# Beehive Bend Subreach Addendum to:

# A Pilot Investigation of Cottonwood Recruitment On The Sacramento River

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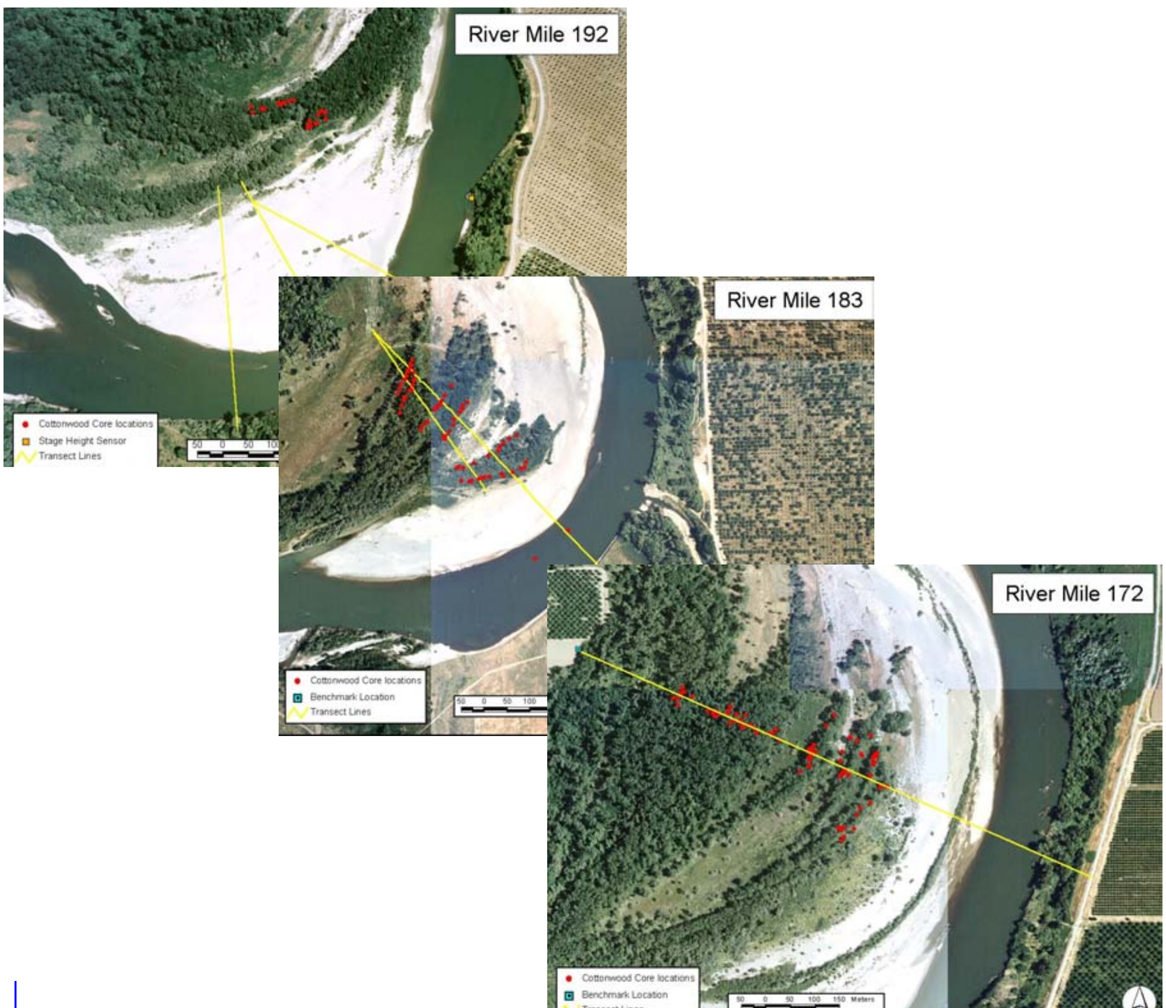
August 31, 2000

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# Key Findings

- Based on 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. A comparison to stands that recruited in the pre-regulation period is needed to quantify differences between pre and post regulation period temporal and spatial characteristics of riparian forest regeneration.

- Recruitment did result from the recent large flood events of 1983-1986, and 1995-1997. Although this recruitment follows a one in ten year frequency, recruitment events may now be limited to larger, less frequent events.

- Similar to the previous study, bank protection appears to further limit recruitment, although the specific degree and mechanism are difficult to quantify. Recent recruitment was limited at the previous study site, which has bank protection and a levee in close proximity. Although large in frequent floods may be required to produce it, recent recruitment did occur at the new study sites. These study sites do not have bank protection or levees in close proximity.

- Recent recruitment appears to favor the downstream ends of point bars and these locations may best meet box model criteria. A complimentary study found that much of this recruitment is dominated by willow species as opposed to cottonwoods. It is unknown if this is a result of altered hydrology on the Sacramento River.

- If large, infrequent floods do not occur to produce a forest cohort, a refined recruitment box model is available to guide a recruitment flow for the Sacramento River. The range of appropriate elevation for recruitment is now 3 to 6 feet above mean low water (8,500 cfs). This new information results in significantly less water required to implement a managed recruitment flow than identified in a previous study.

- A decreasing elevation of recruitment through time may indicate channel degradation, as do other information sources.

- A number of flow management strategies were evaluated, which require a range of water for implementation. When compared to actual wet year flows at these study sites, these managed strategies can require up to 37% less water.

- A managed flow strategy that takes advantage of natural conditions that narrowly miss recruitment needs may best meet multiple water use objectives. Spring 2003 conditions narrowly missed recruitment needs. Based on the information from this study, a change in the timing and recession rate of spring 2003 conditions could have formed a recruitment flow. This recruitment flow would not have placed any new water demands on the system. The water management decision making process needs to be evaluated for the flexibility to implement this conservation strategy.

## INTRODUCTION

Riparian vegetation favorably contributes to critical streamside and in-stream habitat, water quality, bank stability, and aesthetic and recreational values (Patten 1998). Riparian cottonwoods (*Populus* spp.) are a keystone pioneer species that are the foundation of this forest type, but land use and river regulation have caused a widespread reduction in the extent and regeneration of this genus (Braatne et al. 1996, Friedman et al. 1998, Rood and Mahoney 1990). This reduction generated an effort to understand cottonwood recruitment ecology to provide a basis for future management to retain the societal benefits of riparian vegetation.

The fundamental hydro-geomorphic processes that facilitate cottonwood seedling recruitment in wide alluvial valleys are typically quantified by correlating the flow regime and the time of seedling establishment. Studies typically use dendrochronological, geomorphic, and stream flow data to correlate the timing of stream flow and seedling recruitment (Bradley and Smith 1986, Scott et al. 1993, 1996, Friedman et al. 1996, Rood et al. 1998, Mahoney and Rood 1998). Scott et al. (1993) describe how seedling germination and establishment of riparian vegetation occur in response to the character and pattern of stream flow within a given year or growing season. Mahoney and Rood (1998) provide an ecological model, the recruitment box, which describes the relationship between seedling recruitment and alluvial settings. The ecological model specifies a timing and range of elevation above mean low water (MLW) in which a recession rate of approximately one inch per day facilitates recruitment on other rivers studied.

River managers mimic the conditions specified in the box model through flow regulation in order to facilitate significant recruitment. Our study reach of Sacramento River is larger, characterized by bankfull discharge, than the rivers used to generate the model. We previously calibrated this ecological model for one site on the Sacramento River, at river mile (RM) 192, and conducted a preliminary investigation into the nature and extent of limitations to cottonwood recruitment. Results are summarized in a report titled "A Pilot Investigation of Cottonwood Recruitment on The Sacramento River" (Roberts et al. 2000, available at http://www.sacramentoriverportal.org/eco_indicators/forest_regen.htm).

Therefore, we sought to complement this initial investigation with data from two additional study sites at river miles (RM) 183 and 172 to develop a more widely applicable ecological model covering 30 miles of the Sacramento River. River regulation can be changed to benefit many species (Poff et al. 1997) where society deems this appropriate (Schmidt et al. 1998). If society deems re-regulation for ecological benefit as an appropriate action on the Sacramento River, the ecological relationships strengthened through this addendum report can provide the information necessary to facilitate cottonwood recruitment at these, and likely other, sites in this river reach.

## STUDY APPROACH

The effects of river regulation on riparian recruitment on the Sacramento River are not fully quantified. However, the Sacramento River experienced 4 large floods in 1983, 1986, 1995, and 1997. These floods represent a 50-70 year, 5-10, 5-10, and a 10-

20 year return interval event at the Butte City guage based on unregulated flood frequency relationships (United States Army Corps of Engineers, 1998). Return intervals of spring runoff events resulting in seedling recruitment on other rivers often are in the range of a 2-10-year event (Mahoney and Rood 1998), assuming other hydrologic characteristics described above are also present. Therefore, we assumed that significant recruitment should have resulted from at least one of these four large floods. Yet, based on field observation from a boat between RM 199 and 184, the evidence of stands including sapling size trees appears sparse (S. B. Rood personal observation, 1999).

We selected two additional sites to further investigate the hypothesis that recruitment is limited and that flow regulation is the partial cause of the limitation (Figure 1). We collected dendrochronological data, hydrologic data, and topographic survey data at the two additional study sites to complement similar data sets from a previous investigation on the Sacramento River. We again reviewed an analysis of historic stream gage data (Pike, 2000) with respect to the potential nature of limitations to recruitment. Pike used the Indicators of Hydrologic Alteration (IHA) software (Richter et. al. 1996) to identify changes in 33 aspects of pre-regulation and post-regulation hydrology.

## METHODS

### *Study area*

The Sacramento River flows south along the boundary between the Klamath Mountains and the Cascade Range into the Sacramento Valley of California. The valley is approximately 400 miles long and from 30 to 60 miles wide and is bordered by the Sierra Nevada and Cascade Range on the east, the California Coast Range on the west, and the Klamath Mountains on the north. The Sacramento River is California's largest river draining an area of 26,000 square miles with a mean annual discharge of 22 million acre feet. Hydrology is driven both by winter storms and spring snowmelt runoff. For a detailed description of Sacramento River hydrology see Kondolf et al. (2000). The section of river between Red Bluff and Colusa is referred to as reaches 2 & 3 in the Sacramento River Conservation Area Forum's "River Handbook" (Sacramento River Advisory Council, 1998) and our study sites are within reach 3.

These two study sites are distinct from the previous study site in a number of ways. The RM 192 site is located upstream of the ACE Flood Control Project levees whereas the RM 172 site is bordered by these Project levees on both sides of the river. The RM 183 site is bordered only on the west side by these Project levees. The RM 192 site also has bank protection immediately upstream of the investigated point bar. In addition, a large levee is located on the left bank and opposite the RM 192 point bar. The RM 183 and 172 sites have no bank protection nearby.

The Sacramento River captures a rich mosaic of aquatic habitat, oxbow lakes, sloughs, seasonal wetlands, riparian forests, and valley oak woodlands in what amounts to one of the most biologically productive ecosystems in the state (Golet et al., 2003). However, the Sacramento River is in a degraded condition due to land use changes, flow diversion, and river regulation. Only 10% of the original riparian vegetation, historically occupying the Red Bluff to Colusa reach of the Sacramento River, remains (Golet et. al., 2003). Refer to the 1998 River Handbook for a more detailed description of the flora, fauna, geomorphic, and hydrologic characteristics of the study reach.

The additional study sites are located within the meandering reach from Red Bluff to Colusa, California (Figure 1). Within this reach, the channel flows through recent alluvium (Buer 1994). These sites were selected as representative of a meandering bend of the river channel including the point bar and cutbank complex described in the literature to facilitate riparian recruitment. These locations are characterized by actively meandering banks and both sites have an approximate meander belt width of 3000 feet (Buer, 1994). Both sites are also the locations of long-term DWR erosion monitoring. The RM 172 east bank of the river has migrated approximately 112 feet between 1986 and 1993, with 52 feet of migration occurring between 11/92 and 6/93 (Buer 1994). Bank composition was not mapped at this site. The east bank of the RM 183 site has steadily eroded 3000 feet in the last 100 years. The east bank migrated about 34 feet between 1986 and 1992, with a maximum of about 43 feet of migration between 6/92 and 12/93. Much of the upstream bank at this site is underlain by an erosion resistant clay plug, the remnants of an oxbow lake deposit.

Based on field observation of tree height and stem diameter, these sites were also chosen because they appeared to have three to four significant and distinct age cohorts of cottonwood trees on them (Figure 1). These cohorts appeared to exhibit a typical arcuate banding pattern described in the literature. Previous research has demonstrated that this pattern is produced by successive recruitment events, which occur as the channel migrates laterally. These sites also posses geomorphic surfaces which appeared appropriate for recruitment (S. B. Rood personal observation, 1999).

### *Calibration of the Recruitment Box Model*

We surveyed a cross section of the seedbed area at both sites, which were perpendicular to flow and bisected the cottonwood bands occurring on the point bars. Benchmark elevations were established with a survey-grade GPS.

We excavated 34 and 32 cottonwood trees at the RM 172 and 183 sites, respectively, to the depth of the root crown to determine the elevation of establishment. Stems were selected to be representative of individual recruitment bands based on location, stem height, and diameter. Sampling continued farther from the river channel in a more random fashion at the RM172 site because age cohorts were less distinct in the field. Trees were sampled in six transects at the RM 183 site. Elevation of the root crowns were then surveyed with a rod and level into a coordinate system relative to other topographic data.

We used an increment borer to collect two increment cores per stem from the excavated root crowns to determine the year of establishment. Cores from the RM 183 site were sent to the Laboratory of Tree-Ring Research in Tucson, AZ for processing, mounting, and aging. Cores from the 172 site were sent to the Tree Ring Laboratory at the University of Arkansas. When tree cores did not possess pith material, age was estimated in one of two ways. The Arizona lab used the ring widths of the previous 4-6 rings, from the last ring included in the core, to estimate the establishment date. They designated a "confidence" factor of 1-5 depending on how well the width of the last ring corresponded to the previous 4-6 ring's widths. The Arkansas lab developed a regression analysis between the number of rings provided in the core and the available radius sampled. However, because the relationship was weak ($R^2 = 0.43$, see Appendix 4a) and we did not use it for extrapolating dates any earlier than the number of counted rings. Fortunately, a small number of trees contained pith material from the RM 172 site. We used these stems in conjunction with aerial photography and mapped locations of historic channels to date stands.

We installed a continuous read stage recorder (Model SR50, Campbell Scientific, Logan, UT) to develop a stage discharge relationship at the RM 183 site. A Campbell Scientific, Inc. SR50 Sonic Ranging Sensor measured distance to the water surface. The instrument elevation was surveyed and related to the topographic data coordinate system. We used discharge data from the Ord Ferry guage (California Data Exchange Center station ID ORD) approximately 1.5 river miles upstream to generate a stage discharge relationship at this site. We surveyed the water surface elevation at three different discharges and used discharge data from the Butte City guage (United States Geological Survey gauge #11389000) approximately 3.5 river miles downstream to generate a stage discharge relationship at the RM 172 site. We used the stage discharge curves to evaluate which hydrologic events possessed the characteristics described above that temporally correlated with age of the stands.

We also evaluated available GIS information of historic channel locations of the area supplied by Dr. Steve Greco at UC Davis. This information was used to corroborate and increase the precision of dedrochronological and hydrologic data used to identify temporal distribution of recruitment events. We assumed that a recruitment event occurring between two mapped channel locations in plan view recruited sometime between those two years of river position.

### *Evaluation of recruitment limitations*

In the previous pilot study, we conducted field reconnaissance over 37 river miles (RM 201-164) to document the presence or absence of sapling sized cottonwoods. We noted and documented very few sapling and young tree sized stems on point bars. However, we did notice seedlings and saplings in other low elevation locations during this preliminary reconnaissance, most commonly near the downstream ends of point bars. These areas may be the ends of topographic depressions between meander scrolls created as channel migration occurs. These areas are also characterized by finer substrate, likely deposited due to lower velocity conditions at the downstream ends of point bars during the receding limb of flood flows. Determination of relative proportions of recruitment in different fluvial geomorphic conditions was beyond the scope of this report however, this is in an accompanying report (Wood 2003, See Appendix 5).

We also referred to an analysis of Sacramento River hydrology (Pike, 2001). DWR used the Indicators of Hydrologic Alteration (IHA) software (Richter et. al., 1996) to evaluate differences in 33 hydrologic variables between the time periods of 1939 – 1943, 1944 – 1963, and 1964 – 1994. These time periods represent pre- Shasta Dam, pre-Shasta Dam and post Whiskeytown Dam diversion, and post-Shasta Dam post Whiskeytown Dam diversions respectively.

We utilized data derived from this study and the information described above to refine our formulation of a cottonwood “recruitment flow”. We generated a number of different recruitment flow strategies by manipulating the recession rate, the beginning elevation of the recession rate, and the flow conditions to which the application volume was compared (i.e. an average versus a high water year). We used the water year 2000 to represent average conditions during the seed release period and the water year 1995 to represent a high water year during the seed release period. We generated the necessary flow volume only for the recruitment period of mid-April to mid-June. Altered flow conditions during other parts of the year are probably detrimental to other riverine species. However, this study only evaluates regulation affects on cottonwood recruitment.

## RESULTS AND DISCUSSION

### *Calibration of the Recruitment Box Model*

#### Determining the favorable range of recruitment elevation above mean low water

Based on the discussion below, we suggest the range of elevation for recruitment on the Sacramento River is 3-6 feet above mean low water (MLW). Rood and Mahoney (2000) confirmed a range of 2.5 to 4 feet above MLW for seedling cohorts on the St. Mary River in Alberta, Canada. Determining the range of elevation of successful cottonwood establishment is an important step in calibrating Mahoney's recruitment box for the Sacramento River.

An initial step in this investigation is to identify the stage and discharge of MLW at our sites. We selected the elevation of MLW corresponding to a discharge of 8500 cfs at each site. (Table 1).

Table 1

| Site | Elevation (ft.) above mean sea level (msl) of MLW at 8500 cfs (Rounded to the nearest 0.5 feet.) |
|---|---|
| 192 | 113 |
| 183 | 92 |
| 172 | 73.5 |

We assumed that in general the summer months of June, July, and August would pose the most significant ecological threshold of drought stress for seedlings attempting to reach the receding water table. Pike's (2001) IHA analysis reveals that 8500 cfs approximates the mean low water discharge during these months from 1944-1994 (Figure

2). Average water stage and discharge may actually be lower in September through November. Observations from revegetation sites show the highest mortality occurring within the first 3 months. Although revegetation site conditions are often different than those found on a point bar, we assumed seedlings would be more established and resistant to drought stress by September.

The average elevations of establishment above MLW are 7.2, and 9.1 for our RM 183 and 172 sites, respectively (Figure 3). The previous pilot study indicated an average of 7.1 feet above MLW, and the overall average for all three sites is 7.8 ft. Using this overall average to guide a managed flow strategy would be in agreement with earlier results from the RM 192 site investigation where two different aged cohorts occurred at similar ranges of elevation. However, the additional sites in this study depict a much wider range of establishment elevations compared to RM 192 (Figures 4, 5, & 6). Therefore, an average value that includes unknown historic conditions (i.e. channel geometry, stage discharge relationships) may not represent current conditions which facilitate recruitment.

## Changes in recruitment elevation through time

Excavating and aging tree stems provides the data to evaluate recruitment elevation through time. However, because increment core data was very poor we can only provided a rough approximation of establishment period. Tree diameters were very large and the 18 inch increment corer length limited our ability to collect growth rings earlier than those produced in the late 1960's to early 1970's. Therefore, we relied on recently improved historic channel mapping data, and recent aerial photography to compliment increment core data. We bracketed establishment to approximate 5 year periods or less. The 183 and 172 sites contain both earlier and later recruitment events than the 192 site. These events occur at lower and higher elevations, respectively, than the 192 data.

### Older recruitment

Older recruitment events, characterized as pre-1983, at all three sites appear to occur at higher elevations than more recent recruitment (Figure 7). In Figure 7, recruitment bands were numbered to match with bands at other sites with similar approximate establishment periods. This provides some comparison of recruitment elevation within the same approximate time frame among sites. For example, the first band sampled at RM 192 is referred to as "band 3" in Figure 7 in order to match its period of establishment with similarly aged bands at other sites. Bands 1 and 2, identified at other sites, are absent from or very sparse at the RM 192 site.

### Recent recruitment

In contrast to initial findings from the 192 site, it appears that some degree of recruitment has occurred as recently as 1997 at the RM 172 and 183 sites (Figure 8 & 9). The RM 183 data represents the most complete time series of recruitment and documents recruitment correlating with the recent 1983-1986 and 1995-1997 flood periods. Although much of these recent bands of recruitment appear limited to a width of one stem, it is difficult to assess whether this represents a limited spatial extent as a function of river regulation. To address this question, these stands would need to be compared to forests that established under pre-regulated conditions.

Although not sampled, and therefore not reflected in Figure 7, we did observe some evidence of recruitment in the 1995-1997 at the RM 172 site. This recent band was not sampled because only 2 cottonwood stems were in proximity to the surveyed cross section. However, these cottonwood stems appear very similar in height, diameter, and placement on the point bar when compared to the cored and dated 1995-1997 band on the RM 183 site.

The recent recruitment events at RM 183 and 172 did not occur at the average recruitment elevation of 7.8 feet above MLW, which includes the elevation range of older recruitment at these sites. In fact, these recent bands at the RM 183 site occur between 3 to 6 feet above MLW, close to other research directing the calibration of the cottonwood recruitment box model (Figure 7).

An apparent decrease in the elevation of establishment over time is different than findings at the RM 192 site. These different findings suggest at least one hypothesis relevant to river management. Cottonwood recruitment elevation may be decreasing due to a decreasing elevation of a degrading channel.

Channel degradation is a common result of river regulation. Buer (1994) found channel narrowing and degradation in some locations, between Red Bluff and Colusa, on the Sacramento River. Singer and Dunne (2001) characterize the reach of the river containing our study sites as undergoing accelerated erosion based on suspended sediment modeling. In addition, Brice (1977) observed a depletion of islands and bars in this reach. This depletion may be evidence of channel simplification, and formation of a narrower and deeper channel.

Evaluation of historic cross sections near the study sites does not yield a clear trend of channel response to regulation in this area. Buer (1994) depicts historic cross sections at RM 175.4 and RM 168.5, which are the closest historic cross sections to our study sites. Although the RM 168.5 cross section reflects approximately 15 feet of degradation between 1979 and 1986, the 175.4 cross section indicates approximately 5 feet of aggradation during the same time period. We also reviewed an historic cross-section comparison recently completed by DWR (Red Bluff office) which depicts roughly 5 feet of degradation at RM 167 between 1909 and 1997. An historic cross section evaluated in the RM 192 pilot investigation indicated no clear pattern of channel change.

Although the available cross sections do not convey a clear trend in channel change, the channel may have degraded approximately 5 feet over the last four to five decades, the time period captured within the sampled cottonwood stands. Approximately 5 feet of channel degradation may explain the approximate 5 foot reduction in the elevation above MLW seen in cottonwood recruitment over time.

A trend of decreasing elevation of establishment is only suggestive of channel degradation and does not represent a full geomorphic analysis of long term channel changes. This hypothesis warrants further investigation and a more full evaluation of all historic cross section data. Additional historic cross sections exist but this information has never been condensed into one analysis to assess long term changes in channel adjustment (width, depth, slope, roughness, etc.) to various regulation. Dr. Steve Greco and others at U.C Davis have initiated a compilation of historic cross section data, which can facilitate such an analysis.

Channel degradation could have consequences for the riparian system of the Sacramento River. Other studies have shown channel degradation and a decreasing elevation of baseflows to lead to a "drying out" of the riparian vegetation community and slow replacement with more xeric species. If these conditions do exist on the Sacramento, the riparian community may become more susceptible to invasion by exotic vegetation.

A range of 3-6 feet is likely appropriate for facilitating recruitment on the Sacramento River. The lower end of this range is documented with recent recruitment and has less scientific uncertainty associated with it because no assumptions are made regarding shifts in stage discharge relationships and other channel changes through time. A higher degree of scientific uncertainty exists in determining the top end of the recruitment zone, however, recent recruitment falls within this range. It is very likely that seedlings on the Sacramento River may recruit at higher elevations, as indicated by older recruitment. Without further evaluation of historic channel conditions, the top elevation of recruitment is difficult to determine. Rood (pers. com.) states that it is reasonable that the range of elevation for cottonwood recruitment would be slightly higher on the Sacramento River than on the smaller rivers that were studied previously because this slightly higher range of elevation tend to occur on 1) larger rivers, 2) rivers with finer substrate, and 3) rivers in warmer climates with longer growing seasons.

## Spatial patterns in establishment

Conditions facilitating recruitment under regulated conditions may be more favorable at the downstream ends of point bars. Occurrences of recent mixed species recruitment were noted at the downstream ends of point bars in the 1999 field reconnaissance conducted for the RM 192 study. The spatial pattern of recruitment on point bars was further investigated in complimentary study (Wood 2003, See Appendix 5), which found that downstream areas of point bars had a disproportionate amount of riparian tree species recruitment. Fremont cottonwood, Gooding's black willow, and sand bar willow all had a mean overall elevation of establishment above low water of 0.65 to 5.74 feet, and a narrower range of 3.9 to 5.24 feet above MLW on downstream transects. Mean low water was defined as 9700 cfs in their study and only differs by a few tenths of a foot from the elevations we used. Although recent recruitment was documented in their study, the authors point out that it is unknown whether the recruitment they observed will perpetuate through time. In addition, they found that recent recruitment was dominated by willow species.

The recent cottonwood recruitment sampled at our study sites and documeted in the Wood (2003) study tends to concentrate at the downstream ends of the point bar that remains relatively fixed in space. New cohorts from recruitment events then extend off of this hub, in the typical arcuate banding pattern, and taper off farther upstream on the point bar (Figure 8 & 9). Cottonwood recruitment often tapers off to one stem width representing an age cohort. The more recent bands of recruitment often occur within topographic depressions between meander scrolls along the point bar as seen in Figure 4. These areas are the likely location were box model conditions are met and deposition of finer particle sizes likely increases moisture-holding capacity in these areas. Although these areas may be the most likely point bar areas where box model conditions are met under the current hydrology, it is unkown whether this spatial pattern is an artifact of regulated hydrology. It is also less clear whether the river reach between Butte City and Colusa is characterized by the lack of riparian forest recruitment suggested in the previous RM 192 study. A comparison of spatial and temporal characteristics of recruitment between pre and post-regulation periods is needed to inform this questions. For example, does a sparse line of single stems represent a sustainable level of riparian forest regeneration?

Quantitative comparison of recruitment area.

In this study we sought to determine if the spatial patterns described above coincide with locations of appropriate ranges of elevation on the point bar in addition to those areas characterized by cross section data. In the previous study, we conducted an analysis to examine the extent of "young" stands relative to available recruitment area over 37 river miles. This reconnaissance was conducted between Hamilton City and Butte City, primarily upstream of the current study reach, however it did overlap with the RM 172 and 183 study sites. In that analysis we estimated that only 10% of the available, appropriate seedbed was colonized by recent recruitment. We also estimated approximately 600 acres of this seedbed exists between Red Bluff and Colusa that can be further colonized. We sought to improve the analysis above through the use of a digital terrain model.

In this study, we used a digital terrain model (DTM) developed, and graciously shared by, Dr. Steve Greco at U.C. Davis. We used the DTM to determine if some form of recruitment was occurring within the box model elevations that we developed for the Sacramento River. Figures 10 and 11 display the areas between 3 to 6 feet above MLW and represents the DTM depiction of appropriate seedbed area at these sites. Recently completed vegetation mapping at these sites includes a "riparian scrub" category. In the field, these areas often coincide with recent recruitment. The dominant species recruiting in these areas is typically sandbar willow (Salix exigua) but cottonwood seedlings are also observed in these areas (Wood 2003).

Modeled areas of appropriate seedbed (light blue) frequently overlap with either riparian scrub (light green) or cottonwood forest (dark green) at both sites. This analysis suggests that the areas that should contain young riparian species do contain these species, even though these communities are dominated by willow and not cottonwood.

At the RM 172 site, the match is almost perfect near the channel edge of the point bar. The model successfully depicts the location of the recent 1995-1997 recruitment event. Recruitment from the 1983-1986 periods also occupies locations on the point bar very close to the locations of appropriate elevations characterized by the model. The comparison of model output and recent recruitment at the RM 183 also matches relatively well. The model also identifies point bar area not colonized by riparian vegetation. This reason for this area not being colonized is unknown.

This analysis suggests that the spatial extent of riparian forest recruitment is not as limited as suggested in the RM 192 study. However, the majority of new recruitment is dominated by willow. In addition, cottonwood recruitment is often limited to a width of one stem per band. These observations lead us to ask whether willow communities are displacing cottonwoods as early colonizers on Sacramento River point bars, as suggested in the previous RM 192 study. Flow regulation may be responsible for a shift in species distribution towards willow and in place of cottonwood. Species such as Salix exigua successfully recruits from vegetative mechanisms. Rood and Mahoney (1995) suggest that regulation on other rives may resulted in a shift from seedling recruitment towards vegetative recruitment mechanisms. Amlin and Rood (2002) found that Salix exigua prefers a slower rate of recession, about 1 cm/day, and tends to occur at lower recruitment elevations. Current management of the Sacramento River's hydrology may often duplicate these conditions where river flow is often maintained one or two feet below the typical cottonwood recruitment box.

### *Geomorphic influences on recruitment*

Recent recruitment, correlating with 1983-1986 and the 1995-1997 flood periods, was documented at the RM 172 and 183 sites and neither of these sites have bank protection in their vicinity. Investigating the rate of channel migration was beyond the scope of this report. However, at both sites the channel appears to be migrating both downstream and laterally (Figures 12 & 13) and this pattern assumes other factors, such as resistant geologic formations, are not affecting development of the meander loop (Larsen 1995). Geologic formations and bank protection do not appear to affect the bends at the study sites. Given the appropriate hydrology, these patterns of channel migration would be expected to create new seedbed area at these sites and facilitate recruitment. In contrast, recruitment is much sparser at the RM 192 site and was not documented in the cross sections during the pilot study. Bank protection and a levee on the opposite bank of the river channel likely played a role in limiting recruitment at that site. We hypothesize that bank protection and levees may shift water velocity and other factors controlling bar morphology, in a more downstream direction and negatively affect seedling recruitment. Both the Kondolf et al. (2000) report and the Wood (2003) report document steeper point bar morphology at sites with bank protection on the opposite bank. Specifically, Wood (2003) documents a steeper point bar morphology at the RM 192 site compared to the RM 172 site (Figure 2 in that study).

A steeper bar morphology limits the amount of bar area occurring within the appropriate elevation range for establishment. The RM 192 site has approximately 44 feet of bar area (in plan view) occurring within the 3-6 foot elevation range. In contrast, the RM 172 and 183 sites have 78 and 65 feet occurring within this elevation range. The RM 172 site is however, migrating towards an ACE flood control project levee. Continued monitoring should reveal if this becomes a limiting factor to future recruitment. Steeper bar morphology alone probably does not preclude recruitment. However, this affect in addition to other impacts of regulation likely further decrease the chances of successful regeneration.

### *Hydrologic influences on recruitment*

The hydrologic cycle, and the geomorphic processes driven by it, also exerts a primary influence on the temporal distribution of recruitment events. The previous study suggested that altered hydrology played a role in limiting the frequency of recruitment events. The frequency of recruitment events at the additional study sites approximates one in ten years. Although the literature documents a range of frequencies, once in ten years is more similar to "functioning" systems where recruitment temporarily correlates to the one in ten year flood. However, it is important to consider the magnitude of flood events correlating to recruitment at these sites.

Lowney and Greco (2003) compared flood magnitudes between pre and post Shasta hydrology at the Bend Bridge gage (Table 2). They found that a pre-Shasta 5 year return interval event is now characterized as a post-Shasta 20 year return interval event. Although we did not compare pre and post regulated hydrology at the gages used in our study (Ord Ferry and Butte City), the USACE's 1998 Post flood assessment characterizes the floods of 1983, 1986, 1995, and 1997 as unregulated 50-70 year, a 5-10 year, a 5-10 year, and a 10-20 year return interval events, respectively. This indicates that at least the 1986, 1995, and 1997 floods represent the typical magnitude of flood resulting in recruitment on other rivers.

Flood characterizations, in addition to the designation of a return interval, also facilitate formulation of ecologically beneficial flows. Designation of a return interval is a function of the period of record of river flows and therefore is subject to change. Richter and Richter (2000) found that the duration of a flood greater than 125% of bankfull flows was important in driving lateral channel migration on the Yampa River in Colorado, which is the initial step of riparian forest recruitment.

Regardless of the limitations of using a flood's return interval as the only flood characteristic indicative of riparian forest recruitment, the Bend Bridge comparison suggests that recent floods would now be characterized as larger, less frequent floods at the gauges used in our study. If recruitment is indeed dependent upon these larger floods then a reduced frequency or recruitment events may be expected.

We also reviewed Pike's IHA analysis at the Butte City gage to evaluate flow regime limitations to recruitment. This analysis of flows during the pre-Shasta dam, post Shasta dam, and post Trinity River trans-basin diversion time periods demonstrated that the flow regime is most altered during the period of seed release and the summer months (Figure 15). Flow is less altered during winter months when it is still similar to recorded ranges of natural variability. Based on stage discharge curves at our sites, a discharge range of 23,000 cfs to 37,000 cfs inundates the appropriate seedbed at all 3 sites (Figure 16). The IHA analysis indicates this range of discharges occurring much more frequently in the pre-regulated spring time period coinciding with seed release.

Mean daily discharge at the Butte City gauge indicate that a number of years contain flows capable of inundating the seedbed. Assuming a stable channel geometry over time, the flood events which inundated the seedbed during the period of seed release include calendar years 1952, 1957, 1958, 1963, 1965, 1967, 1974, 1978, 1982, 1982, 1993, and 1995. We did not evaluate all of the above years for an appropriate rate of recession or inundation period of the seedbed, only that seedbeds were inundated at least once during the seed release period in these years. We are not confident in our ability to correlate recruitment to these exact years using increment core data from this study. However, the recruitment periods in Figure 7 roughly coincide with the years above at a frequency of at least once per decade. Again, a comparison to the frequency of stand recruitment under pre-regulated conditions is needed.

In summary, it does appear that recruitment correlates with recent, large flood events. Although recent recruitment is currently dominated by willows, cottonwoods do occur in bands which are often limited to one or two stem widths. Box model conditions, and perhaps soil moisture, are most conducive to recruitment at the downstream ends of point bars. Without further comparison to stands developed under pre-regulated hydrology, it is difficult to determine if this level of recruitment represent some limitation within the system compared to pre-Shasta hydrology. Regardless of regulation of flow by Shasta Dam, tributary inputs may be responsible for producing the large floods now required and may be important for recruitment in the future. Recruitment appears additionally limited at sites where bank protection, and perhaps levees, are in close proximity to point bars but the degree of this limitation is not fully understood.

A number of water planning efforts are currently considering further regulation of flows, specifically in the spring run-off season. It is possible further regulation could reduce the large exceptional flood events that recruitment appears to now depend upon. It is no longer apparent that recruitment is limited, because of the frequency of these recent large floods. However, managers of the riparian resources of the Sacramento River cannot depend upon the continued frequent occurrence of these large floods to produce a viable riparian forest. Therefore, the information in this report may be used as a baseline against which future management actions may be viewed. In addition, the Department of Water Resources is continuing to monitor seedling success. This monitoring has shown that as of August, the spring 2003 cohort appears to be failing despite partially favorable hydrology. This is discussed in more detail later in this report. Should continued monitoring indicate a lack of forest regeneration, the strategy outlined below may be used to recruit new forest.

### *Calculation of a recruitment flow application*

We used the updated information above to build upon results from the earlier study and develop a strategy for river management that promotes forest recruitment. Changes from the previous study include new rating curves, a newly defined range of elevation, and recent information on timing of seed release. In this analysis, we use a timing of late April (Figure 17), as opposed to mid-April based on information reported by Peterson (2000).

We compared three strategies, which require different amounts of water and represent testable hypotheses regarding different degrees of cottonwood survival (Figure 18). A minimal water use strategy (strategy 1) uses the lower range of recruitment elevation, and a recession rate of 1.3 inches per day. This strategy would likely result in a reduced chance of seedling survival. A maximum water use strategy (strategy 2) is initiated at the top of the elevation range, uses a recession rate of 1 inch per day. This would likely result in the highest degree of cottonwood survival. A compromise between water use and cottonwood survival is likely in between these two strategies. Therefore, we developed a third strategy to create a balance between multiple goals. This strategy is initiated at the top of the elevation range, uses a stepped recession of 2 inches per day, but plateaus at each elevation for 3 days. Kalischuk et.al. (2000) identify a recession rate of 1.9 in/day as stressful yet not lethal to cottonwoods on the Castle River. We hypothesize that soil moisture may be available for seedlings to withstand this higher rate of recession on the Sacramento River until roots systems reach each elevation plateau (Figure 18). The timing of this strategy also takes advantage of water volume available from a storm event in mid-May in order to maximize water savings. All three strategies are continued until the elevation of common summer discharge is reached.

We evaluated each strategy relative to different types of water years by using actual spring-time flow volumes from 1995 to represent a wet year and actual spring-time flow volumes from 2000 to represent a normal water year. These designations do not represent any other classification of water year types (e.g. DWR). Figure 18 includes a table of water volumes associated with each strategy. Water volume requirements vary widely with each strategy yet it is clear that managers would not seek to implement a cottonwood recruitment flow in dry or normal water years. This could require up to a 60% increase in water volume needs (strategy 2). Instead, recruitment flows should be implemented during naturally wet years to increase the likelihood that water is available to meet ecological needs. Implementing the most water conservative strategy could actually represent a 37% reduction in water volume when compared to the actual 1995 spring-time flow regime. Strategy 3, which seeks to balance the multiple goals of acceptable seedling survival and reasonable water use, represents a 23% reduction in water volume compared to a wet year. Implementing these strategies does not represent massive new demands on an already scarce resource.

From the comparisons above, it is clear that a managed recruitment flow may be most successful at meeting multiple demands when implemented during favorable conditions. Most recently, the spring 2003 flow regime provides an example where the appropriate timing and magnitude of flows to promote seedling root growth were narrowly missed. The spring 2003 conditions included a relatively rare late spring peak that coincided with seed release in late April and early May, however the rate of recession was rapid. Recent monitoring conducted by DWR staff indicates that seedlings did germinate and begin to grow in an elevation range roughly 2-4 feet above MLW. They noted seedlings at a slightly higher elevation range at the RM 172 site that grew to a height of 6 inches to a foot (Figure 5). However, as of August 2003 these seedlings along with seedlings at the other study site were desiccating, suggesting that the 2003 springtime rate of recession was too rapid.

We evaluated altering the characteristics of the spring 2003 flow regime to produce riparian forest. We compared the shape of the spring recession between Shasta inflow and that of strategy 3 (Figure 19A), and the shape of the recession of Shasta outflow and that of the RM 183 study site (Figure 19B). The first comparison represents the altered flow regime under current regulation. The second comparison represents the un-altered flow regime. Although the magnitudes of the flow volumes differ due to tributary input, the shapes of the recession limbs are very similar in both comparisons. Figure 20A shows that the regulated recession rate crosses through the recruitment zone in approximately 5 days. The un-altered flow volume in Figure 20B is not of sufficient magnitude because downstream tributary input is not included. However, the un-altered recession rate takes weeks to move through the recruitment zone.

The similarity in the shape between Shasta outflow and the altered regime of the study site suggests that conditions at the study sites are governed, in part, by upstream management decisions. In contrast, the shape of the hypothetical recruitment flow is very similar to the actual unregulated inflow pattern at Shasta. The total volume of water to implement this flow in the month of May was essentially the same, actually 2% less, as the volume that passed the study site.

The information above demonstrates that the change in conditions needed for a recruitment application is not so much a change in volume as it is a change in timing of water delivery, or the shape of the spring hydrograph. If the information from this report was integrated into the water management decision making process, perhaps a recruitment flow could have been implemented in the spring of 2003 and placed no new demand on the water supply system. Successful recruitment of a new cohort of riparian forest in the spring of 2003 would have resulted in roughly a one in ten year frequency because seven years have transpired since the last documented recruitment event.

The current water supply infrastructure does not appear to be a limiting factor in the implementation of this process-based conservation strategy. Although new infrastructure may assist in meeting other ecological goals, theoretically there was already enough water in the system to implement a riparian forest recruitment strategy without the creation of new infrastructure. Flexibility in the management decision making process needs to be evaluated for the potential to alter only the timing of water delivery, not the volume.

Much work and collaboration is needed to solve the challenges of supply, storage, and conveyance on a parallel track while evaluating potential ecological benefits. Managing the spring time recession limb of the hydrogrpah is a significant challenge. Numerous demands are already placed on the supply and conveyance system. Water management during this period is also driven by regulatory actions for listed species. Examples include management of the “cold water pool” in Shasta to meet salmonid water temperature requirements, and curtailing of pumping in the Delta due to concern over entrainment of Delta smelt into pumping facilities.

Perhaps re-regulating the spring time recession period, and other ecologically important components of the flow regime, to within more natural ranges of variation could serve multiple species needs. Ecological synergies may become apparent with more investigation into riverine organisms’ life history needs. Riparian forest, salmonids, Sacramento River split tail, Delta smelt, and other species may benefit by “utilizing” the same spring time ecological flow event. Meeting as many species’ life history needs prior to their listing may prove a more effective approach than continued species listings and further regulation impacting management decisions. In addition, it may be more effective to attempt these types of approaches under an adaptive management framework prior to additional regulation placed on the system due to species declines. This regulation itself may hindered the adaptive management process.

Restoration through managed flows is a complimentary conservation strategy to cultivated planting techniques. The two strategies ensure that both the short and long timescale are considering when managing for biodiversity. Cultivated restoration will remain an appropriate tool during the next few decades because it addresses the ecosystem stressors of habitat fragmentation, provides habitat documented to host species of concern, and provides options for willing sellers of floodprone agriculture land. . Fortunately, we are now at a phase in cultivated restoration of the Sacramento River ecosystem where additional species and processes are used as indicators of success in addition to a decade of research documenting benefits to neo-tropical migrants. We now have an indication of the beneficial affects of cultivated restoration techniques on bats, terrestrial invertabrates, and soil formation processes. We also have a draft framework within which to combine and monitor these ecosystem indicators (See http://www.sacramentoriverportal.org/reports/index.htm to download copies of reports covering the topics above.) Pending funding, many additional avenues of research are planned for evaluation and refinement of cultivated restoration techniques.

This study, and others like it, represents the beginning of a new phase of process-based river restoration. In this approach, conservation partners and research collaborators seek to understand the underlying processes governing the system. Similar work is being conducted on many other rivers, not only in California but internationally as well. This growing body of science suggests that this approach offers ecosystem-wide and longer term benefits (Postel and Richter, 2003). Most importantly, this new work is pushing beyond the minimum in-stream flow approaches. Minimum in-stream flows have formed the foundation of streamflow management for ecosystem benefit largely since the 1970's after the development and subsequent widespread application of tools like the Instream Flow Incremental Methodology (IFIM) and it's model sub-component (PHABSIM). An additional important characteristic of this new body of work is that it is conducted with the goal of balancing river management for both the services that rivers provide to society and the ecosystems they support. This approach has also provided the foundation of this report.

## Conclusions

New information from this report better informs the first pilot study investigating riparian forest regeneration of the Sacramento River. Data from additional study sites indicates that the elevation of the recruitment box is still slightly higher on the Sacramento River yet not as high as previously suggested. Based on this study, the appropriate elevation for cottonwood recruitment on the Sacramento River is 3-6 feet above mean low water.

Increment core data was not accurate enough to identify the recruitment years in this study due to very large diameter stems. However, additional data from this study do indicate that recruitment appears to occur roughly once every ten years, at least under regulated hydrologic conditions. Recruitment documented in this study includes cohorts that likely resulted from the recent large flood events of 1983-1986, and 1995-1997. Larger and less frequent floods than those typically described in the literature may now be required to generate recruitment. A comparison with stands that recruited in the pre-regulation period is still needed to evaluate the spatial and temporal characteristics of recruitment under the current altered hydrology.

Similar to the original pilot study, this study also suggests that recruitment is further limited by bank protection. However, the specific mechanism and degree of this limitation is difficult to quantify.

Rood and Mahoney (2000) demonstrated that a managed flow strategy successfully recruited seedlings in 1995, 1996, and thereafter on the St. Mary River in Alberta, Canada. Our study found that a similar recruitment flow strategy may be implemented on the Sacramento River with no change in total water volume during conditions such as those of spring 2003. The decision-making process for river management needs to be evaluated to investigate whether situations such as these could be modified through management actions to mimic a recruitment flow.

Regulatory processes currently drive the inclusion of ecosystem parameters in the water management decision making process. A new body of literature is beginning to support a more ecosystem-wide approach that may create synergies among numerous ecosystem targets and preclude the need for future regulation. Additional work is needed to link species' life history traits and ecosystem process mechanisms to aspects of the flow regime. A better understanding of these linkages will provide the necessary information to balance the many demands on water.

## ACKNOWLEDGEMENTS

We thank CALFED for funding this work. We would also like to thank the many staff at the Northern District Office of the Department of Water Resources whose assistance made this study possible. We thank Shawn Pike for graciously providing access to the IHA analysis, and Adam Henderson for assistance with GIS and topographic data and his leadership of associated fieldwork supporting this study. We also thank Dr. Eric Larsen and Dr. Steve Greco of U.C. Davis. They graciously shared their data, and their work provides much of the larger scale foundations within which our study is couched. We thank our collaborators at CSU Chico and specifically Eric Ginney for his leadership and organization of field data collection at the RM 183 site. Stacy Cepello and his foresightful perspective on the river was invaluable to these efforts. We would also like to thank Dave Jukkola for taking the lead on field data collection at the RM 172 site and general data processing and analysis.

Lastly, we thank the many people who braved the Central Valley sun and poison oak to collect the data for this study. These include Dave Jukkola, Jose Luis Ojeda, Gildardo Punzo, Ignacio Arce, Eric Ginney, Megan Hudzik, Alison Groom, Jim West, Walter VanGroningen, Teresa Connor, John Elko, Sara Taddo, Tara Morgan, Jeff Jukkola, Mark Fuller, and Michele Cederborg

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