CHAPTER 8

Monitoring Flood Protection Elevation Grades in High Subsidence Areas

8-1. Purpose. This chapter provides technical guidance for referencing project elevation grades in areas subject to relative sea level change, land subsidence, or crustal uplift. Sea level rise, coupled with subsidence, reduces protection elevations on HSPP structures; while at the same time increasing the depths of authorized/maintained navigation project grades, resulting in over-dredging. The reverse effects occur in crustal uplift regions where apparent mean sea level is falling. (Subsequent references to "subsidence" in this chapter are intended to apply to "uplift" regions as well).

a. Much of the information in this chapter is abstracted from Volume II of the "Interagency Performance Evaluation Taskforce" report (IPET 2007) that was published following Hurricane Katrina in August 2005. Volume II of this IPET study, performed jointly by USACE, NGS, and CO-OPS, focused on the development and application of a high-accuracy, time-dependent geodetic network in a high subsidence area in Southern Louisiana. This Southern Louisiana example is, therefore, applicable to other USACE project areas experiencing subsidence issues.

b. Districts involved with projects subject to significant subsidence uncertainties should closely coordinate with the NGS to ensure a suitable vertical reference framework is established to monitor elevation changes. This effort can be accomplished following NGS "height modernization" standards and specifications. In some cases, time dependent vertical networks outlined in this chapter can be established to periodically update control in unstable regions. In coastal regions, additional coordination with NOAA CO-OPS is recommended to monitor sea level datum changes in the project region. Reference marks at NOAA or local tide gages must be directly linked to NGS vertical networks in order to monitor sea level changes relative to orthometric/geodetic datums.

8-2. Background. Published elevations relative to the vertical datums in subsidence or uplift areas must be used with caution. This applies not only to NSRS or local district PBMs but also to topographic survey data derived from these bench marks (e.g., floodwall and levee protection elevations). Surveyed or published map elevations will have uncertainties due to the uneven temporal and spatial movement of the land. Thus, any geodetic or terrestrial-based elevation on a bench mark or control structure is not constant, and elevations must be periodically reobserved and adjusted for local subsidence. Likewise, hydraulic or sea level based reference datums are subject to variations due to subsidence and/or sea level change at each gage site. Sea level datums also have time varying astronomical components making their reference definition more complex than terrestrial based datums. Hydraulic low water reference datums used to define navigation grades on the Lower Mississippi River may also be subject to subsidence and other long-term variations: thus, these datums are spatially and temporally variable, and are periodically revised.

a. Long-term primary bench mark subsidence. Figure 8-1 illustrates the varying orthometric and sea level elevations recorded at a primary control bench mark at Lake Pontchartrain in New Orleans, LA. In this high subsidence area, the published orthometric elevation of this bench mark has been readjusted numerous times over the 50+ year period—with an elevation change of over 2 ft since 1951. These readjustments include datum conversions from NGVD29 to NAVD88. Evaluating settlement rates, masked with sea level rise, from legacy elevations on this bench mark is not straightforward in that leveling networks were adjusted between other unstable marks. If a tide gage had been continuously operated at this site over the 50-year period, a better estimate of relative settlement could have been made. Levee or floodwall design elevations in a high subsidence area must factor in the elevation datum uncertainties and subsidence rates at the primary bench mark.

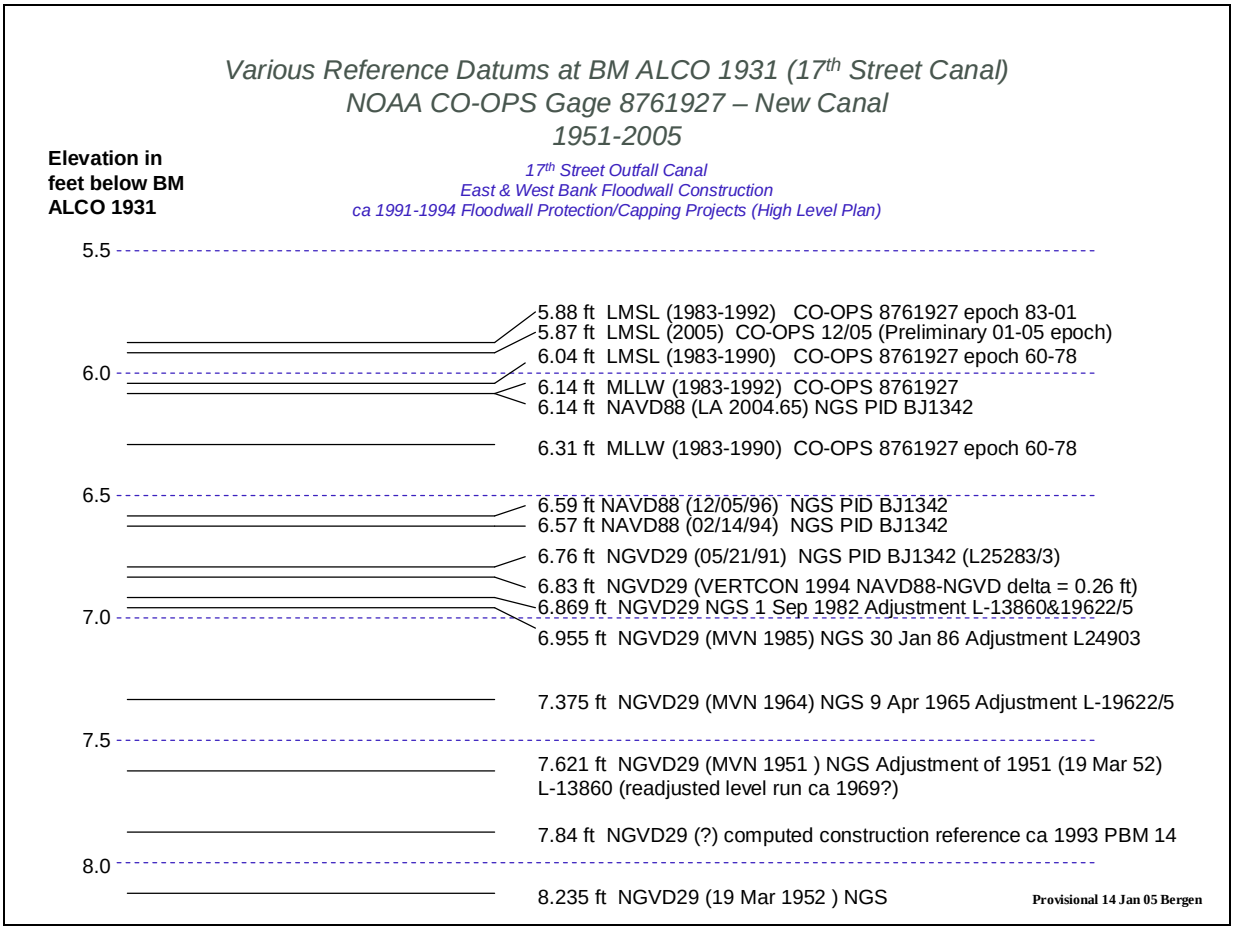


Figure 8-1. Elevations recorded at NSRS bench mark ALCO in New Orleans: 1951 to 2005.

b. Relative mean sea level. Relative or local mean sea level is the average water surface as measured by a tide gage with respect to the land upon which it is situated. Relative sea level change occurs where there is a local change in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. In areas subject to rapid land level uplift, relative sea level can fall. These sea level changes result from a variety of processes, several of which can occur simultaneously. Part II of EM 1110-2-1000 (*Coastal Engineering*

Manual) lists the following processes that can contribute to long-term relative mean sea level change:

(1) Eustatic rise. Refers to a global change in the oceanic water level. Contributors to eustatic rise include melting of land-based glaciers and the expansion of near-surface ocean water due to global ocean warming.

(2) Crustal subsidence or uplift from tectonic uplifting or downwarping of the earth's crust. These changes can result from uplifting or cooling of coastal belts, sediment loading and consolidation, subsidence due to volcanic eruption loading, or glacial rebound.

(3) Seismic subsidence. Caused by sudden and irregular incidence of earthquakes.

(4) Auto-subsidence. Due to compaction or consolidation of soft underlying sediments such as mud or peat.

(5) Climatic fluctuations. May also create changes in sea level; for example, surface changes produced by El Niño due to changes in the size and location of high-pressure cells.

c. Subsidence. The subsidence effects listed above are the major contributor to elevation changes in most unstable regions. It is especially pronounced in portions of Central California (Sacramento and San Joaquin River Basins), Southwestern California, and coastal portions of Texas and Louisiana. Uplift, or apparent sea level rise, is evident in Northwest CONUS and portions of Alaska. In Southern Louisiana, subsidence is occurring at a rate of up to 0.1 foot every three years in some areas. There are many potential factors that contribute to subsidence, such as the geologic composition of the area and withdrawal of ground water and oil.

d. Subsidence at reference bench marks. Bench marks set on deep-driven rods to "apparent refusal" or bedrock will often exhibit relative subsidence to the local land surface, as shown in Figure 8-2. This relative chance is not necessarily a definitive measure of local settlement as the bench mark’s refusal point may also have settled at a differing rate. Thus, the difference in elevation between the deep-driven bench mark and the TBM in the figure may or may not represent the local subsidence. The apparent subsidence of the mark on the lower left figure may be due more to local levee settlement as opposed to subsidence. The Shell Beach tidal bench mark in the figure was set in 1982 on then dry land, illustrating the rapid subsidence (or apparent sea level rise) that has occurred over the intervening 23 years in this region.

Figure 8-2. Local subsidence relative to deep-driven bench marks.

e. Monitoring elevation changes in subsidence areas with "Vertical Time Dependent Positioning" (VTDP) geodetic surveys. Changes in elevation caused by subsidence can be measured and/or periodically monitored using a combination of conventional leveling procedures and GPS techniques. Determining subsidence rates requires long-term observations and considerable analysis.

(1) Prior to the use of GPS observations, subsidence estimates were made using regional leveling networks. Presumed "most stable" bench marks were held fixed for different leveling campaigns and settlement estimates were made based on the elevation changes in these campaigns. The ability to measure accurate relative elevation differences to < 0.1 ft with GPS over long baselines (>100 miles) now provides a mechanism to connect unstable areas with reference bench marks in known stable regions

(2) As an example, Figure 8-3 shows the difference in elevations in southern Louisiana due to the differences between NGVD29 and NAVD88 adjustments along with regional subsidence. The leveling for this line was performed by NOAA in 1984 and adjusted to the NGVD29 datum at that time. In 1991, NGS adjusted the entire CONUS to the NGVD29 datum in preparation for the NAVD88 adjustment. In Southern Louisiana, an extensive “GPS Derived Height” network was completed in 2004, establishing new heights (elevations) for 85 bench marks in Southern Louisiana. The differences are shown in Figure 8-4. This "Vertical Time Dependent Positioning (VTDP)" adjustment, known as NAVD88 (2004.65), held control outside of the subsidence area to establish new NAVD88 adjusted heights for the 85 bench marks.

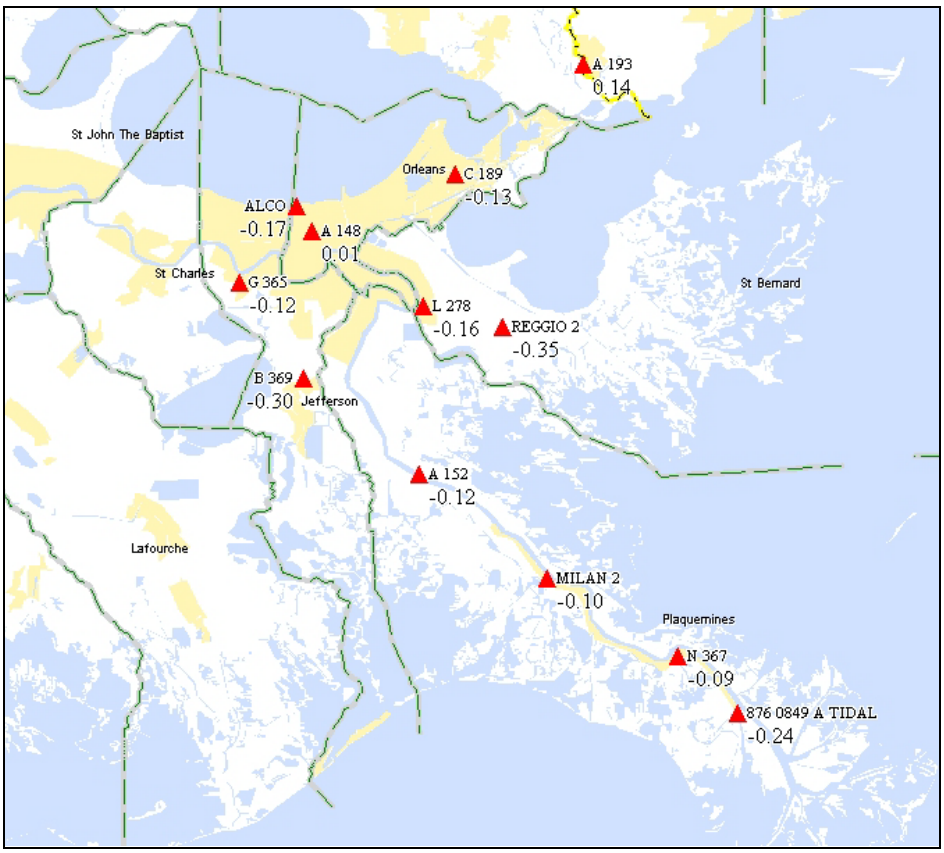


Figure 8-3. Elevation changes (ft) due to datum shift (NGVD29 to NAVD88) and regional readjustment.

(3) Because the 1991 NAVD88 adjustment held control outside of the area, as did the NAVD88 (2004.65) adjustment, the change in the heights reflects the apparent movement of the marks between the observation periods. In order to determine the amount of subsidence from the time the original leveling was done, it is necessary to determine the amount of movement between the original adjustment and the 1991 national readjustment of the NGVD29 and then the amount of movement between the original NAVD88 adjustment and the NAVD88 (2004.65) adjustment.

f. Monitoring elevation changes in subsidence areas with water level gages. Monitoring subsidence or sea level changes on flood risk management, hurricane protection, or coastal (tidal) navigation projects requires continuous leveling or GPS surveys between water level recording gages and fixed NSRS bench marks. Geodetic surveys alone cannot determine sea level changes. Records from these gages, if reasonably well documented, can provide an independent means to investigate and determine reliable rates of local subsidence and/or validate rates determined via a VTDP geodetic survey analysis. Reference PBMs at these gages must be connected to an external geodetic network that is not impacted by subsidence. A New Orleans District study on the use of gage data in evaluating subsidence changes in Southern Louisiana is at Appendix L.

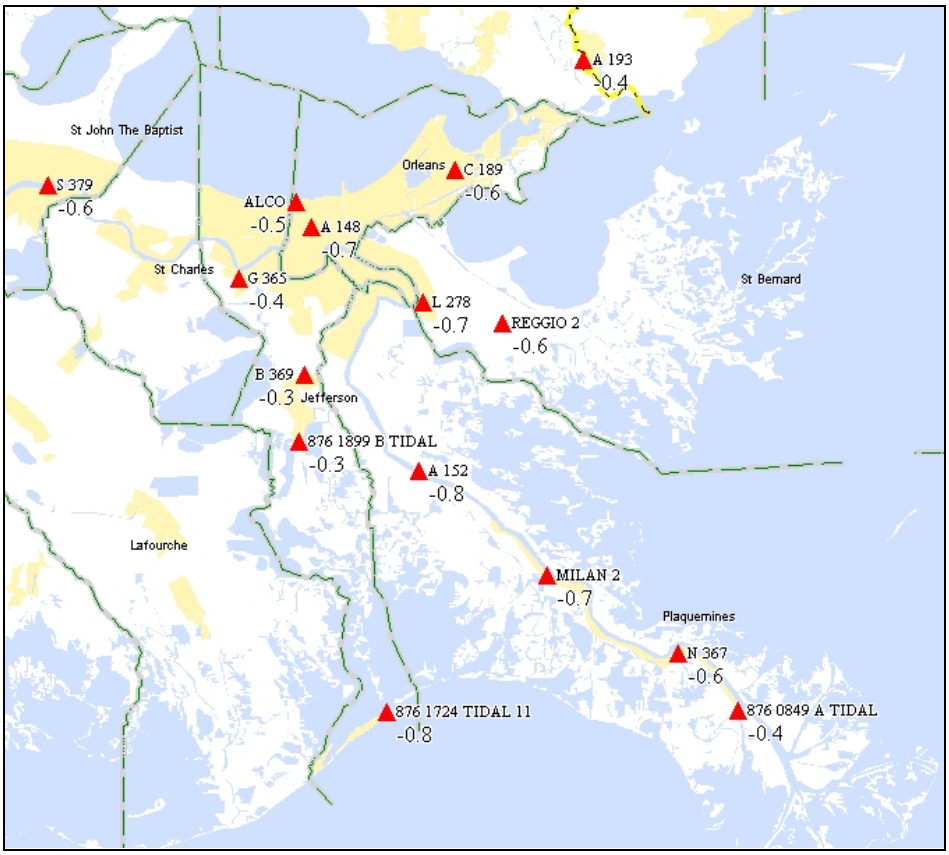


Figure 8-4. Elevation changes (ft) between NAVD88 (1996) adjustment and the VTDP NAVD88 (2004.65) regional readjustment.

g. Applications. EM 1110-2-1100 (*Coastal Engineering Manual*) notes that long-term subsidence must be factored in to the design of flood/hurricane protection structures. It states that "...the [reference] datums described above, and the reported variability of those datums, represent design criteria considerations that directly impact the expected lifetime of a project. If, for example, a coastal project is to be situated in an area of known subsidence, then design elevations need to reflect additional freeboard as a factor-of-safety consideration ..." Estimating future subsidence out 50 or more years, like sea level change, is difficult, and must be based on extrapolated trends from past geodetic surveys and water level gage data.

8-3. <u>Development of a Vertical Time Dependent Positioning Reference Framework to Monitor Bench Mark Subsidence in Southern Louisiana</u>. This section describes the process developed by the NGS for establishing a VTDP network in Southern Louisiana. This VTDP network is used to evaluate subsidence at bench marks in the subsidence area. A VTDP network must be continuously monitored and periodically updated—i.e., the NAVD88 (2004.65) VTDP network was subsequently updated to a NAVD88 (2006.81) epoch. The procedures outlined below are applicable to other USACE projects subject to subsidence.

a. Beginning in 2004, NGS began a series of reobservations in Louisiana for the purpose of updating the NAVD88 published heights in the region in support of hurricane evacuation

route mapping. These reobservations included both GPS campaigns and leveling observations. The GPS data were collected according to NGS standards in "*Guidelines for Establishing GPS-Derived Ellipsoid Heights: Standards: 2 cm and 5 cm*" (NOAA 1997) and in "*Guidelines for Establishing GPS Derived Orthometric Heights: Standards: 2 cm and 5 cm*" (NOAA 2005). These guidelines required a set of three 5½ hour static DGPS sessions with at least a 4 hour difference in the starting time of one session on different days. The data collected was processed using the NGS program "PAGES" and adjusted using the NGS program "ADJUST." However, prior to this adjustment, the published orthometric heights of bench marks in the Gulf Coast region from Pensacola, FL west to Houston, TX (which included bench marks occupied in the GPS reobservations in Louisiana) were updated using the most recent subsidence rates as published in NGS Technical Report 50—"*Rates of Vertical Displacement at Benchmarks in the Lower Mississippi Valley and the Northern Gulf Coast*" (NOAA 2004). These rates were applied to previous observation data and adjusted. This readjustment used 151 previously observed level lines connecting across the entire region, consisting of 16,331 bench marks. Rates of all published bench marks included in NGS Technical Report 50 (NOAA 2004) were applied. A total of 85 such bench marks were part of this reobservation campaign, as shown in Figure 8-5.

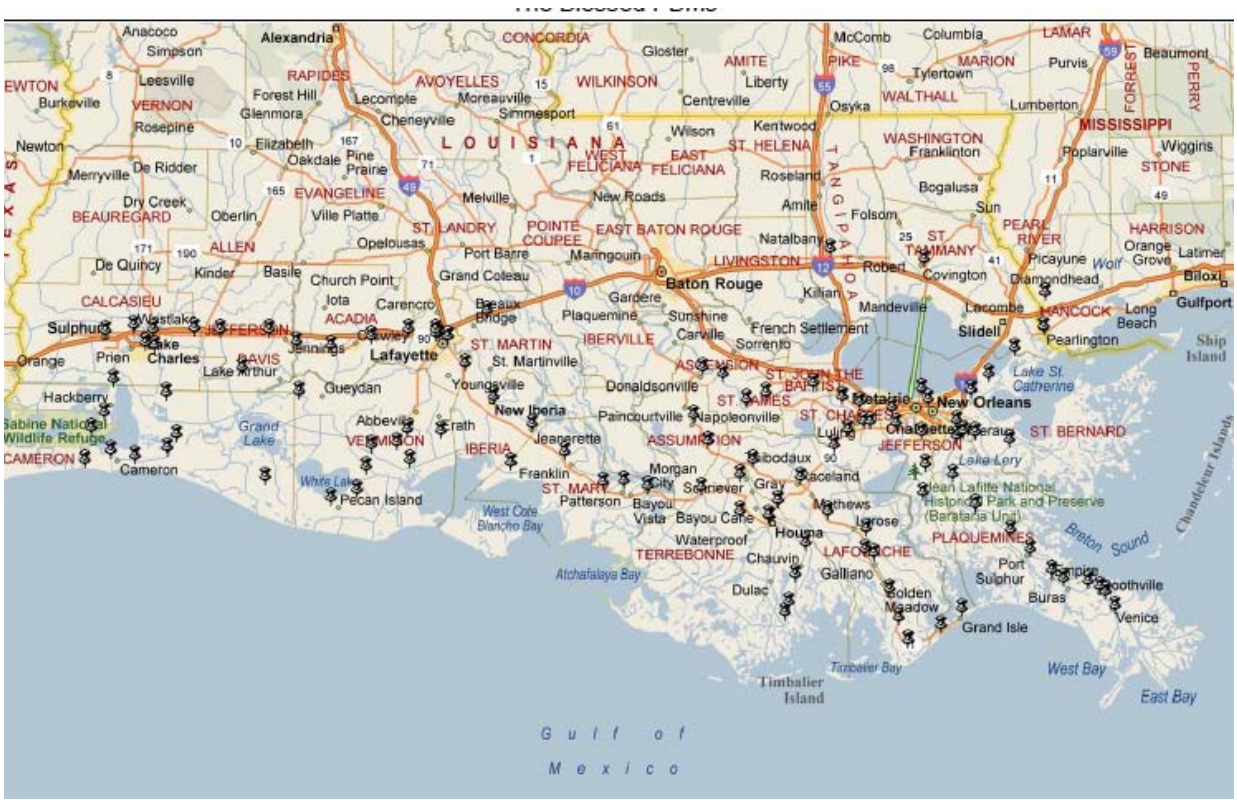


Figure 8-5. Southern Louisiana Vertical Time Dependent Network (adjustment epoch 2004.65).

b. When the GPS-derived orthometric heights were compared with leveling data at these 85 bench marks, as corrected for subsidence rates and tied to non-subsiding bench marks outside the subsidence area, there was a variety of agreements and disagreements. First, 32 of the 85 bench marks showed better than 2 cm agreement between the GPS-derived and leveling-derived orthometric heights, indicating a good estimate of subsidence rates at those points.

c. After finding the 32 points with the most reliable estimated subsidence rates, their heights were then held as stochastic constraints in a constrained adjustment of all 85 bench marks (along with fixing the heights of 4 points outside the subsidence area). The resultant adjustment of 85 heights was given the notation "NAVD88 (2004.65)", where the 2004.65 is the date in years and decimal portions of a year of the midpoint of the observation campaign. The formal accuracy estimates on these 85 bench marks fall in the 2 to 5 cm range. Note that even as these points have been adjusted to 2004.65, they are all susceptible to subsidence, and therefore it will be critical to use CORS data and possibly future re-leveling to re-adjust these heights and recompute their subsidence rates with a higher accuracy than the 2004.65 adjustment produced.

d. The NAVD88 (2004.65) adjustment, again, was not a local adjustment. It went outside of the subsidence area and held fixed what were felt to be stable bench marks. The four bench marks held fixed were: LAKE HOUSTON 2050, which is a galvanized steel pipe driven to a depth of 2050 feet; 872 9816 TIDAL 1 a TIDAL Bench mark in Pensacola, Florida; FOREST EAST BASE in Scott County, Mississippi; and M 237 in Latanier, Louisiana. A free adjustment holding LAKE HOUSTON 2050 fixed was run with the results shown in Table 8-1. The difference between the NAVD88 (1994) and NAVD88 (2004.65) reflects the apparent subsidence of the bench marks due to the procedures used in the adjustment.

Table 8-1. Louisiana VTDP Free Adjustment.

DESIGNATION	PUBLISHED (m)	ADJUSTED (m)	PUB-ADJ (m)
872 9816 TIDAL 1	1.3479	1.3741	-0.0262
FOREST EAST BASE	136.4527	136.4622	-0.0095
LAKE HOUSTON 2050	17.0714	CONSTRAINED	0.0000
M 237	20.3830	20.3422	0.0408

e. The geographical location of these fixed bench marks relative to the Southern Louisiana subsidence area is shown in Figure 8-6.

8-4. Estimating Subsidence Rates in the Southern Louisiana Region from Geodetic Observations. This section focuses on subsidence occurring at bench marks throughout the Southern Louisiana project area. A bench mark's subsidence rate may be different from that occurring in the adjacent ground—see Figure 8-2 where the deep-driven rod bench mark protrudes well above the subsided ground. Over the years, there have been several studies that have been published documenting the subsidence of New Orleans and Southern Louisiana.

Figure 8-6. Location of fixed bench marks defining NAVD88 (2004.65) in Southern Louisiana.

a. A NOAA report "Subsidence in the Vicinity of New Orleans as Indicated by Analysis of Geodetic Leveling Data" (NOAA 1986) used three different adjustments to determine the apparent movement of bench marks in this area. This report does not show sea level rise--only the apparent movement of the benchmarks. It should also be noted that the movement reflected in this report, as well as in NOAA Technical Report 50 (NOAA 2004), reflects the movement of the mark based on leveling observations. Table 8-2 shows not only the apparent subsidence but also that the subsidence is neither linear nor at the same rate based on location and different epochs.

Table 8-2. Apparent Movement (in mm/year) without Sea Level Rise from Three Leveling Networks (1951-1955, 1964, and 1984-85) to Estimate Apparent Crustal Movement. (NOAA 1986)

PBM Designation	1985.0 – 1964.0	1985 – 1951	1964 – 1951
A 148 (AU0429)	-6.88 (21 yr)	-5.57 (34 yr)	-3.1 (13 yr)
PIKE RESET (BH1164)	-1.36	-1.59	-1.97
231 LAGS (BH1073)	-16.39	-10.90	-2.03
A 92 (BH1136)	-2.36	-2.66	-3.13

b. The rate of subsidence varies from epoch to epoch (survey to survey) due to many factors, such as compaction, removal of subsurface fluids, and geologic events. Therefore, one cannot predict future subsidence with any degree of accuracy. Table 8-3 shows the rate of

change reflected in at least two different epochs of First-Order, Class II leveling, as published in NOAA Technical Report 50 (NOAA 2004).

Table 8-3. Apparent Movement from Two Epochs of Leveling Data. (NOAA 1986)

PBM Designation	Rates of Movement (mm/year)
A 148 (AU0429)	-11.01
PIKE RESET (BH1164)	-6.99
231 LAGS (BH1073)	-16.08
A 92 (BH1136)	-7.39

c. The average rate of apparent subsidence across the region was found to be about 0.6 ft subsidence per 10 years. This indicates that elevations published in the 1960's, 70's, 80's, and early 90's may have changed even more than 1 ft. A long-term objective is to continually improve upon the vertical reference system in Southern Louisiana—e.g., NAVD88 (2004.65) was later updated to NAVD88 (2006.81). This provides a consistent framework from which the monitoring of previously constructed and proposed flood risk management and hurricane protection structures can be performed.

d. Figure 8-7 depicts estimated subsidence rates occurring at 18 benchmarks in the New Orleans region based on the adjusted elevations. The subsidence rates were computed using the difference between the published NAVD88 (2004.65) and superseded values and dividing them by the number of years between the adjustments. These rates, compared with those published in NOAA Technical Report 50 (NGS 2004), do not all agree since the adjusted elevations contain distributed errors from the adjustment computations. Therefore, Figure 8-7 illustrates the need to use unadjusted values in determining subsidence rates as documented in NOAA Technical Report 50.

8-5. Sea Level Trends in Southern Louisiana. Long term tide station records provide estimates of local relative sea level trends as opposed to the absolute rates of global sea level that are the subject of basic research in climate change. These local relative sea level trends from tide stations are a combination of global sea level variations, regional climate scale water level variations, and local vertical land movement due to local or regional subsidence. Thus the tide stations provide the information because they provide direct information on variations of water levels relative to the local land elevations.

a. Figure 8-8 depicts the apparent sea level increase (i.e., mostly subsidence) over a 60-year period at the USACE Florida Avenue gage on the Inner Harbor Navigation Canal (IHNC) in New Orleans, LA. The apparent sea level rise at this gage supports independent geodetic observations and observed elevation decreases on hurricane protection structures in this area.

PID	Designation	Rate (m/yr)	NAVD88 2004.65 (m)	Procedure	Sup/Date	Sup (m)	Sup (ft)	Leveling Year	NAVD88 (2004.65) minus Sup (ft)
BH1119	C 189	-0.016	0.63	LEVELING(2004.65)	12/5/1996	0.794	2.60	1994	-0.54
AU2163	B 369	-0.015	1.84	LEVELING(2004.65)	12/5/1996	1.975	6.48	1995	-0.44
AU2310	876 1899 B TIDAL	-0.015	0.01	LEVELING(2004.65)	12/5/1996	0.141	0.46	1995	-0.43
AU0429	A 148	-0.015	1.77	GPS OBS(2004.65)	12/5/1996	1.915	6.28	1994	-0.48
BJ1342	ALCO	-0.014	1.87	LEVELING(2004.65)	12/5/1996	2.008	6.59	1994	-0.45
AT0804	REGGIO 2	-0.012	1.52	GPS OBS(2004.65)	2/14/1994	1.714	5.62	1988	-0.64
BH1212	A 193	-0.012	0.75	LEVELING(2004.65)	2/14/1994	0.879	2.88	1993	-0.42
AU2110	G 365	-0.011	0.24	GPS OBS(2004.65)	12/5/1996	0.342	1.12	1995	-0.33
AT1390	876 0849 A TIDAL	-0.011	0.85	GPS OBS(2004.65)	8/31/2001	0.972	3.19	1993	-0.40
AT0407	A 152	-0.010	0.67	GPS OBS(2004.65)	2/14/1994	0.870	2.85	1984	-0.66
BJ3744	S 379	-0.010	4.31	GPS OBS(2004.65)	2/14/1994	4.482	14.70	1986	-0.56
AT0376	R 194	-0.008	1.39	GPS OBS(2004.65)	2/14/1994	1.554	5.10	1984	-0.54
AT0357	D 194	-0.008	1.68	LEVELING(2004.65)	2/14/1994	1.835	6.02	1984	-0.51
AT0200	MILAN 2	-0.008	-0.15	GPS OBS(2004.65)	2/14/1994	0.005	0.02	1984	-0.51
AT0332	L 278	-0.007	2.11	LEVELING(2004.65)	2/14/1994	2.253	7.39	1984	-0.47
AT0231	EMPIRE AZ MK 2 1934 1966	-0.007	-0.01	GPS OBS(2004.65)	2/14/1994	0.129	0.42	1984	-0.46
AT0247	C 279	-0.007	-0.23	GPS OBS(2004.65)	2/14/1994	-0.100	-0.33	1984	-0.43
AT0731	N 367	-0.007	0.34	GPS OBS(2004.65)	2/14/1994	0.470	1.54	1984	-0.43

Figure 8-7. Estimated subsidence rates at selected bench marks in New Orleans Region. (IPET 2007) (Note: "Sup" = superseded)

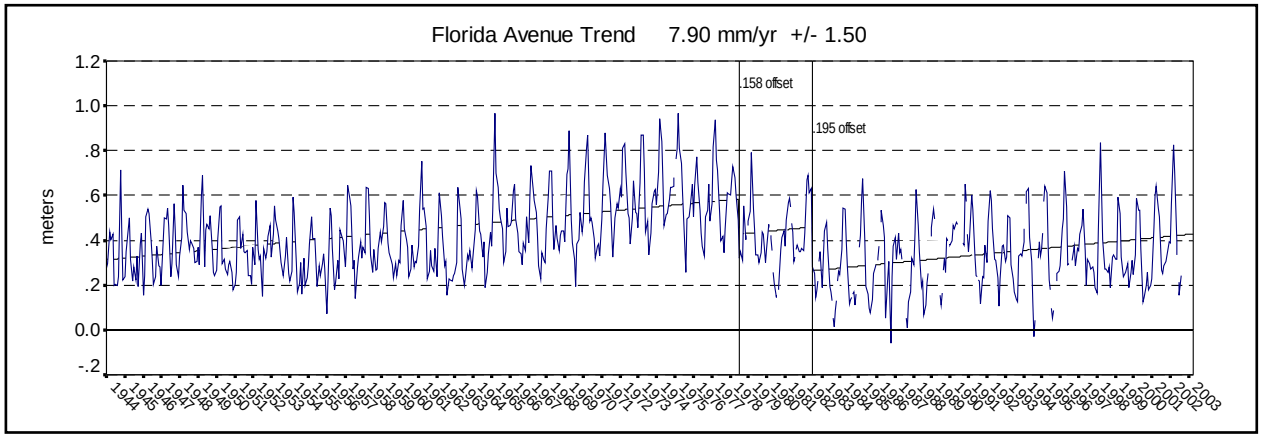


Figure 8-8. Apparent sea level rise at Corps IHNC Florida Ave. gage from 1944 to 2003. Gage zero adjustments were estimated. (IPET 2007)

b. NOAA CO-OPS has performed analyses of relative sea level trends for all of the long-term NWLON stations in their network. Unfortunately, the New Orleans area and Lake Pontchartrain are geographical areas of data gaps for locations with measurements of sea level variations necessary to estimate sea level trends with high certainty. The closest NWLON stations in this category are Dauphin Island, AL; Pensacola, Fl; and Grand Isle, LA. The analyses done for estimating relative sea level trends in the New Orleans area include using a 23-year monthly mean time series pieced together from Waveland, MS (3.52 mm/yr with a ± 2.6 mm/yr 95% confidence interval) and a 10-year monthly mean time series at New Canal, LA (3.98 mm/yr with an 95% confidence interval > ± 3.0 mm/yr). Historical once-per-day readings from long term USACE stations have also been analyzed; however, there have been many adjustments to the gages that were not readily available for this review.

(1) Analysis of the USACE record at Florida Avenue, New Orleans, LA provides a composite estimate of 7.90 mm/yr with a 95% confidence interval of ± 1.5 mm/yr.

(2) Using an assumption of similar ratio relationships of shorter period trends to longer period trends, the relative sea level trend at NWLON New Canal gage was estimated to be 6.83 mm/yr for a 23-year period (comparing with Waveland trends).

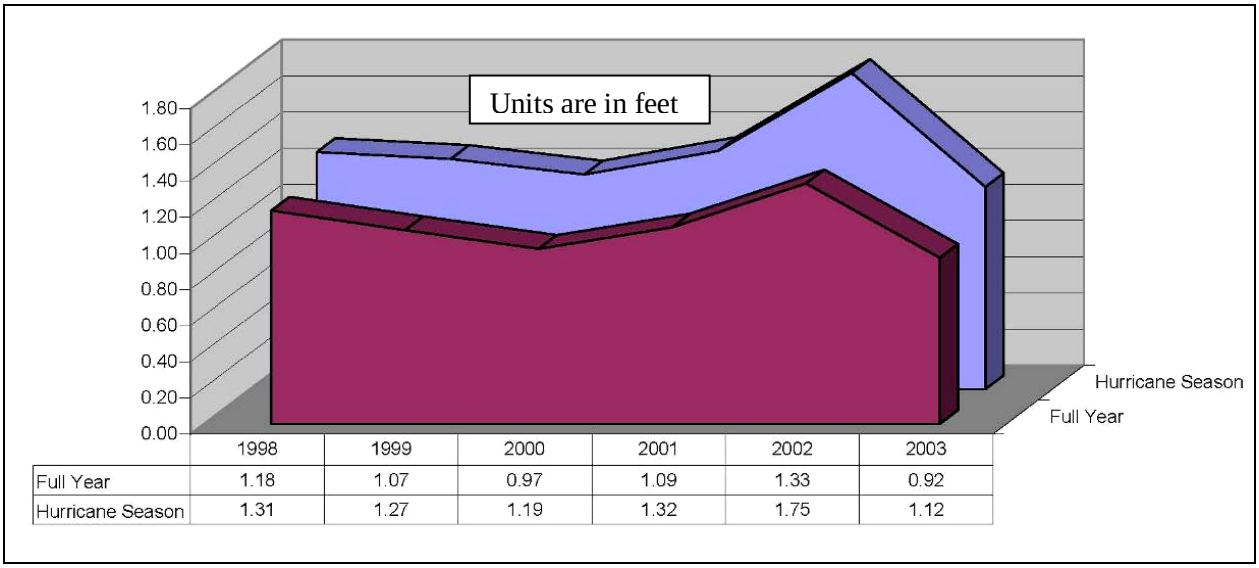
(3) By performing a difference of the simultaneous monthly mean sea levels between New Canal and Waveland, a trend fit to the differences shows that relative LMSL is rising 1.9 mm/yr faster at New Canal than at Waveland. Adding the 1.9 mm/yr rate to the 3.98 mm/yr estimate for 10-months gives an estimate of 5.88 mm/yr.

c. Although limited by the 10-year period length and with a spread of 2 mm/yr, these three independent estimates of the relative sea level trend at the New Canal gage are consistent with independent estimates of local subsidence in the region based on NOAA Report 50 (NOAA 2004), which relied on repeat geodetic surveys.

d. The results of the analyses used to estimate relative sea level trends for the Southern Louisiana study area provide corroboration of the drawbacks of estimating sea level trends from only a few decades of measurement, and the need to look at simultaneous time periods when comparing trends across a region.

8-6. Seasonal Variation in Mean Sea Level in Southern Louisiana. The average seasonal cycles in monthly local mean sea level can show wide variations depending on the seasonal variations in water temperature, winds, and circulation patterns currents in the nearby coastal ocean. Figure 8-10 shows four plots of monthly local mean sea levels the coastal region from Pensacola west to Grand Isle. It can be seen that there is as low progression from a single mode of a seasonal high and low sea level stand at Pensacola (high in September, low in January) to a bi-modal variation at Galveston, TX with secondary high and low in May and July respectively. Hurricane season, from June through November, coincides with the periods of high monthly local mean sea levels--this generally adds to the elevation of storm surge. Seasonal variations in the New Orleans IHNC are shown in Figure 8-9. This data were constructed by computing average water surface elevations for selected years at the USACE Florida Avenue gage. Elevations are in feet and are referred to approximate LMSL or NGVD29 (1983 adjustment). Figure 8-10 clearly shows a

quarter-foot bias in average surface elevation during the fall hurricane season. Hydrodynamic modeling, risk analysis, and design criteria need to consider this seasonal bias in evaluating flood protection elevations.



	1998	1999	2000	2001	2002	2003
Full Year	1.18	1.07	0.97	1.09	1.33	0.92
Hurricane Season	1.31	1.27	1.19	1.32	1.75	1.12

Figure 8-9. Seasonal variations (in feet) at the New Orleans IHNC Florida Avenue gage.

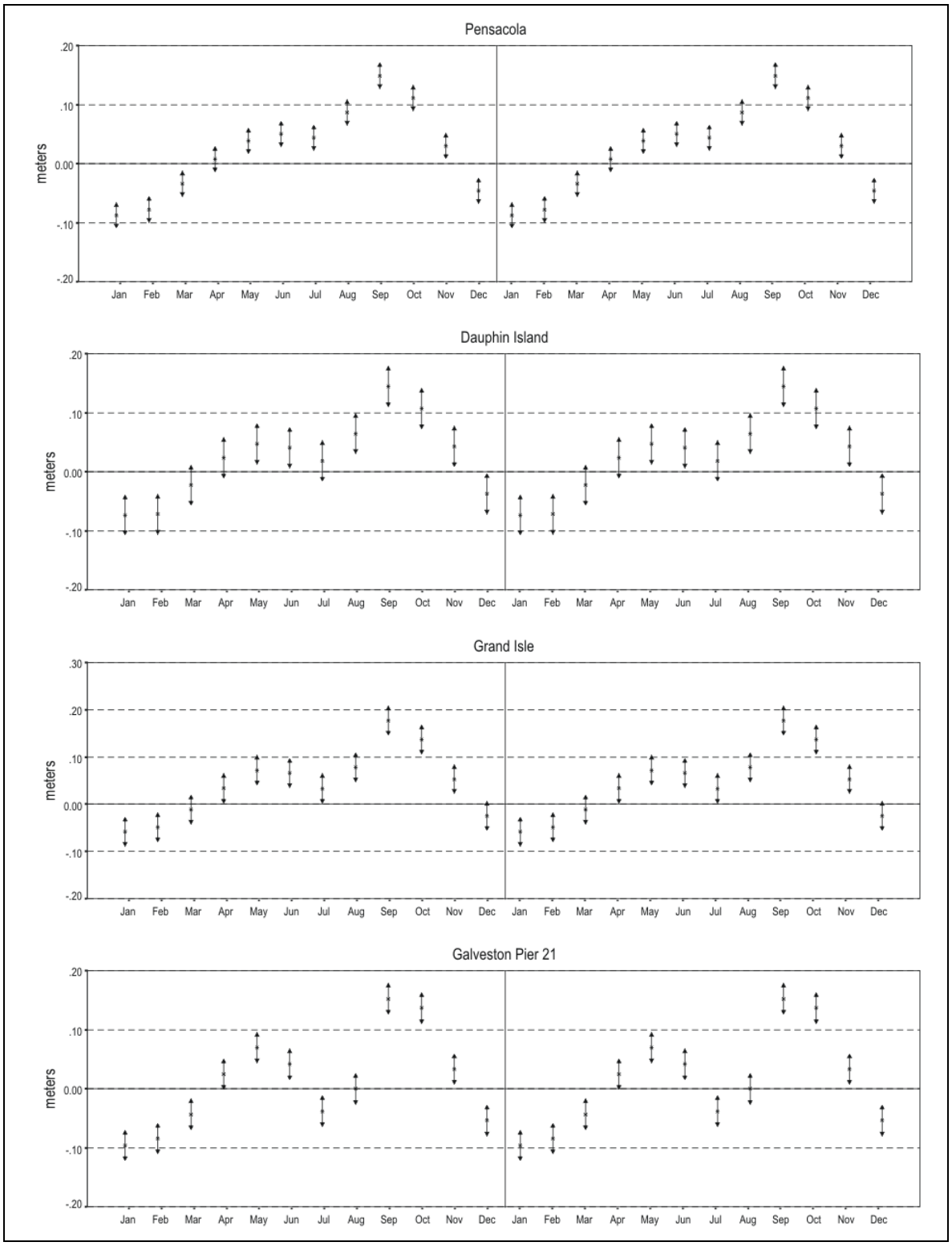


Figure 8-10. Monthly local Mean Sea Levels from Pensacola to Galveston. (in meters above LMSL)