Sacramento-San Joaquin Delta
Regional Ecosystem Restoration Implementation Plan

Ecosystem Conceptual Model

Floodplain

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PREFACE

This Conceptual Model is part of a suite of conceptual models which collectively articulate the current scientific understanding of important aspects of the Sacramento-San Joaquin River Delta ecosystem. The conceptual models are designed to aid in the identification and evaluation of ecosystem restoration actions in the Delta. These models are designed to structure scientific information such that it can be used to inform sound public policy.

The Delta Conceptual Models include both ecosystem element models (including process, habitat, and stressor models); and species life history models. The models were prepared by teams of experts using common guidance documents developed to promote consistency in the format and terminology of the models
http://www.delta.dfg.ca.gov/erpdeltaplan/science_process.asp .

The Delta Conceptual Models are qualitative models which describe current understanding of how the system works. They are designed and intended to be used by experts to identify and evaluate potential restoration actions. They are not quantitative, numeric computer models that can be "run" to determine the effects of actions. Rather they are designed to facilitate informed discussions regarding expected outcomes resulting from restoration actions and the scientific basis for those expectations. The structure of many of the Delta Conceptual Models can serve as the basis for future development of quantitative models.

Each of the Delta Conceptual Models has been, or is currently being subject to a rigorous scientific peer review process. The peer review status of each model is indicated on the title page of the model.

The Delta Conceptual models will be updated and refined over time as new information is developed, and/or as the models are used and the need for further refinements or clarifications are identified.

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Floodplain Models Overview

Elements common to all models (Figure 1). Gray shapes ("plaques" in Word parlance) are **other DRERIP models**. Brown polygons are **modifying factors**. Pink rectangles are **primary outputs** of direct interest to Delta restoration planners (e.g., splittail). Blue rectangles are **hydrological characteristics** or variables, primarily pertaining to the primary river that is the source of inundation to the floodplain of interest but some rectangles represent "secondary hydrology" such as water deriving from direction precipitation on the floodplain, and groundwater and tributary inputs. Blue-green rectangles represent **inundated habitat characteristics** – properties of the floodplain during periods of inundation.

Model 1 (Creating the Template) captures the linkages and processes that create the **habitat mosaic**—the physical template of a given floodplain, such as topography and vegetative communities (Figure 2). Note that habitat mosaic is more than vegetative communities as it also includes topographic features like side channels, oxbows, and wetlands. This is a very basic model, so we didn't attempt to use the information-coded arrows to indicate importance, predictability, etc. This model describes how floodplain topography and vegetation, important features treated as more or less static in the other models, are created and maintained. This model encompasses time scales ranging from a single flood event (e.g., bank erosion) to decades or centuries (successional processes in a floodplain forest). Delta restoration planners can use model 1 to understand management options for creating and maintaining habitat mosaics on a given floodplain.

Model 2 (Inundating the template) depicts how a given floodplain, with topography and vegetation created within Model 1, is inundated by river flows and other sources of water to create specific conditions within the inundated floodplain that are important to the species or processes described in model set 3 (Figure 3). The hydrology first encounters river-floodplain topography (e.g., the relative elevations of floodplain to river stage) to determine if the floodplain becomes inundated; the other linkages only occur if flow magnitude is capable of exceeding the inundation threshold. Inundation is a function of flow magnitude in the river, along with contributions from other hydrological sources (e.g., local tributaries, high water table), and the relative elevation and connectivity of the river-floodplain topography. If inundation occurs, the floodwaters interact with the topography and vegetation created in Model 1. As inundation occurs across this mosaic it results in a variety of **inundated habitat characteristics**—conditions that directly affect biota and processes during the period of inundation. These inundated habitat characteristics are the primary inputs for Model Set 3. This model is primarily focused at the temporal scale of a single flood season. Delta restoration planners can use model 2 to evaluate how management actions can influence the inundation of floodplain habitat mosaics and characteristics of the inundated habitat.

Model Set 3 (Management outputs) illustrates how the inundated habitat characteristics, developed in Model 2, interact with a few other key elements to influence the production of biota of direct interest to delta restoration planners, including algae, zooplankton, splittail, and juvenile Chinook salmon (Figures 4 - 7). Model Set 3 encompasses a temporal scale of a single flood season. Model Set 3 can be used to evaluate how specific characteristics of the inundated floodplain affect specific outputs of management interest. Figure 4 provides a basic overview of the inputs and outputs and relationships between the models in Model Set 3. Figure 5 focuses on the production of algae (phytoplankton and epibenthic algae) and zooplankton, structured as a food web. Figures 6 and 7 show how the inundated habitat characteristics and base of the food web (algae and zooplankton) affect the production of splittail and Chinook salmon, respectively.

<u>Primary management outputs from floodplain models</u>

1. **Primary productivity**, in terms of phytoplankton, the most nutritious organic matter for the downstream delta (Muller-Solger et al. 2002) and **secondary productivity** (zooplankton and macroinvertebrates). Because several important species in the delta are food-limited, as indicated by low first-year survival, floodplain restoration has been promoted as a means of increasing productivity to these species and ecosystems (Jassby and Cloern 2000).
2. **Juvenile Chinook**
3. **Splittail**
4. **Habitat mosaic** and riparian structure for a variety of species.

The first three management outputs are Model 3 outputs. For these a user can work backwards through the models to understand how management options can increase the productivity of a specific desired output. For example, if the desired output is biologically available Carbon for downstream ecosystems (algae), then Figure 5 (Model 3) indicates that residence time and intra-annual frequency are important characteristics; for these characteristics of inundation to occur, Figure 3 (Model 2) indicates that the frequency of inundation can be influenced either through hydrologic or topographic manipulations, and the narrative for Model 1 provides background information on the processes that create and maintain floodplain topography. The management output 'riparian structure' is a Model 1 output.

Model 1: Creating the Template

Scales and boundaries

Model 1 encompasses biophysical processes occurring throughout the lower Central Valley and riverine floodplain portions of the delta (i.e., where fluvial, not tidal, processes predominate). The model can be used across a broad range of spatial scales, from a site to a reach or larger. In the narrative, 'floodplain site' refers to the floodplain of interest to the user, which can range across these spatial scales. Model 1 encompasses processes that occur over temporal scales ranging from single flood events (e.g., bank erosion) to decades or centuries (development of mature floodplain forest on an alluvially deposited surface). Central Valley hydrology (e.g., the Sacramento River and San Joaquin River systems) and sediment are primary inputs to the model. Other inputs external to the system include groundwater, which is affected both by the river and by local conditions, and large wood and vegetative reproductive elements originating from upstream of the floodplain site. Large wood and vegetative reproductive elements can also originate from within the floodplain site. All of these inputs can be influenced by management to some degree.

Model objectives

Model 1 describes the biophysical processes that create the physical habitat template upon which floodplain ecosystems develop (also see the **Woody Riparian Vegetation model**), inundation occurs (**Model 2**), and biophysical processes occur during periods of inundation (**Model 2 and Model set 3**). The model objective is to describe the basic processes that create and maintain floodplain ecosystems and how management actions either stress or restore these processes. The primary mechanisms by which management can influence the processes in Model 1 are through the flow regime and changes to the modifying factors that affect connectivity between river and floodplain (e.g., levees and rip-rap). In addition, management actions can attempt to mimic the outputs created by the dynamic processes captured in this model through actions such as topographic manipulation and vegetation management.

Model elements

Model 1 is fairly coarse but provides information on basic processes and modifying factors and can inform the evaluation of management actions for floodplain restoration. In summary, the four external inputs (hydrology, sediment, large wood, and vegetative reproductive elements) interact—through geomorphic processes—with the existing floodplain template (topography, vegetative communities) to create the future floodplain template. Brown polygons denote modifying factors and the pink box encompasses the range of habitat "outputs." Because of the coarse level of this model, we do not use the information-coded arrows, and only include a few negative signs to indicate that levees and rip-rap reduce the interaction between the river and the floodplain and that flow regulation reduces the frequency and/or magnitude of geomorphically effective flows.

The single lines indicate processes operating at the time step of a flood event while the double lines indicate processes that occur over longer time periods. For example, geomorphic processes that affect topography and vegetation are represented by single lines as they occur during the time scale of a flood event. Floodplain vegetation, influenced by groundwater hydrology, develops on the post-flood topographic template to create the post-flood habitat mosaic; all these processes are represented by double lines as they occur over longer time periods than a flood event. The line linking the habitat mosaic with 'current morphology and vegetation' indicates that the habitat mosaic that results from a flood event and subsequent ecosystem development becomes the 'current morphology and vegetation' for the next flood event.

Assumptions and limitations

This model describes broad-scale processes and therefore doesn't provide in-depth attention to a specific process and response (e.g., finer scale hydraulic and sedimentary mechanisms operating during floodplain erosion and deposition processes.) Some of the detail not represented by the model is described in the narrative.

Outcomes

The primary model outcome is a habitat mosaic – comprised of topography and vegetative communities – that are components of and/or inputs to Models 2 and 3. More specific response variables could include the proportion of different habitat types within the matrix or attributes of a specific habitat type (e.g., species composition, structure, etc.). Specific characteristics of the habitat mosaic, such as the proportion or extent of a specific habitat type, exert primary influence on species' life histories, both those described here in conceptual models (e.g., splittail) and those not described here, such as bank swallows, valley elderberry longhorn beetle, waterfowl, wading birds, and passerines. Riparian forests, and communities and species dependant on these forests, are a primary management output of interest to Delta restoration planners.

Model narrative

The model can be read from left to right. During a flood event, flood flows and fluvially mobilized sediment, large wood and vegetative reproductive elements interact with existing floodplain morphology and vegetation and alters its characteristics. Floodplain vegetation continues to evolve on the new topography, influenced by groundwater hydrology, creating a habitat mosaic at a given time step. This habitat mosaic becomes the "new" 'current morphology and vegetation' with which subsequent flood flows interact. These flows can range from a subsequent high magnitude event that reshapes topography and removes vegetation to smaller events that affect vegetative communities primarily through the effects of inundation and deposition of sediment, nutrients and organic matter.

The model has five inputs external to the spatial scale of the model; the first four operate primarily during an inundation event while the fifth, groundwater, operates during ecosystem development between flood events. The five external elements are:

(1) **Surface hydrology** encompasses the various sources that provide flows of water to a given river-floodplain system. For performing geomorphic work (i.e., to move

sediment), the most important part of the surface hydrology is flow from the main river of the river-floodplain system (i.e., direct precipitation and small tributary input likely have minor influences on the geomorphic work performed by the primary river on the floodplain site, although antecedent inundation of the floodplain by these sources can influence patterns of subsequent riverine inundation and thus sediment deposition (Wohl 2000)). For floodplain sites in the lowland Central Valley and Delta, the surface hydrology for a given floodplain is a sum of discharges from regulated and unregulated portions of the upstream watershed and, thus, is a function of precipitation, runoff, and dam operations as well as upstream land use (both in terms of runoff and floodplain storage).

(2) Similarly, the inputs of **sediment** are a sum of the sediment loads deriving from regulated and unregulated portions of the Central Valley watershed as well as more proximate upstream sources such as bank erosion.

(3) **Large wood** should also be considered a basic input to the system that shapes floodplain topography and vegetation. Although large wood is undoubtedly much less common in Central Valley floodplains than it was in the past, due to a legacy of forest clearing and snagging in addition to ongoing trapping behind dams, it has been shown to be a primary structural element in other floodplain rivers (Abbe and Montgomery 1996, Gurnell et al. 2005) and within a lowland Central Valley floodplain (the Cosumnes River Preserve; Florsheim and Mount 2002). The pool of large wood available to a given floodplain site is the sum of both external inputs and local inputs from the floodplain forest.

(4) The pool of **vegetative reproductive elements** (e.g., seeds along with branches, stems and whole trees of the family *Salicacae*) available to a given floodplain is also a product of upstream inputs and local sources. Some tree species' seeds can be deposited by wind, but many of these reproductive elements, including seeds, branches, and trees, are deposited fluvially.

(5) **groundwater hydrology** strongly influences the hydroperiod of floodplain wetlands and the depth to groundwater influences the development of vegetative communities. Groundwater hydrology can be strongly influenced by the adjacent primary river but is also influenced by local factors such as sediment characteristics and groundwater pumping.

The central portion of the model is the interaction of **hydrology**, **sediment** and **large wood** with the existing floodplain topography and vegetation. In the model, these three primary inputs interact with (flow through) the box **current morphology, vegetation and downstream boundary conditions,** in the form of geomorphic processes (the arrow connecting these elements with 'floodplain topography' and 'floodplain vegetation' represents geomorphic processes). **Current morphology** includes the spatial arrangement and relative elevation of floodplain surfaces and the geomorphic character of those surfaces (e.g., grain size, erodibility). **Downstream boundary conditions,** including sea level, grade controls, and topographic features that create backwater effects, also influence the hydrologic and geomorphic processes operating at the given floodplain site. In summary, river hydrology, in concert with sediment and large wood, shapes floodplain topography and vegetation through various geomorphic processes. These geomorphic processes operate through a filter of 'current morphology, vegetation, and downstream boundary conditions.'

Levees and rip-rap are depicted as modifying factors that influence the type, rate, and extent of geomorphic process; these factors can effectively prevent geomorphic processes from occurring on the floodplain site during all but the highest magnitude flood events. **Flow regulation** is also depicted as a modifying factor because it reduces the frequency and magnitude of high flow events that allow floodwaters, sediment and large wood to interact with floodplain topography and vegetation.

Geomorphic processes

Collectively, geomorphic processes operate upon the **current morphology and vegetation**, creating a new arrangement of floodplain **topography** and surfaces and **vegetation**. The type of geomorphic process (e.g., bank erosion vs. crevasse splay formation) and the spatial extent of the area influenced by the geomorphic process depend on complex interactions between all the model elements described above (hydrology, sediment, large wood, existing morphology and vegetation, modifying factors). In general, higher magnitude floods (e.g., > 25-year recurrence interval) result in more dramatic processes, such as channel avulsion, and affect a larger area. Lower magnitude events (e.g., bankfull events) contribute to bank erosion and meander migration. Existing riparian vegetation exerts some influence on geomorphic processes, for example, Micheli et al. (2004) reported that long-term migration rates on the Sacramento River increased from 2.8 m yr^{-1} during the first half of the 20th century to 4.2 m yr^{-1} during the second half of the century, potentially due to the conversion of floodplain forest to agriculture which increased bank erodibility.

For geomorphic work to occur, high energy river flows must interact with floodplain surfaces. **Levees and rip-rap** can dramatically reduce this interaction. Additionally, **channel incision**—due to channelization, levees that confine high-energy flows to narrow channels causing bed degradation, or "hungry water" below sediment-trapping dams (Kondolf 1997)—can also reduce interaction between rivers and floodplains as higher magnitude floods are required to fill or exceed the channel. Thus, levees, rip-rip and channel incision are characterized as modifying factors that have a negative influence on geomorphic processes that are a function of hydrology, sediment, and existing topography.

Large wood, derived from local and upstream sources, potentially can play a significant role in floodplain geomorphic processes. Major wood jams in the channel can induce bank erosion, splay formation or channel avulsion and raise river stage upstream. Wood may have been a primary element influencing rates of channel avulsion in the historic Central Valley lowland river system. Within the channel and on floodplains, large wood influences the local hydraulics of flood flows and influences patterns of erosion and deposition. Within channels, large wood can be a primary influence on pool formation (Beechie and Sibley 1997). On floodplains, wood contributes to topographic heterogeneity (Florsheim and Mount 2002). Large wood deposited on the floodplain during flood flows can promote deposition of fine sediment and protect from subsequent high flows the seedlings and saplings that regenerate in this deposited alluvium. This process can lead to the formation of forested islands in the floodplain (Abbe and Montgomery 1996, Fetherston et al. 1995). Edwards et al. (1999) report that much of the initial regeneration on an 'island nucleus' can come from sprouts of the original deposited and partially buried 'living' large wood (usually willows and poplars). In addition to originating from outside the floodplain site, large wood can also derive from within the floodplain site represented by the arrow from 'floodplain/riparian forests' (within the Habitat Mosaic) with 'large wood.'

Over time various flows performing geomorphic work result in several forms of heterogeneity on the floodplain:

(1) *soils and sediment*, ranging from coarser deposits on abandoned channel beds to areas with very fine sediment; deposited sediment is continuously modified by subsequent flows and by biological activity so that the soils also vary widely in their organic matter content.

(2) *topographic*, with topographic features including natural levees, crevasse splays, side channels, and abandoned channels and off-channel waterbodies. These topographic features vary in their sediment grain sizes and proportions of organic matter in the soil (as described above) and in their elevations relative to the river channel.

(3) *hydroperiod (depth, duration, and frequency of inundation) varies according* to variable elevation, connectivity to the river, and soil characteristics.

Ecosystem Development (see also Woody Riparian Vegetation Model)

Ecosystems develop upon this heterogeneous physical template with species, communities and successional trajectories influenced by the physical heterogeneity (topography, soils, and hydroperiod). In addition to this heterogeneity, dynamic hydrologic and geomorphic processes frequently alter the physical template, community composition and structure of a given floodplain habitat patch during the process of ecosystem development (e.g., ecological succession) resetting communities to earlier successional stages.

Riparian vegetation dynamics—regeneration, succession, and heterogeneity—are linked to inter- and intra-annual variability of the hydrograph and the dynamic hydrologic and geomorphic processes of the floodplain environment (Decamps et al. 1988, Trush et al. 2000). The relationship between riparian forest dynamics and a variety of flow characteristics represents one of the best studied examples of the linkages between hydrological variability and floodplain ecosystems development. Multiple types of flows have significance for riparian forests, including flows ranging from periodic high flows to minimum base flows. Additional specific characteristics of the hydrograph (e.g., the rate of recession) and patterns of interannual variability (e.g., very high flows during the winter following successful establishment can cause high mortality of saplings) influence riparian forest dynamics. These relationships have been summarized in conceptual models such as the recruitment box model (Mahoney and Rood 1998).

Vegetative reproductive elements include seeds and vegetative elements that are capable of sprouting and regenerating a new tree or trees, primarily from trees of the family *Salicacae* which include willows and cottonwoods. These elements range from branches to whole trees which can be deposited and initiate regeneration. Vegetative reproductive elements can also derive from within the vegetative communities of the floodplain site; trees such as narrow-leaved willow (*Salix exigua*) are also capable of regenerating on-site through clonal growth from root suckering (Douhovnikoff et al. 2005). This internal source of vegetative reproductive elements is represented by the two-way arrow between 'vegetative reproductive elements' and 'floodplain vegetation.'

Vegetative reproductive elements are distributed onto floodplain surfaces during flood events with a distribution and extent influenced by the magnitude of the flood (areal extent of inundation during the event), the geomorphology of the floodplain and, to a lesser extent, presence of other trees in relation to their effects on flow routing. The timing of a flood event is closely linked to the reproductive success of reproduction through seed; riparian species in the Central Valley appear to have evolved to release their seed during the period when snowmelt would lead to spring floods (Stella et al. 2006). These spring floods would distribute seeds onto freshly deposited alluvial surfaces created during flood events (e.g., point bars and other locations of deposition created during gemorphically effective floods) which provide the suitable conditions for germination of willow and cottonwood (mineral soil with low levels of litter and shade competition). Successful establishment of willows and cottonwoods from seed is then strongly influenced by the rate of decline of the water table which is controlled by the rate of recession of flows from spring to summer (Mahoney and Rood 1998).

Early successional riparian tree species, such as willow and cottonwood, are adapted to frequent inundation and can reproduce through vegetative processes (e.g., regenerating from sprouts on buried trees, branches, and root masses, and through root suckers) (Yarie et al. 1998). Clonal growth may predominate in riparian corridors along highly regulated rivers that lack the appropriate geomorphic and hydrologic dynamics to support sexual reproduction (Douhovnikoff et al. 2005). In European rivers, riparian vegetation can become established when entire trees are deposited on floodplains and then resprout (essentially clonal growth following uprooting, transport, and deposition) (Edwards et al. 1999, Gurnell et al. 2005). This form of regeneration is also influenced by the rate of decline of the water table with survivorship and establishment greater on sites where the sprouting tree can maintain contact with the water table (Francis et al. 2006). These sprouting trees trap fine sediment and other vegetative reproductive elements during subsequent flows and can lead to the formation of forested islands. These processes haven't been documented on California floodplains but likely do occur based on the biology of the riparian tree species.

Patterns of tree regeneration are influenced by geomorphic forces operating on the floodplain but, conversely, trees can influence floodplain geomorphology (Gurnell and Petts 2002). For example, trees such as willows can grow on alluvial plugs between side channels and the main channel. The trees encourage further deposition on the alluvial plug and can eventually lead to hydrologic isolation of the side channel, except during high flows. Very high flows can restore the connectivity by blowing out the alluvial plug and trees (Amoros 1991). As described above, large wood and trees that regenerate in the protected, low-velocity areas behind the wood influence patterns of sediment deposition and can contribute to island formation and development (Edwards et al. 1999, Gurnell et al. 2005).

Though geomorphically effective high flows structure floodplain vegetative communities through patterns of erosion and deposition, other hydrological patterns also influence strongly the distribution of plant communities. The hydroperiod of a patch of floodplain (the duration and frequency of inundation or waterlogging of the soils, influenced both by surface flows and groundwater) exerts a fundamental influence on the distribution and development of floodplain plant communities (Mitsch and Gosselink 2000). Patches with frequent and long durations of inundation or waterlogging are dominated by wetland plant communities or annual terrestrial plant communities. Woody riparian plants generally grow in areas that are free of inundation or waterlogging for most of the growing season (Trowbridge et al. 2005). Riparian vegetation establishment is thus strongly influenced by the small scale topography created by geomorphic processes such as sand splays. In the Cosumnes River, riparian vegetation established with greater density on sand splays than the surrounding floodplain, as the sand splays had higher elevation and better drainage and thus a shorter hydroperiod (Florsheim and Mount 2002).

Similarly, the depth to the water table can affect the distribution and development of floodplain vegetative communities. Excessive depths to the water table can lead to stress or mortality of riparian trees (Scott et al. 1993, Shafroth et al. 2000). The water table can be influenced by the stage of the river or local effects such as groundwater pumping.

Beavers and ungulate herbivores can exert strong influence on riparian vegetation (Andersen and Cooper 2000, Case and Kauffman 1997, Opperman and Merenlender 2000) as can seed predators that consume acorns (Griggs, pers. comm.).

Habitat mosaic

The processes described above—ecosystem development periodically affected by dynamic hydrologic and geomorphic processes that shape and reshape floodplain topography and vegetation—collectively create a shifting **habitat mosaic** on the floodplain. Note that this mosaic is more than just a collection of vegetative communities but also includes topographic features (which may or may not be vegetated) such as bars, cut banks, oxbow lakes and side channels. Many of the features of the habitat mosaic are direct management objectives, such as a riparian forest with a certain species composition and structure. Further, this mosaic provides the habitat features required by a number of species that are management objectives, including threatened and endangered species and other species of concern such as Valley Elderberry Longhorned Beetle, and Swainson's hawk, bank swallows, yellow-billed cuckoo, willow flycatcher, and numerous other birds including wading birds, waterfowl, and songbirds.

The habitat mosaic at any time period becomes the **current morphology and vegetation** with which subsequent floods interact. This sequential feedback is denoted by the sinuous line connecting the box **habitat mosaic** with the box **current morphology, vegetation and downstream boundary conditions.**

Spatial scale and context

The benefits provided by the floodplain habitat mosaic are generally proportional to the size of the floodplain site, or 'patch' in landscape ecology terms. In addition to size, the location and spatial context of the patch also will influence the benefits provided by the site, including characteristics such as patch shape, connectivity and proximity to other patches, degree of fragmentation, and proximity to modifying factors such as sources of invasive species.

The importance of spatial scale applies to the subsequent two models (Model 2 and Model Set 3). These models describe processes that happen on floodplains during the period of inundation. These processes produce benefits, along with the benefits described in this model (e.g., habitat for songbirds). The benefits produced by floodplains are proportional to the spatial extent of floodplains. For example, the small size of the Cosumnes results in relatively low residence time during flood events (Ahearn et al. 2006), limiting its ability to process materials and to produce phytoplankton and zooplankton during large flow events (during which the small Cosumnes floodplain essentially acts like a wide part of the river with very low residence times). Conversely, the massive scale of the Yolo Bypass (60,000 acres) allows it to have population-scale benefits for splittail (Moyle et al. 2004, Sommer et al. 1997).

Management influences

Management activities can influence several of the drivers, linkages and outcomes of Model 1. As described earlier, flow regulation, levees and rip-rap all greatly reduce the frequency, magnitude and spatial extent of dynamic hydrologic and geomorphic processes. All three of these modifying factors can be adjusted through management such as flow releases to promote floodplain inundation, levee breaches, removal or setting back to increase connectivity between river and floodplain, and removal of rip-rap to increase the geomorphic interactions between river flows and channel banks and floodplain features.

Vegetation management and other direct human activities such as fires influence vegetative structure and habitat characteristics of riparian forests and other floodplain vegetative communities. For example, trees can be cleared from levees and tree growth is often removed or minimized on floodplain surfaces within bypasses or inside levees to maintain low hydraulic roughness. Riparian restoration, including active planting, irrigation, and protection from herbivory can also influence riparian forest composition. Though active riparian restoration approaches can lead to development of riparian forests, experience at the Cosumnes River Preserve indicates that dynamic hydrologic and geomorphic processes are more effective at lower cost for regenerating riparian forests (Swenson et al. 2003).

Similarly, topographic manipulation, such as excavation and grading, can mimic some of the outcomes of dynamic geomorphic process, however direct topographic manipulation can be quite expensive. Topographic manipulation may be one of the few options, however, for promoting inundation of floodplain surfaces where the adjacent rivers have become incised such that providing flows that can exceed channel capacity to inundate the surface are impossible or too expensive.

Model 2: inundating the template

Model 2 shows how a given floodplain, with topography and vegetation created within Model 1, is inundated by river flows and other sources of water to create specific conditions within the inundated floodplain that are important to the species or processes described in Model Set 3.

Objectives

Model 2 illustrates processes and conditions that (1) result in inundation of a given floodplain; and (2) influence habitat characteristics on the floodplain during the period of inundation. In this model, the physical template is relatively static, unlike Model 1 which emphasizes the dynamic processes that, over time, create, alter, and maintain the physical habitat template. Model 2 can be used to scientifically evaluate strategies to alter inundation patterns (e.g., frequency, duration, season of inundation) and to influence habitat conditions within the inundated floodplain.

Scale and boundaries

As with Model 1, Model 2 can be applied across a range of spatial scales. However, while Model 1 depicts processes that are applied with great variability across space and time resulting in a shifting mosaic, Model 2 is more appropriate for a relatively discrete patch of floodplain undergoing an inundation event. Temporally, Model 2 encompasses a single flood season.

Model Elements

The model is presented with a cartoon diagram of (moving from left to right) a river channel, levee (either natural or human-made), and floodplain. The cartoon contains four primary elements: (1) In a column above the river channel are characteristics of **river flood hydrology** such as duration, frequency and magnitude. These characteristics are within blue boxes and are derived from a river hydrograph with flow data. Suspended sediment is also placed above the river, in a brown box, as it primarily pertains to the load of sediment in river water that remains as it inundates a floodplain; (2) To the right of the river is a levee with a dashed line extending vertically from the levee crown. This part of the cartoon captures **river-floodplain topography**. This refers specifically to the topographic relationship between the river channel and floodplain, including the relative elevation of the channel and floodplain surfaces and features that connect the river and floodplain such as levee breaches, sloughs, and side channels. The processes that create, maintain, and alter this topographic relationship are described in model 1. The dashed vertical line, along with the box "threshold for inundation," graphically illustrates that the riverine flood hydrology characteristics do not begin to influence habitat characteristics on the floodplain until the flows exceed this threshold (the exception is rising river stage, through groundwater connectivity, can influence characteristics of the water quality and quantity within floodplain wetlands prior to the connection of surface waters). In this model, modifying factors, denoted by red polygons, act to increase the threshold for inundation; (3) If the threshold is exceeded, then river water enters and inundates the floodplain and interacts with the **habitat mosaic** created in Model 1. Note that the **habitat mosaic** is more than vegetative communities as it also includes topographic features like side channels, oxbows, and wetlands**;** (4) The interaction of riverine flood hydrology with floodplain habitat mosaic results in a variety of **inundated habitat characteristics**, which are the primary inputs to Model Set 3.

Assumptions and limitations

1. The model doesn't capture groundwater interactions with floodplain water quality and quantity prior to surface water connections; note that riverine hydrology can affect habitat characteristics on the floodplain without direct surface water connectivity through changes in water table. This can affect the depth and water quality of floodplain water bodies and influence the depth to water table on the floodplain, influencing floodplain vegetative communities. However, this model emphasizes direct inundation through connectivity of surface waters.
2. Antecedent conditions are not graphically represented in the model but their effect on inundated habitat characteristics are described in the narrative.
3. The model doesn't capture characteristics of floodplain waterbodies before, between, and after inundation events (e.g., a floodplain pond in September).
4. Even in relatively small floodplains there can be great spatial and temporal heterogeneity during an inundation event (Ahearn et al. 2006). This heterogeneity can be discussed in the narrative but is not illustrated graphically.

Outcomes

The outcomes of this model are a variety of **inundated habitat characteristics** that are the primary inputs to Model Set 3. These characteristics include variables such as duration, residence time, temperature, dissolved oxygen, inundated vegetation (defined below) and depth. These characteristics strongly affect biota and processes during the period of inundation and thus influence the production of desired outputs such as juvenile salmon and phytoplankton. Thus, to determine how to increase outputs of salmon, one would start with model 3, determine the most important inundated habitat characteristics, then refer to Model 2 to see what factors influence the range of those inundated habitat characteristics, which are a function of riverine hydrology (within a flood event or season) and the floodplain habitat mosaic, created over time and depicted in Model 1. Delta restoration planners can use model 2 to evaluate how to increase inundation of floodplain habitat mosaics and how to affect the inundated habitat characteristics.

Model Narrative

Threshold for inundation

The threshold for inundation is the river stage at which connectivity begins between river surface water and the floodplain. A primary control on this threshold is the floodplain elevation above the river channel; the greater the elevation the greater the threshold for inundation (i.e., a higher discharge and stage is required to exceed the threshold). **Channel incision**—due to channelization, levees that confine high-energy flows to narrow channels causing bed degradation, or "hungry water" below sediment-trapping dams (Kondolf 1997)—increases the elevation difference and thus increases the threshold for inundation. **Connectivity** also affects flooding dynamics by decreasing the threshold for inundation. **Levees**, both natural and human-made, generally achieve higher elevations than the adjacent floodplain, which increases the stage required for river water to overtop the levee and then inundate the floodplain. In this model, **connectivity** refers to low points or breaches in a flanking levee that provide preferential flowpaths and allow waters to inundate the floodplain at a lower stage than would be required to overtop the levee. For natural levees, sloughs and crevasses can provide this connectivity, while with man-made levees, connectivity can be provided by accidental or intentional breaches, or with weirs. In the model, (intact) levees are shown as a modifying factor that decreases connectivity and thus increases the threshold for inundation.

Secondary hydrology represents hydrological inputs to the floodplain from sources other than the primary river. These include direct precipitation leading to additional surface water and an elevated water table, groundwater inflows, and other tributaries that cross the floodplain. These other sources can begin to inundate the floodplain and mix with rising groundwater inflows and/or surface water from the main river. In some systems, significant inundation of the floodplain can occur from secondary hydrology without inundation from the primary river. Additionally, secondary hydrology can contribute to variability in the water quality of the floodplain, for example by contributing nutrients (Schemel et al. 2004); whether these water quality influences are beneficial or detrimental depends on the specific nature of the secondary hydrology. In this model, secondary hydrology is shown to reduce the threshold for inundation; while secondary hydrology doesn't directly affect the connectivity or relative elevation of the river and floodplain, it can begin the process of inundation and so is shown to reduce the threshold.

Management actions and inundation

To increase the frequency, depth, or duration of inundation, management actions can address the threshold for inundation. Possible actions include increasing connectivity by breaching or removing natural or flood-control levees. The relative elevation difference between floodplain and river channel can also be reduced. Floodplain surfaces can be graded to a lower elevation. A specific example of this is the grading of a swale that extends from a river channel up into a floodplain. The addition of roughness to a channel can also increase the stage for a given discharge and thus reduce the elevation difference between river and floodplain. Large wood or other features can add such roughness and, at one time, large wood likely had a strong influence on the stage at which floodplain inundation occurred. Large-scale land lowering is also possible but generally carries high costs compared to these other strategies for reducing elevation differences. Replicating the inundation dynamics provided by secondary hydrology sources, management actions can direct water from other sources (e.g, pumped groundwater or through irrigation canals) on to the floodplain (e.g., as occurs on the Yolo Widlife area) to create inundation.

Inundated habitat characteristics

Once the threshold for inundation is exceeded and river water enters the floodplain (or inundation occurs through secondary hydrologic sources) the floodplain **habitat mosaic** becomes inundated. Model 2 focuses on the processes that occur within that inundated habitat and how riverine and secondary hydrology interacts with the habitat mosaic to create **inundated habitat characteristics.** These characteristics structure the biotic and abiotic environment for several important "outputs" that depend on inundated habitat, such as splittail, juvenile salmon, and the production of phytoplankton. The habitat mosaic itself is an important driver of these characteristics as are river hydrology and processes that occur within the water column. Topographic heterogeneity and the specific type and structure of vegetation that is inundated can influence the production of these important outputs.

This section of the narrative is organized by listing the various **inundated habitat characteristics** (inputs to Model set 3); for each characteristic, the narrative describes the factors that influence it, including both hydrological and other inundated habitat characteristics. The characteristics are numbered, starting in the upper left. These numbers are just for organization and do not rank relative importance or chronological sequence.

1. Duration refers to how long a given portion of the floodplain is inundated, without regard to the residence time of the water inundating that portion. The duration of floodplain inundation, once inundated, is largely a function of its drainage characteristics (**drainage connectivity** to the river channel which typically is far smaller in cross sectional area than the flood connectivity; groundwater infiltration; evapotranspiration). Achieving inundation is a function of the **river flows** that exceed the threshold for inundation; duration is also driven by the **duration of inputs from secondary hydrology**[1]**,** with the importance dependent upon the relative magnitude of these secondary sources. **Residence time** (see #7 below) also influences duration. Combining these processes yields a typical hydrograph of a rapid climb in stage during storm inflows followed by a gradual stage decline following the storm (Ahearn et al. 2006). The duration of river flows determines how much water is being contributed to a floodplain and residence time influences how long water remains after inputs cease. Duration increases with **intra-annual frequency** of floods, depending on the interval between floods. Re-flooding a patch before it has drained extends the inundation duration and generates greater variability in inundation depth.

[1] This relationship is not currently shown on Figure 3 to reduce complexity and overlapping arrows. It would be represented by an arrow connecting 'secondary hydrology' with 'duration'

2. Intra-annual frequency. The intra-annual frequency of inundation events is directly related to the intra-annual frequency of flood events, which is generally driven by weather patterns each winter (though dam releases can disaggregate the weather-storm flow relationships). Secondary hydrology (not depicted graphically) can also affect the intra-annual frequency of inundation. For example, on the Yolo Bypass, inundation events can occur from secondary hydrology sources (west side tributaries) during periods when the Sacramento River does not overtop Fremont Weir (Schemel et al. 2004).

3. Hydraulic roughness describes the resistance to flow exerted by a surface. Vegetation and topographic variability influence roughness.

4. Nutrients and organic matter are supplied both by the river and by the floodplain vegetation and soils that become inundated. Prior to surface connectivity, nutrients can be delivered to floodplain water bodies from groundwater seepage due to rising river stage (Tockner et al. 1999). Secondary hydrology can be an important source of nutrients to the floodplain (Schemel et al. 2004). This model does not attempt to depict the processing of nutrients and organic matter on the floodplain, which is covered in Model 3 (e.g., transformation, uptake, depletion, etc.). The exception is that a relationship is shown between nutrients and organic matter and dissolved oxygen.

5. Inundated vegetation simply refers to the habitat conditions created when terrestrial vegetation becomes inundated during the flood. The characteristics of inundated vegetation therefore depend on the characteristics of the vegetation on the floodplain available for inundation (e.g., trees, shrubs, grass, rice stubble). This relationship is shown as non-linear because the emphasis is on the structural, or other, characteristics of the vegetation. For example, successional processes can replace low annual vegetation with increasingly taller cottonwood; while the biomass of vegetation that can be inundated increases, this is also simply one form of vegetation replacing another. If splittail preferred the low annual vegetation for spawning then this increase in vegetation biomass is not an increase in inundated vegetation that corresponds to splittail requirements.

6. Temperature. During an inundation event, floodplain water temperature initially corresponds closely to the **river water temperature**. Mixing of waters on the floodplains, including water from the river, water from other sources (other tributaries, groundwater) and antecedent water on the floodplain can create heterogeneous patches of water of different temperature on the floodplain (Ahearn et al. 2006). Floodplain water temperature generally begins to rise above that of the river with longer **residence time** and/or reduced inflow and mixing with river water (Ahearn et al. 2006, Sommer et al. 2001b). Once no longer connected directly to the flooding source, floodplain water temperature is influenced by the season of inundation, as shallow floodplain waters will equilibrate with air temperature. Water temperature can vary vertically in the water column based on mixing (e.g., from wind) and stratification. During the course of the year, average air and thus water temperatures increase from winter to spring to summer. A primary reason for the increase in temperatures is due to **light** as direct sunlight warms the water.

7. Residence time is the length of time that a given unit of water remains in a given place and thus reflects the exchange rate of water at that place (residence time can also be used to describe the dynamics of sediment or nutrient but here we focus on hydrological residence time). Residence time can be calculated in many ways. One simple method is dividing the volume of the area of interest (e.g,. floodplain site) by the flow rate**.** Residence time is inversely related to **velocity;** slow-moving water has longer residence times (i.e., exchanges more slowly) and fast-moving water has low residence times (i.e., exchanges more rapidly). Residence time differs from duration in that duration refers more simply to the amount of time that a given area is inundated; an area can remain inundated by water with either very long residence time (e.g., a pond) or very short residence time (e.g, a river). A part of the floodplain could have very long duration because it is continuously inundated by water moving in from the river, but very low residence time because the water has high velocity resulting in a high exchange rate. **Topographic heterogeneity** affects residence time, primarily through its effects on velocity but also by influencing **depth** and drainage pathways which affect the rate of floodplain draining; longer draining time leads to longer residence time.

8. Light. Similar to temperature, sunlight increases in duration and sun angle (height in the sky) from winter to summer. The intensity of sunlight that irradiates the water column is a function of day length, sun angle, cloud cover, and air quality. **Suspended sediment** in the water reduces the amount of light available within the water column.

9. Dissolved oxygen refers to the amount of oxygen available in the water. For more information, refer to the DRERIP Dissolved Oxygen conceptual model. The ability of water to hold oxygen declines with increasing **temperature** so colder water generally has higher DO values. Water column DO increases with algal photosynthesis and decreases with algal respiration, leading to a diel (day-night) cyclic pattern with the net effect on DO depending on relative length of day vs. night (i.e., season). Organic matter decomposition reduces DO; low DO values can result from long **residence time** on a patch of floodplain with a high stock of dead vegetation available for decomposition; (see food web (Model 3b) for further discussion of decomposition and dissolved oxygen). The complex mixing of waters during a flood event (river flows mixing with antecedent water on the floodplain) can create heterogeneous "patches" of water with varying DO levels. For example, on the Cosumnes floodplain, floodwaters displaced water with high levels of phytoplankton into a very high residence time corner of the floodplain during a time of year when respiration exceeded photosynthesis, resulting in a rapid increase in respiration and dramatic decline in DO (Ahearn et al. 2006), which can be lethal to native fish (Jeffres, unpublished data).

10. Velocity. At a given location, velocity initially generally increases with **flow magnitude** (Ahearn et al. 2006, Sommer et al. 2004), although high magnitudes can lead to backwater effects and actually reduce velocities on the floodplain**. Topographic heterogeneity** contributes to heterogeneous velocities on the floodplain. **Vegetation** provides another source of **hydraulic roughness** which slows velocities on the floodplain. At very high flow magnitudes and flow depths, the effect of vegetation on velocity becomes reduced because it influences a smaller proportion of the overall flow and because much vegetation on the floodplain can bend and “lie down” in high flows, including annual vegetation and young willows and cottonwoods. Velocities typically are highest at flooding locations and decrease once on the flood plain as the cross sectional of the flow enlarges dramatically. Sloughs and channels on the flood plain can carry higher velocity waters further into the floodplain.

11. Depth. Depth on the floodplain is largely a function of the **magnitude of the discharge** in the river, any additional inputs from **secondary hydrology**, **topographic heterogeneity,** and **drainage rates**. Topographic depressions on the floodplain, such as ponds, wetlands, and abandoned channels will contain deeper water.

12. Drainage connectivity refers to the ability of water to drain back off the floodplain after an inundation event. **Topographic heterogeneity** can both reduce and increase drainage connectivity: off-channel waterbodies (e.g., oxbow lakes, ponds) can reduce connectivity by serving as terminal drainage locations, while sloughs and side channels can increase connectivity by facilitating drainage back to the river channel. **Human-built floodplain features,** such as gravel pits, ditches and berms can reduce drainage connectivity (Sommer et al. 2005, Whitener and Kennedy 1999) and so are depicted here as a modifying factor.

13. Inter-annual frequency of inundation is directly related to the inter-annual frequency of flood events in the river, which are controlled by climate and upstream reservoir operations.

14. Suspended sediment is delivered to the floodplain from the river and is a function of the suspended sediment produced by the upstream watershed and transported by the river. The amount of suspended sediment within water on the floodplain declines with decreasing **velocity**; with lower velocity water suspended sediment begins to settle out. Sediment on the floodplain can be resuspended by flows or other other turbulence (e.g., waves caused by wind). Sediment deposition therefore is common at locations where flow velocities decline such as just interior of flooding locations, where internal topography and vegetation reduce velocities, and when spilling onto the floodplain from internal sloughs and channels.

Model Set 3: Management Outputs from an Inundated Template

Objectives

Model Set 3 illustrates how the inundated habitat characteristics, developed in Model 2, interact with a few other key elements to influence the production of biota of direct interest to Delta restoration planners, including algae, zooplankton, splittail, and juvenile Chinook salmon. These models are intended to describe the most important floodplain habitat characteristics for these important management ouputs (e.g., algae or salmon). DRERIP has commissioned other models for these management outputs that are more complex and complete. These models are restricted to the important habitat conditions on the floodplain during a period of inundation. For example, Model Set 3 includes a model for juvenile salmon rearing. This model is only concerned about the manner in which inundated habitat characteristics affect juvenile salmon while they are rearing on the floodplain. For a broader perspective on salmon life history, see the conceptual model for Central Valley Chinook salmon. The model presented here shares some content, but less detail, than two sub-models for floodplain rearing and mortality contained within the Chinook salmon conceptual model.

Scale and Boundaries

The spatial scale for Model Set 3 is similar to Model 2: a discrete floodplain that is undergoing inundation. Model Set 3 encompasses a temporal scale of a single flood season.

Model elements

The primary inputs to Model Set 3 are the inundated habitat characteristics created in Model 2. The outputs are management outputs such as splittail or algal Carbon.

Assumptions and limitations

- Even in relatively small floodplains there can be great spatial and temporal heterogeneity during an inundation event (Ahearn et al. 2006). This heterogeneity can be discussed in the narrative but is not illustrated graphically.
- Species such as Chinook salmon and splittail are influenced by many factors external to the floodplain model that are not captured or described here.

Figure 3 shows the basic structure of these models. From the left, a habitat mosaic (output of model 1) is inundated by water from the river and secondary hydrology sources (model 2 threshold for inundation) to produce inundated habitat characteristics (central green box). These characteristics are the primary environmental variables influencing the floodplain biota of management interest during the period of inundation. To the right of the inundated habitat characteristics box is a simplified food web. The main components of this food web include the primary outputs that managers seek from inundated floodplains, including biologically available carbon, splittail and Chinook salmon. These models can interact with species models (splittail and Chinook salmon) and models for organic Carbon and mercury.

Model 3a: Food web model

Inundated floodplains can produce phytoplankton and other algae (Ahearn et al. 2006), a source of biologically available carbon that is particularly important to downstream food-limited ecosystems such as the Sacramento-San Joaquin Delta (Sobczak et al. 2002). Phytoplankton and attached algae are likely the primary sources of carbon that drive floodplain food webs (Ahearn et al. 2006, Sobczak et al. 2002), so this model (Figure 4) focuses on those algae rather than macrophytes or the detritral loop involving terrestrially derived organic matter. The flow of energy from phytoplankton to zooplankton and other invertebrates strongly influences floodplain benefits for native fish. The primary output of this model is zooplankton and other invertebrates which provide a primary input to subsequent models (3b and 3c).

This narrative focuses more on the production of phytoplankton than periphyton because periphyton have received comparatively little study in floodplains and its relative importance is not certain (Ahearn et al. in press). Ahearn et al. (in press) noted that periphyton could have been exported from the floodplain in the form of coarse particulate organic matter (CPOM; e.g., mats of macrophytes and attached algae) which they didn't study. Although CPOM in the form of detritus has been found to be less nutritious than phytoplankton, the algal component of CPOM could be important and more nutritious.

Basic components

Floodplain organic matter, during inundation, is derived from organic matter delivered to the floodplain by the river (in dissolved and particulate forms) and the pool of organic matter already present on the floodplain, such as coarse particulate organic matter (CPOM) in the form of leaf litter, twigs, etc. As plants, ranging from aquatic macrophytes to phytoplankton, grow and die they contribute to the pools of organic matter within the inundated floodplain.

Nutrients in the water column are also derived both from nutrients delivered by river flows, secondary hydrology sources, and by nutrients already present in the floodplain in the soil, organic matter, and within floodplain waterbodies. Nutrients can become depleted through uptake by phytoplankton. Nutrients in the water column can be replenished by subsequent inundation (Ahearn et al. 2006) or mineralization of organic matter (see biogeochemical processes and nutrient cycling), or inflows of nutrients from other sources, such as secondary tributaries (Schemel et al. 2004)

Biogeochemical processes and nutrient cycling. The organic matter and nutrients on the floodplain undergo biogeochemical processing and nutrient cycling, modifying the amount and form of nutrients available in the water column.

Dissolved oxygen. The river water also influences levels of dissolved oxygen in the water column of the floodplain. Dissolved oxygen (DO) in floodplain waters is initially high upon first inundation, due to high DO in river water and turbulent mixing, but then drops as floodplain vegetation begins to decay. For example, on an experimental floodplain along the Rio Grande River, DO in floodplain water dropped from an initial level 3 mg/L DO (40% saturation) to approximately 0.5 mg/L DO (Valett et al. 2005). DO levels can vary across a floodplain based on amount of available organic matter and rates of decomposition (biogeochemical processes, this model) as well as the source of water, temperature, and hydraulic residence time (see Model 2). Algae and other plants also produce oxygen during photosynthesis; however, at night when plants are not photosynthizing they continue to respire, using oxygen. Phytoplankton blooms can lead to low DO during die-offs leading to high microbial respiration. The level of DO strongly affects biogeochemical processes. Also see the Delta Low Dissolved Oxygen conceptual model.

Phytoplankton and other algae

This section of the narrative describes the primary characteristics that affect the production of phytoplankton and periphyton. Periphyton can be very hard to measure and quantify, but it produces labile carbon and some researchers suggest it can be a primary source of energy for floodplain foodwebs (Bunn et al. 2003) and may equal or exceed phytoplankton in terms of importance to the floodplain food web (Welcomme 1979).

The most important variables influencing algal growth are the standard limiting factors of temperature, light, and nutrients, along with residence time and grazing pressure by zooplankton and macroinvertebrates.

Velocity. In general, phytoplankton concentration is inversely related to flow and velocity (Sommer et al. 2004) as higher velocities act to physically displace and thus transport phytoplankton; consequently, phytoplankton are generally found within very low velocity waters (Cushing and Allan 2001). Periphyton are less vulnerable to displacement due to high velocities, although exposure to very high velocities will displace periphyton and/or entrain their supporting structures.

Residence time. Phytoplankton productivity is initially positively correlated with residence time (Ahearn et al. 2006, Schemel et al. 2004, Sommer et al. 2004); phytoplankton concentrations are low during inundation events when residence time is low, due to both dilution and displacement. To the extent that concentrations are lower due to dilution, total biomass of phytoplankton can actually be higher during higher flows because the total water surface area and volume increases (Welcomme 1979). However, high velocity flows (with very low residence time) can flush phytoplankton from the floodplain and transport them downstream; if residence time is shorter than phytoplankton growth rate, then biomass accumulation will not occur (Schemel et al.

2004). Long residence time can result in a depletion of nutrients and reduced productivity, which is why this is shown as a non-linear relationship. Further, during long residence time, zooplankton can graze phytoplankton and reduce standing biomass; both grazing pressure and nutrient depletion, and specifically N-limitation, can lead to transition to more grazing resistant N-fixing phytoplankton as time progresses since a "resetting" flood event (Grosholz and Gallo 2006). For more on the relationship between residence time and productivity, see the discussion for *intra-annual frequency.* Periphyton likely have a similar relationship with residence time in terms of grazing pressure and nutrient limitation. As described above, under *velocity*, periphyton are somewhat less vulnerable to displacement and so are less likely to be affected by the displacement component of residence time.

Temperature. Phytoplankton productivity increases with temperature (Cushing and Allan 2001, Sommer et al. 2004). Although this relationship has a threshold beyond which increasing temperatures will retard phytoplankton growth, under the common conditions of floodplain inundation in the Central Valley this can be considered a straightforward positive relationship as those threshold temperatures typically are well above ranges found in the Delta. Flooding in the spring, with more sunlight and warmer temperatures, will lead to greater productivity of phytoplankton than winter flooding. Sheibley et al. (Sheibley et al. 2006) found that nitrate removal from the water column increased with increasing water temperature, attributed to increased uptake activity of phytoplankton. Overall warmer waters can change the species composition of phytoplankton and warmer waters favor cyanobacteria that can produce nuisance or harmful blooms (Jassby et al. 2003). Research elsewhere has shown that, on temperate floodplains, productivity and Flood Pulse benefits can be limited if floods don't occur within a proper temperature range (Schramm Jr. and Eggelton 2006).

Light. Photosynthesis increases with increasing light so greater light availability in the water column leads to increased production of phytoplankton (Cushing and Allan 2001).

Nutrients. Algal growth depends on the uptake of nutrients from the water column. These nutrients can be supplied in dissolved form through river inflow or from the processing or organic matter (transported by the river or present on the floodplain, from terrestrial and aquatic plant litter) through biogeochemical pathways. Low nutrient availability can limit algal growth. On the Cosumnes River it was reported that phytoplankton was initially N-limited (Ahearn et al. in press); later in the season there was an increase in the proportion of N-fixing phytoplankton and the system shifted to being P-limited (Grosholz and Gallo 2006). Phytoplankton blooms can deplete the water of nutrients leading to declines in productivity. Subsequent inundation (Ahearn et al. 2006) or mineralization of organic matter, or inflows of nutrients from other sources, e.g. other tributaries (Schemel et al. 2004) can replenish nutrients in the water column and continue to maintain phytoplankton growth.

Intra-annual frequency. Phytoplankton concentrations tend to be greatest during the draining period of an inundation event (Ahearn et al. 2006, Schemel et al. 2004) and thus researchers have recommended that total phytoplankton production from a given floodplain could be maximized by increasing the intra-annual frequency of floods. Ahearn et al. (2006) reported that phytoplankton productivity peaked 2-5 days following disconnection with the river (and cessation of river inflow). They suggest at least two days between connections to “prime” the “productivity pump.” However, the peak in phytoplankton occurs in more than two days (Hein et al. (2004) suggests 10 days, so there may be a truly optimal interval of sequencing of floods).

Dissolved oxygen. While algae produce dissolved oxygen as a photosynthesis by-product, they also consume dissolved oxygen during respiration, leading to a diel cycle of water column DO levels that can affect habitat suitability for other aquatic organisms. Photosynthetic activity from phytoplankton and periphyton adds oxygen to the water and can result in floodplain waters having significantly higher levels of DO than river water (Grosholz and Gallo 2006). However, death and decomposition of algal biomass can lead to low levels of DO (sometimes quickly) which can cause mortality of fish (Ahearn et al. 2006; and Jeffres, unpublished data).

Inundated vegetation. The shade produced by tall vegetation (trees, shrubs) can limit algal production and thus phytoplankton production is generally highest in open areas (Ahearn et al. 2006). However, vegetative structure, from either inundated terrestrial vegetation or aquatic macrophytes, provides attachment sites for periphyton. Tall vegetation, such as trees, can also shade periphyton, reducing growth rates.

Zooplankton and aquatic macroinvertebrates consume phytoplankton and periphyton, reducing the standing stock of algae.

Zooplankton

Zooplankton in Central Valley floodplains include *Daphnia,* and *Cladocerans* and rotifers. Below are the factors that influence production of zooplankton.

Food resources (phytoplankton and periphyton). Zooplankton can consume both algal and detrital carbon[2]. Research has shown that zooplankton may be food limited if phytoplankton concentrations drop below a level corresponding to 10 µg l^{-1} Chl *a,* based on laboratory trials with Cladocerans (Muller-Solger et al. 2002). Detrital organic matter appears to be a less important food resource and even where detrital carbon dominates the carbon budget, phytoplankton availability exerts the strongest control on zooplankton growth (Muller-Solger et al. 2002, Sobczak et al. 2002). Phytoplankton productivity is greatest during the draining stage, and on the Cosumnes floodplain Chl *a* was measured at 19 and 18 µg L^{-1} during two draining periods in 2005, approximately four times that level found in the river (Ahearn et al. 2006). In the Yolo Bypass, phytoplankton density can be high

The most important variables influencing zooplankton production are hydraulic residence time and the availability of food resources (e.g., phytoplankton and periphyton)

[2] The relationship between detrital caron and zooplankton is not currently shown on Figure 5 to reduce complexity and overlapping arrows. It would be represented by an arrow from 'organic matter' to 'zooplankton' (medium in thickness, green, and positive).

enough to produce a Chl *a* concentration of up to 23 μg l^{-1} (Schemel et al. 2004). Thus floodplains during the draining stage can produce concentrations of phytoplankton that provide adequate food resources for zooplankton growth.

Velocity. High velocity flows can displace zooplankton so they can be orders of magnitude higher in low-velocity floodplain waters than in river channels (Grosholz and Gallo 2006). Crustacean zooplankton densities in the Yolo Bypass were inversely related to flow (velocity); in addition to effects of flow transporting zooplankton from the floodplain, velocities may have precluded successful zooplankton reproduction (Sommer et al. 2004). Zooplankton reproduction is rare above flow velocities of 0.4 m s^{-1} (Rzoska 1978, cited in Sommer (2004))

Residence time. Zooplankton density initially increases with residence time, due to low velocities and reduced transport rates and to increases in the availability of algae. With further increases in residence time, zooplankton reach a peak density and then begin to decline (Baranyi et al. 2002). Grosholz and Gallo (2006) found that zooplankton densities peaked about 2-3 weeks after disconnection between river and floodplain (draining phase) and therefore recommended several pulses during the year, separated by 2-3 weeks, to maximize production of the zooplankton eaten by juvenile fish. The decline in zooplankton with increasing residence time is due to a reduction of the food base and predation by fish. Despite warmer water and higher productivity, the Yolo Bypass didn't support significantly higher densities than did the Sacramento River; even though residence time in the bypass was significantly longer than in the river, the residence time was still probably insufficiently long for complete zooplankton development and reproduction (Sommer et al. 2004).

Temperature. Zooplankton require a minimum temperature for growth. Grosholz and Gallo (2006) reported that there was only a weak positive relationship between zooplankton productivity and average temperature. In the Danube, the density of one taxa of zooplankton (*Trichocerca*) were positively correlated with temperature (Reckendorfer et al. 1999). Although temperature may not be the most important variable, zooplankton have higher growth with higher temperatures (Reckendorfer et al. 1999), so it is likely that spring flooding (April and May) will result in greater productivity than winter flooding (January and February).

Dissolved oxygen is required by zooplankton for survival.

Suspended sediment can inhibit zooplankton feeding (Baranyi et al. 2002, Sommer et al. 2004).

Macroinvertebrates

Velocity. Drift macroinvertebrates, including chironomids and terrestrial invertebrates, were the primary food resource for juvenile Chinook in the Yolo Bypass (Sommer et al. 2001b) and, were positively correlated with flow (discharge and flow velocity). In the Yolo Bypass, these organisms attain high densities soon after inundation, providing a food source to fish that is available prior to the development of food web productivity associated with long residence times (e.g., phytoplankton and zooplankton responses to inundation) (Sommer et al. 2004). Thus, higher velocity water at a floodplain site may increase the amount of drift and terrestrial invertebrates that are transported to a site. However, high velocity water can also displace inverterbrates from the site downstream (e.g., 'catastrophic drift') (Cushing and Allan 2001) so, within this conceptual model, the relationship between velocity and invertebrates is shown to be nonlinear.

Dissolved oxygen. Macroinvertebrates obtain oxygen from the water (Cushing and Allan 2001) and thus require sufficient dissolved oxygen within floodplain waters for growth and persistence.

Food resources (phytoplankton and periphyton, zooplankton, and organic matter)[3]. Macroinvertebrates feed on a broad range of food resources, and thus macroinvertebrate productivity will generally increase with increasing availability of food resources.

Inundated vegetation. Macroinvertebrates are often associated with floating and emergent plants and higher densities of macroinvertebrates are often associated with vegetative structure (Welcomme 1979).

Model 3b: Splittail

Splitail may be one of the few native California fish that can be considered an obligate floodplain spawner and splittail population dynamics are strongly associated with annual patterns of flow and floodplain inundation (Moyle et al. 2004). For example, the strength of splittail year class (age-0 abundance) is highly correlated to the duration of inundation of the Yolo Bypass (Sommer et al. 1997).

Depth. Successful splittail spawning occurs if the floodplain "maintains appropriate depths…" (Moyle et al. 2004). Spawning preferences haven't been rigorously tested, but observations from the Cosumnes found spawning occurring in open areas < 1.5 m deep with dense growth of terrestrial plants (Crain et al. 2004). In the Sutter Bypass, spawning occurred with a water depth of approximately 2 m (Moyle et al. 2004 citing R. Baxter, unpublished data). Sommer et al. (2002) found that young-of-the-year (YOY) splittail used a range of depths throughout the day in a model floodplain wetland: deeper water at night and shallow water edge habitat during the day.

Season. Adult splittail move into inundated areas in late February or early March and spawning occurs in March and April; however, spawning can occur later in April and into May as well. The spawning time range is perhaps as broad as late February to early July, but later than May is "highly unusual" (Moyle et al. 2004). Recent research from the Yolo Bypass suggests that spawning is most likely to occur near the vernal equinox (late March) (Feyrer et al. 2006). Splittail YOY have been observed leaving floodplains (Yolo

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[3] This relationship is not currently shown on Figure 5 to reduce complexity and overlapping arrows. It would be represented by an arrow connecting 'organic matter' to invertebrates (green, thick, positive)

Bypass and Cosumnes) in May (Moyle et al. 2004). Thus, inundation in March through May is conducive to successful splittail spawning.

Duration. Continuous inundation is necessary for successful spawning, incubation and initial rearing of larval splittail. Splittail eggs require 3-5 days to hatch (Moyle et al. 2004). Larval and juvenile splittail will remain on the floodplain while conditions are appropriate. Emigration from the floodplain appeared to be related to fish size as most YOY leaving the Yolo Bypass were between 30-40 mm in length. This size range suggests that a duration sufficient for fish to reach this size will be optimal (Feyrer et al. 2006). Spawning success may also be improved by longer duration flooding that allows adults time to feed on earthworms on floodplains prior to spawning. The energy gained by feeding on worms may improve adult condition factor and egg production (Moyle et al. 2004). Thus the optimal duration will allow for adults to enter floodplains, feed and spawn, for eggs to incubate and hatch, and then provide sufficient duration for the YOY to reach 30-40 mm in length. The strongest year classes of splittail occur in years with continuous inundation of floodplains (e.g, Yolo Bypass, Cosumnes) during March and April (Moyle et al. 2004).

Temperature. Spawning has been observed at water temperatures < 20º C; 18.5 C is suitable for eggs to hatch (Moyle et al. 2004). Otherwise there are few data on temperature preferences for splittail spawning.

Inundated vegetation. Splittail eggs are adhesive and adhere to vegetation for incubation (Moyle et al. 2004). On the Cosumnes River floodplain, spawning was observed in open areas < 1.5 m deep with "dense growths of annual terrestrial plants; dead cocklebur plants may be especially favored because they provide shelter from predators and high flows and are a source of invertebrate prey" (Moyle et al. 2004 citing Crain et al. 2004). In the Sutter Bypass, spawning sites were characterized by both annual and perennial vegetation (Moyle et al. 2004 citing R. Baxter, unpublished data). Larval fish may also prefer to rear within inundated terrestrial vegetation (Moyle et al. 2004).

Velocity. There are few specific data available for velocity preferences for splittail. Because of their preference for floodplain spawning presumably splittail prefer relatively low velocities (i.e., much lower than river flow velocities). However, they also do not seem to prefer still water as Moyle et al. (2004) report that "spawning areas are…characterized by the presence of flowing water, which helps keep water temperature and clarity low." Spawning in the Sutter Bypass occurred with "detectable flow" (Moyle et al. 2004 citing R. Baxter, unpublished data).

Dissolved oxygen. Splittail are tolerant of very low levels of dissolved oxygen (< 1 mg O_2 L^{-1}) (Young and Cech 1996) and thus likely can tolerate the levels of dissolved oxygen typically found on floodplains. For example, a portion of the Cosumnes floodplain experienced low DO due to long residence time and the decomposition of vegetation; the level of DO that occurred (3 mg O_2 L^{-1}) was lethal to juvenile Chinook (Jeffres, unpublished data) but is still above the level that splittail can tolerate.

Food resources (zooplankton and a macroinvertebrates) (from food web model); productivity is very important for successful splittail utilization of floodplain habitats. Adult feed within floodplains prior to spawning and YOY begin feeding not long after emergence. YOY primarily feeds on chironomids and cladocerans during early life stages (Moyle et al. 2004). Although there aren't specific studies on the relationships between food availability and the growth and survival of YOY, we can infer from basic understanding of fish ecology that the availability of prey items will strongly influence these outcomes.

Drainage connectivity. For successful floodplain rearing, YOY splittail must be able to emigrate from the floodplain. Certain floodplain features can serve as barriers or stranding areas for juvenile fish; in particular, human-built features such as gravel pits, canals, and berms can prevent emigration back to the river (Sommer et al. 2005).

Interannual frequency. Splittail populations can be maintained without annual occurrence of the appropriate spawning conditions on floodplains, both because occasional strong year classes can maintain populations and because there is some spawning even in very dry years (e.g., along channel margins) (Moyle et al. 2004). However, splittail populations will generally increase with increasing frequency of appropriate spawning and rearing conditions on floodplains.

Model 3c: Juvenile Chinook Salmon

Juvenile Chinook salmon have been documented to use floodplain habitats in California (Sommer et al. 2001b, Whitener and Kennedy 1999). Fall run have been documented rearing in the Yolo and Sutter Bypasses and spring-run Chinook may use these habitats (Sommer et al. 2005 and Feyrer et al. 2006). Juveniles from the Cosumnes River's small fall run have been documented utilizing the Cosumnes floodplain (Swenson et al. 2003). It is not known to what extent steelhead trout use floodplain habitats, so the section below focuses on juvenile Chinook salmon.

Temperature. Salmon have specific and well-studied temperature tolerances. However, tolerable or optimal temperatures are influenced by food availability (Myrick and Cech 2004). Optimal temperatures for growth of Chinook juveniles are considered to be 13-18º C (Moyle 2002). Floodplains generally have warmer water temperature than do rivers, and this increased temperature has generally been considered to be beneficial to rearing salmonids (within but not exceeding the optimal temperature range). For example, the Yolo Bypass was up to 5º C warmer than the river (Sommer et al. 2001b) and off-channel habitats along the upper Sacramento River were 2 - 4º C warmer than the river (e.g., 2001: 16º C in the floodplain, 13º C in the river; 2002: 13º C in the floodplain, 11º C in the river) (Limm and Marchetti 2003). Thus within the range of temperatures generally observed within rivers and floodplains during the common period of inundation (winter to early spring), salmon growth can be considered to increase with temperature. Sommer et al. (2001b) note that the increased prey availability in the Yolo Bypass likely offset any increased metabolic requirements from the warmer floodplain water (relative to the Sacramento River). It is possible that floodplains could experience very high temperatures during spring flooding that could be detrimental to salmon. However, juvenile Chinook within enclosures on the Cosumnes River floodplain continued to grow rapidly even as daily afternoon temperatures reached levels generally considered lethal to salmon (25º C). This observation suggests that the salmon were able to tolerate these temperatures due to the high density of prey items; the availability of prey can influence the range of temperatures tolerable to salmonids (Myrick and Cech 2004).

Duration. In general, floodplain benefits for juvenile Chinook should increase with increasing duration of flooding (thus this is a linear positive relationship). However, even relatively short periods of access may provide benefits as fish reared in enclosures on floodplain habitats showed rapid growth in a two-week interval on the Cosumnes River floodplain (Jeffres, unpublished data).

Season. The migration of juvenile salmon generally coincides with peak flows and so also generally coincides with access to floodplains. However, the specific timing of emigration varies from run to run, from river to river, and from year to year. Most fall-run fish emigrate between December and March (Williams 2006). Non-native fish begin to access the floodplain later in the spring (Crain et al. 2004) so, in general, flooding to benefit native fish over non-natives would occur in the winter and early spring, ending in April.

Velocity. Juvenile salmon are generally considered to prefer low velocity habitats (Bjorn and Reiser 1991) but the velocity preferences of salmon on floodplains has not been well studied. Presumably, however, salmon are utilizing floodplains in large part because of the low velocity, shallow habitat available.

Drainage connectivity. For successful floodplain rearing, juvenile salmon must be able to emigrate from the floodplain. Emigration may be triggered by rising water temperatures or other visual cues. In general, floodplains have not appeared to be population "sinks" and preliminary evidence suggests that salmon reared in the Yolo Bypass have similar or higher long-term survival rates as salmon reared in the river (Sommer et al. 2005). However, certain features can serve as barriers or stranding areas for juvenile fish; in particular, human-built features such as gravel pits, canals, and berms can prevent emigration back to the river.

Depth. In general, juvenile Chinook are considered to prefer relatively shallow habitats (15 – 60 cm) (Bjorn and Reiser 1991), although depth may not be particularly important for Chinook utilization of floodplains as Ahearn et al. (2006) found that, during various portions of the flood-draining cycle, both deep and shallow portions of the floodplain had high productivity.

Vegetation. Juvenile salmon have been caught using a wide range of habitats on the Yolo Bypass, ranging from rice stubble to bare ground (Ted Sommer, pers. comm.) It is not well established what vegetation types are preferable for juvenile Chinook on floodplain. The most important characteristic of vegetation is likely to be its effect on prey availability, and secondarily as cover.

Dissolved oxygen. In general, salmon require well oxygenated water. Floodplain conditions can produce low levels of DO (e.g., long residence time and decaying vegetation) that are lethal to juvenile Chinook. For example, a patch of low DO water on the Cosumnes floodplain (3 mg O_2 L^{-1}) was quickly lethal to juvenile salmon within an enclosure (Jeffres, unpublished data). However, it is not known how common such conditions are and salmon would likely avoid low-DO patches of water. Further, as described for temperature, tolerances to DO are influenced by the availability of food. Therefore, even though the relationship between DO and salmon has been well studied, there are several unknowns for transferring information about this relationship to floodplain environments. In general, however, it can be assumed that higher DO is better on floodplains.

Interannual frequency. Salmon population benefits will increase with increasing interannual frequency of flooding.

Food resources (zooplankton and a macroinvertebrates) (from food web model); The higher growth rates of juvenile Chinook on Central Valley floodplains, relative to river habitats, has largely been attributed to the greater availability of prey items within floodplain habitats (Jeffres et al. in press, Sommer et al. 2001b). For example, Sommer et al. (2001b) reported that density of Dipterans could be 1-2 orders of magnitude greater in the Yolo Bypass then within the adjacent Sacramento River and Grosholz and Gallo (2006) found that zooplankton biomass was 10 – 100 times greater within floodplain habitats of the Cosumnes River than within the main channel.

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Figure 1. Common model elements

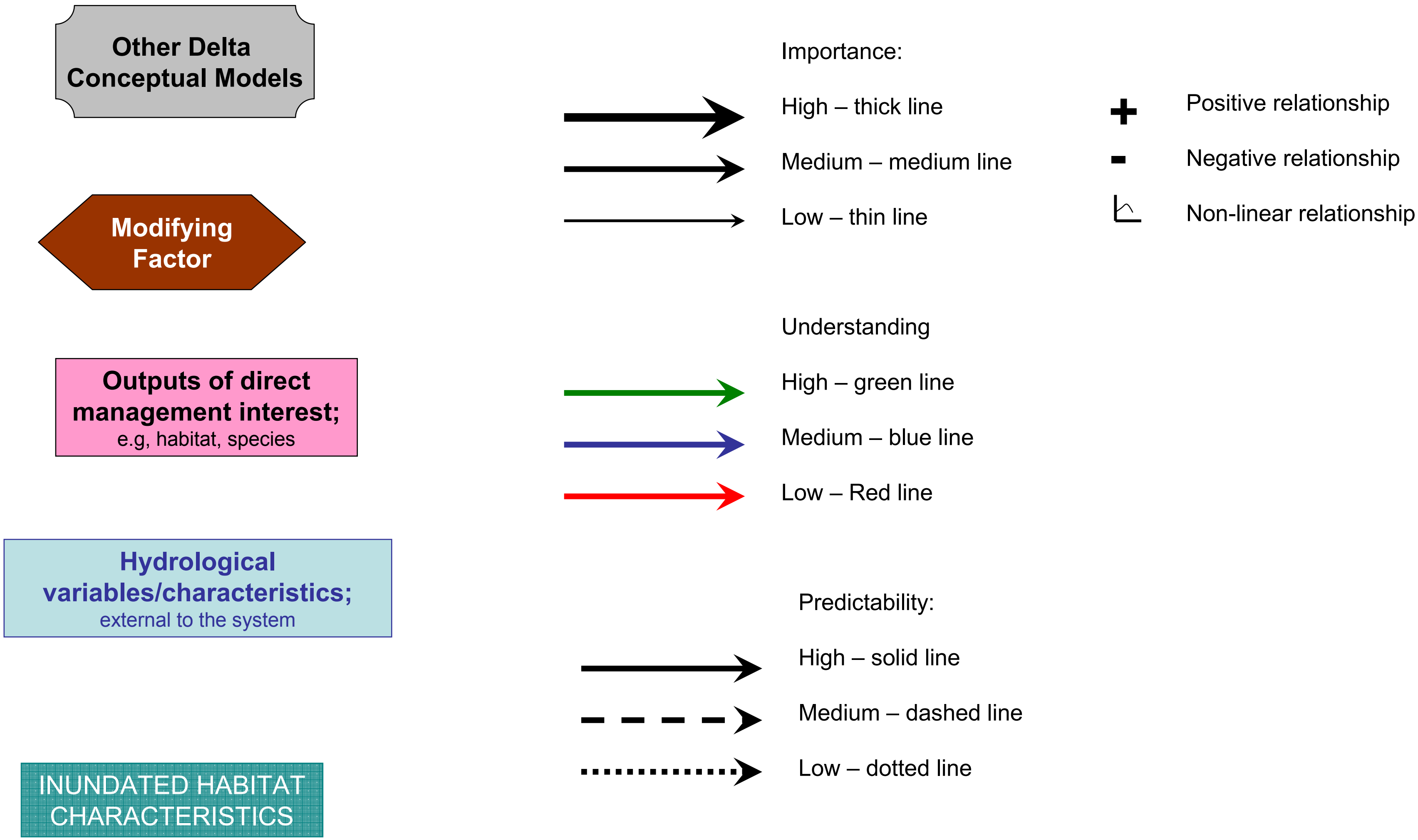


Figure 2. MODEL ONE – Creating the template

(see also Woody Riparian Vegetation model)

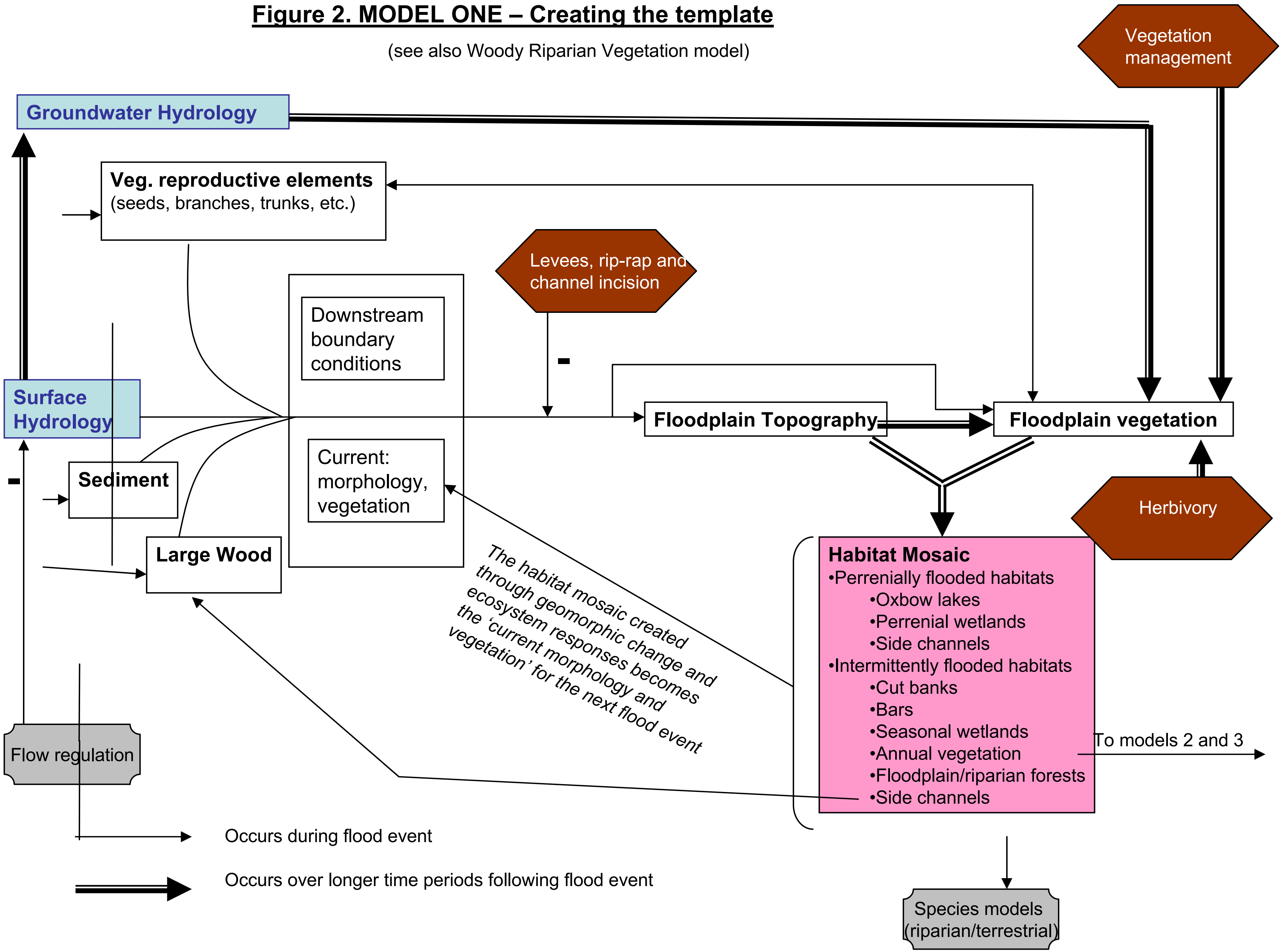
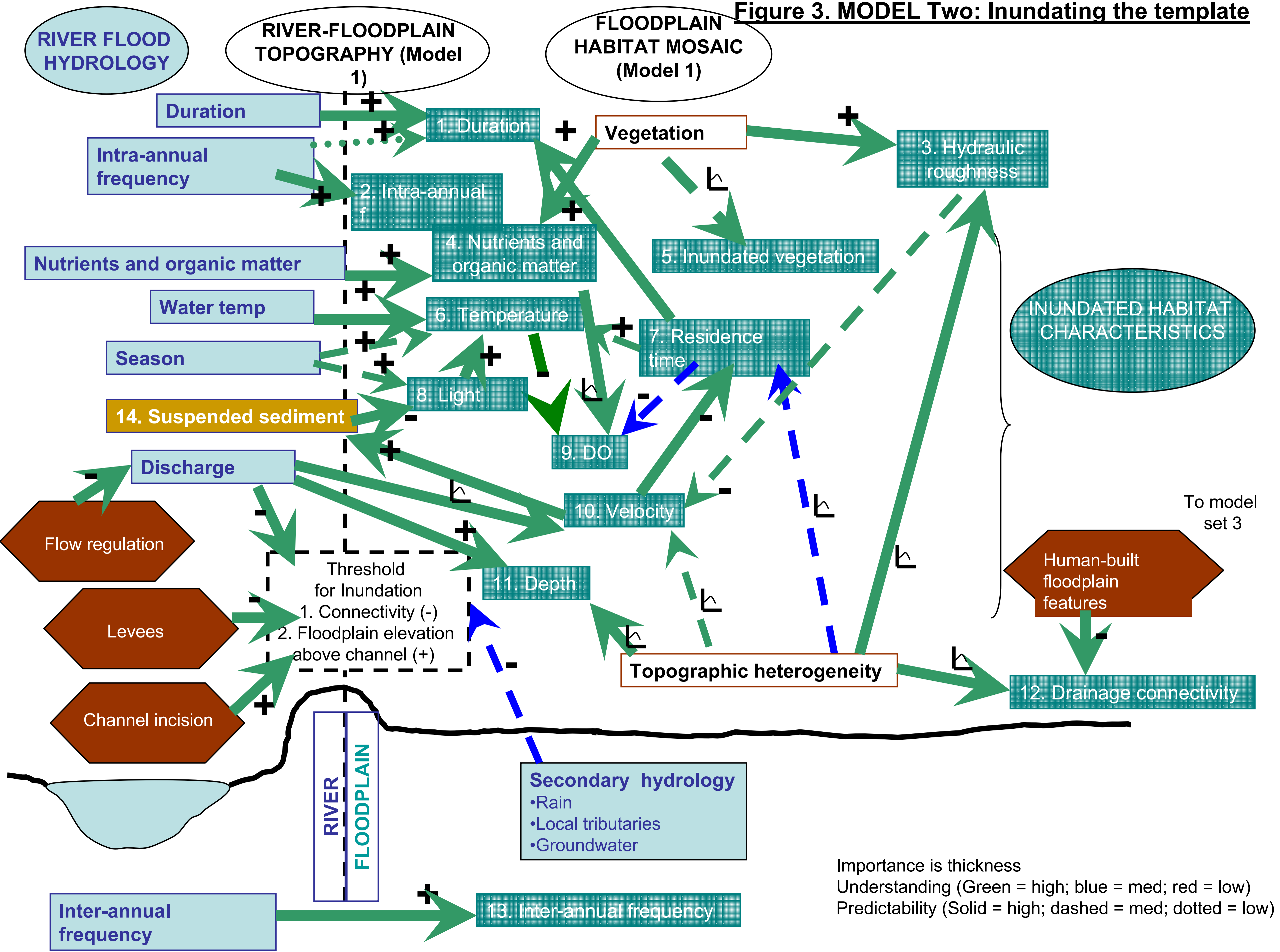


Figure 3. MODEL Two: Inundating the template



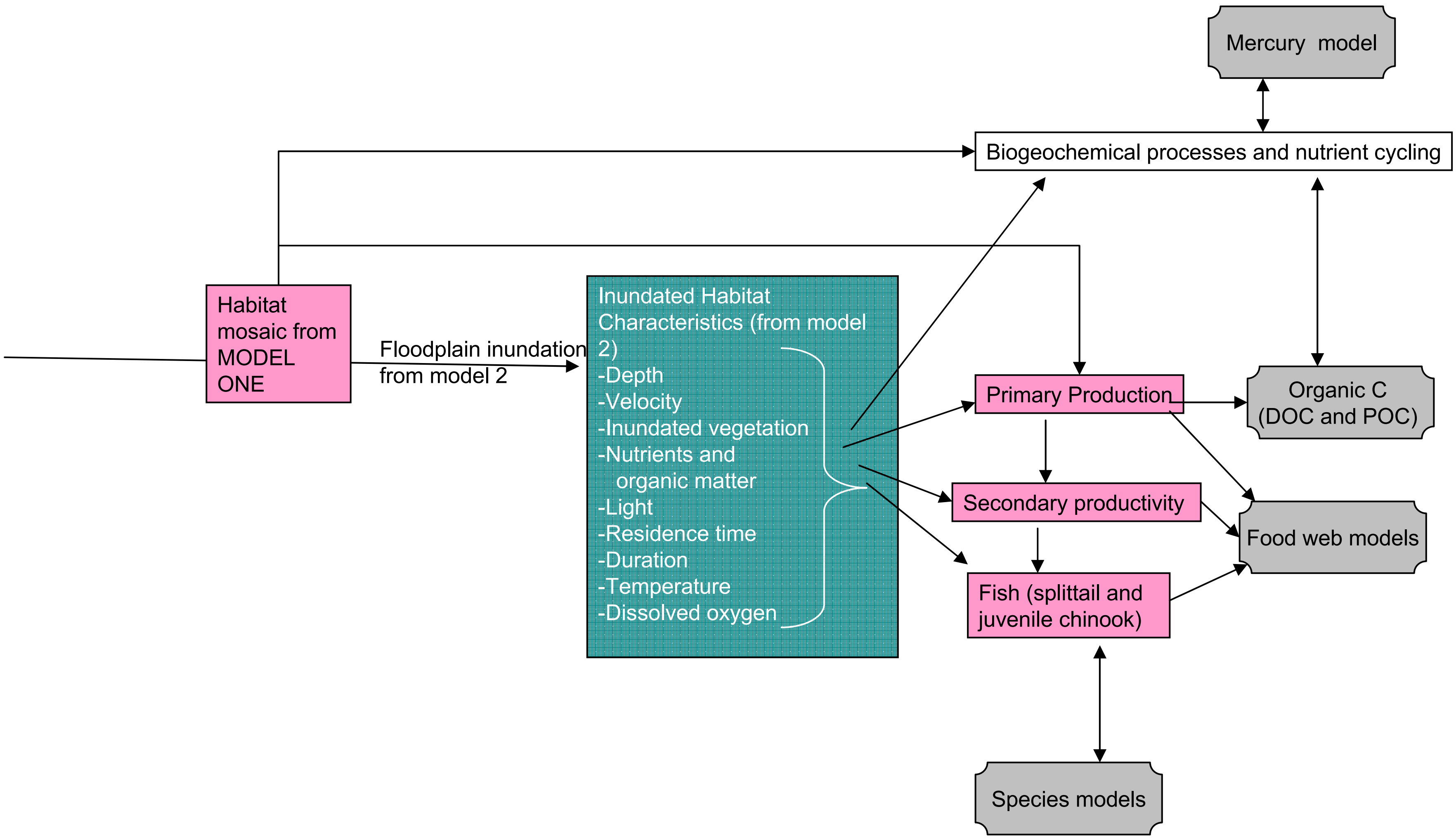


Figure 4. MODEL Set Three - *Framework for* management outputs from an inundated template

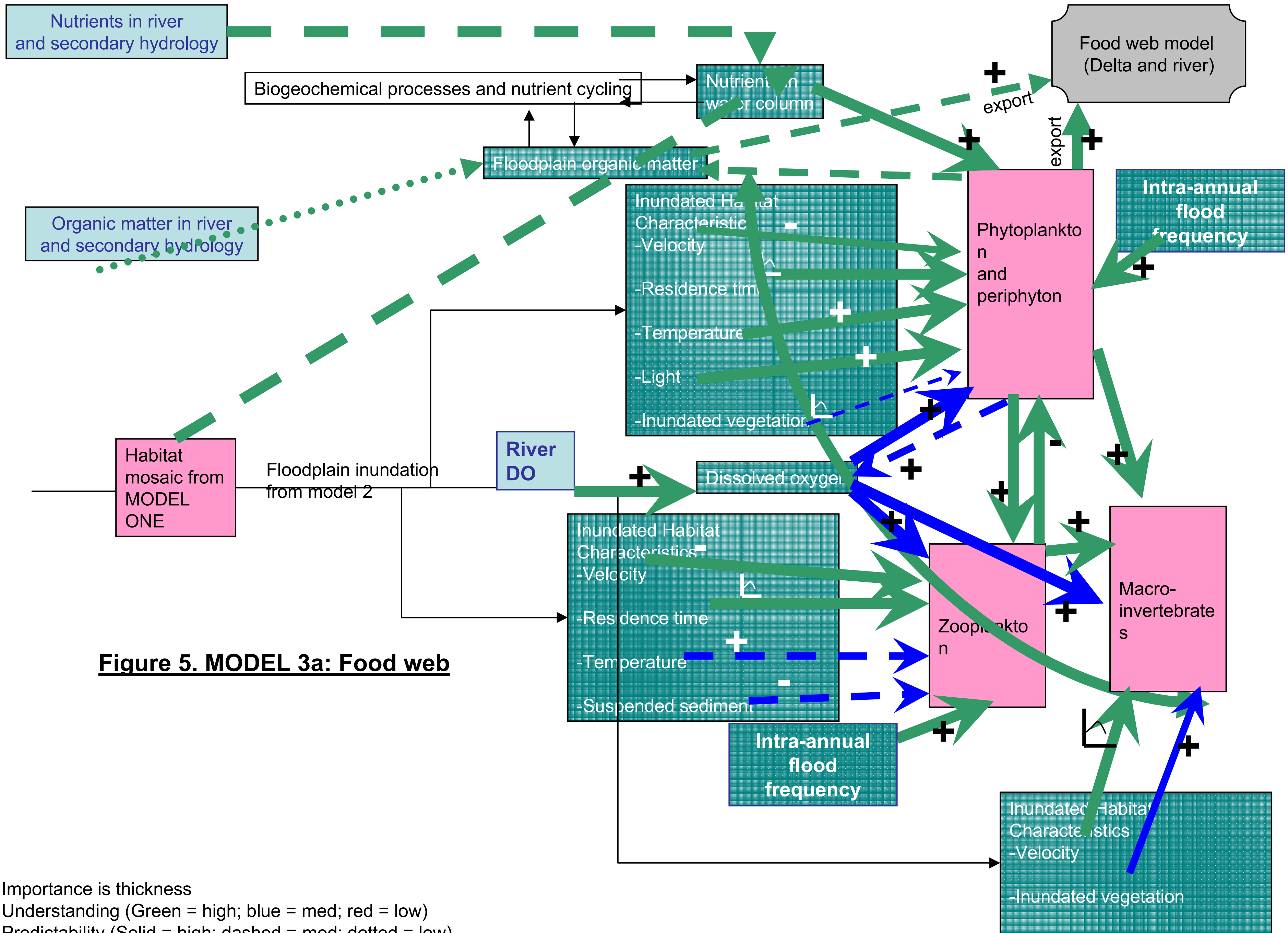
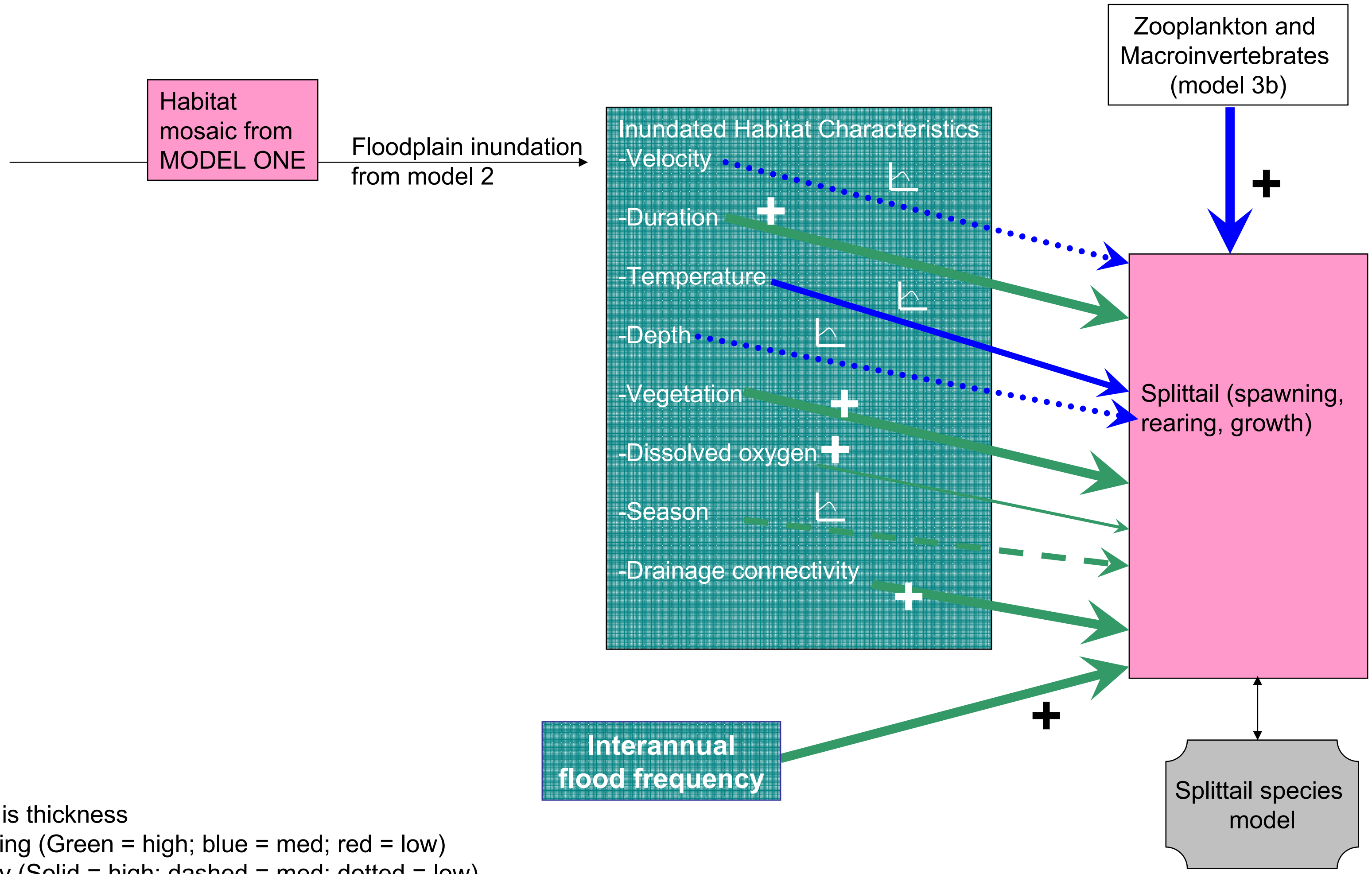


Figure 5. MODEL 3a: Food web

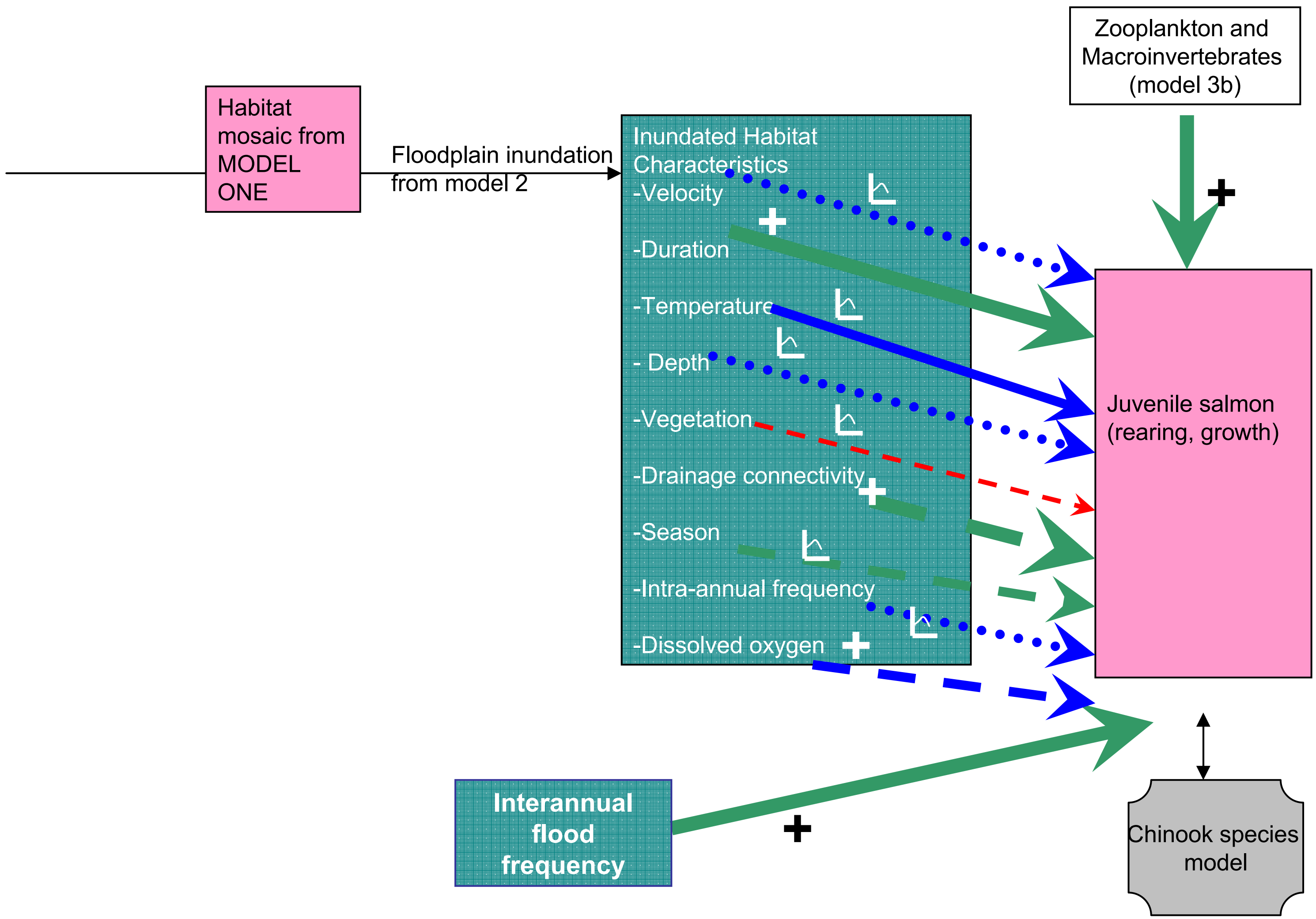
Importance is thickness
Understanding (Green = high; blue = med; red = low)
Predictability (Solid = high; dashed = med; dotted = low)

Figure 6. MODEL 3b Splittail



Importance is thickness
Understanding (Green = high; blue = med; red = low)
Predictability (Solid = high; dashed = med; dotted = low)

Figure 7. MODEL 3c Juvenile salmon



Importance is thickness
Understanding (Green = high; blue = med; red = low)
Predictability (Solid = high; dashed = med; dotted = low)