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TECHNICAL MEMORANDUM

ULDC Analysis of the RD 17 Levee
Wind Setup and Wave Runup Calculations

Prepared for: City of Lathrop & City of Manteca *December 21, 2015*

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Reviewed by: Mike Rossiter, PE and Dave Peterson, PE

Purpose

The *Urban Levee Design Criteria* (ULDC) defines minimum top of levee (MTOL) requirements as the median 200-year water surface elevation (WSEL) plus the higher of (a) 3 feet, or (b) height for wind setup and wave runup. This Technical Memorandum (TM) presents the analysis used to determine the height for wind setup and wave runup along the RD17 levee system.

Study Methodology

The methodology for determining the wind setup and wave runup values for this study follow the requirements presented in the ULDC. The wind setup and wave runup calculations are based on the potential wind speed, wind direction, fetch length, and water depth along the fetch line. Guidance for developing these parameters is 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 ULDC defines the wind speed to be used as that which has a 50 percent non-exceedance probability in any year during a 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, 57 years of hourly wind speed data were analyzed from the shared National Oceanic and Atmospheric Administration (NOAA) and Western Regional Climate Center (WCRR) weather station at the Stockton Metropolitan Airport[1]. Prior to use in the wind setup and wave runup calculations, the computed design wind speed was standardized to a 10-meter observation level using the CEM 1/7 rule (CEM Equation II-2-9). For fetch lengths less than 16km, the CEM recommends a factor of 1.2 to increase the wind speed for over water conditions.

The ULDC 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 ULDC, 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. In dryland settings, the fetch is limited by the extent of the floodplain (a 200-year floodplain will be used for this study). Under these circumstances the fetch length will be determined by extending 9 radials from the point of interest at 3-degree intervals until they intercept the edge of the floodplain. 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. Hydraulic modeling results[2] were used to determine average depths along the fetch lines.

Wind Analysis

The wind data from the Stockton Metropolitan Airport 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)

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[1] Period of Record from 1948 - 2014. No data was available from 1955 to 1962, but the remaining 57 years of data was available.

[2] *200-year Freeboard Analysis & Floodplain Mapping within RD17.* Prepared for Cities of Lathrop and Manteca, May 23, 2014.

- 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 7.9m over land. For use in the wind setup and wave runup calculations, 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" column will be used.

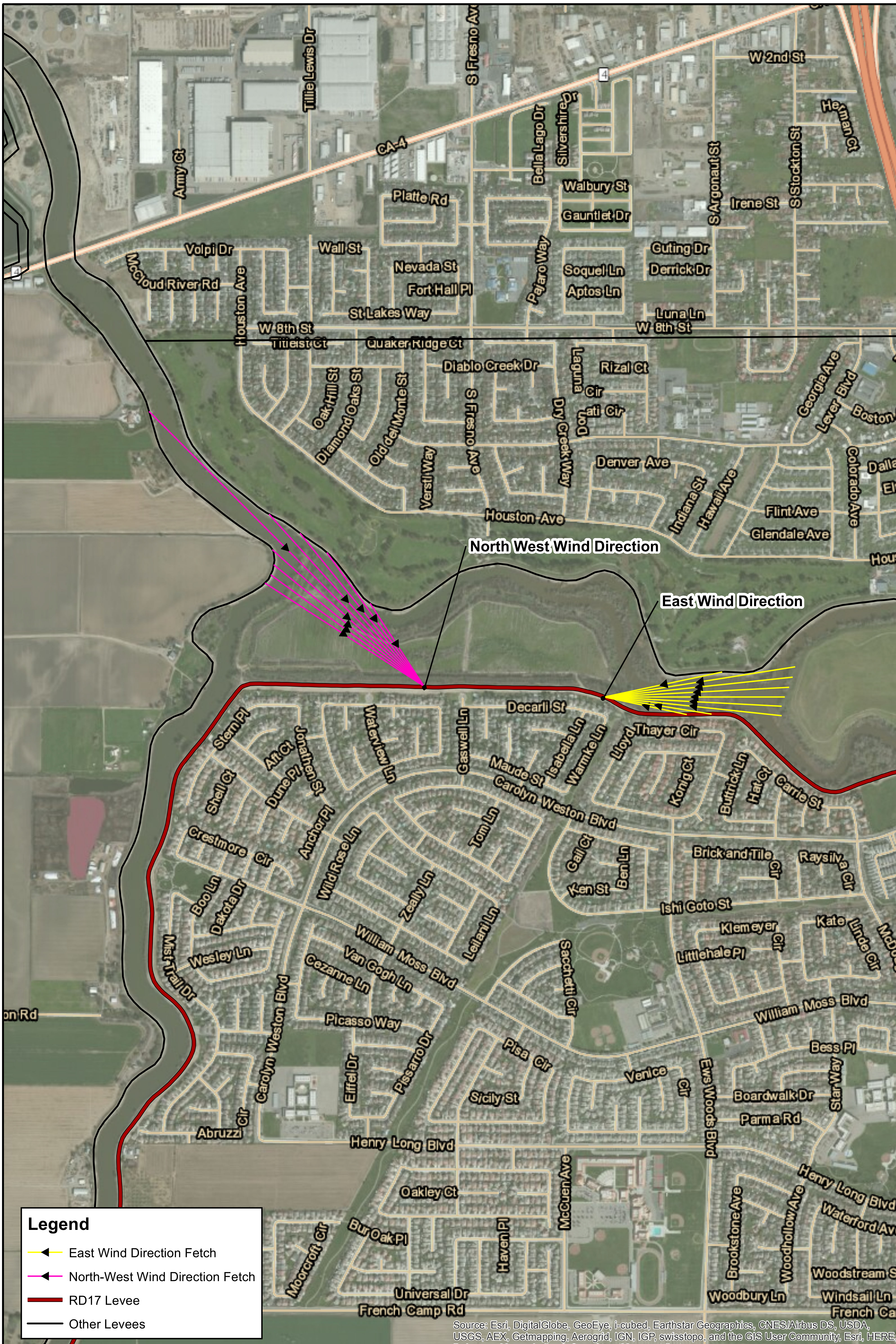
Table 1. Design wind speed for each wind direction

Wind Direction	72.6-year Return Period, 60-minute Wind Speed (mph)		
	Observed at Stockton Metropolitan Airport Weather Station	Corrected for 10m Elevation	Corrected for Over Water Wind Speed
North	47	49	58
Northeast	26	27	32
East	34	35	42
Southeast	47	49	58
South	51	53	63
Southwest	37	38	46
West	39	40	48
Northwest	44	46	55

Fetch Length Determination

Figures 1 and 2 present the fetch lengths for each wind direction along the riverine segment of the RD17 levee. Due to the narrow corridor between the left and right banks of the San Joaquin River, the fetch lengths were minimal.

Figure 3 presents the south wind direction fetch lines that are the worst case wind scenarios for the RD 17 dryland levee. Three different analysis points were selected along the dryland levee. An additional fetch length was analyzed at the edge of the floodplain, approximately 3,000 feet east of the RD17 dryland levee. The south wind is the controlling wind for the dryland segment of the levee as it has the highest wind speeds, the longest fetch lengths, and the most direct wave angle approach.



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N

0 1,000 Feet

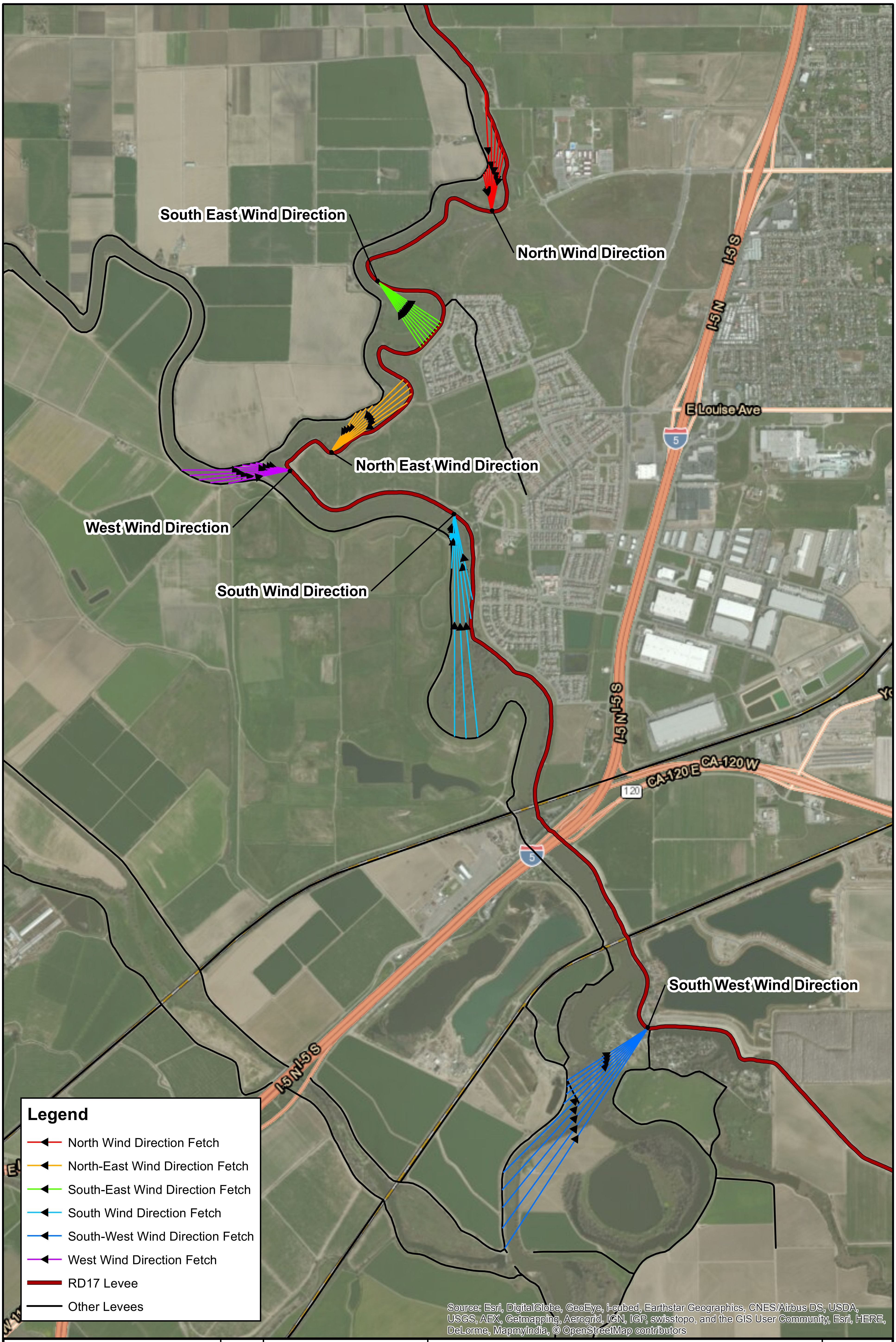
1 in = 1,250 ft

DECEMBER 2, 2014

CITY OF LATHROP/MANTECA - 200YR PLAN

RD 17 LEVEE
WORST CASE FETCH LENGTHS

FIGURE
1



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N

0 2,000 Feet
1 in = 2,500 ft

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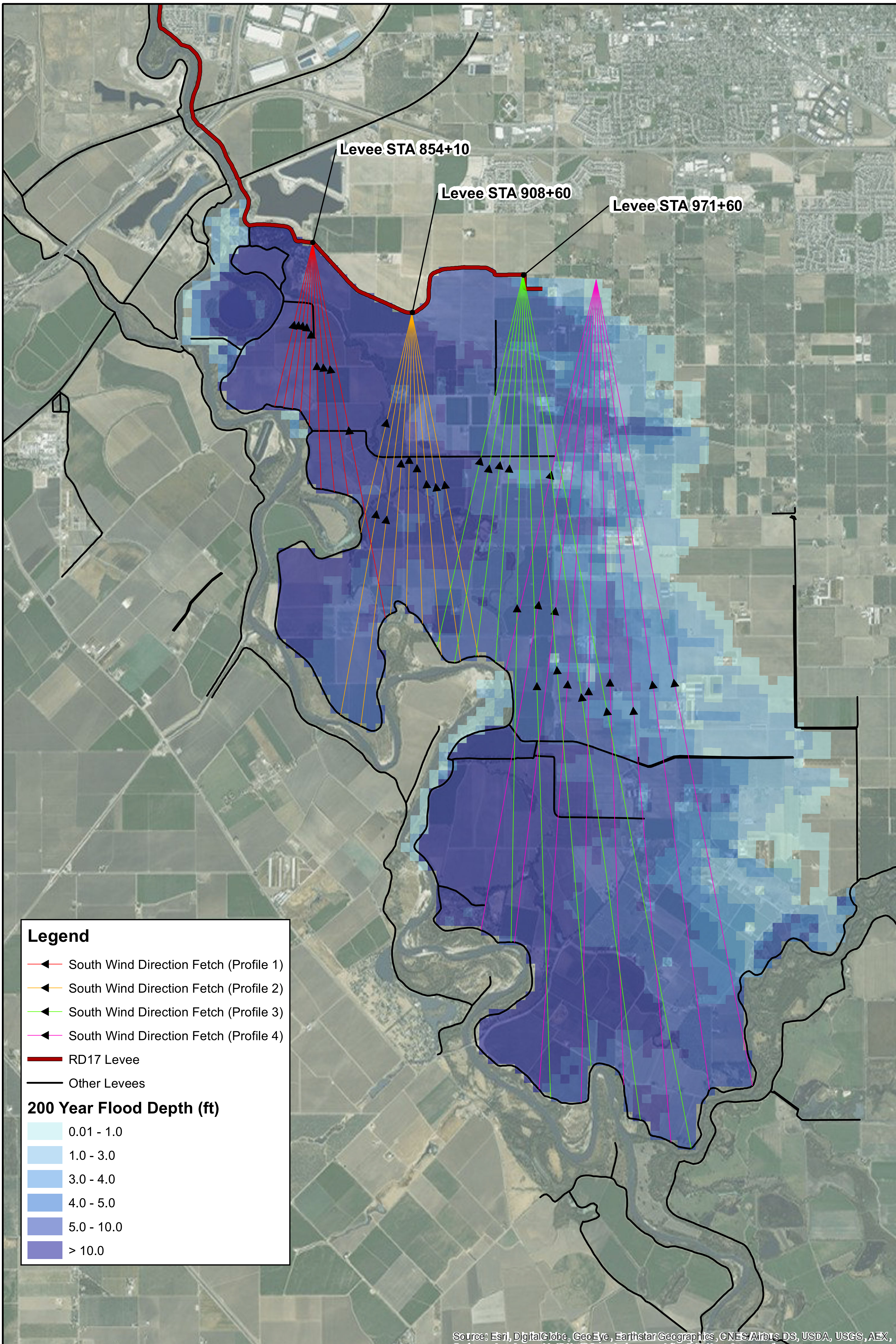
RD 17 LEVEE
WORST CASE FETCH LENGTHS

FIGURE
2



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N

0 5,000 Feet

1 in = 5,000 ft

DECEMBER 4, 2015

CITY OF LATHROP/MANTECA - 200YR PLAN

RD 17 DRYLAND LEVEE FETCH LENGTHS

FIGURE 3

In the calculation of wind setup and wave runup, a longer fetch is one of the key factors that results in a greater wind/wave value. To evaluate the worst case wind setup and wave runup values, the location along the RD17 riverine levee that would yield 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 along the RD17 riverine levee. Table 3 presents a summary of the fetch lengths for the south wind direction for the RD 17 dryland levee.

The wave approach angle also impacts the calculation of wave runup – with waves that approach perpendicular to the levee generating the greatest wave runup.

Note that in the case of Profile 4 on the dryland levee, the placing of fill to create high ground is assumed in place of a dryland levee extension. Therefore, wave runup is not included as part of the analysis for Profile 4.

Note also that Table 2 presents the wind direction relative to the 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 wave runup.

Table 2. Fetch Length Determination by Wind Direction for the RD17 Riverine Levee

Wind Direction[(1)]	Worst Case Location (Approx. Levee STA)	Fetch Length (ft)	Wave Approach Angle[(2)] (degrees)	Wind Direction Relative to River Flow
Riverine Levee				
North	518+65	3,928	5	Upstream
Northeast	631+95	2,262	22	Upstream
East	61+05	2,183	70	Downstream
Southeast	558+35	2,119	78	Downstream
South	688+25	3,110	37	Downstream
Southwest	822+25	4,928	35	Downstream
West	646+15	1,964	42	Upstream
Northwest	80+95	2,860	45	Upstream

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.

Table 3. Fetch Length Determination by Wind Direction for the RD17 Dryland Levee

Wind Direction[1]	Location (Approx. Levee STA)	Fetch Length (ft)	Wave Approach Angle[2] (degrees)
Dryland Levee			
South	854+10	9,658	0
South	908+60	14,573	0
South	971+60	27,139	0
South	N/A[3]	32,442	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.
[3] Analysis point is approximately 3,000 feet east of the existing RD17 dryland levee and is in an area that will be re-graded to become high ground.

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 which is most appropriate for large reservoirs. For shallow water bodies, the Sibul equation below is more appropriate.

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

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

Recent USACE study suggested averaging the two equations when dealing with shallow impoundments (*Design Criteria Memorandum 2*, USACE/South Florida Water Management District, 2006).

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 for the riverine segments and the FLO-2D median 200-year flood depth for dryland segment. Table 4 presents the estimated average water depth and the calculated wind setup height for each worst case wind direction for the RD17 riverine levee. Table 5 presents the estimated average water depths and the calculated wind setup heights for the four analysis points along the RD17 dryland levee.

For average water depths greater than 16 feet, the calculated wind setup height was derived from the Zeider Zee equation only. Where average water depths were estimated to be less than 16 feet, the calculated wind setup height was taken by averaging the Zeider Zee equation and the Sibul equation.

In general, the greatest wind setup values are generated from the north and south wind directions which are the directions with the greatest wind speeds and the longest fetches.

Table 4. Wind Setup Height for the RD17 Riverine Levee

Wind Direction	Worst Case Location (Approx. Levee STA)	Average Water Depth (ft)	Zeider Zee Wind Setup (ft)	Sibul Wind Setup (ft)	Applied Wind Setup (ft)
Riverine Levee					
North	518+65	12	0.15	0.11	0.13
Northeast	631+95	14	0.02	0.01	0.02
East	61+05	8	0.07	0.05	0.06
Southeast	558+35	15	0.07	0.06	0.06
South	688+25	21	0.08	0.07	0.08
Southwest	822+25	18	0.08	0.05	0.08
West	646+15	24	0.03	0.02	0.03
Northwest	80+95	11	0.10	0.08	0.09

Table 5. Wind Setup Height for the RD17 Dryland Levee

Wind Direction	Location (Approx. Levee STA)	Average Water Depth (ft)	Zeider Zee Wind Setup (ft)	Sibul Wind Setup (ft)	Applied Wind Setup (ft)
Dryland Levee					
South	854+10	12	0.43	0.25	0.34
South	908+60	11	0.75	0.41	0.58
South	971+60	9	1.62	0.84	1.23
South	N/A(1)	7	2.41	1.26	1.83

Notes:
(1) Analysis point is approximately 3,000 feet east of the existing RD17 dryland levee and is in an area that will be re-graded to become high ground.

Wave Runup

Wave runup is defined as the vertical height above the still water 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:

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

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

After defining the wave and wave breaking characteristics, 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 ε_p ($\varepsilon_p < 2$, A = 1.6, C = 0 and ($2 < \varepsilon_p < 9$, A = -0.2, C = 4.5 per CEM Table VI-5-2)
- γ_r = reduction factor for levee slope roughness (assumed $\gamma_r = 0.9$ for 3 cm grass slopes along the riverine levee and 0.55 for 1 layer of rip rap along the dryland levee per CEM Table VI-5-3)
- γ_b = reduction factor for influence of a berm
- γ_h = reduction factor for influence of shallow waves
- γ_β = reduction factor for influence of angle of incidence, β, of the waves on the levee = $1 - 0.0022 * \beta$

Wave Runup Reduction Factors

Several factors can influence a wave as it travels along a fetch line and approaches a levee. Berms, shallow water environments, and vegetation can all serve to reduce wave runup. Reduction factors used to account for these influences are described in this section.

Wave Runup Reduction Due to Influence of a Berm

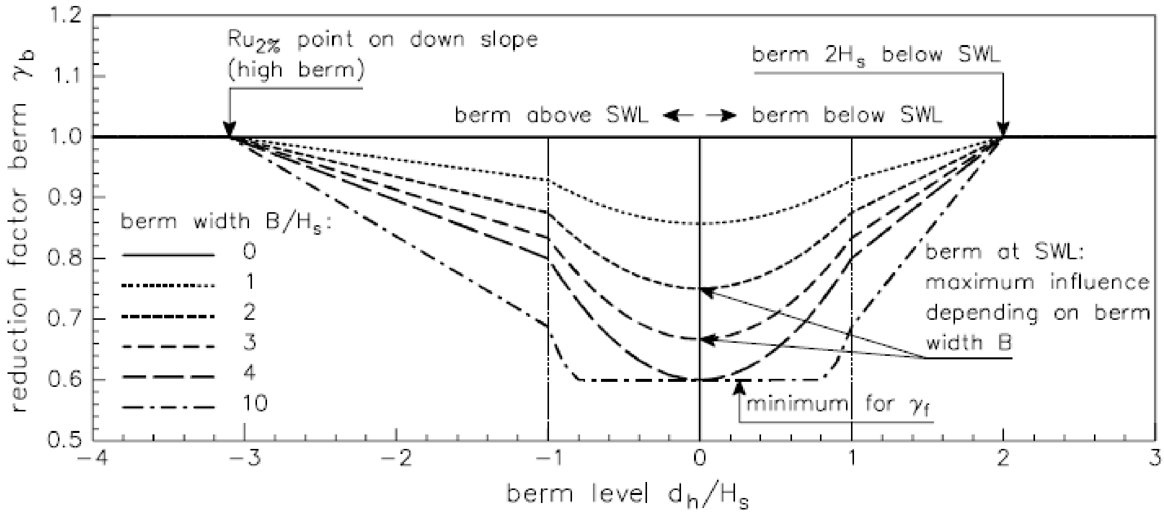
The berm reduction factor, γ_b, was determined based on CEM guidance and a reference chart from Chapter 8 of Van der Meer's analysis[3] (Figure 4).

The influence of a berm can be neglected when the berm horizontal surface is positioned more than $H_s\sqrt{2}$ below the still water level. As shown in Figure 4, the influence of a berm is dependent on the relative depth (d_h/H_s) and the berm width (B/H_s). The reduction factor is limited to a value of 0.6 and reaches its minimum value if the berm is at the still water level.

The berm reduction factor did not apply to the riverine segments, but only to the dryland levee analysis (Table 6). The berm reduction factor was applied only for berms near the waterside toe of the RD17 dryland levee. Major berms such as roadways, farm field borders, and other high ground were also identified throughout the floodplain, however due to their distance from the RD17 dryland levee, these types of berms were not incorporated into the calculations of the berm reduction factors. Spreadsheets for the berm reduction factor calculations are provided in Attachment A. Note that in the case of Profile 3, there is a berm in close proximity of the dryland levee between STA 959+00 and STA 972+00 that is significant enough to apply a reduction factor.

[3] *Wave run-up and overtopping. Chapter 8 in: "Seawalls, dikes and revetments."* Van der Meer, J.W. 1998.

Figure 4. The reduction factor γ_b for a bermed slope



*H_s and H_{mo} are used interchangeably for significant wave height

Table 6. Berm Reduction Factors for the RD17 Dryland Levee

Wind Direction	Location (Approx. Levee STA)	Berm Reduction Factor, γb
South	854+10	-
South	908+60	-
South	971+60	0.72
South	N/A(1)	-

Notes:
(1) Analysis point is approximately 3,000 feet east of the existing RD17 dryland levee and is in an area that will be re-graded to become high ground.

Wave Runup Reduction Due to Influence of Shallow Waves

The shallow wave reduction factor, γ_h, was determined based on guidance outlined in Van der Meer and Janssen's analysis[4]. The following equations are applicable for a foreshore slope that does not considerably deviate from 1:100:

$$\gamma_h = 1 - 0.03\left(4 - \frac{h_m}{H_s}\right)^2 \qquad \text{for} \qquad \frac{h_m}{H_s} < 4$$

$$\gamma_h = 1 \qquad \text{for} \qquad \frac{h_m}{H_s} \geq 4$$

[4] *Wave run-up and wave overtopping at dikes and revetments*. Van der Meer, J.W. and Janssen, J.P.F.M. 1994.

Water depth at the location of the toe of the structure (h_m) is used for representing the influence of a shallow foreshore. If water depth at the location of the toe is four times greater than the significant wave height, the influence of shallow waves can be neglected.

The shallow wave reduction factor did not apply to the riverine segments, but only to sections of the dryland levee (Table 7). Spreadsheets for the shallow wave reduction factor calculations are provided in Attachment B. Note that the shallow reduction factor applies along the edge of the floodplain where water depths are less than 5 feet at the toe of the dryland levee.

Table 7. Shallow Wave Reduction Factors for the RD17 Dryland Levee

Wind Direction	Location (Approx. Levee STA)	Shallow Wave Reduction Factor, γ_h
South	854+10	-
South	908+60	-
South	971+60	0.78
South	N/A(1)	0.52

Notes:
(1) Analysis point is approximately 3,000 feet east of the existing RD17 dryland levee and is in an area that will be re-graded to become high ground.

Wave Runup Reduction Due to Vegetation

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 vegetation:

- 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 and an aerial survey of vegetation cover along the presented fetch lines, an average vegetative factor of 0.67 will be used in this study.

Summary of Wave Runup Calculations with Reduction Factors

The following table provides a summary of wave runup calculations along with the reduction factors that were applied.

Table 8. Wave Runup Height

Wind Direction	Location (Approx. Levee STA)	Significant Wave Height (ft)	A	ε_p	C	Reduction Factor					Final 2% Wave Runup Height (ft)
						γ_r	γ_β	γ_b	γ_h	γ_{Veg}	
Riverine Levee											
North	518+65	1.12	-0.2	2.76	4.5	0.9	1.0	1.0	1.0	0.67	2.63
Northeast	631+95	0.39	1.6	1.36	0	0.9	1.0	1.0	1.0	0.67	0.48
East	61+05	0.54	1.6	1.83	0	0.9	0.8	1.0	1.0	0.67	0.80
Southeast	558+35	0.82	-0.2	2.62	4.5	0.9	0.8	1.0	1.0	0.67	1.63
South	688+25	1.11	-0.2	2.97	4.5	0.9	0.9	1.0	1.0	0.67	2.40
Southwest	822+25	0.91	1.6	2.15	0	0.9	0.9	1.0	1.0	0.67	1.73
West	646+15	0.61	1.6	2.11	0	0.9	0.9	1.0	1.0	0.67	1.13
Northwest	80+95	0.87	1.6	2.49	0	0.9	0.9	1.0	1.0	0.67	1.88
Dryland Levee											
South	854+10	1.96	-0.2	4.35	4.5	0.55	1.0	1.0	1.0	0.67	2.62
0.34	908+60	2.41	-0.2	4.50	4.5	0.55	1.0	1.0	1.0	0.67	3.19
0.58	971+60	3.28	-0.2	4.74	4.5	0.55	1.0	0.7	0.8	0.67	2.41
1.23	N/A(1)	3.59	-0.2	4.81	4.5	0.55	1.0	1.0	0.5	0.67	N/A

(1) Analysis point is approximately 3,000 feet east of the RD17 dryland levee.

Conclusions

Table 9 presents the combined wind setup and wave runup calculations for each of the worst case wind direction conditions for the RD17 riverine levee. Note that the impact of wind setup and wave runup is less than 3 feet in all riverine cases. Table 10 presents the combined wind setup and wave runup calculations for the four analysis points for the RD17 dryland levee.

Table 9. Combined Wind Setup and Wave Runup Heights for the RD17 Riverine Levee

Wind Direction	Location (Approx. Levee STA)	Calculated Wind Setup (ft)	2% Wave Runup with Correction Factors (ft)	Combined Wind Setup and Wave Runup (ft)
Riverine Levee				
North	518+65	0.13	2.63	2.8[(1)]
Northeast	631+95	0.02	0.48	0.5 [(1)]
East	61+05	0.06	0.80	0.9
Southeast	558+35	0.06	1.63	1.7
South	688+25	0.07	2.40	2.5
Southwest	822+25	0.06	1.73	1.8
West	646+15	0.02	1.13	1.2 [(1)]
Northwest	80+95	0.09	1.88	2.0[(1)]

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

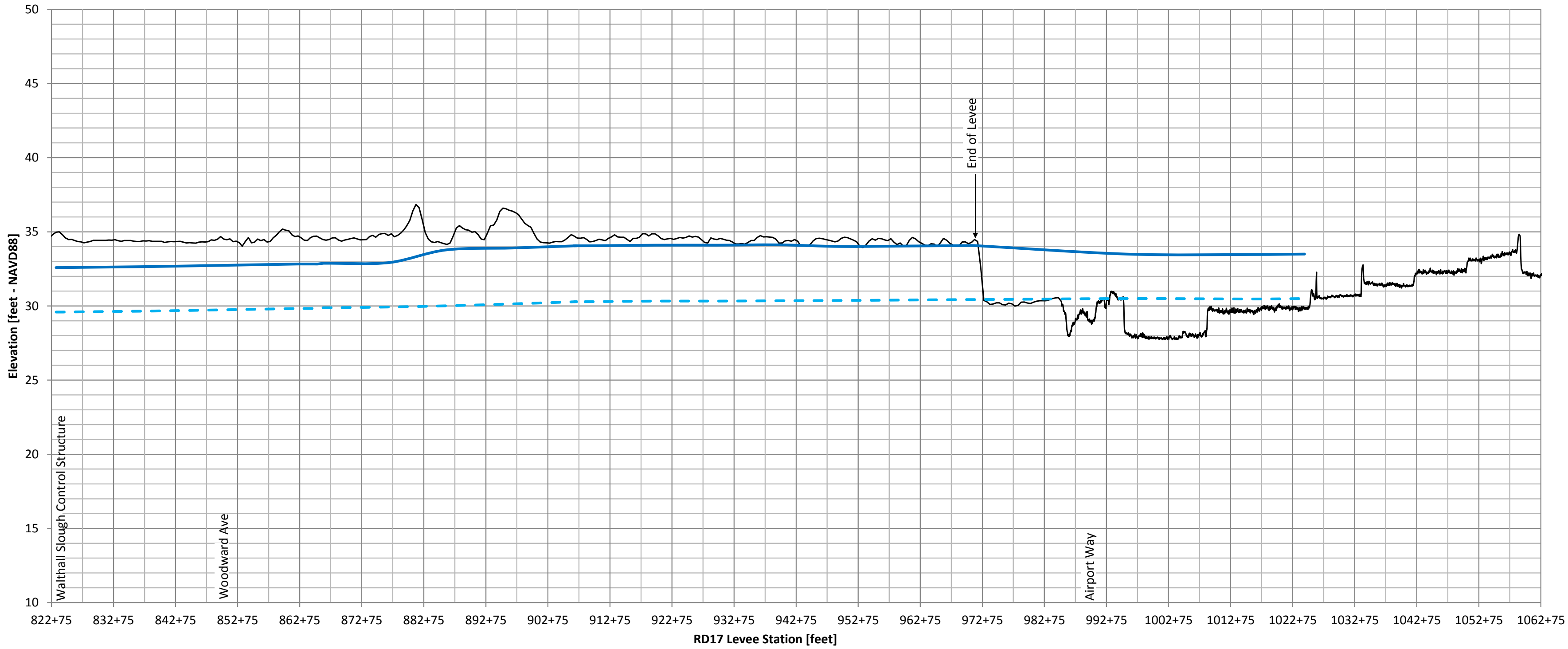
Table 10. Combined Wind Setup and Wave Runup Heights for the RD17 Dryland Levee

Wind Direction	Location (Approx. Levee STA)	Calculated Wind Setup (ft)	2% Wave Runup with Correction Factors (ft)	Combined Wind Setup and Wave Runup (ft)
Dryland Levee				
South	854+10	0.34	2.62	3.0
South	908+60	0.58	3.19	3.8
South	971+60	1.23	2.41	3.6
South	N/A[(1)]	1.83	N/A	2.8[(2)]

Notes:
[(1)] Analysis point is approximately 3,000 feet east of the RD17 dryland levee.
[(2)] A safety factor of 1 foot was added.

The analysis for the riverine levee segments showed that the design wind wave height is less than 3-feet. The minimum ULDC freeboard requirement is 3-feet which will therefore be the applied standard for the riverine levees.

The analysis for the various locations along the RD17 dryland levee calculated wind-wave height between 2.8 feet and 3.8 feet. A minimum of 3-feet of freeboard will be applied to the dryland levee, with freeboard exceeding 3-feet for areas where the wind-wave calculations governed. Figure 5 presents a profile of the required MTOL along the RD17 dryland levee alignment. The profile also extends to the edge of the floodplain where the land will be re-graded to become high ground. Spreadsheets for the dryland levee calculations are provided in Attachment C.



LEGEND

- RD17 Top of Levee (2014 KSN Survey)
- Minimum Top of Levee
- Still Water Surface

ULDC Analysis of the RD 17 Dryland Levee

Minimum Top of Levee along
RD17 Levee Alignment

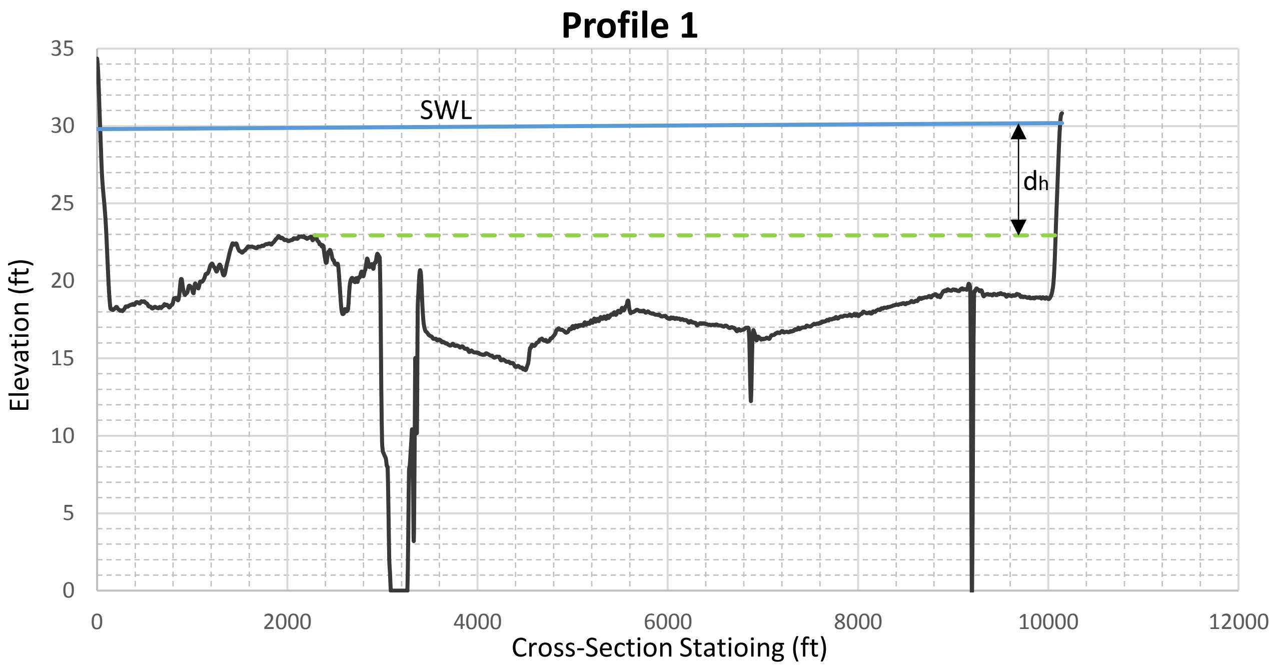
PETERSON . BRUSTAD . INC
ENGINEERING . CONSULTING

December 4, 2015

FIGURE 5

ATTACHMENT A

CALCULATIONS FOR BERM REDUCTION FACTOR



Significant Wave Height (H_{mo}) Calc:

Assumed Fetch Length, F:	1.83 mi
Drag Coefficient, C_D:	0.00087
Friction Velocity, uf:	2.74 ft/sec
Significant wave height, H_{mo}:	1.96 ft

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

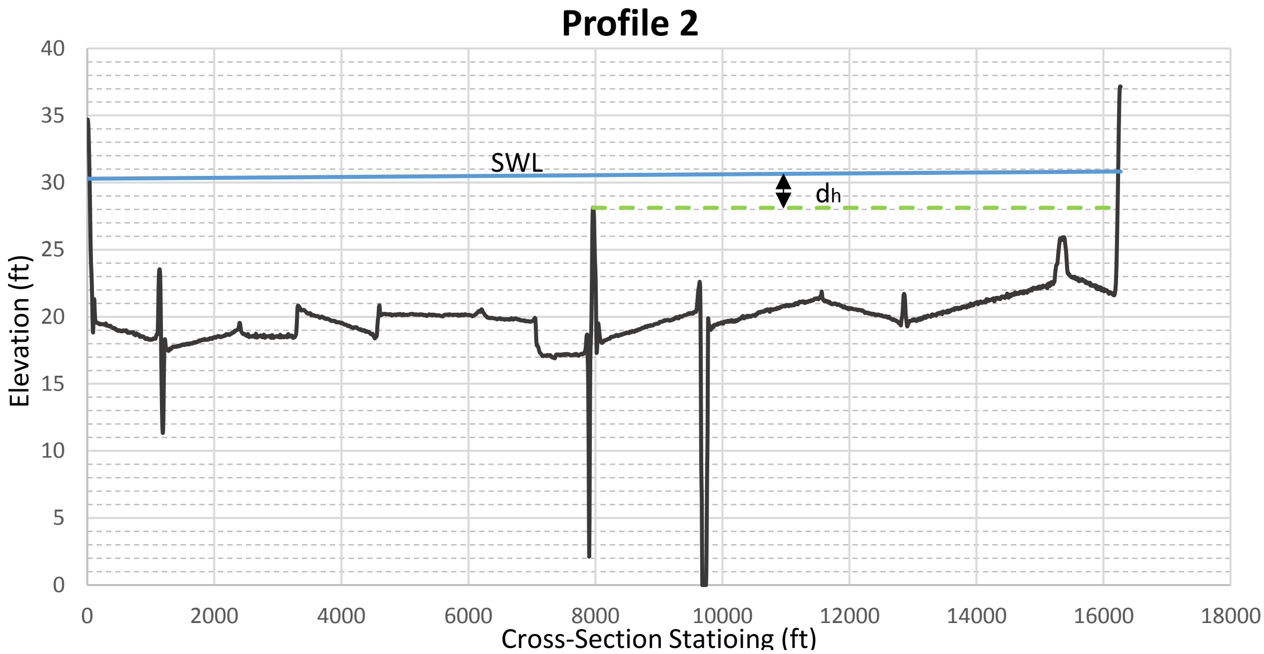
Where:

- 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)

γ_b Calculation

d_h:	7.06 ft
$H_{mo}\sqrt{2}$:	2.77 ft
Is $H_{mo}\sqrt{2}$ > dh:	No

DOES NOT APPLY



<u>Significant Wave Height (H_{mo}) Calc:</u>

Assumed Fetch Length, F:	1.35 mi
Drag Coefficient, C_D:	0.00087
Friction Velocity, uf:	2.74 ft/sec
Significant wave height, H_{mo}:	1.68 ft

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

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)

<u>γ_b Calculation</u>

d_h:	2.38 ft
$H_{mo}\sqrt{2}$:	2.38 ft
Is $H_{mo}\sqrt{2}$ > dh:	No

DOES NOT APPLY

Significant Wave Height (H_{mo}) Calc:

Assumed Fetch Length, F:	5.14 mi
Drag Coefficient, C_D:	0.00087
Friction Velocity, uf:	2.74 ft/sec
Significant wave height, H_{mo}:	3.28 ft

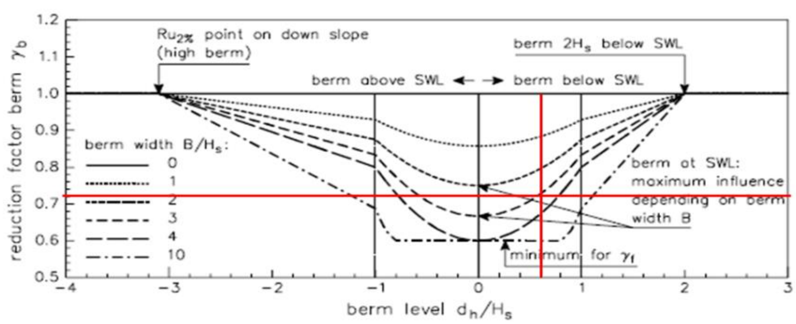
$$\frac{g*H_{mo}}{u_f^2} = 0.0413 * \left(\frac{g*X}{u_f^2}\right)^{\frac{1}{2}} \quad \text{and} \quad \frac{g*T_p}{u_f^2} = 0.751 * \left(\frac{g*X}{u_f^2}\right)^{\frac{1}{3}}$$

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)

γ_b Calculation

d_h:	1.86 ft
$H_{mo}\sqrt{2}$:	4.64 ft
Is $H_{mo}\sqrt{2}$ > dh:	Yes
Berm width, B:	10 ft
B/H_{mo}:	3
d_h/H_{mo}:	0.57
γ_b:	0.72

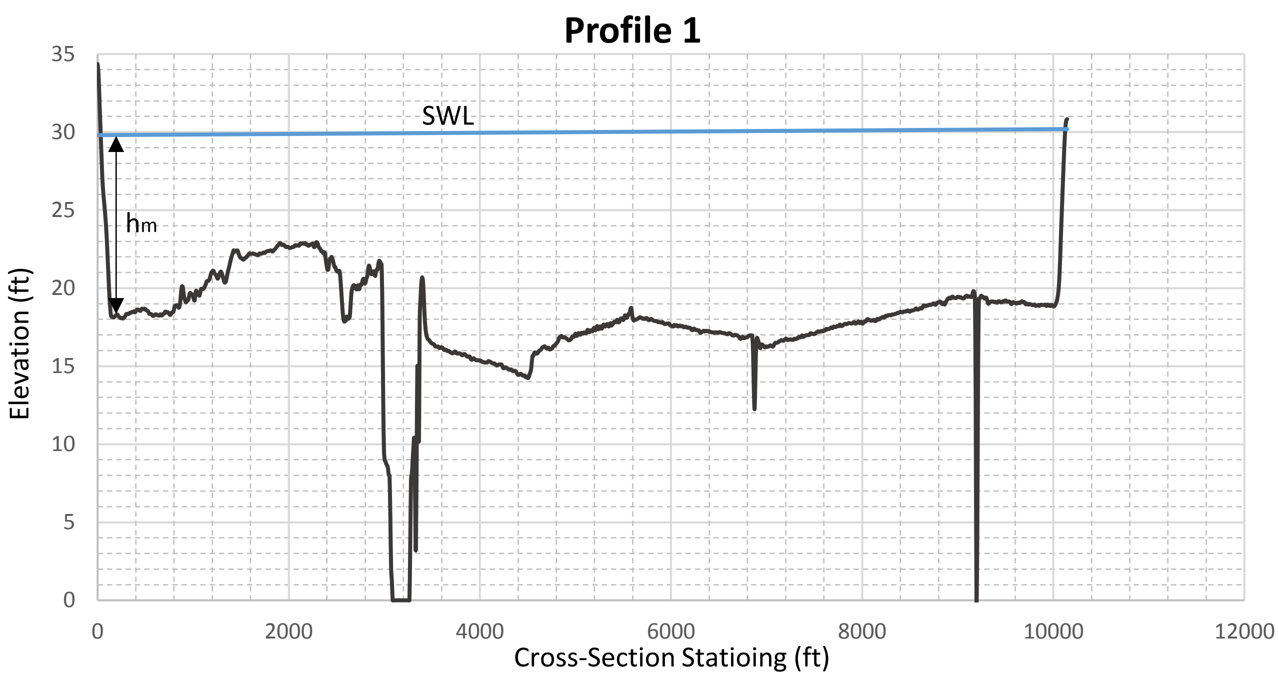
`



Van Der Meer 1998, p.9

ATTACHMENT B

CALCULATIONS FOR SHALLOW WATER REDUCTION FACTOR



<u>Significant Wave Height (H_{mo}) Calc:</u>

Assumed Fetch Length, F: 1.83 mi

Drag Coefficient, C_D: 0.00087

Friction Velocity, uf: 2.74 ft/sec

Significant wave height, H_{mo}: 1.96 ft

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

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)

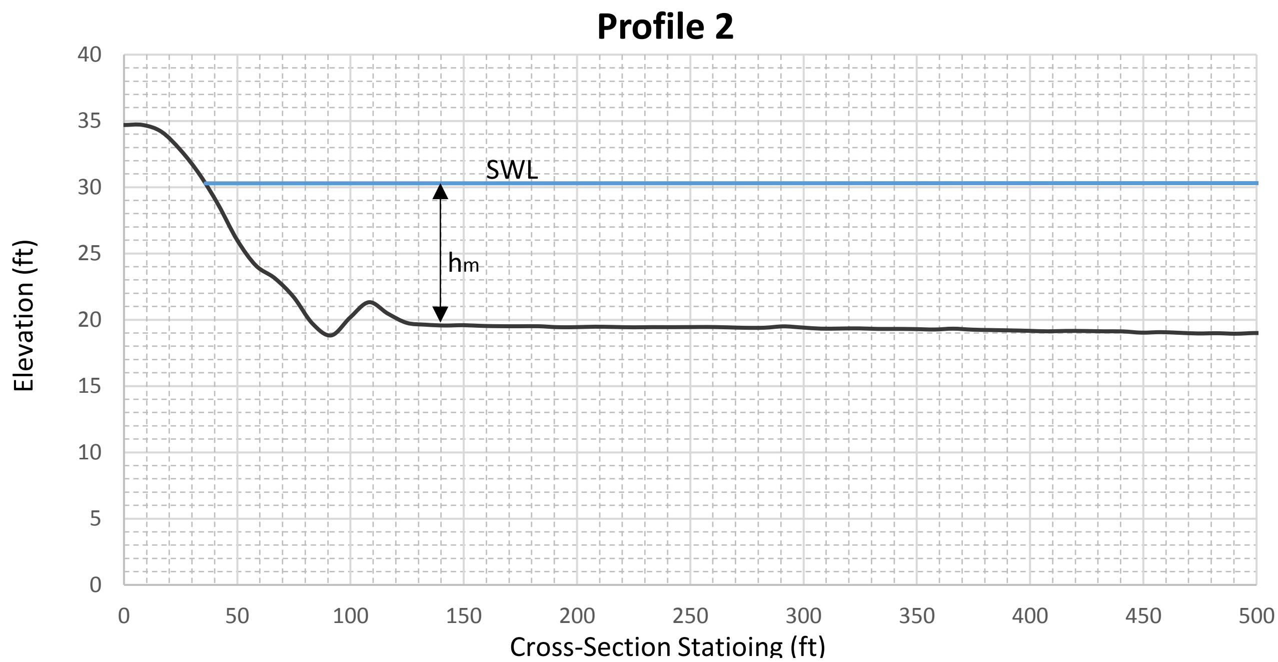
<u>γ_h Calculation</u>

Water Depth at the toe, h_m: 11.50 ft

h_m/H_{mo}: 5.87 ft

Is $h_m/H_{mo} < 4$: No

DOES NOT APPLY



Significant Wave Height (Hmo) Calc:

Assumed Fetch Length, F:	1.35	mi
Drag Coefficient, CD:	0.00087	
Friction Velocity, uf:	2.74	ft/sec
Significant wave height, Hmo:	1.68	ft

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

Where:

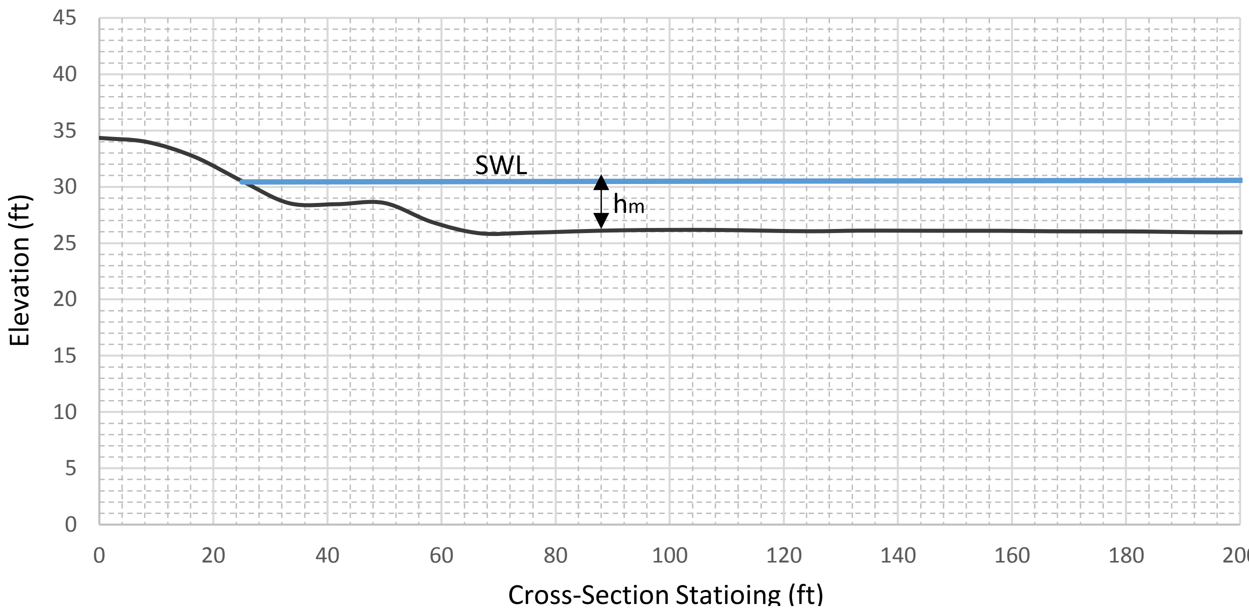
H_{mo} = significant wave height (ft)
T_p = peak wave period (sec)
X = fetch length (ft)
g = gravitational constant = 32.2 ft/sec
u_f = friction velocity (ft/sec)
$= (C_D * U_{10}^2)^{\frac{1}{2}}$
C_D = drag coefficient
$= 0.0002 * (1.1 + 0.035 * U_{10})$
U_{10} = wind speed at 10m elevation (ft/sec)

y_h Calculation

Water Depth at the toe, h_m:	10.69	ft
h_m/H_{mo}:	6.35	ft
Is $h_m/H_{mo} < 4$:	No	

DOES NOT APPLY

Profile 3



<u>Significant Wave Height (H_{mo}) Calc:</u>

Assumed Fetch Length, F:	5.14 mi
Drag Coefficient, C_D:	0.00087
Friction Velocity, uf:	2.74 ft/sec
Significant wave height, H_{mo}:	3.28 ft

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

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)

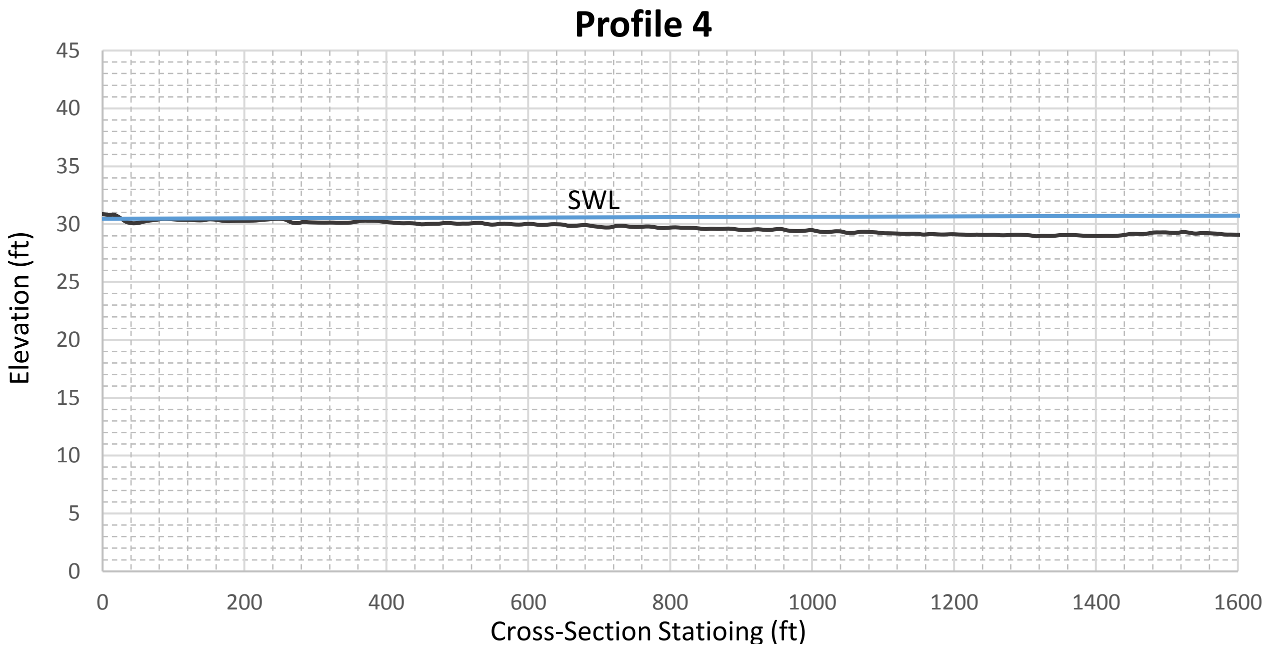
<u>γ_h Calculation</u>

Water Depth at the toe, h_m:	4.33 ft
h_m/H_{mo}:	1.32 ft
Is $h_m/H_{mo} < 4$:	Yes
γ_h:	0.78

$$\gamma_h = \frac{H_{2\%}}{1.4\ H_s} = 1 - 0.03\left(4 - \frac{h_m}{H_s}\right)^2 \quad \text{for} \quad \frac{h_m}{H_s} < 4$$

$$\gamma_h = 1 \quad \text{for} \quad \frac{h_m}{H_s} \geq 4$$

Van Der Meer & Janssen 1994, p. 9



Significant Wave Height (H_{mo}) Calc:

Assumed Fetch Length, F:	6.14 mi
Drag Coefficient, C_D:	0.00087
Friction Velocity, uf:	2.74 ft/sec
Significant wave height, Hmo:	3.59 ft

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

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)

γ_h Calculation

Water Depth at the toe, h_m:	0.00 ft
h_m/H_{mo}:	0.00 ft
Is $h_m/H_{mo} < 4$:	Yes
γ_h:	0.52

$$\gamma_h = \frac{H_{2\%}}{1.4\ H_s} = 1 - 0.03\left(4 - \frac{h_m}{H_s}\right)^2 \quad \text{for} \quad \frac{h_m}{H_s} < 4$$

$$\gamma_h = 1 \quad \text{for} \quad \frac{h_m}{H_s} \geq 4$$

Van Der Meer & Janssen 1994, p. 9

ATTACHMENT C

CALCULATIONS OF WIND SETUP AND WAVE RUNUP ALONG THE RD17 DRYLAND LEVEE

RD17 Dryland Levee
Wind/Wave Analysis
Profile 1

Peterson Brustad, Inc.
Mike Rossiter, PE
11/21/2014

COMBINED WIND SETUP & WAVE RUNUP [FEET]: 3.0 ft

WIND SETUP & WAVE RUNUP INPUTS

Primary Inputs			
Design 72.9yr Wind Speed, U_z:	51	mph	
Height at Which Observations were Taken, z:	7.9	m	
Assumed Fetch Length, F:	1.83	mi	Avg 9 radials at 3 degree intervals, pg 3-24 SPM (1984)
Average Water Depth Along Fetch Line, d:	12.08	ft	Avg depth at cell every half mile of median radial
Waterside Levee Slope (H/V):	2.25		
Angle of Incidence for Waves Approaching the Levee, β:	0	degrees	
Reduction Factors			
Reduction Factor for Levee Slope Roughness, γ_r:	0.6		CEM Table VI-5-3 ---------->
Reduction Factor for Influence of a Berm, γ_b:	1.0		If no berm, γ_b = 1.0. Otherwise, see discussion on CEM pg. VI-5-12.
Reduction Factor for Influence of Shallow Waves, γ_h:	1.0		No shallow wave influence, γ_h = 1.0. Based on depth at toe of levee. See equation and discussion on CEM pg. VI-5-13
Reduction Factor for Influence of Angle of Incidence, γ_β:	1.000		CEM Equation VI-5-11: Short-crested waves $\gamma_\beta = 1 - 0.0022\,\beta$
Reduction Factor for the Presence of Vegetation Along the Fetch Line, $\gamma_{Veg.}$:	0.67		See discussion on pgs. 6 & 7 in PBI TM, *SBFCA's Feather River West Levee Strengthening EIP Project, Wind Setup and Wave Runup Analysis* , January 10, 2011. (rip rap reduces up
Secondary/Calculated Inputs			
Design 72.9yr Wind Speed Corrected for 10m Observation Height, U_{10}:	52.7	mph	Wind corrected to 10m Observation Level with the 1/7 rule (CEM Equation II-2-9) $U_{10} = U_z\left(\frac{10}{z}\right)^{\frac{1}{7}}$
Design 72.9yr Wind Speed Corrected for Over Water:	63.3	mph	For fetch lengths less than 16km, the CEM recommends a factor of 1.2 to increase the wind speed for over water conditions (CEM pg. II-2-36 (c))
Design 72.9yr Wind Speed Corrected for Over Water:	92.8	ft/sec	
Assumed Fetch Length, F:	9,658	ft	

Table VI-5-3
Surface Roughness Reduction Factor γ_r in Equation VI-5-3, Valid for 1 < ξ_{op} < 3-4

Type of Slope Surface			γ_r
Smooth, concrete, asphalt			1.0
Smooth block revetment			1.0
Grass (3 cm length)			0.90 - 1.0
1 layer of rock, diameter D, (H_s/D = 1.5 - 3.0)			0.55 - 0.6
2 or more layers of rock, (H_s/D = 1.5 - 6.0)			0.50 - 0.55
Roughness elements on smooth surface (length parallel to waterline = ℓ, width = b, height = h)			
Quadratic blocks, $\ell = b$			
h/b	b/H_s	area coverage	
0.88	0.12 - 0.19	1/9	0.70 - 0.75
0.88	0.12 - 0.24	1/25	0.75 - 0.85
0.44	0.12 - 0.24	1/25	0.85 - 0.95
0.88	0.12 - 0.18	1/25 (above SWL)	0.85 - 0.95
0.18	0.55 - 1.10	1/4	0.75 - 0.85
Ribs			
1.00	0.12 - 0.19	1/7.5	0.60 - 0.70

WIND SETUP CALCULATIONS

Wind Setup (Zeider Zee Equation), S:	0.433	ft
Wind Setup (Sibul Equation), S:	0.254	ft
AVERAGE WIND SETUP, S:	**0.34**	**ft**
Wind Setup (Zeider Zee Equation), S:	**-**	**ft**

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

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

Equation 15-1, USACE *Hydrologic Engineering Requirements for Reservoirs* (EM 1110-2-1420)

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

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

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

Use average wind setup for average depth less than 16 ft. Use Zeider Zee equation for average depth greater than 16 ft.

WAVE RUNUP CALCULATIONS

Significant Wave Height (H_{mo}) Calculation		
Drag Coefficient, C_D:	0.00087	
Friction Velocity, u_f:	2.74	ft/sec
Significant Wave Height, H_{mo}:	1.958	ft
		0.834744
		0.597071
Peak Wave Period (T_p) Calculation		
Peak Wave Period, T_p:	6.05	sec
Surf Similarity (ε_p) Calculation		
Waterside levee slope angle, tan α:	0.44	
Surf Similarity Parameter, ε_p:	4.35	
2% Wave Runup ($R_{2\%}$) Calculation		
A:	-0.2	
C:	4.5	
2% Wave Runup, $R_{2\%}$:	3.91	ft
2% Wave Runup with Vegetative Correction, $R_{2\%,Veg.}$:	**2.62**	**ft**

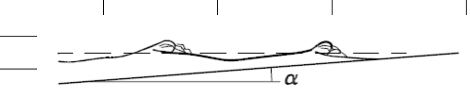
$$\frac{g * H_{mo}}{u_f^2} = 0.0413 * \left(\frac{g * X}{u_f^2}\right)^{\frac{1}{2}} \quad \text{and} \quad \frac{g * T_p}{u_f^2} = 0.751 * \left(\frac{g * X}{u_f^2}\right)^{\frac{1}{3}}$$

CEM Equation II-2-36

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)

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

CEM Equation VI-5-2



tan α = opposite/adjacent = vertical/horizontal

Where:
ε_p = surf similarity parameter
tan(α) = waterside slope of levee (assumed 1V:3H for all wind direction conditions)

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

CEM Equation VI-5-3

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

Finding A & C:

Table VI-5-2
Coefficients in Equation VI-5-3 for Runup of Long-Crested Irregular Waves on Smooth Impermeable Slopes

ξ	R_u	ξ-Limits	A	C	σ_{Ru} / R_u
ξ_{op}	$R_{u2\ percent}$	$\xi_p \le 2.5$	1.6	0	≈ 0.15
		$2.5 < \xi_p < 9$	-0.2	4.5	
	R_{us}	$\xi_p \le 2.0$	1.35	0	≈ 0.10
		$2.0 < \xi_p < 9$	-0.15	3.0	

COMBINED WIND SETUP & WAVE RUNUP

Wind Setup, S:	0.34	ft
2% Wave Runup with Vegetative Correction, $R_{2\%,Veg.}$:	2.62	ft
COMBINED WIND SETUP AND WAVE RUNUP:	**2.96**	**FT**

RD17 Dryland Levee
Wind/Wave Analysis
Profile 2

Peterson Brustad, Inc.
Mike Rossiter, PE
11/21/2014

COMBINED WIND SETUP & WAVE RUNUP [FEET]: 3.8 ft

WIND SETUP & WAVE RUNUP INPUTS

Primary Inputs			
Design 72.9yr Wind Speed, U_z:	51	mph	
Height at Which Observations were Taken, z:	7.9	m	
Assumed Fetch Length, F:	2.76	mi	Avg 9 radials at 3 degree intervals, pg 3-24 SPM (1984)
Average Water Depth Along Fetch Line, d:	10.59	ft	Avg depth at cell every half mile of median radial
Waterside Levee Slope (H/V):	2.25		
Angle of Incidence for Waves Approaching the Levee, β:	0	degrees	
Reduction Factors			
Reduction Factor for Levee Slope Roughness, γ_r:	0.6		CEM Table VI-5-3
Reduction Factor for Influence of a Berm, γ_b:	1.0		If no berm, γ_b = 1.0. Otherwise, see discussion on CEM pg. VI-5-12.
Reduction Factor for Influence of Shallow Waves, γ_h:	1.0		No shallow wave influence, γ_h = 1.0. Based on depth at toe of levee. See equation and discussion on CEM pg. VI-5-13
Reduction Factor for Influence of Angle of Incidence, γ_β:	1.000		CEM Equation VI-5-11: Short-crested waves $\gamma_\beta = 1 - 0.0022\,\beta$
Reduction Factor for the Presence of Vegetation Along the Fetch Line, $\gamma_{Veg.}$:	0.67		See discussion on pgs. 6 & 7 in PBI TM, *SBFCA's Feather River West Levee Strengthening EIP Project, Wind Setup and Wave Runup Analysis* , January 10, 2011. (rip rap reduce
Secondary/Calculated Inputs			
Design 72.9yr Wind Speed Corrected for 10m Observation Height, U_{10}:	52.7	mph	Wind corrected to 10m Observation Level with the 1/7 rule (CEM Equation II-2-9) $U_{10} = U_z\left(\frac{10}{z}\right)^{\frac{1}{7}}$
Design 72.9yr Wind Speed Corrected for Over Water:	63.3	mph	For fetch lengths less than 16km, the CEM recommends a factor of 1.2 to increase the wind speed for over water conditions (CEM pg. II-2-36 (c))
Design 72.9yr Wind Speed Corrected for Over Water:	92.8	ft/sec	
Assumed Fetch Length, F:	14,573	ft	

Table VI-5-3
Surface Roughness Reduction Factor γ_r in Equation VI-5-3, Valid for 1 < ξ_{op} < 3-4

Type of Slope Surface			γ_r
Smooth, concrete, asphalt			1.0
Smooth block revetment			1.0
Grass (3 cm length)			0.90 - 1.0
1 layer of rock, diameter *D*, (H_s/D = 1.5 - 3.0)			0.55 - 0.6
2 or more layers of rock, (H_s/D = 1.5 - 6.0)			0.50 - 0.55
Roughness elements on smooth surface (length parallel to waterline = ℓ, width = *b*, height = *h*)			
Quadratic blocks, ℓ = *b*			
h/b	b/H_s	area coverage	
0.88	0.12 - 0.19	1/9	0.70 - 0.75
0.88	0.12 - 0.24	1/25	0.75 - 0.85
0.44	0.12 - 0.24	1/25	0.85 - 0.95
0.88	0.12 - 0.18	1/25 (above SWL)	0.85 - 0.95
0.18	0.55 - 1.10	1/4	0.75 - 0.85
Ribs			
1.00	0.12 - 0.19	1/7.5	0.60 - 0.70

WIND SETUP CALCULATIONS

Wind Setup (Zeider Zee Equation), S:	0.746	ft

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

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

Equation 15-1, USACE *Hydrologic Engineering Requirements for Reservoirs* (EM 1110-2-1420)

Wind Setup (Sibul Equation), S:	0.407	ft

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

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

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

AVERAGE WIND SETUP, S:	**0.58**	**ft**
Wind Setup (Zeider Zee Equation), S:	**-**	**ft**

Use average wind setup for average depth less than 16 ft. Use Zeider Zee equation for average depth greater than 16 ft.

WAVE RUNUP CALCULATIONS

Significant Wave Height (H_{mo}) Calculation		
Drag Coefficient, C_D:	0.00087	
Friction Velocity, u_f:	2.74	ft/sec
Significant Wave Height, H_{mo}:	2.406	ft
		0.834744
		0.733415
Peak Wave Period (T_p) Calculation		
Peak Wave Period, T_p:	6.94	sec

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

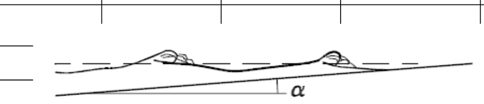
CEM Equation II-2-36

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)

Surf Similarity (ε_p) Calculation	
Waterside levee slope angle, tan α:	0.44
Surf Similarity Parameter, ε_p:	4.50

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

CEM Equation VI-5-2



tan α = opposite/adjacent = vertical/horizontal

Where:
ε_p = surf similarity parameter
tan(α) = waterside slope of levee (assumed 1V:3H for all wind direction conditions)

2% Wave Runup ($R_{2\%}$) Calculation		
A:	-0.2	
C:	4.5	
2% Wave Runup, $R_{2\%}$:	4.76	ft
2% Wave Runup with Vegetative Correction, $R_{2\%,Veg.}$:	**3.19**	**ft**

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

CEM Equation VI-5-3

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

Finding A & C:

Table VI-5-2
Coefficients in Equation VI-5-3 for Runup of Long-Crested Irregular Waves on Smooth Impermeable Slopes

ξ	R_u	ξ-Limits	A	C	σ_{Ru} / R_u
	$R_{u2\,percent}$	$\xi_p \le 2.5$	1.6	0	≈ 0.15
		$2.5 < \xi_p < 9$	-0.2	4.5	
ξ_{op}	R_{us}	$\xi_p \le 2.0$	1.35	0	≈ 0.10
		$2.0 < \xi_p < 9$	-0.15	3.0	

COMBINED WIND SETUP & WAVE RUNUP

Wind Setup, S:	0.58	ft
2% Wave Runup with Vegetative Correction, $R_{2\%,Veg.}$:	3.19	ft
COMBINED WIND SETUP AND WAVE RUNUP:	**3.77**	**FT**

RD17 Dryland Levee
Wind/Wave Analysis
Profile 3

WIND SETUP & WAVE RUNUP INPUTS

COMBINED WIND SETUP & WAVE RUNUP [FEET]: 3.6 ft

Peterson Brustad, Inc.
Mike Rossiter, PE
11/21/2014

Primary Inputs			
Design 72.9yr Wind Speed, U_z:	51	mph	
Height at Which Observations were Taken, z:	7.9	m	
Assumed Fetch Length, F:	5.14	mi	Avg 9 radials at 3 degree intervals, pg 3-24 SPM (1984)
Average Water Depth Along Fetch Line, d:	9.083	ft	Avg depth at cell every half mile of median radial
Waterside Levee Slope (H/V):	2.25		
Angle of Incidence for Waves Approaching the Levee, β:	0	degrees	
Reduction Factors			
Reduction Factor for Levee Slope Roughness, γ_r:	0.6		CEM Table VI-5-3
Reduction Factor for Influence of a Berm, γ_b:	0.7		If no berm, γ_b = 1.0. Otherwise, see discussion on CEM pg. VI-5-12.
Reduction Factor for Influence of Shallow Waves, γ_h:	0.8		No shallow wave influence, γ_h = 1.0. Based on depth at toe of levee. See equation and discussion on CEM pg. VI-5-13
Reduction Factor for Influence of Angle of Incidence, γ_β:	1.000		CEM Equation VI-5-11: Short-crested waves $\gamma_\beta = 1 - 0.0022\,\beta$
Reduction Factor for the Presence of Vegetation Along the Fetch Line, γ_{Veg}:	0.67		See discussion on pgs. 6 & 7 in PBI TM, *SBFCA's Feather River West Levee Strengthening EIP Project, Wind Setup and Wave Runup Analysis* , January 10, 2011. (rip rap reduce
Secondary/Calculated Inputs			
Design 72.9yr Wind Speed Corrected for 10m Observation Height, U_{10}:	52.7	mph	Wind corrected to 10m Observation Level with the 1/7 rule (CEM Equation II-2-9) $U_{10} = U_z\left(\frac{10}{z}\right)^{\frac{1}{7}}$
Design 72.9yr Wind Speed Corrected for Over Water:	63.3	mph	For fetch lengths less than 16km, the CEM recommends a factor of 1.2 to increase the wind speed for over water conditions (CEM pg. II-2-36 (c))
Design 72.9yr Wind Speed Corrected for Over Water:	92.8	ft/sec	
Assumed Fetch Length, F:	27,139	ft	

Table VI-5-3
Surface Roughness Reduction Factor γ_r in Equation VI-5-3, Valid for 1 < ξ_{op} < 3-4

Type of Slope Surface			γ_r
Smooth, concrete, asphalt			1.0
Smooth block revetment			1.0
Grass (3 cm length)			0.90 - 1.0
1 layer of rock, diameter D, (H_s/D = 1.5 - 3.0)			0.55 - 0.6
2 or more layers of rock, (H_s/D = 1.5 - 6.0)			0.50 - 0.55
Roughness elements on smooth surface (length parallel to waterline = ℓ, width = b, height = h)			
Quadratic blocks, ℓ = b			
h/b	*b/H_s*	area coverage	
0.88	0.12 - 0.19	1/9	0.70 - 0.75
0.88	0.12 - 0.24	1/25	0.75 - 0.85
0.44	0.12 - 0.24	1/25	0.85 - 0.95
0.88	0.12 - 0.18	1/25 (above SWL)	0.85 - 0.95
0.18	0.55 - 1.10	1/4	0.75 - 0.85
Ribs			
1.00	0.12 - 0.19	1/7.5	0.60 - 0.70

WIND SETUP CALCULATIONS

Wind Setup (Zeider Zee Equation), S:	1.619	ft	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)

Wind Setup (Sibul Equation), S:	0.838	ft	More recent studies show that for shallow water (< 16 ft deep) the value from the equation above should be averaged with the Sibul equation (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

AVERAGE WIND SETUP, S:	1.23	ft	Use average wind setup for average depth less than 16 ft. Use Zeider Zee equation for average depth greater than 16 ft.
Wind Setup (Zeider Zee Equation), S:	-	ft	

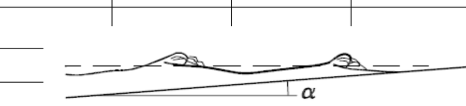
WAVE RUNUP CALCULATIONS

Significant Wave Height (H_{mo}) Calculation			
Drag Coefficient, C_D:	0.00087		CEM Equation II-2-36
Friction Velocity, u_f:	2.74	ft/sec	
Significant Wave Height, H_{mo}:	3.283	ft	
		0.834744	
		1.000861	
Peak Wave Period (T_p) Calculation			
Peak Wave Period, T_p:	8.54	sec	

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

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)

Surf Similarity (ε_p) Calculation			CEM Equation VI-5-2
Waterside levee slope angle, tan α:	0.44		tan α = opposite/adjacent = vertical/horizontal
Surf Similarity Parameter, ε_p:	4.74		



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

Where:
ε_p = surf similarity parameter
tan(α) = waterside slope of levee (assumed 1V:3H for all wind direction conditions)

2% Wave Runup ($R_{2\%}$) Calculation			CEM Equation VI-5-3
A:	-0.2		
C:	4.5		
2% Wave Runup, $R_{2\%}$:	3.60	ft	
2% Wave Runup with Vegetative Correction, $R_{2\%,Veg}$:	**2.41**	**ft**	

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

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

Finding A & C:

Table VI-5-2
Coefficients in Equation VI-5-3 for Runup of Long-Crested Irregular Waves on Smooth Impermeable Slopes

ξ	R_u	ξ-Limits	A	C	σ_{Ru}/R_u
ξ_{op}	$R_{u2\,percent}$	$\xi_p \le 2.5$	1.6	0	≈ 0.15
		$2.5 < \xi_p < 9$	-0.2	4.5	
	R_{us}	$\xi_p \le 2.0$	1.35	0	≈ 0.10
		$2.0 < \xi_p < 9$	-0.15	3.0	

COMBINED WIND SETUP & WAVE RUNUP

Wind Setup, S:	1.23	ft
2% Wave Runup with Vegetative Correction, $R_{2\%,Veg}$:	2.41	ft
COMBINED WIND SETUP AND WAVE RUNUP:	**3.64**	**FT**

RD17 Dryland Levee
Wind/Wave Analysis
Profile 4

WIND SETUP & WAVE RUNUP INPUTS

Primary Inputs			
Design 72.9yr Wind Speed, U_z:	51	mph	
Height at Which Observations were Taken, z:	7.9	m	
Assumed Fetch Length, F:	6.14	mi	Avg 9 radials at 3 degree intervals, pg 3-24 SPM (1984)
Average Water Depth Along Fetch Line, d:	7.29	ft	Avg depth at cell every half mile of median radial
Waterside Levee Slope (H/V):	2.25		
Angle of Incidence for Waves Approaching the Levee, β:	0	degrees	
Reduction Factors			
Reduction Factor for Levee Slope Roughness, γ_r:	0.6		CEM Table VI-5-3 --->
Reduction Factor for Influence of a Berm, γ_b:	1.0		If no berm, γ_b = 1.0. Otherwise, see discussion on CEM pg. VI-5-12.
Reduction Factor for Influence of Shallow Waves, γ_h:	0.5		No shallow wave influence, γ_h = 1.0. Based on depth at toe of levee. See equation and discussion on CEM pg. VI-5-13
Reduction Factor for Influence of Angle of Incidence, γ_β:	1.000		CEM Equation VI-5-11: Short-crested waves $\gamma_\beta = 1 - 0.0022\,\beta$
Reduction Factor for the Presence of Vegetation Along the Fetch Line, γ_{Veg}:	0.67		See discussion on pgs. 6 & 7 in PBI TM, *SBFCA's Feather River West Levee Strengthening EIP Project, Wind Setup and Wave Runup Analysis* , January 10, 2011. (rip rap reduces upru
Secondary/Calculated Inputs			
Design 72.9yr Wind Speed Corrected for 10m Observation Height, U_{10}:	52.7	mph	Wind corrected to 10m Observation Level with the 1/7 rule (CEM Equation II-2-9) $U_{10} = U_z\left(\frac{10}{z}\right)^{\frac{1}{7}}$
Design 72.9yr Wind Speed Corrected for Over Water:	63.3	mph	For fetch lengths less than 16km, the CEM recommends a factor of 1.2 to increase the wind speed for over water conditions (CEM pg. II-2-36 (c))
Design 72.9yr Wind Speed Corrected for Over Water:	92.8	ft/sec	
Assumed Fetch Length, F:	32,442	ft	

COMBINED WIND SETUP & WAVE RUNUP [FEET]: 2.8 ft

Peterson Brustad, Inc.
Mike Rossiter, PE
11/21/2014

Table VI-5-3
Surface Roughness Reduction Factor γ_r in Equation VI-5-3, Valid for $1 < \xi_{op} < 3\text{-}4$

Type of Slope Surface			γ_r
Smooth, concrete, asphalt			1.0
Smooth block revetment			1.0
Grass (3 cm length)			0.90 - 1.0
1 layer of rock, diameter D, (H_s/D = 1.5 - 3.0)			0.55 - 0.6
2 or more layers of rock, (H_s/D = 1.5 - 6.0)			0.50 - 0.55
Roughness elements on smooth surface (length parallel to waterline = ℓ, width = b, height = h)			
Quadratic blocks, ℓ = b			
h/b	b/H_s	area coverage	
0.88	0.12 - 0.19	1/9	0.70 - 0.75
0.88	0.12 - 0.24	1/25	0.75 - 0.85
0.44	0.12 - 0.24	1/25	0.85 - 0.95
0.88	0.12 - 0.18	1/25 (above SWL)	0.85 - 0.95
0.18	0.55 - 1.10	1/4	0.75 - 0.85
Ribs			
1.00	0.12 - 0.19	1/7.5	0.60 - 0.70

WIND SETUP CALCULATIONS

Wind Setup (Zeider Zee Equation), S:	2.413	ft	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)

Wind Setup (Sibul Equation), S:	1.255	ft	More recent studies show that for shallow water (< 16 ft deep) the value from the equation above should be averaged with the Sibul equation (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

AVERAGE WIND SETUP, S:	1.83	ft	Use average wind setup for average depth less than 16 ft. Use Zeider Zee equation for average depth greater than 16 ft.
Wind Setup (Zeider Zee Equation), S:	-	ft	

WAVE RUNUP CALCULATIONS

Significant Wave Height (H_{mo}) Calculation		
Drag Coefficient, C_D:	0.00087	
Friction Velocity, u_f:	2.74	ft/sec
Significant Wave Height, H_{mo}:	3.589	ft
	0.834744	
	1.094287	
Peak Wave Period (T_p) Calculation		
Peak Wave Period, T_p:	9.06	sec

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

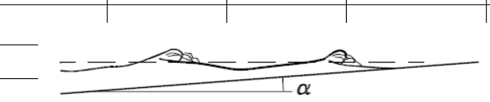
CEM Equation II-2-36

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)

Surf Similarity (ε_p) Calculation		
Waterside levee slope angle, tan α:	0.44	
Surf Similarity Parameter, ε_p:	4.81	

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

CEM Equation VI-5-2



tan α = opposite/adjacent = vertical/horizontal

Where:
ε_p = surf similarity parameter
tan(α) = waterside slope of levee (assumed 1V:3H for all wind direction conditions)

2% Wave Runup ($R_{2\%}$) Calculation		
A:	-0.2	
C:	4.5	
2% Wave Runup, $R_{2\%}$:	3.63	ft
2% Wave Runup with Vegetative Correction, $R_{2\%,Veg}$:	**2.43**	**ft**

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

CEM Equation VI-5-3

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

Finding A & C:

Table VI-5-2
Coefficients in Equation VI-5-3 for Runup of Long-Crested Irregular Waves on Smooth Impermeable Slopes

ξ	R_u	ξ-Limits	A	C	σ_{Ru}/R_u
ξ_{op}	$R_{u2\,percent}$	$\xi_p \le 2.5$	1.6	0	≈ 0.15
		$2.5 < \xi_p < 9$	-0.2	4.5	
	R_{us}	$\xi_p \le 2.0$	1.35	0	≈ 0.10
		$2.0 < \xi_p < 9$	-0.15	3.0	

COMBINED WIND SETUP & WAVE RUNUP

Wind Setup, S:	1.83	ft	
2% Wave Runup with Vegetative Correction, $R_{2\%,Veg}$:		ft	In the case of Profile 4, high ground is assumed in place of a dryland levee. Therefore, wave runup is not included as part of the analysis for Profile 4
Safety Factor:	1.00	ft	A safety factor is considered to take into account climate change
COMBINED WIND SETUP AND WAVE RUNUP:	**2.83**	**FT**	