*Technical Memorandum*

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# SBFCA's Feather River West Levee Strengthening EIP Project

*Wind Setup and Wave Runup Analysis* *January 10, 2011*

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## Purpose

The levee design criteria for SBFCA's Feather River West Levee Strengthening EIP Project include setting the top of levee elevation. To determine this elevation, the freeboard requirements above the design surface water elevation must first be determined. The *Interim Levee Design Criteria for Urban and Urbanizing Areas in the Sacramento-San Joaquin Valley, Version 4*, DWR, 12/15/10 (ILDC) defines freeboard requirements as the greater of wind setup plus wave runup or 3 ft. The purpose of this study is to determine the values for wind setup and wave runup along the Feather River west levee.

## Study Methodology

The methodology for determining the wind setup and wave runup values for this study are based on the requirements of the ILDC. The wind setup and wave runup calculations are based on the potential wind speed, wind direction, fetch length, and water depth along the fetch. Guidance for developing these parameters is also given in the following USACE documents:

- *Coastal Engineering Manual*, EM 1110-2-1100 (CEM)
- *Shore Protection Manual* (SPM)
- *Process for the National Flood Insurance Program Levee System Evaluation*, EC 1110-2-6067

Note that no guidance is given for addressing the impact of downstream river flow on the wind setup and wave runup calculation due to upstream and/or downstream winds.

### *Wind Speed and Duration*

The ILDC defines the wind speed to be used as that which has a 50 percent probability of not being exceeded in any 50-year design period. This criterion yields a design wind speed with a return period of 72.6 years, or an annual probability of 0.0138. For this study, 27 years of hourly wind speed and direction data were analyzed from the California Irrigation Management Information System (CIMIS) Nicolaus #30 weather station – located just south of the Sutter-Butte basin. Prior to use in the wind setup and wave runup, the observed winds need to be standardized to a 10m observation level and corrected for increased overwater wind speed. The CEM procedures for adjusting observed winds were used to correct for the elevation of the CIMIS weather station from 4m using CEM Figure II-2-6. For fetch lengths less than 16km, the CEM recommends a factor of 1.2 to increase the wind speed for over water conditions.

The ILDC also states that the wind speed duration to be used in these calculations should be less than one-hour duration. The CEM notes that the wind duration that generates maximum wave runup is a function of the fetch length and the wind speed. When the fetch is limited, as in a river application, CEM Figure II-2-3 can be used to provide an equivalent duration for wave generation. For the fetch lengths analyzed in this study, the equivalent wind speed durations ranged from 60 to 90 minutes. To meet the requirements of the ILDC, a one-hour wind speed duration was selected for all conditions. This selection represents a conservative approach to the calculation of wind setup and wave runup.

### *Wind Direction and Fetch Length*

The fetch is defined as the region in which the wind speed and direction are reasonably constant. In river settings, the fetch is limited by surrounding landforms. Under these circumstances, the SPM recommends determining the fetch length by extending 9 radials from the point of interest at 3-degree intervals (centered on the maximum wind direction) until they intercept the opposite shoreline. The average of the 9 radial lengths represents the fetch length for a given wind direction.

### *Water Depth*

The water depth at the toe of the levee at the design surface water elevation is used in the calculation of wave runup. The average water depth across the entire fetch length is used in the calculation of wind setup. For the purposes of this study, it is assumed that the design surface water elevation is the median 200-year still water elevation.

## Wind Analysis

The wind data from the CIMIS Nicolaus #30 weather station is recorded as an hourly average wind speed with the prevailing wind direction in degrees. For this analysis, the wind speeds were separated into wind direction categories:

- North (337.5 to 22.5 degrees)
- Northeast (22.5 to 67.5 degrees)
- East (67.5 to 112.5 degrees)
- Southeast (112.5 to 157.5 degrees)
- South (157.5 to 202.5 degrees)
- Southwest (202.5 to 247.5 degrees)
- West (247.5 to 292.5 degrees)
- Northwest (292.5 to 337.5 degrees)

The wind speed data was then analyzed using HEC-SSP to perform a generalized frequency analysis to determine the 72.6-year return period wind speed for each wind direction. The resulting wind speeds represent the 72.6-year return period 60-minute wind speed at an elevation of 4m over land. For use in the wind setup and wave runup, these wind speeds must be corrected for an elevation of 10m over water. Table 1 presents the HEC-SSP output wind speed for each wind direction category along with the necessary elevation and over water corrections. Note that for the remainder of the wind setup and wave runup analysis, the wind speeds presented in the "corrected for over water wind speed" will be used.

**Table 1. 60-minute Wind Speed by Wind direction**

| Wind Direction | 72.6-year Return Period, 60-minute Wind Speed (mph) | | |
|---|---|---|---|
| | Observed at CIMIS Weather Station | Corrected for 10m Elevation | Corrected for Over Water Wind Speed |
| North | 26 | 29 | 35 |
| Northeast | 17 | 19 | 23 |
| East | 16 | 18 | 21 |
| Southeast | 37 | 41 | 49 |
| South | 35 | 39 | 47 |
| Southwest | 19 | 21 | 25 |
| West | 20 | 22 | 27 |
| Northwest | 26 | 29 | 35 |

# Fetch Length Determination

Figure 1 presents the water surface profile for the median 200-year stage along the Feather River. Due to the configuration of the river, the wind setup and wave runup calculations will vary for each segment of the west levee. The majority of the Feather River west levee is susceptible to wind generated wave action from the east. There are also several segments where wind from the northeast and southeast will generate waves perpendicular to the west levee. There are even fewer segments where wind from the north, south, or southwest will generate waves that are, at best, 45 degrees angles into the west levee. There are no segments where wind from the west or northwest will generate waves that will impact the west levee.

In the calculation of wind setup and wave runup, a longer fetch results in greater values. To evaluate the worst case wind setup and wave runup values, the longest fetch for each of the 8 wind directions was determined. Table 2 presents a summary of the worst case fetch length for each wind direction. The wave approach angle also impacts the calculation of wave runup – with perpendicular wave generating the greatest wave runup. In addition, Table 2 presents the wind direction relative to the Feather River flow. While there is no guidance for calculating a reduction in wind setup and wave runup, the effect of river flow on upstream wind should reduce the values of wind setup and wave runup.

**Table 2. Fetch Length Determination by Wind Direction**

| Wind Direction[1] | Location (Levee Station) | Fetch Length (ft) | Wave Approach Angle[2] (degrees) | Wind Direction Relative to River Flow |
|---|---|---|---|---|
| North | 2700+00 | 10,000 | > 45 | Downstream |
| Northeast | 4415+00 | 25,000 | 0 | Downstream |
| East | 3930+00 | 10,000 | 0 | -- |
| Southeast | 4150+00 | 25,000 | 0 | Upstream |
| South | 4220+00 | 30,000 | > 45 | Upstream |
| Southwest | 2170+00 | 30,000 | > 45 | Upstream |
| West | -- | 0 | -- | -- |
| Northwest | -- | 0 | -- | -- |

Notes:
(1) Wind direction represents the direction the wind is coming from (e.g. North wind direction represents wind out of the north)
(2) Wave approach angle equals zero for wave perpendicular to the levee.

## Wind Setup

When wind blows over water it exerts a shear stress on the water surface. Although the wind shear stress is usually very small, its effect, when integrated over a large body of water, can result in an increase of water level at the leeward end. This effect is called wind setup. Wind setup can be estimated for small bodies of water based on Equation 15-1, USACE *Hydrologic Engineering Requirements for Reservoirs* (EM 1110-2-1420):

$$S = \frac{U^2 F}{1400d}$$

Where S = wind setup (ft)
U = average wind speed (mph)
F = fetch distance (miles)
d = average water depth along the fetch line (ft)

This equation is known as the Zeider Zee equation. More recent studies show that for shallow water (< 16 ft deep) the value from the equation above should be averaged with the Sibul equation below (*Design Criteria Memorandum 2*, USACE/South Florida Water Management District, 2006).

$$S = d * 2.44 * 10^{-5} * \left(\frac{F}{d}\right)^{1.66} * \left(\frac{U^2}{F*g}\right)^{\left(2.02*\left(\frac{F}{d}\right)^{-0.0768}\right)}$$

Where S = wind setup (ft)
d = average water depth along the fetch line (ft)
F = fetch distance (ft)
U = average wind speed (ft/sec)
g = gravitational constant = 32.2 ft/sec

The average water depth along the fetch line was estimated using the ground surface profile along the fetch line in conjunction with the HEC-RAS median 200-yr water surface elevation. Table 3 presents the estimated average water depth and the calculated wind setup height for each worst case wind direction. Note that the greatest wind setup values are generated from the south and southeast wind directions – the directions with the greatest wind speed and the longest fetch.

**Table 3. Wind Setup Height**

| Wind Direction | Average Water Depth (ft) | Zeider Zee Wind Setup (ft) | Sibul Wind Setup (ft) | Average Wind Setup (ft) |
|---|---|---|---|---|
| North | 12 | 0.1 | 0.1 | 0.1 |
| Northeast | 13 | 0.1 | 0.0 | 0.1 |
| East | 10 | 0.1 | 0.0 | 0.1 |
| Southeast | 12 | 0.7 | 0.3 | 0.5 |
| South | 13 | 0.7 | 0.3 | 0.5 |
| Southwest | 14 | 0.2 | 0.1 | 0.1 |
| West | -- | -- | -- | -- |
| Northwest | -- | -- | -- | -- |

## Wave Runup

Wave runup is defined as the vertical height above the stillwater level to which an incident wave will run up the bank of the levee. The wave runup depends primarily on the levee bank slope, the water depth at the levee toe, fetch length, wind speed, and wave approach angle. One method to determine wave runup determines the 2% wave runup elevation, which represents the elevation above the still water level that is exceeded by only 2% of the waves. Before the wave runup can be calculated, the wave characteristics must be determined – specifically the significant wave height and the peak wave period. These two parameters were determined using CEM Equation II-2-36:

$$\frac{g*H_{mo}}{u_f^2} = 0.0413 * \left(\frac{g*X}{u_f^2}\right)^{\frac{1}{2}} \quad \text{and} \quad \frac{g*T_p}{u_f^2} = 0.751 * \left(\frac{g*X}{u_f^2}\right)^{\frac{1}{3}}$$

Where:
- $H_{mo}$ = significant wave height (ft)
- $T_p$ = peak wave period (sec)
- $X$ = fetch length (ft)
- $g$ = gravitational constant = 32.2 ft/sec
- $u_f$ = friction velocity (ft/sec) $= (C_D * U_{10}^2)^{\frac{1}{2}}$
- $C_D$ = drag coefficient $= 0.0002 * (1.1 + 0.035 * U_{10})$
- $U_{10}$ = wind speed at 10m elevation (ft/sec)

Wave runup on a structure depends on the type of wave breaking. Wave breaker types are identified by their surf similarity parameter. With the wave characteristics defined, $H_{mo}$ and $T_p$ can be used to determine the surf similarity parameter per CEM Equation VI-5-2:

$$\varepsilon_p = \frac{\tan(\alpha)}{\sqrt{\frac{2\pi * H_{mo}}{g * T_p^2}}}$$

Where: $\varepsilon_p$ = surf similarity parameter
$\tan(\alpha)$ = waterside slope of levee (assumed 1V:3H for all wind direction conditions)

Now that the wave and wave breaking characteristics have been defined, the 2% wave runup elevation can be calculated per CEM Equation VI-5-3:

$$R_{2\%} = H_{mo} * \left(A * \varepsilon_p + C\right) * \gamma_r * \gamma_b * \gamma_h * \gamma_\beta$$

Where: $R_{2\%}$ = 2% wave runup elevation (ft)
A,C = coefficients dependent on $\varepsilon_p$ ($\varepsilon_p < 2$, A = 1.6, C = 0 for all wind direction conditions in this study per CEM Table VI-5-2)
$\gamma_r$ = reduction factor for levee slope roughness (assumed $\gamma_r = 0.9$ for 3 cm grass slopes per CEM Table VI-5-3)
$\gamma_b$ = reduction factor for influence of a berm (assumed non-bermed fetch, $\gamma_b = 1$)
$\gamma_h$ = reduction factor for influence of shallow waves (assumed no shallow wave influence, $\gamma_h = 1$)
$\gamma_\beta$ = reduction factor for influence of angle of incidence, $\beta$, of the waves on the levee
$= 1 - 0.0022 * \beta$

## Wave Runup Reduction Due to Vegetation

The Three Rivers Levee Improvement Authority *Feather River Setback Levee Design Report* (January 2008) addresses the presence of trees and thick brush growing along parts of the Feather River floodplain. Figure 2 shows that similar vegetation is present in the worst case wave runup levee segments subject to wind from the south and southeast. Vegetation in the vicinity of the levee hinders wind-wave formation because it shelters the water surface from the wind. More importantly, this vegetation impedes wave travel and dissipates wave energy. These effects should result in a smaller-than-calculated wave runup on the levee and a correction factor should be applied. However, there is no theoretical guidance in the literature to account for this factor, but recent project studies in the Sacramento River watershed have made empirical corrections to account for this effect:

- The USACE Sacramento District (Natomas General Re-Evaluation Report Wave Runup Analysis, Draft Revised May 2006) estimated vegetation correction factors based on field inspection at various points of analysis. Factors ranged from 1.0 (no vegetation) to 0.2 for areas where the vegetation on the levee was so dense that wave action will have little effect. The report presented 17 different correction factors with an average reduction factor of 0.66.

- Mead & Hunt (SAFCA Wind Setup and Wave Runup Analysis for Natomas Levee Improvement Program, May 2007) performed a visual evaluation of aerial images of the levees and classified vegetative cover into three categories – none, normal, and high – and assigned corresponding reduction factors of 1.0, 0.75, and 0.6.
- GEI Consultants performed field observations of wind-wave action along the Feather River and Bear River levee during a high-water event in early January 2006. The average wind speed over the water was estimated at 35 mph from the southeast and the observed wave runup was less than 1 ft. The calculated wave runup was about 2 ft, so a 0.5 correction factor was applied as part of the TRLIA Feather River Setback Levee project.

Based on these three studies, an average vegetative factor of 0.67 will be used in this study.

Table 4 presents a summary of the 2% wave runup heights (both calculated and with vegetative correction) for each wind direction.

**Table 4. Wave Runup Height**

| Wind Direction | Calculated 2% Wave Runup Height (ft) | 2% Wave Runup Height with Vegetative Correction (ft) |
|---|---|---|
| North | 1.4 | 0.9 |
| Northeast | 1.6 | 1.1 |
| East | 1.0 | 0.7 |
| Southeast | 3.3 | 2.2 |
| South | 3.2 | 2.1 |
| Southwest | 1.7 | 1.1 |
| West | -- | -- |
| Northwest | -- | -- |

## Conclusions

Table 5 presents the combined increase in stillwater elevation due to wind setup and wave runup for each of the worst case wind direction conditions. Note that in all cases, the impact of wind setup and wave runup is less than 3 ft. It should also be noted that in the areas with the greatest exposure from south and southwest wind, the top of levee is about 6 ft above the median 200-year water surface elevation.

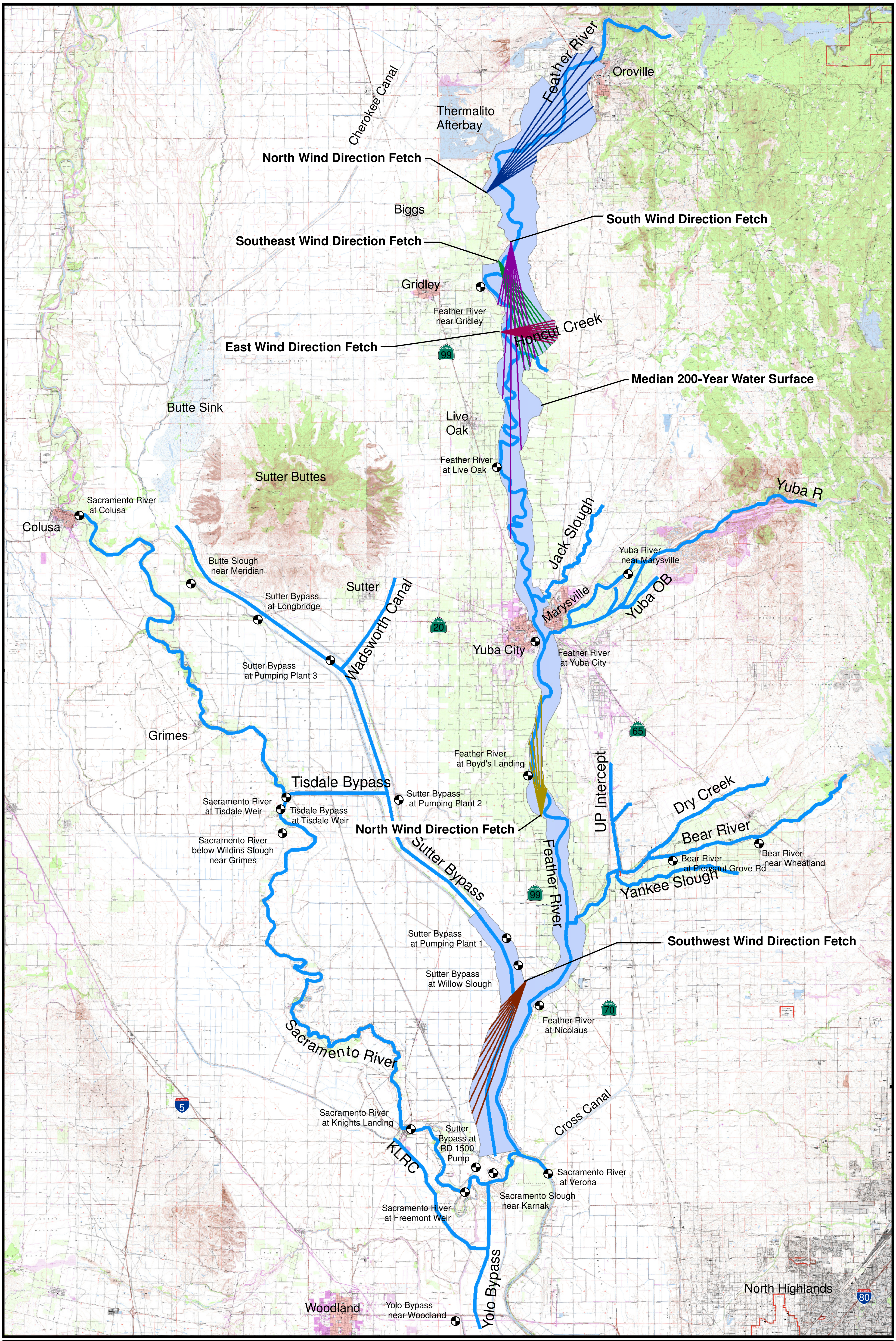
**Table 5. Combined Wind Setup and Wave Runup Heights**

| Wind Direction | Average Wind Setup (ft) | 2% Wave Runup Elevation with Vegetative Correction (ft) | Combined Wind Setup and Wave Runup Elevation Increase (ft) |
|---|---|---|---|
| North | 0.1 | 0.9 | 1.0 |
| Northeast | 0.1 | 1.1 | 1.2 |
| East | 0.1 | 0.7 | 0.8 |
| Southeast | 0.5 | 2.1 | 2.7(1) |

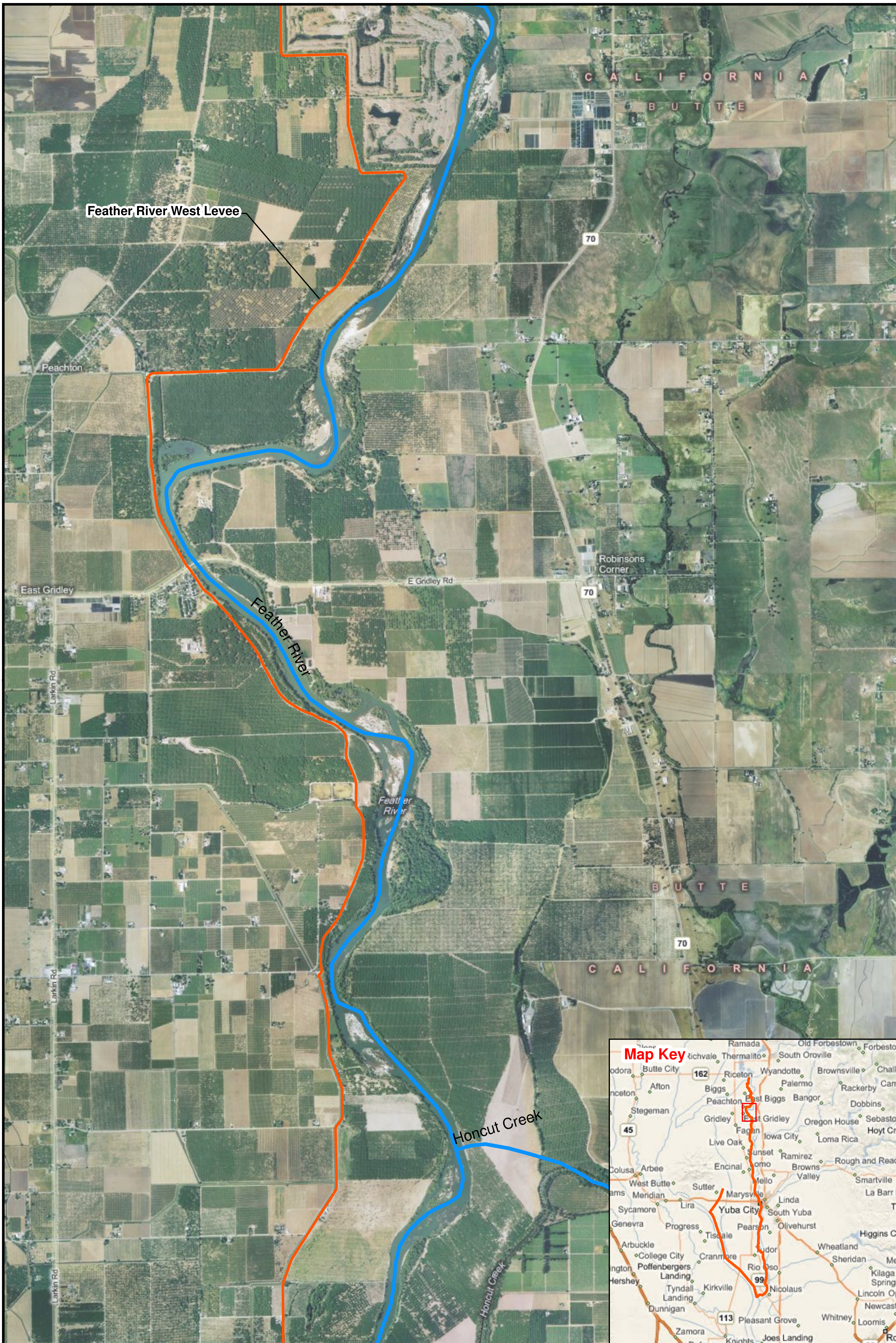
| Wind Direction | Average Wind Setup (ft) | 2% Wave Runup Elevation with Vegetative Correction (ft) | Combined Wind Setup and Wave Runup Elevation Increase (ft) |
|---|---|---|---|
| South | 0.5 | 2.1 | 2.6[1] |
| Southwest | 0.1 | 1.1 | 1.2[1] |
| West | -- | -- | -- |
| Northwest | -- | -- | -- |

Notes:
[1] Note that these cases are for upstream traveling waves. No reduction factor has been applied to address this situation.

Based on these results, the ILDC freeboard requirement is 3 ft.




| N | 0 1.25 2.5 5 Miles<br>JANUARY 2011 | PETERSON . BRUSTAD . INC<br>ENGINEERING . CONSULTING<br>1180 Iron Point Rd., Suite 260<br>Folsom, CA 95630<br>Phone: (916) 608-2212<br>Fax: (916) 608-2232 | SUTTER BUTTE FLOOD CONTROL AGENCY<br>FEATHER RIVER WEST LEVEE WORST CASE FETCH LENGTH | FIGURE<br>1 |
|---|---|---|---|---|




| | | | | |
|---|---|---|---|---|
| N | 0 0.15 0.3 0.6 Miles<br>JANUARY 2011 | PETERSON . BRUSTAD . INC<br>ENGINEERING . CONSULTING<br>1180 Iron Point Rd., Suite 260<br>Folsom, CA 95630<br>Phone: (916) 608-2212<br>Fax: (916) 608-2232 | SUTTER BUTTE FLOOD CONTROL AGENCY<br>TYPICAL VEGITATION WITHIN THE FEATHER RIVER FLOODPLAIN | FIGURE<br>2 |