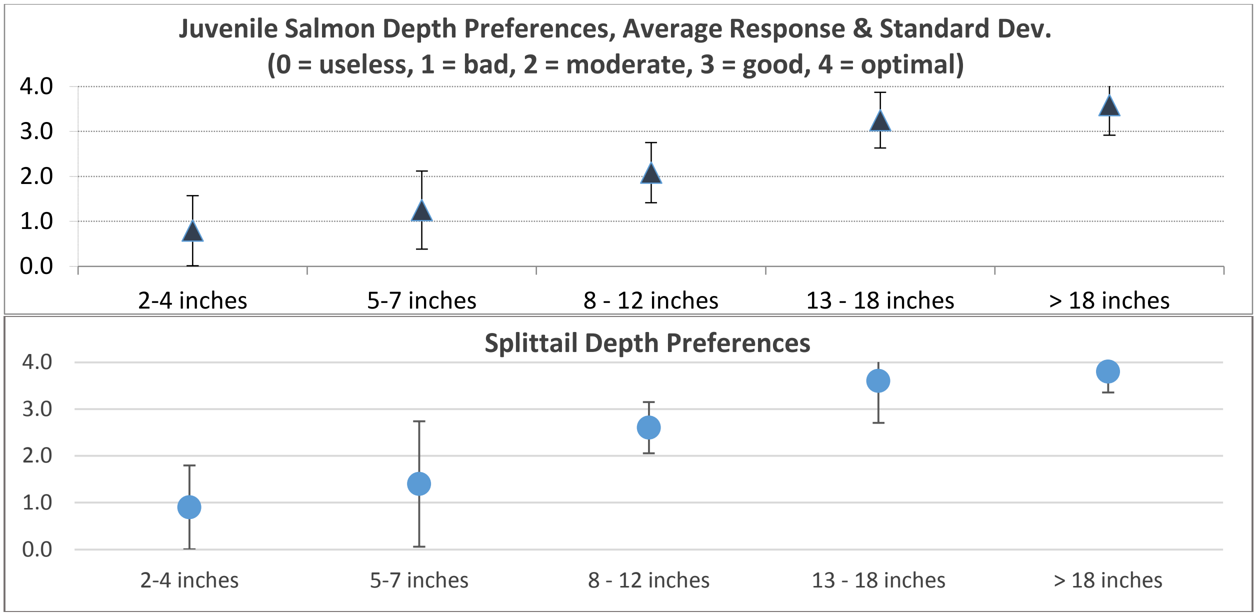


Figure A.5. Fish preference for varied depth zones. (Expert Opinion Survey, March 2013)

Question 3:

> *Consider two contributing factors to salmon benefits from managed flooding on the Yolo Bypass: (1) total acres of each land use type flooded, with considerations of habitat structure and soil-derived invertebrate abundance as in question 1 of this survey, and (2) complexity or variety of land uses flooded.*
>
> *You have 10 'benefit points' to distribute among these two metrics for a total benefit of 10. Please distribute the points among them. (Thus, if you think land use type and acreage is the most important characteristic of flooding, regardless of complexity of land use, you might produce numbers like this: Land Use Type (and total acres) – 9; Complexity – 1;)*

Answers to this question ranged between 0 and 5 benefit points for complexity, and between 5 and 10 for the larger land use and total acres term, with an average of 3 for complexity, and 7 for total acres and land use type.

Question 4:

Assume a LARGE run of wild juvenile salmon / splittail coming through the system, and the potential for passage into the Yolo Bypass at its northern end. Which range best represents the MINIMUM acreage needed for inundation to have potential population-scale benefits for salmon / splittail in such a scenario? (You may choose more than one if the ranges provided don't adequately capture uncertainties.)

NOTE: The entire Yolo Bypass covers 59,000 acres (approximately 240 square km).

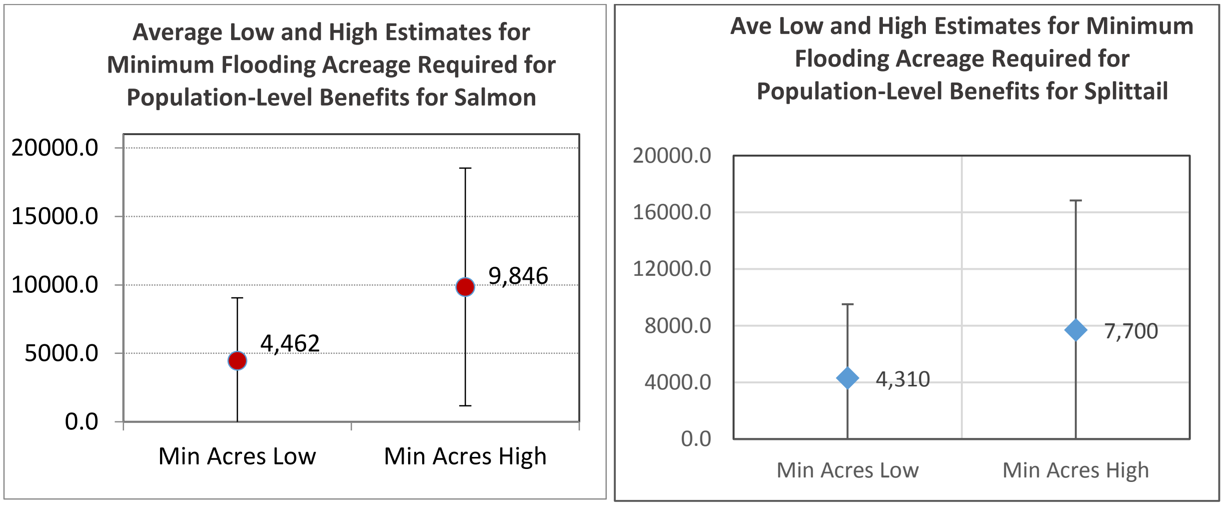


Figure A.6. Average expert opinion on the minimum flooded acres required for population-level benefits for juvenile Fall-run Chinook salmon and Sacramento splittail on the Yolo Bypass. Experts gave a range. The average low and high ends of given ranges are reported. (Expert Opinion Survey, 2013)

Answers to Question 4 are shown in Figure A.3. Experts generally agreed that this was a very difficult question to answer. Many respondents commented that the amount of flow entering the bypass would be a better metric than area. However because this study is not directly coupled with a 2-D flow model, increased area is assumed roughly correlated with increased flow. Other experts noted that the lower end of their indicated range for minimum flood extent would be large enough as long as all other flood characteristics were ideal (timing, duration, etc…). This lower estimate varied from 500 to 10,000 acres for both fish species, with an average of around 4,000 acres. The higher end of respondents' estimates was slightly lower for splittail than for salmon, but in both cases standard deviation was extremely high around a mean value of 9,800 acres for salmon, and 7,700 acres for splittail. This again is the higher end of an estimate of minimum acreage necessary, not the estimated point of diminishing marginal returns for added habitat. Because extent of flooding is so important for other land uses on the bypass especially in March and April (Chapter 2), this is certainly an area that warrants further research as lower, managed flows become available.

Question 5:

> *Assuming all other things equal (depth, timing, duration, land use, and acres flooded), is it reasonable to say that the benefit of additional flooded acres increase linearly above the minimum number given in your answer to question 4? i.e. 100 acres is twice as good as 50, and 200 is twice as good as 100, etc…?*
>
> *Please type YES or NO (and add any comments as necessary).*

Many respondents skipped this question, or replied that it depends on the number of fish in the system or too many other factors. Three respondents said "yes", but only up to a point at which diminishing returns begin. Four respondents said "no" with no added explanation. Two respondents again indicated that benefits increase more linearly with added flow than with flood extent. Because incoming flows are assumed related to increased area, and three respondents thought linearity would be a reasonable simplification, the habitat objectives were kept linear in terms of added flooded acres. However this, like the above question, has huge implications for other land uses on the Bypass, and warrants further sensitivity analysis and research.

Question 6:

Please rate the following weeks as low, medium, or high priority floodplain inundation timing for juvenile salmon / splittail.

Because standard deviations were generally low for responses to this question, salmon and splittail responses are plotted in the same graph (Figure A.4):

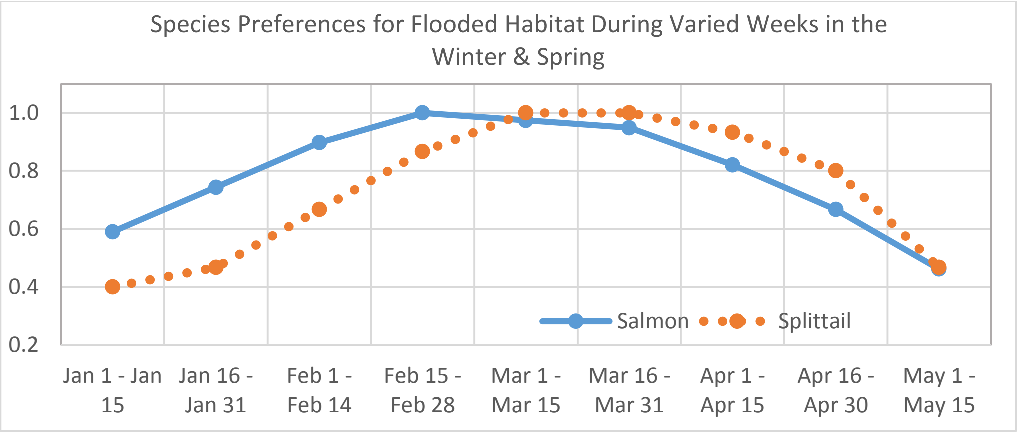


Figure A.7. Priority of floodplain habitat on the Yolo Bypass for different fish species over time. (Expert Opinion Survey, 2013)

Figure A.4 shows that both fish species highly value the availability of floodplain habitat in late February through the end of March. Salmon are more prevalent in January and early February than splittail, and the opposite seems to be true in April and May.

DEVELOPING THE WATER BIRDS HABITAT SURVEY: EXPERT INTERVIEWS SEPTEMBER 2012

Eight experts familiar with wetland management and waterfowl in the Central Valley (a mix of wildlife biologists and wetland managers from private duck clubs, public wetlands, government agencies, and academia) were interviewed to develop a formal waterfowl habitat survey, and to be sure the habitat quality objective function captured all important aspects of flooded habitat on the Bypass for relevant bird species. To help focus these efforts, interviewees were first asked to identify those water bird species that are abundant and dependent enough on the Bypass that they should be included in the broader waterfowl category. All eight interviewees said dabbling ducks and shorebirds should be included, whereas only 2 indicated that geese and/or diving ducks should be included. When asked whether added flooding on the Yolo Bypass could benefit dabbling ducks (dabblers) and shorebirds, most experts said yes, although with qualifiers like "it depends on when and how deep."

Most experts indicated that the primary metrics for habitat quality in the late winter and early spring for dabbling ducks and shorebirds are current year foraging habitat accessibility and availability, and development of the following year's food bank. When asked about current year food availability, experts pointed to depth as the primary driver, with dabbling ducks able to forage in water between 4 and 18 inches, and shorebirds preferring water between 0 (mudflat) and 4 inches deep, with some shorebird species able to take advantage of habitats up to 12 inches deep. However availability of flooded habitat is only important for varied species within certain timeframes. Respondents agreed that the most important time period for dabblers on the Bypass is January through early March, and shorebirds lag about a month behind (February through early April). The caveat was also given that the exact timing of peak bird densities can change year to year depending on conditions in other places, weather, and other factors.

Wildlife biologists were also prompted on whether habitat quality for birds increases linearly with added acres and/ or added weeks of flooded habitat. Most respondents thought that with depth and timing correct, a linear relationship could be assumed between added acres and overall benefits to birds. Some experts additionally pointed out that increased acreage decreases disease and provides more choices and escape from predators. As was the case for fish, the idea of linear benefits with added weeks of flooding (or longer duration) was not as well received. Only 2 interviewees thought it might be possible with well-managed land and proper timing. However most experts instead agreed that dabblers especially take advantage of a flush of nutrients that are available immediately after a field or wetland is flooded (by foraging on seeds), but then after about 5-10 days that food source is depleted and the birds move to new area. With time invertebrate food sources build up in the mud and water column and provide a new type of food for the birds to come back to. This invertebrate food supply is especially available to birds when fields are being drawn down and the invertebrates are concentrated. In general all experts thought that added weeks were a good thing, just not necessarily linear in the benefits they might provide.

When asked about bird usage of different land use types, most experts thought rice, wild rice, corn, and seasonal wetland were all pretty good food sources. All of them thought corn was the least valuable of these four land use types, but there was disagreement about whether rice or wetland was number one. Grazing, Fallow, and Safflower seemed to be considered moderate food sources, although one expert said they'd had great success on fallow fields before. Almost all agreed that tomatoes were practically useless. Permanent wetland was sometimes ranked above grazing / fallow areas, while others deemed it useless as food supply in the time period of interest.

Finally, in describing the relationship between winter / spring flooding and following year food supplies for birds, experts pointed to two plants that are most important on the Bypass; swamp timothy and watergrass. When asked if the two food sources were interchangeable, most said no, that the seeds of each are specialized for certain species. Watergrass seeds are larger and benefit species like mallards and northern shovelers, whereas swamp timothy's smaller seeds benefit the smaller bird species. Answers about moist soil management for these plants indicated that swamp timothy should start being drawn down sometime in March, and watergrass in late April.

EXPERT BIRD SURVEYS AND SUMMARIZED RESPONSES

These early interviews helped with the development of a more formal online expert survey about dabbling ducks and shorebirds. The survey also added questions for some qualified respondents about the economics of wetland management. Surveys were sent to 47 experts in September 2013, with experts representing a mix of academic wildlife biologists, public agency scientists or wetland managers, non-profit scientists, and private wetland owners and managers. The survey received 32 total responses. All survey respondents were provided this introduction:

> *Thank you so much for your participation. The following survey takes about 20 minutes and focuses on various aspects of wetland management on the Yolo Bypass, specifically for dabbling ducks and shorebirds. (These two types of waterbird were identified in a preliminary interview process as the two most important to or dependent upon the Yolo Bypass.) Your individual*

answers will remain anonymous. This survey will inform a larger study that is focused on a scenario, or future, in which it is possible to bring additional low flows into the bypass in what are currently dry years, and to manage the depth, timing, placement, and duration of that water. The survey will help to quantify the effects of this kind of managed winter and spring flooding in the Yolo Bypass from three different perspectives:

1. *Current Year Foraging Habitat for dabbling ducks and shorebirds*
2. *Moist Soil Management for following year food supplies (for birds), and*
3. *Economic effects for public and private wetlands.*

[Please note that the effects on agriculture and fish are also being considered in the larger study, even though they are not covered in this survey.]

Please help us make your survey experience as efficient as possible by answering this question first.

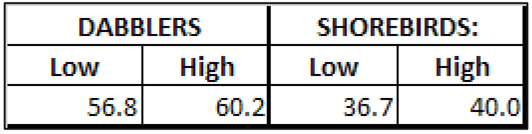
At this point in the survey respondents were asked to identify their area of expertise as (1) Waterbird biology / ecology, (2) Moist soil management, (3) Running a private wetlands / hunting club, or (4) Management of public wetlands. 12 respondents self-identified as waterbird biologists or ecologists. They were given some specific questions about habitat preferences of dabbling ducks and shorebirds before also receiving some wetland management questions that were asked of the whole group of respondents. They were told that their answers would help inform a quantitative description of the value (or losses) of various late winter or spring flooding scenarios for waterbirds on the Yolo Bypass, and were asked to consider water bird use of the Bypass in the context of the larger Central Valley and/or Pacific Flyway. These first 9 questions were given only to those respondents who identified as biologists or ecologists.

Questions 1 and 3 (dabblers and shorebirds, respectively):

> *Assume a good year for dabbling duck/shorebird populations coming into the Valley, so that the number of birds is high. The entire Yolo Bypass covers 59,000 acres (approx. 240 sq km). In your view, what is the minimum percentage of this area that you think should be managed for water birds? (Feel free to provide a range if needed).*

9 respondents answered this question, with most providing a range. Table A.1 shows the average responses for dabblers and shorebirds.

Table A.1. Expert estimates of minimum % of Yolo Bypass acreage that should be managed for dabbling ducks and shorebirds. (Expert opinion survey, 2013)



DABBLERS		SHOREBIRDS:	
Low	High	Low	High
56.8	60.2	36.7	40.0

These responses imply that at least 33,000 acres should be managed for dabbling ducks, and 21,000 for shorebirds, with experts noting that land could be managed for both species groups together (i.e. they are not mutually exclusive). Standard deviations were high, with dabbler answers ranging between 30% and 90%, and shorebird estimates ranging from 20% to 75%. This high number of acres seems odd considering that the bypass currently only has about 9,500 acres of managed wetlands, but birds are also known to use rice, wild rice, and some other agricultural crops as foraging habitat. One respondent explicitly said that all wetlands and rice fields should be managed for birds. Respondents may also not have been thinking of the uplands portions of the southern bypass as included in total acreage. If not, responses would translate instead to an average minimum of 26,000 acres for dabblers and 16,500 acres for shorebirds. Finally, one respondent also provided the caveat that his/her answer assumed areas outside the bypass within the basin are not protected. Regardless of different underlying assumptions, responses generally indicate that most water bird biologists think a significant portion of agricultural land uses on the bypass, and especially rice, should consider dabbling duck and shorebird preferences when making land management decisions.

Question 2 and 4 (dabblers and shorebirds, respectively):

> *Alternatively, if you could manage flooding such that most of it was shallow enough to be useful dabbler / shorebird habitat, is there an upper threshold beyond which added acreage does not add much value? What would you estimate as being the MAXIMUM (ranges are OK) percentage of total Yolo Bypass acreage up to which dabbling ducks would be able to obtain added benefits? Or, if you don't think such a threshold exists, just write "NO" in the comments box.*

Respondents generally agreed that almost the entire bypass could be managed for birds (an average response of 99% for dabblers, and 93% for shorebirds) before added acres would no longer bring added value. This does not mean that each acre would bring the same value (i.e. linear benefits). That issue is addressed in the following question.

Question 5:

> *Between the minima and maxima percentages identified in the previous section, is it a reasonable simplification to say that benefits to water birds increase linearly with added habitat acreage? i.e. 1000 acres is twice as good as 500, and 2000 is twice as good as 1000, etc? Please assume all other things equal (depth, timing, duration, and type of land use flooded).*
>
> *Type YES or NO (and add any comments if necessary).*

70% of respondents answered "yes" to this question for dabblers, and 60% responded "yes" for shorebirds. However half of those that said yes qualified their answer by saying there would likely also be a threshold at which birds would start receiving diminishing marginal value for added habitat. This is similar to the response given for fish: "yes benefits are linear, but only to an unknown point."

The next set of questions shift focus to the assignment of weights, or bird preferences, for different land use and flooding characteristics. Questions 6 through 9 were introduced with the following:

> *There are many different land uses on the Yolo Bypass. During the time period of interest (January through April), most agricultural lands are in the process of being harvested or have already been plowed / disked in preparation for next season's planting. The bypass is also home to numerous managed wetlands. Please answer the following questions to help us better understand the relative value of these different land uses as foraging habitat for dabbling ducks and shorebirds.*

Questions 6 and 7 (dabblers and shorebirds, respectively):

> *Assume that all land uses are flooded at the same time of year (sometime January – April), for the same number of weeks, with relatively low and uniform flow velocities. In terms of physical habitat structure and food availability for dabbling ducks / shorebirds, please fill out the table below with the relative "value" of each land use type (on a scale from 0 to 10) during a shallow flooding event (shallow enough for dabbling duck / shorebird foraging). Some land use types will be better for structure than for food, and others vice versa – please try and combine both of these habitat properties into one overall rating, given the species' needs that time of year. This scale is relative within the bypass only. In other words, 10 = best possible food supply and habitat WITHIN the Yolo Bypass, NOT over all habitats ever available to a dabbling duck / shorebird. 0*

= no value whatsoever, and 5 = moderate habitat and foraging value relative to other bypass land uses.

Figure A.5 shows average responses and standard deviation for dabbling ducks and shorebirds. As was indicated in earlier interviews, experts generally believe that seasonal wetlands, rice and wild rice are the best habitats for dabbling ducks and shorebirds on the bypass, followed by semi-permanent wetlands. Experts also thought corn might provide valuable food supplies for dabblers, and that fallow and pasture lands could be good habitat for shorebirds because of invertebrate production. Tomato, riparian, and safflower all ranked low for both species groups. Some respondents noted that for shorebirds, almost all agricultural crops could be turned into good habitat with the correct treatment post-harvest, since they are more dependent on invertebrates than seeds for food.

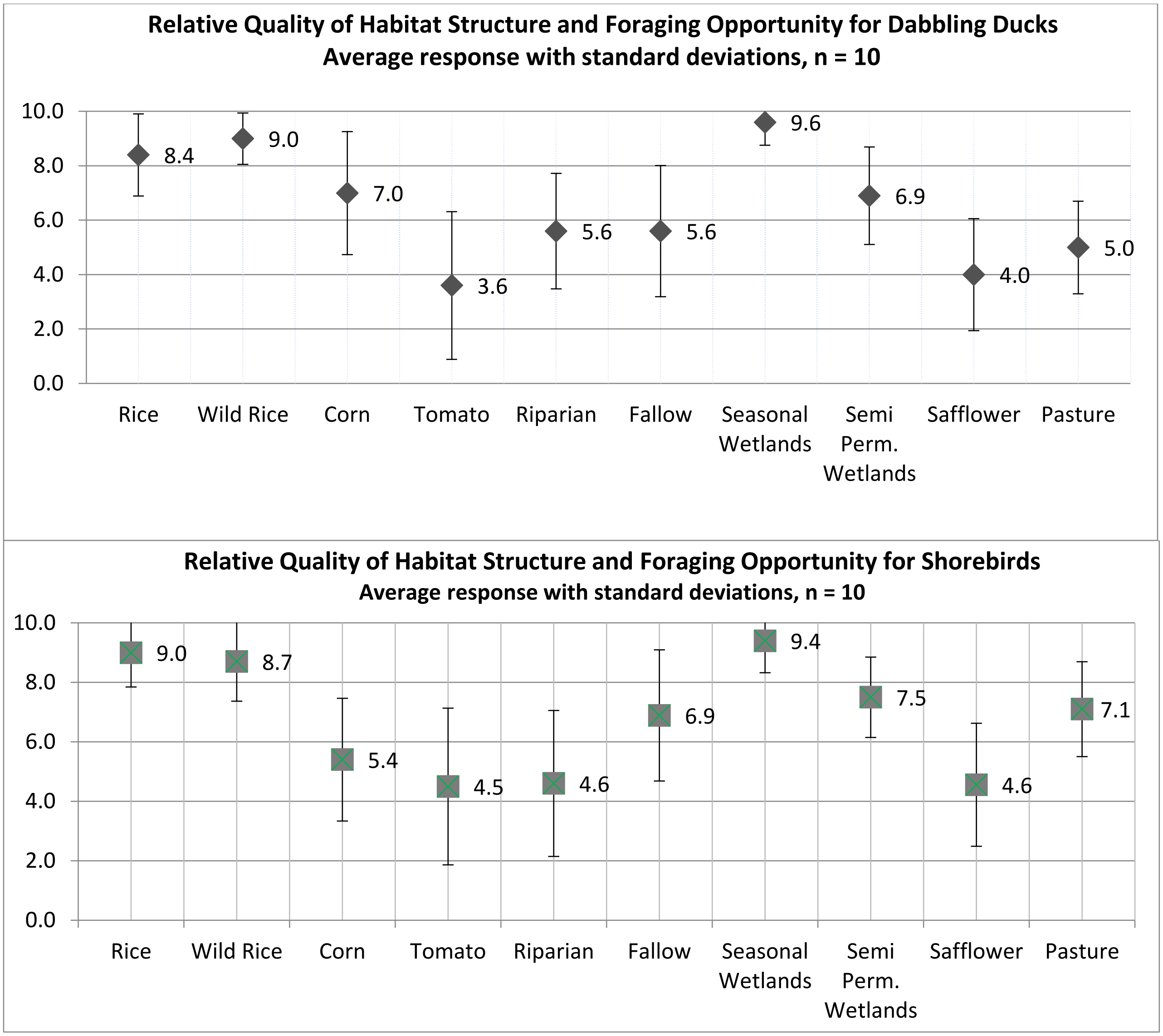


Figure A.8. Expert Opinion (2013) on dabbling duck and shorebird preferences for different land use types on the Yolo Bypass for structure and foraging habitat.

Questions 8 and 9 (dabblers and shorebirds, respectively):

> *Assume all flooding is shallow enough for dabbling duck / shorebird foraging and occurring at the same time and for the same duration. Consider two contributing factors to dabbling duck / shorebird benefits from shallow, managed flooding on the Yolo Bypass: (1) total acres of each land use type flooded, with considerations of habitat structure and food abundance as in previous questions, and (2) variety, or number and mix, of land uses flooded.*

You have 10 'benefit points' to distribute among these two metrics for a total benefit of 10. Please distribute the points among them.

As an example, if you said that rice was the best habitat available on the bypass to a dabbling duck, and because of this you think it preferable to have only flooded rice habitat rather than a mix of different land use types flooded, you might produce numbers like this:

Land use type (and total acres): 10

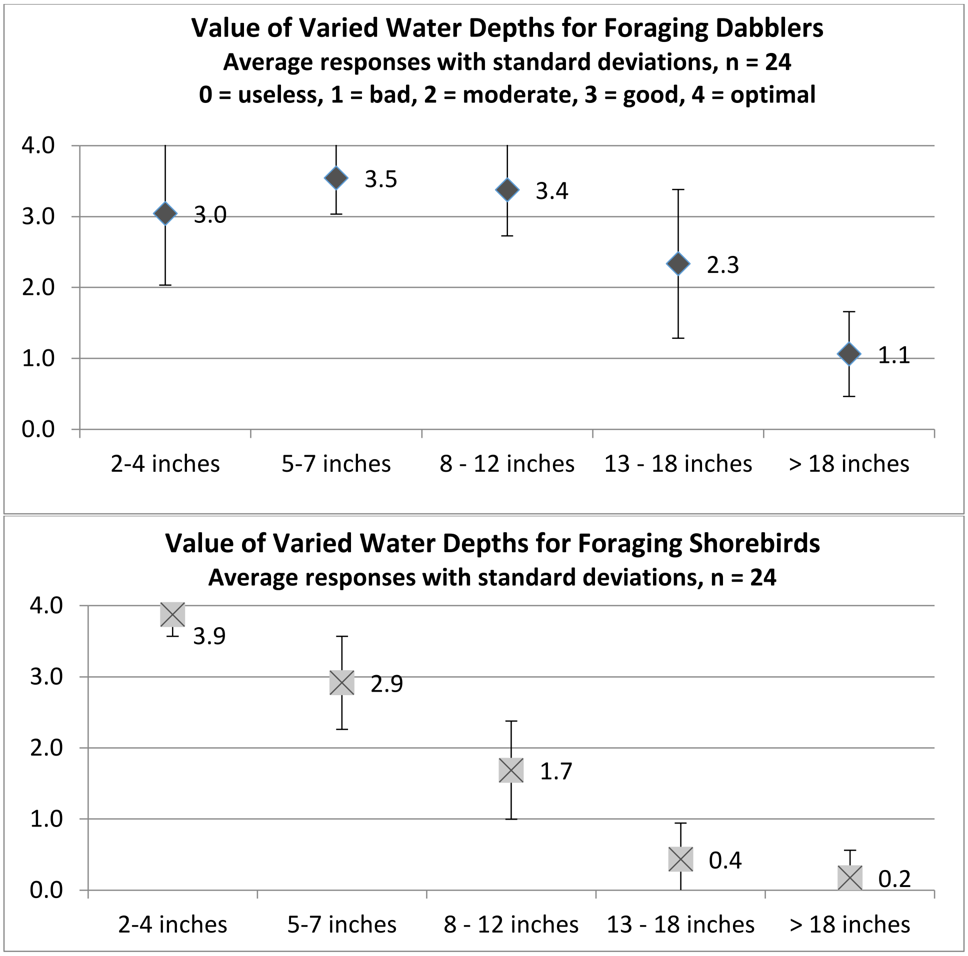
Variety or number of different land use types: 0

Answers were the same for both species groups, with an average of 3.2 benefit points assigned to variety or complexity, and 6.8 assigned to the total acreage of each land use type flooded. Standard deviations were around 1.8 for dabblers and 2 for shorebirds.

This marks the end of those questions that were only asked of experts who self-identified as biologists or ecologists. The following questions were asked of all 32 respondents, including wetland managers, duck club owners, and agency scientists.

Questions 10 and 11 (dabblers and shorebirds, respectively):

Please rate the usefulness (for foraging) of each depth range below to a dabbling duck / shorebird by selecting optimal, good, moderate, bad, or useless. Please average across the dabbling duck species that utilize the bypass. It is OK to assign the same rating to more than one depth range. (For example, you might say that all depths listed are "good.")


Value of Varied Water Depths for Foraging Dabblers
Average responses with standard deviations, n = 24
0 = useless, 1 = bad, 2 = moderate, 3 = good, 4 = optimal

Value of Varied Water Depths for Foraging Shorebirds
Average responses with standard deviations, n = 24

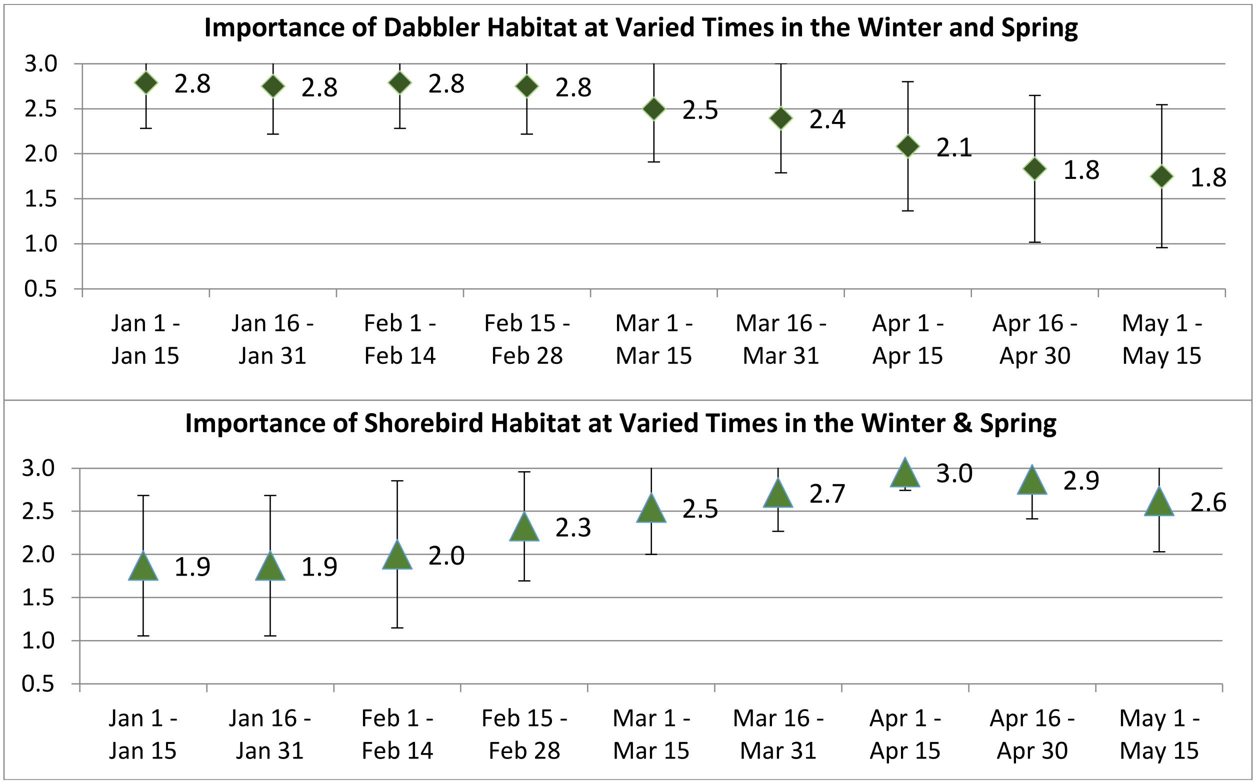
Figure A.9. Depth preferences for dabbling ducks and shorebirds in the Yolo Bypass (averaged across all Bypass dabbling duck or shorebird species). 0 = useless, 1 = bad, 2 = moderate, 3 = good, and 4 = optimal. N = number of experts who responded to this question. (Expert Opinion Survey, 2013)

Experts generally agreed that any water below 8 inches is good or optimal foraging habitat for shorebirds, and anything between 5 and 13 inches is good (or optimal) for dabblers Figure A.6). There was also largely agreement that anything deeper than 12 inches is bad or useless habitat for shorebirds, although some respondents also pointed out that any flooding will have shallow areas for shorebird use around the edges. Standard deviations are higher around responses in the very shallow (2 – 4 inches) or moderately deep (greater than 12 inches) ranges for dabbling ducks, but average responses indicate that any habitat below 18 inches is at least useable.

Questions 12 and 13 (for dabbling ducks and shorebirds, respectively):

> *Please rate the following weeks as low, medium, or high priority for maintaining flooded habitat for dabbling duck / shorebird foraging in the Yolo Bypass.*

Figure A.7 shows average responses for dabblers and shorebirds. Standard deviations were high in late March through May for dabblers, and in January and early February for shorebirds. However experts generally agreed that January through February are high priority months for dabblers, and that shorebirds are most dependent on habitat in April. Also, almost all time periods were given medium priority by most experts.



Importance of Dabbler Habitat at Varied Times in the Winter and Spring

Importance of Shorebird Habitat at Varied Times in the Winter & Spring

Figure A.10. Importance of habitat availability for dabbling ducks and shorebirds on the Yolo Bypass during different weeks in the winter and spring. (Expert Opinion Survey, 2013)

Questions 14 and 15 (dabblers and shorebirds, respectively)

> *Assume that flooding occurs within the appropriate land uses, weeks, and depth scales to be useful habitat for dabbling ducks / shorebirds. Is it fair to say that benefits increase linearly with each additional week of inundation (within the above listed constraints)? If not, please explain.*

Figure A.8 shows that a majority of experts think that linear duration benefits are not likely for dabblers, whereas a majority think it's possible that duration benefits are linear for shorebirds. This has mostly to do with the fact, already discussed in preliminary interviews, that dabblers use both seeds and invertebrates in the water column, whereas shorebirds eat only invertebrates.

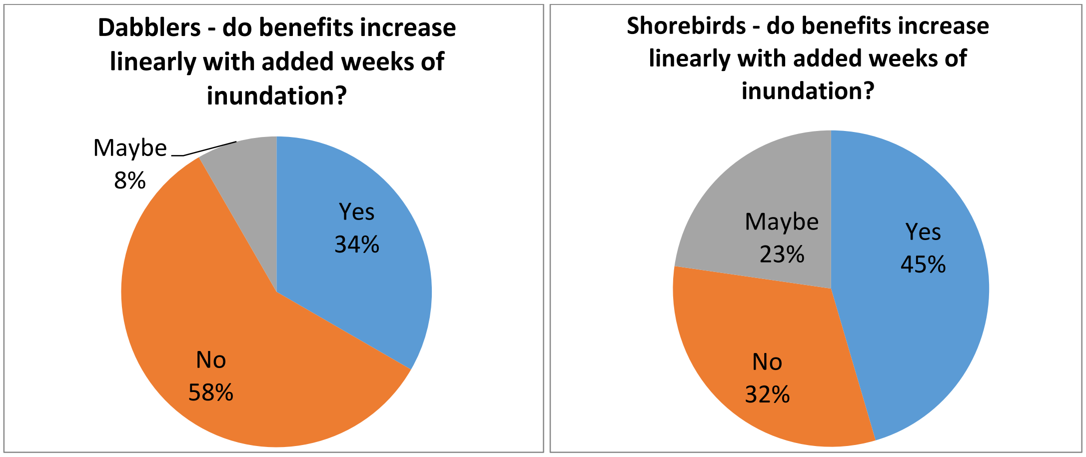


Figure A.11. Expert opinion on whether simplifying the relationship between added weeks of habitat inundation with benefits for birds is viable.

This marks the end of the survey taken by those who self-identified as biologists and ecologists. Moist soil and wetland managers and/or owners were asked a short series of additional questions about moist soil management on the Bypass and the economic effects of added wetlands or flooding on wetlands:

Questions 16 and 17 (For watergrass and swamp timothy, respectively)

> *For each of the following drawdown dates (or date at which one could start managing the unit for the summer watergrass / swamp timothy growing season), please estimate the percentage LOSS in following year food production from a delayed drawdown (to the best of your knowledge and experience). Note that loss could be due to a variety of factors related to late drawdown, including a shortened growing season, growth of other undesirable plant species, soil temperature, etc…*

Only 9 survey respondents felt qualified to answer this question. Figure A.9 plots responses for watergrass and swamp timothy, with red curves plotting the average estimates for each week. The curves show that watergrass may actually suffer from an early drawdown, requiring water until sometime in mid-April. Swamp timothy, however, is believed by respondents (on average) to experience yield losses of approximately 10% with each week of delayed drawdown past April 6th. Many respondents noted that yields for these plants are also dependent on temperatures during the germination period (spring) and summer irrigations during the growing season. As with other factors, this can vary from year to year.

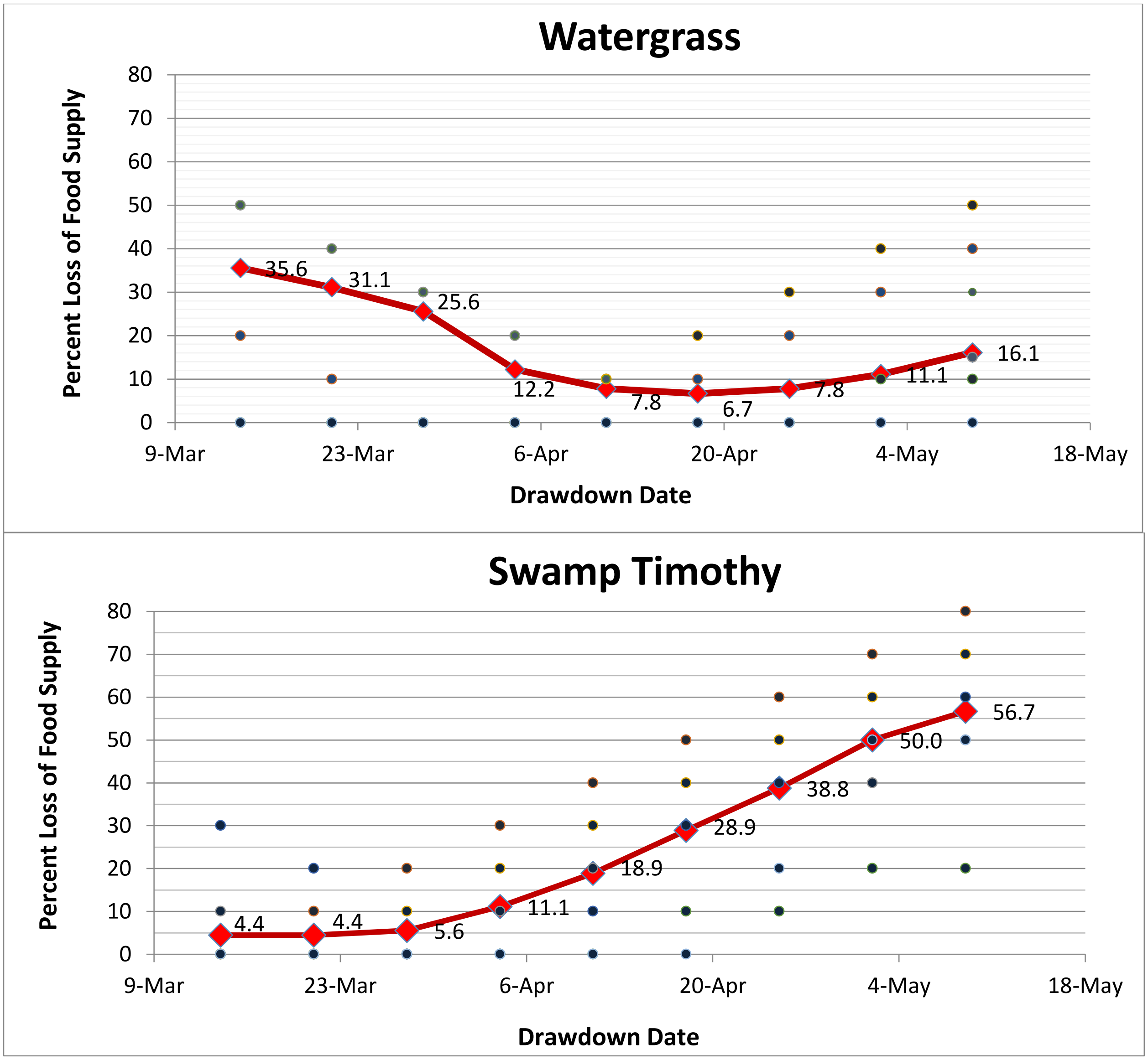


Figure A.12. Estimated loss in biomass or yield from moist soil plants with early or delayed drawdown. (Expert Opinion Survey, 2013)

Question 18

Following on the moist soil management questions from the previous section, are there any extra costs associated with a delayed drawdown for plants like swamp timothy and watergrass (e.g. mowing)? If so, please estimate an average cost per acre and write it (or a range of costs) in the box below.

Only 6 respondents gave estimates. The average low end of given ranges was $24 per acre, and the average high was $71, with answers ranging from $5 to $125. Experts cited herbicide, mowing, and disking, (to mitigate unwanted vegetation) and extra irrigations (to increase summer growth) in calculating these costs.

Questions 19 and 20 (semi-permanent and seasonal wetland, respectively):

> *Including capital, maintenance, water, and operational costs, what is the average annual cost per acre of semi-permanent / seasonal wetland habitat? (Please provide a range if you don't feel comfortable providing an exact number.)*

12 respondents answered these questions, but only 7 gave cost estimates. These are summarized in Table A.2 below.

Table A.2. Estimated annual costs of seasonal and semi-permanent wetlands on the Yolo Bypass.

	Average Annual Costs			
	Seasonal Wetland		Semi-Permanent	
Average Response	$ 142	$ 175	$ 204	$ 246
Standard Deviation	$ 80	$ 88	$ 135	$ 144

The average response for annual costs of private seasonal wetland was about $160 per acre, and $220 per acre for semi-permanent wetland. However standard deviations were very high (80 and 135, respectively), with seasonal wetland estimates ranging from $80/acre to $300/acre. Follow-up interviews with some willing participants indicated that this variance (even within the bypass itself) is possibly due to differences in management intensity, with some clubs spending more money on continued structural habitat maintenance and moist soil management. Differences may have also occurred with varied interpretation of the question: Some respondents only considered the cost of managing the wetlands themselves, whereas others included basic costs of ownership (e.g. for the land, infrastructure, and salaries for paid managers). As such, it is likely that the higher estimates more closely represent the true total annualized costs of owning and running a private wetland.

DISCUSSION - COMPARING RESPONSES FOR ALL BIRD AND FISH SPECIES

Similar questions were asked of fish and water bird experts, for four species groups in total: Fall-run Chinook salmon, Sacramento splittail, dabbling ducks, and shorebirds. The results compiled above allow for a comparison of preferences across these important species to help guide management on the Bypass as managed flows become available, and highlight some areas in which current understanding is consistently low.

How much flooded habitat is needed?

Fish and wildlife experts generally did not have a consistent answer to this question. Fish experts gave numbers that ranged from 500 acres all the way to 18,000 acres for the minimum required flood footprint, and waterfowl expert opinion ranged from 11,000 to 50,000 acres needed for bird habitat. Because of the wide range of economic and water management implications related to flood extent and footprint, further research seems necessary to refine general understanding about how much habitat is required for native bird and fish species on the Bypass.

Which Land Use Types Show the Most Promise as Habitat for Fish and Birds on the Bypass?

Figure A.10 summarizes expert opinion on the relative value or preference that species might have for different land use types on the Yolo Bypass. While both fish species have similar preferences, there are a few differences between dabblers and shorebirds. Overall, experts believe that all species are likely to prefer seasonal wetland habitats to any others on the bypass. However there are also 4 agricultural land uses that ranked somewhere between moderate and good for all four species groups: fallow, pasture, rice, and wild rice. Together, these 5 different land uses (wetlands included) represent the habitat-friendly bypass. These land use types should potentially all be managed with multiple (economic and ecological) purposes in mind, with implications for ideal location relative to one another, and best land management practices to encourage invertebrate and other food supplies (Appendix B).

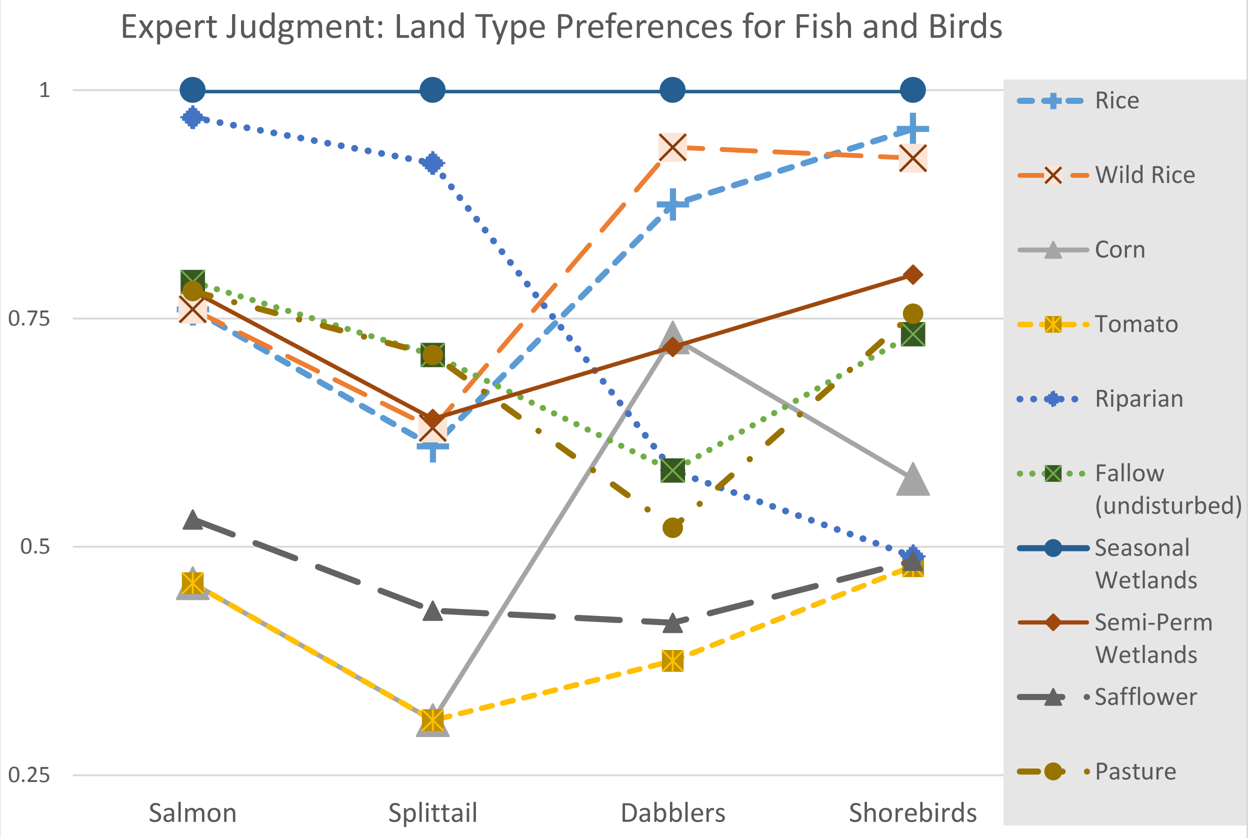


Figure A.13. Comparison of species preferences for different land use types on the Yolo Bypass in terms of structure and foraging opportunities.

How does habitat quality change with depth?

Depth is the great divider when it comes to habitat quality for fish and birds. Generally, birds prefer shallow water and fish prefer deeper water. But there are some depth ranges in which all four species might find useable habitat. Figure A.11 shows that water between 8 and 18 inches was thought to be at least moderately useful for salmon, splittail and dabblers, and water between 8 and 12 inches might even be someone useful for some shorebird species. Dabblers and splittail are more tolerant of a wider range of water depths than salmon or shorebirds. These results suggest that while some habitats and weeks can be geared towards multiple fish and bird species at once with flows between 8 and 12 or 18 inches deep, providing good shorebird and salmon habitat will require that both deep and shallow water is available. However depths can vary in both space and time. Experts pointed out that some shallow water will always be available at the edges of a flood, but shallow water can also be available at the front and tail ends of a flood, especially during drawdown when bird species can take advantage of a concentrated source of invertebrate food supplies.

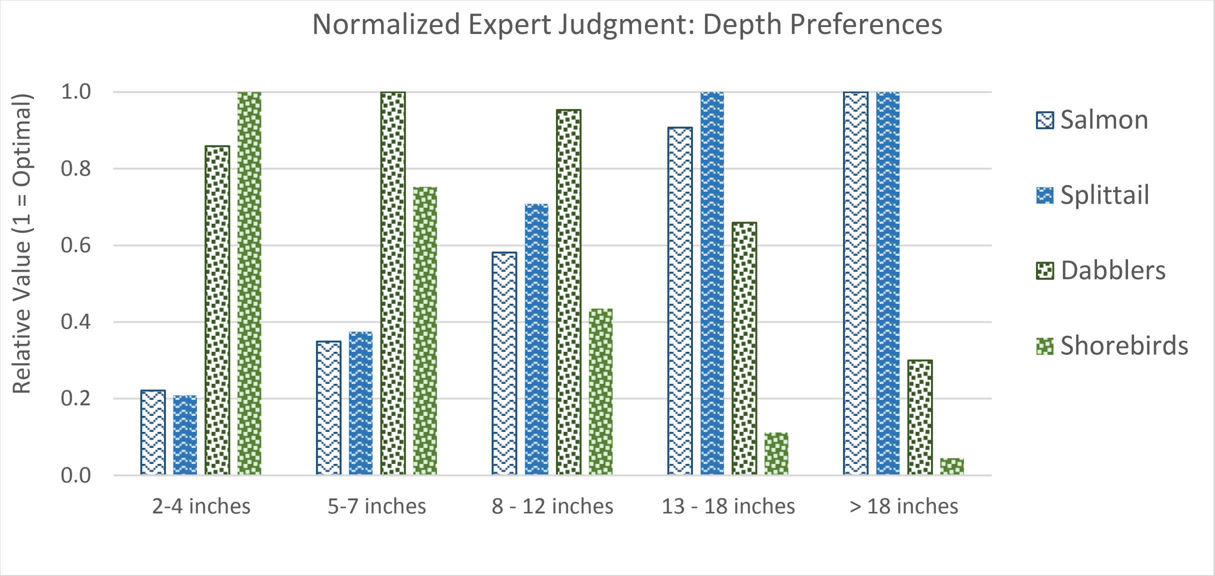


Figure A.14. Normalized expert estimates of the value different depth ranges have for fish and birds. Average responses for each depth range were divided by 4 (the score that indicated optimal depths) to get relative scores ranging from 0 to 1.

How does habitat quality change with time?

Bird and fish species are most dependent on flooded habitats on the Yolo Bypass during varied weeks in the winter and spring. This relates back to the question of managing water depth for targeted habitat – Figure A.12 would suggest that water depths be geared primarily towards dabbling ducks in January and early February, then balanced across all four species late February through March, and finally geared towards shorebirds in April. It is during that period between February and March, when all species highly value and use flooded habitats on the Bypass, that a balanced management approach is likely to be most important. This means ensuring a large habitat mosaic of different land use types and depths for species to choose from.

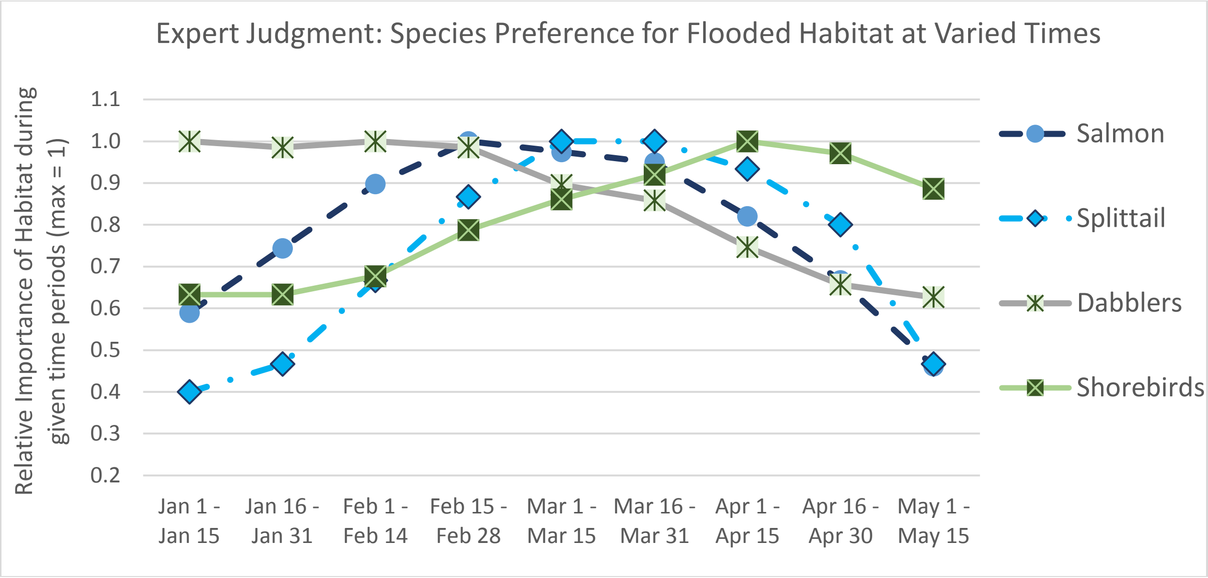


Figure A.15. Normalized expert opinion on the importance of varied weeks for fish and bird habitat availability on the Yolo Bypass. Original responses were either 1(low priority), 2(medium priority) or 3(high priority). Average response for each time period was divided by 3 to get normalized values as reported above.

CONCLUSIONS

These expert interviews and opinion surveys highlighted some important considerations for land and water managers on the Yolo Bypass. It seems possible for managed flooding to serve both bird and fish habitat simultaneously, with strategic placement, timing, and depth management of added flows. This is a somewhat surprising finding – some stakeholders on the Bypass worried that fish and bird habitat may be mutually exclusive, but these results suggest that they are not. This exercise also showed the value of expert opinion in decision-making processes and the development of tools for complex, multi-objective water and land management problems.

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To the many fish and bird biologists and wetland managers willing to spend their time answering questions and furthering understanding of wildlife habitat and preferences within a human-dominated, agricultural floodplain. This work would have been impossible without their expertise.

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(And many others who chose to remain anonymous.)

Appendix B

Soil-Emergent Invertebrate Abundance on Varied Land Uses in the Yolo Bypass, California

Nicholas Corline and Robyn Suddeth

INTRODUCTION

This appendix describes the methods and results of a study of soil-derived invertebrate abundance on varying land uses on the Yolo Bypass. Floodplain habitat in California and on the Yolo Bypass is seasonal and ephemeral in nature, dry during the summer and fall months and inundated intermittently during the winter and spring months. Californian floodplain habitats are similar to those of temporary pools and wetlands and thereby may have similar invertebrate communities. Temporary aquatic habitats contain a mixture of opportunistic (mainly flying insects) and resident (propagule) invertebrates (King, Simovich and Brusca 1996). Most aquatic insects in ephemeral wetlands are eliminated or reduced in numbers during the dry season and must recolonize in the subsequent wet season; however, crustaceans can remain *in situ* with physiological adaptations to survive dry periods, remaining in the soil as desiccation resistant eggs or other dormant forms (Ripley and Simovich 2009). Because these soil-emergent invertebrates are thought by most fish and wildlife biologists to be an important component of habitat quality and food supply for fish and birds on the Yolo Bypass, field studies were conducted in the fall of 2011 to test for variations in soil-derived invertebrate abundance with different land uses. These results are intended to add context to the expert opinion efforts discussed in Appendix A, and to the Habitat Quality objective functions developed for the Yolo Bypass Multi-Objective Model presented in Chapters 2 and 3.

BACKGROUND

Invertebrate densities in ephemeral floodplains are frequently high, making aquatic invertebrates an important food resource for birds and fish within the floodplain (Tronstad, Tronstad and Benke 2005). Tronstad et al. (2005) described three ways in which floodplain waters become colonized by invertebrates: aerial colonization, drift from the main river channel, and local colonization from soil propagules. Flying insects colonize from the air, entering the water as adults or depositing eggs (Tronstad et al. 2005). Drift colonization involves invertebrates suspended in the water column, attached to entrained solids, or crawling along the benthos (Tronstad et al. 2005). In soil colonization invertebrates emerge from propagules (eggs or dormant stages) from within or on the soil surface (Tronstad et al. 2005). Soil emergent aquatic invertebrates often appear after a sufficient inundation, photoperiod, temperature regime, or a combination of all three (Gleason et al. 2003).

Macroinvertebrates in floodplain soil studies vary in density and life history strategies. Not all are adapted to temporary waters, with some being semi-aquatic or terrestrial (Tronstad et al. 2005). These amphibious species utilize newly flooded soils; this is especially true for chironomid midges, other Dipterans, and Collembolans (Tronstad et al. 2005). Chironomid midges are ubiquitous in aquatic habitats and can dominate ephemeral water sources like floodplains and seasonal wetlands (Tronstad et al. 2005, Merritt, Cummins and Berg 2008, Willaims 1998). Secondary productivity is heavily influenced by chironomids as they are able to grow and colonize areas quickly, and can potentially have a large cumulative biomass (Merritt et al. 2008, Berg and Hellenthal 1992). Several chironomid species have adapted to ephemeral aquatic habitats by remaining dormant within the soil during dry periods and emerging during seasonal inundation (Benigno and Sommer 2008, Willaims 1998, Anderson 2007). The endemic chironomid found in the Yolo bypass (*Hydrobaenus saetheri*), has an obligate dormant stage as a second or third instar, ultimately emerging during winter flooding (Anderson 2007). Benigno and Sommer (2007) found that the majority of insects that emerged from rehydrated soil samples from the Yolo Bypass were *H. saetheri,* and hypothesize that *H. saetheri* is the first food resource to appear for rearing fish during flooding.

Insects, however, are not the only invertebrates to emerge from floodplain soils. By far the greatest numbers of soil-derived individuals are microcrustaceans, namely ostracods and copepods. These tiny crustaceans lay desiccation resistant eggs or remain in dormant resting stages within the soil (Gleason et al. 2003, Dahms 1995). Copepod resting stages can be sensitive to environmental extremes, while Ostracod eggs are resistant to many environmental stresses, especially desiccation (Stenert et al. 2010). Ostracod eggs are extremely recalcitrant, and are even able to survive straw burning regimes in rice fields, the digestive tracts of fish, and freezing (Chittapun 2011, Karanovic 2012).

Ostracods are well suited to floodplain and temporary pool habitats in California's Mediterranean climate. In soil rehydration studies ostracod densities range from 5,000 - 20,000 individuals per square meter (Tronstad et al. 2005, Simpson et al. 1994). Ostracods are benthic microcrustaceans, feeding on benthic algae and detritus. The ability to utilize the latter maybe advantageous in winter conditions when pelagic primary productivity is low (Thorp and Covich 2010, Karanovic 2012, Lemke and Benke 2009).

Studies on Brazilian rice fields may foreshadow invertebrate patterns in the Yolo Bypass because of similarities in agricultural practices. Stenert et al (2010) found that recently cultivated rice field soils had the highest number of copepods, while fallow fields had the greatest numbers of ostracods and cladocerans. Copepods were most abundant in soils that had been dry for 20 days, whereas ostracods had greater densities in soils that were dry for one to two years (Stenert et al. 2010). This disparity is most likely due to the environmental parameters of the respective crustacean's dormant stages. Stressors from agriculture can also decrease abundance of microcrustaceans by blocking or initiating emergence (Stenert et al. 2010). Another possible reason for differences between taxa is sedimentation, which can impede microcrustacean emergence by blocking or changing temperature, light, and dissolved oxygen cues (Gleason et al. 2003).

The Yolo bypass is a large, diverse working landscape with many different land use types, all of which could have differing effects on invertebrate densities and assemblages to emerge from the soil during hydration. Some land use practices might stress dormant life stages of macroinvertebrates and microcrustaceans, while others may benefit certain taxa. This study examined the invertebrate soil fauna of several land use types and two flood zones within the Yolo Bypass, and the effect of soil disturbance on invertebrates in rice and fallow field soils. Three questions were addressed: (i) What are the dominant invertebrates to emerge from the soil invertebrate seed bank and are there differences in abundance and diversity between land use types; (ii) Does physical disturbance (disking) affect the soil invertebrate seed bank, and (iii) Is there a difference in soil emergent invertebrates between flood zones?

METHODS

Study Site

The Yolo Bypass encompasses 24,000 hectares of historic Sacramento River floodplain and is currently managed for flood protection, agriculture, and wildlife. Periodic inundation occurs during the winter from high flow events in the Sacramento River or local storm activity (Chapters 1 and 2). The Toe Drain is the largest channel in the floodplain, running almost the entire length of its eastern edge from about a mile below Fremont Weir in the north (where it is sometimes called the Tule Canal), to Liberty Island in the south. Flows in the Toe Drain originate in one of four ways: 1) agricultural runoff, 2) irrigation water pumped in from the Sacramento River, 3) tidal water coming up from Liberty Island, or 4) Sacramento River water flowing over Fremont Weir. Distance from this drain is a proxy for non-managed flood frequency, as most of this type of flooding within the bypass is initiated with overflow out of the channel following an overtopping event at Fremont Weir. However, rice and wild rice fields are flooded for production during the summer, and are occasionally inundated during the winter with water that is pumped or gravity fed through irrigation ditches.

Samples were collected within the Yolo Bypass across 6 primary land use types and at varying distances from the Toe Drain (Figure B.1). Riparian soil samples were taken from areas adjacent to the Toe Drain near each site. Samples were taken both before and after disking in the rice and fallow fields. The fallow site constituted an uncultivated rice field closer to the Toe Drain. Prior to collection rice fields were harvested and dried, but the wild rice field was not completely dry. Similar to the fallow site, a walking wetland constitutes a rice field that is not cultivated for 1 - 4 years, but is in rotation with other rice and fallow fields. In this way, the wetlands change location every few years as rice fields get worked back in. Walking wetlands have a dominance of weeds. The old wetland site had been completed abandoned by agriculture for at least 10 years. It contained a mixture of grasses, weeds, and trees built up on higher ground that is likely only flooded from occasional large winter storms. The grazing site was dominated by tall grasses and weeds, suggesting a low level of cattle grazing, and is only inundated during winter storm events.

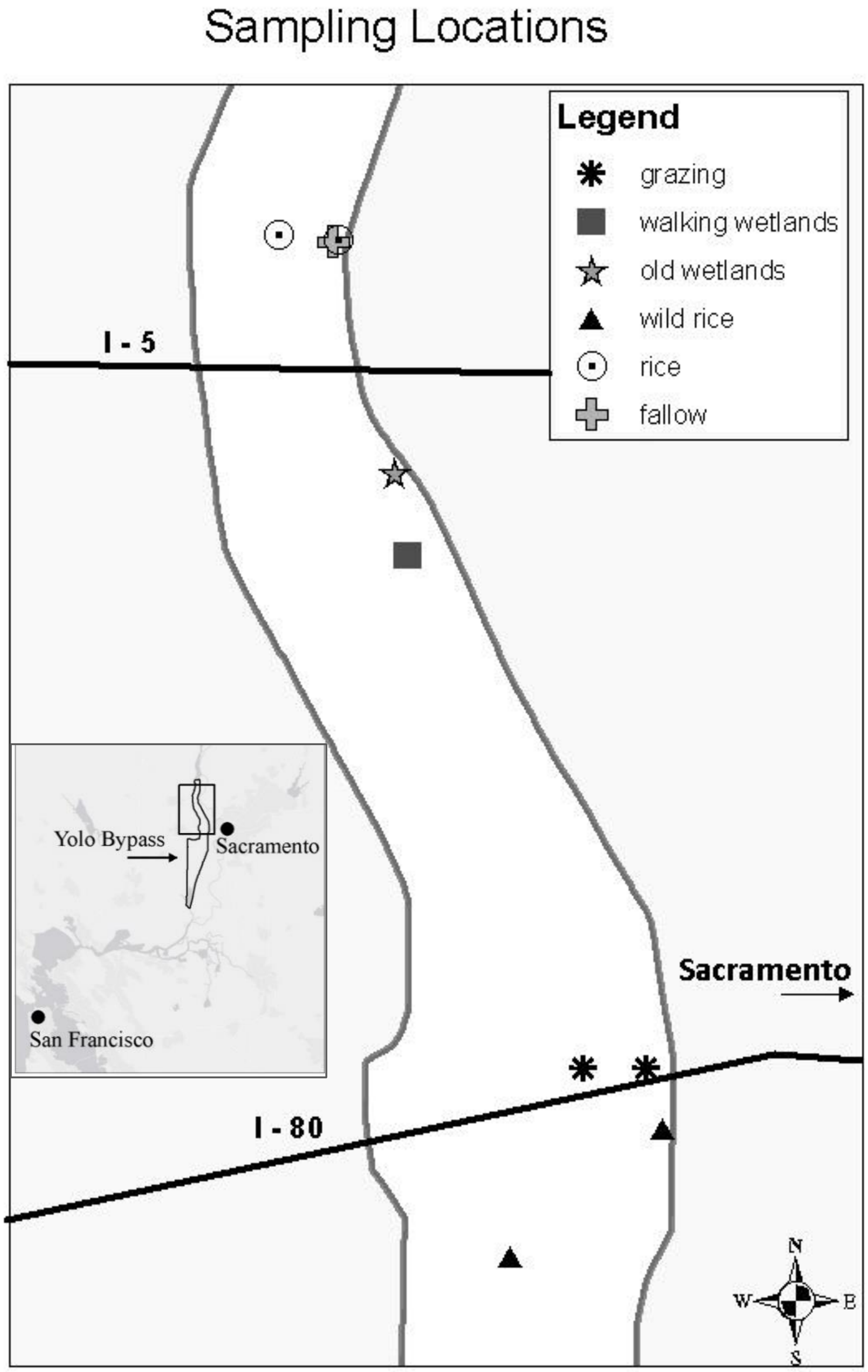

Figure B.1. Sampling Locations for soil-derived invertebrates in the Yolo Bypass

Sampling

Soil samples were collected from November 9th to 16th, 2011. Six soil samples were removed from random points within each site. A 28x40.6x15.2 cm metal form was used to cut and remove the soil; samples were placed in 28x40.6x15.2 cm plastic containers and transported to the Center for Aquatic Biology and Aquaculture (CABA) on the University of California, Davis campus. Containers were fitted with mesh emergence trap lids to capture adult aquatic insects that emerged from the water. Soil samples were re-hydrated to a depth of 16 cm with well water at CABA's indoor facility on November 23rd. The water column within each container was swept twice a week for two weeks with a brine shrimp net for one minute to collect invertebrates. Emergence traps were also checked twice a week for two weeks. Adult emergent invertebrates were killed with acetone. Collected invertebrates were preserved in 70% ethyl alcohol.

Sorting/Identification

Due to the small number of invertebrates per collection, samples were not sub-sampled. Inverterbrates were enumerated and identified with the aid of a dissecting microscope at 4 times magnification. Invertebrates were identified to the lowest taxonomic level possible using keys from *Ecology and Classification of North American Freshwater Invertebrates (3rd edition)* by Thorp and Covich, *Recent Ostracoda of the World* by Ivana Karanovic, and *An Introduction to the Aquatic Insects of North America (4th edition)* by Merrit and Cummins. Copepods, however, were only identified to order. Terrestrial invertebrates were not included in final counts. Final counts were used in diversity and statistical calculations. Simpson index of diversity ($D=1-\Sigma(n/N)^2$) takes into account species richness and evenness and was calculated for each land use type.

Statistical Analyses: All statistical analyses were performed with the R Commander software package. The data were separated into six species categories: chironomids, collembola, copepods, ostracods, other, and total. A linear model was created for each of these categories, with factors Land Use Type and Toe Drain Distance. The data were also tested for sensitivity to a North South gradient. This provided 6 sets of 68 residuals (one set per species category) that were used in Shapiro Wilk normality tests. The data were assumed normally distributed if the test statistic was large ($W > 0.94$) or the results insignificant ($p > .05$). A log transform of the data was required to dull the effect of some large outliers. For chironomids, Winzorization was also required. These were considered viable transformations because outliers followed general trends in the data, and the analysis focuses on relative abundances rather than exact differences between treatments. After the necessary transforms and normality tests were conducted, MANOVA was used to determine which factors (if any) likely contributed to variance between treatments. Results were considered significant if $P(F) < 0.05$. The MANOVA was run with and without an interaction term included (between habitat and toe drain distance). While the test statistic and significance levels changed slightly with these different models, general results did not.

RESULTS

For most species, land use type was the only significant factor affecting mean abundance, with p ranging from 6.27E-06 to 0.002. (Collembola is the exception; abundance was driven by land use and toe drain distance, and also with location on a north-south gradient). Figure B.2 shows total abundance varying across land use types. Rice, fallow land, walking wetlands, and grazing land all produced a mean of more than 200 invertebrates per sample (11,574.5 individuals / cubic meter). This was a much larger number of invertebrates than found in wild rice, old wetland, or either of the disked fields.

Ostracods were the most abundant species, largely driving totals across land use types. The box plots in Figure B.3 display individual species mean abundances across land use types on a consistent scale, highlighting this dominance.

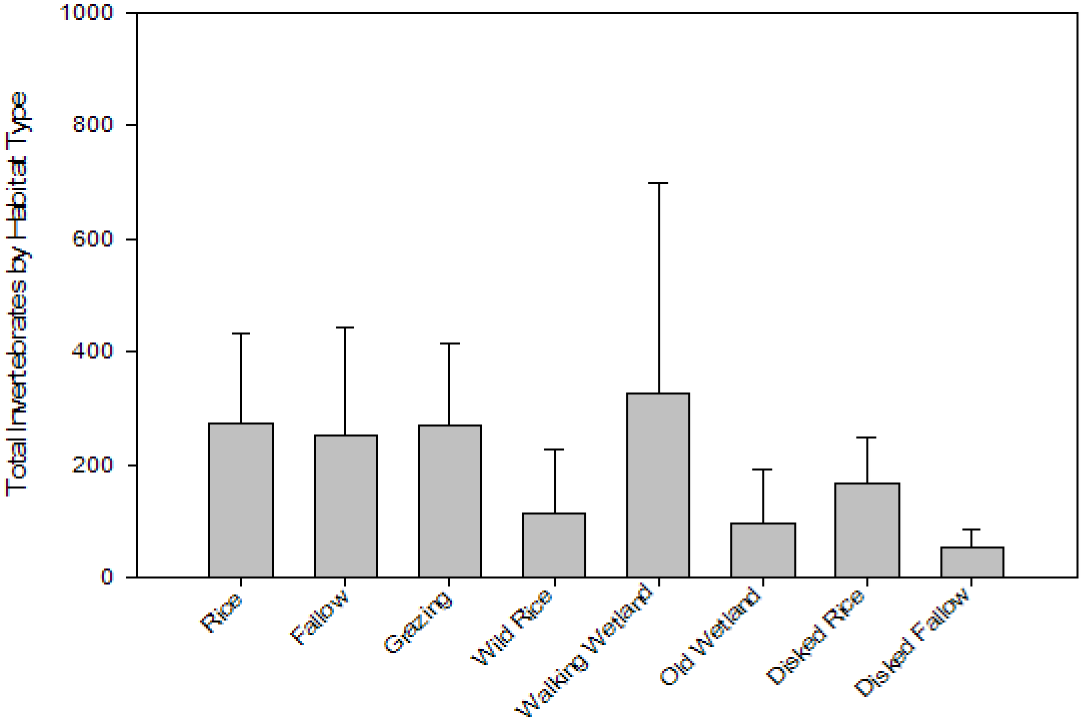

Figure B.2. Mean Invertebrate Abundance by Land Use Type

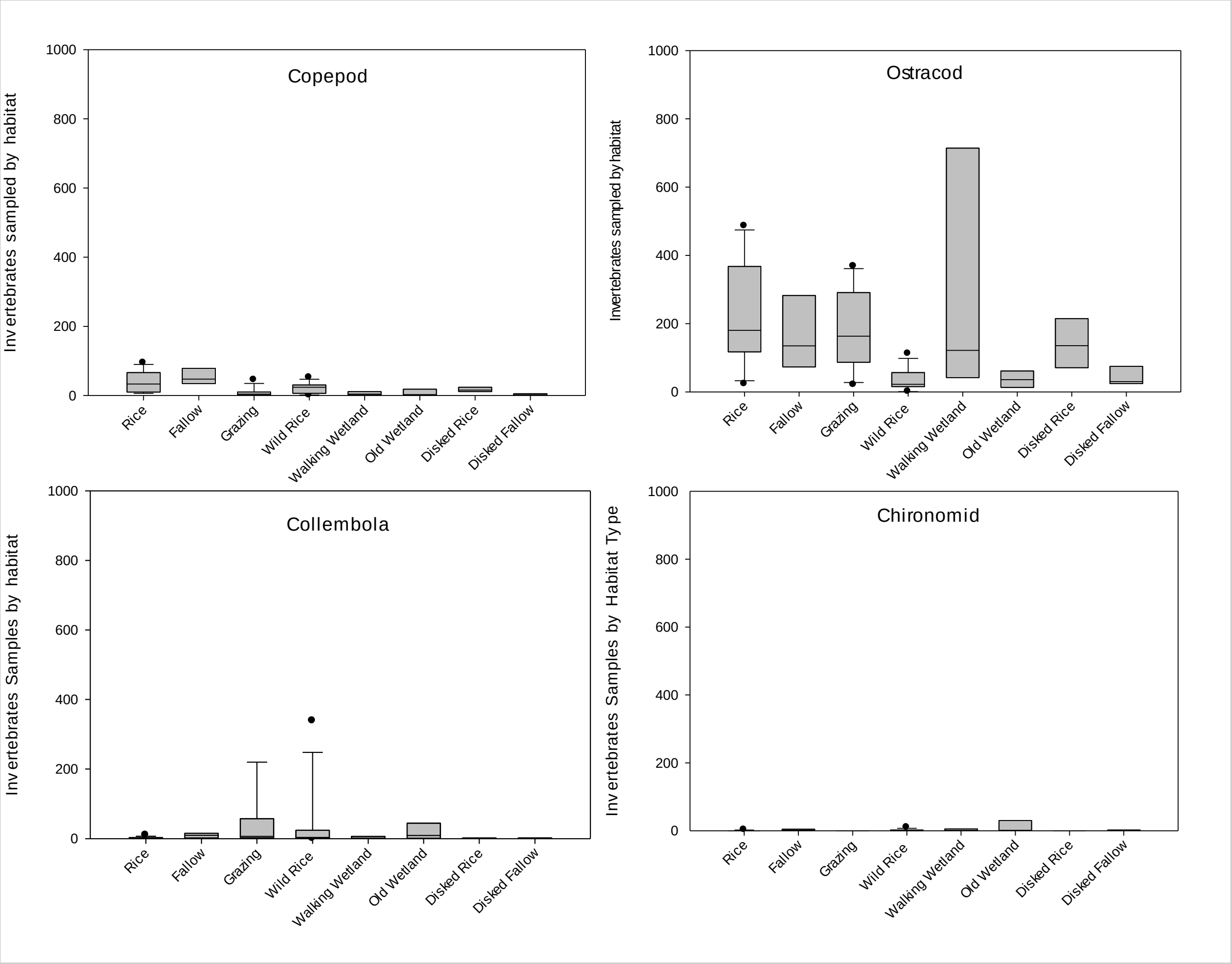

Figure B.3. Box plots showing species mean, upper and lower quantiles, and outlier abundances per land use type.

Copepods were most abundant in fallow and rice fields, with an average of above 25 individuals per sample (1400 / m^3). Ostracod mean abundance was highest in rice and grazing lands, both with an average of over 150 individuals per sample (5700 / m^3). The highest abundance of chironomids occurred in old wetlands, with an average of 17.3 per sample (1016 / m^3), and finally collembola emerged with greater frequency from old wetlands and fallow fields. Figures B.4a through B.4d display boxplots for each species on varied scales to more clearly show how abundance differs across land use types for each species category.

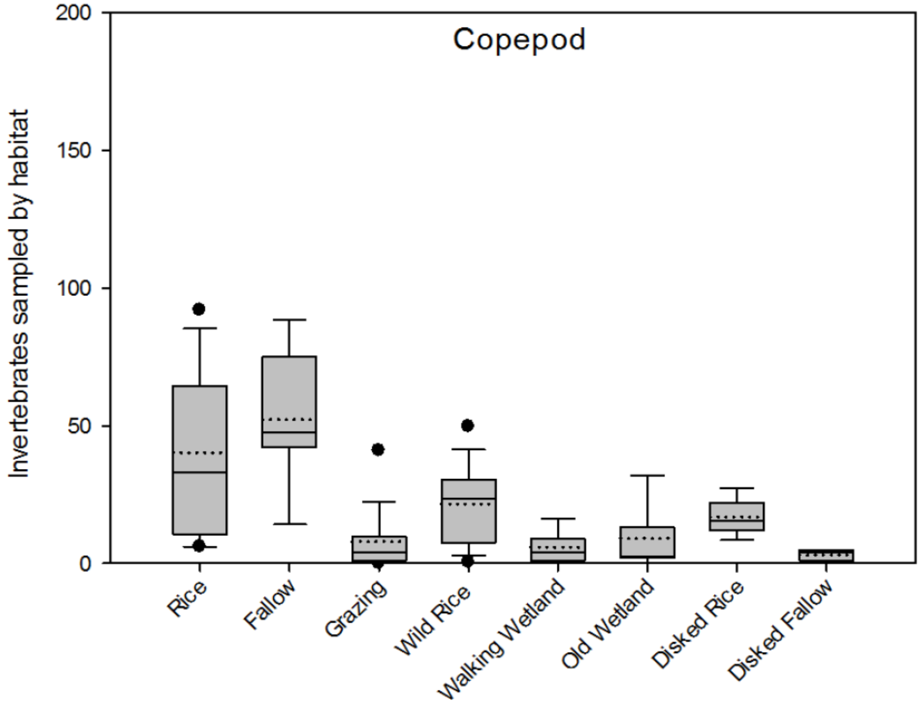

Figure B.4a. Median (solid line) and mean (dotted line) abundace of copepods per land use type, with upper quantiles, lower quantiles, and outliers

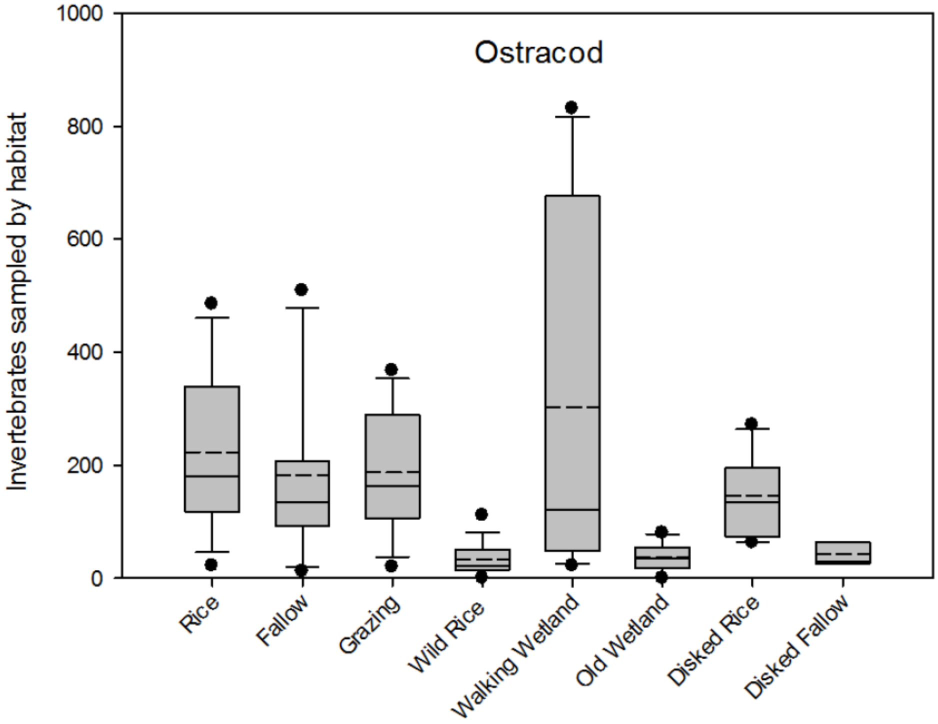

Figure 4b. Median (solid line) and mean (dotted line) abundace of ostracods per land use type, with upper quantiles, lower quantiles, and outliers

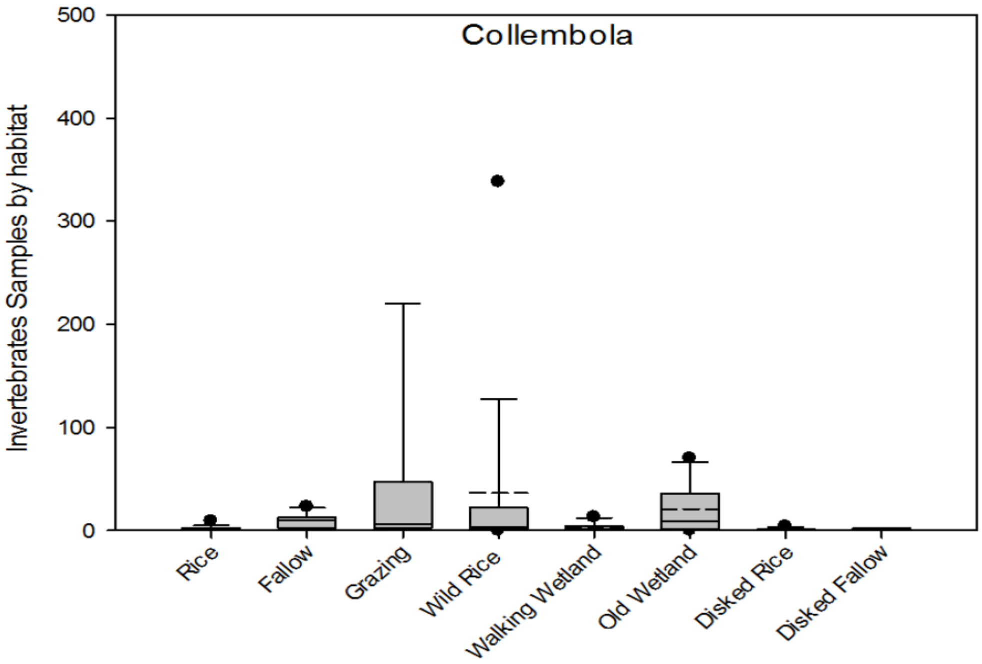

Figure B.4c. Mean abundace of ostracods per land use type, with upper quantiles, lower quantiles, and outliers

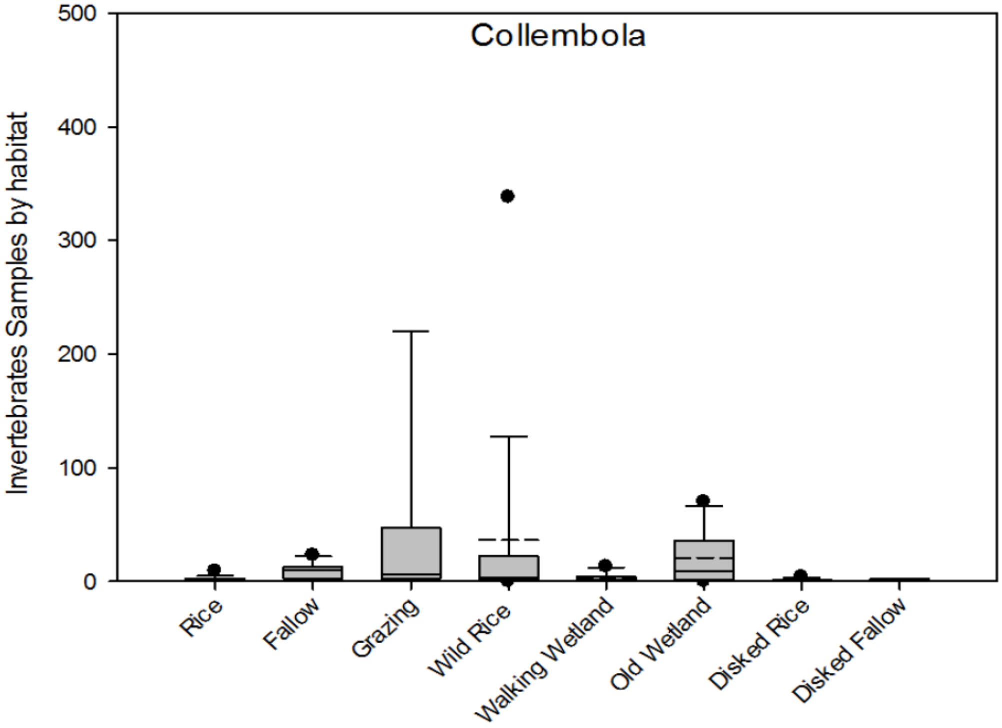

Figure B.4d. Mean abundace of chironomids per land use type, with upper quantiles, lower quantiles, and outliers

DISCUSSION

Floodplains are essential and increasingly rare elements in fluvial systems. The Yolo Bypass is a remnant of the historic Sacramento River floodplain, and is currently managed for a variety of uses including agriculture. While lacking the heterogeneous geomorphic forms and vegetation of a natural floodplain, the bypass still has the means to be highly productive habitat for native fish and birds in California's Central Valley. Aquatic invertebrates provide a crucial link between primary production and higher trophic levels. This study focused on soil emergent invertebrates on the Yolo Bypass, with results suggesting that land use can be a significant factor in overall abundance, and that ostracods are the dominant soil-emergent species across almost the entire floodplain. The following sections discuss these findings and suggest possible causes and implications.

Abundance and Diversity in Varied Land Uses

Land use, whether due to soil treatment, flooding practices, or some other factors, has a strong effect on invertebrate abundance. Agricultural soils were equally or even more productive of soil-emergent invertebrates than non-cultivated soils (i.e. old wetland). Greater invertebrate abundance in rice fields is likely attributed to two farming methods and treatments: fertilization and summer irrigation. Fertilization increases primary production, the base of the food web, allowing for a larger invertebrate populations persist and contribute to the soil seed bank. Simpson et al. (1994), for example, found that ostracods in experimental rice fields responded positively to nitrogen fertilization, exhibiting accelerated population growth.

Rice and fallow field soils can also gain additional cysts and eggs during the summer hydroperiod as the fields likely receive invertebrates in the water applied for inundation.

Fertilization and summer hydroperiod does not explain high invertebrate abundance in un-irrigated pasture. High abundance in these soils is more likely due to ponding, grass residue, and nutrients from cow manure. Unlike the rice fields, the grazing area is ungraded and contains cattle trails, ditches, and depressions. Some of these depressions form ponds that can remain hydrated into late summer, allowing for increased ostracod egg production. The ponds, when dry, can act as sources of ostracod eggs that are dispersed to the surrounding area by wind (Vanschoenwinkel et al. 2009). Tall grasses dominate the grazing area contributing to a significant layer of grass residue on the soil surface. A deep layer of detritus provides increased surface area for the deposition of ostracod eggs (Aguilar-Alberola and Mesquita-Joanes 2011). Ostracods may further benefit from amplified primary production, as cow manure deposited in pasture can raise nutrient levels in adjacent aquatic systems (Belsky, Matzke and Uselman 1999).

Although agricultural lands had overall higher abundances of invertebrates, disking in rice and fallow fields negatively affected emergence numbers possibly due to disturbance to resting stages and/or sedimentation. Disking may physically break the cases of midges or cysts of copepods. Alternatively, ostracod eggs and other microcrustacean propagules may have been buried upon hydration when disked soil aggregates lost their structure and dissolved, which would have an effect similar to sedimentation. Sedimentation, as shown by Gleason et al (2003), inhibits the emergence of soil invertebrates by blocking or altering emergence cues such as photoperiod, temperature, DO or soil moisture. Disking decreased both abundance and diversity.

Implications for Fish and Bird Use of Flooded Fields and Wetlands on the Yolo Bypass

The results herein largely mirror what fish and wildlife biologists generally believe about the value of many agricultural land use types as habitat for fish and birds on the Yolo Bypass. When asked to evaluate different land uses for fish and bird habitat quality based on soil-emergent food supply and structure, most experts surveyed (Appendix B) thought that fallow fields, grazing lands, rice and wild rice would be at least moderately productive habitat for fish and birds (with rice more important for birds because of nutritional value in its seed bank). This study showed that, indeed, all of those agricultural land use types produce a high abundance of soil-derived invertebrates when hydrated, with the exception of lands that have been disked. This also agrees with comments made by many survey respondents who indicated that land management and treatment is as important as land use type; when agricultural lands are managed with habitat in mind, significant improvements can be made for fish and bird habitat without large impacts to overall farming operations. This may be why crops like tomato (which are usually disked following harvest) are thought to provide low-quality habitat for fish and birds (Appendix A).

LIMITATIONS AND NEXT STEPS

Because they were flooded in the fall months when this study was conducted, it was impossible to extend sample sites to seasonal and permanent wetland habitats on the Bypass.

The only non-agricultural land uses surveyed are therefore currently only wet when Fremont Weir is overtopping – invertebrate abundance on those lands might increase with more frequent inundation. This also makes it impossible to draw comparisons between invertebrate abundance on agricultural versus managed seasonal wetland land uses on the Bypass. Further research might find a way to compare hydrated agricultural lands with flooded wetlands. Finally, this study was only conducted over one year, and could be affected by weather, crop rotation, or other conditions that change year to year. Further research would benefit from a longer study period that covers several years and seasons.

CONCLUSIONS

Within the Yolo Bypass agricultural lands produced high numbers of aquatic soil emergent invertebrates, as much if not more than non-agricultural land uses. Farming methods in rice fields and heterogeneity and cow manure within the pasture land likely influence invertebrate abundance. Disking in rice and fallow fields, however, decreased abundance by interfering with emergence cues and disturbing resting stages. While previous studies found a predominance of chironomids on the Yolo Bypass, more recent studies show ostracods making up about 13% of juvenile salmonid diet, while the remaining diet consists mostly of drift invertebrates (C. Jeffries, pers. comm.). This supports the conclusion that Ostracods are a dominant soil emergent species on the Yolo Bypass, and further that they provide dietary value for endangered fish species. These findings support a theory that has already been broadly suggested for the Yolo Bypass – that agricultural land use, if managed correctly, can provide valuable habitat and food resources for native fish and bird species on an engineered floodplain.

REFERENCES

Aguilar-Alberola, J. A. & F. Mesquita-Joanes (2011) Population dynamics and tolerance to desiccation in a crustacean ostracod adapted to life in small ephemeral water bodies. *Limnologica,* 41**,** 348-355.

Ahearn, D. S., J. H. Viers, J. F. Mount & R. A. Dahlgren (2006) Priming the productivity pump: flood pulse driven trends in suspended algal biomass distribution across a restored floodplain. *Freshwater Biology,* 51**,** 1417-1433.

Ahmadi-Nedushan, B., A. St-Hilaire, M. Berube, E. Robichaud, N. Thiemonge & B. Bobee (2006) A review of statistical methods for the evaluation of aquatic habitat suitability for instream flow assessment. *River Research and Applications,* 22**,** 503-523.

Anderson, T. 2007. Contributions to the Systematic and Ecology of Aquatic Diptera: A tribute to Ole Saether. Columbus, OH: The Caddis Press.

Bellmore, J. R., C. V. Baxter, K. Martens & P. J. Connolly (2013) The floodplain food web mosaic: a study of its importance to salmon and steelhead with implications for their recovery. *Ecological Applications,* 23**,** 189-207.

Belsky, A. J., A. Matzke & S. Uselman (1999) Survey of livestock influences on stream and riparian ecosystems in the western United States. *Journal of Soil and Water Conservation,* 54**,** 419-431.

Benigno, G. M. & T. R. Sommer (2008) Just add water: sources of chironomid drift in a large river floodplain. *Hydrobiologia,* 600**,** 297-305.

Berg, M. B. & R. A. Hellenthal (1992) The Role of Chironomidae in the Energy Flow of a Lotic Ecosytem. *Netherlands Journal of Aquatic Ecology,* 26**,** 471-476.

California DFG, Yolo Basin Foundation & EDAW. 2008. Yolo Bypass Wildlife Area Land Management Plan. ed. C. D. o. F. a. Game. Sacramento, CA.

CBEC. 2010. BDCP Effects Analysis: 2D Hydrodynamic Modeling of the Fremont Weir Diversion Structure. Sacramento, CA: Prepared for the SAIC and the California Department of Water Resources.

Chittapun, S. (2011) Fire and recovery of resting egg bank: an experimental study in paddy fields in Pathum Thani province, Thailand. *Hydrobiologia,* 662**,** 163-170.

Dahms, H. U. (1995) Dormancy in the Copepoda - an Overview. *Hydrobiologia,* 306**,** 199-211.

de Neufville, R. 1990. *Applied Systems Analysis*. New York: McGraw-Hill, Inc.

Duffy, W. G. & N. K. Sharon (2011) Wetland ecosystem services in California's Central Valley and implications for the Wetland Reserve Program. *Ecological Applications,* 21**,** S18-S30.

Gleason, R. A., N. H. Euliss, D. E. Hubbard & W. G. Duffy (2003) Effects of sediment load on emergence of aquatic invertebrates and plants from wetland soil egg and seed banks. *Wetlands,* 23**,** 26-34.

Henning, J. A., R. E. Gresswell & I. A. Fleming (2006) Juvenile salmonid use of freshwater emergent wetlands in the floodplain and its implications for conservation management. *North American Journal of Fisheries Management,* 26**,** 367-376.

Jeffres, C. A., J. J. Opperman & P. B. Moyle (2008) Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. *Environmental Biology of Fishes,* 83**,** 449-458.

Junk, W., P. Bayley & R. Sparks (1989) The flood pulse concept in river-floodplain systems. *Can J Fish Aquat Sci,* Special Publication**,** 110 - 127.

Junk, W. J. 1996. Ecology of floodplains - a challenge for tropical limnology. In *Perspectives in Tropical Limnology,* ed. F. S. K. T. Boland, 255-265. Amsterdam, The Netherlands: SPB Academic Publishing.

Karanovic, I. 2012. *Recent Freshwater Ostracods of the World; Crustacea, Ostracoda, Podocopida*. New York, New York: Springer.

Katz, J., C. Jeffres, L. Conrad, T. Sommer, N. Corline, J. Martinez, S. Brumbaugh, L. Takata, N. Ikemiyagi, J. Kiernan & P. Moyle. 2013. Experimental Agricultural Floodplain Habitat Investigation at Knaggs Ranch on Yolo Bypass, 2012-2013. US Bureau of Reclamation.

King, J. L., M. A. Simovich & R. C. Brusca (1996) Species richness, endemism and ecology of crustacean assemblages in northern California vernal pools. *Hydrobiologia,* 328**,** 85-116.

Lehman, P. W., T. Sommer & L. Rivard (2008) The influence of floodplain habitat on the quantity and quality of riverine phytoplankton carbon produced during the flood season in San Francisco Estuary. *Aquatic Ecology,* 42**,** 363-378.

Lemke, A. M. & A. C. Benke (2009) Spatial and temporal patterns of microcrustacean assemblage structure and secondary production in a wetland ecosystem. *Freshwater Biology,* 54**,** 1406-1426.

Merritt, R. W., K. W. Cummins & M. B. Berg. 2008. An Introduction to the AQUATIC INSECTS of NORTH AMERICA. Dubuque, Iowa: Kendall/Hunt Publishing Company

Opperman, J. J., G. E. Galloway, J. Fargione, J. F. Mount, B. D. Richter & S. Secchi (2009) Sustainable Floodplains Through Large-Scale Reconnection to Rivers. *Science,* 326**,** 1487-1488.

Opperman, J. J., R. Luster, B. A. McKenney, M. Roberts & A. W. Meadows (2010) Ecologically Functional Floodplains: Connectivity, Flow Regime, and Scale. *Journal of the American Water Resources Association,* 46**,** 211-226.

Ripley, B. J. & M. A. Simovich (2009) Species richness on islands in time: variation in ephemeral pond crustacean communities in relation to habitat duration and size. *Hydrobiologia,* 617**,** 181-196.

Roloff, G. J. & B. J. Kernohan (1999) Evaluating reliability of habitat suitability index models. *Wildlife Society Bulletin,* 27**,** 973-985.

Schemel, L. E., T. R. Sommer, A. B. Muller-Solger & W. C. Harrell (2004) Hydrologic variability, water chemistry, and phytoplankton biomass in a large floodplain of the Sacramento River, CA, USA. *Hydrobiologia,* 513**,** 129-139.

Simpson, I. C., P. A. Roger, R. Oficial & I. F. Grant (1994) Effects of Nitrogen-Fertilizer and Pesticide Management on Floodwater Ecology in a Wetland Ricefield .3. Dynamics of Benthic Mollusks. *Biology and Fertility of Soils,* 18**,** 219-227.

Sommer, T., B. Harrell, M. Nobriga, R. Brown, P. Moyle, W. Kimmerer & L. Schemel (2001) California's Yollo Bypass: Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries,* 26**,** 6-16.

Stenert, C., R. C. Bacca, A. C. Avila, L. Maltchik & O. Rocha (2010) Do Hydrologic Regimes Used in Rice Fields Compromise the Viability of Resting Stages of Aquatic Invertebrates? *Wetlands,* 30**,** 989-996.

Thorp, J. H. & A. P. Covich. 2010. Ecology and Classification of North American Freshwater Invertebrates. San Diego, CA: Academic Press.

Thorpe, J. E. (2008) Influence of restricted access to floodplains on life-history patterns in fish: implications for conservation. *Ecohydrology & Hydrobiology,* 8**,** 159-167.

Tockner, K., M. Pusch, D. Borchardt & M. S. Lorang (2010) Multiple stressors in coupled river–floodplain ecosystems. *Freshwater Biology,* 55**,** 135-151.

Tockner, K. & J. A. Stanford (2002) Riverine flood plains: present state and future trends. *Environmental Conservation,* 29**,** 308-330.

Tronstad, L. M., B. P. Tronstad & A. C. Benke (2005) Invertebrate seedbanks: rehydration of soil from an unregulated river floodplain in the south-eastern US. *Freshwater Biology,* 50**,** 646-655.

U.S.D.O.I. 2013. Chapter 3: Conservation Strategy. ed. U. S. B. o. R. U.S. Department of the Interior, California Natural Resources Agency, California Department of Water Resources. Sacramento, CA.

Vanschoenwinkel, B., S. Gielen, M. Seaman & L. Brendonck (2009) Wind mediated dispersal of freshwater invertebrates in a rock pool metacommunity: differences in dispersal capacities and modes. *Hydrobiologia,* 635**,** 363-372.

Ward, J. V., K. Tockner & F. Schiemer (1999) Biodiversity of floodplain river ecosystems: Ecotones and connectivity. *Regulated Rivers-Research & Management,* 15**,** 125-139.

Willaims, D. D. (1998) The role of dormancy in the evolution and structure of temporary water invertebrate communities. *Arch. Hydrobiol. Spec. Issues Advanc. Limnol. ,* 52**,** 109-124.

Williams, P. B., E. Andrews, J. J. Opperman, S. Bozkurt & P. B. Moyle (2009) Quantifying activated floodplains on a lowland regulated river: its application to floodplain restoration in the Sacramento Valley. *San Francisco Estuary and Watershed Science,* 7.