Estimating Ecologically Based Flow Targets for the Sacramento and Feather Rivers

THE NATURAL HERITAGE INSTITUTE

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PREFACE

This report was prepared as part of a collaborative investigation by the Glenn Colusa Irrigation District (GCID) and the Natural Heritage Institute (NHI) to explore opportunities to expand water supplies in the Sacramento Valley through conjunctive management of surface water and groundwater supplies. These expanded supplies could contribute toward achieving three primary objectives: (1) improve local in-basin water supply reliability for farms, cities, and the environment; (2) contribute to improvement of statewide water supply reliability; and (3) enhance ecosystems in the rivers in the Sacramento Valley. The investigation was funded by the California Department of Water Resources and Bureau of Reclamation.

The Scope of Work of the federal and state grants includes a task to define a range of environmental flows to restore in stream and riparian ecosystem processes to the maximum extent compatible with the protection of the interests of the riparian landowners in the floodplain improvements. Flows shall be defined for both the Sacramento River below Shasta and Keswick dams, and the Feather River below Oroville and Thermalito dams, in terms of magnitude, duration, frequency, seasonality and reach. This will be defined in a manner to avoid any uncompensated risks to affected landowners. The range may include various assumptions about levee setbacks in the floodplains. Flood-routing models will be used to estimate the potentially inundated area and system capacity to carry environmental flows.

This report was prepared by the NHI in partial fulfillment of the above-defined task. It postulates hypothetical environmental flow regimes for the Sacramento and Feather Rivers that are significantly different from those that presently exist. It is not yet known to what extent the flows can be achieved through conjunctive water management or, potentially, by other means that are outside the scope of this investigation, while other existing and future water demands are satisfied. Also, the risks that the recommended flows may pose to affected landowners are not addressed in the report, but will be addressed in subsequent work. NHI has prepared this report for the purposes of this planning investigation only. To the extent this report is used or referenced for other purposes, it will be subject to review, modification, and acceptance by the larger number of entities and stakeholders necessarily involved in crafting water management policies, projects and practices in the Sacramento Valley and downstream affected areas.

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1. EXECUTIVE SUMMARY

This study identifies an environmental flow regime for the Sacramento and the Feather Rivers in order to:

- Test the feasibility of reoperating terminal reservoirs in the Sacramento River Basin without diverting additional water away from agriculture,
- Develop a comprehensive hypothesis regarding the range of flows that may be necessary to restore ecological processes to the Sacramento River, and
- Use the environmental flow targets to inform and guide conjunctive use scenarios.

The development of environmental flow regimes is as much an art as a science, but we attempted, to the extent possible, to use established methods to develop a transparent and replicable approach for identifying and environmental flow regime. We conducted a detailed literature review of various methods and approaches previously utilized to develop environmental flow recommendations, and employ 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 and Feather Rivers. This approach relies heavily on hydrological evaluations, previous studies and modeling efforts analysis of historical hydrology, and expert opinion to estimate environmental flow requirements.

Our approach consists of five basic steps:

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 achieve environmental objectives.
3. Compare and analyze existing and historical hydrology to understand natural hydrologic patterns and how they have been altered.
4. Identify obvious gaps between flows necessary to achieve objectives and existing flows.
5. Modify the existing hydrograph into an environmental flow hydrograph based on an understanding of natural hydrology and the flows necessary to achieve key objectives.

These five steps will ultimately need to be followed by an adaptive management research program to test and refine an improved environmental flow regime over time.

We designed the environmental hydrograph to achieve the following three types of objectives

- Geomorphic Functionality: Bed mobility, channel migration, and floodplain inundation.

- Riparian Habitat Sustainability: Recruitment and maintenance of Fremont Cottonwood.
- Chinook Salmon: Improved habitat, particularly rearing habitat, for all runs.

We relied on field data, modeling results, and studies , particularly the recent Nature Conservancy Study of the Sacramento River, to identify the minimum flows and critical thresholds to achieve each of our objectives. We then analyzed historical and existing hydrology to understand how the objectives may have been achieved under pre-dam conditions and to evaluate how existing hydrology may fall short of meeting those objectives.

A sharp reduction in the magnitude and duration of the late winter and early spring hydrograph and a corresponding reduction of inundated floodplain habitat is the most obvious and significant change in the hydrograph on both the Sacramento and Feather Rivers. The reduction in late winter and spring flows reduces the frequency of geomorphic and riparian flows and substantially reduces the extent and frequency of occurrence of inundated floodplain rearing habitat for salmonids. Restoring spring flows alone, however, will not be sufficient to dramatically increase the amount of floodplain habitat. Modifications of the levees and bypass system will also be necessary to enable high flows to inundate historical floodplains. We evaluate the amount of flow necessary to inundate the Yolo and Sutter Bypasses assuming modification of the weirs controlling flows into those bypasses in the interest of identifying water efficient strategies for creating large areas of inundated floodplain habitat.

The last chapter identifies an environmental flow regime for the Sacramento and Feather Rivers. An increase in late winter and early spring flow is the primary component of the environmental flow regime, but a corresponding reduction in summer base flows is also recommended. Reduced summer flows are primarily needed to free-up water needed to restore the spring hydrograph but may also provide ecological benefits by better approximating the natural hydrograph. Reducing summer base flows could, however, increase summer temperatures and harm salmonids including the endangered winter-run Chinook salmon. On the other hand, cool water temperatures in the upper Sacramento River are largely controlled by the volume of cold water storage behind Shasta Dam and the environmental flow regime identified here does not involve modifying coldwater pool management.

The summer temperature issue is one of several key uncertainties that must be addressed before any significant modifications to the flow regime can be refined and implemented for environmental purposes. Articulating a hypothetical environmental flow regime is the first step in identifying and addressing constraints and uncertainties associated with improving environmental flow regimes on regulated rivers. To that end, NHI welcomes comments and criticisms so that we can improve upon this report as we learn more about the rivers and the people who depend upon them for their livelihood.

2. INTRODUCTION

This study identifies environmental flow targets for the Sacramento River and the Feather River. The purpose of developing environmental flow targets is to:

- Test the feasibility of reoperating terminal reservoirs in the Sacramento River Basin without diverting additional water away from agriculture,
- Develop a comprehensive hypothesis regarding the range of flows that may be necessary to restore ecological processes to the Sacramento River, and
- Use the environmental flow targets to inform and guide conjunctive use scenarios.

Our thesis is that reservoirs operated today for a limited set of water supply and flood control objectives could be reoperated to achieve newly defined ecological objectives without compromising existing objectives. This opportunity was recognized by the authors of CALFED's Strategic Plan for Ecosystem Restoration:

> "There is underutilized potential to modify reservoir operations rules to create more dynamic, natural high-flow regimes in regulated rivers without seriously impinging the water storage purposes for which the reservoir was constructed. Water release operating rules could be changed to ensure greater variability of flow, provide adequate spring flows for riparian vegetation establishment, simulate effects of natural floods in scouring riverbeds and creating point bars, and increase the frequency and duration of overflow onto adjacent floodplains."

Clearly defining this new set of ecological objectives and estimating the flows necessary to achieve them is the first step toward evaluating the feasibility of restoring these flows. The biological and physical processes that support natural riverine functions are complex and the task of defining environmental flow regimes is enormously difficult. For the purpose of defining an environmental flow regime and assessing the feasibility of attaining it, we have identified a simplified but broad set of water intensive ecological objectives that best capture the full range and magnitude of environmental flow requirements in the Sacramento Basin. These objectives include:

- Geomorphic Processes: sediment transport, channel geomorphology, floodplain inundation.
- Riparian vegetation: cottonwood recruitment and maintenance flows
- Chinook and Steelhead: stream temperatures and adequate flow for various life stages.

This study focuses on the magnitude and timing of flows necessary to replicate key ecological and geomorphic processes, and considers the flows necessary to provide suitable conditions for various life stages of Chinook salmon and steelhead. This study does not identify specific population targets for salmonid restoration, nor does it address important non-flow objectives such as habitat area required for restoration of target species or augmentation of coarse sediment supplies necessary to restore full geomorphic structure and function. Rather this study focuses on magnitude, pattern, and quantity of water necessary to restore ecological functions assuming that adequate physical habitat exists or will be created to complement a suitable environmental flow regime. The rationale of this focus is to identify a hypothetical environmental flow regime for the purpose of evaluating whether it is possible to reestablish ecological and geomorphic flows on the rivers of the Sacramento Basin without reducing water supply deliveries to existing water users.

This report would not have been possible without the foundational analysis conducted by the Nature Conservancy and their consulting team, but it differs substantially from the Sacramento River Ecological Flows Study (SREFS) developed by the Nature Conservancy with funding from the CALFED Bay-Delta Program. The SREFS compiled information on the state of the Sacramento River ecosystem and developed a decision support tool to predict how changes in the flow regime of the Sacramento River might affect key attributes and species of the riverine ecosystem. The SREFS did not, however, attempt to develop an environmental flow prescription for the river and did not address ecological conditions or flow requirements for the Feather River. The SREFS decision support tool could be used to test and refine the flow regime developed for this report, but the SREFS did not and will not propose an environmental flow regime. We relied heavily on the information developed for the SREFS to generate the environmental flow regime described in this report.

Our study relies heavily on analysis of historical hydrology and the habitat it created to provide a reference point for identifying ecosystem restoration goals, but we recognize that it is not possible to restore historic conditions in highly altered systems such as the Sacramento River. Historical hydrologic analysis is useful for identifying patterns in the timing, magnitude, duration, and frequency of flows that may be important for maintaining native species, but it is less useful in developing specific flow prescriptions, because physical habitat has been so profoundly changed by dams and levees. We recognize that it is not possible to fully restore historical hydrology or habitat conditions in the Sacramento Valley, but ecosystem restoration will require reestablishment of a minimum threshold of both hydrologic and physical habitat conditions.

Although this study identifies hypothetical restoration flow regimes for the Sacramento and Feather Rivers, we recognize 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 hypothetical flow regime serves as a reasonable starting point for evaluating the economic feasibility of reoperating reservoirs and a long-term adaptive management program. The assumptions and uncertainties associated with the hypothetical flow regime are important to acknowledge and understand. 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 modeling, pilot flow studies, model calibration, and long-term implementation.

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

We conducted a detailed literature review of various methods and approaches previously utilized to develop environmental flow recommendations, which is described in further detail in Appendix A. 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.

4. IDENTIFY ENVIRONMENTAL OBJECTIVES AND UNDERLYING CONCEPTUAL MODELS

4.1. Environmental Objectives

The geomorphic, riparian, and salmonid objectives considered in this report are summarized below. A more detailed description of the objectives, background information, and the underlying conceptual models is included in Appendix B.

Geomorphic Objectives

- Sediment Transport: bed mobilization and bed scour
- Channel Migration
- Floodplain Processes: inundation and fine sediment deposition

Riparian Objectives

- Fremont cottonwood seedbed preparation
- Fremont cottonwood seed germination
- Fremont cottonwood seedling growth
- Periodic large-scale disturbance of the riparian zone
- Riparian stand structure and diversity

Chinook Objectives

- Chinnook salmon: suitable flow conditions and temperatures for all life stages.
- Provide inundated floodplain habitat for rearing juveniles during the later winter and early spring.
- Maintain and recruit spawning habitat, but avoid scouring gravels while eggs or alevon are present

We purposely did not identify population targets for salmonids. The extent and magnitude of restoration actions depends on the size of the population fish managers are attempting to restore. More fish require presumably require more habitat particularly for spawning and rearing. Creating more habitat may require both physical changes in channel conditions and increased flows. .

Appendix B describes the underlying assumptions and rationale (conceptual model) for environmental flow requirements. It describes the science of how and why river flows are necessary to achieve the objectives listed above, and identifies some of the challenges associated with developing environmental flow prescriptions.

5. ENVIRONMENTAL FLOW THRESHOLDS AND REQUIREMENTS

5.1 Geomorphic Thresholds

Flow requirements broadly fall into two categories: threshold and targets. Thresholds are flow prescriptions that only achieve their objective if the threshold is reached or exceeded. For example, bed mobility flows must be high enough to mobilize the bed. If they are below the threshold, the bed does not mobilize and no progress toward the objective occurs. In actuality, however, bed mobilization may occur at different flows in different reaches making it difficult if not impossible to name a single threshold number. Targets are flow requirements that are desirable but not essential to achieve. Benefits still accrue when there is progress toward the target even though the target is not actually reached. For example, a flow release to meet a target of 5,000 cfs to achieve an optimal water temperature for twenty four hours a day will still provide temperature benefits even if the release only achieves 4,000 cfs and optimal water temperatures eighteen hours per day. At some point, however, there is a minimum threshold or minimum flow below which temperatures are lethal or flows are insufficient to support fish.

This paper focuses on thresholds for key ecological and geomorphic objectives that generally require high flow thresholds, but also identifies flow targets to sustain salmon. We have not attempted to define minimum flow thresholds for salmon, but rather have identified more generous targets based on historical base flow conditions. We identify the basis for these thresholds and targets in this section and compile them into a environmental hydrograph in the final chapter of this report.

For each threshold, we have estimated the magnitude, duration, frequency, and timing of flows necessary to achieve a desired outcome and have organized table X and the following text accordingly.

5.1.1. Bed Mobilization:

Magnitude: There is limited information regarding the magnitude of flows required to initiate bed mobilization on the Sacramento River, but less information regarding flows necessary to precipitate full-scale bed mobilization. Under natural conditions the gravel bedded reaches of the Sacramento River were theoretically mobilized by peak flows exceeding the 1.5 to 2 year recurrence interval of the annual instantaneous peak (Leopold et al 1964), which is approximately 80,000 cfs to 120,000 cfs. For comparison, the post dam Q1.5 and 2.0 recurrence interval flow is approximately 65,000 and 80,000 cfs respectively. The Department of Water Resources estimated that the threshold for spawning gravel mobilization immediately below Keswick Dam was 50,000 cfs (CDWR 1981), but this is considered to be a minimum because it was based on observations of gravel that was artificially deposited below the dam *(Stillwater,* *2006).*[1] DWR added 13,300 yd^3 of gravel below Keswick Dam in 1978 and 1979, and estimated that 85% of it was eroded by high flows of 36,000 and 50,000 cfs during the winter of 1980 (CDWR 1981). Latter, Koll Buer of the USBR measured mobility and transport downstream of Keswick with "flower box" samplers – boxes placed into the channel bed before a high flow event. Buer's measurements indicate that gravel transport begins at 24,000 cfs but did not provide information about when larger gravels and the entire bed begin to mobilize. The coarser riffles downstream of Keswick (small boulders and large cobbles) are probably armored due to years of erosion from sediment free water released from Shasta Dam. These armored riffles appear not to change and thus probably remain immobile even at flows exceeding 100,000 cfs (K. Buer, personal communication in Kondolf, 2000).

There are not empirical studies or observations regarding bed mobility on the Feather River. Historical flow data is the only information available to estimate the discharge necessary to mobilize the bed on the Feather River. The 1.5 to 2 year recurrence interval of the annual instantaneous peak prior to the construction of Oroville Dam was 33,000 to 50,000 cfs respectively.

Frequency: Relatively frequent bed mobilization is necessary to prevent vegetation establishment and encroachment on gravel bars. Willows can become well established and resistant to scour in three to four years (cite). Therefore, bed mobilization flows are necessary at a greater frequency then every three to four years to prevent vegetation establishment.

Duration: The duration of peak flows may vary depending on the objective. A short duration may be enough to clean gravels on a spawning riffle while a longer duration flow may be necessary to maintain overall transport of gravels. Because coarse sediment inputs are limited by the upstream dam and riffles already show signs of armoring, long duration peak flows may actually degrade riffles. For this reason and to both reduce flood hazards and economize water, a short duration bed mobilization flow of approximately 12 hours at the recommended peak flow and then ramping down thereafter consistent with historical patterns may be optimal.

Timing: Ideally, bed mobility flows should occur after fall run fry have emerged from the gravel and before swallows begin nesting on stream banks in late march. We therefore recommend a 30 day target window between February 20 and March 20.

5.1.2 Bed Scour

[1] These gravels may have mobilized at lower flows because of their unnatural position relative to the high flows or because they were not integrated into the gravel/cobble matrix of the natural bed

Less is known about the bed scour process, flows exceeding the natural 5–10 year recurrence interval are probably necessary to precipitate bed scour (Trush et al. 2000). The pre-dam Q5 and Q10 recurrence interval on the Sacramento are 150,000 and 200,000 cfs respectively. During the post dam era, flows of 150,000 cfs or more occurred roughly once every 10 years. On the Feather River, the pre-dam Q5 and Q10 were 104,000 and 144,000 respectively. Flows of this magnitude have only occurred twice in the forty years since Oroville Dam was constructed. Because of the lack of information regarding bed scour and the probable flooding impacts of these flows, it is exceptionally difficult to develop and achieve a bed scour flow recommendation.

5.1.3 Bank Erosion and Channel Migration

Magnitude

Stillwater reports that there is general disagreement on the exact magnitude of flow to initiate substantial bank erosion, but claims there is growing evidence that flows between 20,000 and 25,000 cfs will erode some banks while flows above 50,000 to 60,000 cfs are likely to cause widespread bank erosion (Stillwater, 2007). Meander migration modeling analysis for the Sacramento River assumed that 15,000 cfs was the lower threshold for meander migration (Larsen, 2007). Total bank erosion and channel migration, however, is dependent on both the duration and magnitude of flows, which together produce a cumulative streampower in any given year. Analysis of cross section surveys (Buer, 1994a) over more than ten years shows that rates of bank erosion are closely correlated with cumulative annual stream power (Larsen, et al., unpublished in Stillwater, 2006). Bank erosion.

On the Feather River, there is very little information regarding flows necessary to initiate bank erosion and channel migration. The pre-dam Q1.5 on the Feather River (35,000 cfs) is approximately forty four percent of the pre-dam Q 1.5 on the Sacramento River (80,000) cfs. If channel migration flows on the Feather were similarly proportioned channel migration flows on the Sacramento (50,000 – 60,000 cfs), then one could expect significant and wide spread bank erosion on the Feather River at flows between 20,000 and 25,000 cfs. Instantaneous peak flows of this magnitude reoccur every 2.5 years on average, and large areas of channel revetment along the Feather River indicate that the unprotected bank is subject to erosion under the current flow regime.

Duration

The stream power relationship between magnitude and duration make it difficult to identify a specific threshold. Without modeling analysis, it is difficult to assess whether two weeks at 30,000 cfs could result in as much bank erosion as two days at 60,000 cfs.

Frequency

Bank erosion and channel migration are important for maintaining general riparian habitat, nesting habitat for bank swallows, and turbidity for juvenile fish cover. We are uncertain how often migration and erosion should occur but suspect that some bank erosion every year is a reasonable target. Slight but annual bank erosion may be beneficial for maintaining optimal bank swallow habitat. More significant and annual erosion events may be necessary for producing turbid water conditions. Moderate but less frequent bank erosion, every (2-4) years, may be adequate for generating new riparian habitat.

Timing
Erosive flows during the bank swallow nesting period, which generally begins in late March, can actually disrupt bank swallows. Therefore, it may be most beneficial to bank swallows to achieve bank erosion objectives prior to late march.

5.1.4 Floodplain Inundation and Rearing Habitat Flows

The occurrence of inundated floodplain habitat has been substantially altered by both levees and dams. Dams have reduced the frequency of high flows sufficient to inundate floodplains, while levees have prevented high flows, even very high flows, from inundating floodplains particularly in the lower reaches of the river below Colusa. It is not reasonable to reestablish inundated floodplains by overtopping levees, because it would require extremely, even unnaturally, high flows and would cause widespread flood damage.

Adequate duration of flooding in the designated flood bypasses generally occurs in the wet years and sometimes in normal wet years creating excellent conditions for salmon and splittail. But overtopping the weirs and flooding the bypasses in normal dry and dry years would require prohibitive amounts of water to achieve in normal dry and dry years. For efficiency sake, it is probably only realistic to achieve prolonged (30-60 days) floodplain inundation in normal dry and dry years by notching (or removing) the upstream weirs to allow a small amount of water to pass (3,000-5,000 cfs) and installing inflatable weirs in the low flow channels of the bypasses to back-up water.

Strategically breaching levees and flood control weirs to inundate flood bypasses and other undeveloped land is a much more prudent and achievable approach for creating inundated habitat. Although there may be many places to create inundated flood plain habitat with strategic levee modifications, we have focused on identifying flows that would create inundated habitat in the Yolo and Sutter Bypasses if modifications are made to the weirs that control flow onto the bypass. The area of inundation under a given flow is determined by topography and drainage. We assume changes in the topography and drainage of the bypasses (i.e. berms or inflatable wiers) to maximize the area of inundation at lower flows and minimize the potential for stranding. While it might be possible to create large areas of habitat at low flows, more flows may be necessary to optimize temperatures on the flood plain and conveyance of nutrients from the floodplain to the Delta.

Magnitude
We evaluated two questions associated with magnitude: the magnitude of flow necessary in the Sacramento or Feather Rivers necessary to inundate the bypasses and the magnitude of flow in the bypasses necessary to create large areas of suitable floodplain habitat. It may be possible to inundate large areas of the bypass with relatively little flow by installing flow barriers in the bypass to back-up water onto the floodplain. While this

may be suitable for creating large areas of inundation, it might not create the right residence time and temperature for optimal habitat. Habitat characteristics such as velocity, depth, temperature, residence time, primary productivity are negatively correlated with flow, while Diptera, an important food resource, was positively correlated with flow (Sommer et al, 2004).

According to DWR modeling analysis, large areas of the bypass become inundated with as little as 5,000 cfs flowing through the bypass (figure 5.1) (Harrell, B., 2008). Flows in excess of 25,000 cfs in the Sacramento River, however, may be necessary before it is possible to get 5,000 cfs down the bypass.

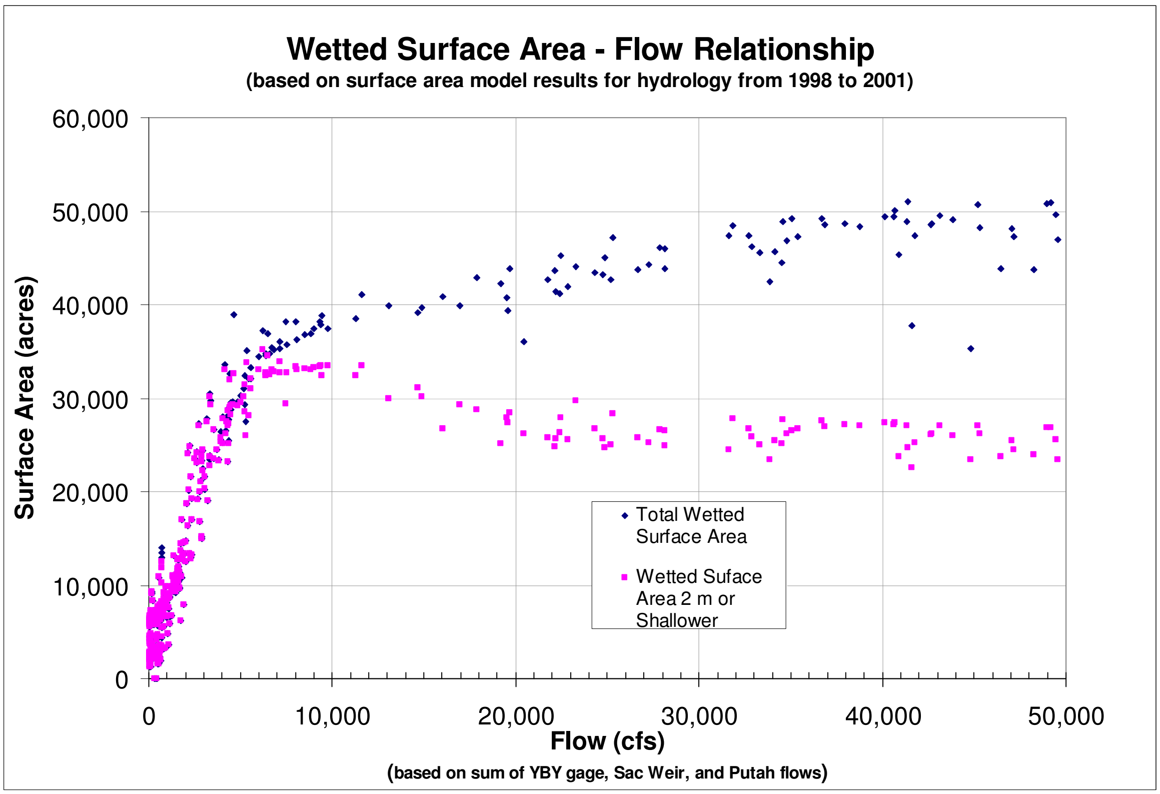


Figure 5.1: Wetter surface area-flow relationship for flows in the Yolo bypass (cite)

To estimate the amount of flow necessary to inundate the Sutter and Yolo Bypasses, we referred to USGS topographic maps to determine ground elevations at Tisdale and Freemont weirs which currently control flows onto the bypass, and then used stage discharge relationships for nearby gauges to estimate the amount of flow necessary to achieve a stage equal to the ground elevation at the weir – an overbank flow assuming the weir did not exist or was operable (table 5.1). The overbank flow, however, is not enough to push substantial amount of water down the bypasses. We therefore assumed that a minimum of 5,000 to 10,000 cfs above the overbank flow was necessary to create substantial inundated floodplain in the bypass.

Table 5.2 identifies flow recommendations for various year types at four key sites: Tisdale Weir, Freemont Weir, and Verona Gauge on the Sacramento River and Nicolaus

Gauge on the Feather River. Tisdale Weir spills into the Sutter Bypass and then flows back into the Sacramento River near Freemont Weir. The sum of Freemont and Nicolaus should equal Verona. Note, however, that table 5.1 flows at Verona are lower then the sum of Freemont and Nicolaus. This is because large amounts of the Sutter Bypass (ground elevation of 25 feet) will flood with backwater from the Sacramento at flows above 27,000 cfs at Freemont Weir. In other words, if Freemont or Verona is greater then 30,000 cfs, then large amounts of the Sutter Bypass are flooded irregardless of flows in the Feather River or at Tisdale Weir.

Table 5.1: Overbank flows in the Yolo or Sutter Bypass assuming levees or weirs along the Sacramento and Feather Rivers are breached or removed

Gauge or Weir	Ground Elevation	Overbank Flow	Notes
Nicolaus Gauge (Feather)	30	10,500	
Freemont Weir	25	27,000	Approximate based on Verona Gauge
Freemont with Excavation	13	15,000	Invert of the Toe Drain
Tisdale Weir	40	25,000	Approximate
Sacramento Wier (I Street Bridge)	15	49,000	
Sac Weir with Excavation	10	31,000	Sac Weir with excavation
Right Bank at Verona	25	42,000	Remove right bank levee

Table 5.2: Recommended flows to create inundated floodplain habitat in the Yolo and Sutter Bypasses for various year types.

	Year Type				
	C	D	BN	AN	W
Nicolaus (Feather)			12,000	15,000	20,000
Freemont Wier		25,000	30,000	37,500	45,000
Tisdale Weir		25,000	30,000	35,000	40,000
Verona		25,000	35,000	45,000	55,000

Duration and Timing

Provide floodplain inundation flows for 30 – 60 days between February 15 and April 30 into Sutter and Yolo Bypasses to provide rearing habitat for salmon and splittail and spawning habitat for splittail. Where possible, time releases to coincide with and extend duration of high releases on the Yuba and Sacramento.

Frequency

Ideally, it would be possible to inundate the bypass in every year to enhance foodweb productivity and improve rearing habitat for every year class of salmon. It may be possible to do this while economizing on water by inundating relatively small areas in dry years and very large areas in wet years with no inundation in critical dry years.

5.2 Riparian Flow Requirements

A sequence of hydrologic, geomorphic, and biologic phenomena is necessary to recruit cottonwood seedlings to the riparian forest. 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). Analysis of hydrologic data, dendrochronologic data, historic channel mapping, and aerial photography riparian recruitment appears to occur approximately once per decade in the post-regulation period (Roberts, 2003). But recruitment may now be limited to larger, less frequent events due to greater hydrologic modification in recent years. Recruitment did result from the recent large flood events of 1983-1986, and 1995-1997, (Roberts, 2003) but willows dominate while cottonwood recruitment is spatially limited.

In order to maintain or re-establish woody riparian vegetation using a process-based restoration approach, managed flows need to mimic natural hydrographs in the following key ways (Stillwater, 2007):

- High flow peaks, which should mimic to some degree the characteristics of peak flows associated with winter peak rain events in the unimpaired hydrograph are necessary to control vegetation encroachment by herbaceous and weedy species and prepare seedbeds prior to seedling recruitment flows in wet years (scouring or encroachment prevention flows) and seedbed preparation flows.
- High spring snow-melt peak flows with relatively gradual recession rates during wet years to moisten the seedbeds and induce seed germination on geomorphic surfaces suitable for long-term establishment (recruitment flows for seedling initiation).
- Summer and fall base flows are needed to ensure that new seedling cohorts and older cohorts of saplings and mature trees have adequate soil moisture for summer growth and survival during the annual dry season (seedling establishment and maintenance flows).

In regulated rivers it may also be necessary to limit unnaturally high summer flows. Summer base flows higher than spring flows may give a competitive advantage to non-native species that reproduce by seed during the summer months. Establishment of non-natives could impede later recruitment of natives such as cottonwood (cite).

5.2.4 Site Preparation

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). The magnitude of flows necessary to scour or deposit seed beds is presumably much larger then the amount of water necessary to inundate these sites. For this analysis, we assume that flows sufficient to mobilize the bed (80-100k cfs on the Sacramento and 35,000-50,000 on the Feather) are sufficient and that seedling establishment flows will only occur in wetter years after bed mobilization generally occurs.

5.2.5 Seedling establishment:

In order to assure long-term survival, seedlings must become established in a zone that is high enough on the bars and banks to avoid scour from peak flows, but low enough to avoid desiccation during low flows in summer and fall. Rood and Mahoney (2000) developed a recruitment box model that placed this zone at 2.5 to 4 feet above mean low (MLW) water for the St. Mary River in Alberta Canada. Roberts (2003) calibrated the recruitment box model on the Sacramento placing the recruitment zone at 3-6 feet above MLW and developed a stage discharge relationship at three representative sites to determine that recruitment zone is inundated at flows between 23,000 and 30,000 cfs. Roberts recruitment zone, however, is based on the artificially high summer flows in the Sacramento River. Under natural summer flow conditions the recruitment zone, and flows necessary to inundate it, may be somewhat lower.

Little to no information exists regarding seedling establishment elevation for the Feather River. Furthermore, it is difficult to identify a suitable recruitment zone at some distance from the mean low water, because mean low water levels in the summer are two to three times higher then pre-dam, natural levels. The stage discharge relationship for the Feather River at Nicolaus combined with topographic maps indicate that the Feather River overflows its banks at Nicolaus at approximately 12,500 cfs. The banks further upstream are higher and can convey more flow before overtopping. Since cottonwoods generally become established on the banks and gravel bars of alluvial rivers, it is reasonable to assume that the recruitment zone is below the stage of the bankfull discharge. The seedling establishment flow on the Sacramento (23,000 – 30,000 cfs) is twenty seven to thirty seven percent of the bankfull discharge (Q1.5 to Q2) on the Sacramento. Assuming a similar proportional relationship on the Feather River, flows in the range of 9,500 to 18,000 would be suitable for seedling establishment. Analysis of historical flow data (section seven of this report) indicate that flows in this range were common during April and May when germination is most likely to occur.

Post-germination decline of river stage, which is presumed to control adjacent groundwater levels, 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.

Information necessary to design a gentle recession limb is limited. Stage discharge data from gauging stations may not be representative of Cotonwood recruitment sites, because they are generally sited at geomorphically stable and simple sites while cottonwood recruitment often occurs on complex and dynamic sites. Kondolf and Stillwater (Kondolf, 2007) measured stage discharge relationships at several representative gravel bars along the Sacramento River and determined that stage drops 0.1 meter (.34 feet) per

1000 cfs at flows ranging from 7,000 to 15,000 cfs, but cautioned against extrapolating this relationship to flows outside the observed range. Within this range, however, a discharge decline of 250 cfs per day would yield a stage decline of one inch per day.

To estimate a suitable recession rate flow schedule, we assumed that cottonwood seedlings would become established six feet above the mean low water and then calculated that it would take 72 days to drop river stage six feet at a rate of one inch per day. On this basis, we recommend a 72 day recession period from the establishment flow to the summer base flow. The actual recession flow required may vary substantially depending where seedlings become established relative to the mean summer flows.

5.2.6 Recruitment stage:

After the second year, growth rates level. Despite extensive root development during this stage, cottonwoods are still somewhat susceptible to drought stress. 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. Acute draw down and corresponding drought stress is primarily a problem in arid river ecosystems and will probably not be a problem on the Sacramento River where summer flows are artificially high.

5.3 Chinook Flow Requirements

<u>Adult Upstream Migration</u>

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.

<u>Spawning</u>

In order to provide quality areas of spawning habitat, adequate flows need to be released from dams into the tributaries during the spawning period. Due to channel alteration from gravel mining, artificial gravel habitat construction and enhancement may be necessary. 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 after mid-February so they reduce mortality to incubating salmon eggs (McBain and Trush, 2000). Increased flows may also be needed to decrease water temperatures in late October and early November to prompt earlier spawning, expand the area with suitable temperatures for spawning and incubation, to increase egg viability, and to reduce the probability of superimposition of redds. If flows are increased during this mid-fall period, it is important to continue to maintain adequate flows for spawning and to prevent dewatering of redds.

Egg Development and Emergence
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.

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.

Rearing and Outmigration

We hypothesize that increasing rearing habitat will improve growth rates and successful smolt outmgration and may also reduce mortality from diversions and predation, because larger fish are less vulnerable to these sources of mortality. 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. We describe the flow regimes necessary to create inundated floodplain in section 6.3 above.

In addition to inundated floodplain habitat, seasonally inundated off-channel habitats may also provide valuable rearing habitats for juvenile salmon. Kondolf and Stillwater (Kondolf, 2007) determined that secondary scour channels on gravel bars along the upper Sacramento River become inundated and connected to the mainstem at flows above 12,500 cfs. They also determined that these same secondary channels become disconnected and desiccated at flows below 8,500 cfs. To assist juvenile rearing, it may therefore be advantageous to maintain flows between 8,500 and 12,500 cfs or greater during winter and spring when fish are rearing. To prevent establishment of non-native, resident predator fish populations that thrive in shallow or warm water habitats, however, it may be beneficial to maintain flows below 8,500 cfs during the summer months. Preventing inundation and connectivity of the off-channel habitats during summer months could also reduce temperatures by significantly reducing wetted perimeter and surface area. Lower temperatures should favor native fish over exotic fish populations.

6. EVALUATION OF EXISTING AND HISTORIC FLOW REGIMES

To identify specific hydrograph component alterations between historical and current conditions which may limit the attainment of environmental objectives an analysis of existing and historical hydrologic patterns was conducted using daily flow data from USGS gages at multiple locations on the Sacramento and Feather Rivers. We used two approaches to compare existing and historical hydrologic patterns, a statistical approach similar to IHA whereby specific hydrograph components were graphed using box plots for different year types and a visual approach similar to HCA whereby median hydrographs for historical and current conditions were compared.

We evaluated pre- and post-project hydrology using statistical methods similar to IHA and HCA methods to generate hypotheses regarding the causal links between historical hydrograph components and ecological conditions relevant to our restoration objectives. The Index of Hydrologic Alteration (IHA) method (Richter et al. 1996) provides a statistical overview of how several important hydrologic attributes change between historical and regulated conditions. The Hydrograph Component Analysis (HCA) method developed by McBain and Trush provides a detailed graphical analysis of historical and existing hydrologic conditions. Instead of using a formal IHA and HCA analysis the fundamental principals of these methods were used to conduct an analysis based on first principles.

To conduct this analysis USGS daily discharge data was organized into water year types based on the Sacramento Four Rivers Index. The water year data was divided into pre project or post project data sets. The project id defined by the construction of a dam in the headwaters of the river under consideration. For the Sacramento River the project is Shasta Dam which was constructed in 1945. For the Feather River the project is defined by Oroville Reservoir which was constructed in 1968. Hydrograph components for each water year were compared for pre and post project periods using box plots. This statistical approach was coupled with a visual comparison of the pre and post project median flows hydrographs. The pre project period was further defined by the 25th and 75th percentile hydrographs. The 25th and 75th percentile captured the natural range of variability around the median hydrograph during the pre project period for each year type. When the current hydrograph was outside of this acceptable range of variability then a significant discrepancy between the historic and current flow regimes could be identified.

The hydrograph components that were considered for the statistical analysis were: 1) summer baseflow, 2) winter peaks, 3) winter baseflows and 4) spring peaks(Figure 5). A useful way to describe streamflow hydrology and relate it to geomorphic, riparian, and biological ecosystem components is by quantifying these hydrograph components. Kondolf et. al. 2000 described these four primary components of the annual hydrograph in the following way:

(1) Summer base flows extending from July through Spetember/October

(2) Large magnitude, short duration winter floods during December through April

(3) Sustained high winter base flows intermittent between high flow events

(4) Spring snowmelt flood and recession limb of long duration, but typically moderate magnitude

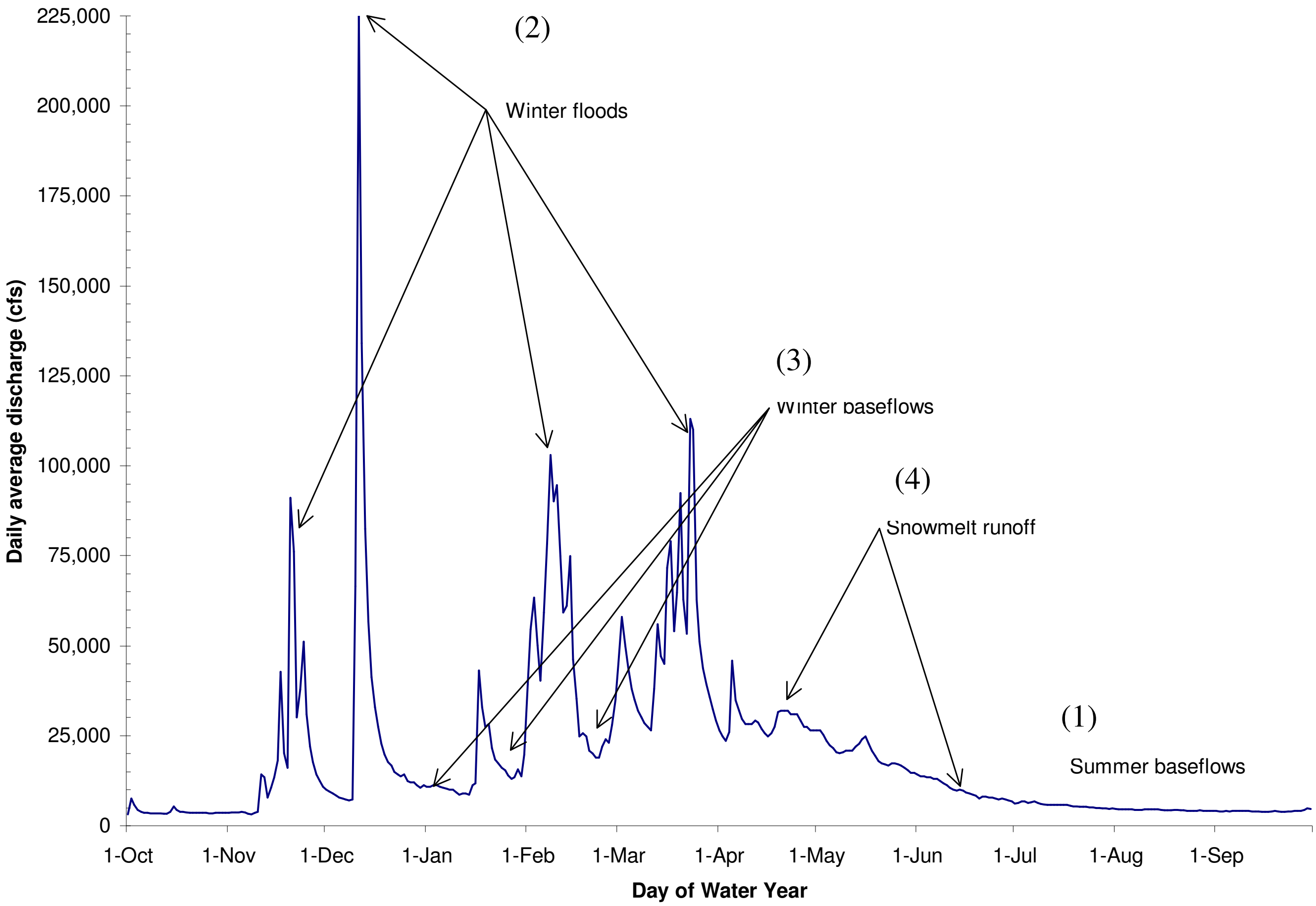


Figure 6.1: Sacramento River hydrograph components illustrated in the 1938 hydrograph for the Sacramento River above Bend Bridge, near Red Bluff gauging station. Modified from Kondolf et al. 2000.

a. Methods

Data Source

We analyzed hydrologic data for periods before and after dams were constructed on the Sacramento and Feather Rivers. Table 4 shows the gauges analyzed their period of record, and the pre and post-dam analysis periods. We divided data into five year types based on the Sacramento Basin Index: wet, above normal, below normal, dry, and critical.

Period of Analysis	River	Description	USGS Gage Number	Period of Record
Pre Shasta	Sacramento River	Bend Bridge	11377100	1906-1944
Post Shasta	Sacramento River	Bend Bridge	11377100	1945-2006
Pre Shasta	Sacramento River	Verona	11425500	1929-1944
Post Shasta	Sacramento River	Verona	11425500	1945-2006
Pre New Bullards Bar	Yuba River	Marysville	11421000	1944-1969
Post New Bullards Bar	Yuba River	Marysville	11421000	1970-2006
Pre Oroville	Feather River	Oroville	11407000	1906-1967
Post Oroville	Feather River	Oroville	11407000	1968-2006
Post Oroville	Feather River	Thermalito AfterBay	11406920	1968-2006

Table 6.1: USGS gauges used for hydrologic analysis, the period of analysis, location, description and the period of record.

Hydrographs

For each year type we compared post-dam median flows to pre-dam median flows. Median flows bounded by the 25th and 75th percentiles represent the natural range of variability during the pre-dam period for each water year type. Hydrographs provide a visual tool to identify portions of the current hydrograph that are outside of the historic range of variability. When the current hydrograph is outside of the natural range of variability we would expect the greatest potential loss of environmental flow benefits.

Box Plots

Box plots were used to statistically compare hydrograph components including summer baseflows, winter floods, winter baseflows, and spring peak flows. The lower edge of the boxes represent the 25th percentile and the upper end represents the 75th percentile, with the whiskers at the maximum and minimum values. The various components of the hydrograph were computed as follows.

- **Summer baseflows** were computed as average August discharge. Summer baseflows begin following the spring snowmelt recession in July and August and last through autumn when the first rainfall events occur.
- **Winter floods** were computed as the maximum daily average discharge over the course of the entire water year.
- **Winter baseflows** were computed as the median flow for February and March.
- **Spring peak flows** were computed as peak flows in April and June.

Flood Frequency Analysis

We conducted the food frequency analysis for a range of reoccurrence intervals for pre and post project periods using the peak instantaneous flow records at USGS. The flood frequency analysis enables further quantification of storm events and their geomorphic potential.

b. Results

The analysis utilized 100 years of daily flow data from the Bend Bridge gage near Red Bluff on the Sacramento River (11377100). This gage was selected for the analysis because it has a long period of record 1906-2006, and best characterizes flow conditions where salmon concentrate. The Bend Bridge gage is at the upstream end of what is considered the most valuable habitat in the Sacramento River. However, flows at Bend Bridge are not fully representative of downstream conditions, particularly in the irrigation season because irrigation diversions operate downstream. Four major diversions are listed below:

- The Glenn-Colusa Irrigation District (GCID) diversion, located just upstream of Hamilton City at RM 206, began diverting summer flows for irrigation around the turn of the century, and has a diversion capacity of about 3,000 cfs.
- The Anderson-Cottonwood Irrigation District (ACID) diversion, located on the north side of the City of Redding downstream of Shasta Dam, began diverting for irrigation during the summer months, around 1917.
- The Red Bluff diversion and Tehama-Colusa Canal at Red Bluff was built in 1964, and diverts during the summer months for irrigation.
- The Trinity River Division of the Central Valley Project was completed in 1963, and typically diverted over 1,000,000 acre-ft/yr of Trinity River flows into the Sacramento River basin just below Shasta Dam between 1963 and 2000. Due to new flow requirements for the Trinity River, substantially less flow is now diverted into the Sacramento River.

The hydrograph at Bend Bridge reflects operations at Shasta Reservoir in timing and magnitude, but it is only by looking at the hydrograph from a downstream gage that we can evaluate the impacts of diversions operations and the degree of hydrograph recovery from tributary inputs. It is for this reason that we used the eighty year record, from 1926-2006) daily discharge data at the USGS gage at Verona (11425500). Major tributary inputs to the Sacramento below Bend Bridge include Mill Creek, Deer Creek and the Feather River. The Feather River flow regime exhibits similar characteristics to the Sacarmento below Red Buff because of the operation of Oroville Dam. The major tributary to the Feather is the Yuba River which also displays similar characteristics due to the operation of Bullards Bar. For this reason a hydrograph comparison for the Feather (11407000, 11406920) and Yuba River (11421000) was also conducted.

5.2.1 Sacramento River at Bend Bridge

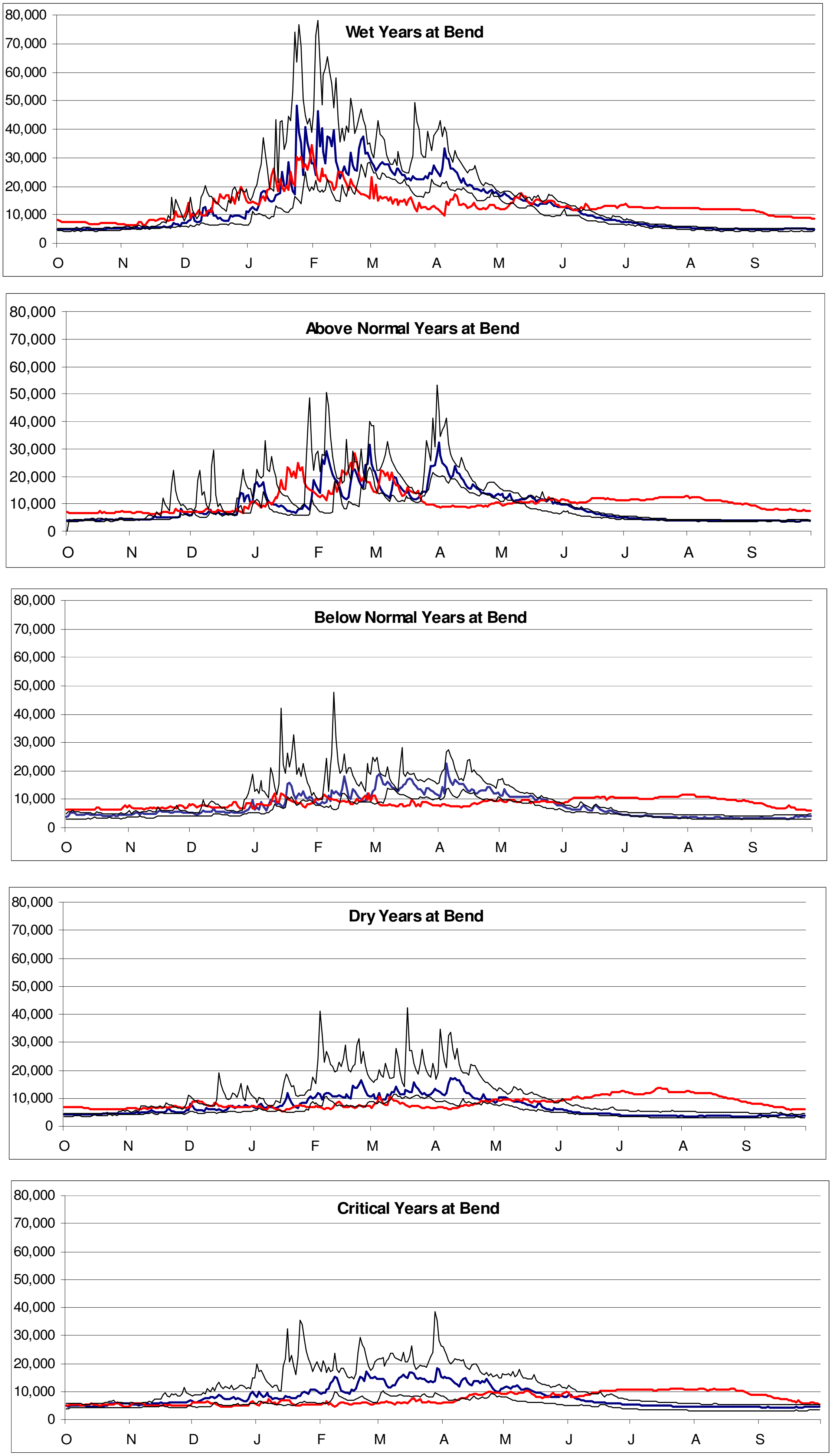
Hydrologic Changes
The hydrographs and box plots for pre and post Shasta at Bend Bridge (Figures 6 and 7) illustrate significant differences in all hydrograph components.

- Summer base flows are significantly higher post Shasta for all water year types. The average summer base flow pre-Shasta was 3,000-4,000 cfs which is significantly less than the current average of 10,000-12,000 cfs. These artificially high summer flows are driven by summer water supply demands for agriculture and power.

- Spring peak flow events are significantly reduced in the post Shasta era for below normal, above normal and wet year types and there is a truncated spring and early summer recession limb, particularly in wet years. The reduction in spring peak flows hampers cottonwood recruitment, seed establishment and germination.

- Winter peak flows are significantly reduced in the post Shasta era. The magnitude and duration of winter peak flows are responsible for channel forming flows. Channel forming flows effect cottonwood recruitment and off channel habitat formation critical to Chinook Salmon rearing and survival.

- In addition to significantly altered hydrograph components there is also a general decline in hydrologic variability in the post Shasta era.



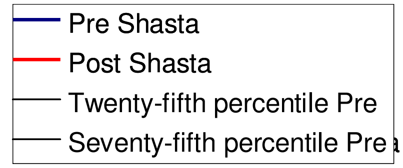


Figure 6.2: Bend Bridge median hydrographs : Historical data was used to construct hydrographs for five water year types at Bend Bridge (USGS Gage 11377100). The median hydrographs pre and post Shasta represent the natural and impaired flow regimes. The twenty-fifth and seventy-fifth percentile hydrographs represent the natural range of variability in the pre-dam era. When the median post project hydrograph is not within the historic range of variability then there is a significant discrepancy between the historic and current hydrographs. The greatest discrepancies include the lack of spring peak flows and un-naturally high summer flows for all water year types. (The y-axis is discharge in cubic feet per second or cfs.) See the table of the number of water year types below.

Water Year Type	Pre Shasta (1906-1944)	Post Shasta (1945-2006)
W	13	22
AN	5	10
BN	7	11
D	8	12
C	6	7
Total	**39**	**62**

Figure 6.3: Sacramento River Box Plots at Bend Bridge. Box plots display the median and the range of variability for each hydrograph component. Summer baseflows are represented by the average August discharge for each water year type. Winter floods are represented by the maximum daily average discharge for each water year type. Winter base flows are represented by the median discharge in February and March for each water year type. Spring peak flows are represented by peak average daily discharge value in April-June for each water year type. The top of the box plot is the 75th percentile and the bottom of the box is the 25th percentile. The 25th percentile means that 75% of the data is above this point. The wiskers represent the maximum and minimum values. The dark line inside the box is the median value, or 50th percentile. When the boxes do not over lap then there is a very highly significant difference between the data sets.

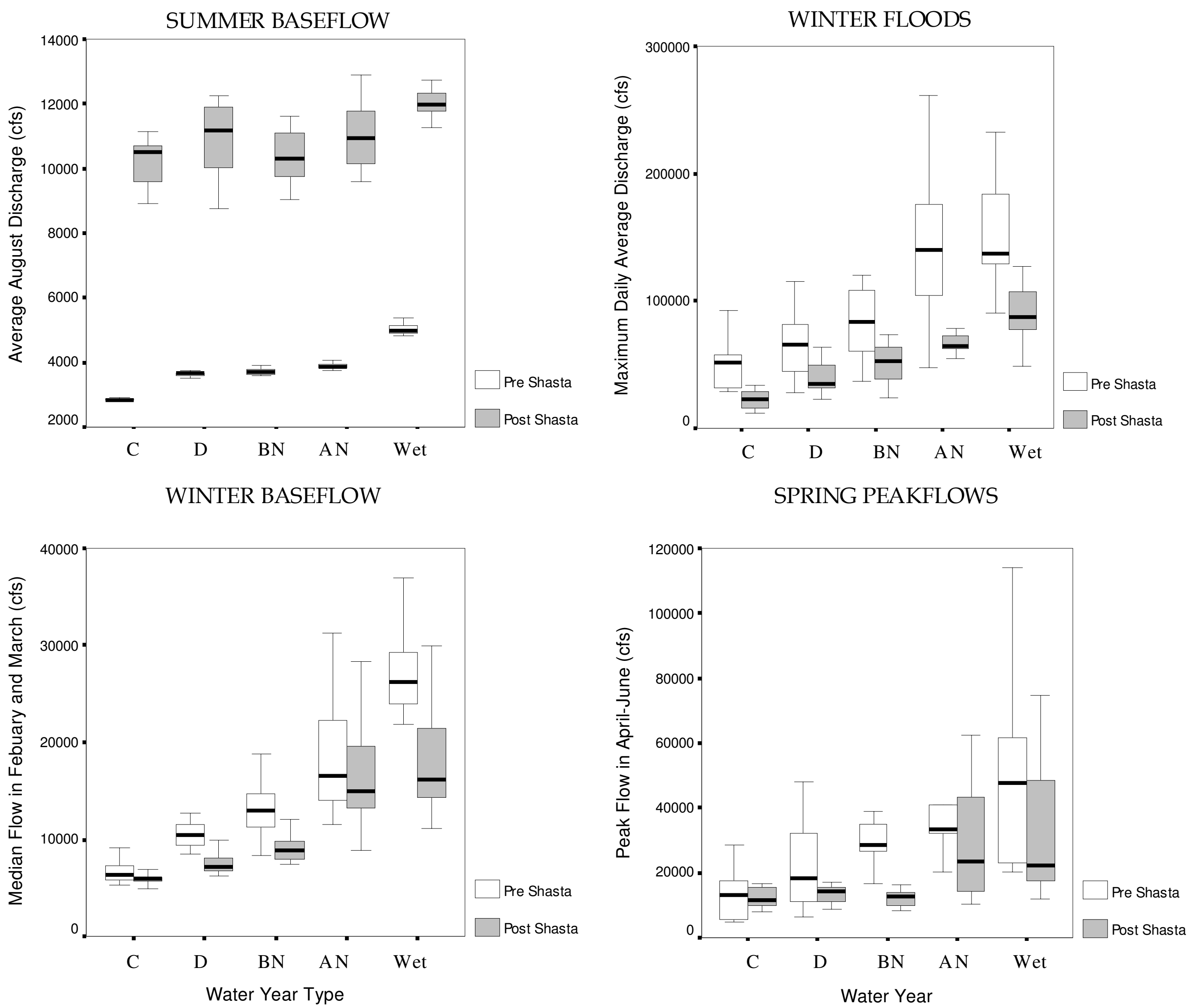


Figure 6.4: Flood frequency analysis at Bend Bridge Pre and Post-Shasta. The flood frequency analysis displays the magnitude of flows expected to occur in a 1.5, 2, 2.5, 5, 10, 20….year flood. The two year flood event in the pre Shasta era is ~100,000 cfs. Bed mobility is expected at the 1.5 year flood (Q1.5) or 82,795cfs.

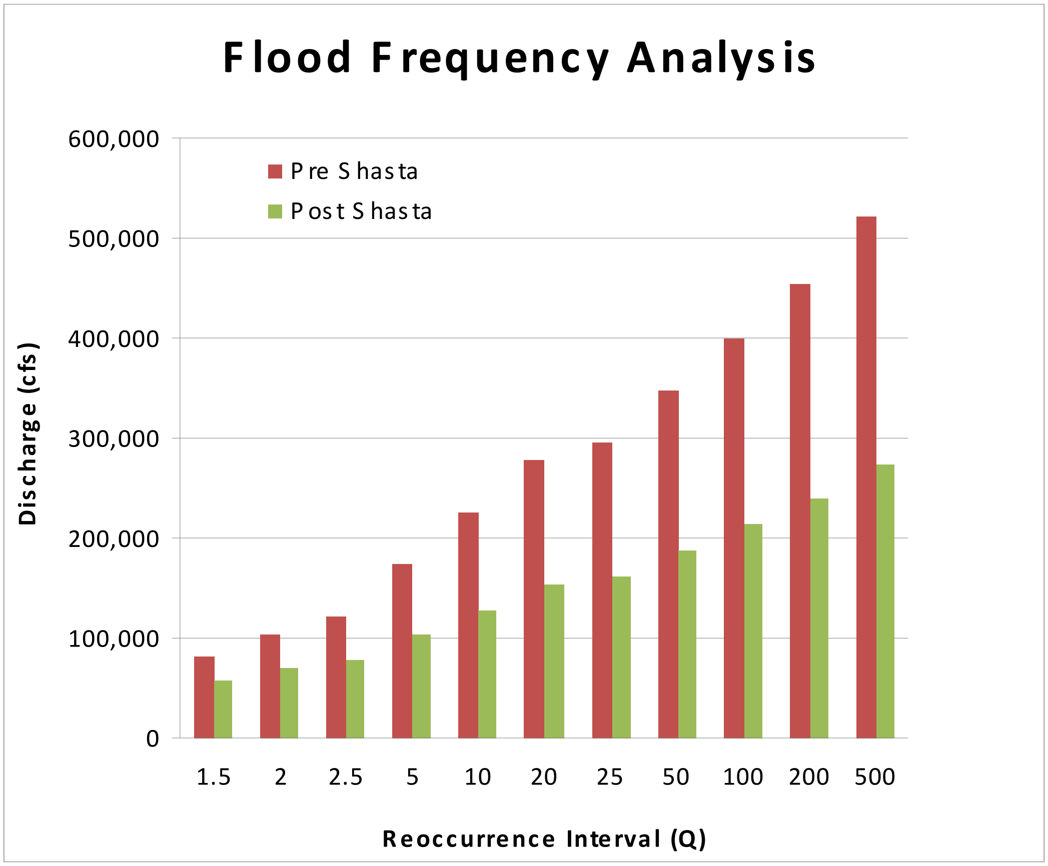


Table 6.2: Sacramento River Flood Frequency

Recurrence Interval (years)	Post 1939 (cfs)	Pre 1939 (cfs)
1.5	65,000	87,000
2	78,000	105,000
2.5	87,000	120,000
5	120,000	160,000
10	153,000	225,000
20	160,000	285,000
50	190,000	350,000
100	210,000	400,000

Table 6.3: Summary of Geomorphic Flow Thresholds				
Sacramento River	**Pre-Dam ($Q_{1.5}$)**	**Bed Mobility ($Q_{1.5}$)**	**Channel Scour and Migration (Q_{10})**	**Floodplain Inundation (Q_{1})**
Flows at Bend	82,795	82,795	226,476	52,087

6.2.1 Feather and Yuba Rivers

Introduction

Oroville Dam and Reservoir on the Feather River were completed in 1968 and have a storage capacity of 3.5 million acre feet (maf). It is managed for water supply, hydropower, and flood control. The average annual yield of the upstream Feather River basin at Oroville is about 4.2 maf. Due to several diversions in the upper watershed, average annual inflow into Oroville Reservoir is approximately 4.0 maf, but varies annually depending on precipitation. From 1979 to 1999, annual inflows ranged from a minimum of 1.7 maf to as high as 10 maf . Most of the water released from the dam, except during flood spills, is routed through the Thermalito diversion pool and afterbay and therefore bypass a 7 mile stretch below the dam known as the low flow channel. A minimum flow of 700-800 cfs is released into the low flow channel to maintain habitat for salmonids.

We evaluated change in hydrology that resulted from construction and operation of Oroville Dam. We compared pre and post dam hydrology at the USGS gauge below Oroville. In order to account for the water in the post-dam period that is discharged into the Thermalito diversion pool and bypasses the Oroville gauge, we summed daily values from the Thermalito (11406920) and Oroville (11407000) gauges to calculate the average daily flow for the river below the low flow channel.

Minimum instream flows below Thermalito Afterbay range from 1,000 cfs in the late spring and summer to 1,200 -1,700 cfs during the fall winter months. Minimum flows for the low flow channel are between 700 and 800 cfs all year. Minimum flows are slightly higher during the fall and winter to provide flow for spawning and incubating salmonids. Minimum flows in the summer are necessary to maintain cool temperatures for over summering juveniles and adult salmonids.

Most irrigation releases are made directly into irrigation canals, so relatively little water is conveyed to irrigators via the Feather River channel. Most irrigation water is released from Oroville Reservoir into Thermolito Diversion Pool, Forebay, and Afterbay where it is subsequently diverted into irrigation canals. Thus, it is possible to substantially meet summer irrigation demands without conveying water through the Feather River Channel.

The Feather River is joined downstream by a major tributary, the Yuba River. The hydrology of the Yuba River was modified early in the 19th century, but the first big storage reservoir, Bullards Bar, was not constructed until 1968. As a result, the hydrology of both the Yuba and Feather River were substantially altered at the same time by large reservoirs constructed in the late 1960s.

Hydrologic Changes

The construction and operation of Oroville dam and reservoir have significantly altered the hydrograph of the Feather River downstream of Oroville. Figures 10 and 11 depict the hydrologic patterns during different year types before and after 1968 when Oroville

Dam was completed. Figure 12 and Table 6 show changes in peak flow magnitude and duration. The most significant changes to the hydrograph are:

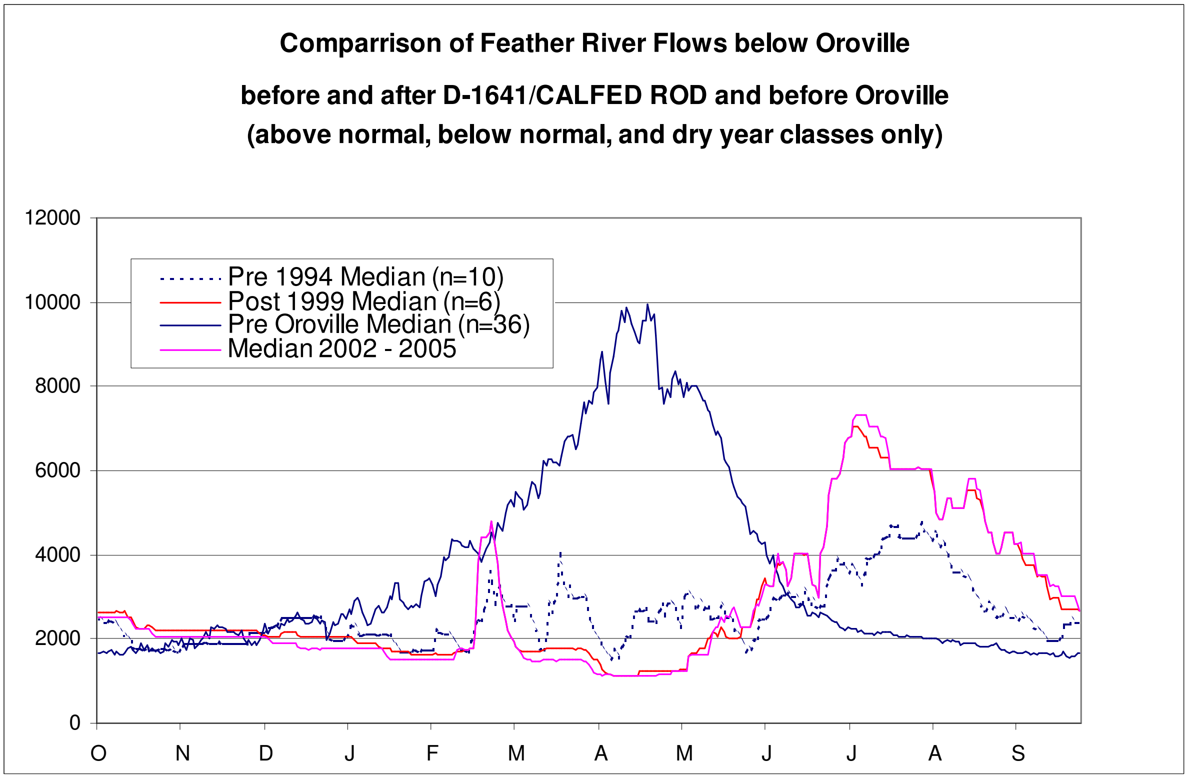
- Very significant reductions in spring flows during all year types, particularly during April and May. Storage of spring run-off and snow melt behind Oroville Dam has virtually eliminated any spring flows above a base flow of approximately 2,000 cfs.
- Increases in summer flows by 150-200% in all year types during July, August, and September.
- Reduction in the frequency and magnitude of peak flows, such as Q1.5[2] or channel forming flow by an order of magnitude. Substantially less reduction in the magnitude of the 5 year recurrence interval event (Table 6)
- Reduction in the frequency of short duration fall and winter flow pulses.

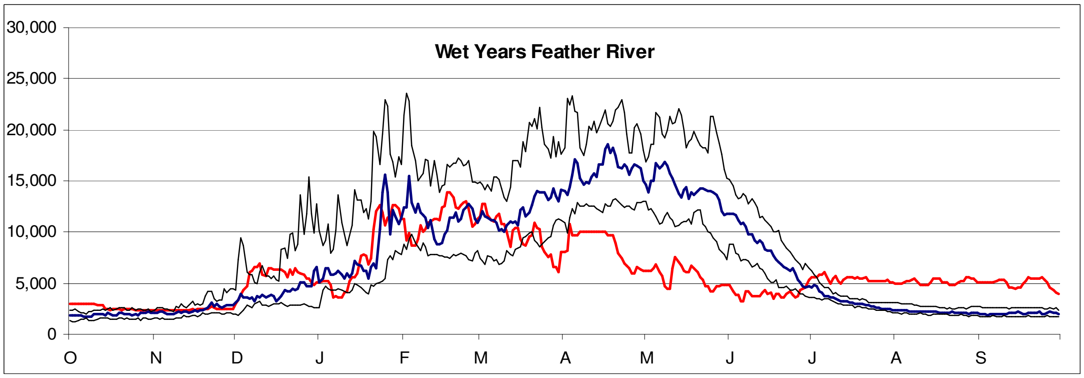
These hydrograph modifications are a result of Oroville Reservoir's water supply, flood management, and hydropower operations. Oroville Reservoir captures high flows in the winter and spring for use during the summer months. Stored water is released to meet minimum instream flows, irrigation demand in the Feather River region between April 1 and October 31, generate hydropower primarily in the summer, and meet water quality and export water demands in the Delta. Large volumes of stored water are periodically released during the winter months to create reservoir space for flood management purposes.

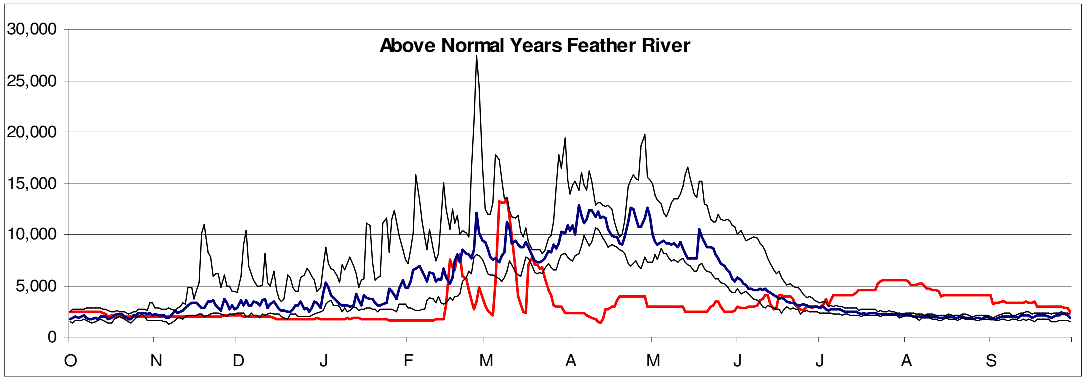
Most of the increases in summer flow in the Feather River channel are the result of Oroville releases to meet water quality and export demands in the Delta. As a unit of the State Water Project, Oroville is specifically operated to meet water quality and export demands in the Delta. An analysis of pre-1995 and post 1995 hydrology shows that Feather River flows changed significantly after the 1995 Water Quality Control Plan tightened restrictions on the timing of Delta diversions. After implementation of the plan, spring flow in the Feather River has been further diminished while summer flow has been further increased.

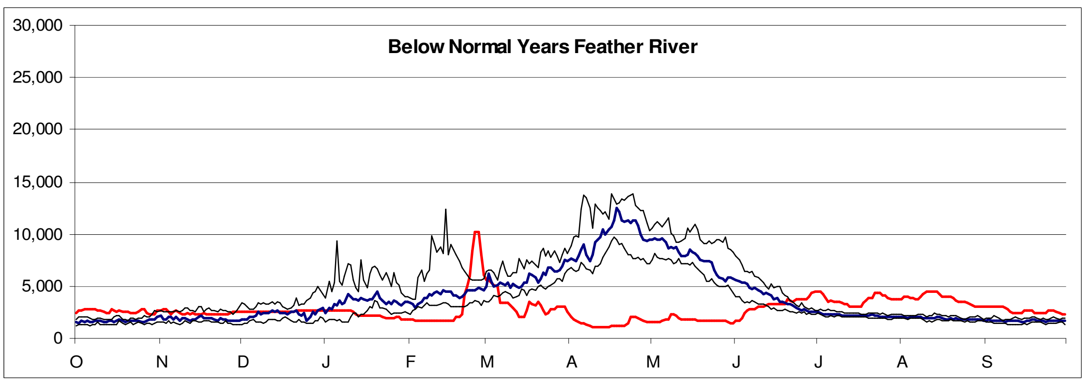
[2] The instantaneous peak annual flow with a recurrence interval of 1.5 years.

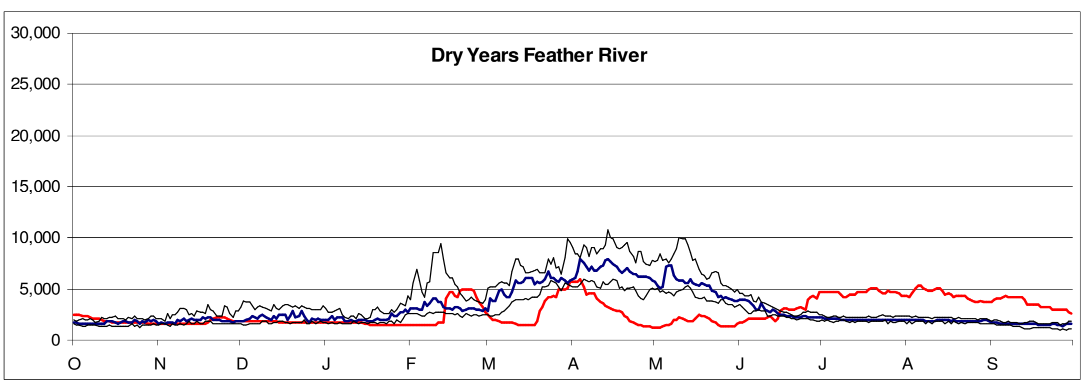
Figure 6.5: Influence of Sacramento-San Joaquin Delta Regulations on Feather River Hydrograph. The blue line of pre Oroville median flows represents the most natural hydrograph. In 1995 the Water Quality Control Plan tightened restrictions on the timing of Delta diversions. The pre 1994 hydrograph compared to the post 1999 illustrates how the hydrograph shifted spring flows to summer releases to meet Delta requirements.

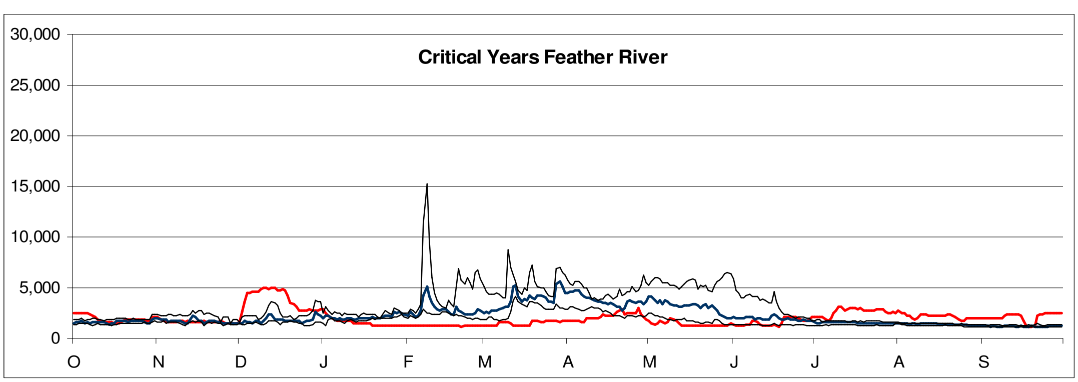












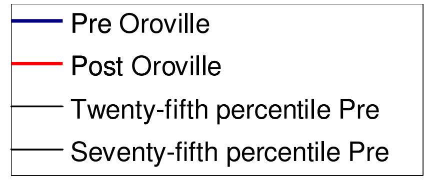


Figure 6.6: Feather River median hydrographs : Historical data was used to construct hydrographs for five water year types on the Feather River (USGS Gage11407000 and 11406920). The median hydrographs pre and post Oroville represent the natural and impaired flow regimes. The twenty-fifth and seventy-fifth percentile hydrographs represent the natural range of variability in the pre-dam era. When the median post project hydrograph is not within the historic range of variability then there is a significant discrepancy between the historic and current hydrographs. The greatest discrepancies include the lack of spring peak flows and un-naturally high summer flows for all water year types. (The y-axis is discharge in cubic feet per second or cfs.) The hydrographs post Oroville (1968-2006) are the sum of the Oroville (11407000) and Thermolito Afterbay gages (11406920). See the table of the number of water year types below.

Water Year Type	Pre Oroville (1906-1967)	Post Oroville (1968-2006)
W	20	15
AN	8	7
BN	14	4
D	14	6
C	6	7
Total	**62**	**39**

Figure 6.7: Feather River box plots for Oroville gauge. Box plots display the median and the range of variability for each hydrograph component. Summer baseflows are represented by the average August discharge for each water year type. Winter floods are represented by the maximum daily average discharge for each water year type. Winter base flows are represented by the median discharge in February and March for each water year type. Spring peak flows are represented by peak average daily discharge value in April-June for each water year type. The top of the box plot is the 75th percentile and the bottom of the box is the 25th percentile. The 25th percentile means that 75% of the data is above this point. The wiskers represent the maximum and minimum values. The dark line inside the box is the median value, or 50th percentile. When the boxes do not over lap then there is
a very highly significant difference between the data sets.

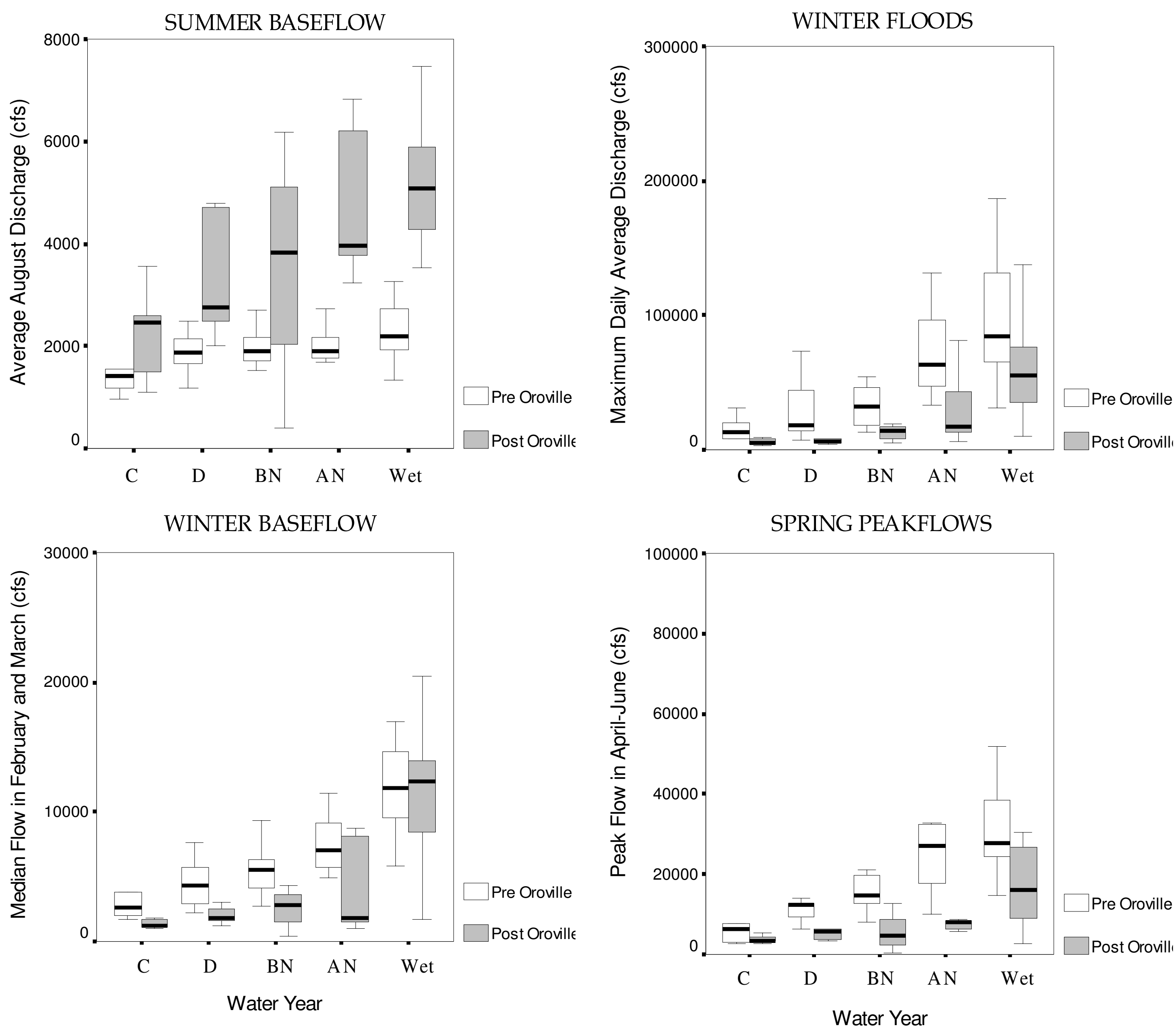


Figure 6.8: Flood Frequency Analysis for Feather River Flood frequency analysis at Bend Bridge Pre and Post-Shasta. The flood frequency analysis displays the magnitude of flows expected to occur in a 1.5, 2, 2.5, 5, 10, 20….year flood. The two year flood event in the pre Shasta era is ~50,000 cfs. Bed mobility is expected at the 1.5 year flood (Q1.5) or 33,224cfs.

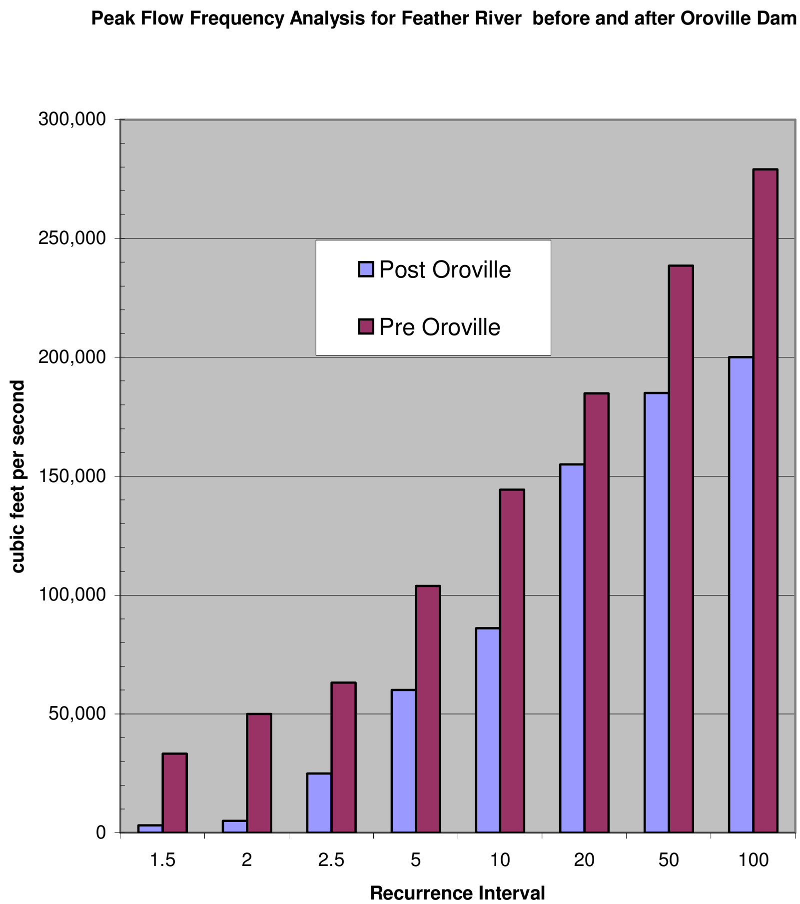
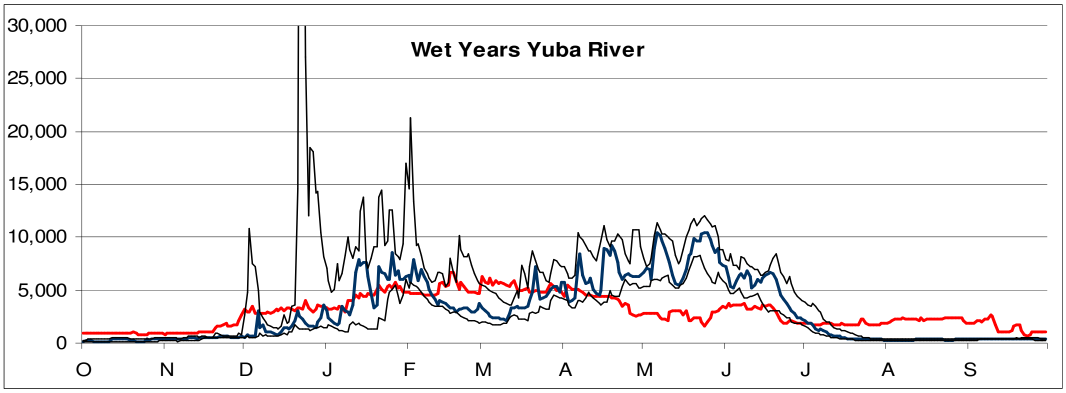
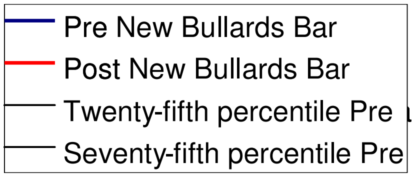
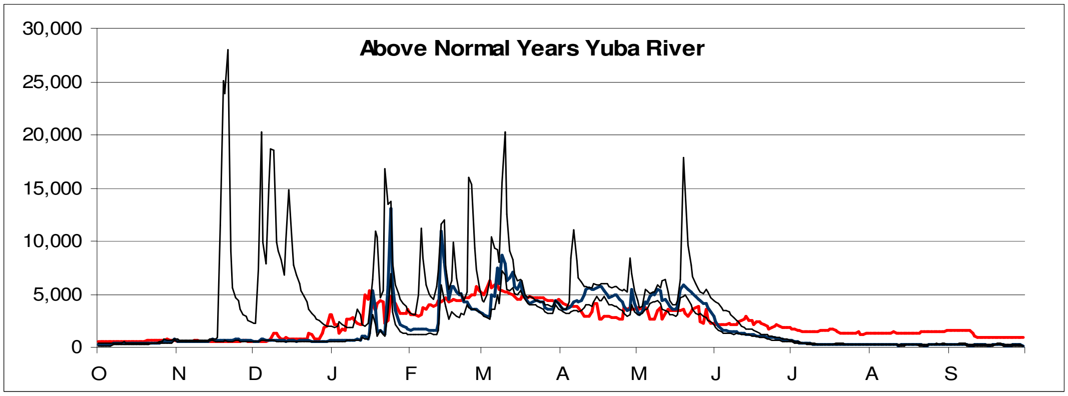


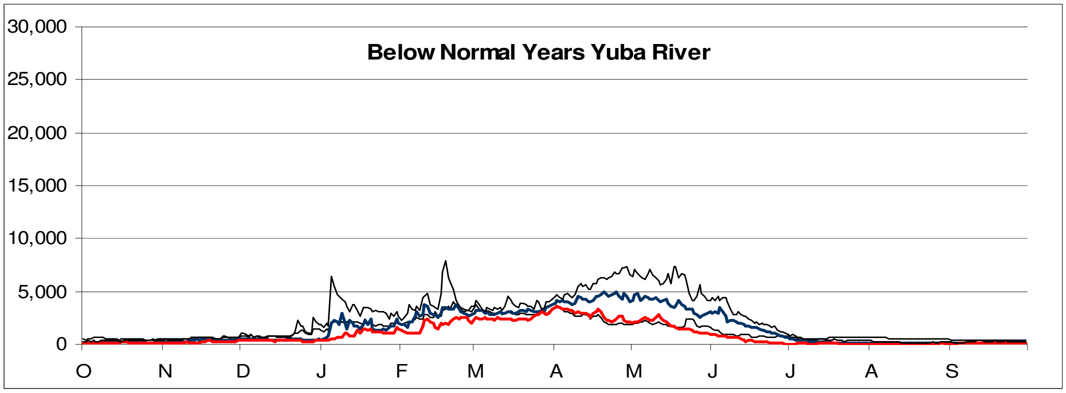
Table 6.4: Feather River Flood Frequency

Recurrence Interval (years)	Post 1968 (cfs)	Pre 1968 (cfs)
1.5	3,170	33,224
2	5,000	50,065
2.5	25,000	63,128
5	60,000	103,704
10	86,000	144,281
20	155,000	184,858
50	185,000	238,498
100	200,000	279,075









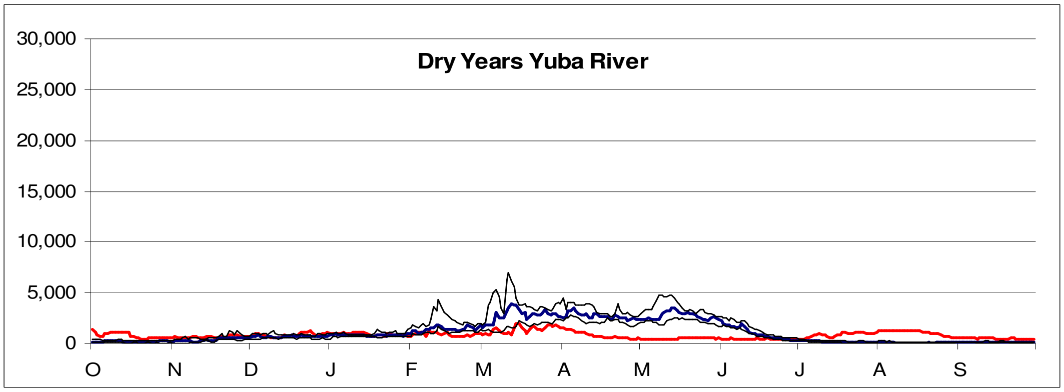


Figure 6.9: Yuba median hydrographs : Historical data was used to construct hydrographs for different water year types for the Yuba (USGS Gage 11421000). The median hydrographs pre and post New Bullards Bar represent the natural and impaired flow regimes. The twenty-fifth and seventy-fifth percentile hydrographs represent the natural range of variability in the pre-dam era. When the median post project hydrograph is not within the historic range of variability then there is a significant discrepancy between the historic and current hydrographs. The greatest discrepancies include the lack of spring peak flows and un-naturally high summer flows for all water year types. (The y-axis is discharge in cubic feet per second or cfs.)There is no median hydrograph for the Critical Year type because there were no critical years between 1944 and 1969. See the table of the number of water year types below.

Water Year Type	Pre New Bullards Bar (1944-1969)	Post New Bullards Bar (1970-2006)
W	7	13
AN	3	7
BN	8	3
D	7	6
C	0	7
Total	25	36

6.3 Sacramento River at Verona

Analysis of the Sacramento and Feather Rivers at gauges near the large dams only tells part of the story. The Verona gauge is downstream of the confluence of the Sacramento and Feather River, and measures run-off from numerous large tributaries not measured by the gauges at Oroville and Bend Bridge. Several of these tributaries do not have large storage reservoirs and thus continue to exhibit relatively natural hydrographs. Figure 14 shows the hydrographs from Mill and Deer Creek which are characterized by large, gently receding spring flows. As a group, these less regulated tributaries tend to dampen the effect of Shasta, Oroville, and New Bullards Bar, but only to a limited extent.

Figures 16 shows hydrologic patterns for four periods: before Shasta, after Shasta but before Oroville Dam, after Oroville Dam, and after the implementation of the 1995 water quality control plan that established stringent limits on the timing of water exports from the Delta. The hydrology from all four periods shows a clear and consistent trend: progressively less spring flow and continuously increasing summer time flows. The decrease in spring flows and increase in summer flows is particularly striking after 2000 when the water quality control plan was in full effect in the Delta. Due to stringent export restrictions in the spring, the state water project, which operates Oroville Reservoir and controls the Harvey O'Banks pumping plant in the Delta, has apparently shifted operations to minimize spring time releases from Shasta and favor summer time releases so that it can deliver water to the Delta when pumping restrictions are less severe.

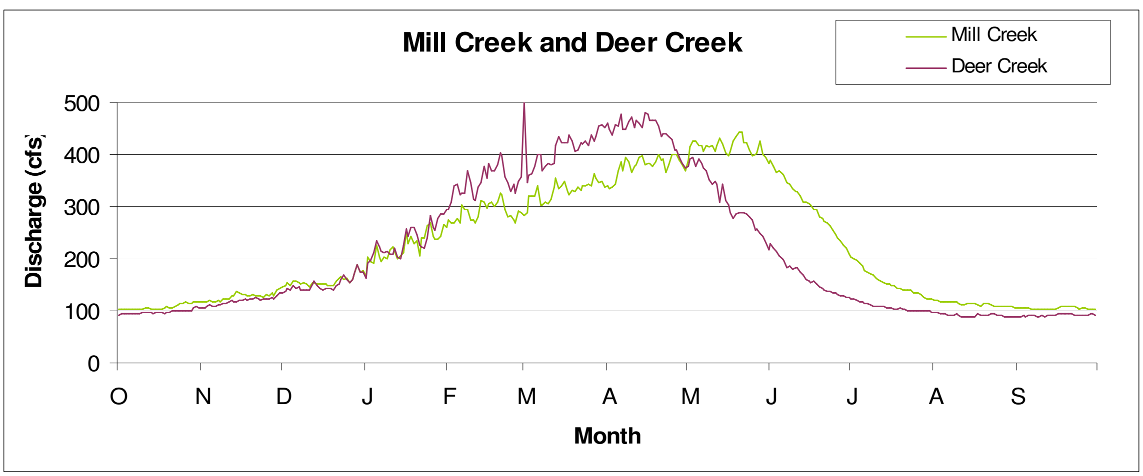
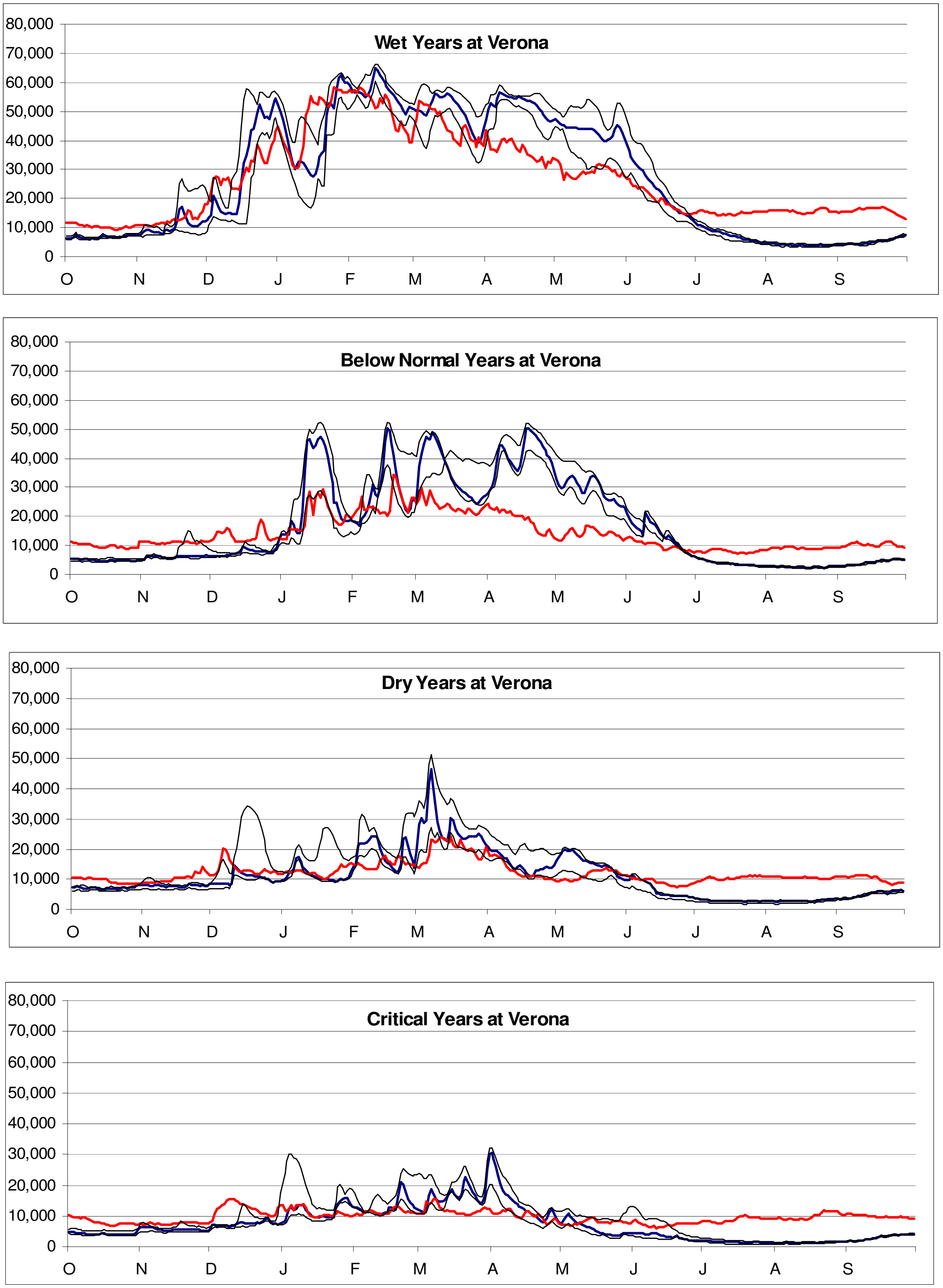


Figure 6.10: Median hydrographs for Mill and Deer Creek.



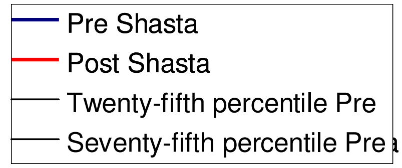


Figure 6.11: Verona median hydrographs : Historical data was used to construct hydrographs for different water year types at Verona (USGS Gage 11425500). The median hydrographs pre and post Shasta represent the natural and impaired flow regimes. The twenty-fifth and seventy-fifth percentile hydrographs represent the natural range of variability in the pre-dam era. When the median post project hydrograph is not within the historic range of variability then there is a significant discrepancy between the historic and current hydrographs. The greatest discrepancies include the lack of spring peak flows and un-naturally high summer flows for all water year types. (The y-axis is discharge in cubic feet per second or cfs.) There is no median hydrograph for an Above Normal Year type because there was only one year of this type between 1929 and 1944. See the table of the number of water year types below.

Water Year Type	Pre Shasta (1929-1944)	Post Shasta (1945-2006)
W	4	22
AN	1	10
BN	3	11
D	4	12
C	3	7
Total	15	62

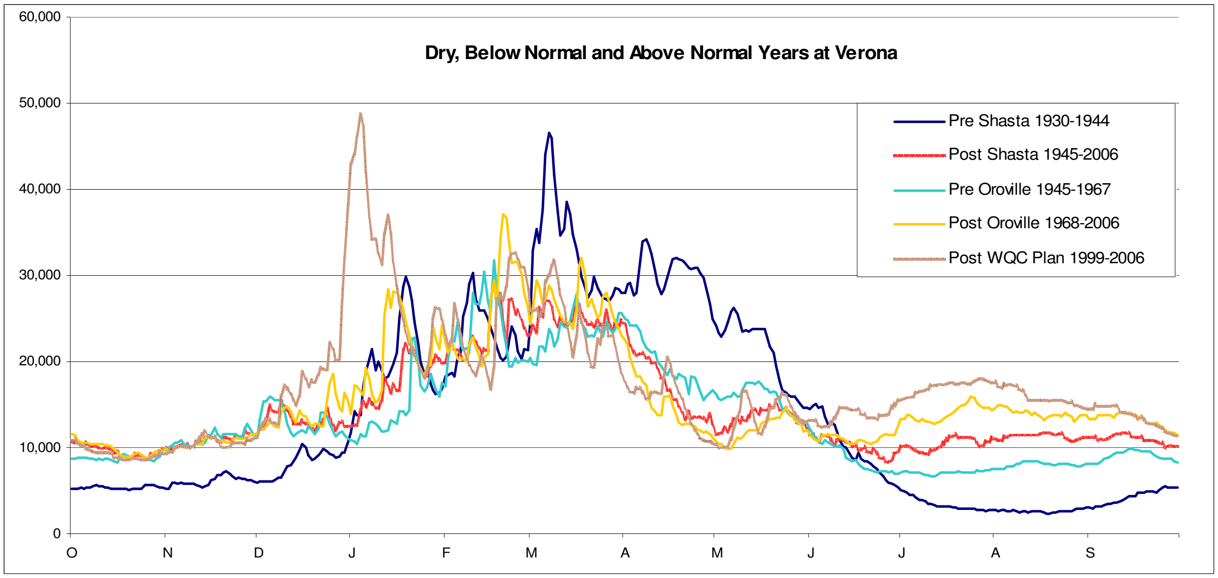


Figure 6.12: Median hydrographs for different time periods indicate a progression towards increased summer flows and decreased spring peaks. The increased regulation of the Sacramento and Feather Rivers with Shasta in 1945, Oroville in 1968 and the implementation of the Water Quality Control Plan in 1999 all had the effect of releasing increased flows during the summer when demands are high and as a consequence eliminated spring peak flows.

Summary of Results

From the hydrograph comparisons of current hydrographs to pre project, or natural hydrographs, a consistent trend immerges for all sites. This trend is the result of reservoir operations where by water is stored until periods of peak demand arise. In the Sacramento River basin peak demands occur in the summer months which means that reservoirs hold water through the spring, eliminating peak spring flows and augmenting summer base flows well above pre project levels. In this way reservoirs alter the timing and magnitude of the spring and summer hydrographs. In addition the presence large reservoirs in the headwaters dampen winter floods in all but the wettest of years. Loss of these geomorphic and riparian flows impacts riparian vegetation and Chinook Salmon habitat.

7.0 IDENTIFY OBVIOUS GAPS BETWEEN OBJECTIVES FLOW REQUIREMENTS AND EXISTING FLOWS

7.1 Gaps in Riparian Vegetation Objectives

Bed Mobilization

The frequency and size of large flows capable of mobilizing the bed have been reduced, but large flows occur in more than half of the years on the Sacramento River. The size of the Q1.5 has been reduced by twenty fiver percent. The pre-dam Q1.5 of 87,000 cfs now has a recurrence interval of every 2.5 years instead of every 1.5 years. While this is a significant reduction, it is a relatively small reduction in comparison to hydrologic alteration on other rivers such as the Feather or San Joaquin Rivers. The abundance of active riffles in the Sacramento River meander belt suggests that the river still periodically mobilizes its bed. Lack of bed mobility in the upper reach below Keswick Dam may be more a result of armoring due to coarse sediment trapping upstream then it is a result of reduced flows.

On the Feather River, the frequency and magnitude of peak flows has been reduced more substantially. The historical instantaneous Q1.5 – 2 has of 33,000 – 50,000 has been reduced by an order of magnitude to 3,000 – 5,000 cfs. The Q2.5, however, is 25,000 cfs. Under the post dam regime, several 4-5 years can pass without exceeding a bed mobilizing flow. This enable riparian vegetation to become established on gravel bars leading to long term stabilization and degradation of the channel.

Bed Scour

The frequency of very large, bed scouring events has been reduced substantially. The pre-dam Q5 of 160,000 cfs now has a twenty-year recurrence interval rather then a five-year recurrence interval. Similarly, the pre-dam ten-year flow now has a one hundred year recurrence interval. The physical processes and ecological function of these large events is not well understood. It is possible that smaller flows substantially scour the bed, rearrange the channel, and form new channel habitat. If so, the reduction in very large flows may not be as important. On the other hand, these very large events may be very important for creating and maintaining important habitats such as oxbow lakes and other off-channel habitats.

Bank Erosion and Channel Migration

We did not conduct an assessment of changes in stream power, but figure 5.2 illustrates that the occurrence of flows exceeding 15,000 or 20,000 cfs in dry, critical dry, and below normal years has been reduce substantially. Larson (2007) identified 15,000 cfs as the lower threshold for bank migration. Median flows frequently reached 15,000 cfs in these drier year types during the pre-dam period, but in the post-dam period median flows seldom rise above 10,000 cfs. During the wettest forty percent of years, wet and normal wet years, median flows frequently exceed 20,000 cfs and thus maintain some level of bank erosion and channel migration processes. Reduction in the frequency and duration of erosive events may have substantial impacts on the colonization and succession of riparian habitat over time. It definitely has habitat implications for bank swallow, a listed species that nests on recently eroded stream banks. Reduced bank erosion almost certainly lowers the suspended sediment levels and could therefore have significant impacts on instream fish habitat for juvenile salmon or Delta smelt that appear to prefer or concentrate in turbid waters (citation?). Although the reduction in the frequency or duration of bank erosion events may have significantly ecological impacts, it may be less important then the widespread presence of bank revetments along the Sacramento Rivers (Larson, 2007).

<u>Inundated Floodplain and off-channel habitat during late winter and spring</u>

The lack of prolonged flows of sufficient magnitude to inundate floodplain and off-channel habitats during the late winter and early spring months is perhaps the most significant ecological change to the Sacramento and Feather Rivers. Large, prolonged flows still occur in wet and normal wet years, but they are largely disconnected from the floodplains due to levees that prevent inundation of the vast historic floodplain of the lower Sacramento River. Large areas of the Sutter and Yolo Bypass become inundated in wet and normal wet years, but little or no floodplains become inundated for any length of time in the drier sixty percent of the years. This is a result of both levees and flow alteration, but flow alteration alone is sufficient to preclude floodplain inundation in the drier years.

Loss of shallow water habitats in secondary channels and floodplains not only reduces the amount of rearing habitat, it also may reduce foodweb productivity in the spring months when juvenile fish are rearing and moving downstream to the Delta. Increase connectivity between shallow water habitats and open water can substantially increase aquatic productivity in estuaries (Cloern, 2008).

Inundated off-channel habitat such as high flow channels can also provide rearing habitat for salmon (Peterson and Reid, 1984), but regulated spring flows are generally insufficient to inundate these habitats for prolonged periods (30-60) days. A recent study of these habitats in the Sacramento River determined that a large proportion of secondary channels between Red Bluff and Colusa become fully connected to the river at flows above 12,000 cfs (Kondolf, 2007). Regulated flows seldom exceed 10,000 cfs in the drier year types (dry and below normal) during late winter and spring when salmon are most likely to require spawning habitat. Even in normal wet years, median April flows are generally below 10,000 cfs.

7.2 Gaps in Riparian Vegetation Objectives

Peak spring flows are conspicuously absent under current conditions. On both the Sacramento and Feather River, median summer flows are significantly greater then median spring flows in all but wet years. As a result, any seeds that might germinate during the cottonwood seed release period in April and May are at risk of mortality from prolonged inundation throughout the summer months. If seeds to become established, they are less likely to grow deep roots during their first growing season due to high groundwater levels and therefore may be more vulnerable to desiccation mortality when water levels do drop.

In addition to the overall decapitation of the spring hydrograph, rapid flow declines during the spring months create a hostile environment for establishment of Fremont cottonwoods. Changes in the rate of the spring snowmelt recession are not obvious from the composite hydrographs depicted in figure 6 because they are of average spring flows over several years. The recession rate is more directly controlled by reservoir release operations in specific wet and above normal years. Our evaluation of hydrographs for individual years indicates that the recession rates are often characterized by abrupt changes in flow during the seed germination period on both the Sacramento and Feather rivers as illustrated in figures 6.1 and 6.2. Abrupt changes in reservoir releases during germination and initial seedling establishment period can limit recruitment by abruptly desiccating recently germinated seedlings before their roots reach the water table or by scouring and inundating newly established seedlings with high summer flows shortly after germination.

Even in wet years, median flows do not reach the documented threshold of 23,000 cfs on the Sacramento necessary to recruit riparian vegetation in a zone that is not vulnerable to subsequent channel scour. Similarly, the Feather River only reaches the assumed threshold of 8,000 -10,000 in median wet years. While it is true that the median numbers depicted in figure 6 obscure the variability that actually occurs in various years, figure 6 clearly illustrates how dramatically the critical spring and summer hydrograph has been altered in non-wet years. Even in wet years, the hydrographs are often not suitable due to the rapid fluctuation in flows (figures 6.1 and 6.2).

Figure 7.1: Annual hydrograph for Sacramento River at Bend Bridge illustrating abrupt flow decline in mid April during cottonwood germination period.

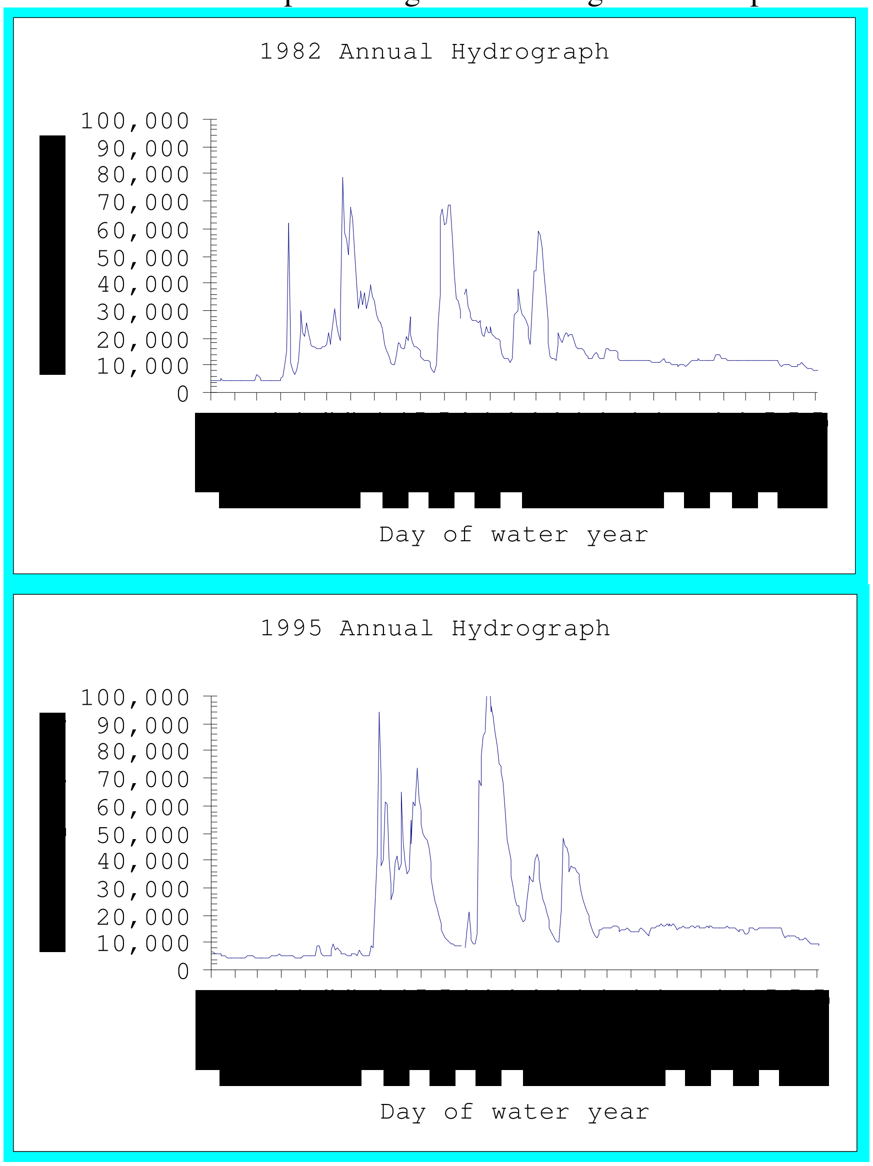
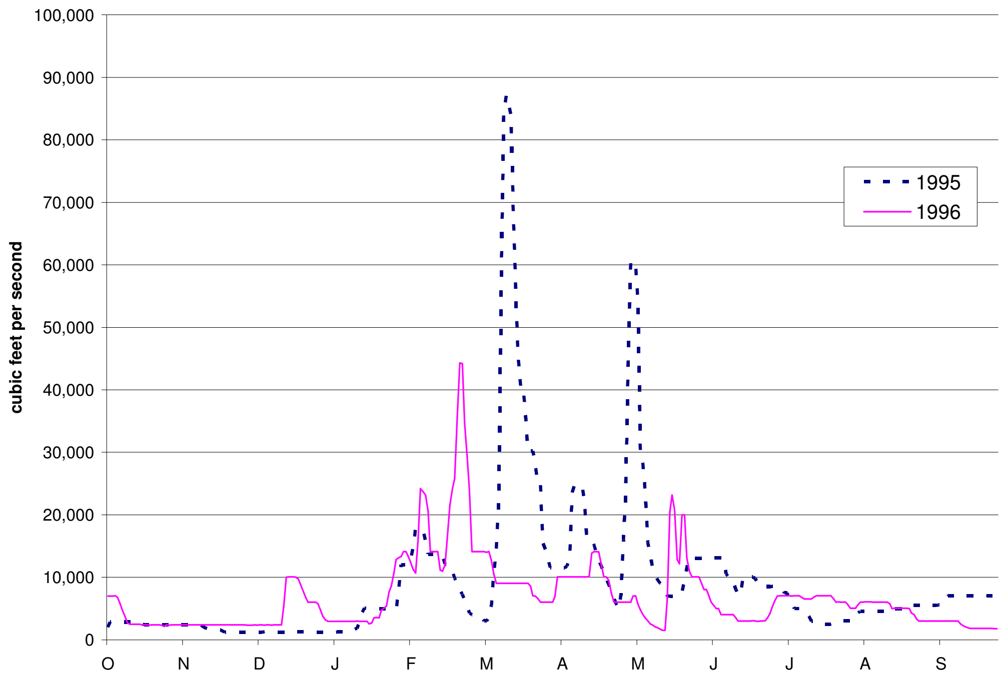


Figure 7.2: Annual hydrograph for Feather River at (sum of Oroville and Thermolito gauges) illustrating abrupt flow decline in mid April during cottonwood germination period.



7.3 Gaps in Chinook Salmon Objectives

<u>Spring Pulse</u>

Elimination of high winter and spring flows has substantially reduced the amount of rearing habitat on inundated floodplains and in off-channel habitats. A close examination of flow patterns indicate that later winter and early spring flows are increasingly the lowest flows of the entire year on both the upper Sacramento and Feather River. Under natural conditions, the highest prolonged flows of the year consistently occurred in the late winter and spring. This “spring rise” in flows inundated gravel bars, secondary channels and associated backwaters, and floodplains during the larger events.

Late winter and early spring flows at Bend Bridge on the Sacramento are about fifty to sixty five percent of what they were historically. A recent study of off-channel habitats on the upper Sacramento River (Kondolf and Stillwater, 2007) identified 12,500 cfs as an important threshold for inundating side channel habitats. On the Sacramento River, median spring flows at Bend Bridge seldom fell below 12,000 cfs between February and April prior to Shasta Dam. In the post dam era, median flows are consistently below 10,000 cfs in all but the wettest years. Meanwhile, summer flows which were historically below 5,000 cfs are now consistently above 10,000 cfs. The shift from spring to summer has become even more pronounced in recent years as dam operators have shifted operations to meet water quality and water supply demands for the Sacramento-San Joaquin Delta.

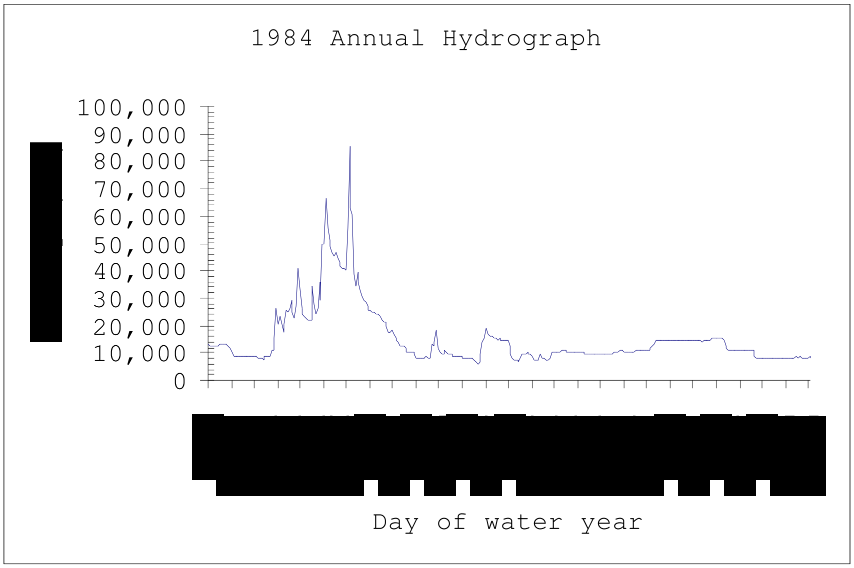
The pattern of reduced spring flows is even more pronounced on the Feather River where median spring flows are fifteen to thirty percent of what they were historically in most year types. The only exception is wet years when they are approximately fifty percent of the historical median. But even in these wetter years, the spring flows are characterized by abruptly fluctuating flood flows as illustrated in figure 6.2, rather then the prolonged spring pulse that characterized historic flows.

<u>Fluctuating Flow Events</u>

The median flow analysis presented in the previous chapter is not well suited for evaluating the frequency of abrupt flow changes, because the composite hydrographs depicted in figure 6 do not reveal individual flow events, which may harm salmon populations. The recent Nature Conservancy study of the Sacramento River (Stillwater, 2007, 2008 appendix F) hypothesized that abrupt increases or decreases in flows in the Sacramento may impact salmon and other species by scouring or dewatering reds, stranding fish, or eroding bank swallow nesting sites. Our cursory analysis of annual hydrographs, illustrated in figures x and xx, indicate that abrupt fluctuations in flow do occur in some years. The timing of these fluctuations may be a significant problem for fish in individual years. Large, rapid fluctuations in the winter or spring could strand juvenile salmon on floodplains or was juveniles downstream to poor habitat. Large reservoir releases in the fall, followed by declines to a significantly lower stage during the remainder of the winter, as illustrated in figure 6.3, could result in dewatering and stranding of redds. Large fall releases are usually limited to periods following very wet years when reservoir levels are high and need to be reduced prior to the rainy season for flood control purposes.

It is clear that large fluctuations in flow occurred under natural conditions on both the Feather and Sacramento Rivers. It is unclear how and whether individuals and populations of these salmon survived these events. Did very high flows that scoured the bed result in reproductive failure? How often did this occur? It is likely that today’s regulated flow regime fluctuates in the present day riverine conditions is more likely to harm salmon then fluctuating flows under historical conditions. Under historical flow conditions, high peak flows are often followed by subsequent peaks that might enable stranded fish to reenter the river. More habitat complexity under historical conditions increased the probability that salmon could spawn or take refuge in areas safe from the potential negative effects of high flows. In today’s environment, large peaks are often abruptly ended only to be followed by weeks of low flows. Levees and channelization have cut-off important refuge and foraging habitat that fish might have otherwise used during high flows.

Figure 7.3: 1984 annual hydrograph from the Sacramento illustrating high flow falls that could result in salmon redd stranding and reproductive failure.



<u>Base Flows</u>

Base flows in the Sacramento and Feather Rivers have been increased in most months except the spring, as previously discussed. Increased base flows during the summer and fall probably lower water temperatures and improve fish passage conditions. It is unclear whether unnaturally high base flows in the summer and fall have any deleterious impacts on fish such as harboring exotic species.

8 ENVIRONMENTAL FLOW REGIME RECOMENDATION

This chapter identifies flow recommendations for the Sacramento River based on the objectives and flow thresholds identified in chapters three and four, and the analyses of natural and regulated hydrology presented in chapters five and six.

Although this study identifies hypothetical restoration flow regimes for the Sacramento and Feather Rivers, we recognize that the most reliable method for developing a restoration flow regime is through a long-term adaptive management program. The hypothetical flow regime that we have developed and identified is imperfect, but it serves as a reasonable starting point for evaluating the feasibility of reoperating reservoirs without impacts on existing reservoir functions.

The assumptions and uncertainties associated with the hypothetical flow regime are as important as the flow regime itself. To cost effectively achieve restoration, managers will ultimately need to test these assumptions and address the uncertainties through a program of modeling, pilot flow studies, model calibration, and long-term restoration implementation. In the text below, we have explicitly identified some of these uncertainties so that they can be further evaluated.

8.1 Summary Recommendation

The key component of the environmental flow proposal for both the Sacramento and Feather Rivers is to restore higher flows during the late winter and spring. This period was once characterized by sustained, high flows. Under regulated conditions, however, spring flows are nearly half their historic volume and substantially below summer flows. We recommend restoring a stable spring base flow that is sufficient to inundate secondary channels, as well as, a spring pulse flow to inundated floodplains, particularly the Yolo and Sutter Bypasses.

A second key objective of the flow regime is to ensure adequate flows for the geomorphic and riparian processes that are necessary to sustain riverine and riparian habitat. We recommend short duration, high magnitude flows during the late winter to increase the frequency of hydrologic events that will mobilize the river bed or erode river banks. During late winter and early spring, we recommend prolonged duration moderately high flows to create inundated floodplain habitat for salmon. During the spring of wet and normal years, we recommend moderate duration, high flow evernts in wet and normal wet years to facilitate recruitment of Fremont cottonwoods and other riparian vegetation.

Restoring higher flows in the spring will necessarily reduce flows during other times of the year We propose reducing summer base flows to enhance spring flow, but realize that this could reduce suitable habitat for winter-run salmon during the summer months. We are not proposing any changes in the cold water pool management regime, which currently assures cold water releases from Shasta Reservoir. We recommend against diverting additional water away from the winter months, because we believe that existing winter flood events are necessary to create and maintain riverine and riparian habitat.

8.2 Sacramento River

Summary recommendations for Sacramento River base flows, key ecological flows, and a flow schedule are presented in tables 7.1 – 7.3. Illustrative flow recommendation hydrographs for each year type are presented in figure 7.2.

Table 8.1: Sacramento Environmental Flow Targets for Bend Bridge and Verona

	Critical	Dry	Below Normal	Above Normal	Wet	Location
Bed Mobilization		35,000	65,000	85,000	105,000	Bend
Floodplain Inundation			25,000	35,000	45,000	Verona
Riparian Establishment Flow				23,000	37,000	Bend
Bed Scour	No Recommendation					
Channel Migration						

Table 8.2: Sacramento River Base Flow Target Summary for Bend Bridge

	Critical	Dry	Normal Dry	Normal Wet	Wet
Fall base flow	5,250	5,250	5,250	5,250	5,250
Winter base flow	4,500	6,000	6,500	7,000	8,000
Spring base flow	10,000	12,000	12,500	14,000	14,000
Summer Base	8,000	8,000	8,000	8,000	8,000
Summer Base at Colusa	4,000	4,000	4,000	4,000	4,000

Table 8.3: General Timing and Duration of Sacramento Environmental Flow Targets

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Geomorphic					2/15 -3/15							
Floodplain Inundation					Only 45 Days							
Riparian Establishment Flow												
Riparian Recession Limb												
Spring Rise												
Fall Base Flow												
Winter Base Flow												
Spring Base Flow												
Summer Base Flow												

8.2.1 Fall Base Flows

We propose stepping flows down from a stable summer base flow (see below) in late September in the upper river (between Keswick and Red Bluff). Under both natural and regulated conditions, flows in early fall are the lowest flows of the year. The primary purpose of lowering fall base flows closer to their historic levels is to economize on water and shift the saved water to the spring months when it is more important. The secondary purpose is to provide stable base flows for spring and fall-run spawning salmon and suitable rearing conditions for winter-run 5,500 cfs release from Keswick is about 1,000 – 1,500 cfs below existing fall base flows, but should be adequate for spawning habitat. The fall base flows must be stable to avoid dewatering or redds that may occur when flows are substantially dropped from the norm. Lower base flows in October could also potentially improve rearing habitat for winter run by creating slightly warmer fall water temperatures and thus an increased food supply.

Below Keswick	5,500
Below Red Bluff Diversion	5,250
Below GCID Diversion	5,000
Below Colusa	4,750

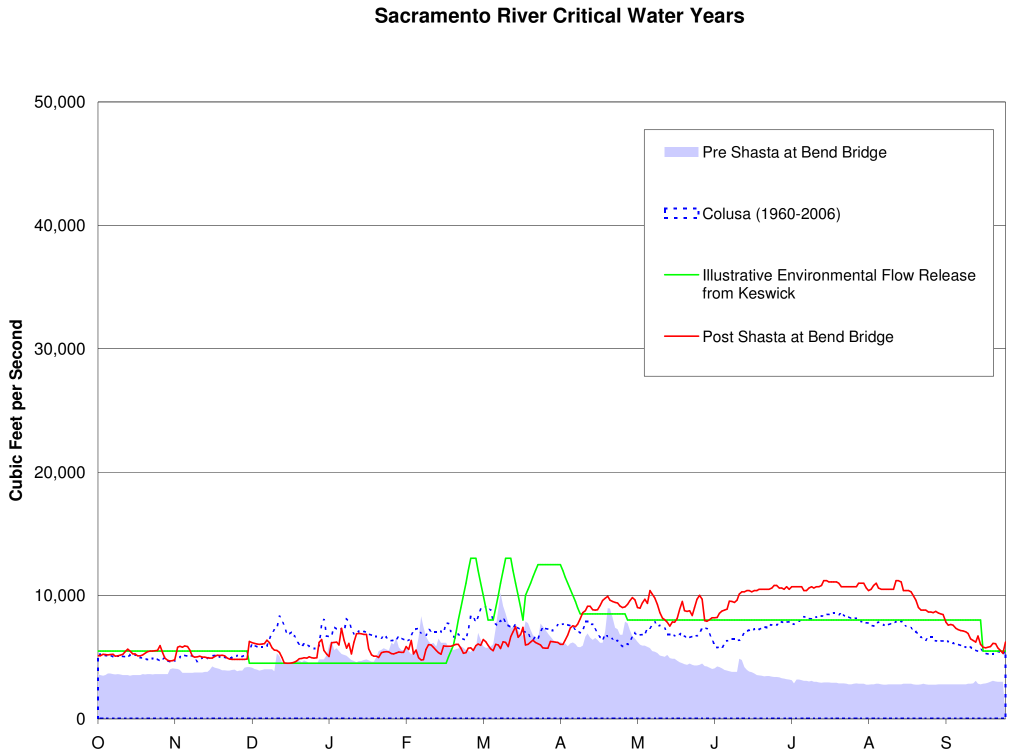
Key Uncertainties

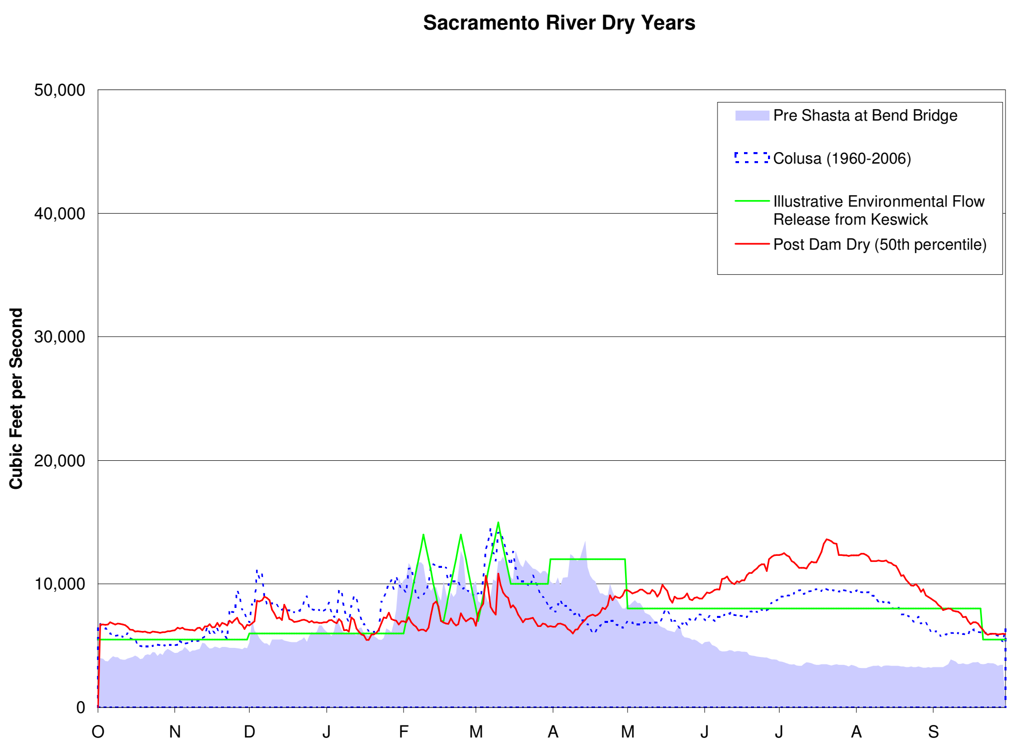
- Are proposed fall base flows sufficient for area of spawning habitat?
- Will lowering fall base flows provide warmer, slower velocity habitat for rearing winter run juveniles, and will this improve their growth and survival?
- Will reduce fall base flows cause adverse impacts in the Delta ecosystem?

8.2.2 Fall Pulse Flow

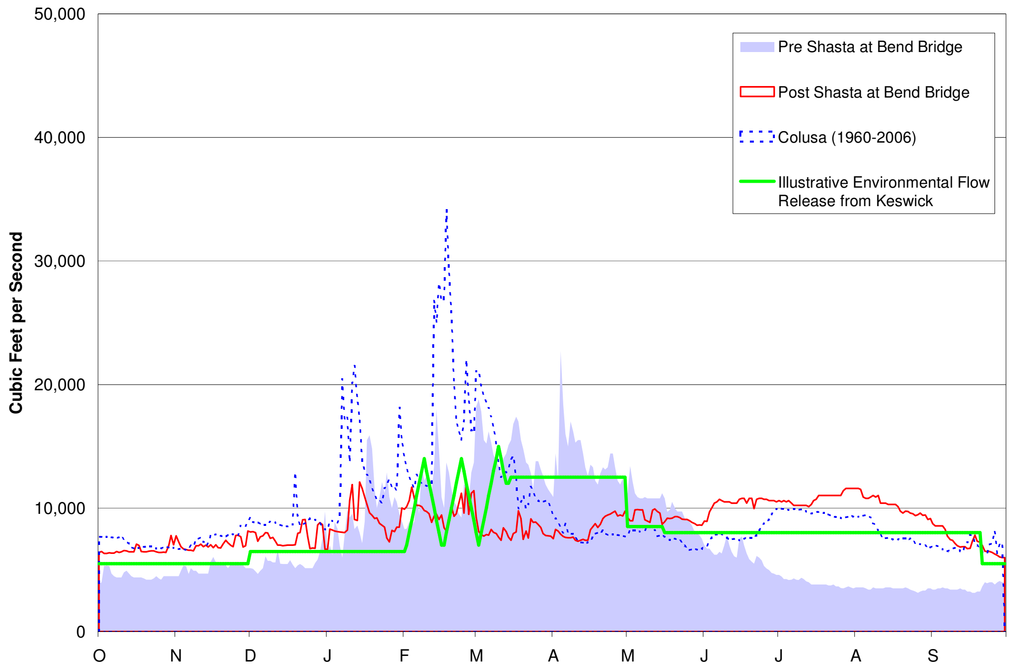
We considered a pulse flow to improve rearing conditions for juvenile salmon in the fall but did not include it in figure 7.2. The purpose of the fall pulse flow would be to improve food supply and rearing conditions for the winter run salmon and is loosely

Figure 8.2: Illustrative environmental hydrographs for five year types on the Sacramento River relative to existing regulated hydrograph and pre-Shasta hydrograph.

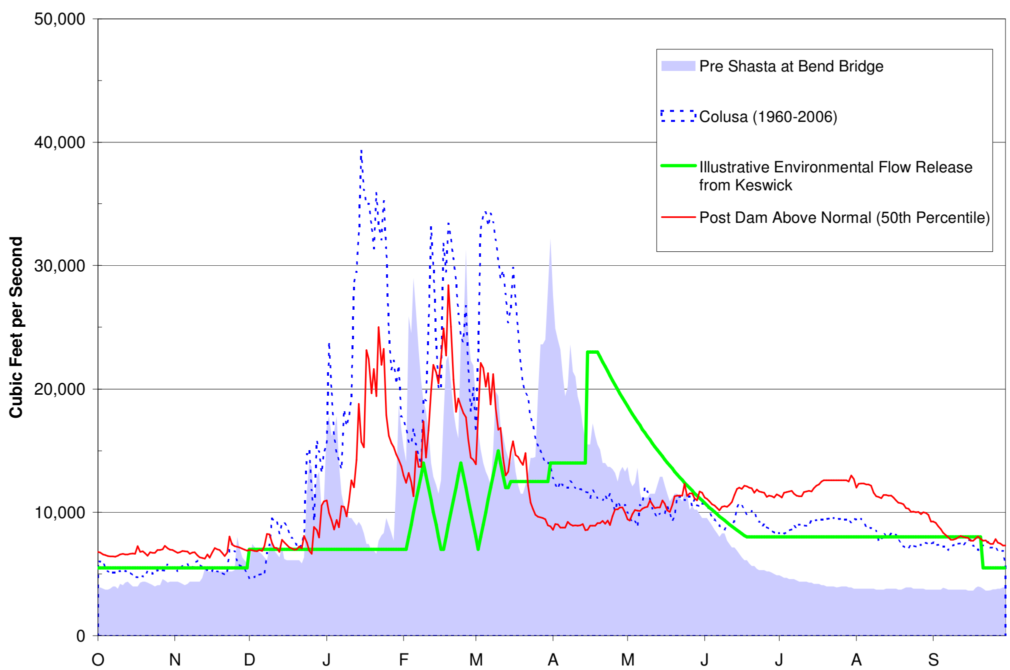


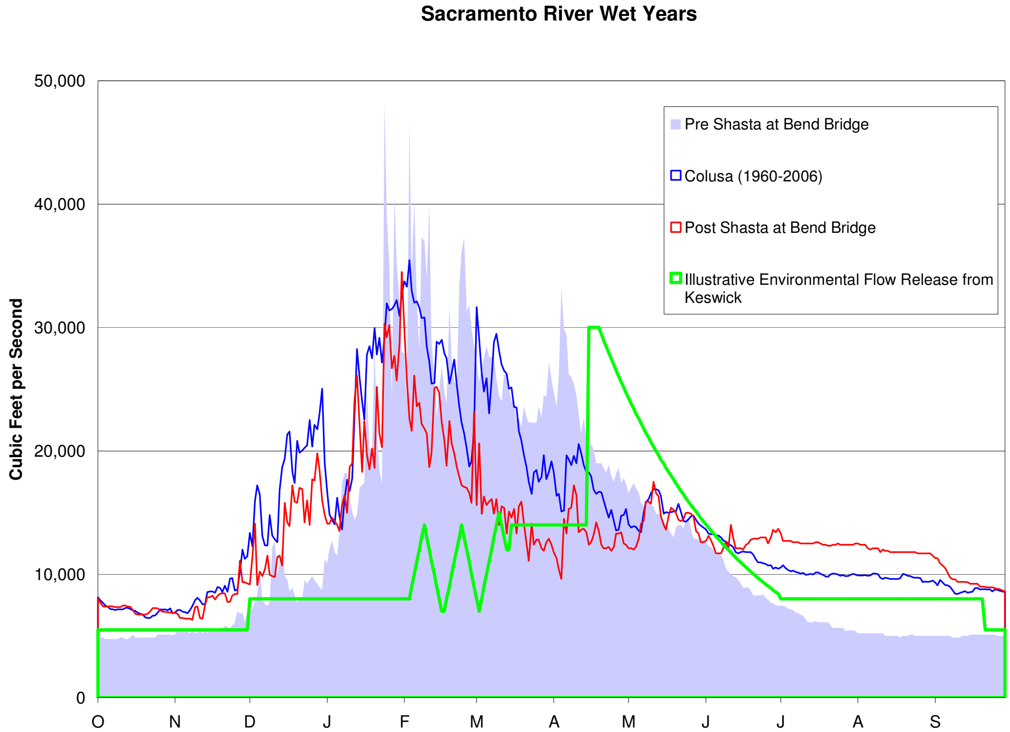


Sacramento River Below Normal Years



Sacramento River Above Normal Years

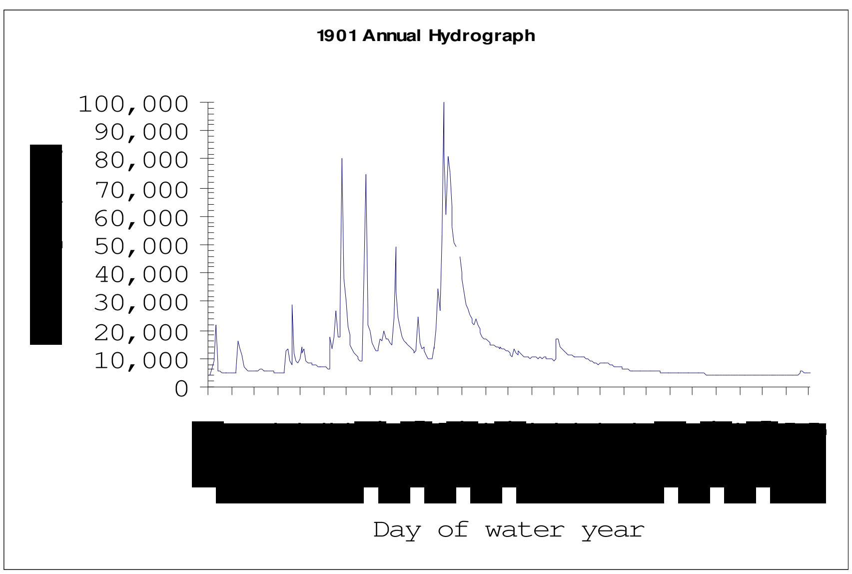



Sacramento River Wet Years
Cubic Feet per Second
50,000
40,000
30,000
20,000
10,000
0
O
N
D
J
F
M
A
M
J
J
A
S
Pre Shasta at Bend Bridge
Colusa (1960-2006)
Post Shasta at Bend Bridge
Illustrative Environmental Flow Release from Keswick

based on recommendations of the recently published Sacramento River Environmental Flows Report (Stillwater, 2007; ESSA Technologies, 2008). Rather then releasing a long duration rearing flow as proposed by Stillwater, it may be more economical to release two or three short duration pulses (3-5 days) of 12,000 cfs in late September and early October to inundate secondary channels and channel margins. The initial pulses would inundate the side channels and then be lowered to allow high residence times in the side channels. Each pulse would be followed by a subsequent pulse to flush food resources into the main channel and prevent fish stranding.

The main potential problem with a fall pulse flow would be to enable salmon, particularly spring run, to spawn on areas that would subsequently be dewatered. If the pulses are short enough, this problem may be limited. But the shorter the pulses will provide less potential for rearing habitat and food supply. Early fall pulse flows were rare under natural conditions, but they did occur occasionally as illustrated by the 1901 hydrograph (figure 7.1). Under regulated conditions, the winter run are confined to the mainstem river. The fall pulse, although largely unnatural, is designed to improve rearing conditions for them before cool winter months when food resources will presumably be less abundant.

Figure 8.1: 1901 hydrograph at Bend Bridge illustrating the rare, but natural occurrence of early fall pulse flows.



Key Uncertainties

- Will fall pulse flows for a few days result in dewatered reds once the pulse subsides?
- How long do secondary channel habitats need to be inundated in order to provide prolonged and substantial food supply benefits in the main channel?

8.2.3 Winter Base Flows

The purpose of the winter base flows is to provide stable conditions for incubating salmonids and reduce flashy regulated hydrology that can result when run-off from unregulated tributaries, primarily on the west side, is not modulated by less flashy natural hydrology from the larger, regulated watersheds. We recommend base flows of between 4,500 cfs in critical dry years and 8,000 cfs in wet years (table 7.4), which is similar to both existing regulated conditions and pre-dam historical conditions.

The winter base flows are a minimum base flow and are designed to occur in combination with unregulated run-off and flood control releases. Figure 7.2 shows the winter base flows as a straight line, but it is just a base flow that supports larger, unregulated peak flows. As a result, actual flows at Bend Bridge will be far more variable then depicted in figure 7.2.

Table 8.4: Winter base flow release from Keswick

	Critical	Dry	Normal Dry	Normal Wet	Wet
Winter base flow	4,500	6,000	6,500	7,000	8,000

Fairly substantial winter base flows combined with run-off events from less regulated tributaries will increase the frequency of inundation of channel margins and secondary channels that may serve as important rearing habitat.

8.2.4 Winter and Spring Peak Flows

The geomorphic flow targets discussed below may require additional releases from Shasta but are not explicitly included in figure 7.2 because they are short duration flow events that would be constructed upon unregulated run-off peaks. Smaller magnitude winter and spring peaks for fish rearing discussed below should be sufficient, particularly if reshaped, to achieve geomorphic targets below Red Bluff when combined with unregulated run-off.

Bed Mobilization

We recommend increasing the frequency of channel migration and bed mobilization flows during dry and below normal years for the reasons discussed in Appendix B. On the basis of thresholds discussed in chapter six, we recommend measures to achieve bed mobilization flows in most years (table 7.5). Based on the analysis of flow thresholds presented in chapter five, 35,000 cfs in dry years should be enough to initiate bed mobilization, at least locally, but it is probably not enough to precipitate widespread bed mobilization. The recommended peak flows in wetter years should be sufficient to precipitate significant bed mobilization in below normal, above normal, and wet years.

Table 8.5: Bed mobilization flow targets for Sacramento River between Keswick and Bend Bridge during different year types.

	Critical	Dry	Below Normal	Above Normal	Wet
Bed Mobilization		35,000	65,000	85,000	105,000

Some fish biologists have expressed concerns that high flow, even relative modest high flowss, could scour redds and thereby harm salmonid reproduction (ESSA, 2008; Stillwater, 2007). Based on our flow threshold analysis (chapter 5), we doubt that flows below 25,000 cfs will substantially mobilize the bed or scour redds. Much higher flows will significantly mobilize the bed, but the biological impact is not well documented and dependent on timing.

The ideal timing for bed mobilization is in early March after most salmon fry have emerged from the gravel and before bank swallow initiate nesting on cut banks. We expect that most mobilization events will result largely from unregulated run-off that humans are unable to control. While it seem logical that scouring flows would impair salmon reproduction, the natural hydrograph was characterized by multiple bed mobilization events in most years, raising the question of whether high, scouring flows actually limit salmonid reproduction. Under natural conditions, however, young fish would have had abundant floodplain and backwater habitat that is now scarce due to levees and reduced channel complexity.

Bed Scour

Information regarding the bed scour process and the magnitude of flow necessary to scour the bed is limited. While we recognize the potential importance of bed scour processes, we have not recommended any measures to precipitate bed scour due to the high level of uncertainty and the sheer magnitude of flow that may be necessary. We do, however, expect some bed scour to occur during the larges flow events once every ten years or more.

Channel Migration

Bank erosion and channel migration is a natural process that shapes the river ecosystem and provides habitats for riverine species. Bank swallows nest in recently eroded cut banks. Coarse and fine materials eroded from cut banks create substrates for growth of riparian vegetation and spawning salmon respectively. Turbid water resulting from bank erosion can provide important cover habitat for juvenile fish that would otherwise be very vulnerable to predation.

Some degree of bank erosion and channel migration will occur at the bed mobilization flows identified above and the spring pulse flows described below. Flows sufficient to erode unprotected banks already occurs and will continue to occur in wet and above normal years due to unregulated flows irregardless of a flow prescription. Furthermore, removal of bank revetment may be a more cost water efficient measure to facilitate natural channel migration then intentional flow releases. For all of these reasons, we have not developed a specific flow recommendation for bank erosion and channel migration at this time.

Key Uncertainties:

- How much does the bed need to be mobilized? Is it sufficient to barely move the gravel and cobble substrate on the surface of the bed, or is it necessary to achieve full scale mobilization.
- What duration of peak flow is necessary to adequately mobilize the bed?
- How much does or could natural rates of bank erosion contribute to the overall turbidity and sediment load of the Sacramento River.

8.2.5 Spring Base Flow

The purpose of the spring base flow is to substantially increase rearing habitat along channel margins and within high flow channels for 45 to 120 days. Under natural conditions, spring flows (March and April) were consistently the highest, prolonged flow of the water year and resulted in widespread inundation of flood plain habitats. Under existing conditions, spring flows are substantially reduced, and a system of levees prevents widespread floodplain inundations.

We propose base flows to inundate secondary channels for rearing habitat during the spring months (table x). According to a recent study, a large number of secondary channels become fully connected to the channel at flows above 12,000 cfs (Kondolf, 2007). In critical dry years, flows would average 10,000 for thirty days after March 15, but small pulses greater then 12,000 cfs would increase connectivity with rearing habitat. In wetter years, larger flows would presumably create more rearing habitat and connectivity for longer periods of time.

Figure 8.6: Spring Pulse Flows at Bend Bridge

	3/15 - 3/31	4/1 - 4/14	4/15 - 4/30	4/30 - 5/14	5/1 - 5/14	5/15 - 5/31	6/15 - 6/30
Critical	10,000	10,000	8,500				
Dry	10,000	12,000	12,000	8,500			
Below Normal	12,500	12,500	12,500	8,500			
Above Normal	12,500	14,000	14,000	14,000	8,500		
Wet	14,000	14,000	14,000	14,000	14,000	8,500	

Key Uncertainties:

- Do flows in excess of what is necessary to inundate high flow channels create better rearing habitat and more food then flows barely sufficient to inundate these habitats?

- What is the optimal flow and residence time to create ideal rearing habitat conditions (food supply, temperature, and depth) in the secondary channels.
- Is the secondary channel habitat significant enough to substantially improve rearing conditions relative to the rearing habitat in the channel.

8.2.6 Floodplain Inundation Flows

The purpose of the floodplain inundation flows is to inundate floodplains in the Sutter and Yolo flood bypasses for rearing habitat and food web productivity. The flow objective is to create substantial inundated floodplain habitat for 30-60 days between February 15 and April 15 in most year types. To economize on the amount of water necessary to inundate these bypasses, we propose modifying the Tisdale and Fremont weirs to created inundated flood plain habitat more frequently and for a longer duration. Based on the floodplain process analysis in chapter 5, we developed a schedule of flood flow targets for various year types to create good conditions for floodplain rearing and foodweb productivity in nearly all year types (table 7.7).

The floodplain inundation flows are not explicitly included in figure 7.2. The winter and spring pulse flows described above combined with unregulated run-off at Colusa and environmental flows from the Feather and Yuba should be sufficient to achieve the table 7.7 targets.

Table 8.7: Recommended average monthly flows at Verona and Nicolaus on the Feather to create inundated floodplain habitat in the Yolo and Sutter Bypasses for various year types (30-60 days).

	Year Type				
	C	D	BN	AN	W
Nicolaus (Feather)			12,000	15,000	20,000
Freemont Wier		25,000	30,000	37,500	45,000
Tisdale Weir		25,000	30,000	35,000	40,000
Verona		25,000	35,000	45,000	55,000

Key Uncertainties:

- What magnitude of flow is necessary in the Sacramento and Feather Rivers to move water across the bypasses assuming a modified weir structure?
- What is the optimal timing and flow to create optimal habitat conditions on the bypasses (depth, velocity, temperature, residence time) and food web productivity for the estuary?

8.2.7 Spring Snowmelt Recession Limb

The purpose of the spring, snowmelt recession is to periodically provide conditions for recruitment of Fremont cottonwoods, a keystone species in the riparian ecosystem. As discussed in appendix A and chapter 5, recruitment of cottonwoods requires a high spring flow followed by a gradual decline in order to enable cottonwoods set roots into the groundwater on higher surfaces that are relatively immune from scour during subsequent winter floods. An earlier analyses (TNC, 2003) determined that a range of 23,000 cfs to 37,000 cfs inundates the appropriate seedbed for establishment of cottonwood. Cottonwood trees need not be recruited in all years to ensure a sustained riparian forest ecosystem.

We recommend recruitment flows of 23,000 in above normal years and 37,000 cfs (or somewhere in that general range) in wet years for 4-7 days between mid April and mid May followed by a gradual recession for 8-10 weeks. This flow regime should enable seeds released in mid spring to germinate on relatively high surfaces and then gradually extend roots to the permanent water table before the subsequent growing season.

8.2.8 Summer Base Flow June 15 to September 15

We have designed summer base flows between Keswick and Red Bluff to economically provide suitable conditions for winter run, spring run, and steelhead that spend a temperature sensitive portion of their life cycle between Keswick Dam and Red Bluff diversion Dam (table 7.8). Under natural conditions, these fish would have migrated upstream of Keswick and Shasta, but there mainstem habitat is now limited to the cold tail water provided by reservoir releases. Current base flows are artificially high to deliver water to Sacramento Valley irrigation districts and the Delta. Ideally, these unnaturally high flows could be shifted to the early spring to restore a prolonged spring pulse flow for rearing habitat and aquatic productivity, but providing a more natural flow regime (3,000 to 5,000 cfs) could result in lethal water temperatures for incubating winter run-eggs. Furthermore, flows of only 3,000-5,000 cfs would not provide sufficient water for both diversion into the north valley canals and base flows all the way downstream to the Delta. Therefore, we have proposed an intermediate level summer base that falls at the mid-range between historic base flows and existing base flows between Keswick and Red Bluff.

Table 8.8: Summer base recommendation at various points on the Sacramento River for all year types.

Below Keswick	8,000
Below Red Bluff Diversion	6,000
Below GCID Diversion	4,500
Below Colusa	4,000

Below Red Bluff and the GCID diversions, we have proposed substantially reduced summer base flows in order to shift more flow to the early spring months without disrupting the cold water pool management regime. The primary purpose is to provide better habitat conditions in the spring, but restoring a more natural summer base flow may have environmental benefits in its own right. Summer base flows substantially below the 8,000 cfs needed to inundate off-channel backwaters will create more natural summer conditions and thus may discourage invasive plant and animal species that may out compete natives under the existing artificial summer base flow regime. Seasonally desiccated off-channel habitats may be more productive then perennially inundated wetlands and less likely to harbor exotics predators such as bull frogs and bass. Lower summer water levels may be less beneficial to late germinating invasive vegetation such as tamarisk that can out compete native cottonwoods.

Key Uncertainties:

1. Assuming no changes to the cold water pool management, what flow is necessary to maintain sufficient water temperatures for over summering life stages of winter-run, spring-run, late fall-run and steelhead?
2. Will low flows and corresponding higher temperatures increase populations of non-native warm water fish that prey upon or compete with native species?
3. Will summer base flows be sufficient between Red Bluff and GCID to maintain water temperature conditions suitable for juvenile salmonids or adult migrating salmonids?
4. Will more "natural" conditions provide better habitat and feeding conditions for native species?

8.3 Feather River

Summary recommendations for Sacramento River base flows, key ecological flows, and a flow schedule are presented in tables 7.1 – 7.3. Illustrative flow recommendation hydrographs for each year type are presented in figure 7.2.

Table 8.9: Feather River Environmental Flow Targets for Bend Bridge and Verona

	Critical	Dry	Below Normal	Above Normal	Wet	Location
Bed Mobilization		10,000	20,000	55,000	50,000	Bend
Floodplain Inundation		6,000	8,000	10,000	12,000	Verona
Riparian Establishment Flow				10,000	12,000	Bend
Bed Scour	No Recommendation					
Channel Migration						

[redacted]

[redacted]

8.3.1 Fall Base Flows

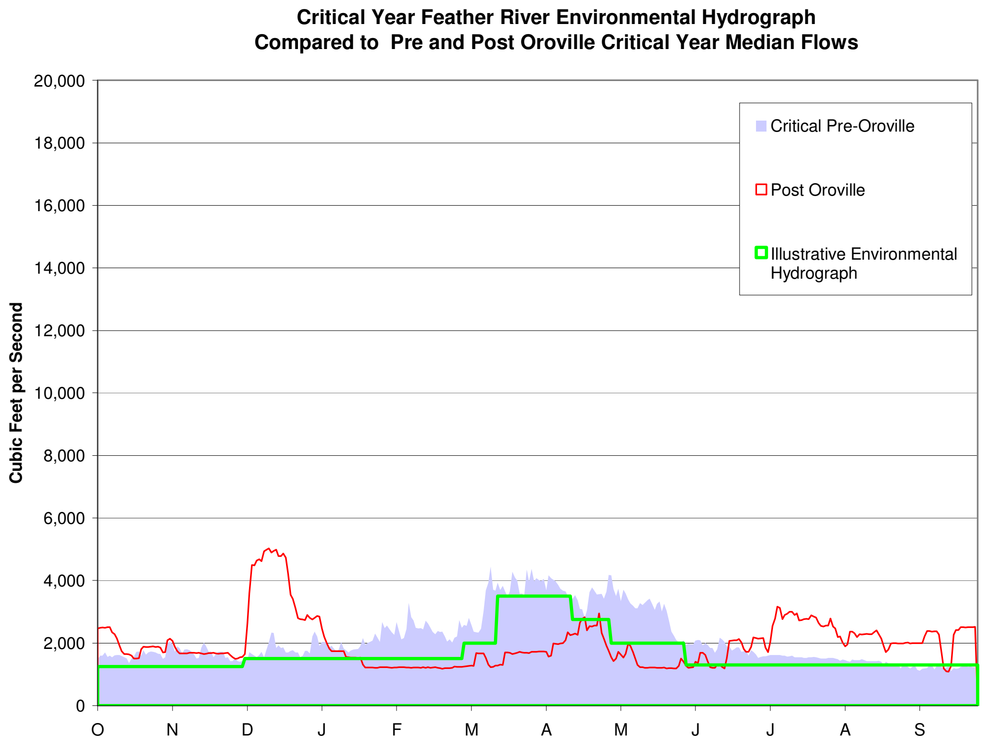
We propose stepping flows down from a stable summer base flow (see below) in late September (table 7.10) to fall spawning flows specified by the recent Oroville relicensing proceeding. The new minimum instream flows below Thermalito Afterbay range from 1,000 cfs in the late spring and summer to 1,200 -1,700 cfs during the fall winter months. Under both natural and regulated conditions, flows in early fall are the lowest flows of the year. The primary purpose of lowering base flows in the fall closer to their historic and regulatory minimum levels is to economize on water and shift the saved water to the spring months when it is more important. The secondary purpose is to provide stable base flows for spring and fall-run spawning and potentially to trigger spring-run spawning. The fall base flows must be stable to avoid dewatering or redds that may occur when flows are substantially dropped from the norm.

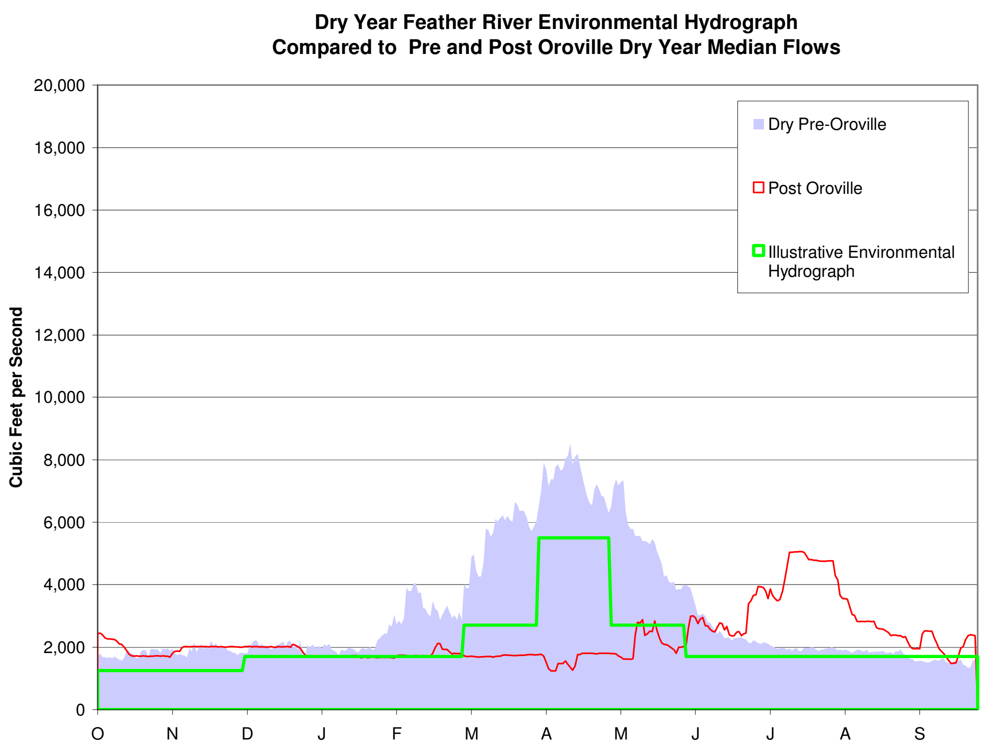
Key Uncertainties

- Are proposed fall base flows sufficient for area of spawning habitat?

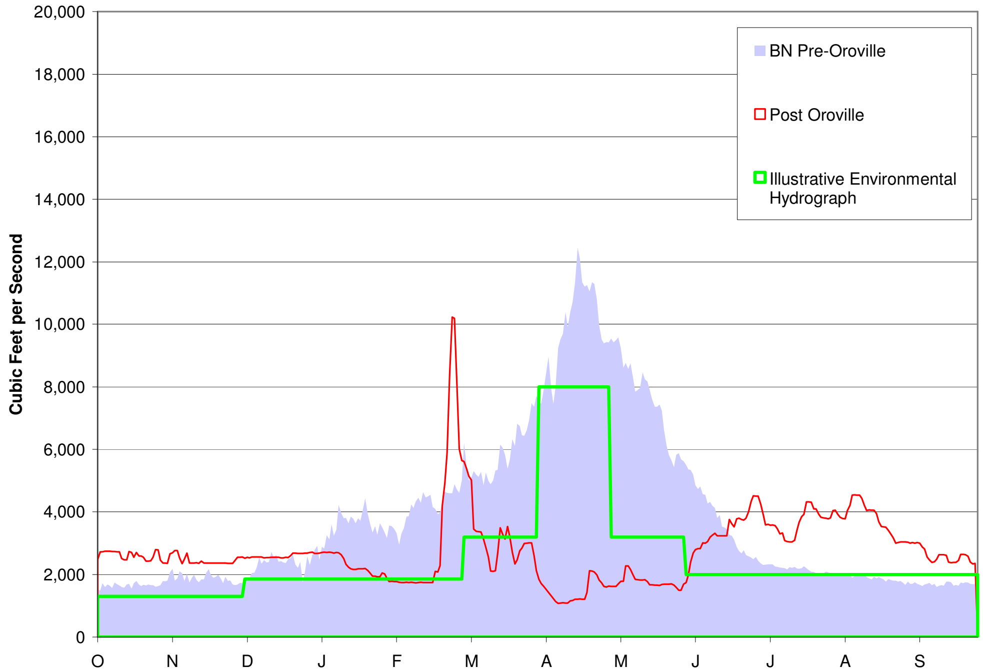
Will reduce fall base flows cause adverse impacts in the Delta ecosystem?

Figure 8.3: Illustrative environmental hydrographs for five year types on the Feather River relative to pre and post Oroville hydrographs.

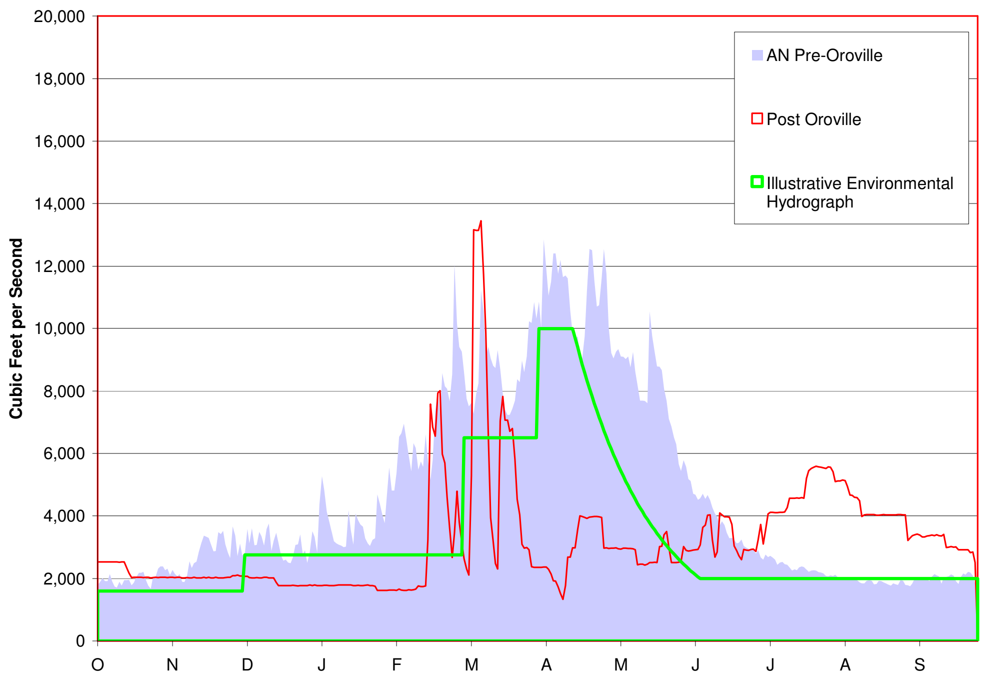


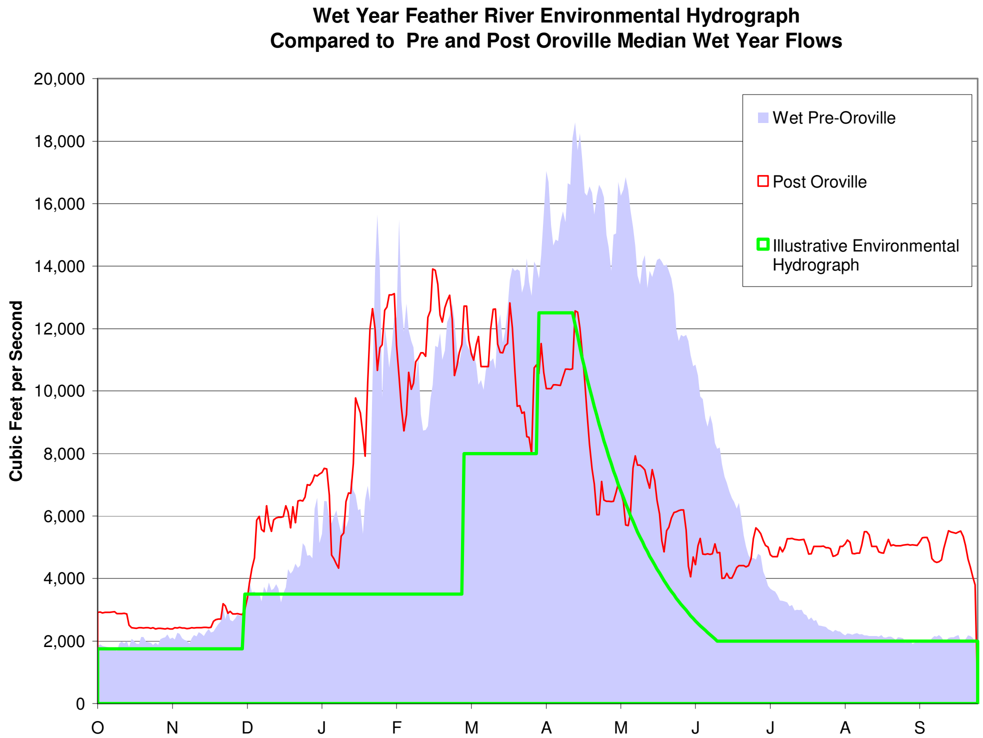


Below Normal Year Feather River Environmental Hydrograph Compared to Pre and Post Below Normal Oroville Median Flows



Above Normal Year Feather River Environmental Hydrograph Compared to Pre and Post Oroville Above Normal Median Flows





8.3.2 Winter Base Flows

The purpose of the winter base flows is to provide stable conditions for incubating salmonids and reduce flashy regulated hydrology that can result when run-off from unregulated tributaries, particularly the South Fork Yuba, is not modulated by less flashy natural hydrology from the larger, regulated watersheds. We recommend base flows of between 1,500 cfs in critical dry years and 3,500 cfs in wet years (table 7.10), which is similar to both existing regulated conditions and pre-dam historical conditions.

The winter base flows are a minimum base flow and are designed to occur in combination with unregulated run-off and flood control releases. Figure 7.3 shows the winter base flows as a straight line, but it is just a base flow that supports larger, unregulated peak flows. As a result, actual flows below the confluence with the Yuba will be far more variable then depicted in figure 7.3.
Fairly substantial winter base flows combined with run-off events from less regulated tributaries will increase the frequency of inundation of channel margins and secondary channels that may serve as important rearing habitat.

8.3.4 Winter and Spring Peak Flows

The geomorphic flow targets discussed below may require additional releases from Shasta but are not explicitly included in figure 7.3 because they are short duration flow events that would be constructed upon the spring rise or ordinary flood control releases. Smaller magnitude spring pulse flows for fish rearing discussed below should be sufficient, particularly if reshaped, to achieve geomorphic targets.

Bed Mobilization
We recommend increasing the frequency of channel migration and bed mobilization flows during dry and below normal years for the reasons discussed in Appendix B. On the basis of thresholds discussed in chapter six, we recommend measures to achieve bed mobilization flows in most years (table 7.5). Based on the analysis of flow thresholds presented in chapter five, 35,000 cfs in dry years should be enough to initiate bed mobilization, at least locally, but it is probably not enough to precipitate widespread bed mobilization. The recommended peak flows in wetter years should be sufficient to precipitate significant bed mobilization in below normal, above normal, and wet years.

Table 8.12: Bed mobilization flow targets for Feather River below Oroville

	Critical	Dry	Below Normal	Above Normal	Wet
Bed Mobilization		10,000	25,000	35,000	50,000

Some fish biologists have expressed concerns that high flow, even relative modest high flowss, could scour redds and thereby harm salmonid reproduction on the Sacramento River (ESSA, 2008; Stillwater, 2007). Because are bed mobilization flows for the Feather River are based on statistical estimates rather then empirical evidence of bed mobility, the potential for red scour is a big uncertainty, but we doubt it will occur at 25,000 cfs or less and the greater magnitude flows prescribed for above normal and wet are likely to happen from flood control releases regardless of our flow recommendations.

The ideal timing for bed mobilization after late February when most salmon fry have emerged from the gravel. We expect that most mobilization events will result largely from unregulated run-off that humans are unable to control. While it seem logical that scouring flows would impair salmon reproduction, the natural hydrograph was characterized by multiple bed mobilization events in most years, raising the question of whether high, scouring flows actually limit salmonid reproduction. Under natural conditions, however, young fish would have had abundant floodplain and backwater habitat that is now scarce due to levees and reduced channel complexity.

Bed Scour
Information regarding the bed scour process and the magnitude of flow necessary to scour the bed is limited. While we recognize the potential importance of bed scour processes, we have not recommended any measures to precipitate bed scour due to the high level of uncertainty and the sheer magnitude of flow that may be necessary. We do, however, expect some bed scour to occur during the larges flow events once every ten years or more.

Channel Migration
Bank erosion and channel migration is a natural process that shapes the river ecosystem and provides habitats for riverine species. Bank swallows nest in recently eroded cut banks. Coarse and fine materials eroded from cut banks create substrates for growth of riparian vegetation and spawning salmon respectively. Turbid water resulting from bank erosion can provide important cover habitat for juvenile fish that would otherwise be very vulnerable to predation.

Some degree of bank erosion and channel migration will occur at the bed mobilization flows identified above and the spring pulse flows described below. Flows sufficient to erode unprotected banks already occurs and will continue to occur in wet and above normal years due to unregulated flows irregardless of a flow prescription. Furthermore, removal of bank revetment may be a more cost water efficient measure to facilitate natural channel migration then intentional flow releases. For all of these reasons, we have not developed a specific flow recommendation for bank erosion and channel migration at this time.

Key Uncertainties:

- How much does the bed need to be mobilized? Is it sufficient to barely move the gravel and cobble substrate on the surface of the bed, or is it necessary to achieve full scale mobilization.
- What duration of peak flow is necessary to adequately mobilize the bed?
- How much does or could natural rates of bank erosion contribute to the overall turbidity and sediment load of the Sacramento River.

8.3.5 Spring Base Flow

The purpose of the spring base flow is to substantially increase rearing habitat along channel margins and within high flow channels for 45 to 120 days. Under natural conditions, spring flows (March and April) were consistently the highest, prolonged flow of the water year and resulted in widespread inundation of flood plain habitats. Under existing conditions, spring flows are substantially reduced, and a system of levees prevents widespread floodplain inundations.

On the Feather River, we do not have good information regarding the flows necessary to inundate back-water channels. As a result we developed spring flow targets based on historical hydrology and an assessment of the flows necessary to inundate the Sutter Bypass (table 7.13). Wetter year spring flow pulses begin later in the spring and last longer, while dryer year targets economize on water early to get salmon out of the river before temperatures could become a problem in the lower Sacramento.

Figure 8.13: Spring Pulse Flows below Oroville

	3/1-3/14	3/14-3/30	4/1-4/14	4//14 - 4/30	5/1 - 5/14	5/15 – 5/31
Critical	2,000	3,500	3,500	2,000		
Dry	2,700	2,700	5,500	5,500	2,700	
Below Normal	3,200	3,200	8,000	8,000	3,200	
Above Normal	6,500	6,500	10,000	10,000	5,000	3,000
Wet	8,000	12,500	12,500	11,000	6,000	4,000

Key Uncertainties:

- Do flows in excess of what is necessary to inundate high flow channels create better rearing habitat and more food then flows barely sufficient to inundate these habitats?
- What is the optimal flow and residence time to create ideal rearing habitat conditions (food supply, temperature, and depth) in the secondary channels.
- Is the secondary channel habitat significant enough to substantially improve rearing conditions relative to the rearing habitat in the channel.

8.3.6 Floodplain Inundation Flows

The purpose of the floodplain inundation flows is to inundate floodplains in the Sutter and Yolo flood bypasses for rearing habitat and food web productivity. The flow objective is to create substantial inundated floodplain habitat for 30-60 days between February 15 and April 15 in most year types. To economize on the amount of water necessary to inundate these bypasses, we propose modifying the Tisdale and Fremont weirs to created inundated flood plain habitat more frequently and for a longer duration. Based on the floodplain process analysis in chapter 5, we developed a schedule of flood flow targets for various year types to create good conditions for floodplain rearing and foodweb productivity in nearly all year types (table 7.7).

The floodplain inundation flows are not explicitly included in figure 7.3. The spring pulse flows described above combined with unregulated run-off from the Sacramento and Yuba Rivers will be sufficient to achieve the table 7.7 targets.

Table 8.14: Recommended average monthly flows at Verona and Nicolaus on the Feather to create inundated floodplain habitat in the Yolo and Sutter Bypasses for various year types (30-60 days).

	Year Type				
	C	D	BN	AN	W
Nicolaus (Feather)			12,000	15,000	20,000
Freemont Wier		25,000	30,000	37,500	45,000
Tisdale Weir		25,000	30,000	35,000	40,000
Verona		25,000	35,000	45,000	55,000

Key Uncertainties:

- What magnitude of flow is necessary in the Sacramento and Feather Rivers to move water across the bypasses assuming a modified weir structure?
- What is the optimal timing and flow to create optimal habitat conditions on the bypasses (depth, velocity, temperature, residence time) and food web productivity for the estuary?

8.3.7 Spring Snowmelt Recession Limb

The purpose of the spring, snowmelt recession is to periodically provide conditions for recruitment of Fremont cottonwoods, a keystone species in the riparian ecosystem. As discussed in appendix A and chapter 5, recruitment of cottonwoods requires a high spring flow followed by a gradual decline in order to enable cottonwoods set roots into the groundwater on higher surfaces that are relatively immune from scour during subsequent winter floods. Since we did not have estimates of flows suitable for riparian recruitment on the Feather River, we estimated a seedling establishment flow target based on the Sacramento riparian recruitment target. We simply scaled down the Sacramento target based on the ratio of the seedling establishment flow to the Q1.5. The seedling establishment flow on the Sacramento (23,000 – 30,000 cfs) is twenty seven to thirty seven percent of the bankfull discharge (Q1.5 to Q2) on the Sacramento. Assuming a similar proportional relationship on the Feather River, flows in the range of 9,500 to 18,000 would be suitable for seedling establishment.

We recommend seedling establishment flows of 10,000 in above normal years and 12,500 cfsin wet years for 4-7 days between mid April and mid May followed by a gradual recession for 8-10 weeks. This flow regime should enable seeds released in mid spring to germinate on relatively high surfaces and then gradually extend roots to the permanent water table before the subsequent growing season.

8.3.8 Summer Base Flow June 15 to September 15

The purpose of the summer base flow is to provide suitable temperature and rearing conditions for over summering salmonids, both juvenile and adult spring-run and steelhead. We propose base flow targets ranging from 1,300 in critical dry years to 2,000 cfs in above normal and wet years. These flows are very similar to natural summer base flows and are higher then the minimum existing minimum flows established during the recent relicensing proceedings. Existing minimum regulatory flows are 1,000 cfs in the summer. Existing actual flows are far higher then are recommendation.

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