TECHNICAL MEMORANDUM

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City of Lathrop and City of Manteca ULDC Evaluation
Sea Level Rise Analysis

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

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Introduction

Per ULDC guidelines, the effects of sea level rise (SLR) should be estimated and addressed for the duration over which a Finding that the urban level of flood protection may be valid. The PBI study *San Joaquin River Delta Base Flood Elevation (BFE) Refinement Stage Frequency Analysis*, dated September 2, 2010 and provided in Appendix 3, details methods used to determine stage-frequency statistics as well as SLR estimates at the Burns Cutoff (ID: B95660) and Rindge Pump (ID: B95620) gage stations located within the San Joaquin River tidal zone.

Sea level rise estimates in the 2010 BFE study were prepared using EC 1165-2-211, which expired July 1, 2011, and has been replaced by ETL 1100-2-1. The empirical equation for calculation of intermediate and high sea level rise was revised in ETL 1100-2-1, replacing the reference year of 1986 with 1992 (Equation 1).

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2) \quad (1)$$

where:

$E(t_2) - E(t_1)$ = represents sea level rise between current and future years
$E(t_1)$ = current sea level, meters
$E(t_2)$ = future sea level, meters

t_1 = current year since 1992 (was 1986)
t_2 = future year since 1992 (was 1986)
b = constant = 2.71E-05 for intermediate-level NRC Curve I (was 2.360E-05)
1.13E-04 for high-level NRC Curve III (was 1.005E-04)

Results

The revised equation for calculation of high-and intermediate-level sea level rise by 2050 results in estimates less than 0.1 ft lower than the original estimates. The updated estimates of sea level rise by 2050 are presented in Table 1 along with the historical rate of sea level rise as originally calculated in the BFE study.

Table 1: Revised estimates of sea level rise, from 2015.

	Sea Level Rise (ft)		
Year	**Low**	**Intermediate**	**High**
2025	0.1	0.1	0.3
2050	0.2	0.5	1.3
2075	0.4	0.9	2.7
2100	0.6	1.5	4.6

The low, intermediate, and high estimates of sea level rise for the Burns cutoff pump station are shown in Figures 1 along with 90% confidence intervals. Confidence intervals shown in Figure 1 were produced with statistical analysis features of HEC-SSP as part of the BFE study.

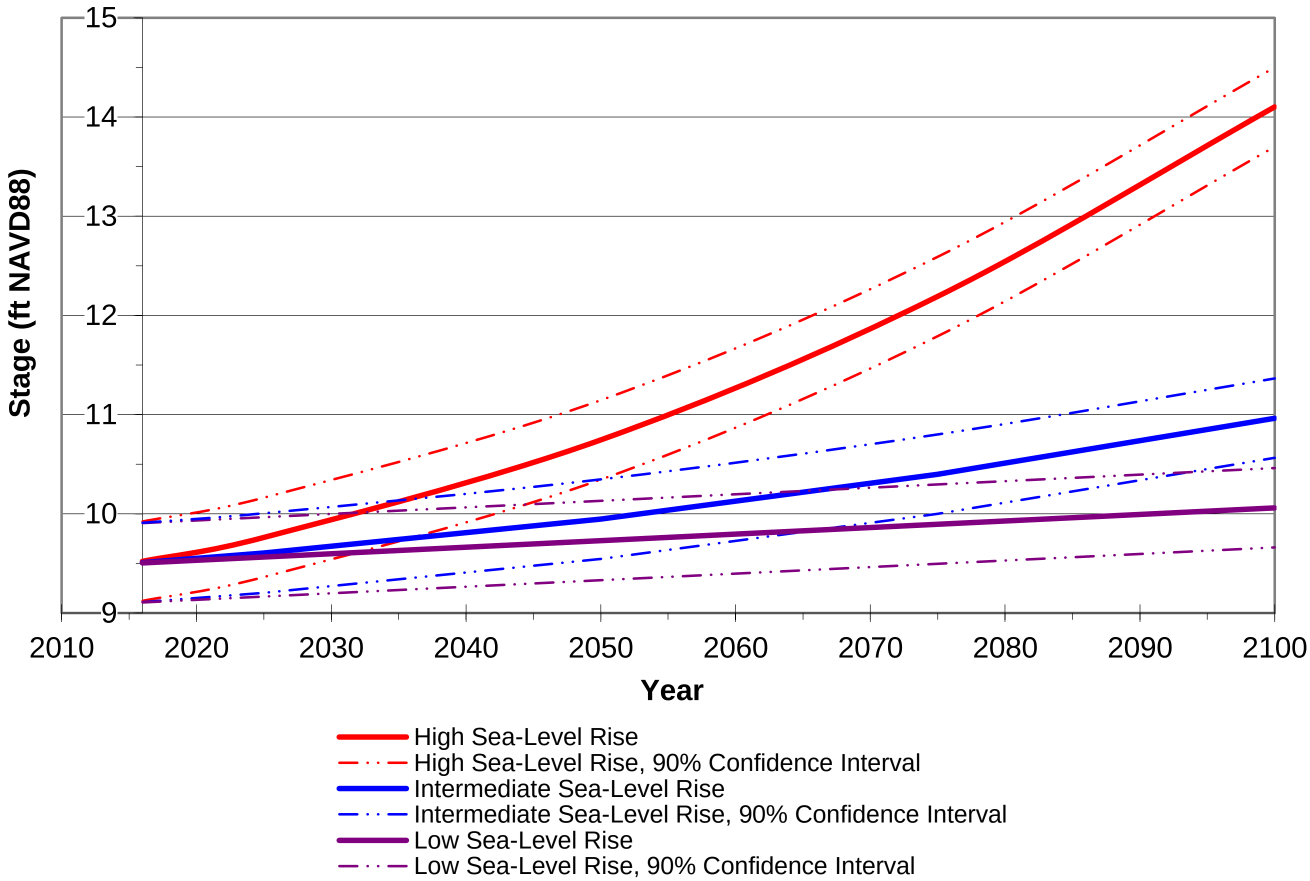

Figure 1: Low, intermediate, and high rates of sea level rise at the Burns Cutoff gage station along with 90% confidence intervals.

The intermediate SLR estimate for 2050 of 0.5 ft was incorporated into the HEC-RAS model for all analyses in this study.

ATTACHMENT A

San Joaquin River Delta Base Flood Elevation Refinement Stage Frequency Analysis
San Joaquin Area Flood Control Agency, September 2010

SJAFCA

San Joaquin Area FLOOD CONTROL Agency

San Joaquin River Delta Base Flood Elevation Refinement Stage Frequency Analysis

Rindge Pump Gage Station (B95620)
Burns Cutoff Gage Station (B95660)

September 2, 2010

Prepared By

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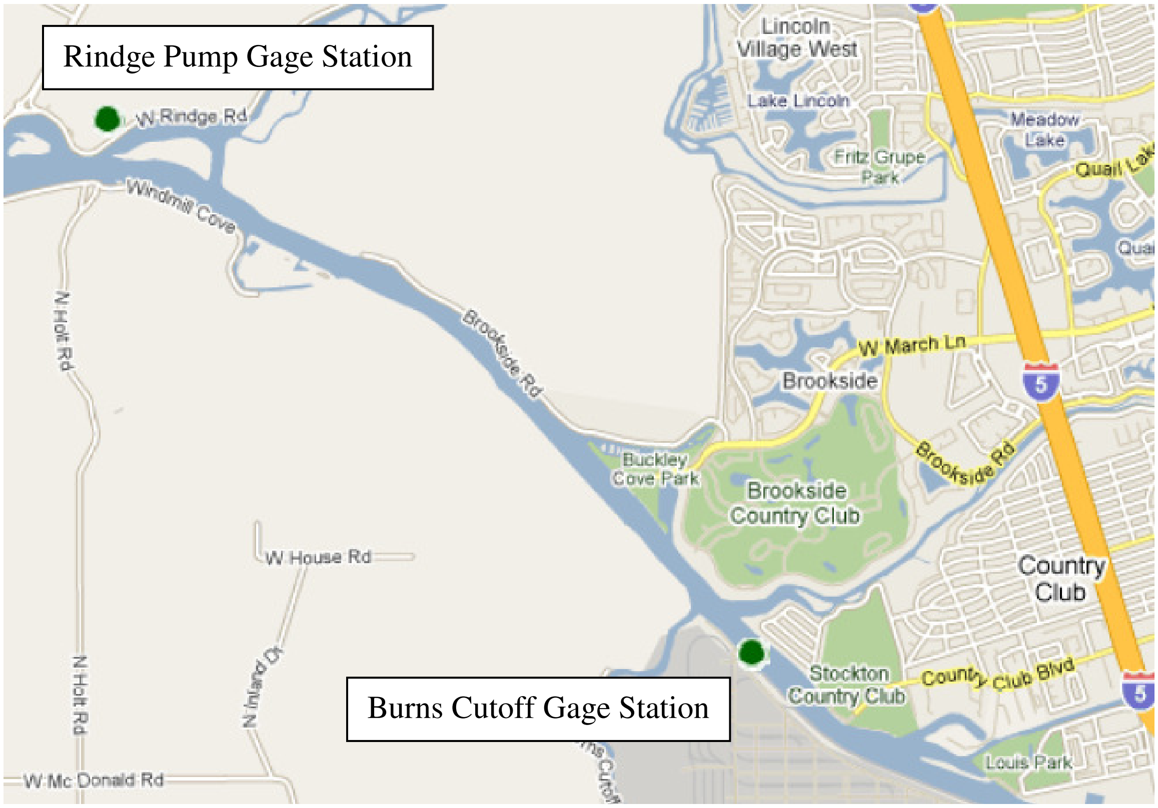
1.0 Introduction

The Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRMs) for the Stockton Metropolitan Area reflect base flood elevations (BFEs) developed in 1978 by the United States Army Corps of Engineers (USACE). The BFEs were developed from stage frequency analyses from tidal gage data collected from the Delta. The USACE updated these analyses in 1982 and 1992, but FEMA mapping remains tied to the 1978 study. This study updates the 1992 stage-frequency analysis at two gage stations near the City of Stockton: San Joaquin River at Rindge Pump (Rindge Pump) and Stockton Ship Channel at Burns Cutoff (Burns Cutoff). Figure 1 presents the location of these two gage stations. The updates for these gage stations presented in this study include the following changes from the previous study:

- **Datum** – all previous studies were prepared using the National Geodetic Vertical Datum of 1929 (NGVD29). This study converts the raw data into the North American Vertical Datum 1988 (NAVD88).
- **Period of Record** – this study extends the period of record through water year 2009 and includes a total of 57 years for each gage station; the 1992 study included 43 years of data for Rindge Pump and only 30 years of data for Burns Cutoff.
- **Tide Cycles** – astronomic tides follow a 19-year epoch cycle, requiring analysis of an entire 19-year epoch cycle to eliminate effects of the tide cycle on the measured river stage; the period of record for this study includes the data from three complete 19-year epoch cycles.
- **Lower-Low Tide Analysis** – Since the annual lower-low tide has minimal hydraulic affects, the trend in the lower-low tide level over time represents the combined impact of gage station subsidence and sea level rise at the gage station; the average annual lower-low tide over 19-year epoch cycles was used to determine this combined impact at each gage station; changes in stage readings due to subsidence were based on historical survey information when available; the historical sea level rise at San Francisco was used to estimate subsidence in the absence of historical survey information.
- **Climate Change Impacts** – the results of the stage frequency analysis will be impacted over time by climate change in the form of future sea level rise; this study projects a range of climate change impacts on the stage frequency results through the year 2100.

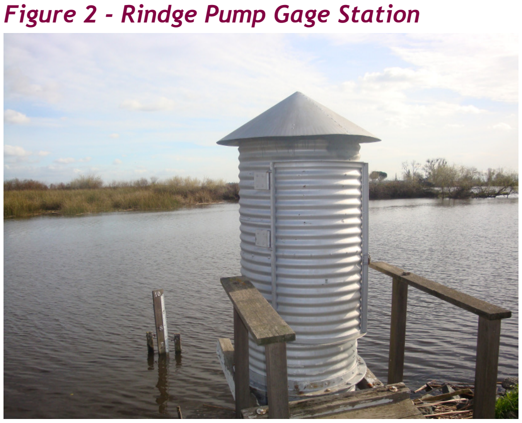
Figure 1 - Rindge Pump and Burns Cutoff Gage Station Location Map



1.1 Gage Stations

The Rindge Pump gage station, California Department of Water Resources (DWR) No. B95620, was installed on July 27, 1939. The station consists of a gage housing unit and a staff gage located in 14 Mile Slough (see Figure 2). Stage data was collected from DWR for water year (WY) 1939 through WY 2009. Note that the stage data prior to WY 1945 was not used in previous stage frequency analysis studies because Shasta Dam was not in operation.

Figure 2 - Rindge Pump Gage Station



The stage data for the Rindge Pump gage station was evaluated to determine the annual higher-high and lower-low tide from the following sources:

- Weekly chart graphs for WY 1939 through WY 1960
- Monthly and/or annual summaries for WY 1957 through WY 1982
- Daily data for WY 1983 through WY 2009

The Burns Cutoff gage station, DWR No. B95660, was installed in 1940. The gage station is located within the ship channel for the Port of Stockton (see Figure 3). Stage data was collected from DWR for WY 1958 through WY 2009. Note that even though the gage station was installed in 1940, no data prior to WY 1958 can be located.

Figure 3 - Burns Cutoff Gage Station

The stage data for the Burns Cutoff gage station was evaluated to determine the annual higher-high and lower-low tide from the following sources:

- Monthly and/or annual summaries for WY 1957 through WY 1975
- Daily data for WY 1975 through WY 2009

Stage records for each gage station from WY 1983 to WY 2009 were collected from the DWR's online Water Data Library. Prior to WY 1983, hardcopies of stage data were used for analysis.

2.0 Data Adjustments

The raw data collected was adjusted to address the following issues:

- **Missing Data** – In some cases, one of the two gages was out of service or no data was available during the annual higher-high and/or lower-low tide event.
- **"Zero on Gage" Corrections** – Both gage stations were adjusted for "zero on gage," which were documented through WY 1964; these adjustments were considered to be corrections for subsidence by this study.

- **Datum Conversion** – The raw data was collected in four different datums that need to be converted to the current datum, NAVD88.
- **Subsidence/Sea Level Rise** – The combined effect of subsidence and sea level rise was determined from the 19-year running average of the annual lower-low tide data; separation of the combined impact of subsidence from sea level rise was based on the quality of the data available.

2.1 Missing Data

From WY 1983 through WY 2009, nearly all of the annual higher-high tides occurred on the same day (26 out of 27) at the Rindge Pump and Burns Cutoff gage stations. The difference between the annual higher-high tides on different days was less than 0.05 ft. During the same period, most of the annual lower-low tides occurred on the same day (21 out of 27) at the two gage stations. The greatest difference between the annual lower-low tides on different days was 0.16 ft.

2.1.1 Gages Out of Service

Assuming that the annual higher-high tide events occur on the same day for the two gage stations, missing data was identified during periods when one gage was out of service during the other gage's higher-high tide event. This was observed twice during WY 1986 and WY 2006 when the Burns Cutoff gage station was out of service during the higher-high tide event for the Rindge Pump gage station.

Similarly, assuming the annual lower-low tide events occur on the same day at the two gage stations, missing data was identified during periods when one gage was out of service during the other gage's lower-low tide event. This was observed during WY 1984 when the Burns Cutoff gage station was out of service during the lower-low tide event for the Rindge Pump gage station. This was also observed during WY 1965 when the Rindge Pump gage station was out of service during the lower-low tide event for the Burns Cutoff gage station.

Missing data was replaced for the four instances discussed above where one gage was out of service during the other gage's high/low tide event. The new data was generated by averaging the difference between the two gages for the 7-days around the second highest/lowest tide event for that water year when both gages were operational and adding/subtracting the difference from the operating gage reading.

2.1.2 No Data Available

Data for the Burns Cutoff gage station prior to WY 1958 was not available from DWR. Data prior to WY 1958 was not used in any of the previous stage frequency analyses performed by the USACE in 1978, 1982, and 1992. In order to evaluate three complete 19-year epoch periods, data is required for both gage stations from WY 1953 through WY 2009. Therefore, data was missing for both annual higher-high and lower-low tide events for the Burns Cutoff gage station for WY 1953 through WY 1957.

The missing data was estimated from the average difference between the two gages over the remainder of the 19-year epoch period (ending in WY 1971). For annual higher-high tide events, the Burns Cutoff gage station was 0.14 ft NGVD29 higher than the Rindge Pump gage station. For annual lower-low tide events, the Burns Cutoff gage station was 0.02 ft NGVD29 higher than the Rindge Pump gage station. The resulting equations used to generate the missing data for WY 1953 through WY 1957 are presented below:

Higher-High Tide: Burns Cutoff = Rindge Pump + 0.14 ft NGVD29

Lower-Low Tide: Burns Cutoff = Rindge Pump + 0.02 ft NGVD29

2.2 "Zero on Gage" Correction

The annual data summaries collected from WY 1961 through WY 1975 include a table to present the "zero on gage" measurement along with the datum used. These summaries show that in 1964 the gage reading was corrected for 0.52 ft of subsidence between 1940 and 1964 at the Rindge Pump gage station. These summaries also show that in 1964 the gage reading was corrected for 0.52 ft of subsidence between 1951 and 1964 at the Burns Cutoff gage station.

For the Rindge Pump gage station, the difference between the "zero on gage" measurements between WY 1940 and WY 1964 was assumed to be a linear correction. This results in an average rate of correction of 0.022 ft/yr (6.7 mm/yr) over this period of time.

Similarly, for the Burns Cutoff gage station, the difference between the "zero on gage" measurements between WY 1951 and WY 1964 was assumed to be a linear correction. This results in an average rate of correction of 0.039 ft/yr (11.9 mm/yr) over this period of time.

These "zero on gage" were assumed to be subsidence corrections and were made on a linear basis from WY 1953 through WY 1964 for each of the gage stations.

2.3 Datum Conversion

Four vertical datums were used to record the raw stage data:

- USED – United States Engineering Datum
- USCGS – United States Coast and Geodetic Survey
- NGVD29 – National Geodetic Vertical Datum of 1929, and in some cases the datum NGVD29+3ft was used to avoid negative stage values
- NAVD88 – North American Vertical Datum 1988

The datum conversions between USED, USCGS, and NGVD29 are straightforward. Per the stage data summaries, 3.0 ft USED equals 0.0 ft USCGS. The USCGS datum became the NGVD29 datum with a general change to the determination of the combined mean sea level used as its basis. Therefore, the USCGS and NGVD29 datums are assumed to be equal.

The conversion between NGVD29 and NAVD88 is site specific. The adjustment can be estimated using the VERTCON conversion program developed by the National Oceanographic and Atmospheric Administration's (NOAA's) National Geodetic Survey (NGS). The calculated adjustment for each gage station per the VERTCON conversion program is as follows:

Rindge Pump: NGVD29 + 2.14 ft = NAVD88

Burns Cutoff: NGVD29 + 2.06 ft = NAVD88

In 2002, the DWR in association with the NGS, conducted a global positioning system (GPS) survey of the Sacramento-San Joaquin Delta to establish new NAVD88 elevations at over 100 bench marks throughout the area. This survey resulted in adjustments to the calculated conversion from NGVD29 to NAVD88. The resulting conversion for NGVD29 to NAVD88 for each gage station is as follows (+/- 0.07 ft):

Rindge Pump: NAVD88 = NGVD29 + 2.50 ft
= (NGVD29+3ft) – 0.5 ft

Burns Cutoff: NAVD88 = NGVD29 + 2.13 ft
= (NGVD29+3ft) – 0.87 ft

Note that the conversion is presented in both NGVD29 and NGVD29+3ft datums. The NGVD29+3ft datum was in use at both gage stations just prior to the conversion to NAVD88 in WY 2006. Therefore, the adjustments listed by DWR were to the NGVD29+3ft datum.

The NAVD88 adjustment used in this study is based on the 2002 DWR survey adjustment factors. Figure 4 and Figure 5 present the data for the Rindge Pump and Burns Cutoff gage station in the NAVD88 datum with no correction for subsidence or sea level rise other than the "zero on gage" corrections made prior to WY 1965.

Figure 4 - Rindge Pump Gage Station Data, Converted to NAVD88

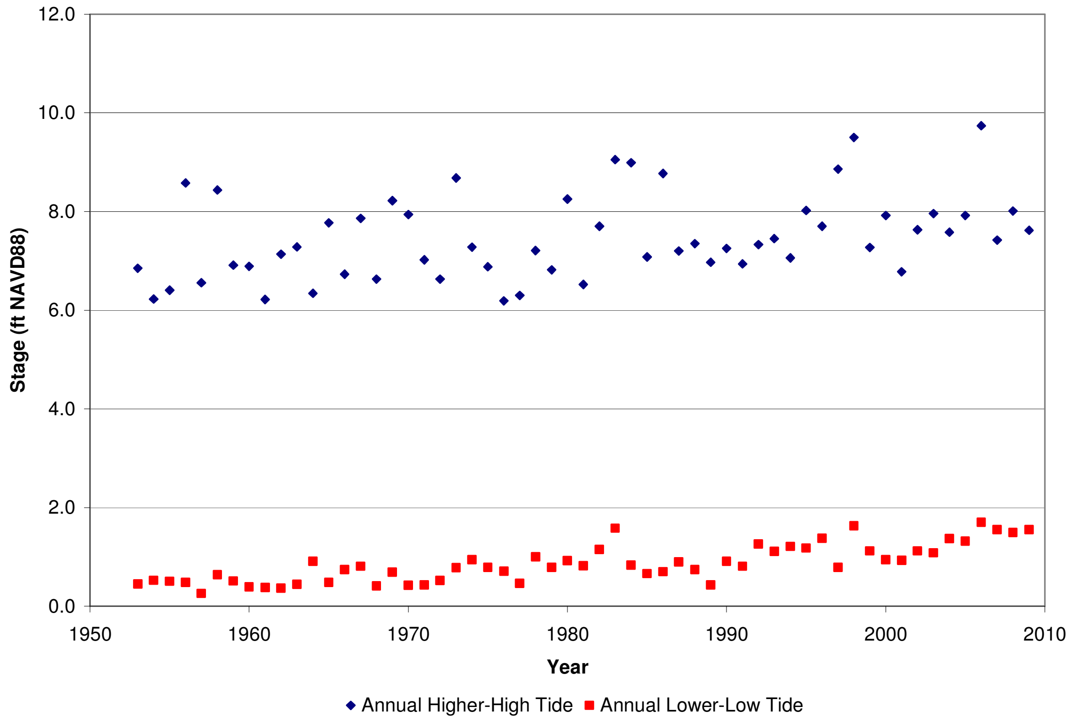
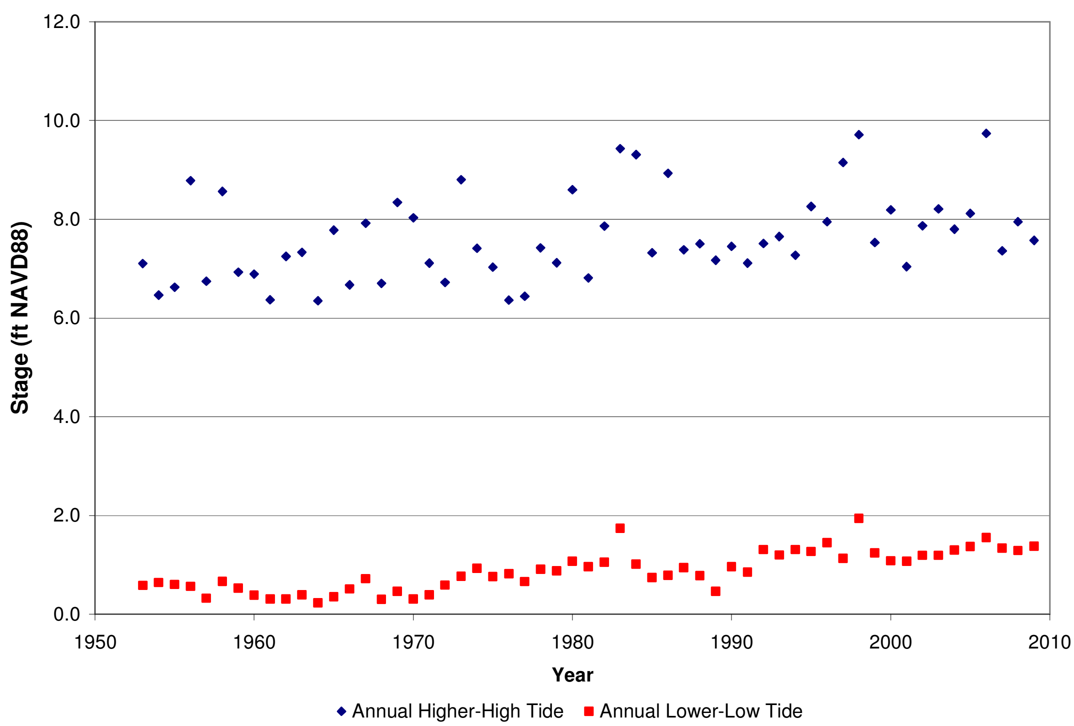


Figure 5 - Burns Cutoff Gage Station Data, Converted to NAVD88



2.4 Lower-Low Tide Analysis

The annual lower-low tide data can be used to estimate the combined impact of subsidence and sea level rise over time. Lower-low tide data is used because hydraulic impacts on the stage data are minimized. The annual lower-low tide data is evaluated for three 19-year epoch periods, to eliminate variability due to the astronomic tide cycle:

- Period 1: WY 1953 to WY 1971
- Period 2: WY 1972 to WY 1990
- Period 3: WY 1991 to WY 2009

Figure 6 and Figure 7 present the running 19-year average of the annual lower-low tide data for the Rindge Pump and Burns Cutoff gage stations. Note that the averages are presented at the mid-point of the 19-year period (e.g. the 19-year average for WY 1972 through WY 1990 is presented in WY 1981).

Figure 6 - Rindge Pump Gage Station 19-Year Running Average of Annual Lower-Low Tides

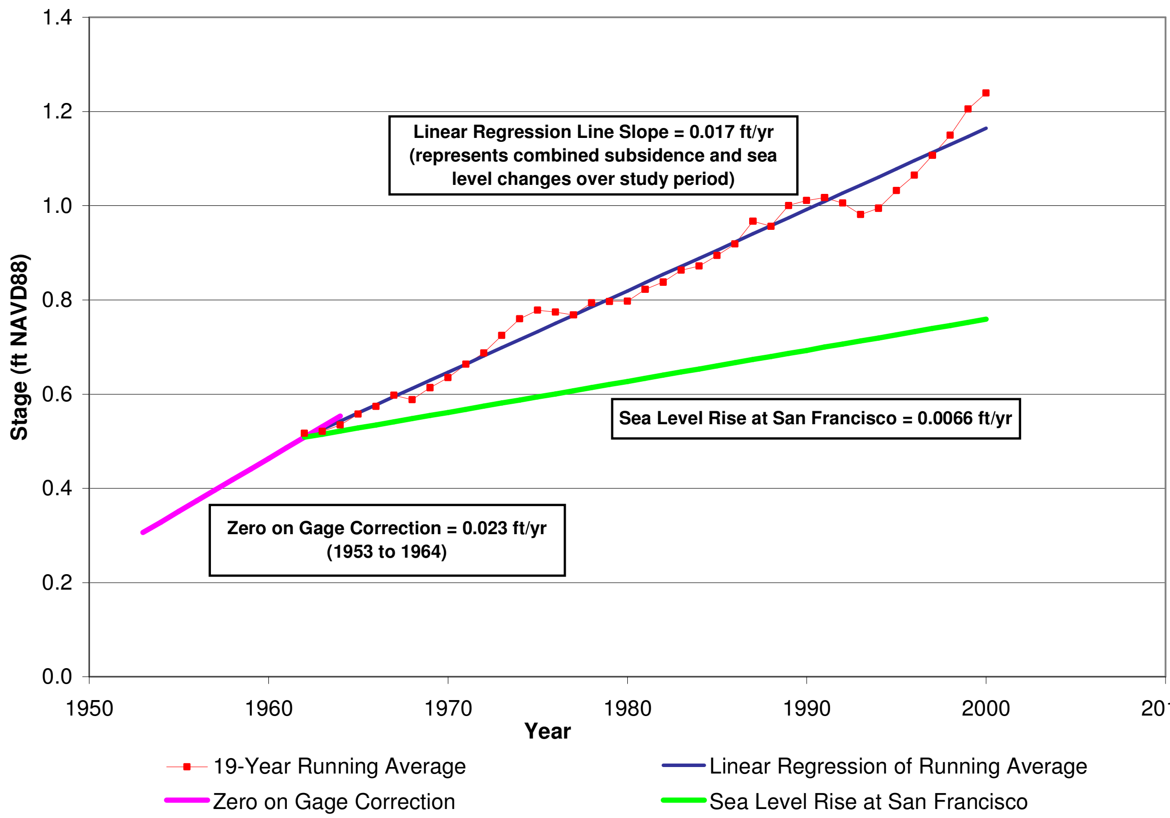
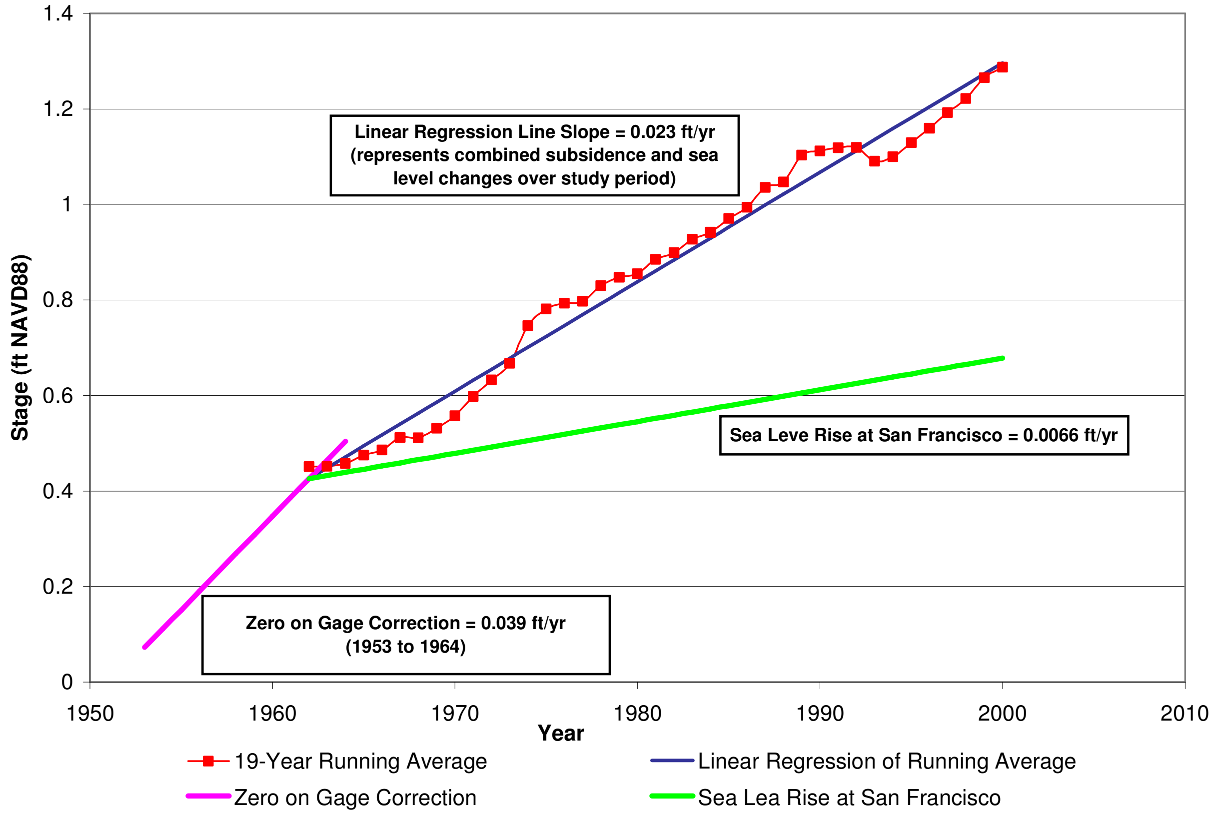


Figure 7 - Burns Cutoff Gage Station 19-Year Running Average of Annual Lower-Low Tides



Each of these figures includes a line representing the linear regression that was performed on the 19-year running average annual lower-low tide data. The slope of this line represents the combined rate of subsidence and sea level rise at each gage station. These results show that the combined impact of subsidence and sea level rise is greater at the Burns Cutoff gage station. Since the sea level rise should be the same at both gage stations (Figure 6 and Figure 7 present the sea level rise at San Francisco for comparison), the impact of subsidence is greater at the Burns Cutoff gage station when compared to the Rindge Pump gage station. For reference, these figures also show the “zero on gage” corrections from the early years of the study relative to the combined impact of subsidence and sea level rise over the entire study period.

2.4.1 Subsidence

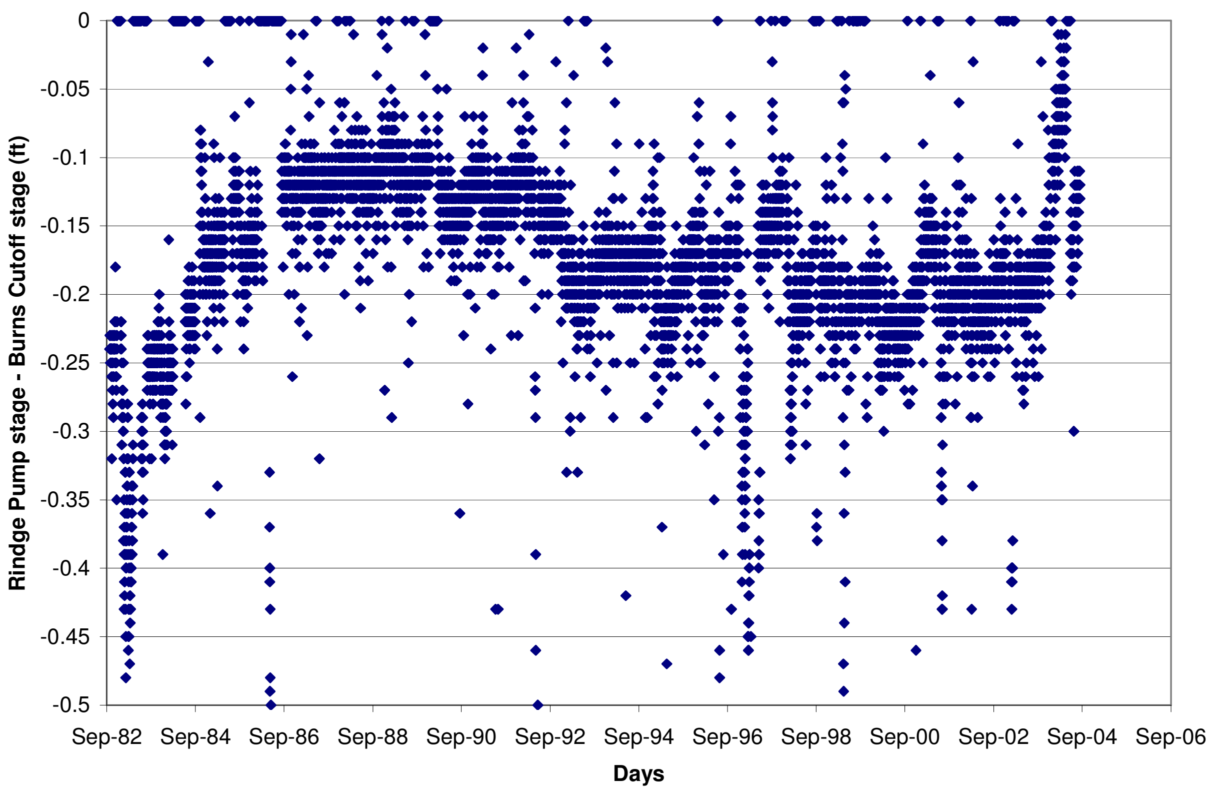
Recall that the “zero on gage” corrections prior to WY 1965 were used to account for subsidence up to WY 1964 in Section 2.2 above. These rates of subsidence are much greater than the combined impact of subsidence and sea level rise shown by the data in Figure 6 and Figure 7. These differences could indicate several possible scenarios:

- The rate of subsidence decreased over time

- The 1964 "zero on gage" correction was not a correction for subsidence only
- The 1964 "zero on gage" correction was made to faulty benchmarks due to land subsidence in the delta region

Figure 8 presents the daily difference between the Rindge Pump and Burns Cutoff gage station lower-low tide since WY 1983 (the first year data is available electronically). Days when the difference equals zero represent days when one of the two gage stations was out of service. The difference between the daily gage readings at the two gage stations would remain constant over time if there was no difference in rates of subsidence at the two gage station. A difference in subsidence rates, suggested by the 1964 "zero on gage" corrections, should result in an overall trend that increases/decreases the daily difference between the lower-low tide levels over time. Note the Figure 8 shows both increasing and decreasing trends in the difference between the lower-low tide levels at the two gage stations. Note also that there appear to be shifts in the data presented in Figure 8 following each time one of the gages is out of service. These shifts could represent undocumented corrections for subsidence over time.

Figure 8 - Daily Lower-Low Tide Gage Reading Differences between the Rindge Pump and Burns Cutoff Gage Stations (WY 1983 through WY 2005)



Subsidence should be separated from sea level rise first using survey data over the entire period of record. There is no documented data to record subsidence rates after WY 1964. Data from the 2002 DWR GPS survey is only a single point with nothing to use for comparison. Due to the lack of reliable subsidence data and documentation, subsidence is estimated using two methods – depending on the period of record:

- **WY 1953 through WY 1964** – Use the 1964 "zero on gage" correction as the linear representation of the rate of subsidence. Note that the data has already been corrected for "zero on gage" during the datum conversion.
- **WY 1965 through WY 2009** - Use the known sea level rise at San Francisco (0.0066 ft/yr) to determine the rate of subsidence on a linear basis. This results in an estimated subsidence of 0.5 ft (0.011 ft/yr) at the Rindge Pump gage station and 0.8 ft (0.017 ft/yr) at the Burns Cutoff gage station.

2.4.2 Sea Level Rise

Theoretically, the subsidence correction would have been based on actual survey data over the entire period of record. This would allow the calculation of the local sea level rise at each of the gage stations. Since this survey data was not available over the entire period of record, the sea level rise at the Rindge Pump and Burns Drive gage stations was assumed to be equal to the historic sea level rise at San Francisco – 0.0066 ft/yr (2.0 mm/yr). All data was adjusted using a linear rate of sea level rise to raise all values over the period of record to the 2009 sea level.

3.0 Stage Frequency Analysis

3.1 Data Used

Prior to performing the stage frequency analysis, the annual higher-high tide data was adjusted to address the following issues discussed previously in this report:

- Conversion to NAVD88 Datum
- Subsidence
- Sea Level Rise

Table 1 and Table 2 present the data used in the stage frequency analysis for the Rindge Pump and Burns Cutoff gage stations. Figure 9 presents the annual higher-high tide data for both gage stations in graphical form for comparison.

Table 1 - Rindge Pump Gage Station Adjusted Annual Higher-High Tide Data					
19-Year Epoch Period 1		**19-Year Epoch Period 2**		**19-Year Epoch Period 3**	
Water Year	**Stage (ft NAVD88)**	**Water Year**	**Stage (ft NAVD88)**	**Water Year**	**Stage (ft NAVD88)**
1953	7.2[(1)]	1972	6.79	1991	6.76
1954	6.6[(1)]	1973	8.83	1992	7.13
1955	6.8[(1)]	1974	7.41	1993	7.24
1956	8.9[(1)]	1975	6.99	1994	6.83
1957	6.9[(1)]	1976	6.28	1995	7.77
1958	8.8[(1)]	1977	6.37	1996	7.43
1959	7.2[(1)]	1978	7.27	1997	8.57
1960	7.21	1979	6.86	1998	9.20
1961	6.53	1980	8.27	1999	6.95
1962	7.45	1981	6.52	2000	7.58
1963	7.59	1982	7.68	2001	6.42
1964	6.64	1983	9.02	2002	7.25
1965	8.06	1984	8.94	2003	7.57
1966	7.00	1985	7.01	2004	7.17
1967	8.11	1986	8.68	2005	7.49
1968	6.87	1987	7.09	2006	9.29
1969	8.44	1988	7.23	2007	6.95
1970	8.14	1989	6.83	2008	7.53
1971	7.20	1990	7.09	2009	7.12

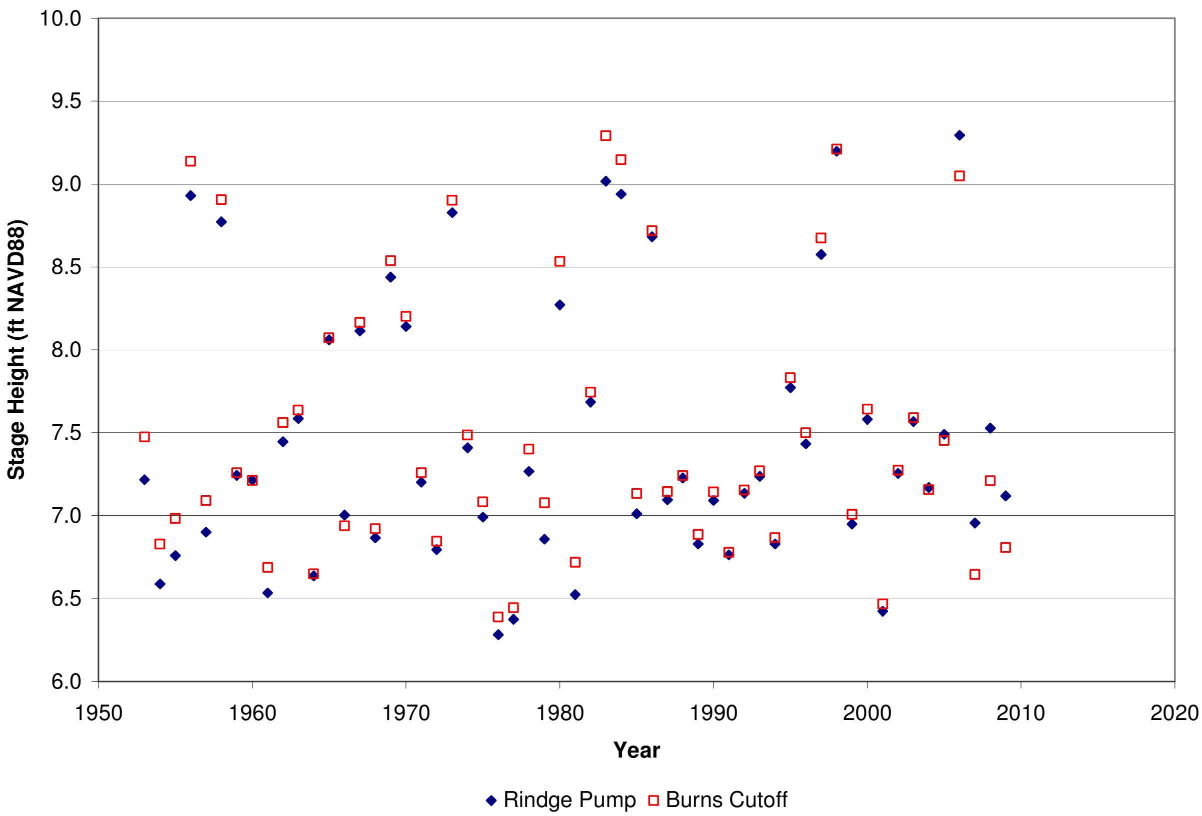
Notes:
[(1)] Tide Stage Data recorded prior to 1960 was recorded to the tenths of a foot. Therefore, the precision of the adjusted annual higher-high tide data is presented only to the tenths of a foot. Tide Stage Data recorded in 1960 and later was recorded to the hundredths of a foot.

Table 2 - Burns Cutoff Gage Station Adjusted Annual Higher-High Tide Data					
19-Year Epoch Period 1		**19-Year Epoch Period 2**		**19-Year Epoch Period 3**	
Water Year	**Stage (ft NAVD88)**	**Water Year**	**Stage (ft NAVD88)**	**Water Year**	**Stage (ft NAVD88)**
1953	7.5[(1)]	1972	6.84	1991	6.78
1954	6.8[(1)]	1973	8.90	1992	7.15
1955	7.0[(1)]	1974	7.49	1993	7.27
1956	9.1[(1)]	1975	7.08	1994	6.87
1957	7.1[(1)]	1976	6.39	1995	7.83
1958	8.9[(1)]	1977	6.44	1996	7.50
1959	7.3[(1)]	1978	7.40	1997	8.67
1960	7.21	1979	7.08	1998	9.21
1961	6.69	1980	8.53	1999	7.01
1962	7.56	1981	6.72	2000	7.64
1963	7.64	1982	7.74	2001	6.47
1964	6.65	1983	9.29	2002	7.27
1965	8.07	1984	9.15	2003	7.59
1966	6.94	1985	7.13	2004	7.16

Table 2 - Burns Cutoff Gage Station Adjusted Annual Higher-High Tide Data					
19-Year Epoch Period 1		19-Year Epoch Period 2		19-Year Epoch Period 3	
Water Year	Stage (ft NAVD88)	Water Year	Stage (ft NAVD88)	Water Year	Stage (ft NAVD88)
1967	8.16	1986	8.72	2005	7.45
1968	6.92	1987	7.14	2006	9.05
1969	8.54	1988	7.24	2007	6.64
1970	8.20	1989	6.89	2008	7.21
1971	7.26	1990	7.14	2009	6.81

Notes:
(1) Tide Stage Data recorded prior to 1960 was recorded to the tenths of a foot. Therefore, the precision of the adjusted annual higher-high tide data is presented only to the tenths of a foot. Tide Stage Data recorded in 1960 and later was recorded to the hundredths of a foot.

Figure 9 - Adjusted Annual Higher-High Tide Gage Station Data



3.2 Stage Frequency Analysis Results

The data presented in Table 1 and Table 2 was analyzed using the USACE Hydrologic Engineering Center Statistical Software Package (HEC-SSP). The data analyses were performed using the generalized frequency analysis with a Weibull plotting position and a normal probability distribution. Table 3 presents the stage frequency analysis results for the Rindge Pump and Burns Cutoff gage stations using the graphical method to address the S-shaped curve that passes through the data. The graphical method acknowledges that the higher stage events are dependent on higher flows, which in turn can be impacted by channel geometry as well as upstream and downstream overall system operation (e.g. levee failures and dam releases). Appendices A and B present the HEC-SSP analytical plots and stage frequency analysis reports for the Rindge Pump and Burns Cutoff gage stations.

Table 3 - Stage Frequency Analysis Results (WY 2009 Sea Level Conditions)

Annual Exceedance Probability	Confidence Limit(1)	Rindge Pump (ft NAVD88)	Burns Cutoff (ft NAVD88)
1/50	95%	8.9	9.0
	50%	**9.3**	**9.3**
	5%	9.7	9.6
1/100	95%	9.1	9.0
	50%	**9.4**	**9.4**
	5%	9.8	9.8
1/200	95%	9.2	9.1
	50%	**9.6**	**9.5**
	5%	10.0	9.9

(1) The confidence limit represents the percent confidence the stage will be exceeded. For example, there is a 95% confidence that a 1/50 flood stage of 8.9 ft would be exceeded and a 5% confidence that a 1/50 flood stage of 9.7 ft would be exceeded at the Rindge Pump gage station. Note that the range of values between the 95% and 5% confidence limits represents the 90% confidence interval – meaning that there is 90% confidence that the given flood stage will occur between the two values.

3.2.1 Comparison to Previous Studies

Table 4 presents the stage frequency analysis results from the previous USACE studies in 1976, 1982, and 1992. The results were converted from NGVD29 datum to NAVD88 datum using the 2002 DWR GPS survey correction factors for comparison.

Table 4 - Stage Frequency Analysis Results from Previous USACE Studies

USACE Report Year	Annual Exceedance Probability	Rindge Pump		Burns Cutoff	
		ft NGVD29	ft NAVD88	ft NGVD29	ft NAVD88
1976	1/50	7.1	9.6	7.2	9.3
	1/100	7.4	9.9	7.5	9.6
1982	1/50	7.1	9.6	7.2	9.3
	1/100	7.4	9.9	7.5	9.6
1992	1/50	7.2	9.7	7.4	9.5
	1/100	7.4	9.9	7.6	9.7

Because the previous study results presented in Table 4 do not address subsidence and sea level rise, the results of the two studies cannot be compared quantitatively. However, the previous studies showed that the higher-high tide stage was 0.1 to 0.2 ft higher in NGVD29 datum at Burns Cutoff gage station than at Rindge Pump gage station. Since the Burns Cutoff gage station is upstream of the Rindge Pump gages station, this difference is reasonable at the higher-high tide. Without any correction for subsidence and sea level rise, the conversion from NGVD29 to NAVD88 datum for the previous studies shows that the Burns Cutoff higher-high tide stage is 0.2 to 0.3 ft lower than at the Rindge Pump gage station. The results of this study (see Table 3), which take subsidence and sea level rise into account, show that the higher-high tide stage is approximately the same in NAVD88 datum at Burns Cutoff gage station as it is at Rindge Pump gage station – which is consistent with the previous studies and as expected due to their close proximity.

4.0 Climate Change Impacts

Future sea level rise will increase the stage frequency results calculated for WY 2009. USACE Circular No. 1165-2-211, "Water Resources Policies and Authorities Incorporating Sea-Level Change Considerations in Civil Works Programs," states that planning studies and engineering designs should consider alternatives that are developed and assessed for the entire range of possible future rates of sea level rise. Alternatives should be analyzed using "low," "intermediate," and "high" rates of future sea level rise, based on the following:

- **Low** – use local historic rate of sea level rise; assumed to be 0.66 ft/100-yr (2.0 mm/yr) per the value measured at San Francisco
- **Intermediate** - use the modified National Research Council (NRC) Curve I for estimating future sea level rise
- **High** - use the modified NRC Curve III for estimating future sea level rise

The equation for the modified NRC curves to determine the change in sea level since 1986 is presented below:

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2)$$, where

$E(t_2) - E(t_1)$ = represents sea level rise between current and future years
$E(t_1)$ = current sea level rise relative to the 1986 sea level, meters
$E(t_2)$ = sea level rise in the future relative to the 1986 sea level, meters
t_1 = current year – 1986
t_2 = future year – 1986
b = constant = 2.360E-05 for NRC Curve I
1.005E-04 for NRC Curve III

Table 5 presents the estimated sea level rise at the Rindge Pump and Burns Cutoff gage stations. Note that all three rates of sea level rise are identical for the two gage stations.

Table 5 - Estimated Future Sea Level Rise from 2009

Year	Sea Level Rise, ft		
	Low	Intermediate	High
2030	0.1	0.2	0.6
2050	0.3	0.5	1.4
2080	0.5	1.1	3.2
2100	0.6	1.5	4.7

4.1 Estimated Future Stage Frequency

To estimate the future stage frequencies for the Rindge Pump and Burns Cutoff gage stations, the stage frequency analysis results from Table 3 were combined with the estimated sea level rise presented in Table 5. The combination of this information results in a series of figures for each gage station presenting the estimated stage (including the 90% confidence interval) for a given exceedance probability and the three sea level rise scenarios. A description of these figures is presented below:

- Rindge Pump Gage Station –
  - Figure 10, estimated stage with a 1/200 annual exceedance probability
  - Figure 11, estimated stage with a 1/100 annual exceedance probability
  - Figure 12, estimated stage with a 1/50 annual exceedance probability
- Burns Cutoff Gage Station –
  - Figure 13, estimated stage with a 1/200 annual exceedance probability
  - Figure 14, estimated stage with a 1/100 annual exceedance probability
  - Figure 15, estimated stage with a 1/50 annual exceedance probability

For reference, the minimum levee height in the area near each gage station is shown on each of these figures. Note that the stage projections into the future are based on an assumption that the levee height will be increased in the future to accommodate sea level rise.

Figure 10 - Rindge Pump Gage Station Estimated Stage with 1/200 Annual Exceedance Probability, 2010 through 2100

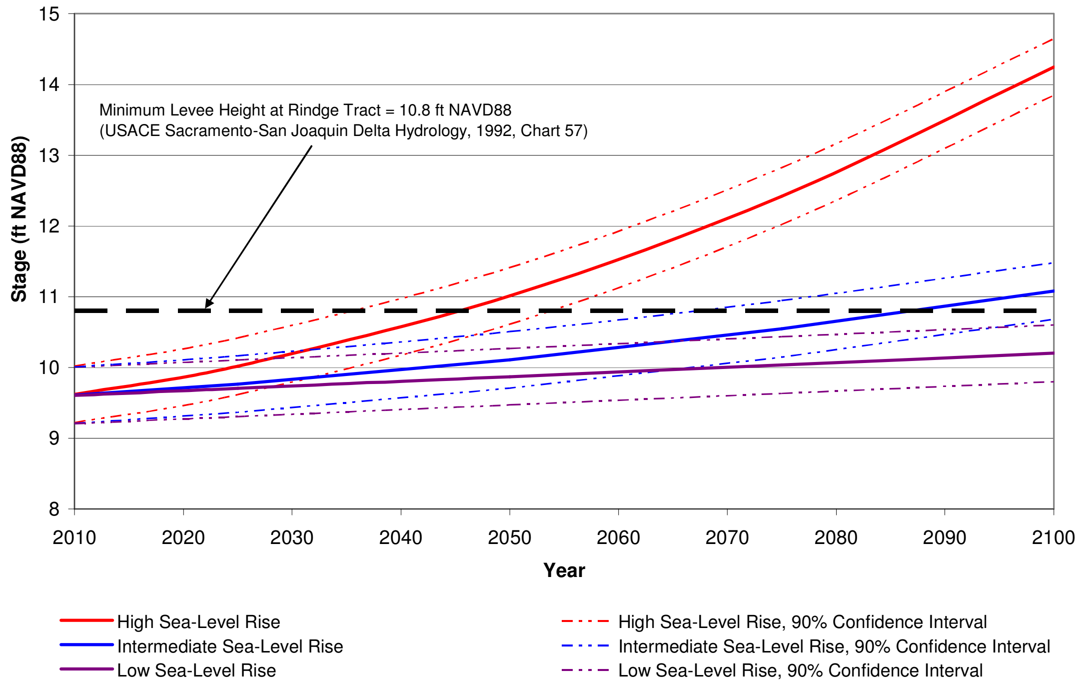


Figure 11 - Rindge Pump Gage Station Estimated Stage with 1/100 Annual Exceedance Probability, 2010 through 2100

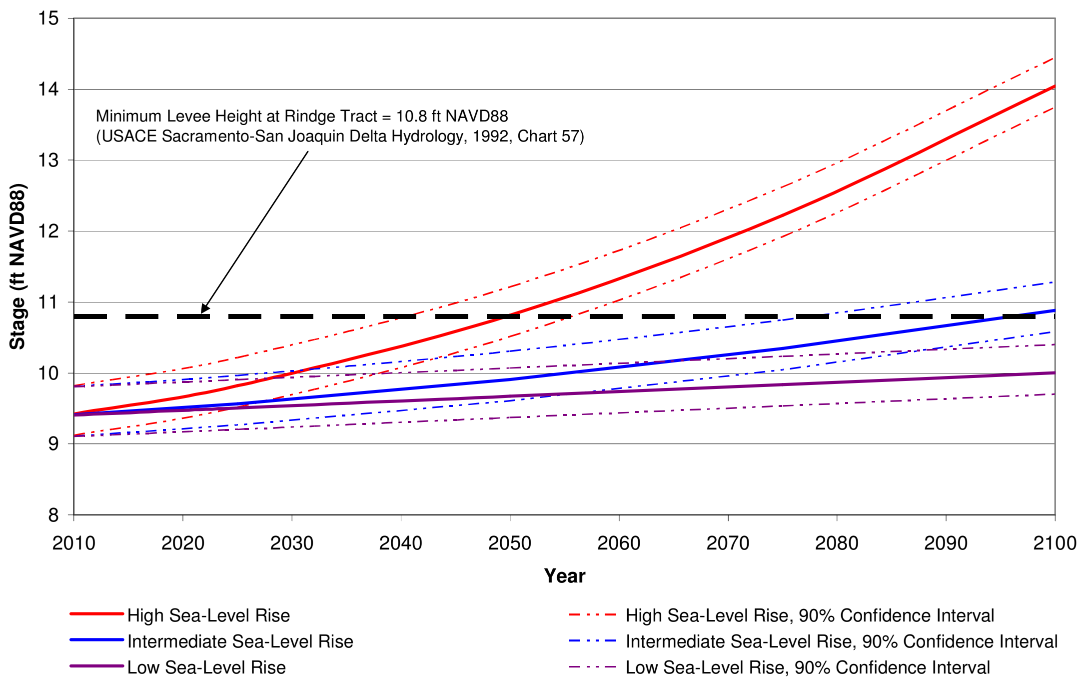


Figure 12 - Rindge Pump Gage Station Estimated Stage with 1/50 Annual Exceedance Probability, 2010 through 2100

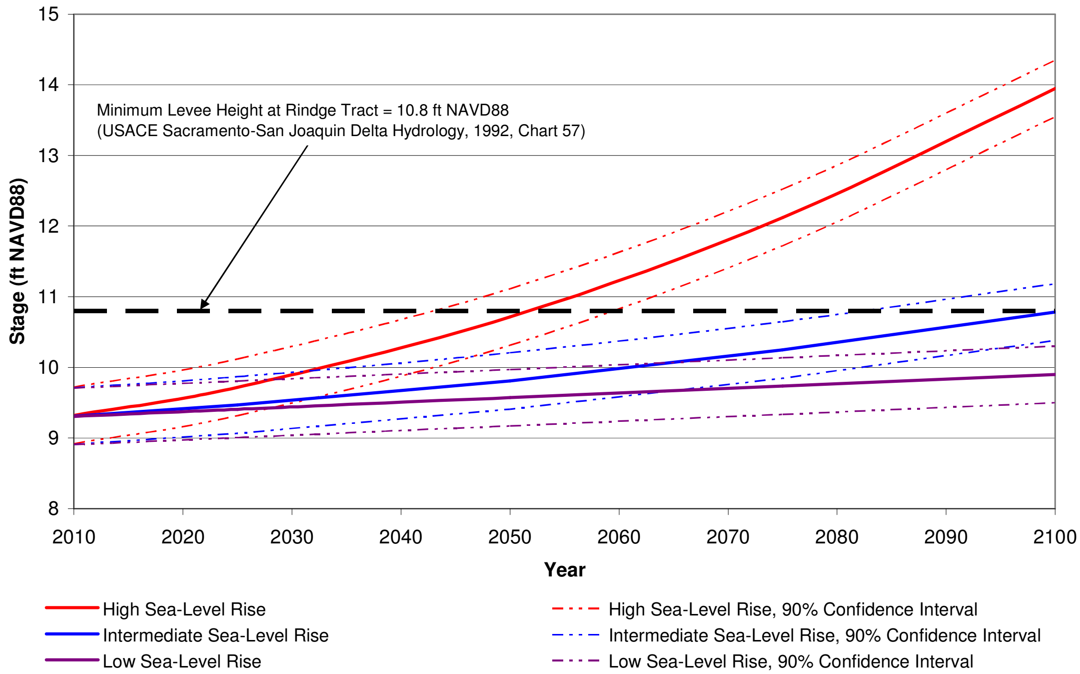


Figure 13 - Burns Cutoff Gage Station Estimated Stage with 1/200 Annual Exceedance Probability, 2010 through 2100

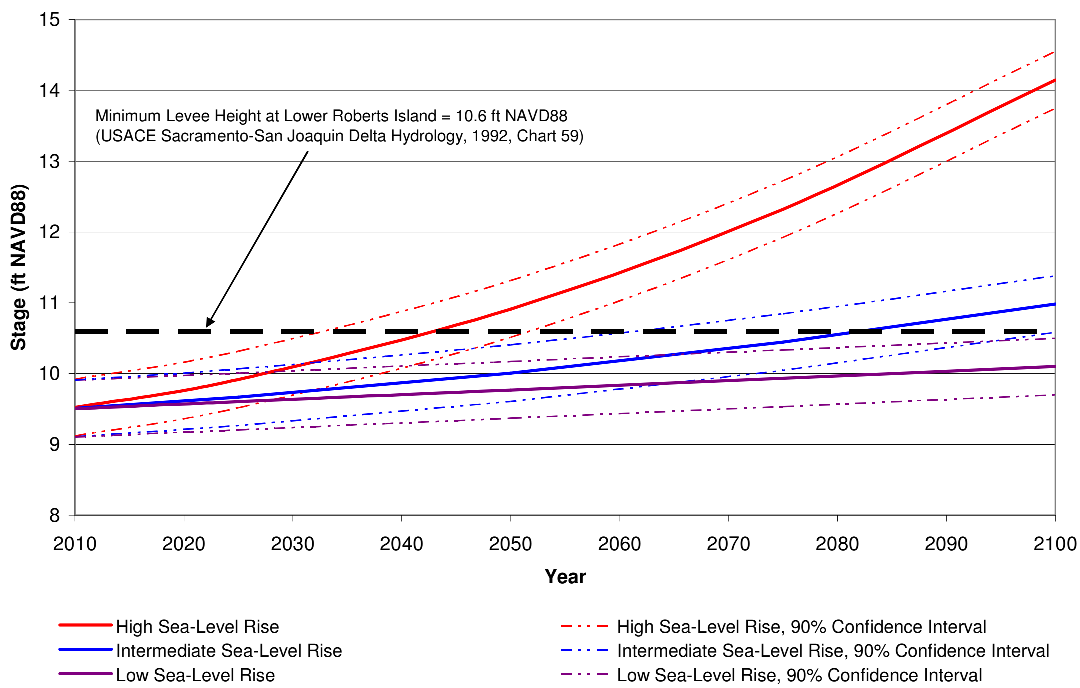


Figure 14 - Burns Cutoff Gage Station Estimated Stage with 1/100 Annual Exceedance Probability, 2010 through 2100

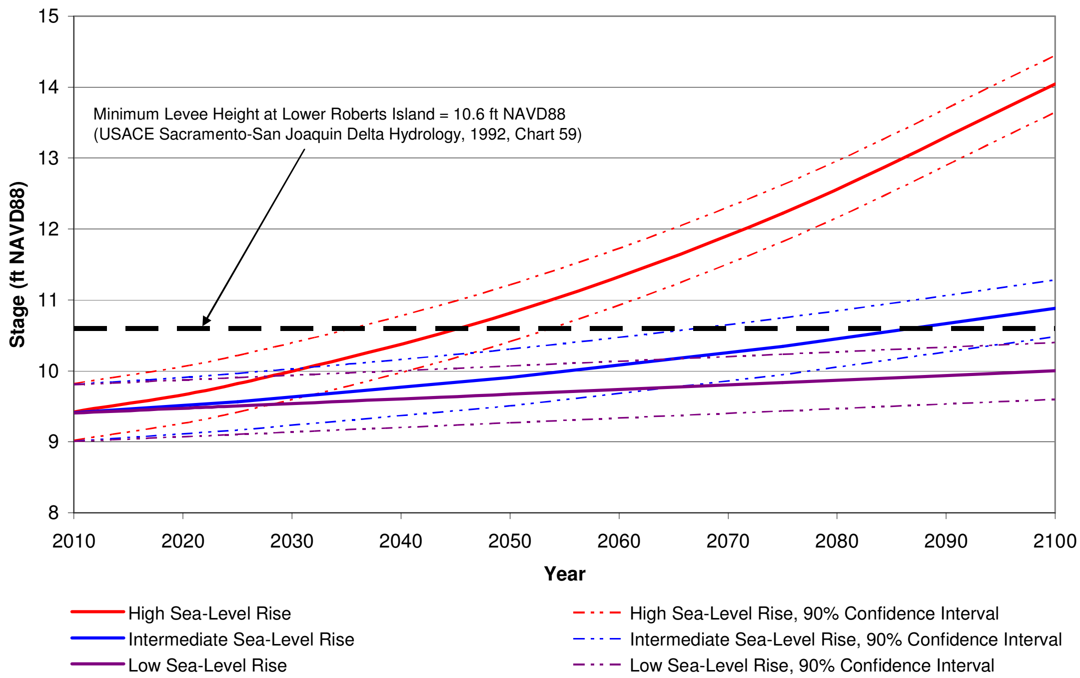
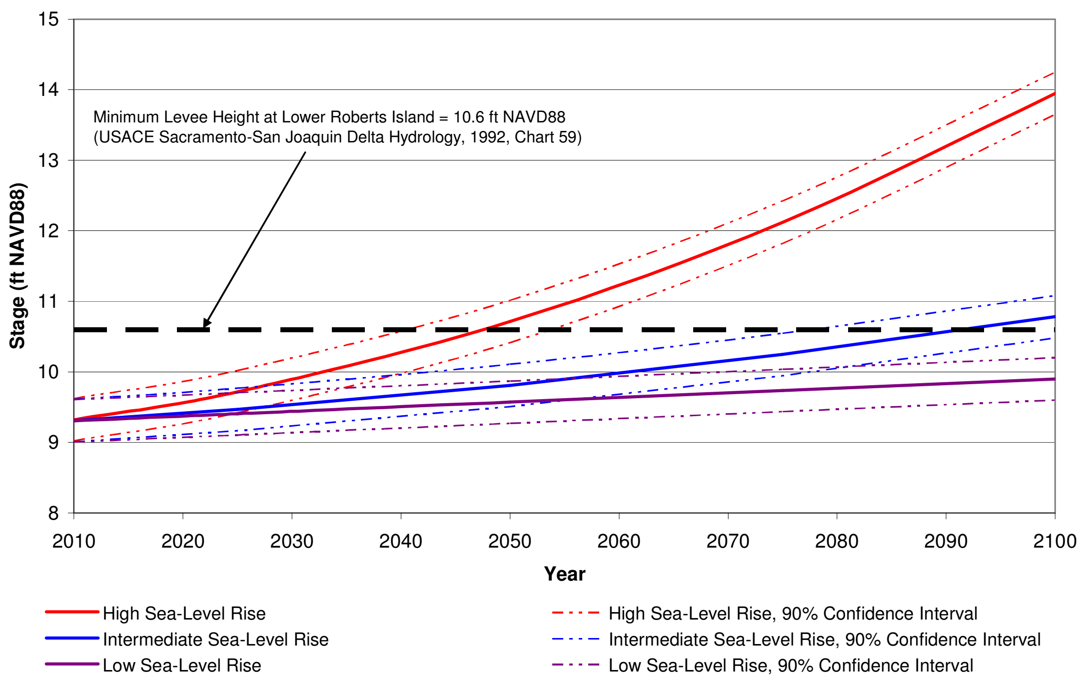


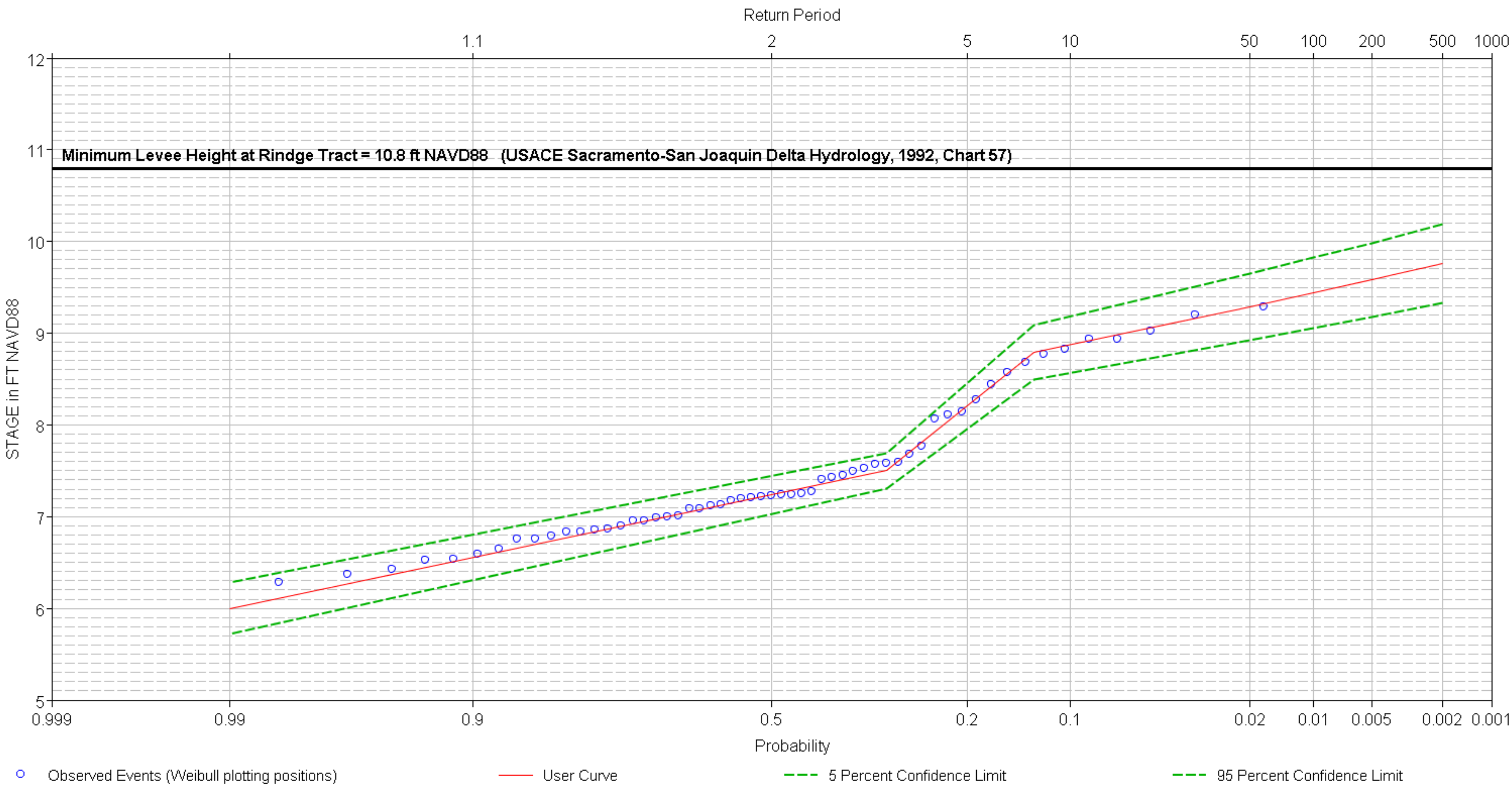
Figure 15 - Burns Cutoff Gage Station Estimated Stage with 1/50 Annual Exceedance Probability, 2010 through 2100



Appendix A

HEC-SSP Analytical Plot and Stage Frequency Analysis Report for Rindge Pump Gage Station

General Frequency Graphical Plot for Rindge Pump Stage Frequency Analysis



General Frequency Analysis
02 Aug 2010 10:05 AM

--- Input Data ---

Analysis Name: Rindge Pump SFA
Description:

Data Set Name: RP Final Report
DSS File Name: C:/Documents and Settings/dmurbach/My Documents/HEC/Rindge_Pump_051010/
Rindge_Pump_051010.dss
DSS Pathname: /STAGE////IR-CENTURY//

Start Date: 01 Oct 1952
End Date: 30 Sep 2009

Project Path: C:\Documents and Settings\dmurbach\My Documents\HEC\Rindge_Pump_051010
Report File Name: C:\Documents and Settings\dmurbach\My Documents\HEC\Rindge_Pump_051010\
GeneralFrequencyResults\Rindge_Pump_SFA\Rindge_Pump_SFA.rpt
Result File Name: C:\Documents and Settings\dmurbach\My Documents\HEC\Rindge_Pump_051010\
GeneralFrequencyResults\Rindge_Pump_SFA\Rindge_Pump_SFA.xml

Plotting Position Type: Weibull

Probability Distribution Type: Normal
Compute Expected Probability Curve

Upper Confidence Level: 0.05
Lower Confidence Level: 0.95

!Gfa.Input.UseNonStandardFrequency.label!
Frequency: 0.2
Frequency: 0.5
Frequency: 1.0
Frequency: 2.0
Frequency: 13.0
Frequency: 31.0
Frequency: 99.0

Display ordinate values using 2 digits in fraction part of value

--- End of Input Data ---

<< High Outlier Test >>

Based on 57 events, 10 percent outlier test deviate K(N) = 2.818
Computed high outlier test value = 9.678

0 high outlier(s) identified above test value of 9.678

<< Low Outlier Test >>

Based on 57 events, 10 percent outlier test deviate K(N) = 2.818
Computed low outlier test value = 5.237

0 low outlier(s) identified below test value of 5.237

--- Final Results ---

<< Plotting Positions >>
RP Final Report

Events Analyzed		Ordered Events			
			Water		Weibull
Day Mon Year	FT	Rank	Year	FT	Plot Pos
01 Dec 1952	7.22	1	2006	9.29	1.72
17 Jan 1954	6.59	2	1998	9.20	3.45
09 Dec 1954	6.76	3	1983	9.02	5.17
26 Jan 1956	8.93	4	1984	8.94	6.90
29 Jun 1957	6.90	5	1956	8.93	8.62
06 Apr 1958	8.77	6	1973	8.83	10.34
16 Feb 1959	7.24	7	1958	8.77	12.07
09 Feb 1960	7.21	8	1986	8.68	13.79
01 Dec 1960	6.53	9	1997	8.57	15.52
15 Feb 1962	7.45	10	1969	8.44	17.24
04 Feb 1963	7.59	11	1980	8.27	18.97
05 Nov 1963	6.64	12	1970	8.14	20.69
27 Dec 1964	8.06	13	1967	8.11	22.41
04 Feb 1966	7.00	14	1965	8.06	24.14
24 Jan 1967	8.11	15	1995	7.77	25.86

08 Jul 1968	6.87	16	1982	7.68	27.59
15 Feb 1969	8.44	17	1963	7.59	29.31
23 Jan 1970	8.14	18	2000	7.58	31.03
30 Nov 1970	7.20	19	2003	7.57	32.76
02 Dec 1971	6.79	20	2008	7.53	34.48
18 Jan 1973	8.83	21	2005	7.49	36.21
08 Jan 1974	7.41	22	1962	7.45	37.93
11 Jun 1975	6.99	23	1996	7.43	39.66
05 Nov 1975	6.28	24	1974	7.41	41.38
30 Jun 1977	6.37	25	1978	7.27	43.10
16 Jan 1978	7.27	26	2002	7.25	44.83
23 Feb 1979	6.86	27	1993	7.24	46.55
18 Jan 1980	8.27	28	1959	7.24	48.28
29 Jul 1981	6.52	29	1988	7.23	50.00
05 Jan 1982	7.68	30	1953	7.22	51.72
29 Jan 1983	9.02	31	1960	7.21	53.45
03 Dec 1983	8.94	32	1971	7.20	55.17
24 Nov 1984	7.01	33	2004	7.17	56.90
21 Feb 1986	8.68	34	1992	7.13	58.62
11 Jul 1987	7.09	35	2009	7.12	60.34
06 Dec 1987	7.23	36	1990	7.09	62.07
04 Jun 1989	6.83	37	1987	7.09	63.79
22 Jun 1990	7.09	38	1985	7.01	65.52
09 Jul 1991	6.76	39	1966	7.00	67.24
15 Feb 1992	7.13	40	1975	6.99	68.97
19 Feb 1993	7.24	41	2007	6.95	70.69
11 Dec 1993	6.83	42	1999	6.95	72.41
21 Mar 1995	7.77	43	1957	6.90	74.14
21 Feb 1996	7.43	44	1968	6.87	75.86
05 Jan 1997	8.57	45	1979	6.86	77.59
06 Feb 1998	9.20	46	1994	6.83	79.31
09 Feb 1999	6.95	47	1989	6.83	81.03
14 Feb 2000	7.58	48	1972	6.79	82.76
06 Mar 2001	6.42	49	1991	6.76	84.48
02 Dec 2001	7.25	50	1955	6.76	86.21
16 Dec 2002	7.57	51	1964	6.64	87.93
24 Dec 2003	7.17	52	1954	6.59	89.66
08 Jan 2005	7.49	53	1961	6.53	91.38
31 Dec 2005	9.29	54	1981	6.52	93.10
11 Jul 2007	6.95	55	2001	6.42	94.83
04 Jan 2008	7.53	56	1977	6.37	96.55
25 Dec 2008	7.12	57	1976	6.28	98.28

<< Frequency Curve >>
RP Final Report

Computed Curve (STAGE, FT NAVD88)	Expected Probability (STAGE, FT NAVD88)	Percent Chance Exceedance	Confidence Limits 0.05 (STAGE, FT NAVD88)	Confidence Limits 0.95 (STAGE, FT NAVD88)
9.73	9.84	0.2	10.18	9.38
9.49	9.58	0.5	9.90	9.17
9.29	9.36	1.0	9.68	9.00
9.08	9.13	2.0	9.43	8.80
8.34	8.36	13.0	8.59	8.14
7.85	7.85	31.0	8.04	7.67
5.62	5.55	99.0	5.92	5.24

<< Systematic Statistics >>
RP Final Report

STAGE, FT NAVD88		Number of Events	
Mean	7.46	Historic Events	0
Standard Dev	0.79	High Outliers	0
Station Skew	0.85	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	0.00	Systematic Events	57

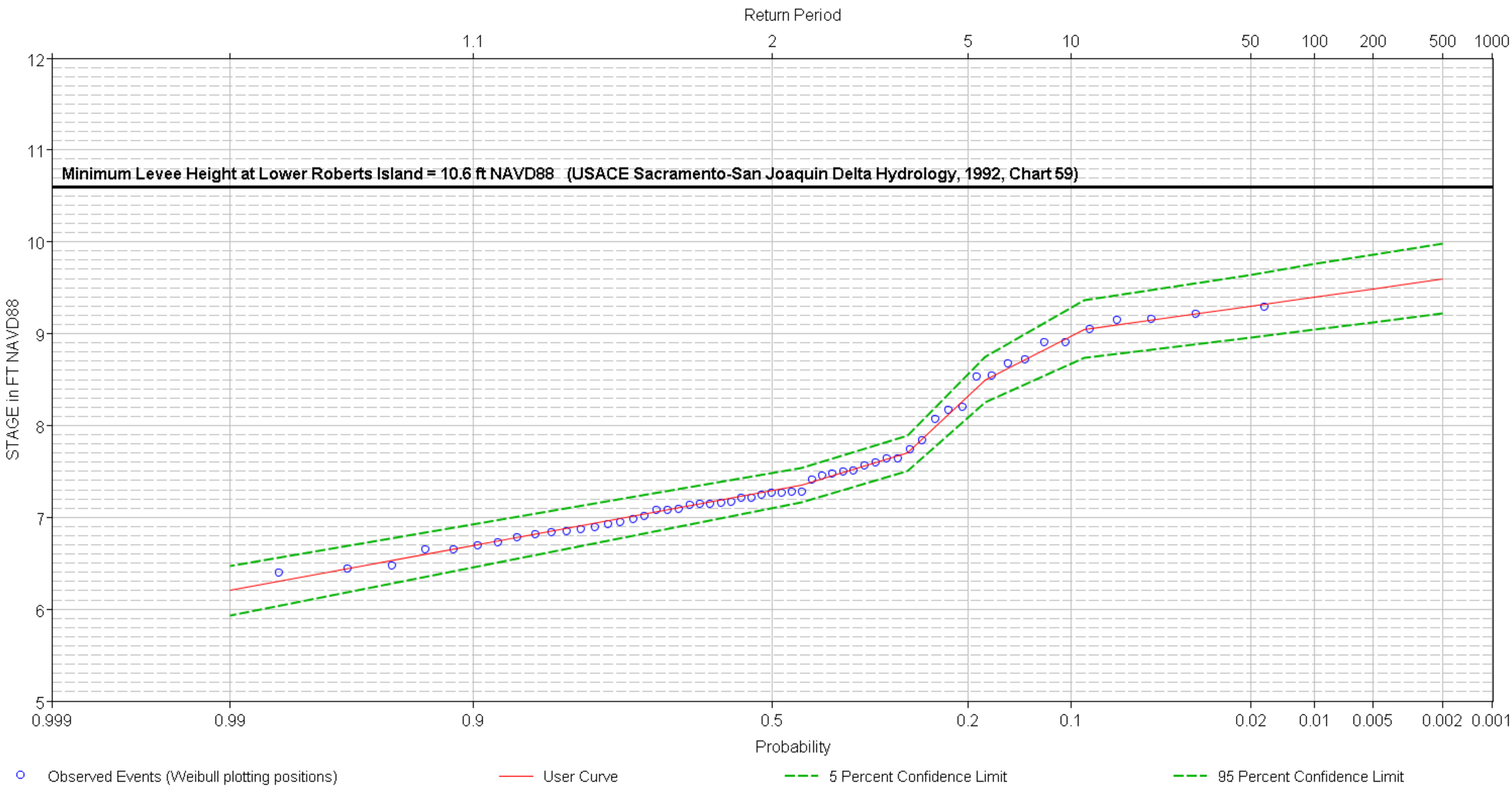
<< User-Defined Graphical Frequency Curve >>
RP Final Report

Computed Curve (STAGE, FT NAVD88)	Expected Probability (STAGE, FT NAVD88)	Percent Chance Exceedance	Confidence Limits 0.05 (STAGE, FT NAVD88)	Confidence Limits 0.95 (STAGE, FT NAVD88)
9.76	---	0.2	10.19	9.33
9.58	---	0.5	9.98	9.18
9.44	---	1.0	9.82	9.06
9.29	---	2.0	9.65	8.93
8.79	---	13.0	9.09	8.49
7.50	---	31.0	7.69	7.31
6.00	---	99.0	6.28	5.72

Appendix B

HEC-SSP Analytical Plot and Stage Frequency Analysis Report for Burns Cutoff Gage Station

General Frequency Graphical Plot for Burns Cutoff Stage Frequency Analysis



General Frequency Analysis
02 Aug 2010   10:54 AM

--- Input Data ---

Analysis Name: Burns Cutoff Stage Frequency Analysis
Description:

Data Set Name: Final Report with Dates
DSS File Name: C:/Documents and Settings/dmurbach/My Documents/HEC/Burns_Cutoff_051110/
Burns_Cutoff_051110.dss
DSS Pathname: /STAGE////IR-CENTURY//

Start Date: 01 Oct 1952
End Date: 30 Sep 2009

Project Path: C:\Documents and Settings\dmurbach\My Documents\HEC\Burns_Cutoff_051110
Report File Name: C:\Documents and Settings\dmurbach\My Documents\HEC\Burns_Cutoff_051110\
GeneralFrequencyResults\Burns_Cutoff_Stage_Frequency_Analysis\
Burns_Cutoff_Stage_Frequency_Analysis.rpt
Result File Name: C:\Documents and Settings\dmurbach\My Documents\HEC\
Burns_Cutoff_051110\GeneralFrequencyResults\Burns_Cutoff_Stage_Frequency_Analysis\Burns_Cutoff_
Stage_Frequency_Analysis.xml

Plotting Position Type: Weibull

Probability Distribution Type: Normal
Compute Expected Probability Curve

Upper Confidence Level: 0.05
Lower Confidence Level: 0.95

Use Low Outlier Threshold
Low Outlier Threshold: 5.0

!Gfa.Input.UseNonStandardFrequency.label!
Frequency: 0.2
Frequency: 0.5
Frequency: 1.0
Frequency: 2.0
Frequency: 9.0
Frequency: 18.0
Frequency: 28.0
Frequency: 45.0

Frequency: 99.0

Display ordinate values using 2 digits in fraction part of value

--- End of Input Data ---

<< High Outlier Test >>

Based on 57 events, 10 percent outlier test deviate K(N) = 2.818
Computed high outlier test value = 9.772

0 high outlier(s) identified above test value of 9.772

<< Low Outlier Test >>

Based on 57 events, 10 percent outlier test deviate K(N) = 2.818
Computed low outlier test value = 5.26

0 low outlier(s) identified below input threshold of 5

--- Final Results ---

<< Plotting Positions >>
Final Report with Dates

Events Analyzed				Ordered Events			
					Water		Weibull
Day Mon Year			FT	Rank	Year	FT	Plot Pos
01 Dec 1952			7.47	1	1983	9.29	1.72
17 Jan 1954			6.83	2	1998	9.21	3.45
09 Dec 1954			6.98	3	1984	9.15	5.17
26 Jan 1956			9.14	4	1956	9.14	6.90
29 Jun 1957			7.09	5	2006	9.05	8.62
04 Apr 1958			8.90	6	1973	8.90	10.34
21 Feb 1959			7.26	7	1958	8.90	12.07
09 Feb 1960			7.21	8	1986	8.72	13.79

01 Dec 1960	6.69	9	1997	8.67	15.52
15 Feb 1962	7.56	10	1969	8.54	17.24
04 Feb 1963	7.64	11	1980	8.53	18.97
05 Nov 1963	6.65	12	1970	8.20	20.69
27 Dec 1964	8.07	13	1967	8.16	22.41
10 Dec 1965	6.94	14	1965	8.07	24.14
24 Jan 1967	8.16	15	1995	7.83	25.86
08 Jul 1968	6.92	16	1982	7.74	27.59
15 Feb 1969	8.54	17	2000	7.64	29.31
23 Jan 1970	8.20	18	1963	7.64	31.03
30 Nov 1970	7.26	19	2003	7.59	32.76
02 Dec 1971	6.84	20	1962	7.56	34.48
18 Jan 1973	8.90	21	1996	7.50	36.21
08 Jan 1974	7.49	22	1974	7.49	37.93
11 Jun 1975	7.08	23	1953	7.47	39.66
05 Nov 1975	6.39	24	2005	7.45	41.38
30 Jun 1977	6.44	25	1978	7.40	43.10
16 Jan 1978	7.40	26	2002	7.27	44.83
23 Feb 1979	7.08	27	1993	7.27	46.55
21 Feb 1980	8.53	28	1971	7.26	48.28
29 Jul 1981	6.72	29	1959	7.26	50.00
05 Jan 1982	7.74	30	1988	7.24	51.72
29 Jan 1983	9.29	31	2008	7.21	53.45
03 Dec 1983	9.15	32	1960	7.21	55.17
24 Nov 1984	7.13	33	2004	7.16	56.90
10 Mar 1986	8.72	34	1992	7.15	58.62
11 Jul 1987	7.14	35	1990	7.14	60.34
06 Dec 1987	7.24	36	1987	7.14	62.07
04 Jun 1989	6.89	37	1985	7.13	63.79
22 Jun 1990	7.14	38	1957	7.09	65.52
09 Jul 1991	6.78	39	1979	7.08	67.24
15 Feb 1992	7.15	40	1975	7.08	68.97
07 Jan 1993	7.27	41	1999	7.01	70.69
11 Dec 1993	6.87	42	1955	6.98	72.41
21 Mar 1995	7.83	43	1966	6.94	74.14
21 Feb 1996	7.50	44	1968	6.92	75.86
05 Jan 1997	8.67	45	1989	6.89	77.59
06 Feb 1998	9.21	46	1994	6.87	79.31
09 Feb 1999	7.01	47	1972	6.84	81.03
14 Feb 2000	7.64	48	1954	6.83	82.76
08 Jan 2001	6.47	49	2009	6.81	84.48
02 Dec 2001	7.27	50	1991	6.78	86.21
16 Dec 2002	7.59	51	1981	6.72	87.93
24 Dec 2003	7.16	52	1961	6.69	89.66
08 Jan 2005	7.45	53	1964	6.65	91.38
03 Jan 2006	9.05	54	2007	6.64	93.10

11 Jul 2007	6.64	55	2001	6.47	94.83
04 Jan 2008	7.21	56	1977	6.44	96.55
25 Dec 2008	6.81	57	1976	6.39	98.28

<< Frequency Curve >>
Final Report with Dates

Computed Curve	Expected Probability	Percent Chance Exceedance	Confidence Limits 0.05	Confidence Limits 0.95
STAGE, FT NAVD88			STAGE, FT NAVD88	
9.82	9.94	0.2	10.28	9.47
9.58	9.67	0.5	10.00	9.26
9.38	9.45	1.0	9.77	9.08
9.16	9.21	2.0	9.52	8.88
8.59	8.61	9.0	8.86	8.37
8.25	8.26	18.0	8.48	8.06
7.98	7.99	28.0	8.19	7.80
7.62	7.62	45.0	7.80	7.44
5.65	5.58	99.0	5.95	5.26

<< Systematic Statistics >>
Final Report with Dates

STAGE, FT NAVD88		Number of Events	
Mean	7.52	Historic Events	0
Standard Dev	0.80	High Outliers	0
Station Skew	0.89	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	0.00	Systematic Events	57

<< User-Defined Graphical Frequency Curve >>
Final Report with Dates

Computed Curve	Expected Probability	Percent Chance Exceedance	Confidence Limits 0.05	Confidence Limits 0.95
STAGE, FT NAVD88			STAGE, FT NAVD88	

9.60	---	0.2	9.98	9.22	
9.49	---	0.5	9.86	9.12	
9.40	---	1.0	9.76	9.04	
9.30	---	2.0	9.64	8.96	
9.05	---	9.0	9.36	8.74	
8.50	---	18.0	8.75	8.25	
7.70	---	28.0	7.89	7.51	
7.35	---	45.0	7.54	7.16	
6.20	---	99.0	6.47	5.93	