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RESEARCH

Multi-Purpose Optimization for Reconciliation Ecology on an Engineered Floodplain: Yolo Bypass, California

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ABSTRACT

Floodplains in California and elsewhere are productive natural habitats with high levels of biodiversity, yet today they are often permanently disconnected from rivers by urban or agricultural development and flood management structures. This disconnection poses a threat to many native fish, bird and other species that evolved to take advantage of seasonal floodplain inundation. The traditional restoration approach to this problem is to recreate historical floodplain by restoring natural hydrologic and successional processes. However levees, dams, and development have made this largely impossible in much of the developed world. Reconciliation ecology recognizes this limitation, and encourages instead the re-engineering of human dominated landscapes to allow for coexistence of native species and human uses. Flood control bypasses are particularly promising places to reconcile historical fish and bird uses of floodplain habitats with human uses. However, the reconciliation approach requires nuanced management of a complex system. Using the Yolo Basin flood bypass in California's Central Valley as an example, this study develops formal multi-objective optimization to help planners identify 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 offer an explicit accounting of relationships and trade-offs between different objectives. This is especially useful in reconciliation planning, where many uses and variables interact on a landscape, and deliberate re-engineering requires consideration of many decisions simultaneously. Initial results suggest that modest land-use changes and inundation management strategies can significantly improve seasonal bird and fish habitat quality at little cost to farmers or other human land uses. The model applications 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.

KEY WORDS

flood management, reconciliation, multi-objective optimization, Yolo Bypass, systems planning

INTRODUCTION

Floodplains are some of the world's most biodiverse ecosystems, and among the fastest disappearing (Bayley 1995; Opperman et al. 2009; Sparks 1995; Tockner and Stanford 2002). Before reclamation, the Sacramento River in California flooded almost yearly, supporting riparian forests and vast permanent and seasonal wetlands. Today, over 90% of those wetlands are gone, disconnected from rivers by levees, and replaced by urban or agricultural development (Kelley 1989). This has eliminated most seasonal habitat for native birds, fish, and other species that evolved in response to the floodplains' winter and spring inundation. However, some floodplain remains partially connected in the form of engineered flood bypasses. These bypasses are central to the Sacramento Valley flood protection system—they strategically divert much of the floodwater onto a portion of the historic floodplain, taking pressure off the levee system and greatly increasing the system's capacity to carry large floods without inundating urban areas.

While typically located on the historical floodplain, engineered flood bypasses differ greatly from their historical counterparts—they are often graded for agricultural drainage and to reduce roughness during floods, are connected to the river in only one or two locations via concrete weirs, and are not inundated with the same frequency, duration, timing, or volume as historically. This more moderated connection to the river means that bypasses lack the topographic, vegetative, and hydrologic heterogeneity important for floodplain ecosystems. Despite this shortcoming, they are the largest expanse of connected floodplain still available in the Sacramento watershed, and still provide important habitat for fish, bird, and other species within the valley (USDOI 2013).

Flood bypasses are therefore excellent case studies 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 to also provide habitat and support for desired (usually native) species (Rosenzweig 2003).

Re-engineering a landscape for multiple human and ecological purposes can be a very complicated task. This paper presents a computer model developed to help with this task by providing a means to organize and integrate large amounts of data, explicitly define objectives, constraints, and possible management decisions, and describe the relationships among system components, decisions, and objectives. The model was applied to the lowest bypass on the Sacramento River, the Yolo Bypass, as a case study for applying multi-objective optimization to reconciliation of an engineered floodplain with ecosystem objectives. Results suggest that such formal tools can describe important aspects of floodplain management holistically and consistently, and can help guide reconciliation so ecological goals are met at less significant cost to human uses.

THE YOLO BYPASS

The Yolo Bypass (bypass), when flooded, serves as the transition between the Sacramento River watershed and the tidal sloughs of the Sacramento–San Joaquin Delta (Figure 1). The main flood inflow to the bypass is its upstream Fremont weir, which begins overtopping when Sacramento River stage exceeds 33.5 ft. 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; however, they sometimes cause localized flooding in other years (CDFG et al. 2008). The bypass' flood capacity is up to four times the flow of the main stem Sacramento River, making it the central component in the area's urban flood management system.

The Yolo Bypass is also especially important as rearing habitat for Chinook Salmon, and as both spawning and rearing habitat for Sacramento Splittail, with higher productivity and growth rates than in the mainstem river (Feyrer et al. 2006; 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 still more productive

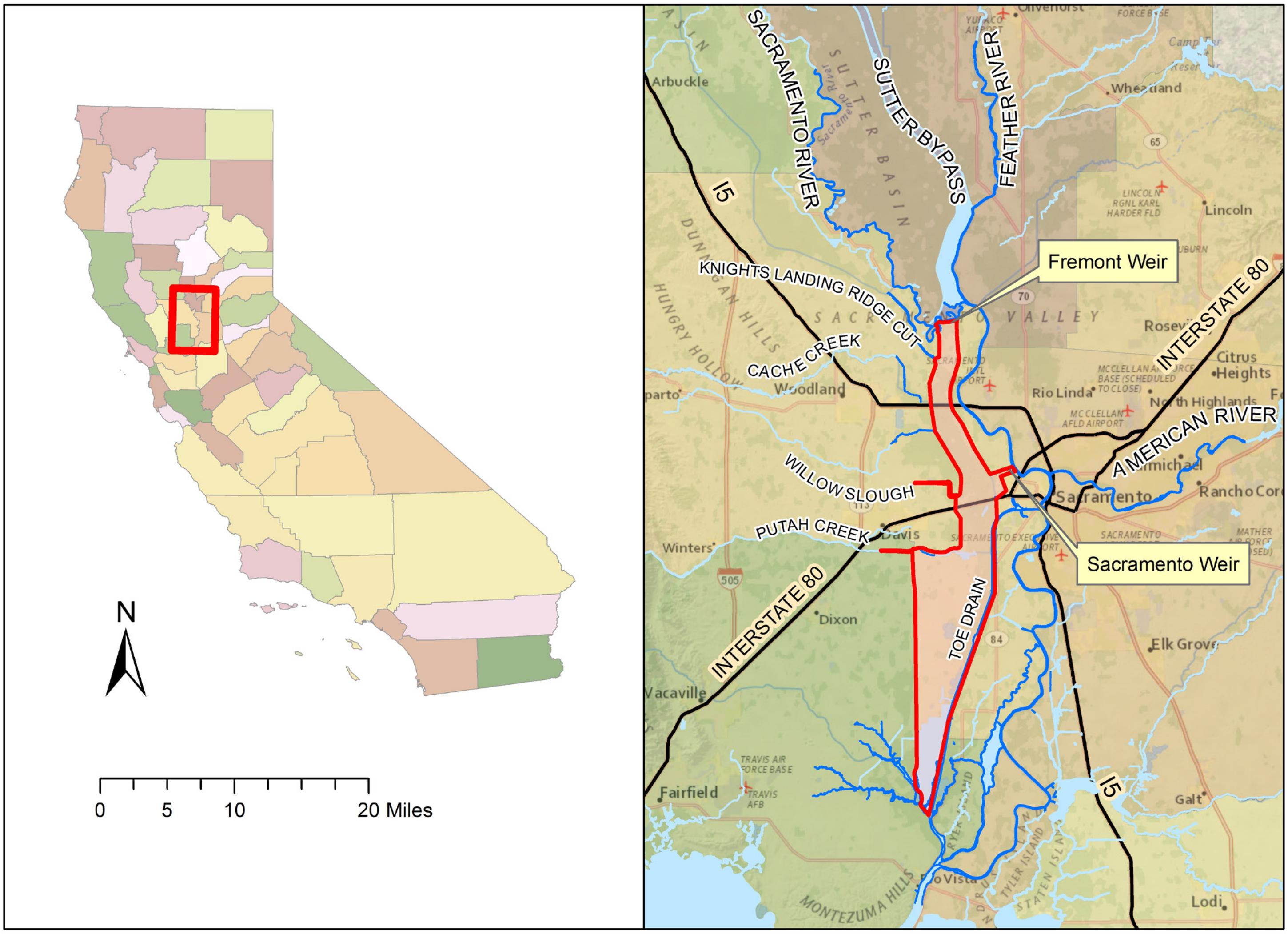

Figure 1 The Yolo Bypass (outlined in red) and major inflows

and accessible to native fish (Williams et al. 2009; USDOI 2013). Because of this and the bypass' size, the California's Bay Delta Conservation Plan (BDCP) and others hail the bypass as the best opportunity to enhance seasonally inundated floodplain for native fish species in the Central Valley (USDOI 2013). The BDCP plan proposed building a gated notch in the Fremont weir to introduce and manage additional flows. Once a notch is constructed, frequency and duration of flooding is expected to especially increase in late February through early April (Table 1).

However, the bypass is also home to a significant agricultural economy and incorporates managed wetlands that serve ducks, geese, and shorebirds (many of which migrate along the Pacific Flyway), favored by recreational hunters and bird watchers (Jones & Stokes, Inc. 2001; Howitt et al. 2013; CDFG et al. 2008). Though the BDCP does provide some detail on the volume and timing of added flows to maximize potential use by targeted fish species, it does not specify more nuanced management of flows to achieve balance amongst the system's other farming and bird uses (Salcido 2012). The challenge is to find a way to manage land and added flows on the bypass in a way that reconciles these human and ecosystem purposes. This type of reconciliation planning is especially important for places like the Sacramento watershed, where few opportunities remain for pure restoration of historical habitats,

Table 1 Summary of the BDCP's list of potential operations for a gated notch in the Fremont Weir

	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 with gated notch in Fremont 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[a]	Up to 6,000[b]
Targeted flood extent (acres)	17,000	17,000	7,000–10,000	7,000–10,000	7,000–10,000
Proposed duration (days)	30–45+	30–45+	30	30	30
Targeted fish species for floodplain habitat (does not include passage)	Winter-run and spring-run Chinook Salmon and Sacramento Splittail	Fall-run, winter-run, and spring-run Chinook Salmon and Sacramento Splittail	Fall-run, spring-run, and Butte Creek spring-run Chinook Salmon and Steelhead	---	Late fall-run Chinook salmon and Steelhead

Source: BDCP Chapter 3, Tables 3.4.2-1 and 3.4.2-2 (USDOI 2013)
a. Only in years with natural overflow (currently 22% of years).
b. Only in years with natural overflow.

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 birds, it offers many ways to re-engineer the system for multi-objective management that includes new fish habitat. Countless existing gates, canals, and other control structures allow water to move strategically and be retained 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; CDFG 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 will make fish and bird habitat mutually exclusive.

Though the system's complexity is advantageous in allowing for nuanced management of land and water, it also presents a challenge in that many intricate combinations of potential decisions exist to be explored and discussed. 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 system model to more precisely define the bypass's most important management objectives and decisions, quantify trade-offs, and suggest promising land and management changes. The model focuses mostly on managed flooding in the February through April period, when the highest number of water bird and fish species depend on at least some flooded habitat. Results can provide decision-makers with a better understanding of how to best leverage various bypass characteristics for birds, fish, farmers, and recreational users.

METHODS

A Introduction to Multi-Objective Optimization

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

Unlike cost-benefit 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 various compromises among conflicting 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. Solutions are “non-inferior” if no other solution exists that can improve one objective without decreasing performance for any other objective (Cohon 1978). Another way to look at the set of non-inferior solutions is as a representation of the most efficient trade-offs among objectives (Woodward et al. 2013).

Formal mathematical models in multi-objective analysis further help decision-makers by providing explicit descriptions of important aspects of the system (objectives, constraints, manageable variables, and relationships between those variables and the system’s objectives) and by providing a record of all data and assumptions used (Loucks et al. 1981; Cohon 1978). This is especially true when the mathematical model is built within widely-accessible software.

The following sections introduce a MS Excel spreadsheet model to evaluate alternative flow management on the Yolo Bypass. The development of this model illustrates some lessons about how various objectives on the Yolo Bypass relate to one another and to potential management decisions. Finally, the model is tested with 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 already been available in those years from a gated notch in the Fremont Weir. This application shows some insights into the trade-offs among fish, birds, and economic returns on the bypass, and the value that extra water could bring.

Model Formulation

There are three main objectives for land and water management on the Yolo Bypass in the late winter and early spring: agricultural profit (or net revenues), fish habitat, and bird habitat. These are all constrained, in turn, by the requirement that the bypass continue to function well as a flood-conveyance structure during large flow events on the Sacramento River, and by other conditions of climate, soil, available acreage, crop rotations, and various habitat and wetland conservation requirements. Economic benefits on the bypass are primarily from agricultural production of 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 gross revenues exceed the cost of business. Increased inundation could potentially reduce revenues for farmers by shortening the growing season, and could increase or decrease hunting revenues depending on the depth, timing, and extent of increased inundation. Net economic returns on the bypass depend, therefore, on total acreage for each land use (and per-acre revenues), and also on the depth, timing, and duration of water applied to those lands.

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 pattern, (2) flooded acreage by land use type, (3) depth of flooding, and (4) time of year (and duration) of flooding. Together, these four land- and water-management decisions create 3,168 variables that take the form A_{jidt}: acres of land use j in zone i (of six zones), flooded to depth d in week t (of 6 to 8 weeks).

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

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

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 $Ø_{ij}$ and Υ_{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 wetland habitat on the bypass (when water is available) depends on similar factors: the availability (extent) and type of land use that is flooded, and flooding depth, timing, and duration. These all affect the physical quality of habitat, and the abundance of food 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, and an extensive literature review was completed (Suddeth 2014). The mathematical form is summarized here:

$$Max\ HQ = \sum_{s}\sum_{\substack{t=start\\date}} \omega_{ts}\delta_{ts}\sum_{d}\delta_{ds}\sum_{j}\beta_{sA}\left(\frac{A_{jtid} * \alpha_{sj}}{Max\left(A_{jtid} * \alpha_{sj}\right)}\right) \qquad \text{(Eq 2)}$$
$$+\beta_{sC}\left(\frac{Entropy\left(A_{jtid}\right)}{MaxEntropy}\right)$$

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,

β_{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,

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

SOME CAVEATS AND THE IMPORTANCE OF SENSITIVITY ANALYSIS

A famous statistician once said "All models are wrong, but some are useful" (Box and Draper 1987). This is especially true when the model must mathematically express one or more environmental outcomes. In reality, the costs or benefits of any flooding condition to various fish and bird species on the bypass are highly non-linear, and depends on weather, climate, access to the bypass, health of that year's populations, conditions in other habitats away from the bypass used at other life stages, and ultimately, what metric is selected to define "costs" and "benefits." The habitat quality objective functions presented above are similar to traditional habitat suitability indices (HSIs), 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).

However, Equation 2 is not meant to exactly simulate fish or bird population responses to flooding. Rather, it attempts to characterize, based on currently available knowledge, how one would optimally design flooded habitat on the bypass for a single group of species. The actual response of these species to particular flood characteristics would need to be evaluated over time. One advantage of having a model available for any system is that the parameters can be adjusted to incorporate new knowledge, and with additional work, the underlying functional form of the objective can be improved as well, 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 to test the implications of changed assumptions. The effect of any objective function error on the preferred management strategy on the bypass can be tested quickly with sensitivity analysis and updated with field experience.

DEVELOPING THE ECONOMIC OBJECTIVE FUNCTION

Agricultural Economics

The profit objective quantifies the annual per acre revenues and costs of each land use type, and the timing and depth effects of bypass inundation on revenues and costs. Agricultural gross revenues per unit area (R_{jti} in Equation 1) are calculated as price × yield for each crop type. Prices are an average of observed 2005 to 2009 prices, from Yolo County Agricultural Commissioner Reports and the National Agricultural Statistics Service. Yields depend on the length and timing of growing season, and therefore on the planting date. (Howitt et al. 2013) developed these time-dependent yield functions using the DAYCENT model, which estimates the yield on a given field while considering production conditions such as climate and the date the crop was planted.

(Howitt et al. 2013) developed the cost functions ($\sum_j, \O_{ij} e^{\Upsilon_{ij} * A_j}$) by crop for an agricultural model specific to the bypass using positive mathematical programming (PMP) to simulate farming decisions. 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 zone in the bypass because of colder climates in the south and varied soil conditions, 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 also vary from east to west, with longer drain times on the east side, which further delays the planting date for eastern fields after the last day of flooding over (or through) Fremont Weir. Given these processes, the bypass was split into seven distinct zones for the PMP-based Bypass Production Model (Howitt et al. 2013), shown in Figure 2. This study considers only Zones 1–6 as those which might be inundated by added flooding from a new notch in the Fremont Weir (USDOI 2013; Howitt et al. 2013).

Calibrating the Bypass Production Model to a set of given land-use data (crop acreage) results in the production of zone (*i*) and land use (*j*) -specific exponential cost functions (Howitt et al. 2013). We calibrated all zones in the model to the maximum observed acreage of each crop type (per zone) for the years 2005 through 2009. We assumed this acreage represented the point at which farmers acted as if marginal costs exceeded marginal revenues, and additional planting no longer increased returns. This calibration resulted in crop- and zone-specific values for $\O_{ij}$ and Υ_{ij} for the cost term of Equation 1. Taken together, these revenue and cost functions represent total agricultural net benefits on the bypass.

Wetland Economics

The above profit functions capture only agricultural land uses. Agricultural land use currently covers over 30,000 acres on the bypass of mixed crop and pasture lands, compared to about 9,500 acres of managed wetlands. Some land-owners might be compensated to reduce agricultural production and increase wetland services (supporting birds and fish). Although some statewide surveys exist on wetland management and ownership costs (Brown 2013), local costs and revenues can vary widely with water supply, mosquito abatement requirements, and land values. (Suddeth 2014) surveyed eight local wetland and duck club managers about costs and net returns specific to the bypass. Their answers are summarized below.

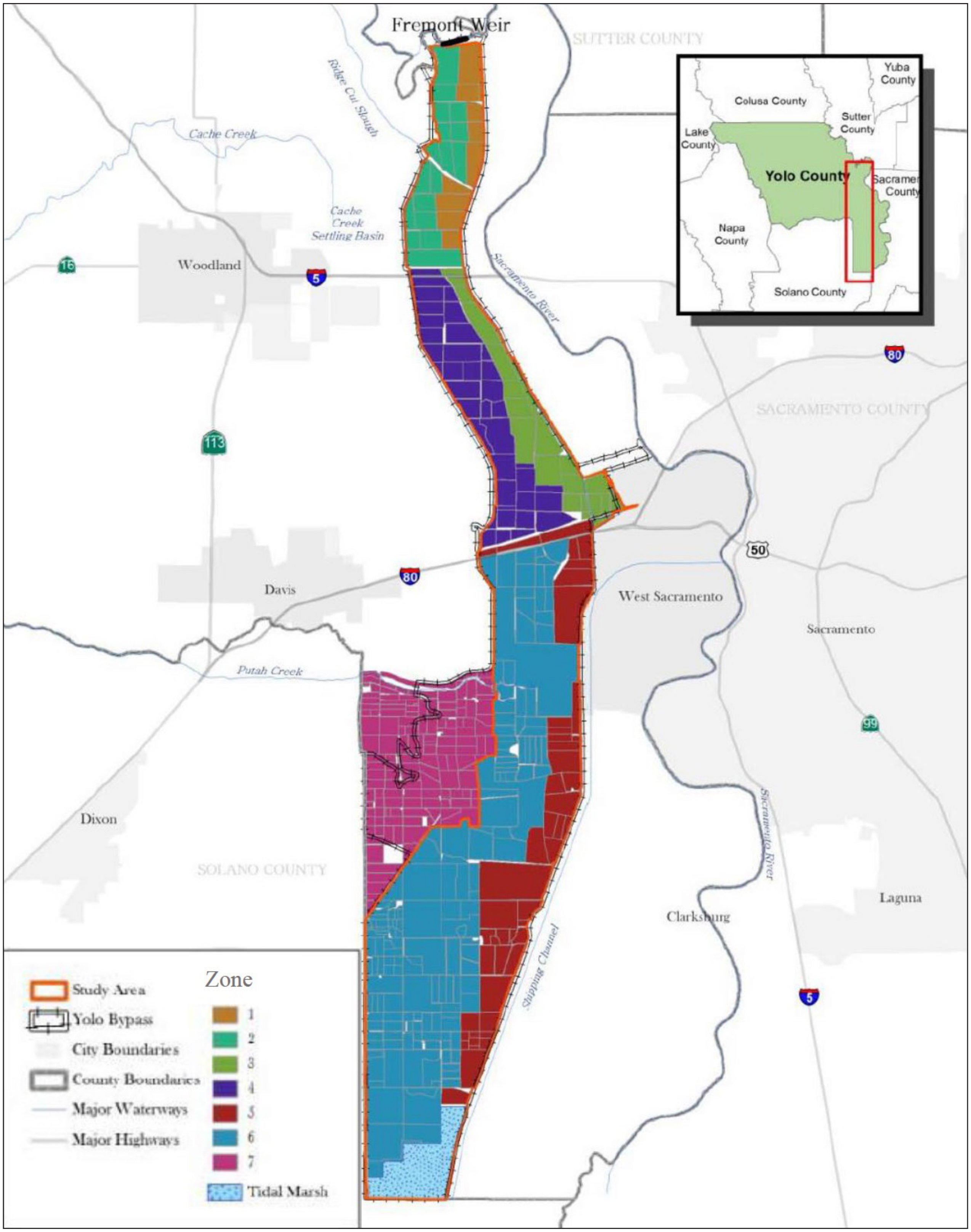

Figure 2 Agricultural zones in the Yolo Bypass. Source: Howitt et al. 2013

Annual Costs and Revenue for Private Wetlands

The annual costs of private seasonal wetland management averaged $160 per acre, with estimates ranging from $80 per acre to $300 per acre. Follow-up interviews indicated that the higher numbers likely represented the true annualized costs of owning and running a private wetland, because these responses included the basic costs of ownership in their estimates (salaries for paid managers, cost of land, etc.) (Suddeth 2014). Revenues come from one-time, up-front buy-in and annual assessments. Annual assessments averaged $1,587, and buy-ins averaged about $143,000, or $7,187, annualized at a 5% discount rate. Taken together, per-member annual revenues averaged around $8,775, which translates to average annual revenues of around $202 per acre. Given annual seasonal wetland costs (an average of $160 per acre to a maximum cost of $300 per acre), these revenues suggested that most private clubs are not netting large annual profits.

In general, private wetland owners are not running a business in the same way as farmers. Instead, members generally pay enough to produce sufficient waterfowl on the property for hunting recreation. When prompted about the profitability of existing clubs being affected by increasing wetland area, interviewed managers indicated that they believed there was a small possibility of declining profits because waterfowl populations on the bypass may not grow at the rate of newly opened wetland areas. This could lead to decreasing densities in existing wetlands as birds move onto newly created wetlands. Because of this and annualized net returns close to break-even, the base case model runs assume zero net hunting revenues per unit area for new wetlands.

Other Costs for Public and Private Wetlands

For existing wetlands, there may be economic costs of added bypass flooding related to moist soil management. If floodwaters cannot be drained by the prescribed drawdown periods, less desirable vegetation may grow in seasonal wetlands, which must then be managed by mowing, spraying, and extra irrigations, all of which require extra labor and, potentially, equipment rental (Smith et al. 1994). However, these costs are small relative to losses to farmers from similar delays in growing season (between $24 and $70 per acre for wetlands, and up to $1,500 per acre for some delayed crops). Because these costs would not, therefore, significantly decrease the bypass's overall economic performance, we have ignored them. Flooding can also sometimes cause economic losses from lost access to wetlands during the hunting season, but we also do not address this in this early model application because flooding is not considered before January 24 (the end of the hunting season).

Developing the Habitat Objective Function

Methods for quantifying costs and benefits of various flooding conditions are less well established for fish and birds than for farmers and hunters. First, which metrics should be used for fish and birds? Because salmon and splittail have other habitats, and many birds are migratory—spending only part of their lives on the bypass—this study does not attempt to relate flooding conditions to population responses that also depend on conditions at other times and places. Instead, we use changes in habitat quality as a proxy for benefits or losses to species from flooding. We describe habitat quality in terms of the extent, depth, land-use type (or substrate), timing, and duration of inundation. We can then use these variables to further imply other components of habitat quality such as the heterogeneity or complexity of available land uses (by looking at the variety of different land use types that appear in a given solution). We ignore connectivity; we assume it is possible with a well-planned notch in the Fremont Weir and strategic land and water placement. This assumption will require testing with a 2-D hydrodynamic model of the bypass in future applications.

This approach is similar to the use of HSIs, 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 vary with species and life stage (Zheng et al. 2009). Most HSIs for stream fishes are based on some combination of water velocity, depth, area, cover, and substratum conditions (Ahmadi–Nedushan et al. 2006).

A similar combination of "indices" is applied here in Equation 2, with depth (d) represented as one of six weighted (δ_d) zones (0 cm, 5–10 cm, 11–18 cm, 19–30 cm, 31–46 cm, and < 46 cm), and area as a percent of the maximum flooded area ($\frac{A_{jtid} * \alpha_{sj}}{Max\left(A_{jtid} * \alpha_{sj}\right)}$). However Equation 2 differs from a typical HSI in several ways:

a. The objective function seeks to maximize habitat quality within the bypass itself, and not across all habitats available to these species. It focuses on added benefit, rather than overall suitability.

b. Velocity during a managed low-flow event (like those the BDCP prescribes) is assumed to be low and uniform across most of the bypass, so we do not consider it.

c. We describe cover and substrate in this study by land-use type (j). Substrate land use is especially important for splittail spawning, and for all bird and fish species as a source of seed or invertebrate food.

d. Flood timing (t) is included, since species migrate to or through the bypass only during some months of the year, and weather conditions in different weeks can affect primary productivity.

e. We also consider flood duration, with its implications for bird and fish food supplies and growth potential. Both fish species, for example, require at least 2 weeks of inundation to develop sufficient zooplankton and invertebrate food supplies (USDOI 2013). We apply a marginal added benefit (ω_{ts}) 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 3 weeks of inundation, but probably see decreasing returns towards the end of a long flood (Suddeth 2014), we assume that the third to fifth weeks deliver much higher returns than the first 2 weeks, and marginally more than any additional weeks thereafter (Figure 3).

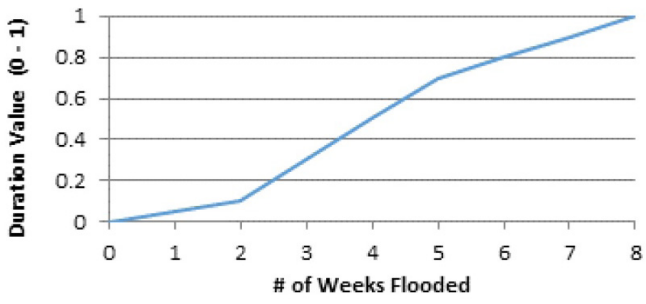

Figure 3 Duration value for salmon and splittail. The duration value for salmon and splittail of any given flooding case increases at varied rates with each added week. Source: Suddeth (2014).

f. We simplify floodplain complexity here to mean the variety of different land use types available as habitat, and is generally assumed to be beneficial for fish and birds. We measure complexity with an entropy function $\left(\frac{Entropy\left(A_{jtid}\right)}{Max\ Entropy}\right)$ in Equation 2, where entropy is calculated as

$$E_t = \sum_j \left[\left(\frac{A_{jt,d>0}}{\sum A_j} * -ln \frac{A_{jt,d<0}}{\sum A_j}\right)\right]$$

(Suddeth 2014). This function is linearlized with new decision variables A_{j1}, A_{j2}, A_{j3}, and A_{j4} as follows:

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

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

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

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

Though much is known about the general benefits to fish and bird species of floodplain habitat, their preferences while on the floodplain are less well understood, especially for greatly altered floodplains such as the Yolo Bypass. The weights applied in Equation 2 depend largely on expert judgment to augment information available from the 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 are commonly employed elsewhere (Vilizzi et al. 2013; Zheng et al. 2009).

A full description of the expert interview and survey appears in Suddeth (2014), 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. Several fish species 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 surveys. Waterbird experts were asked to focus on two species groups: dabbling ducks and shorebirds. Because there are many different species of dabbling ducks and shorebirds, experts were told to average their answers across all species within each of those groups that use the bypass between late January and early May. Tables 2 through 7 present the weights for Equation 2 from those surveys:

Table 2 Relative fish habitat preferences (weights) for varied land-use types and time of year

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[a]	Jan 1–Jan 15	0.40	0.59
Wild Rice	0.63	1.00[a]	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			

a. Rice and wild rice have been proven to be excellent salmon habitat since the administration of the survey (Katz et al. 2013). These weights reflect those findings, rather than average survey responses.

Table 3 Relative fish habitat preference for varied flood depths

Depth, *d* (cm)	Splittail weights ($\delta_{splittail,\ d}$)	Salmon weights ($\delta_{salmon,\ d}$)
Zone 1: 5–10	0.21	0.22
Zone 2: 11–18	0.38	0.35
Zone 3: 19–30	0.71	0.58
Zone 4: 31–46	1.00	0.91
Zone 5: > 46	1.00	1.00

Table 4 Relative importance of the area and particular land-use types flooded versus the overall heterogeneity, or "complexity" of flooded land uses

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

Table 5 Relative dabbling duck and shorebird foraging habitat preferences (weights) for land-use types and time of year

Land-use type (*j*)	Weights (α_{sj})		Timing (*t*)	Weights (δ_{ts})	
	Dabbling ducks	Shorebirds		Dabbling ducks	Shorebirds
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 6 Relative value (weights) to dabbling ducks and shorebirds for specified flood depths in foraging habitat

Depth, *d* (cm)	$\delta_{dabbler}$	$\delta_{shorebird}$
Zone 1: 5 – 10	0.86	1.00
Zone 2: 11 – 18	1.00	0.75
Zone 3: 19 – 30	0.95	0.44
Zone 4: 31 – 46	0.66	0.11
Zone 5: > 46	0.30	0.04

Table 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

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

Developing the Constraint Set

Decision variables can only be manipulated within physical limits. Almost all constraints on decisions developed here are related to land use or water management.

Land Use Constraints

Yolo Bypass' primary societal function as a flood channel requires that its surface roughness not be increased with trees or major topographic changes. So riparian vegetation is constrained to only 5% of total available acreage (based on rough estimates from bypass land use maps from Yolo County), and the model assumes that current major land use classes will persist. Therefore the model limits land use decisions to assigning acreage to rice, wild rice, tomatoes, corn, safflower, pasture, seasonal and permanent wetlands, riparian, and/or fallow land. Geographic data for each land use on the bypass is available from Yolo County for years 2005 through 2009, by agricultural zone shown in Figure 2. We used these data to develop all other land use constraints discussed next.

While some land-use types (e.g., riparian vegetation) have an upper limit, others require a minimum presence. Soil management requires, for instance, fallowing some portion of each zone every year, with crops rotating through on 3- or 4-year cycles. For this constraint, we used the minimum number of acres fallowed in each zone for years 2005 through 2009. Mathematically, constraints for riparian and fallow acreage are written as:

$$\sum_i \sum_d A_{riparian} \le 2400 \text{ acre}, \quad \forall t \qquad \text{(Eq 3)}$$

where

i = zone, is total acreage of riparian land in zone i flooded to depth d, in week t. (2,400 is approximately 5% of total bypass area for zones 1–6 on the bypass). And

$$\sum_{d,zone\ i} A_{fallow} \ge F_{\min,i} \quad \forall t \qquad \text{(Eq 4)}$$

where

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

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

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

$$\sum_{d,zone\ i} A_{seasonal\ wetland} + A_{permanent\ wetland} \ge W_{\min,i} \quad \forall t \qquad \text{(Eq 5)}$$

where

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

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

Finally, other land use constraints define the system, including maximum total acreage per zone (and across the entire bypass), non-negativity, and continuity across all time steps.

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

$$\sum_d \sum_j A_{jtid} \le MaxA_i \quad \forall t,i \qquad \text{(Eq 6)}$$

where

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

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

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

$$A_{jtid} \ge 0 \quad \forall j,t,i,d \qquad \text{(Eq 7)}$$

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):

$$\sum_{d} A_{jtid} \le A_{j(t+1)od} \quad \forall i,j \qquad \text{(Eq 8)}$$

Water Management Constraints

As mentioned earlier, the bypass has many manageable canals, gates, pumps, drainage systems, and other infrastructure available to manage multipurpose inundation with additional flows in the winter and spring. The model limits these floods to be 8 weeks in duration (by containing only 8 time steps). This limit is based on expert interviews and survey results, which indicate small returns for fish after fields or wetlands are flooded for longer than 4 to 6 weeks (Figure 3).

We also attempted to make the solution feasible for water managers on the bypass. For simplicity, the model assumes that acreage devoted to flooding or habitat does not increase significantly from week to week (it remains steady or decreases). This reflects that more water is typically available earlier in the season than later, although this constraint could be changed in later runs to test years when this is not true. It also assumes that any land that becomes dry in week t remains dry in all following weeks. This allows fields to be used for agriculture after being drained. Finally, total flooded area is constrained to 20,000 acres. This maximum flood extent is based on hydrodynamic modeling and on BDCP targets, which suggest that likely water volumes available through a gated notch in Fremont Weir during January through May will not inundate more than roughly 20,000 acres (CBEC 2010; USDOI 2013). Mathematically:

$$\sum_{j} \sum_{d>0} \sum_{i} A_{jtid} \ge A_{j(t+1)id} \quad \forall t \qquad \text{(Eq 9)}$$

$$A_{jti(d=0)} \le A_{j(t+1)i(d=0)} \quad \forall j,t,i \qquad \text{(Eq 10)}$$

$$\sum_{j} \sum_{d>0} \sum_{i} A_{jtid} \le 20{,}000 \quad \forall t \qquad \text{(Eq 11)}$$

SOLUTION METHODS

The Constraint Method

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

Many methods exist to generate this solution set, all of which essentially convert the multi-objective problem into a series of single-objective problems. This converson is usually done by applying weights to each objective to create one overall objective (the weighting method) or by converting some objectives into constraints (the constraint method) (Cohon 1978; Louie et al. 1984; de Neufville 1990). Both methods have been applied in similar problems (Kuby et al. 2005; 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, so we use this method 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 other objectives (de Neufville 1990). Because the fish and bird objectives for the bypass are both expressed in "habitat quality" units, and the economic objective is in dollars, the natural formulation for this problem converts the fish and bird objectives into constraints on an economic optimization. Mathematically:

$$\textit{Maximize Profit}\left(\textit{Eq } 1\right)\textit{such that}$$

$$\frac{HQ_{Birds}}{MAX\left(HQ_{Birds}\right)} \ge x \textit{ and } \frac{HQ_{fish}}{MAX\left(HQ_{fish}\right)} \ge y$$

(and all other physical constraints presented above are also satisfied),

where

x and y are re-set for consecutive optimization runs, increased by intervals of 0.01 to 0.1.

Branch and Bound Algorithm

Solving the converted single-objective profit maximization requires a numerical solution algorithm. This study employs a solver add-on to Excel, What's Best (available online at *http://www.lindo.com*), that has several options for nonlinear optimization. We used the "global solver," which includes a branch and bound scheme (Gau and Schrage 2004).

MODEL VALIDATION AND APPLICATION TO PAST LAND-USE MOSAICS

We used land-use data for years 2005 through 2009 to assess whether the model reasonably estimates farming decisions on the bypass with the bird and fish constraints left inactive (i.e., only maximizing net farm revenues). We manually entered the crop acreage in each zone into the model to simulate economic performance in each year (with no flooding except in wetlands). We then allowed the model to change land-use decisions to maximize profits; this run was named "Optimal Econ." We then completed a second optimization run called "Fish and Bird Optimal." This run re-introduced fish and bird constraints, optimizing habitat benefits for each to the maximum extent possible before trade-offs were needed between them, and allowing economic performance to decrease as needed. After several iterations, we found a balanced optimization of fish and bird habitat quality was found for a January 24th flooding start date with the habitat constraints:

$$\mathit{Maximize\ Profit}\,(\mathit{Eq}\ 1)\,\mathit{such\ that}$$

$$\frac{HQ_{Birds}}{MAX\left(HQ_{Birds}\right)} \geq .75 \text{ and } \frac{HQ_{fish}}{MAX\left(HQ_{fish}\right)} \geq .75$$

We used this and the purely economic optimization were used to compare past land-use mosaics with modeled land-use decisions (Figure 4).

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 between 2005 and 2009 for

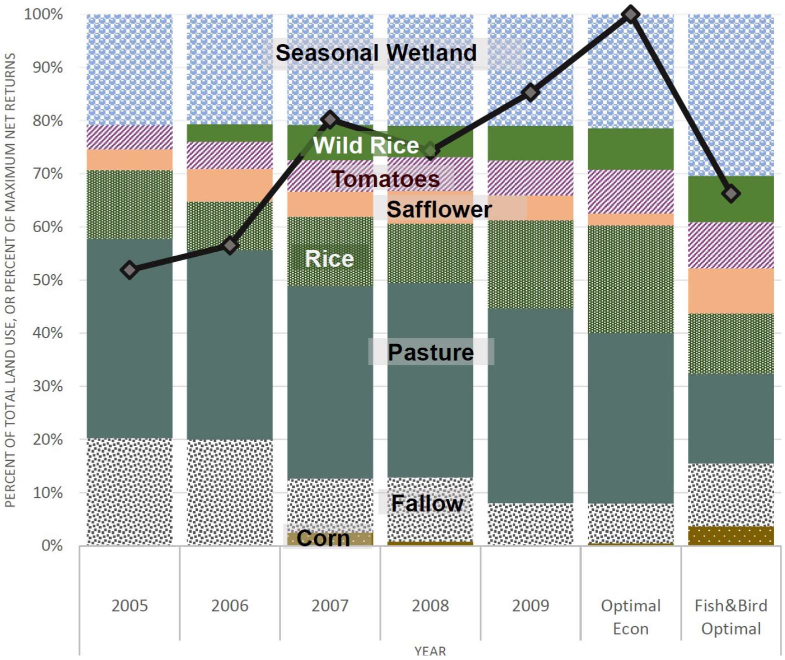

Figure 4 Land-use mosaic versus economic performance. Percent of total area represented by each land-use type (per year) is plotted against the percent of maximum profit netted in each year (black line). Note: Total area can vary in the data from year to year. One hundred percent (100%) does not mean the same thing in 2005 as it does in 2009. This graph is only meant to display the relative prominence of different land use types through time and in modeled decisions. Source for years 2005 – 2009: Yolo County GIS land-use layers.

bypass farmers (assuming average crop prices). Actual acreage is shown for each land-use type for these 2 years for a more direct comparison, and economic performance is shown as a black line with the percent of maximum achievable profits. Modeled land-use decisions in the economic optimization closely resemble the major land uses in 2009, suggesting that the economic objective function (Equation 1) is a fairly good estimate of marginal realities for bypass farmers. However, the optimized decisions suggest that, absent fish and bird objectives, an approximately 15% improvement in net returns might be possible on the bypass with greater shares of tomato and rice production, and a corresponding decrease in pasture.

Alternatively, the run that maximized fish and bird habitat quality in exchange for reduced economic performance suggests that a more habitat-friendly land-use pattern might trade much of the southern bypass' pasture for seasonal wetlands, with a resultant drop in net agricultural returns to about 66% of optimal. Rice acreage also decreases (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 makes sense as a response to their high weights as potential habitat for several birds and fish. Added acreage for the remaining agricultural crops serves to 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, however, it only represents one point along a much larger trade-off curve that needs broader exploration before serious conclusions can be drawn about promising changes to land management on the bypass. However, it shows the model makes logical land use changes as bird and fish habitat is prioritized.

The increases in tomato acreage for both model runs and the increase in rice for the economic optimization are consistent with the general trend in data from 2005 through 2009, with a caution. To maximize profit in "Optimal Econ," the model planted the largest observed zone-specific acreage of rice and tomatoes for the years 2005 through 2009, across all zones at once and in 1 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 because of crop rotations, processing limitations, or other logistical considerations. Crop prices also change between years, which would affect relative profits for different land use types. Later model applications could test sensitivity to added constraints on rice and tomato acreage and the effect of a range of different market prices for bypass crops.

We also ran the model also with varied weights in the salmon habitat quality objective for rice and wild rice preferences, to test the importance of a change in those weights with new information available from recent field work (Katz et al. 2013). These weights were the only ones not derived from expert survey results. We tested the original survey-derived weights (0.76 for rice and wild rice) against the newer assumption that rice is a preferred habitat for salmon on the bypass (or equal in value to wetlands with a weight of 1). Figure 5 shows results for the balanced habitat quality case for fish and birds. Only slight changes occurred in the amount of rice flooded in later weeks, and in resulting economic performance. These results suggest that the modified rice weights for salmon habitat do not significantly change modeled decisions or outputs when improved habitat quality for fish and birds is sought.

APPLYING ADDED WATER TO PAST LAND USE MOSAICS

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

We explored current habitat quality for fish and birds on the bypass by simulating what is already achieved in a dry year (from seasonal and semi-permanent wetlands) versus a year of natural Fremont weir overflow (when almost the entire bypass is inundated). We simulated flood depth and extent for the 2006 March through May flood using data from previous hydrodynamic modeling efforts,

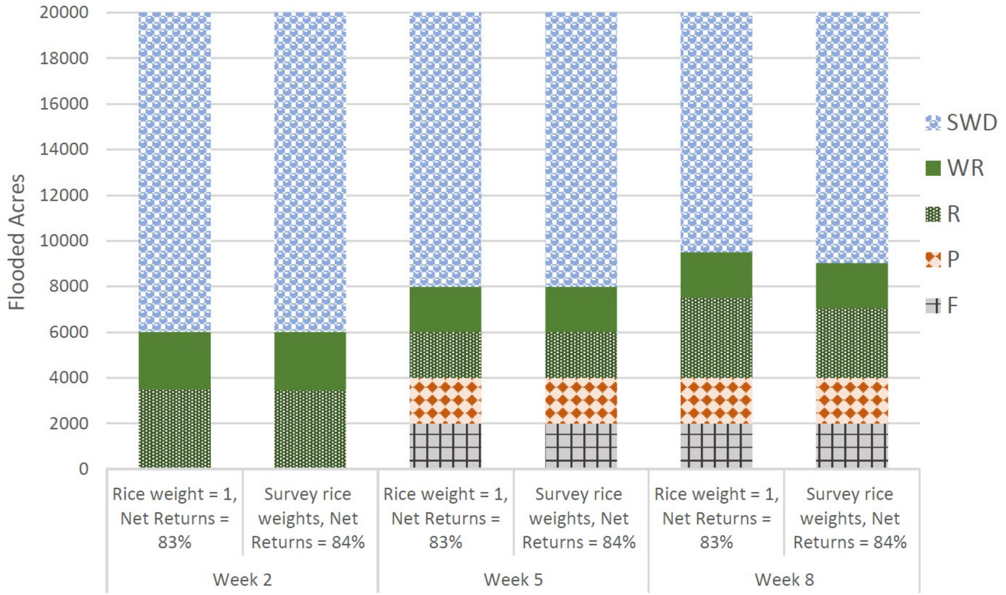

Figure 5 Test of model sensitivity to varied rice weights for the salmon quality objective. Flooded acreage is shown for weeks 2, 5, and 8, to show change over time, with habitat quality at 80% for birds and fish, and varied rice weights in the salmon habitat quality function. SWD = seasonal wetland, WR = wild rice, R = rice, P = pasture, and F = fallow. Only flooded lands are shown.

including detailed results on the depth of flooding (CBEC 2010). We 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 15 cm deep, 19% is between 15 and 30 cm, etc.). We simulated 2 dry years (winters of 2007 and 2009) assuming all wetlands were flooded to whatever depth was needed to maximize bird benefits, but that no other land uses were inundated (wetlands are currently about 9,500 acres). We report results as a small range of potential bird habitat quality in those years to account for uncertainty in the true management decisions made for flood depths across the landscape in either case. Fish habitat quality is assumed near zero in current dry years because salmon and splittail typically lack access to managed wetlands when the Fremont Weir is not overtopping.

After we simulated current habitat quality, we used the model 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 24) and early February of the following winters (2007 through 2010). However we adjusted only some decision variables: we held the acreage of each land-use type constant, while we allowed the depth of flooding to vary only during weeks 1 through 3 when inundation would have no effect on yields or agricultural profits (which are dependent on crop type and zone).

Within this subset of possible decisions for those years, we optimized depth and placement of inundation for fish habitat, then for bird habitat, and finally for a balance of habitat quality. We tightened each habitat constraint until any further adjustment in one decreased performance of the other. In this way a rough estimation of trade-offs amongst fish and bird habitat quality was developed in the context of real land use mosaics and set economic performance. These runs were then compared to a 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 appear in Figure 6, with boxes showing the habitat quality that was actually available on those dry land uses and what was available during the very large March through May flood of 2006.

The curves show that substantial improvement in habitat quality would have been possible for fish with just 3 or 4 weeks of added flooding in February—with no effect on the net economic returns in those years. Bird habitat quality can improve by 5% to 25% compared to current wetland management, and fish habitat quality can improve by as much as 55% above what is currently available. This is all with no modelled effect on profits or land use other than the costs of water management and, of course, initial costs of weir and any other infrastructure modifications needed to obtain and move the added flows.

As shown in Figure 6, balanced habitat management for fish and birds in the winters of 2007 and 2009 could have achieved between 52% and 57% of optimal habitat quality for both species groups, had additional water been available. This is somewhat better than current performance for birds, and a substantial increase in 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 in the spring of 2006, with bird habitat between 65% and 75% of ideal, and fish habitat between 82% and 92% of ideal. Fish fare slightly better than birds in this case because of deeper water (about 54% of inundation was deeper than 46 cm) (CBEC 2010), with foraging habitat for birds only available on the edges of the flood. However these large floods come at great cost

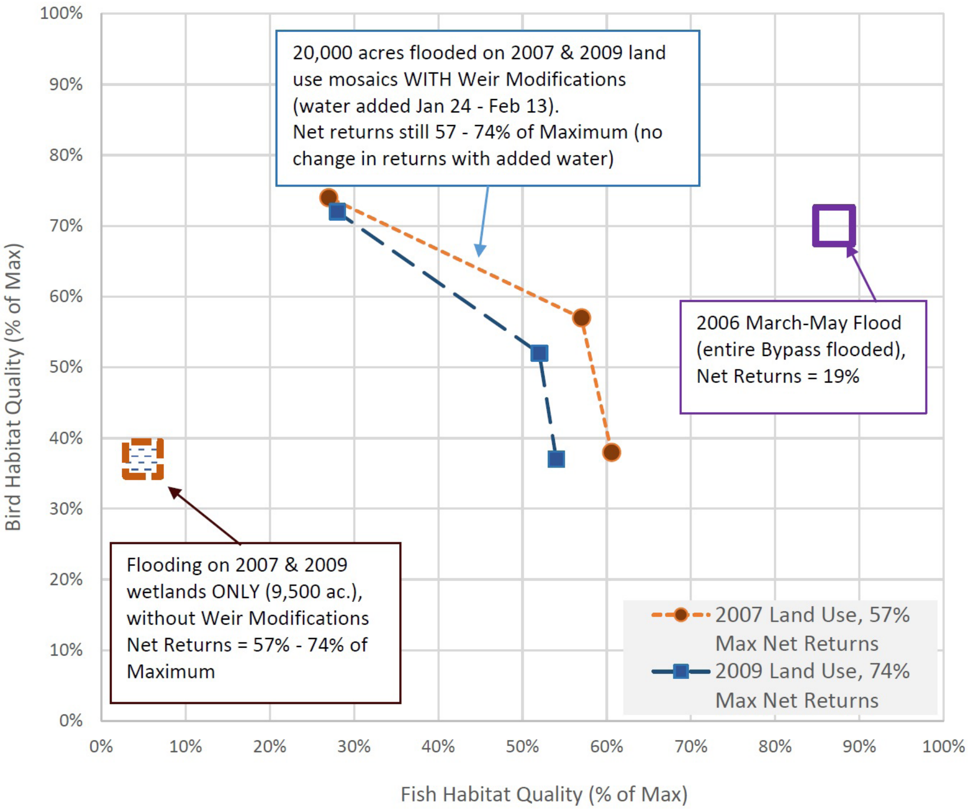

Figure 6 Comparison of bird and fish habitat quality trade-offs for past land-use mosaics without any added water or weir modifications (actual) and with weir modifications (hypothetical). The graph also shows habitat quality during the March–May flood in 2006, simulated on the land-use mosaic that was planted in the spring of 2005. Note: The 2007 and 2009 land-use mosaics were planted in the spring seasons of 2006 and 2008.

to farmers, especially late spring floods; simulated net revenues for that year were only 19% of ideal. 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 also can harm 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 if the three objectives could improve even more with a modified weir (and added flows) if the land use mosaic was allowed to change. Figure 7 shows the potential performance of each real year's land use if bird and fish habitat quality were equally prioritized in managing added flows, compared to performance within an economically optimized bypass ("Optimal Econ" in Figure 7) where the model assigns all land use. 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 8 provides more detail on how these improvements in all three objectives might be possible. Flooding in week 3 (February 7–13) 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 57% of ideal quality on 2006 land uses, and 61% on economically optimal land uses.) This week was chosen because it is a relatively valuable week for fish and dabblers, and illustrates a balancing of habitat preferences across those species groups. Only flooded land uses are shown for each zone, with area of flooding by depth.

These flood distributions show that added wild rice acreage in the economically optimized land use mix also serves as additional fish and bird habitat. Added seasonal wetlands and rice in the south-western bypass also adds habitat beyond 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 half of the bypass.

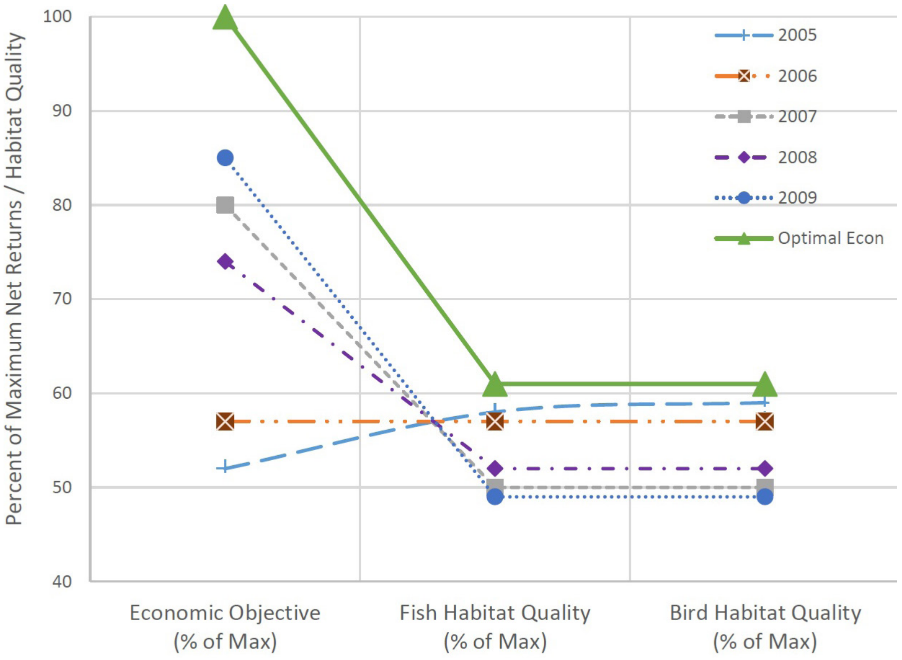

Figure 7 Performance profile showing modeled net returns and habitat quality on real land-use mosaics versus an economically optimal land-use mosaic

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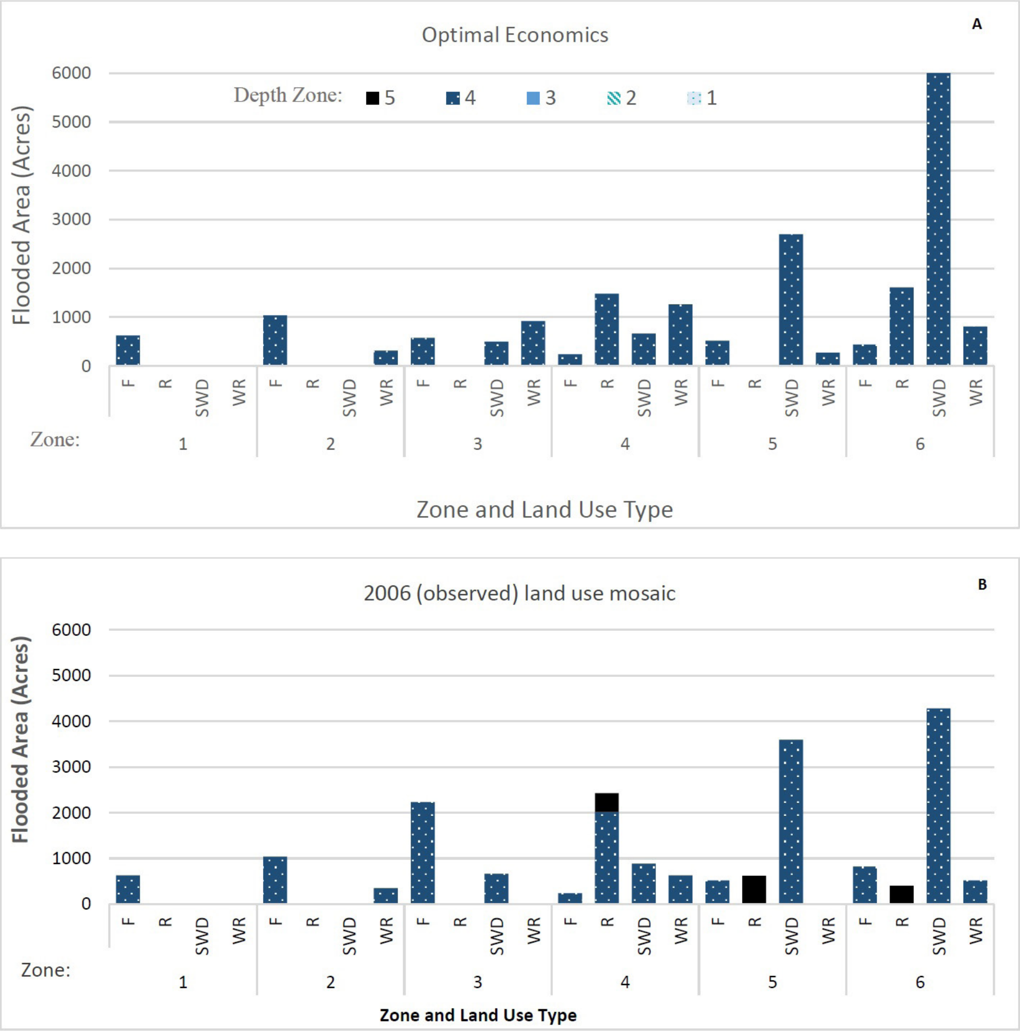

Figure 8 Flood distributions during Week 3 of the Optimal Econ run with the maximum balanced habitat quality for both birds and fish (**A**), and for balanced fish and bird habitat quality on the 2006 land-use mosaic (**B**). In either run, habitat quality was only improved insofar as it did not reduce profits for that year. Only flooded land uses are shown. F = fallow, R = rice, SWD = seasonal wetland, and WR = wild rice. Depth zones: 5 = >46 cm, 4 = 31–46 cm, 3 = 19–30 cm, 2 = 11–18 cm, and 1 = 5–10 cm.

CONCLUSIONS

The model development and application show how a complex multi-objective economic, habitat, and ecosystem reconciliation problem can be more formally understood and modelled, with useful insights for how these objectives might be reconciled on the Yolo Bypass. The application and results, although preliminary, lead to several conclusions about reconciled fish, bird and economic objectives for the Yolo Bypass and similar systems. These conclusions can be considered in terms of: (1) trade-offs between fish habitat, bird habitat, and economic performance in a modified bypass, and (2) land-use implications.

Fish habitat, bird habitat, and economic performance can probably all be improved on the bypass without significant trade-offs if additional water is available through a modified weir or some other means, and some small changes are made to current land use. Optimization of flooding on past land use (2005 – 2010) suggests that just 3 weeks of flooding in late January and early February can increase habitat quality for fish and birds at little or no cost to farmers. Longer-duration and later flooding would likely increase habitat quality for fish and shorebirds, and should be tested in later applications. This study also suggests that more habitat improvement is possible if economic performance is allowed to decrease, but we did not thoroughly explore these trade-offs in this initial application.

In terms of 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 these crops. Fallow lands also can improve habitat at no economic cost, if these fields are easily inundated and accessible to fish and/or birds. This implies that there are ecological benefits to be realized if farmers and land managers incorporate fish and bird habitat considerations into crop placements and rotations; further illustrating the need to develop economic incentives to encourage this behavior. Finally, seasonal wetland acreage also is 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 economically 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 highlights the potential of a ‘meet in the middle’ solution in current dry years. Such a solution would increase habitat benefits for fish and birds with minimal effects 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 fully reveal trade-offs among economic and habitat goals. Future applications could more thoroughly use the constraint method to develop a more exhaustive set of non-inferior solutions to reconcile fish and bird habitat provision with economic uses on the bypass.

These more thoroughly-developed solution sets should be accompanied by additional post-processing of results. Because the results presented here are preliminary, the conclusions should not be used to make detailed management decisions. We did not fully explore trade-offs and synergies between fish and bird habitat, or between individual species or species groups (like salmon or dabbling ducks). Implications for land and water management can be developed in more 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 each zone.

This model is based on many assumptions about fish and bird preferences, agricultural economics, and land-use restrictions. Future applications would benefit from sensitivity analyses on many of these parameters so that results are developed within a range of likely realities. Sensitivity analysis could also guide further Yolo Bypass or more general floodplain research to reduce uncertainties that matter most for future decisions. The objective functions might also be expanded to include additional habitat preferences; for example, the potential value to birds of fields in their dry condition, or of flooding below a 5-cm depth for shorebirds.

Finally, results from these initial runs suggest some areas of potential model refinement. More research is needed to assess if economically preferable increases in wild rice and tomato acreage are actually possible. Crop rotation, equipment, or other constraints might limit the total acreage that can 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 concentrate flooding in the lower, eastern zones. Future runs could limit flooding to Zones 1, 3, 5 and 6 so that model-derived solutions are more easily applicable in real system management.

Next steps aside, these preliminary runs show that the model assigns acreage and water in ways that makes sense relative to past land use decisions and what is currently understood about fish and bird habitat preferences on the bypass. It can be a powerful tool to inform future decision-making for the Yolo Bypass and is a good example for multi-objective optimization’s potential value in planning for ecosystem reconciliation.

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