APPENDIX A

LITERATURE REVIEW OF ENVIRONMENTAL FLOW METHODS

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Over the past five decades, the development and application of environmental flow methodologies (EFMs) has rapidly progressed, as a means to help sustain or restore natural aquatic functions and ecosystems in the face of increasing demands for limited water resources. EFMs are science-based processes for assessing and/or recommending instream flows for regulated rivers. Their purpose may be as general as maintaining a healthy riverine ecosystem or as specific as enhancing the survival of targeted aquatic species. The growing prominence of EFMs in river management planning reflects a trend towards more sustainable use of the world's freshwater resources and a shift in focus from water quality to water *quantity* as a major factor in the degradation of rivers (O'Keeffe 2000).

In a comprehensive study of environmental flow methodologies, Tharme (2000) documented the existence of more than 200 EFMs, recorded worldwide. These included various modifications and hybrids of some commonly applied methods, site-specific approaches with limited applications, and procedures that are no longer in use. In actuality there are only a few dozen EFMs that are still widely applied. They can be divided into four major categories: 1) hydrological, 2) hydraulic rating, 3) habitat simulation, and 4) holistic methodologies (Tharme 2000). An overview of each of these categories is provided below, along with general strengths, weaknesses, and associated trends.

1.1. Hydrological Methods

Hydrological methodologies make up the largest proportion (30%) of environmental flow methodologies developed (Tharme, 2000). Hydrological methods are usually simple office procedures that recommend a proportion of a river's historical unregulated or naturalized flow regime as the minimum flow to maintain a fishery or other aquatic features. Recommended flows may be given on a monthly, seasonal, or annual basis. For example, the Tennant (Montana) method suggests 20% of mean annual flow (MAF) during the wet season and 40% MAF during the dry season to maintain "good" river conditions. Because of their simplicity and low resolution, Tennant and other hydrological methods are most appropriate for early reconnaissance-level project planning, to provide relatively quick and inexpensive estimates of flows to allocate for environmental purposes. Although biological factors are not explicitly considered in these methods, most were developed with some general biological basis (Caissie and El-Jabi 1995). In addition, hydrological methods assume that a minimum flow within the historic flow range for a river will sustain some proportion of native aquatic biota because the species survived such conditions in the past (Jowett 1997).

Hydrological methods have the primary advantages of being simple, straightforward, and relatively inexpensive to apply. Most require only historical flow records for a site, with little or no additional fieldwork. The simplicity of these methods, however, is also their greatest weakness. Because they do not incorporate site-specific habitat data, their ecological validity is often questionable (King et al. 2000). For example, these methods are frequently applied without regard to artificial changes in channel conditions (due to flow regulation or man-made structures) that may influence the ecological impact of recommended flows. EFMs in this category also should not be applied to river systems that do not approximate in size and type the reference river systems on which they were developed. Many hydrological methods do not address ecologically important intra- and interannual variations in flows. And unlike other methods, hydrologically based EFMs usually cannot be used to compare alternative flow regimes. Finally, for some river systems it may be difficult to obtain the unregulated or naturalized flow data necessary to calculate recommended flows.

Despite their many limitations, Tharme (2000) suggested that hydrological methods will continue to be the EFMs of choice for the foreseeable future. However, we can expect to see progress in their development towards more ecologically defensible and sophisticated methodologies. The Range of Variability Approach (RVA) is one such recently developed EFM that is considered to represent a significant advance over earlier hydrological methods. Unlike other EFMs in its category, the RVA captures the complex intra- and interannual variability of natural flow regimes over multiple temporal scales, incorporates a large number of ecologically based hydrologic indices in its analysis, and utilizes an adaptive management program for monitoring and refinement (Richter et al. 1996, 1997). Since its inception, the RVA has attracted considerable interest among river scientists and managers as a new class of ecologically grounded hydrologically based environmental flow methodologies (King et al. 2000).

1.2. Hydraulic Rating Methods

Hydraulic rating methodologies comprise 11% of the global total of EFMs. They differ from purely hydrology-based methods in that they incorporate site-specific information on hydraulic parameters, such as wetted perimeter or maximum depth, as measured across riffles or other limiting river cross sections. These parameters are used as surrogates for the habitat available for target biota such as fish or macroinvertebrate communities. Hydraulic rating methods assess changes in the habitat surrogates in response to changes in discharge. Recommended flows are commonly set at a breakpoint in the parameter-discharge curve, interpreted as the flow below which habitat decreases rapidly with a decrease in flow and above which habitat increases slowly with an increase in flow (Loar et al. 1986).

Although they require some fieldwork and data analysis, hydraulic rating methods enable a relatively quick and simple assessment of flows for maintaining habitat of target biota. They are considered more advanced and biologically relevant than hydrological methods. Their inclusion of site-specific field measurements better adapts them to different river systems. Hydraulic rating methods, however, are based on a number of simplistic assumptions that often cannot be verified. Key among these is that the chosen hydraulic variable(s) can be used to determine the flow requirements of the target species. In addition, the validity of results is highly dependent on appropriate sampling of critical river cross sections and proper identification of a breakpoint in the parameter-discharge curve. The latter is frequently complicated by the existence of multiple breakpoints or the lack of any defined breakpoint in the curve. And like most hydrological methods, EFMs in this category generally do not address ecologically important intra- and interannual variations in flows.

In the past decade there have been few advances in the development or application of hydraulic rating methodologies. Instead, this category of EFMs seems to have been superceded by the more advanced habitat simulation methodologies for which they are precursors. The Wetted Perimeter Approach, the best-known EFM in this category, is still widely applied in North America and globally (Reiser 1989, King et al. 2000). However, it is likely that many other hydraulic rating methods will gradually fall into obsolescence as the science of EFMs advances in alternate directions (Tharme 2000).

1.3. Habitat Simulation Methods

Habitat simulation methodologies (28%) rank second only to hydrological methods in proportion of total EFMs. This group of flow methodologies includes the U.S. Fish and Wildlife Service's Instream Flow Incremental Methodology (IFIM), which is the most widely used EFM in North America and the world (Reiser 1989, Tharme 2000). IFIM and many other habitat simulation methods comprise systems of highly sophisticated computer modeling techniques that integrate site-specific hydraulic and hydrologic data with species specific habitat preference data (in the form of habitat suitability curves). Computer outputs are usually in the form of habitat usability-flow discharge curves for the various factors of interest, e.g., different life stages of one or two fish species. Practitioners evaluate these curves and determine flow regimes based on the levels of protection (habitat usability) desired for each factor of interest. Because there is considerable potential for conflicting habitat requirements in this final step, it is necessary to have clear management objectives and a good understanding of the stream ecosystem when using IFIM and other habitat simulation methods to develop flow regimes.

Habitat simulation methods are flexible and adaptable. They incorporate site-specific and species specific information, so can be tailored for particular conditions and management goals. They can be used to analyze flow-related trade offs among multiple species and life stages. They may be modified to recommend flows for riparian vegetation, sediment flushing, recreation, and any number of other instream purposes. They are capable of addressing ecologically important intra- and interannual variations in flows for target species. Habitat simulation methods are also often perceived as scientifically objective and legally defensible; thus, they may be suitable for allocating instream flows in highly controversial situations (Estes 1996).

The focus of habitat simulation methods on specific target species and/or instream uses raises the risk that other essential components of the stream ecosystem may be overlooked (Prewitt & Carlson 1980). On the other hand, when these methods are used to address multiple management objectives for a river system, there are no set procedures for resolving conflicting flow requirements. The flexibility that habitat simulation methods provide make them among the most difficult EFMs to apply and interpret. Another important consideration, especially for developing countries, is that habitat simulation methods are often time-consuming, costly, and require considerable technical and scientific expertise for proper application. Modeling applications can be run without sufficient understanding of input and output processes; therefore, there is high potential for misuse by improperly trained persons. Other important sources of error or bias for modeling outputs include selection of representative cross sections for collecting hydraulic data, and construction of species-specific habitat suitability curves. Finally, a commonly cited criticism of PHABSIM, the modeling system used with IFIM, is the seeming lack of relation between fish and habitat usability estimates produced by the models (Orth and Maughan 1982).

Habitat simulation models, though the subject of much criticism, are still highly regarded by many river scientists. Current trends in their development are more advanced modeling techniques, multi-dimensional graphics, and integration of GIS display platforms.

1.4. Holistic Methods

These methods are relatively new to the science of environmental flow management. They were first documented by Tharme (1996) and currently make up 7.7% of total EFMs (Tharme 2002). Holistic approaches rely largely on multidisciplinary expert panels to recommend instream flows (Tharme 2000). They represent a significant departure from earlier environmental flow methods, in that their recommendations are almost wholly subjective. However, more advanced holistic methods, such as the Building Block Methodology (BBM), may utilize several of the analytical tools described for other EFMs to assist in the decision-making process (Tharme 2000). An early step in the BBM and some other holistic methods is identification of the magnitude, timing, duration, and frequency of important flow events for various ecosystem components and functions. The decision-making process for integrating these flow events may include a number of activities, including workshops, site visits, and limited data collection and analysis. The final output of the consensus process is a recommended flow regime to meet various specific management objectives.

Most holistic methods are relatively quick and inexpensive to apply. They have limited requirements for technical expertise and hydrologic data. And with appropriate interdisciplinary representation, these methods can comprehensively address all major components of the riverine ecosystem, including geomorphological, riparian, biological, water quality, social and other elements. Holistic methods can recommend flows at a variety of temporal scales. They are site-specific and allow for assessment of whole stretches of river rather than extrapolation from sample cross sections. The major weakness of holistic methods is the subjectivity of their approach, which may open their findings to controversy and criticism.

Holistic methods are still very much in the infancy of their development. Most of these methods have their roots in South Africa and Australia. Few have been applied outside of these countries of origin. Application of holistic methods for environmental flow management is expected to grow rapidly over the next decade, as EFMs become better established as river management tools in developing countries. Holistic methods are well suited for use in these countries, where data, finances, and technical expertise are frequently limited.

2. METHOD FOR DEVELOPING ENVIRONMENTAL FLOW RECOMMENDATIONS FOR THE SACRAMENTO AND FEATHER RIVERS

We have employed a version of the holistic approach practiced in South Africa and Australia (King et. al. 2000) to identify an environmental flow regime for the Sacramento River. This approach relies heavily on hydrological evaluations, previous studies, and expert opinion to estimate environmental flow requirements and develop a long-term adaptive management plan for implementing and refining an environmental flow regime over time. The results of the holistic approach provide a framework for increasing knowledge regarding the relationship between flow and environmental objectives and refining water management practices over time. The output of the holistic method envisioned here provides not only an estimate of environmental flow requirements, but more importantly, an explicit identification of key assumptions and uncertainties that need to be tested overtime to more accurately describe the flow requirements necessary to achieve environmental objectives.

We made two important assumptions in generally applying this method to the Sacramento River.

- Similarities in both the restoration objectives and the hydrologic, geomorphic, and ecological conditions on the Sacramento River will result in relatively similar prescriptions for environmental management flows. We believe this assumption is well supported by the environmental conditions and historical alteration of this river.

- The flow necessary to achieve restoration objectives may vary greatly depending on non-flow restoration actions such as improving spawning habitat, reconstructing degraded channel, removing levees to restore floodplain habitat, modifying and screening water diversions, reducing polluted run-off, managing ocean harvest, and other factors. In general, non-flow restoration actions will reduce the amount of water necessary to achieve restoration objectives.

The holistic approach applied in this study consists of the following 6-step process to identify an environmental flow regime:

1. Identify specific environmental objectives (i.e,. target species, aquatic and riparian communities, and desired ecological conditions that are flow dependent).
2. Approximate the timing, magnitude, frequency, and duration (TMDF) of flows necessary to support target species, communities and desired ecological processes.
3. Compare existing vs. historical hydrology to understand natural hydrologic patterns and how they have been altered.
4. Identify obvious gaps between objective flow requirements and existing flows.

5. Develop an environmental flow hydrograph to achieve ecological objectives based upon a clear understanding of historical and existing hydrologic patterns, and identify key hypotheses and uncertainties regarding the relationship between flow patterns and environmental objectives.
6. Design an adaptive management program to further test and refine environmental flows.

1) Identify specific environmental objectives (i.e,. target species, aquatic and riparian communities, and desired ecological conditions that are flow dependent).

Well-articulated target ecological conditions and desired species and communities are necessary for establishing environmental flows. Despite the correctly vogue concept of restoring ecosystem processes and avoiding species specific approaches, there is no getting around the fact that key species need specific hydrologic conditions at specific times. This analysis will include both aquatic and riparian communities and the flow parameters necessary to sustain these communities such as floodplain inundation, appropriate water temperature, or creation of structural habitat through geomorphic processes. These specific environmental objectives may vary by region, sub-basin, and reach of the river.

2) Approximate the timing, magnitude, frequency, and duration (TMDF) of flows necessary to support target species, communities and desired ecological processes.

An environmental flow regime encompasses the adequate timing, magnitude, duration, and frequency of flows necessary to support target species and facilitate specific ecological processes encompassed in the stated environmental objectives. Where we understand the life cycle timing of various target species, it is relatively easy to identify the approximate timing and duration of flows necessary to support different life stages of target species. Estimating the required flow magnitude is far more difficult but can be informed by field data, results of numerical models, and general relationships described in the literature. Most short lived target species require adequate flows each year to reproduce, while longer lived species can sustain their populations with a lower frequency of flow conditions conducive to reproduction. For example, riparian forest species may only require recruitment flows every five to ten years to establish new seedlings.

Estimating the magnitude of flows necessary to support or optimize conditions for target species and processes is by far the most difficult element of the environmental hydrograph to approximate. Environmental engineers and biologists have developed relatively elaborate methods for determining ideal flow regimes such as physical habitat simulation (PHABSIM) and Instream Incremental Flow Methodology (IFIM) to identify optimum flow magnitudes based on known habitat preferences of target species, measured habitat conditions (velocity and depth) at various flows, and numerical models that predict habitat conditions at a range of flows. Numerical models that describe the width, depth, and velocity of the rivers at various discharges are useful for predicting river stage and temperature at various locations, factors that are important considerations for habitat or facilitating geomorphic and hydrologic processes. As discussed above, these models tend to focus on the needs of specific species and can sometimes produce results that are inconsistent with both holistic ecological process restoration and common sense. Furthermore, these models are often not calibrated, particularly at higher flows relevant to riparian recruitment, geomorphic processes, and spring outmigration temperatures. Nevertheless, we utilized the results of these models as a guide combined with other information to develop our environmental flow management hypothesis.

Where possible, we relied on actual data and measurements to estimate the flows necessary to achieve suitable conditions to support biological, riparian, and geomorphic objectives for temperature, floodplain inundation, and bed mobilization. In particular, we relied on USGS temperature gauges to characterize the relationship between temperature and flow. Similarly, we relied on previous studies of the rivers to characterize flows necessary to mobilize bed material and inundate the floodplain.

3) Compare existing vs. historical hydrology to understand natural hydrologic patterns and how they have been altered.

Analyses of historical hydrologic data is useful for describing natural patterns and identifying potential links between hydrology and the requirements necessary to maintain species and precipitate key processes. An analysis of historical patterns can provide clues about the timing, magnitude, duration, and frequency of flows under which target species have evolved. Identification of major changes between historical and hydrologic patterns combined with the life history requirements of various species can help generate hypotheses about how flow regulation may be limiting target species. We will use the an analysis similar to the Index of Hydrologic Alteration approach (Richter et al. 1996) and the Hydrograph Component Analysis (HCA) (Trush et al. 2000) to evaluate changes in flow patterns. The analysis similar to the IHA provides a quick statistical overview of how several important hydrologic attributes have changed. The analysis similar to the Hydrograph Component Analysis (HCA) method developed by McBain and Trush provides a detailed graphical analysis of historical and existing hydrologic conditions. While valid and useful, the statistical analysis in the IHA method is not substitute for visually comparing and evaluating key components of the pre- and post-dam hydrographs. Similarly, visual comparisons of pre- and post-alteration hydrographs don't always reveal important changes identified by the IHA method.

4) Identify obvious gaps between objective flow requirements and existing flows.

An analysis of historical flow patterns combined with an approximation of the TMDF of flows necessary to achieve objectives compared with the regulated flow regime can help illustrate obvious gaps between regulated flows and flows that may be necessary to achieve environmental objectives. We will plot TMDF flow requirements developed in Step 2 as an annual hydrograph and compare it with average regulated and historical conditions.

5) Develop an environmental flow hydrograph to achieve ecological objectives based upon a clear understanding of historical and existing hydrologic patterns, and identify key hypotheses and uncertainties regarding the relationship between flow patterns and environmental objectives.

This project identifies hypothetical restoration flow regimes but recognizes that the most reliable method for developing a restoration flow regime is through a long-term adaptive management program including a series of trials that test the effectiveness of various flow prescriptions. The purpose of developing the hypothetical flow regime is to develop a comprehensive hypothesis regarding the range of flows that may be necessary to restore ecological processes to the Sacramento River. However, the assumptions and uncertainties associated with the hypothetical flow regime are as important as the flow regime itself.

6) Design an adaptive management program to further test and refine environmental flows.

To cost effectively achieve restoration, managers will ultimately need to test these assumptions and limit the uncertainties through an adaptive management program consisting of a combination of numerical modeling, pilot flow studies, model calibration, and long-term restoration implementation.

APPENDIX B

CONCEPTUAL MODELS

FOR

GEOMORPHIC PROCESSES, FREMONT COTTONWOODS,

AND CHINOOK SALMON

APPENDIX B: CONCEPTUAL MODELS

Geomorphic Conceptual Model

1.0 Geomorphic Conceptual Model

Geomorphic processes are generally initiated at threshold flow levels. Bed mobilization and floodplain inundation do not occur until flows reach a threshold level sufficient to flow over bank or create sheer stresses necessary to mobilize gravel. Theoretically, no benefit occurs unless the threshold flow is achieved. No amount of flows less than the threshold will initiate bed mobilization or floodplain inundation, but in reality the actual threshold flow varies spatially from reach to reach. Research from several gravel bedded river systems indicates that a flow with a natural (unregulated) recurrence interval of every 1.5 years is generally needed to mobilize the bed and initiate over bank flows (Leopold et al. 1964). In reality, however, the threshold flows necessary to initiate geomorphic processes naturally vary from reach to reach depending on channel dimensions, slope, and the size of bed material. In general, sand bedded reaches mobilize at lower flows than gravel bedded reaches with larger particle sizes. Similarly, low gradient reaches flood at lower discharges than steeper reaches, particularly where large woody debris is allowed to accumulate.

Human modifications of the channels from their natural state have changed the relationship between flows and geomorphic processes and have therefore complicated the already difficult task of determining the flows necessary for precipitating various geomorphic processes. Gravel and channel restoration projects have changed and could continue to change the particle size of gravels and the channel dimensions and will thus further change the relationship between flow and geomorphic processes. More importantly, there is no single bed mobility threshold for any reach of the Sacramento River or any other river channel due to spatial vaiabilty in particle size and channel form (Kondolf et al, 2000; Wilcock, 1996).

There are varying degrees of bed mobilization, further complicating the definition of mobility and its distinction with bed scour. For this study, we attempted to estimate the flows necessary to mobilize and scour the bed. Bed mobility and bed scour are two different processes that occur at different flow thresholds. We use the term bed mobility to refer to mobilization of the surface of the channel bed. Bed scour is the process of scouring the bed deeper than its coarse surface layer. Incipient bed mobility is the threshold at which bed material begins to mobilize and occurs when the ratio of the critical sheer stress to the D_{50} equals 1. Incipient mobility can cause small movement of gravel across the top of the riffle without general mobilization of the riffle surface. Relatively frequent (every 1–2 years) incipient motion of gravels on a riffle may be adequate for certain objectives such as flushing fines from the gravels, but is probably not sufficient for certain geomorphic objectives such as restoring sediment transport or maintaining a dynamic, alternating bar sequence (Trush et al. 2000). General bed mobility mobilizes the entire riffle surface and occurs when the ratio of critical sheer stress to particle size D_{50} exceeds 1.3. General bed mobility may be necessary for restoring basic alluvial functions such as transporting coarse sediment from one riffle to the next.

Lastly, there is relatively little information regarding the flows necessary to perform various geomorphic objectives. Geomorphic processes associated with these objectives occur at very high flows, when field measurement is difficult. Hydraulic models and equations have been applied on the Sacramento to provide insight into the flows necessary to mobilize the bed and banks and inundate the floodplain, but in many cases these models have not been adequately calibrated at high flows or do not accurately describe the actual hydraulics at specific cross sections (Kondolf, 2000). Empirical observations are generally more reliable, but are often limited to specific study sites. In this study, we have relied on previously reported field measurements, modeling analysis, and general principles from the literature to roughly estimate the magnitude of flows necessary to initiate geomorphic processes.

For all of the reasons discussed above, it is not possible to estimate future flow levels necessary to initiate geomorphic processes across an entire river, but for the purposes of this study, a rough estimate will be sufficient to evaluate the feasibility of reoperating reservoir releases for the purpose of achieving geomorphic objectives. In this study, we have focused on the flows necessary to mobilize the gravel bedded reaches, because they are more relevant to salmon restoration and because they will also result in mobilization of the sand bedded reaches. For floodplain inundation, we have focused on the lowland floodplains because they can be inundated at lower flows with demonstrated fisheries benefits.

The geomorphic conceptual model in its most succinct form is that high flows exert sheer stress on and transport sediment over the many structural components of a river channel and floodplain (bed, banks, other exposed surfaces) causing them to change, erode, migrate, and otherwise respond in a qualitatively predictable manner.

The geomorphic conceptual model described below is based on inputs and outputs. Inputs into the model are in three categories: flow, topography, and sediment. The outputs of the model are physical functions that in turn support habitat and biotic responses in the river system.

The Sacramento River requires a variety of high flows ($Q_{1.5}$ – Q_{10}) to clean sediment, rejuvenate alternate bar sequences, prepare the floodplain for vegetation recruitment, and drive channel migration. Each one of these functions supports a biotic or habitat response described previously in this chapter.

Figure 1 illustrates the relationships between flow, sediment, and topographic inputs, and ensuing geomorphic processes. The model has been simplified to focus primarily on restoration objectives of this project and the inputs we propose to modify to achieve these restoration objectives (outlined in bold).

Inputs

The driving inputs in the conceptual model fall into three categories: flow, topography, and sediment. In reality, the conceptual model is at least partly cyclic, where the outputs are also inputs into successive cycles.

Flow Inputs

Flow inputs can be divided into three broad categories: regulated runoff, unregulated runoff, and groundwater inputs. Regulated runoff refers to flow releases from reservoirs over which humans exert some control. This is of particular importance to this conceptual model because it is the input we propose to modify. Unregulated runoff refers to flow inputs on streams and rivers over which humans do not exert much control. As the distance between any point on a river and an upstream dam or diversion increases, so too does the influence of unregulated runoff. More tributaries enter the river and the unregulated drainage area increases downstream from the dam or diversion.

Groundwater refers to any inputs from subsurface flows. These are not, in fact, entirely independent of regulated or unregulated runoff. Interaction of high flows with floodplain surfaces, flow durations, and flow frequencies impact the quantity and timing of groundwater inputs. Similarly, groundwater inputs impact base flow levels in both regulated and unregulated systems. For the sake of simplicity and focus, groundwater is considered an independent input.

Topographic Inputs

The shape of the river channel and floodplain, the location of the levees, the amount and type of vegetation in the channel and on the floodplain, and other structural characteristics comprise the topographical inputs of the conceptual model. They determine the distribution and velocity of any given flow quantity. For example, if one hundred acre-feet of water enter into a river, the water will pass much more quickly and smoothly if the river channel resembles a pipe - smooth and straight. If the channel is small, the water may spill onto the floodplain. If the channel is flat and wide, the water may travel very slowly. If the channel is full of vegetation, it may impede the flow of water or concentrate it between walls of vegetation.

Upstream Sediment Inputs

Upstream sediment inputs refer to silts, sands, cobbles, gravels or boulders transported in the river system. The quantity and quality of upstream sediment input create the building blocks for depositional processes. Because dams capture most upstream sediment, in regulated rivers sediment inputs are mostly from unregulated tributaries and storage in banks and bars below the reservoir.

Flow Outputs

Regulated flow, unregulated flow, and groundwater establish the amount of water in a river system. The topographic features determine the surface over which the water flows, and how it flows over that surface. Together, they determine the discharge, stage, and velocity of the flows (producing sheer stress). Combined with the frequency of these flows, and the upstream sediment inputs, they drive various geomorphic processes in river systems (described below).

Process Responses

Gravel Bed Mobilization

Gravel bed mobilization refers to the entrainment of D50[1] gravels. This generally occurs in alluvial rivers during the historic annual or biannual floods or roughly the $Q_{1.5}$ flow or Q_2. The mobilization of the gravels "cleans" them by removing accumulated silt, algae and other fine particulates (Stillwater Sciences, 2001).

Floodplain Inundation

Floodplain inundation is a hydrogeomorphic process that serves important ecological functions. Floodplain inundation provides temporary access to floodplain habitat for aquatic species, recruits nutrients from the floodplain into the river, and helps to recharge groundwater levels in riparian zones. Inundated floodplains provide important spawning and rearing habitat for numerous species. Sacramento splittail are largely dependent on inundated floodplains for successful spawning and rearing. Juvenile salmon grow two to three times as fast on floodplains compared to channels. Due to large surface area, the volume of area in the photo zone, and relatively warm temperatures during cool winter and early spring months, floodplains generate larges amounts of phytoplankton and zooplankton during the critical spring months.

Determining the flow necessary to inundate floodplains is complicated by the fact that different types of rivers and river reaches overflow their banks at different flows. Floodplain inundation in gravel bedded streams generally occurs during flows at or above the historic biannual flood (Q_2) (Stillwater Sciences, 2001). However, floodplain inundation on lowland Rivers such as the lower Sacramento and Feather Rivers occurr far more often, creating extensive flood basins that were inundated for weeks or months in all but the driest years (Bay Institute, 1998). Even under post dam hydrology, many of these basins, such as the Yolo Bypass, would flood for weeks or days at flows far below the bankfull discharge.

It is not realistic to restore floodplain inundation to the historic flood basins of the Sacramento Valley. It would simply be too disruptive to the water supply and economic functions of the Sacramento River and its historical floodplains. It is, however, more realistic to intentionally inundate the system of flood bypasses designed to safely accommodate flood flows in the Sacramento River. The magnitude of flows necessary to inundate bypasses, as well as the frequency of bypass inundation is controlled by weirs at the upstream end of each bypass. Water does not enter the bypass and create inundated habitat until the river stage is high enough to overtop the weir. A study sponsored by the US Army Corps of Engineers, however, demonstrated that it is possible to inundate the bypasses at greater frequency and lower flows by intentionally notching the weirs (NHI, 2002). For the purposes of this study, we have assumed that you could inundate

[1] D refers to the length of the intermediate axis of gravels in a gravel bed. The D50 refers to the gravels in the 50th percentile size class, relative to the other gravels in the bed.

floodplains in flood bypass areas using this method at multiple weirs in the Sacramento Valley.

Bed Scour and Deposition

Bed scour and deposition refer to the removal of sediment and the corresponding replacement of sediment that occurs during storm events. The bed scour and deposition process discourages the river channel from being "fossilized" by riparian encroachment, maintaining it in a dynamic alluvial state. It is a greater level of mobilization than simply gravel bed mobilization, in that the bed degrades during the ascending limb of the hydrograph and aggrades on the receding limb of the hydrograph. Q_5 to Q_{10} floods generally provide the necessary shear stress to scour beds and redeposit with little net change in channel elevation (Trush et al. 2000)

Floodplain Sediment Scour and Deposition

Floodplain sediment scour requires greater sheer stress than simply inundation and generally occurs during flows equivalent to the historic Q_{10}. By exerting sheer stress, scour prepares floodplain surfaces for recruitment of riparian vegetation by removing existing vegetation, depositing clean sand and transporting new seed across the floodplain. Depositional processes also require higher flows to transport sediment away from the channel onto the floodplain. As flows increase, they spill across the floodplain, velocities slow, and the river deposits its sediments. Most floodplain sediments are the result of this process (Leopold et al., 1964). Deposition on the floodplain further reshapes and prepares the surfaces for recruitment.

Channel Migration

Channel migration is a function of stream energy and substrate strength. By eroding, channel migration recruits gravels and large woody debris into the system and directly and indirectly creates habitat complexity in the channel and floodplain. By depositing, channel migration prepares surfaces for pioneer species allowing for a diversity of riparian habitats. The process of channel migration is responsible backwater areas, sloughs, oxbow lakes, and secondary or abandoned channels (Bay Institute, 1998).

Channel migration requires the greatest amount of stream energy and generally requires large flows for a prolonged period, which can require very large volumes of water. Flows larger than the bank full discharge may be necessary to cause major channel migration or channel avulsion, but gradual channel migration may occur each year at some bends with flows well below the bank full discharge.

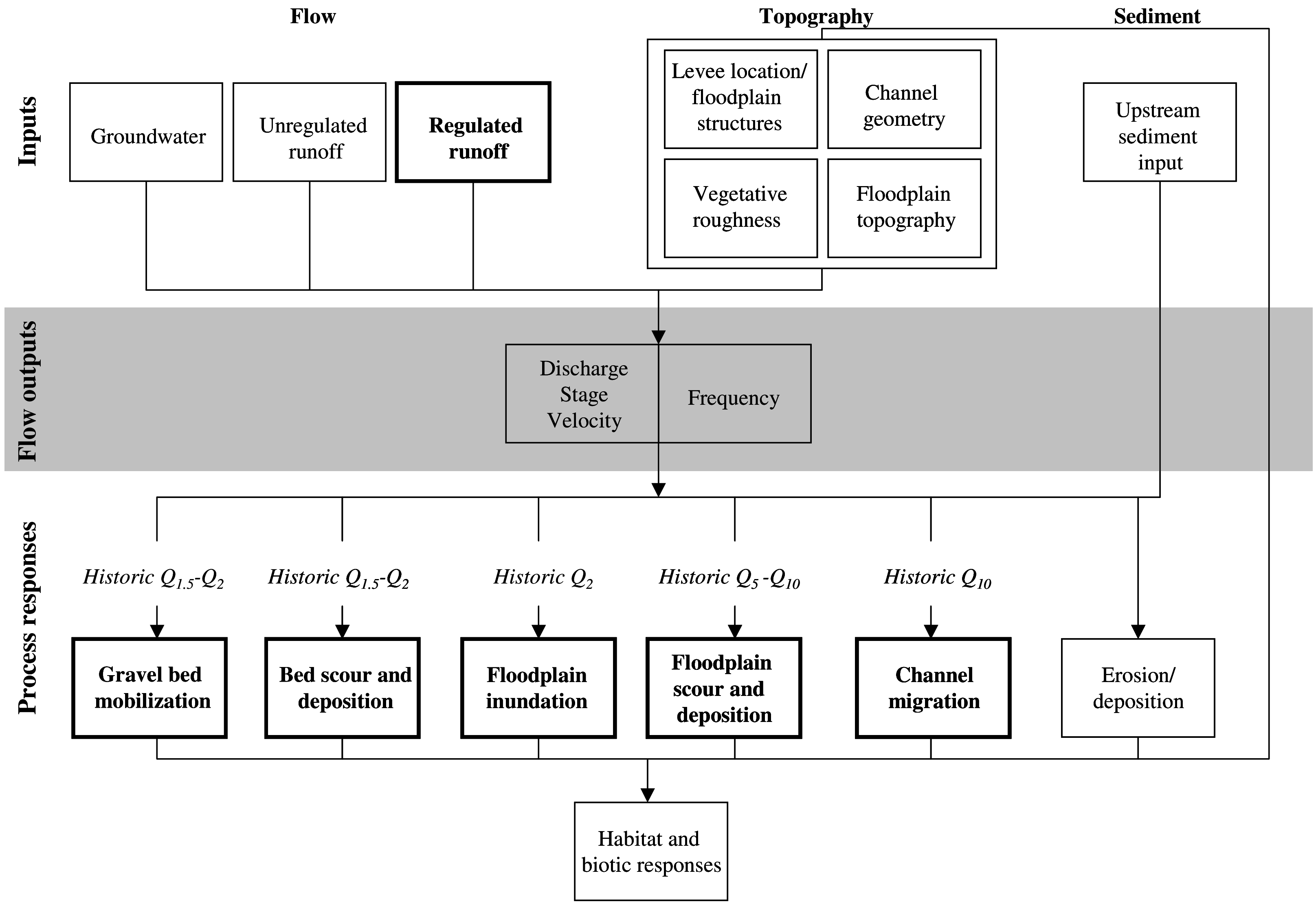

Figure 1. Geomorphic Conceptual Model. The figure above illustrates the relationships between flow, sediment, and topographic inputs, and ensuing geomorphic processes. The model has been simplified to focus primarily on restoration objectives of this project and the inputs we propose to modify to achieve these restoration objectives (outlined in bold).

Appendix C: Cottonwood Conceptual Model

4.2 Cottonwood Conceptual Model

Critical life history stages of cottonwoods and other pioneer riparian species in the Sacramento River basin are tightly linked with the hydrologic and geomorphic processes described in the previous conceptual model. Floodplain scour/deposition, channel migration, channel avulsion, and erosion/deposition processes generate new sites for cottonwood seedling establishment. Floodplain inundation provides moist substrates to sustain seedlings through their first growing season. Gravel and sand bed mobilization and bed scour/deposition help define a minimum elevation for cottonwood recruitment. Over time, these processes play a key role in determining the distribution, extent, and age structure of cottonwood communities in the Sacramento River basin. In turn, as cottonwoods mature, they have the potential to impact sediment deposition processes, channel stability, and channel dynamics. Both geomorphic processes and riparian habitat structure are important determinants of abundance and distribution of aquatic species such as chinook salmon, as described in the next section.

Land use activities and managed flow operations have greatly reduced the extent and integrity of riparian forests, particularly cottonwood forests, in the Sacramento Basin. Most existing cottonwood stands in the basin are mature, exhibiting older age structure than typical under natural conditions (McBain and Trush 2000, Stillwater Sciences 2002a, Jones & Stokes 1998). The absence of sapling cohorts in many reaches of the basin suggests that natural recruitment processes are not occurring under current conditions (McBain and Trush 2000, Jones & Stokes 1998, Stillwater Sciences 2002a). Without younger age classes, senescent trees cannot be replaced as they die, potentially leading to further substantial loss of this once dominant riparian vegetation community.

This conceptual model describes the ecological flows and geomorphic processes that drive establishment and recruitment of cottonwoods under natural conditions (Figure 2). The model identifies factors that currently limit cottonwood recruitment in the Sacramento Basin and opportunities for restoring this process through modification of flows and/or channel-floodplain geomorphology. Because channel attributes may differ widely among rivers and reaches of the Sacramento Basin, flow characteristics for restoration are described qualitatively in this model, with respect to channel and floodplain elevations.

Various species of cottonwoods share the characteristics discussed below. Any discussion specific to the Fremont cottonwood *(Populus fremontii),* the predominant species of the Central Valley (Stillwater Sciences 2002a, 2002b, 2006: McBain and Trush 2000), is noted as such.

4.2.1 Site Preparation

The creation of barren nursery sites through erosional and depositional processes is the first step in cottonwood seedling recruitment. Because cottonwood seeds contain very little endosperm, seedlings require full sunlight to produce photosynthates for growth and development; thus, cottonwood seedlings compete poorly on vegetated sites (Fenner et al. 1984). Under natural flow regimes, moderate 5- to 10-year flood events precipitate channel migration and the creation of point bars suitable for cottonwood seedling establishment (McBain and Trush 2000, Trush et al. 2000). Large flows scour away herbaceous plants and/or deposit fine sediments on floodplains, preparing new seed beds for pioneer riparian species (Mahoney and Rood 1998). In addition to point bars and floodplains, cottonwood forests may occur in high flow scour channels, oxbows, and other off-channel backwaters that receive scouring and sediment deposition (Stillwater Sciences 2002a).

Over the past century, continued agricultural and urban encroachment into riparian zones have greatly decreased the landscape area upon which cottonwood recruitment can occur (Stillwater, 2006; McBain and Trush 2000, Jones & Stokes 1998). In addition, flow regulation has reduced the intensity and frequency of winter and spring flood flows. The lower flows have led to a moderate reduction in the high-energy processes that, in less regulated river systems, create new seedbeds for recruitment—channel migration, point bar accretion, bed scour, and floodplain inundation. Levees and bank stabilization practices have reduced floodplain width and channel migration, in addition to isolating riparian backwaters (Stillwater, 2006). In addition, the loss of upstream sediment supply may have resulted in channel incision, requiring greater discharges for flows to inundate adjacent floodplains (TNC, 2003). The cumulative result of these processes has been a significant reduction in favorable germination sites for cottonwood seedlings.

There are several options for human intervention to increase availability of suitable recruitment sites for cottonwoods. Flood operations can be modified in wet years to allow shorter duration, but higher winter or spring peak flows sufficient to inundate floodplains and mobilize channel sediments (Jones & Stokes 1998). Reservoirs can be operated to release flows that mimic the 5- to 10-year flood events historically associated with cottonwood recruitment. Mechanical approaches include lowering floodplain surfaces for greater inundation frequency at current low flows, setting back or breaching levees to increase floodplain area, restoring the river's connection with abandoned side channels and backwaters, and artificially clearing floodplain sites to reduce plant competition.

Reductions in peak flows can lead to vegetation encroachment of more aggressive native riparian species into the formerly active river channel, further limiting cottonwood recruitment (Jones & Stokes 1998). Under natural hydrologic conditions, surfaces at the edge of low-flow channels were high-scour zones that generally prohibited the establishment of riparian vegetation. Under regulated conditions where the frequency of scouring flows has decreased significantly, vegetation —primarily alders and willows and forbes— can encroach along channel margins that were previously characterized by shifting and exposed gravel or sand bars (Stillwater Sciences 2002a, McBain and Trush 2000, FWUA and NRDC 2002). Vegetation encroachment can ultimately result in simplified and confined river channels resistant to fluvial geomorphic processes (e.g., channel migration) that create barren seedbeds for cottonwood recruitment. This does not appear to be a problem on the Sacramento River due to relatively frequent high flow events, but vegetation studies do indicate that recruitment is currently dominated by willows (TNC, 2003) to the potential detriment of cottonwoods. Therefore, maintaining the proper frequency and magnitude of high flows is necessary for maintaining habitats where cottonwoods are likely to become established and dominant.

4.2.2 Seedling Establishment

Establishment describes the process of seed release, germination, and growth through the end of the first year. This stage in the life cycle of cottonwoods is marked by high mortality rates, in both natural and regulated river systems (Mahoney and Rood 1998).

Most studies on Fremont cottonwood recruitment have focused on establishment of new stands through seed release, rather than vegetative sprouts. In the Sacramento Basin, mature female Fremont cottonwoods release hundreds of thousands to millions of seeds between April and June. Timing and duration of seed release are influenced by photoperiod and temperature, with maximal seed release generally occurring over a three-week period (FWUA and NRDC 2002, Stillwater Sciences 2002a). Seeds are dispersed by wind and water. They may travel up to a couple miles away, but more often they are deposited within a several hundred feet of the parent tree (Braatne et al. 1996). Dry Fremont cottonwood seeds are viable for one to three weeks (Horton et al. 1960). Once they are wet, their viability decreases to a few days (Braatne et al. 1996). Thus, for riparian restoration purposes it is important to understand the mechanisms that influence cottonwood seed release and dispersal, to ensure that timing of spring (snow-melt) pulse flows coincides with cottonwood seed dispersal. The spring pulse flows provide the moist nursery sites necessary for immediate germination of seeds (Mahoney and Rood 1998).

Cottonwoods germinate within 24–48 hours of landing on bare, moist substrates such as silt, sand, or gravel (John Stella, Stillwater Sciences, pers. com., 8 April 2003). For one to three weeks after germination, the upper layer of substrate must maintain moisture as the seedlings' root systems grow. Post-germination decline of river stage, which is presumed to control adjacent groundwater levels (JSA and MEI 2002), should not exceed approximately one inch per day (Mahoney and Rood 1998, Busch et al. 1992). This is the rate at which seedling root growth (0.16–0.47 inches/day; Reichenbacher 1984, Horton et al. 1960) can maintain contact with the capillary fringe of a receding water table in a sandy substrate. Cottonwood root growth and seedling establishment rates are higher in these soils than in coarser textured soils, which are more porous (Kocsis et al. 1991). In reaches with gravelly substrates, slower draw-down rates are necessary to support seedling establishment.

Mahoney and Rood (1998) describe the temporal and spatial window of opportunity for cottonwood seedling establishment as a "recruitment box", defined by timing of spring pulse ("establishment") flows/seed release and by seedling elevation relative to river stage. Optimal timing of seed release for successful establishment is during the gradually declining limb of a spring pulse flow. Optimal elevation relative to river stage is set at the upper end by the seedling's ability to maintain contact with the declining water table, and at the lower end by scouring and inundation flow levels in the first year, especially during the first winter.

The vast majority of cottonwood seedlings in this life stage die of drought stress because root growth is unable to keep pace with the decline in the water table (Mahoney and Rood 1998). Regulated ramp-down rates after spring pulse flows are often steep, in order to conserve water for human uses (Stillwater Sciences 2002b). Alternatively, decreased spring flows in regulated systems may cause seedlings to initiate at elevations too low to protect seedlings from flooding and scouring flows later in the growing season or during the winter (Mahoney and Rood 1998). In some rivers overwinter mortality of cottonwood seedlings is particularly high because flow regulation has reduced spring peak flows relative to winter peak flows (Stillwater Sciences 2002a).

High seedling mortality rates suggest that opportunities for improving cottonwood recruitment may be greatest in this life stage. In the first year of life, drought stress can be minimized by managing flood release flows for slow ramp-down rates after 5- to 10-year flood releases. Since reservoir spills often occur in wet years, reduced ramp-down rates may be accomplished by reshaping existing flood release flows without reducing water supply deliveries.

Artificial floodplain irrigation, either through flooding or a drip system, can also relieve summer drought stress for newly initiated seedlings. Agricultural irrigation close to the channel during the dry season would achieve similar gains in groundwater level. Grazing and trampling of seedlings by livestock can be minimized through grazing management practices or by building exclosures to protect cottonwood nurseries. To reduce winter mortality due to scouring and inundation, establishment flows can be discharged in spring rather than winter.

4.2.3 Vegetative Reproduction

In addition to seed dispersal and seedling establishment, vegetative reproduction is a potentially significant but commonly overlooked method for cottonwood recruitment along newly formed or previously established floodplains and point bars. Fremont cottonwoods can reproduce clonally through sprouting of buried broken or detached branches, or through development of suckers from shallow roots. This little-studied phenomenon has been alluded to in the riparian literature, and reported anecdotally and in unpublished studies (Tu 2000; Mike Roberts, TNC, pers. com., 27 February 2003). Additional insight into the process can be gained from studies of vegetative reproduction in other cottonwood species (Rood et al. 1994, Reed 1995).

Vegetative reproduction may be particularly important for sustaining Fremont cottonwood populations in altered hydrologic systems such as the Sacramento Basin. Tu (2000) reported that three years after the floods of 1996 established a new sandbar along the lower Cosumnes River, successful Fremont cottonwood recruits from vegetative branches outnumbered those from seeds by almost six to one. This is especially notable in light of the fact that the original 1996 cohort studied included 7,898 Fremont cottonwood seedlings compared to only 36 vegetative branches. Thus, the greater number of surviving 3-year-old recruits from vegetative branches compared to seedlings was due to their considerably higher survival rates rather than initial predominance. Most of the seedlings in this study died in their first year post-germination as a result of desiccation. Tu (2000) surmised that vegetative branches were better able to survive the critical first year by virtue of their greater nutrient storage, higher competitive ability for light, and greater proximity to declining water tables (most were partially buried in the soil).

In many parts of the Sacramento Basin, it is possible that the loss of natural recruitment processes under current conditions has increased the importance of vegetative propagation relative to seed propagation for sustaining cottonwood populations. An intervention opportunity based on natural vegetative reproduction is to plant cuttings collected from local cottonwood populations. Although this option would be time and labor intensive, cottonwoods have been successfully re-established by this method in Clear Creek and on the Sacramento and Merced Rivers (Mike Harris, USFWS, pers. com., 26 February 2003; John Stella, Stillwater Sciences, pers. com., 8 April 2003). Once a small number of individuals are successfully recruited to a new site, expansion of the population may subsequently occur via sprouting, suckering, or seed dispersal. Due to the uncertainties of seed dispersal timing, availability of flows, and high cost of flows (unless part of flood release flows), a dual strategy of vegetative reproduction and improved flow management may be the most cost effective option for improving rates of cottonwood recruitment in the Sacramento Basin.

4.2.4 Recruitment

The recruitment phase occurs from the end of the first year to sexual maturity, at five to ten years of age for Fremont cottonwoods (Reichenbacher 1984). Flow-related mortality is relatively low during this period because a plant has generally developed a sufficient root and shoot system to survive seasonal conditions of drought and flooding. Growth rates are very high in the second year, by the end of which roots may be almost ten feet deep (Ware and Penfound 1949). After the second year, growth rates level. Despite extensive root development during this stage, cottonwoods are still somewhat susceptible to drought stress. Thus, yearly flows must be sufficient to maintain groundwater levels within 10 to 20 feet of ground surface elevations (JSA and MEI 2002).

Groundwater extraction and reduced flows can reduce groundwater levels and induce drought stress in cottonwood saplings (Jones & Stokes 1998). In regulated river systems, low frequency of scouring flows may also allow exotics such as eucalyptus, tamarisk, and giant reed to establish and outcompete early successional native species such as cottonwood (Jones & Stokes 1998, McBain and Trush 2000). Relatively low flow-related mortality during this stage diminishes the importance of flow management opportunities. However, mortality due to herbivory (e.g., beavers, voles, mice) may be significant during this phase (John Stella, Stillwater Sciences, pers. com., 8 April 2003). Density-dependent mortality (self-thinning) may also occur if initial seedling density is high.

4.2.5 Maturity & Senescence

Maturity begins with the first flowering of a sexually mature adult. Senescence begins when reproductive capacity declines. Field studies indicate that a large proportion of existing cottonwood stands in the Sacramento Basin comprise mature and senescing individuals (McBain and Trush 2000, Stillwater Sciences 2002a, Jones & Stokes 1998). As these cottonwoods die (lifespan >130 years; Shanfield 1983), they are unlikely to be replaced by new generations of cottonwoods. Although cottonwood seedlings are readily germinating on the Sacramento River, most cohorts are not surviving to reproductive maturity, for the reasons outlined above. In addition, urban and agricultural conversion of mature cottonwood forests in the Sacramento Basin further reduces seed sources and threatens future prospects for this once-abundant riparian habitat (McBain and Trush 2000, Jones & Stokes 1998, Stillwater Sciences 2002a).

Cottonwood Conceptual Model

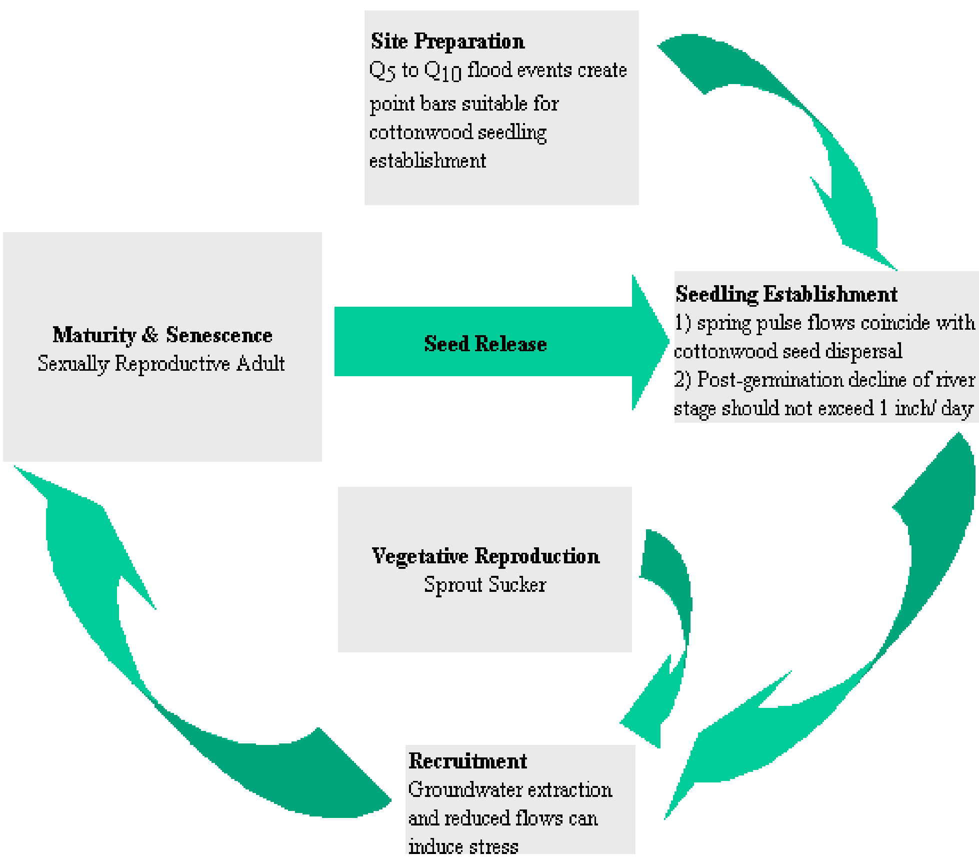

Figure 2. Cottonwood Conceptual Model for Sacramento Basin highlights characteristics of the flow regime that effect different life stages.

Chinook Salmon Conceptual Model

This conceptual model focuses on the flow related factors that affect populations of Chinook in the Sacramento and Feather Rivers. There are many non-flow factors that affect salmon populations, but we have only focused on the flow related factors for the purpose of developing an environmental flow regime. The model addresses flow-related factors for four runs of Chinook salmon and steelhead by life stage.

There are four distinct runs of Chinook salmon in the Sacramento River, the fall-run, the late fall-run, winter-run and spring-run. The different runs of Chinook differ in the timing of their life history. In general each run is named for the time that it begins migrating back to its natal stream. Table 1 shows that each run has the same life stages, but different runs move through the life-cycle at different times of the year and often employ different life stage strategies. For example, fall-run salmon are sometimes referred to as ocean type because they generally migrate to the ocean before their first year, while spring run generally spend a full year in the stream before migrating. Differences in timing and life history strategies mean that different runs can be vulnerable to different stressors. For example, winter run eggs incubate over the summer months and are therefore limited by summer water temperatures, while fall run eggs are much less likely to endure temperature stress since they incubate during the relatively cool winter months. The Chinook Conceptual Model lists the limiting factors that may impact the success of each life stage, the degree to which the limiting factor is relevant may depend on the particular run of Chinook which is being considered.

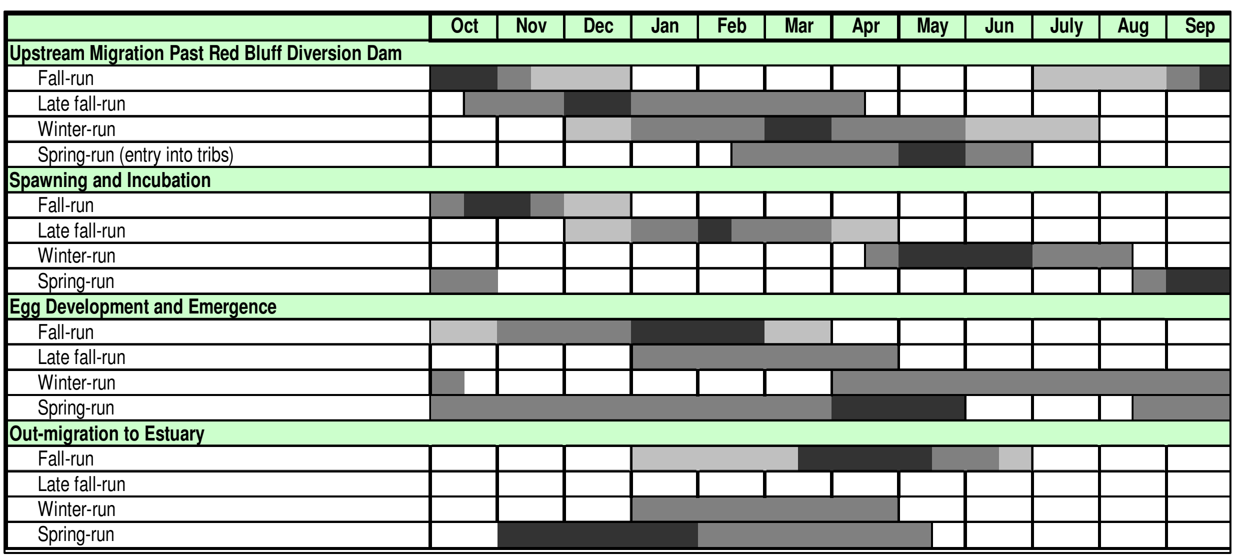

Table 1: Salmon life history table. The timing and duration of the life history stage for each of the salmon runs; These are the periods of time that are most critical to the success of a particular life stage.

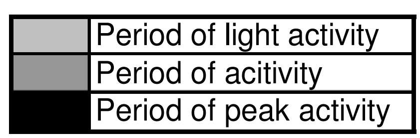

Table 2: Chinook Salmon (CHS) Thermal Tolerances. All lethal temperature data is presented as incipient upper lethal temperatures (IULT), which is a better indicator of natural conditions because experimental designs use a slower rate of change (1°C/d). (Modified from Moyle 2005, information largely from McCullough 1999.)

REVISE TABLE (ERRORS IN LETHAL COLLUMN

	Sub-Optimal	Optimal	Sub-Optimal	Lethal	Notes
Adult Migration	<10°C	10-20°C	20-21°C	21-24°C	Migration usually stops when temps climb above 21ºC. Under most conditions fish observed moving at high temps are probably moving to refugia.
Adult Holding	<10°C	10-16°C	16-21°C	10-20°C	Fish in Butte Creek experience heavy mortality above 21°C but will survive temperatures as high as 23.5°C for short periods of time. In some holding areas fish have been observed in temperaturatures of 20ºC for over 50 days during the summer.
Adult Spawning	<13°C	13-16°C	16-19°C	10-20°C	Egg viability may be reduced at higher temperatures
Egg Incubation	<19°C	9-13°C	13-17°C	10-20°C	This is the most temperature sensitive phase of life cycle American River CHS experience 100% mortality in temperatures greater than 16.7°C; Sacramento River fall-run CHS mortality exceeded 82% in temperatures greater than 13.9°C
Juvenile Rearing	<13°C	13-20°C	20-24°C	10-20°C	Past exposure (acclimation temperatures) has a large effect on tolerance. Fish with high acclimation temps may survive at 28-29ºC for short periods of time. When food is abundant, fish that live under conditions between 16 and 24ºC may grow very rapidly.
Smoltification	<10°C	10-19°C	19-24°C	10-20°C	Smolts may survive and grow at suboptimal temps but are primarily avoiding predators

Temperature is one of the key factors that can limit salmon population numbers, but different life-stages display widely different temperature tolerances (Table 2). In general, salmon are most vulnerable to temperature stress in the egg life stage and least vulnerable in the juvenile life stage. Winter run are acutely sensitive to temperature, because their eggs are present during the summer months. Thus, different runs are effected differently by temperature stress due to the differences in run timing.

4.2.6 Life in the Ocean

All four runs of Chinook salmon spend approximately 1 to 5 years in the ocean before returning to spawn in their natal stream (Moyle, 2002), though historically, most Chinook salmon returning to the Sacramento River are approximately 4 years old (Clark 1929, in USFWS 1995).

Mortality of salmon in the ocean is based on natural and non-natural factors. Natural stressors include predation by other species, and ocean conditions, such as nutrient flow patterns (CMARP and CALFED Appendix C). The non-natural mortality factor affecting salmon is harvest. From 1967 to 1991, 60-80% of total salmon production was harvested (CMARP).

Changes in river management will do little to decrease natural mortality of salmon in the ocean. This study is not considering restoration of Chinook populations by limiting ocean harvest of salmon at this time. However, it is important to emphasize that large-scale harvesting of salmon in the ocean may be severely limiting salmon populations. If we could manage ocean stocks to increase the number of older fish, it may be possible to increase the ecosystem resilience against drought.

4.2.7 Adult Upstream Migration

Adult salmon migration can be limited by high temperatures and low dissolved oxygen. In the Sacramento River where flows are severely limited, adult salmon migration are delayed or disrupted by low flows and poor water quality. In particular, low levels of dissolved oxygen (DO) during summer and early fall at the Stockton Deep Water Ship Channel and high levels of ammonia from the Stockton wastewater plant in October cause poor water quality to delay adult Chinook migration up the lower San Joaquin, which causes an increase in poaching, lower egg and sperm viability and greater threats to outmigrating juveniles (Hallock et al, 1970 in CMARP). Fish migration does not appear to be limited by existing flow conditions, but reduced flows combined with polluted or warm water agricultural discharges could create problems for migrating fish.

Fall-Run
Adult fall-run Chinook salmon migrate into the Sacramento River and its tributaries from June through December (Yoshiyama, et al. 1998) Migration Peaks in September and October and spawning by mature adults begins shortly thereafter. Cool water releases in the Sacramento and Feather rivers are unnaturally high in late-summer and fall due to hypolimnetic discharge from

Shasta Reservoir (Stillwater, 2006). Increased summer and fall discharge, therefore may improve water quality and temperature conditions for migrating fall-run salmon. High ambient temperatures during late summer and early fall combined with warm or polluted agricultural drain water could become a problem for migrating salmon at lower stream flows (Domagalski, et al.). By mid October, however, water and ambient temperatures are cool enough for migrating salmon (Figure 4).

High water temperatures can prevent upstream migration, and can cause physiological damage and exhaustion (CALFED C-9). Temperatures above 70°F (21.1°C) prevented the upstream migration of adult Chinook salmon from the Delta to the Sacramento River, but the Chinook began migrating into the lower Sacramento as water temperatures fell from 72°F-66°F (22°C-18.9°C) (Hallock 1970 in USFWS, 1995). Temperatures ranging between 50°F and 67°F were found to be suitable for upstream migration of fall-run Chinook (Bell, 1986; Bell, 1973 in USFWS, 1995; and Bell, 1991 in Oroville). Although water temperatures below 38°F are reported to decreases adult survival (Hinze 1959 in USFWS, 1995), temperatures this low are not likely to occur in the Sacramento Basin tributaries.

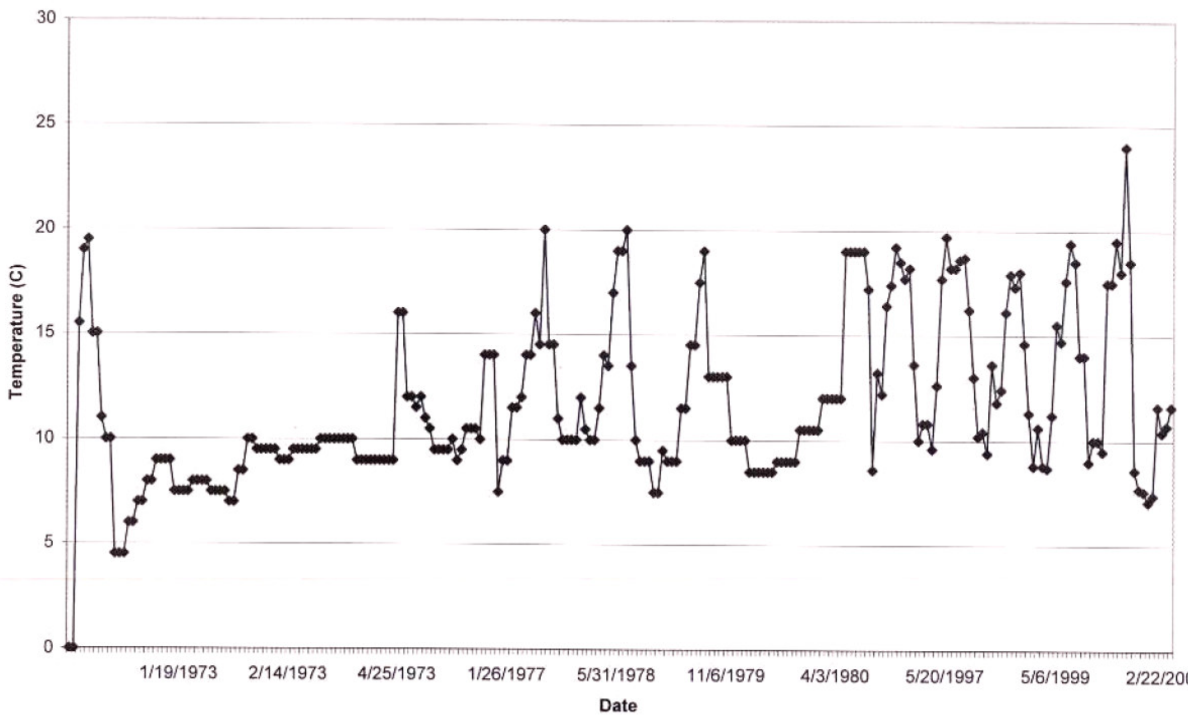

Figure 3: Temperature data collected on the Sacramento River downstream of Wilkins Slough (RM 118) between 1973 and 2000 at the Wilkins Slough gaging station (#11390500). Modified from Figure 4.2-7 in the Sacramento River Ecological Flows Study State of the System Public Review Draft.

A more natural flow regime in the late summer and fall could delay or impede the migration of fall-run salmon. Observations from the San Joaquin Basin where fall flows are lower and warmer suggest that the peak of the fall-run migration would shift to October and November. This may not reduce the overall population of fall-run salmon spawners, but it could create problems for recruitment by delaying emergence until the later spring months. Based on experience from the San Joaquin River (Stillwater, 2003) fall-run that emerge latter may have difficulty migrating out of the Sacramento and Feather Rivers before temperatures begin to rise in the late spring.

Increasing instream flows in the early fall in the Sacramento basin could improve conditions for migrating adult fall-run Chinook by reducing straying, improving water quality, improving passage barriers, decreasing water temperatures and decreasing the delay in migration. If salmon migration is motivated by major storms, early freshets or pulses after the first rain, and most of the large flows from storm events are trapped behind dams, reservoir operators can simulate pulse events by releasing water from the reservoir. However, "There is [a] concern that pulse flow releases in mid October to attract salmon may cause the fish to enter the rivers earlier than normal, which may expose them to high water temperatures when the pulse flows cease." (CMARP). Therefore, if flows are increased during this mid-fall period, it is important to continue to maintain adequate flows for migrating adults and subsequent spawning.

Late-Fall Run
Adult late fall-run Chinook salmon migrate up the Sacramento River between mid-October and mid April, with peak migration occurring in December (Vogel and Marine, 1991). Water temperature and flow conditions within the natural range of variability will be suitable for late fall-run since water temperatures are within optimal levels.

Winter-Run
Adult winter-run Chinook salmon enter San Francisco Bay from November through June (Van Woert 1958, Hallowck et al. 1957 in NMFS 1997). Migration past Red Bluff Diversion Dam begins in mid-December and can continue into early August but the majority of winter run adults migrate past Red Bluff Diversion Dam between January and May with a peak in mid-March (Hallock and Fisher, 1985). Current RBDD operations facilitate upstream passage of winter-run adults by raising gates between September 15 and May 15.

Lower fall and winter flows are unlikely to create temperature adverse to winter-run migration, but lower spring flows could conceivably become a problem in drier years if spring flows are further reduced. Similarly, increased spring flows could be beneficial particularly for the latter part of the migration, but there is no evidence that the current adult migration is stressed by low flows or high temperatures.

Spring-Run
Although spring-run were probably the most abundant run historically in the Sacramento River (Mills and Fischer, 1994), most spring-run fish currently spawn in three tributaries: Deer, Mill, and Butte Creeks. Mainstem habitat was mostly blocked by Shasta Dam, but some spring-run still spawn below the dam, although they have apparently hybridized to some extent with the fall-run (Stillwater, 2006).

Adult spring-run enter the Sacramento-San Joaquin Delta beginning in January, entering their natal spawning streams from March to July (Myers et al. 1998). Adult spring-run migrate upstream to spawn in different tributaries at somewhat different times, suggesting some degree of life-stage flexibility. Butte Creek fish migrate up beginning in February and peaking March and April when flows peak in that stream. Adults from Deer and Mill Creek begin migration in March and peak in May, concluding in June.

Increased spring flows in the Sacramento during the late spring may provide some small benefits for migrating salmon in drier years, but there is no evidence that the adults are currently under stress during their migration. Increased flows in the Sacramento in drier years will not benefit conditions in the tributaries where most spring-run salmon migrate.

4.2.8 Spawning, Egg Incubation, and Emergence

Different runs spawn throughout the year and construct their redds in gravels that are typically 6 inches (15 cm) or less in diameter (Flosi et al., 1998). High water temperatures (greater than 56°F) due to low reservoir storage, high air temperatures and low flow releases could decrease available spawning habitat and affect sperm and egg viability. High temperatures cause spawners to concentrate in the upper reaches where water temperatures are lower, which increases the rate of superimpostion of redds (CMARP). "Mature females subjected to prolonged exposure to water temperatures above 60°F have poor survival rates and produce less viable eggs" (USFWS, 1995) and water temperatures below 38°F also can result in lower egg viability (Hinze 1959 in USFWS, 1995).

In order to provide quality areas of spawning habitat, adequate flows need to be released from dams into the tributaries during the spawning period. Over the long run, periodic high flows are necessary to mobilize gravels and flush-out fine sediments. However, large peak flow events that occur in channels that have been excessively incised and leveed cause excessive gravel mobilization, which can disrupt spawning and cause egg mortality (CMARP). Therefore, these flows should be released during periods when most fry have already emerged from the gravels so they reduce mortality to incubating salmon eggs (McBain and Trush, 2000).

Eggs usually incubate in the gravel for approximately 61-64 days before hatching (Healey 1991) and it takes about 70 days for fry to emerge from the gravel (USFWS 1998 in SP Cramer, 2000). This is consistent with EA Engineering's findings, (1991 in CMARP) which found that eggs incubate for 40-60 days and remain in the gravel for 45-90 days. When fry first emerge from the gravel they are known as alevins and have an attached yolk sac that they depend on for food and nourishment.

The development of eggs into fry appears to be a difficult time for Chinook (Healey, 1991). High water temperatures, fine sediment capping, dewatered redds, poor quality gravel, and low substrate flow may contribute to the high mortality rate during egg and alevin development. High water temperatures (greater than 56°F), due to low reservoir storage, high air temperatures and low flow releases (CMARP, Loudermilk 1996) may cause egg mortality and decrease the incubation period when eggs are in the gravel (EA Engineering 1993 in CMARP). The late-fall and winter period of incubation combined with hypolimnetic discharge from the reservoirs generally maintains adequate water temperatures.

Low substrate flow through spawning gravels is known as an important cause of mortality in egg and alevin development. "Adequate water percolation through the spawning gravel is essential for egg and alevin survival. There is no doubt that percolation is affected by siltation and that siltation in spawning beds can cause high mortality" (Shaw and Maga 1943, Wickett 1954, and Shelton and Pollock 1966 in Healey 1991). Fine sediment capping occurs when redds become covered with fine silt (fines) due to small storm events that transport and deposit fines downstream. Shaw and Maga (1943) observed that siltation resulted in greatest mortality when it affected eggs in their early incubation stage (in Healey, 1991). Although common in steep coastal watersheds, fine sediment capping is relatively rare in the Sacramento basin due to sediment trapping in upstream reservoirs and the general lack of unregulated tributaries upstream of spawning areas.

Dewatering of redds is a known mortality factor effecting development of alevins. (Becker et al., 1982, 1983 in Healey, 1991). Dewatering of redds can be minimized below dams by careful flow regulation. Contaminated groundwater caused by seepage from agricultural or urban areas causes an increase in water temperature and reduces dissolved oxygen within spawning gravel, which may be harmful to incubating salmon eggs (CMARP).

Adequate base flows during the incubation and emergence period combined with periodic flushing flows outside the period should reduce the mortality factor of eggs and alevins. Instream flows, at or above spawning flows, should be maintained throughout the incubation and emergence period to avoid dewatering redds. Siltation and capping from fine sediments could be minimized with small reservoir releases timed to coincide with rainfall induced local run-off. These releases would help convey fine sediments out of the spawning reach.

Fall-Run, Late-Fall, and Spring Run

The mature adults spawn shortly after arriving at their spawning grounds between September and December. In the Sacramento and its tributaries, incubation and alevin development occurs from October through March (CMARP). Flow or temperature conditions are unlikely to be a problem except when Shasta Reservoir levels are drawn down. High water temperatures is probably not an important factor affecting fall, late fall and spring- run Chinook in the Sacramento Basin because incubation occurs between September and April when water temperatures do not rise above 14°C (57.2°F).

Winter-Run

Temperature stress induced by lower flows or lower reservoir levels in the summer, could be a significant problem for winter-run Chinook that incubate during the summer months. Temperatures in the winter-run spawning reach below Keswick Dam are largely controlled by the cold water pool in Shasta Reservoir and the Shasta temperature control device constructed in the 1990's to manage cold water pool releases for the benefit of salmon. Currently, however, summer time flows are unnaturally high. Substantially reducing summer time flows, may result in elevated temperatures to the extent that it substantially increases travel time for cool water releases to reach the downstream end of the spawning reach, resulting in more time for the water to warm. However, stream temperatures will be controlled by a combination of cold water pool management in the reservoir j(reservoir level) and releases from that cold water pool (instream flows).

It is unclear how much, and at what point reduced flows in summer will increase temperature and how much that will negatively impact winter run. If substantially reducing flows creates negative impacts the endangered winter run irregardless of cold water pool management, then managers will be forced to maintain artificially high summer flows during winter run at incubation at the expense of increasing flows during other parts of the year for other species and other life-stages.

4.2.9 Juvenile Development and Rearing

Growth and rearing of juveniles is crucial to ensure that they grow fast enough to smolt before the onset of high temperature stresses common in the late spring. Smolts are typically >70-80mm and are able to survive in saltwater. Larger juveniles have a better chance of succeeding and surviving to the smoltification phase. "The rate of downstream migration of Chinook fingerlings appears to be both time and size dependent and may also be related to river discharge and the location of the Chinook in the river…Larger Chinook traveled downstream faster, and the rate of migration increased with the season" (Healey 1991). Growth is also important for avoiding other sources of stress and mortality such as lack of food, entrainment, predation, and disease. Larger fish are better able to compete for larger prey and avoid entrainment and predation. Larger juveniles have a competitive advantage over smaller fish in selecting prime positions in rearing areas (Fausch 1984 in Myrick and Cech), which can increase feeding rates (Alanara and Brannas 1997 in Myrick and Cech 2001). Larger fish also have more energy stores to withstand stresses imposed by disease.

There is great uncertainty about the suitability of the Delta for juvenile rearing and growth relative to rearing conditions farther upstream in the spawning reaches. The CALFED Strategic Plan for Ecosystem Restoration identified this question as one of the major uncertainties constraining the restoration planning process in the Bay-Delta watershed. Although Chinook salmon use other estuaries for rearing, most research and previous management actions on salmon in the Delta assume that juveniles suffer very high mortality in the Delta and has thus focused on moving smolt through the Delta as quickly as possible. Moyle (2002) found that "juveniles from other runs apparently do not spend as much time in the estuary, but pass through fairly rapidly on their way to sea. Whether or not this rapid passage is a recent phenomenon as the result of drastic changes in estuarine habitat or is the historical pattern is not clear".

Fry appear to develop and grow in the tributaries, on inundated floodplains and in the Delta at different times until they become smolts and are large enough to migrate to the Ocean. There is strong evidence that juveniles rearing on inundated floodplains in the Yolo Bypass, a lowland transition zone between the spawning reaches and the Delta, had significantly higher growth rates than juveniles reared in the mainstem of the Sacramento River (Sommer et al. 2001). Sommer et al. (in preparation) attributed the higher growth rates to the increased area of suitable habitat, increased temperatures and increased food resources. Sommer et al. (2001) found that drift insects (primarily chironomids) were an order of magnitude more abundant in the Yolo

Bypass than the adjacent Sacramento River channel during 1998 and 1999 flood events. Seasonally inundated floodplains are also relatively free of exotic predators. "In the Central Valley during high flow periods, these fish historically moved into the floodplain, where they could rear for several months." (Moyle, 2002). Today, however, most of the rivers in the Sacramento Basin have been cut off from their floodplains, decreasing the available habitat for juveniles to develop and grow.

Less is known about the value of inundated floodplains relative to the gravel bedded reaches of the tributaries, which produce abundant food resources from macro-invertebrate production. Numerous studies indicate that gravel bedded reaches are more productive than sand and clay bottomed reaches that characterize the lower Sacramento. The increased food resources in the gravel bedded spawning reaches may be somewhat offset by the constant cold water, hypolimnetic releases from the dams, which may dampen growth. Channel incision, degraded riparian vegetation and degraded streambed complexity have been found to reduce the supply of organic detritus that invertebrates depend on for food, which may limit growth and survival of juvenile salmon that depend on invertebrates (Allan 1995 in CMARP). Incised channels in the Sacramento basin have cut off the rivers from their floodplains, which further limit access to food supplies (CMARP). These incised channels combined with high flows can result in fry and juveniles being washed down stream into less productive lowland reaches with high predator populations. Despite lower macroinvertebrate production, warmer water temperatures in the low-lying rivers and in the Delta may result in higher growth rates similar to observations from the Yolo bypass. Healey (1991) found that fry grow more rapidly in the Sacramento-San Joaquin estuary than in the rivers. However, others report that "fry that rear in the upper rivers experience a higher survival to smolting than fry that rear in the delta" (Kjelson et al. 1982, Brown 1986 in Healey, 1991).

Temperature has a major impact on growth. High water temperatures were found to stimulate smoltification and growth (Kreeger and McNeil 1992 in CMARP and SP Cramer, 2000 and Castleberry et al., 1991 in Myrick and Cech, 2001). Myrick and Cech (2001) conducted an extensive review of temperature effects on growth of juvenile Chinook in the Central Valley (Table 3.6). Although they found conflicting results, generally temperatures in the 60-66°F (15-19°C) range lead to high juvenile growth rates. When juveniles are rearing in February and March, temperatures in the tributaries are relatively low, cooler than temperatures needed for optimal growth. SP Cramer (2000) found that "higher water years result in cooler river temperatures [in the spring], which in turn can slow growth rates…However, Cramer et al. (1985) concluded from a variety of growth measurements that warmer temperatures, rather than lower flows, were driving growth of juvenile Chinook" (SP Cramer 2000). Higher growth rates may be a factor of slightly higher temperatures on the floodplains and in the Delta during this early spring period.

Table 3. Effects of temperature on growth of Juvenile Chinook in the Central Valley (Myrick and Cech, 2001 and Moyle, 2002)

Source	**Location**	**Maximum Growth**
Moyle (2002 referencing Marine)		55-64°F (13-18°C)
Rich (1987)	Nimbus State Fish Hatchery on American River	56-60°F (13-15°C)
Marine (1997)	Coleman National Fish Hatchery on Sacramento River	63-68°F (17-20°C)
Cech and Myrick (1999)	Nimbus State Fish Hatchery on American River	66°F (19°C)

Water temperatures greater than 77°F (25°C) were found to be lethal to juveniles in the Central Valley when exposed to these high temperatures for a long period of time, but they could withstand brief periods of high temperatures up to 84.2°F (29°C) (Myrick and Cech, 2001).

Although the mid water trawl surveys at Chipps Island measure smolt outmigration from the Delta (Baker et al. 1995), there are no measurements that identify where these outmigrating fish reared. Without this information it is impossible to estimate the relative importance to the population of fry reared in the Delta and on lower river floodplains compared with fry that rear in the tributaries before outmigrating. It is fairly clear, however, that the majority of juveniles migrate to the lower river and Delta soon after emergence. Therefore, we hypothesize that improving rearing conditions in the lower river and the Delta should increase overall escapement. Present management seems to focus on the quality of rearing habitat in the tributaries, but if the majority of young are moving out of the tributaries, it seems prudent to improve conditions for them as well. In order to understand where to focus limited resources where they will have the most impact on successful rearing, we need better information on the relative success of fish rearing in the lower river and Delta relative to fish rearing in the gravel bedded reaches of the tributaries.

Entrainment in water diversion facilities and predation, particularly from non-native bass, are also a major problem for salmon during the juvenile life stage. "Predators are commonly implicated as the principal agent of mortality among fry and fingerlings of chinook…[and] other fish are generally considered to be the most important predators of juvenile salmon" (Healey, 1991). Entrainment and predation are less related to flow then morality associated with high temperatures during the outmigration period. Juvenile growth rates probably affects mortality from predation and entrainment because smaller juveniles are more susceptible to mortality. Juvenile growth rates may also affect ultimate survival because faster growing juveniles and smolts migrate out of the system earlier in the spring before temperature becomes a major source of mortality and because larger juveniles travel downstream faster (Healey 1991, CMARP).

Contaminated agricultural and urban runoff may also increase outmigrating juvenile salmon's susceptibility to disease, such as *Ceratomyxa*, which causes a high mortality rate in Chinook and flourishes in organic sediments and possibly in mine pits (CMARP p 19 and 20).

We hypothesize that improving juvenile growth rates will improve the rates of successful smolt outmgration and may also reduce mortality from diversions and predation. Based on robust results from research in the Yolo Bypass, it appears providing seasonally inundated floodplain habitat is perhaps the best way to ensure adequate growth before outmigration to the Delta and Ocean. If nothing else, providing seasonally inundated floodplain habitat will provide better habitat for the young that migrate or are washed out of the gravel bedded reaches early.

Increased flows during the rearing period combined with floodplain restoration should help increase overall growth rates and potentially decrease predation. Increased flows during this period should also dilute poor water quality. Increased flow may also decrease negative effects on salmon from contaminants and disease. Agricultural return flow from the west side of the San Joaquin did not cause any detrimental effects on growth and survival of hatchery-born Chinook salmon when the return flows were diluted by 50% or more with water from the San Joaquin (Saiki et al., 1992, from CMARP p 19).

Fall-Run

Fall-run Chinook usually emerge from the gravel as fry between January and March. Large portions of fry are immediately dispersed downstream to the lower rivers and the Delta, while some fry remain in the tributaries to rear (Kjelson et al. 1982 in Healey 1991, Moyle, 2002, and SP Cramer, 2000). SP Cramer (2000) found that peak migration of fry on the Stanislaus was associated with an increase in daily average flows. Different studies have found that fry and smolts are more abundant in the Sacramento-San Joaquin Delta at different times, depending on how long they remain in the upstream tributaries, before migrating to the ocean. "Most rearing occurs in freshwater habitats in the upper delta area, and the fry do not move into brackish water until they smoltify" (Kjelson et al., 1981, 1982 in Healey, 1991).

Higher flows during January through March d are more likely to result in inundated flood-plain or channel margin habitat ideal for rearing.

Late Fall-Run

Due to their late emergence in April and May, late-fall run are not able to migrate downstream before summer temperatures in the lower river become lethal. Rather most escapement probably results from juveniles that rear and over summer in the upper river. Increasing late spring and early summer may improve conditions for those fish that attempt to migrate out in the late spring and early summer as juveniles. Very large flows, however, would be necessary to create suitable temperature conditions in the lower river.

Winter-Run

Winter-run fry emerge from the spawning gravels from mid-June through mid-October (NMFS 1997). Because winter-run salmon spawning is concentrated upstream in the reaches below Keswick Dam, the entire Sacramento River serves as a nursery area for juvenile winter-run Chinook as they migrate downstream. Downstream movement of juveniles typically begins in August soon after fry emerge from redds. Rotary screw traps at RBDD usually record peaks in the abundance of winter-run salmon fry in September and October. However, following these initial pulses of fry, winter-run juveniles steadily stream past RBDD through March (Kimmerer and Brown, in prep.). Most juvenile winter-run Chinook reach the Delta between January and April, when they pose a conflict with Delta pumping operations designed to increase South of Delta storage during winter months when conflicts with protections for Delta smelt are reduced.

Higher flows during the out migration period for winter run are likely to result in inundated flood-plain or channel margin habitat ideal for rearing. More food will reduce mortality to the extent food is limiting and faster growing fish will have higher survival against gape limited predators or through the smoltification process.

Spring-Run

The rearing and outmigration patterns exhibited by spring-run Chinook salmon are highly variable, with fish rearing anywhere from 3 to 15 months before outmigrating to the ocean (Fisher 1994). Variation in length of juvenile residence may be observed both within and among streams (e.g., Butte versus Mill creeks, USFWS 1995, as cited in Yoshiyama et al. 1998). Some may disperse downstream soon after emergence as fry in March and April, with others smolting after several months of rearing, and still others remaining to oversummer and emigrate as yearlings (USFWS 1995, as cited in Yoshiyama et al. 1998). Scale analysis indicates that most returning adults have emigrated as subyearlings (Myers et al. 1998). Calkins et al. (1940, as cited in Myers et al. 1998) conducted an analysis of scales of returning adults and estimated that greater than 90% had emigrated as subyearlings, at about 3.5 in (88 mm).

Spring-run that migrate early in their first year could benefit substantially from inundated floodplain habitat and channel margins that higher flows could provide. The excerpt below drafted by Stillwater (2003) clearly explains the phenomena:

> "As stream-type salmon, a fraction of spring-run juveniles may spend a summer rearing in natal streams before emigrating to the ocean. After emergence, spring-run juveniles display agonistic behavior, establishing and defending territories. This behavior means that summer rearing habitat can be quickly saturated, even if escapements are low, because of the area required to support each juvenile. Spring-run that migrate downstream as fry often represent those individuals displaced as a result of rearing habitat saturation in upstream reaches. Because these fry are forced to migrate downstream at a small size < 1.6 m (40 mm), they are vulnerable to predation, such that the fry component may not contribute significantly to future escapements. However, recent research conducted on the Butte Creek population of spring-run salmon suggest that successful rearing by spring-run fry in the Sutter Bypass may be stimulating the recent increase in escapements. Generally, the Deer and Mill creek populations spring-run do not seem to have the same success in fry rearing. To improve fry rearing potential for the Deer and Mill Creek populations, we recommend the creation of a dedicated floodplain/bypass area along the mainstem Sacramento River downstream of Deer and Mill creeks. A bypass in the vicinity of Deer and Mill creeks would provide rearing habitat to fry and juveniles outmigrating to the main stem from these important spawning tributaries for remaining wild-type spring-run Chinook. Such a bypass should be constructed to provide high-quality rearing habitat at relatively low flows, so that the habitat is available for a large portion of every winter, even during drier years.

4.2.10 Smolt Outmigration

As mentioned in the previous section, after fry emerge from the gravel the majority disperse downstream, especially during increases in flows or after storm events. Whether young fish migrate out of the tributaries soon after emergence or whether they rear in the tributaries, they eventually undergo smoltification and make their physiological transition to salt water. Several factors trigger smoltification, including changing hormone concentrations, increasing photoperiod, increasing temperature, and increasing body size (Myrick and Cech, 2001). While most of these factors cannot be influenced by changing management actions in the tributaries or the Delta and are not discussed in this report, temperature and body size are affected by flow and can be influenced by reservoir reoperation.

Smolts require lower temperatures than rearing juveniles. While higher temperatures in the 60-66°F (15-19°C) range can optimize growth of juveniles and better prepare them for smoltification earlier, lower temperatures are more optimal during the smoltification process. A comprehensive study by Myrick and Cech (2001) found that Chinook have a better chance of surviving in the Ocean if they undergo smoltification at lower temperatures, ranging from 50-63.5°F (10-17.5 °C). Warmer temperatures in the February –March period (which occur on floodplains) stimulate growth of juveniles so they are larger before they undergo smolification and therefore larger when they enter the Ocean (Myrick and Cech, 2001). Larger juveniles are also able to smolify before harmful high late spring temperatures set in. Cooler temperatures are necessary in the smolt outmigration period of April – June. The need for warmer temperatures in the early spring and cooler temperatures in late spring reflects the historical hydrograph, where large, cold snowmelt flows dominated the Sacramento Basin later in the spring.

Body size is an important function of the success of outmigrating smolts and the development to smoltification (Dlarke and Shelbourn 1985; Johnssson and Clarke 1988 in Myrick and Cech, 2001). It is important that Chinook reach an appropriate size for smolting before they arrive in saltwater. Relatively warm temperatures can be beneficial for growth provided adequate food supply. Increases inundated floodplain habitat provides the type of habitat that allow juveniles to grow larger before smoltification (Sommer et al, 1991).

High water temperatures, low flows and entrainment may cause increased mortality rates in outmigrating smolts and affect growth of juvenile Chinook. High water temperatures, particularly in May and June may pose the largest threat to juveniles that remain in the tributaries and in the Delta later in the spring. Baker et al (1995) found that 50% of Chinook smolt that migrate through the Delta die when temperatures reach 72-75°F (22-24°C) McCullough (1999 in Moyle) found that few fish can survive temperatures greater than 75.2°F (24°C) even for short periods of time.

Prolonged periods of high flows from January through June, especially from late February through mid-April, will reduce temperatures and help flush out outmigrating juveniles and smolt (CMARP). There are several programs underway and several measures that could be taken to improve juvenile outmigration and survival. Increased flows during outmigration improve juvenile/smolt survival in the Sacramento basin tributaries and Delta. Studies have shown that survival of fry and smolts passing through the Sacramento-San Joaquin River delta were highly correlated with discharge of the Sacramento River (Healey, 1991 and USFWS, 1998 in SP Cramer). Studies from the Stanislaus River shows that Smolt survival was high (about 78%) when releases from were increased in late April in 1986 and 1988, but were low (28%) when releases were lower in April 1989. A substantial increase in migrating juvenile was measured when flows were increased in the Stanislaus River for seven days in April 1995 (SP Cramer 1995 in CMARP).

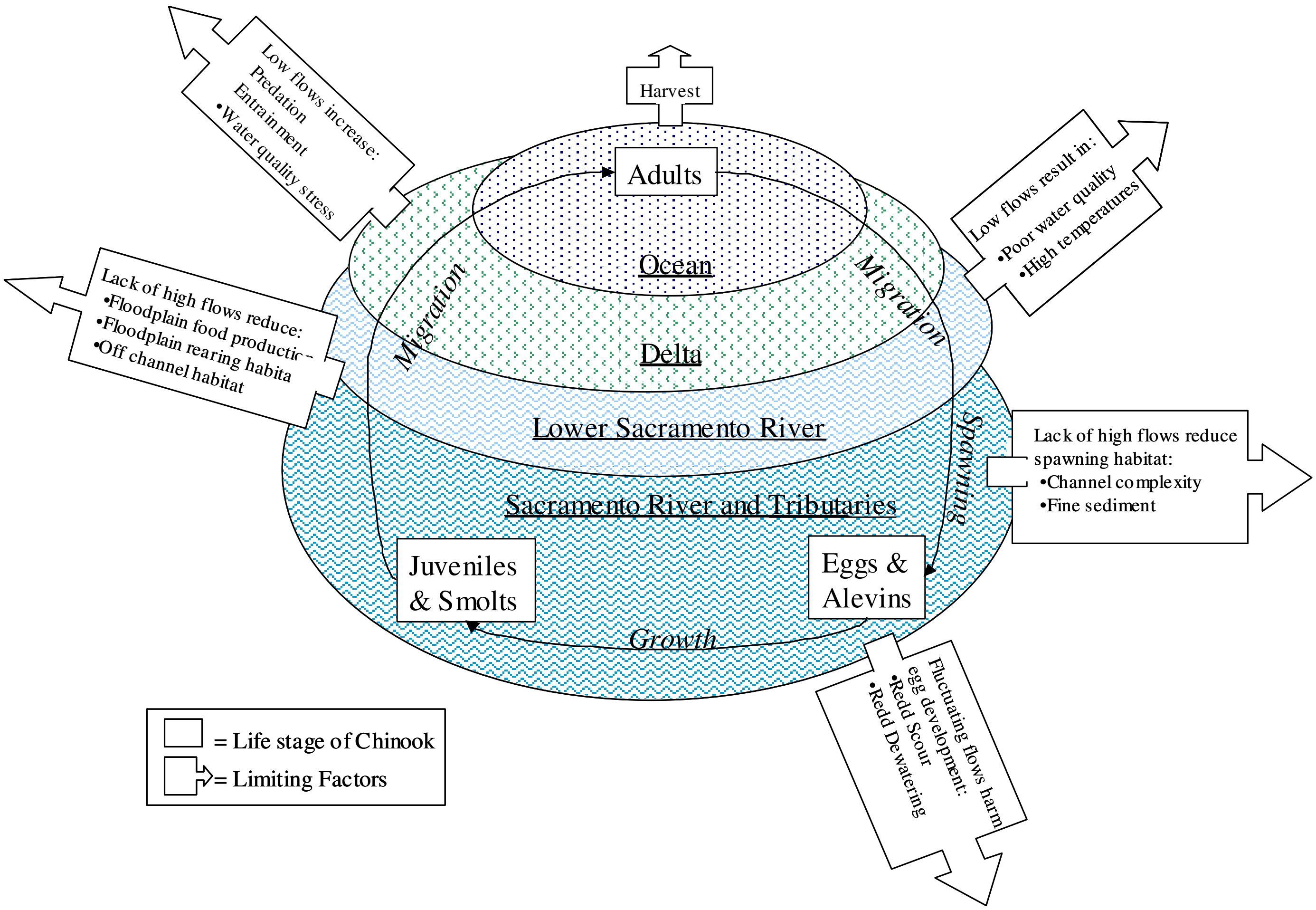

Figure 4: This conceptual model for Chinook salmon illustrates the life cycle of the Chinook in the Sacramento River, factors that increase Chinook mortality during their life cycle, and how restoration can improve the conditions of these fish.