A comprehensive management plan for habitat restoration in the bypass will require analysis across a broad range of topics, including agricultural economics, waterfowl habitat, hydrodynamics (both for fish habitat and to evaluate changes in flood carrying capacity), and finally conjunctive groundwater use. A balanced management approach for ecosystem services attempts to minimize economic costs to all human land/resource uses, while satisfying some minimum habitat requirement (Revelle et al. 1968, Lund et al. 2010). On the Yolo Bypass, this habitat requirement can take the form of acres flooded, residence time of water, and/or a sum value that depends on type of land flooded, duration of flooding, accessibility for fish, and other relevant factors.

This proposal seeks funding for an interdisciplinary study to quantify or describe all uses on the bypass, both human and environmental (ecological), and to incorporate this data into an optimization model to identify management alternatives that provide desired ecosystem services while maximizing the economic returns to land owners and managers. The methodology developed in this study will be broadly applicable to similar floodplains with the potential for conjunctive use for human and ecosystem services.

III. Approach and Scope of Work

Study objectives for this proposal will be organized into three broader tasks, with an additional task for project management.

Task One: Project Management

Cathryn Lawrence, assistant director for the Center for Watershed Sciences at UC Davis, will oversee collaboration amongst project personnel, and timely submission of project deliverables.

Task Two: Agricultural Economics

Economic evaluation of increasing the flooding frequency and total amount of water in the Yolo Bypass requires the development of an agricultural production model and its integration with supplemental agronomic and hydrologic models. Economists and scientists at UC Davis have already begun calibrating the models necessary to work on this issue. Descriptions of the models we are using and the status of our work on this project is outlined below.

Calibrated agricultural production model:
The regional agricultural production model will be a downscaled-version of the State-Wide Agricultural Production model (SWAP) (http://swap.ucdavis.edu/). The agricultural production functions will be specified as constant elasticity of substitution (CES) among inputs. This model

will use the most up-to-date data of cropping patterns in Yolo County (obtained from the 1989 and 1997 Department of Water Resources land use surveys and the annual Agricultural Commissioner Reports). The model will be calibrated against a range of hydrologic year types.

Agronomy simulations with DAYCENT:
DAYCENT is a biogeochemical model that accurately predicts agronomic productivity. DAYCENT provides a flexible modeling platform that can easily integrate change in land management practices or external disturbances, such as flooding or delayed planting date. Our group has already calibrated DAYCENT for Yolo County (DeGryze et al. 2009).

First, we will identify the crops and varieties adapted to new conditions generated under the different flooding scenarios and we will calibrate DAYCENT to account for these conditions. Second, we will simulate yields for all relevant crop varieties farmed under the new flooding conditions in the Yolo Bypass.

IMPLAN Yolo County model:
IMPLAN (Impact analysis for PLANning) is an input-output model. It relies on regional specific economic characteristics which are available by zip code and social accounting matrices and multiplier models. IMPLAN has been effectively applied to reductions in water supply to the Central Valley of California (Howitt et al., 2009), and ongoing work in the Delta region. A version of the IMPLAN model calibrated for Yolo County will be purchased and used to simulate county level impacts on income and employment to economic sectors in the county. 2006 will be used as a model baseline for consistency with other Implan models, but prices will be indexed to correspond to the most recent agricultural production data.

Task Three: Simulating Groundwater Recharge, Recovery and Regional Benefits

Since February 2010, Fogg, Howitt and Garnache (Howitt's Ph.D. student) and DWR staff (Tariq Kadir, Charles Brush, C. Dogrul) have been meeting to work out the interface between the economic and hydrologic modeling. This has culminated in the updating of the Yolo County IGSM model to the newer, more reliable IWFM code by DWR. Additional model development and calibration is needed, followed by the definition of appropriate hydrologic scenario simulations. The results of the simulations will then be used to simulate groundwater system response to bypass inundation and different groundwater pumping schemes in the bypass as well as in the Davis and Woodland vicinities. The driving variables for groundwater recharge, storage and recovery will be inundation frequency and duration, hydrostratigraphy of aquifer and non-aquifer sediments beneath the bypass, cropping patterns and agricultural water use and recharge, and rates and distribution of ground water extraction. The hydrostratigraphy will be based on

well data already available for the bypass from DWR (e.g., West Yost, 1994) and hydrostratigraphic modeling (e.g., Carle et al., 1998; Fleckenstein et al., 2006) that will represent geometry and vertical connectivity of aquifer sediments beneath the bypass. The groundwater model will, in turn, be incorporated into a dynamic economic model that is part of the integrated optimization of flows in the Bypass described in section 6 below.

Task Four: Development of Promising Management Alternatives

Task four will be divided into four sub-tasks, each of which addresses a separate project objective as identified in the Project Purpose section above.

1. **Waterfowl**

The bypass serves as habitat for numerous waterfowl and migrating bird species (YBMP 2001). Spring inundation can be negative or positive, depending on timing and duration. Longer and later inundation periods have the potential of deterring the growth of nutritionally important vegetation, while encouraging the growth of detrimental vegetation (pers comm. Dave Feliz). On the other hand, some inundation can aide in the creation of certain habitats, such as mudflats and ponds. The Yolo County Habitat / Natural Community Conservation Plan (2006) describes habitat requirements of numerous waterfowl species managed in the bypass. Review of this and other management plans will be combined with a formal interview effort with wildlife managers and ecologists. Interview targets include Dave Feliz, Greg Yaris, Josh Ackerman (USGS), John Eadie (UCD), and others. The focus of these efforts will be to define a short list of important characteristics of spring waterfowl habitat, as well as to help quantify the effects of inundation on summer, fall, and winter waterfowl habitat. A summary of interview results will be included in project write-ups, and potentially serve as the basis for one or two organized workshops. Those answers receiving the highest degree of agreement amongst interviewees will be consolidated into a set of metrics for further use in optimization modeling.

2. **Native Fish**

It is known that flood events in the bypass provide essential rearing habitat for Sacramento splittail and also result in increased growth rates and survival of juvenile Chinook salmon that take advantage of extensive food supplies (YBMS 2001, Sommer et al. 2001, 2004, 2005; Feyrer et al. 2006, Williams et al. 2009). However these two fish species enter the bypass from different ends; and use it in different ways. For example, land closer to the Delta is more valuable for splittail than inundated land in the northern bypass. Interviews will be conducted with many ecologists familiar with the Yolo Bypass and greater Delta ecosystem, including Fred

Feyrer, Ted Sommer, William Bennett, and Wim Kimmerer. Like interviews with waterfowl experts, these scientists will be asked to define a short list of important land cover characteristics that distinguish habitat for both species. Potential characteristics include:

i. Complexity of land cover
ii. Drainage
iii. Connection to other external habitats (the Delta, Cache Slough, Sacramento River)
iv. Proximity to permanent water in bypass (Toe Drain, lakes etc.)
v. Vegetation types and structure
vi. Potential for food production

A summary of interview results will be provided, and potentially discussed further in one or two organized workshops. Those answers receiving the highest degree of agreement amongst interviewees will be consolidated into a set of metrics for further use in optimization modeling. Some data will also be collected to explore variations in secondary productivity across the bypass, as this relates to food availability for fish. Finally, an effort will be made to understand (through interviews and reports) the nature of apparent Delta smelt habitat on Liberty Island, to see if it could/should be expanded into other Bypass lands.

3. **Internal Hydraulics and Flood Control**

Internal hydraulics will be investigated using an application of RMA-2, a two-dimensional hydrodynamics model that has been extensively tested and calibrated for use in the Delta (RMA 2008). Use of RMA2 requires a large number of inputs including model geometry and boundary condition data. The bathymetry for this application will be derived from high resolution topographic data for the bypass from a recent LIDAR effort. Boundary conditions include inflow time series for the Sacramento and San Joaquin Rivers as well as tidal stage data at the downstream boundary. The model also requires information on the import and export at the State and Central Valley water projects and gate operations within the Delta. The data for these inputs is readily available and will be attained from the following sources: (1) The Department of Water Resources: http://www.water.ca.gov/iep/; (2) The California Data Exchange Center: http://cdec.water.ca.gov/; and (3) The Delta Simulation Model 2 User Group: http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/dsm2usersgroup.cfm. William Fleenor and Laura Doyle will assist with this effort, supported by $45,862.50 of cost share funds from the Center for Watershed Sciences at UC Davis. The model will be used to test the viability of promising strategies for spring inundation as identified by the optimization model, given flood conveyance constraints. Results will also describe requisite upstream flows given different modifications to Fremont Weir.

4. **Spatial and Temporal Optimization of Restoration Flows**

Identification of optimal spring inundation strategies on the Yolo Bypass for agricultural, water supply, and ecosystem services is a complex problem, requiring analysis at a relatively fine

spatial and temporal resolution that also incorporates numerous interdependent and potentially stochastic parameters. Such a large problem is often difficult to solve analytically because of the high volume of information, time steps, and relationships to be considered. Optimization is a logical approach with which to organize the objectives, inputs, and interdependencies inherent to the problem, and gain insight into promising management strategies (Rogers and Fiering 1986, Labadie 2004). To identify promising inundation scenarios for ecosystem services that minimize costs to landowners and waterfowl managers on the Yolo Bypass, the bypass is divided into separate parcels (i) with attention paid to land use, stream inputs, sub-surface aquifer characteristics, and other important topographic / hydrologic controls. Hypothetical inundation of the bypass will then be both spatially and temporally optimized on a weekly time step from February 1st through mid-April. For each time step, the model inundates individual parcels according to the following equations:

$$\text{Min } Z = \sum_{\tau}\left(\sum_{i}\sum_{j} c_{j\tau} * CROP_{i\tau} * a_{ji}\right) + \sum_{t}\sum_{i}(C'_{Wit} * I_i) * DV_{Wit} - (B_{GWit} * I_i)$$

The first term represents opportunity costs to agriculture in the form of shorter growing seasons and reduced yield, with

c_{jit} = Marginal cost of a shorter growing season (τ) for crop j
$CROP_{i\tau}$ = 1 if parcel *i* is *not* inundated for growing season of duration τ, otherwise = 0

S.T.
$CROP_{i\tau} \geq Crp_{it}$, for all t in growing season τ
$Crp_{it} + I_{it} = 1$, for all parcels *i* and all time steps t

a_{ji} = Area of crop j in parcel i (acres)

The second term represents direct costs of flooding to waterfowl managers for flood conveyance requirements (tule eradication) and other costs related to replacement of desired vegetation in waterfowl areas. These costs are defined as:

$$c_{Wi} = (c_{Yt} * a_{Yi}) + (c_{St} * a_{Si}) + (c_{Ut} * a_{Ui})$$

I_{it} = 1 if parcel inundated in time t, otherwise = 0
c_{Yt} = Cost of inundation at time t for annual wetland managers
c_{St} = Cost of inundation at time t for seasonal wetland managers
c_{Ut} = Cost of inundation at time t for upland habitat

DV_{Wit} = Duration cost of flooding, with longer floods having higher financial implications for wetland managers as they encourage a larger volume of undesirable vegetation growth.

The third term represents potential benefits of groundwater recharge in parcel i, based upon substrate characteristics and estimated recharge rates, where

b_{GW} = Financial benefits of ground water recharge on parcel i at time t

Habitat Constraints

The objective function is subject to several constraints. The first of these is a requirement that available habitat satisfy a minimum criteria:

$$H = \sum_t \sum_i h_{it}^{sp} * I_{it} * DV_{it} \geq x \quad \text{(splittail)}$$

$$H = \sum_t \sum_i h_{it}^{cs} * I_{it} * DV_{it} \geq y \quad \text{(juvenile Chinook salmon)}$$

$$H = \sum_t \sum_i h_{it}^{w} * I_{it} * DV_{it} \geq z \quad \text{(waterfowl)}$$

Where
h_{it}^{sp} = habitat value of inundation of parcel i to splittail at time t
h_{it}^{cs} = habitat value of inundation to Chinook salmon at time t
h_{it}^{w} = " ... " to waterfowl at time t
DV_{it} = duration value of inundation in parcel i at time t

For the base case, x, y and z will be set at 50% the maximum attainable habitat value if inundation were to occur for five weeks in late spring across all parcels. This will be adjusted in sensitivity analyses.

Total Inundated Acreage will also serve as a constraint. There is likely an amount of acreage for which marginal benefits of additional inundation become negligible in terms of growth rates for Chinook salmon. Several estimates will be tested in sensitivity analyses.

Parameters

The costs to agriculture and waterfowl managers, assigned habitat values for each parcel, and specified total inundated acreage all work to determine where and when the

optimization model places water on the bypass. These parameter values are to be determined as follows:

1. **Costs to Agriculture**: The most accurate way to define costs of inundation in early spring for separate crop types in the bypass is to simulate delayed plantings and/or flooding with an agronomic model like DAYCENT. This results in production functions that describe yield losses with either delayed planting or flooding during the growing season, which can be translated into revenue losses. These data and results will come as output from the agricultural economics portion of this study (see Task One).

2. **Costs to Waterfowl Managers:** All landowners on the bypass are subject to flood district rules whereby certain levels of vegetation are not permitted as they increase surface roughness on the floodplain. If inundation in spring causes too large a volume of tule growth in waterfowl ponds, managers will be subject to additional removal costs in the form of both labor and equipment.

3. **Habitat Values**: Each parcel will be evaluated for its relative value as inundated habitat for three different species categories: (1) Sacramento splittail, (2) Chinook salmon, and (3) waterfowl. Research focused on these species' use of the bypass will provide a list of land cover characteristics that are most important for each (see descriptions of objectives 2 and 3 above). Aerial imagery, GIS analysis, and field visits will all be used to determine the existence or absence of these characteristics within each parcel *i*, and assign relative habitat value ratings accordingly. Because such ratings are clearly subject to varied interpretations, a broad range of these values will be tested in sensitivity analyses.

4. **Duration Values**: Several studies have reported higher rates of primary productivity on the bypass during large flood events 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 at the Lower Bypass during late March 2000 was higher than the Delta. These higher rates of primary productivity support additional food for splittail and salmon. As such, timing and length of inundation are important to promote algal and zooplankton growth. Length of inundation is also important for splittail life history strategies. Studies in the Cosumnes floodplain have suggested that a 2-3 week inundation period is needed to stimulate phytoplankton growth, while fish benefit from additional inundation up

to 4 or 5 weeks total to take advantage of the blooms of zooplankton and other food (Moyle et al. 2007). If inundated for too long, the principal beneficiaries are alien species that prefer warmer water. To represent the changing value of inundation over time, a function was created that more heavily weights the habitat value of a flooded parcel i as length of inundation increases from 1 to 4 weeks, and penalizes inundation lasting longer than 5 or 6 weeks. For each time step, the duration value of inundation (DV) is calculated as follows:

$$DV_i = v_1 D_{1i} + v_2 D_{2i} + v_3 D_{3i} + v_4 D_{4i} + v_5 D_{5i} + v_6 D_{6i}$$

v_a is the marginal value of the a^{th} week of inundation, where:

$v_1 = 1$, $v_2 = 2$, $v_3 = v_4 = 0.5$, $v_5 = 0$, and $v_6 = -1$

D_{kt} = duration of inundation ending at time t with duration k

To define these duration values in the model, additional constraints are added:

$D_{1ti} \leq I_{ti}$ (for all parcels)

$D_{2ti} \leq I_{ti}$ and $D_{2ti} \leq I_{ti-1}$ so that D_{2ti} can only equal 1 if that parcel is inundated for 2 consecutive time steps.

Generally: $D_{kt} \leq I_{t-j}$, for all $j \leq k$

Finally, $D_1 \ldots D_6$ are constrained as follows:

$D_{di} \leq D_{d1i}$

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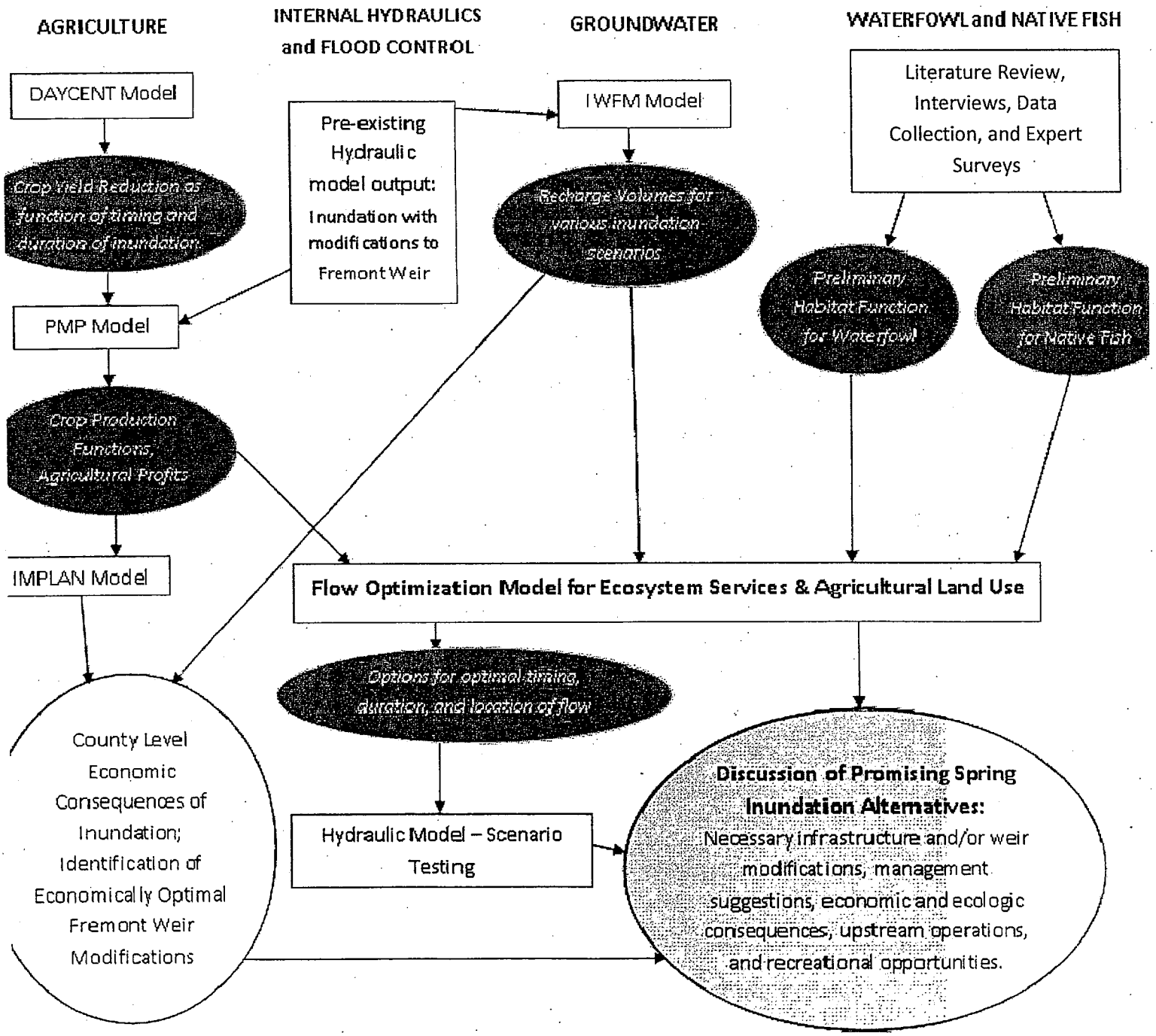
$D_{di} \leq D_{dni}$

Where n = total number of time steps until time t, and d is duration of inundation with $1 \leq d \leq 6$

Figure 3 on the next page summarizes integration and data flow amongst all tasks and study components, culminating with two concluding reports: (1) Identification of economically optimal BDCP-proposed Fremont Weir modifications, and (2) A presentation of this optimal Fremont Weir modification alongside alternative inundation schemes that could further optimize conjunctive benefits to waterfowl, native fish, farmers, and other land managers.


AGRICULTURE
INTERNAL HYDRAULICS and FLOOD CONTROL
GROUNDWATER
WATERFOWL and NATIVE FISH
DAYCENT Model
Crop Yield Reduction as function of timing and duration of inundation
PMP Model
Crop Production Functions, Agricultural Profits
IMPLAN Model
Pre-existing Hydraulic model output: Inundation with modifications to Fremont Weir
IWFM Model
Recharge Volumes for various inundation scenarios
Literature Review, Interviews, Data Collection, and Expert Surveys
Preliminary Habitat Function for Waterfowl
Preliminary Habitat Function for Native Fish
Flow Optimization Model for Ecosystem Services & Agricultural Land Use
Options for optimal timing, duration, and location of flow
Hydraulic Model – Scenario Testing
County Level Economic Consequences of Inundation; Identification of Economically Optimal Fremont Weir Modifications
Discussion of Promising Spring Inundation Alternatives:
Necessary infrastructure and/or weir modifications, management suggestions, economic and ecologic consequences, upstream operations, and recreational opportunities.