APPENDIX L

Computing Historical Subsidence Rates in Southeast Louisiana from USACE Gage Data

L-1. Purpose. This appendix describes procedures for evaluating subsidence rates based on long-term gage records. It is extracted from internal studies performed in the USACE New Orleans District.

L-2. Abstract. The New Orleans District records stream and tide stages at numerous gaging sites throughout its district. Many of these stage data sets extend as far back as 1940. The data through 1998 have been published by the District in "Stage and Discharge" books and much of it has been converted to digital format. As such, it is often readily accessible, reasonably well documented, and may provide an independent means to investigate and determine reliable rates of local subsidence and/or validate rates determined via geodetic survey analysis.

L-3. Introduction. Subsidence, or the generally downward motion of the earth's surface with respect to some "fixed" vertical datum (e.g., NAVD88 or a particular Mean Sea Level epoch), is perceived as a significant threat to coastal Louisiana. It has been detected in both geodetic leveling data throughout the region and at several NOAA tide gages along the Louisiana coast (Shinkle and Dokka, 2004; Dokka, 2006)[1]. From the referenced studies, it appears that rates of subsidence in the region are spatio-temporally variant and often significantly greater than even the highest estimated rates of eustatic sea-level rise. Consideration of the forces and conditions that cause subsidence - and the proportion that each force or condition contributes to total subsidence at a given point and at a given time (Gonzalez and Tornqvist, 2006; Dokka, 2006) - is beyond the scope of this work. The sole purpose here is to extract reliable historical rates of subsidence at various USACE gages and, when/if possible, determine the relationships among the various vertical geodetic datum/epochs and local mean-sea-level epochs.

L-4. Data. Five USACE tide gage stations in the New Orleans area were selected for this study. They are as follows: 76040 - The Intracoastal Waterway (IWW) at the Paris Road Bridge; 76060 - The Inner Harbor Navigation Canal (IHNC) at the Seabrook Bridge; 76120 - The IHNC at the Florida Avenue Bridge; 85675 - Lake Pontchartrain at Irish Bayou; 85700 – Lake Pontchartrain at the Rigolets (see Figures L-1, L-2, and L-3).

[1] References cited in this Appendix are listed in Section L-10.

Figure L-1. Vicinity map of Greater New Orleans showing gage locations.

a. These tidal gages were selected because of their proximity and relevance to post-Katrina reconstruction activities in New Orleans East, the availability of near-continuous, long-term (40+ years) digital data, and adequate documentation of periodic gage inspections and adjustments. This collection of gages also encompasses an area of detailed study on modern-day tectonic subsidence in coastal Louisiana performed by Dokka (2006).

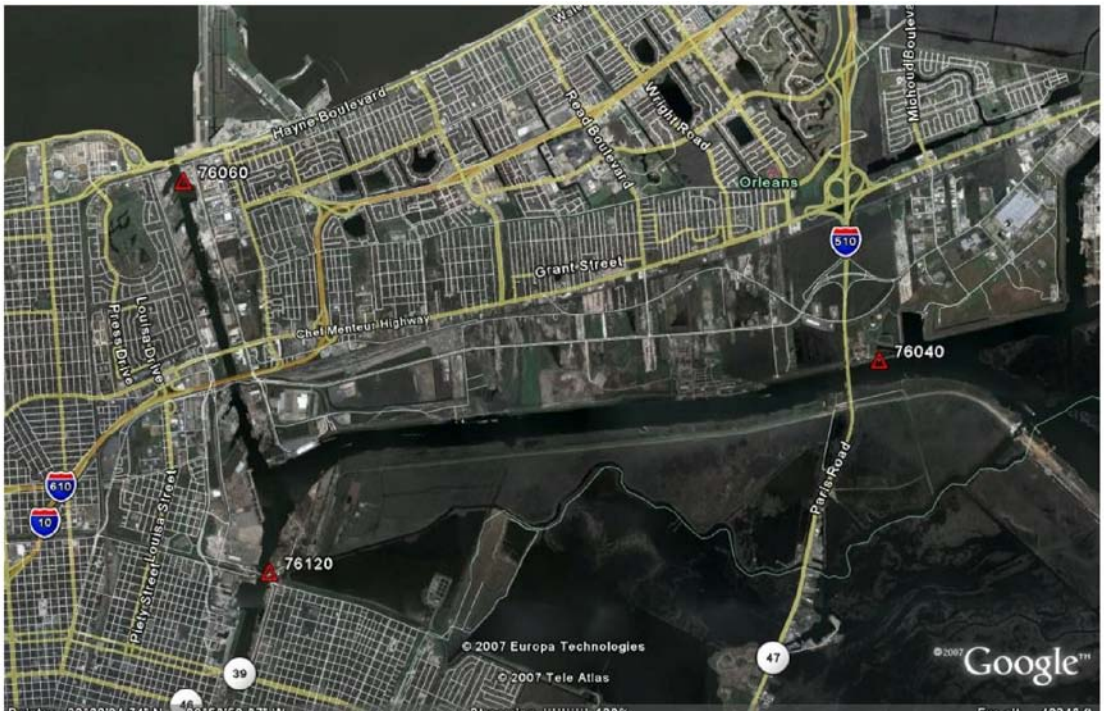


Figure L-2. Vicinity map of East New Orleans showing gage locations.

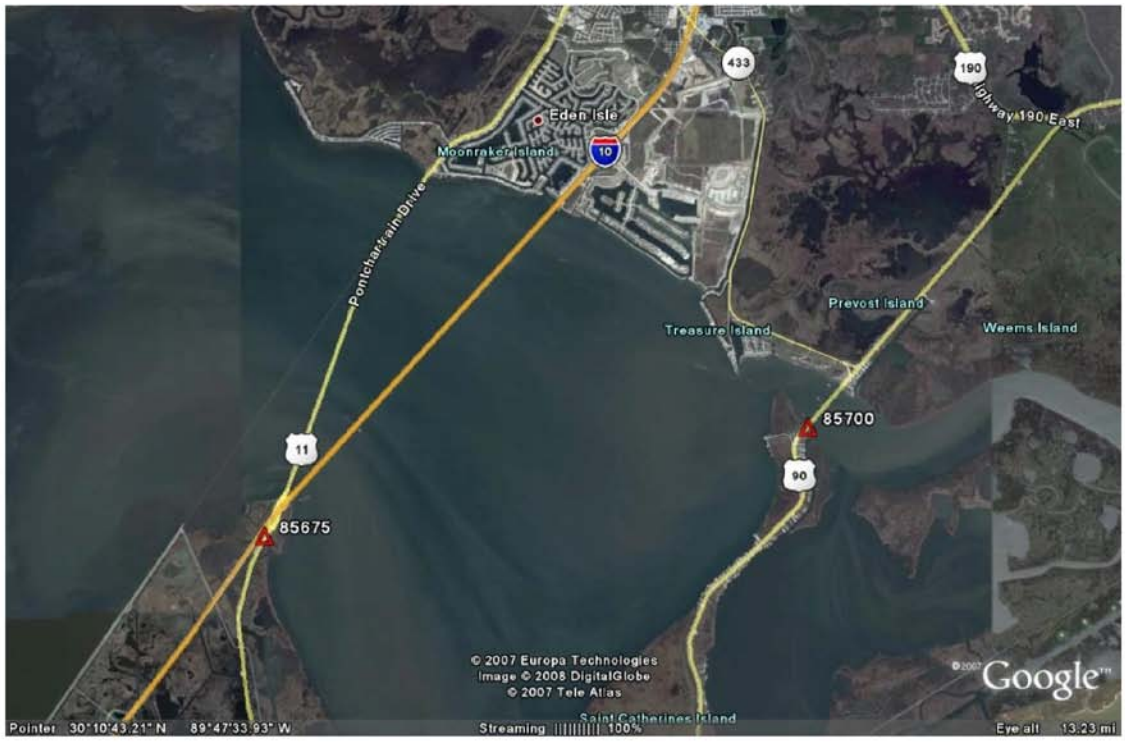


Figure L-3. Vicinity map of Western Lake Pontchartrain showing gage locations.

b. The available digital data ranges for the selected gages are shown in Table L-1. The data sets are, for the most part, continuous through their respective time periods, but there are several gaps (of days, weeks, and sometimes months) in each of the data sets. More significantly, all of the original data sets are nominally referred to as "Daily 8 A.M. Stage Readings in Feet." Occasionally, stage readings were made directly by an observer at times other than 8 A.M. In addition, the type of gage employed, its precise location, and the type of structure on which it was mounted were all altered one or more times at each of the gaging sites over the life of its operation. As such, the data sets may be somewhat "noisy," as compared to a theoretically continuous data set of hourly or six-minute-interval stage readings from a single, calibrated instrument at a fixed location.

Table L-1. The Available Digital Data Ranges for Selected Gages

Gage	Year Period Began	Year Period Ended
76040	1959	2007
76060	1962	2005
76120	1944	2003
85675	1959	2000
85700	1961	2001

c. The most significant artifacts evident in each of the data sets were the discontinuities resulting from the deliberate change in the vertical position of the gage zero with respect to nearby benchmarks. These alterations were periodically carried out so that the "zero" of the gage would correspond to the "zero" of a particular epoch of a vertical geodetic datum (see Figure L-4, for example). Fortunately, these vertical movements or adjustments of the gage zeros are reasonably well documented in the gage inspection records together with the explanatory notes in the "Stages and Discharges" books. Accounting for these adjustments was essential to the development of continuous, normalized data sets of daily, 8 A.M. stage readings from which monthly means could be reliably computed and subsidence rates determined.

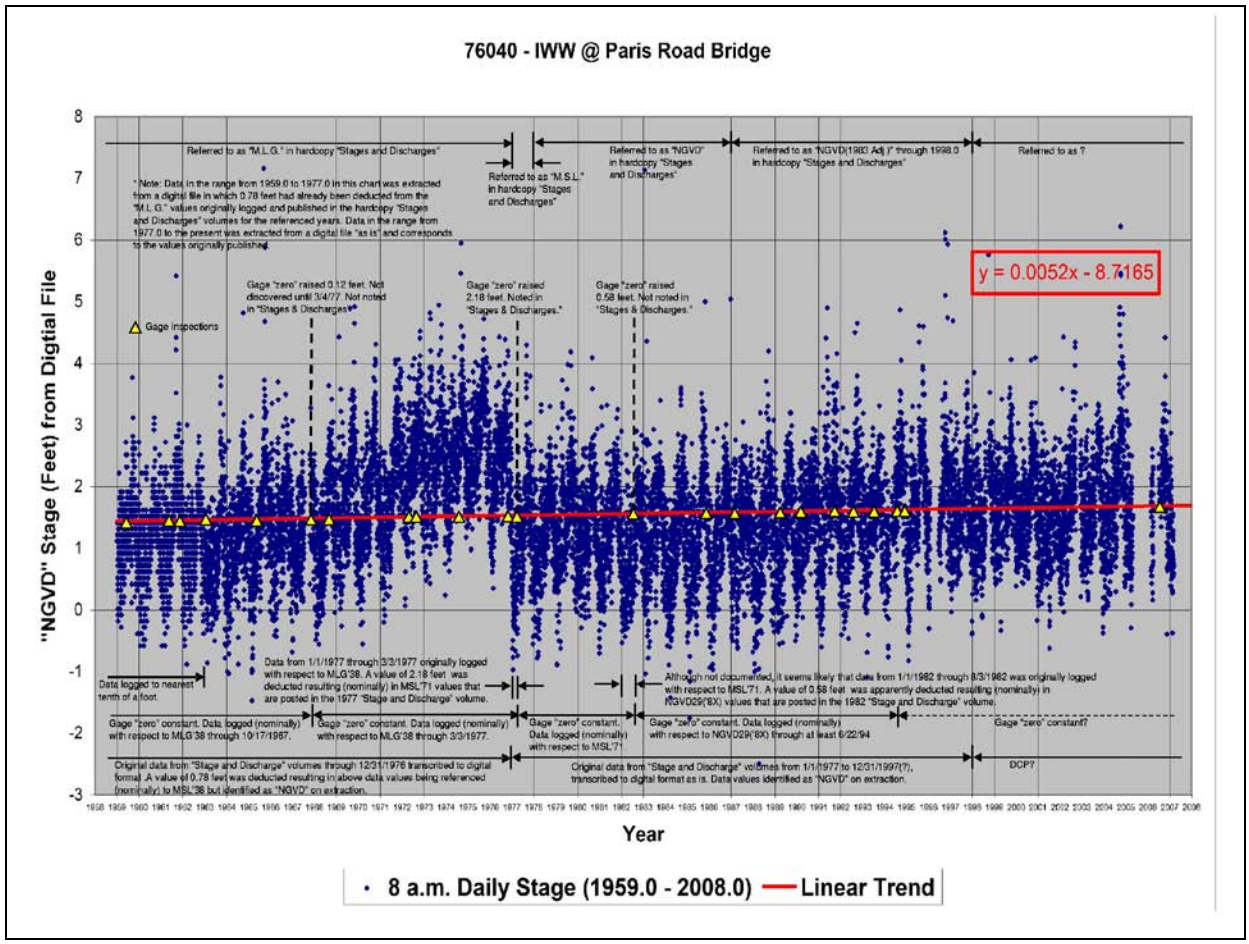


Figure L-4. Gage readings for gage 76040 – IWW @ Paris Road.

L-5. Data Normalization. In normalizing the digital stage data, it was first necessary to account for differences between the digital stage values extracted from the USACE database, and those corresponding values recorded in the "Stages and Discharges" books. These differences are due to a bulk shift - applied on extraction by USACE software - to that portion of a given stage data set originally recorded with respect to a gage zero intentionally offset from nominal mean-sea-level (i.e., "Mean-Low-Gulf" or "-10.00 ft MSL" or "-20.55 ft MSL). This is apparently done in order to roughly harmonize it with subsequent stage values nominally referenced to MSL/NGVD. Removal of this shift was necessary to reproduce the actual stage values recorded

in the "Stage and Discharge" books. Following this adjustment, the digital stage data were corrected for intentional vertical movement of the gage zero due to epoch updates as indicated in the inspection records. The desire here was to compute, as nearly as possible, the stage data set that would have been generated if the gage zero had never been intentionally moved from its initial vertical position with respect to the surrounding terrain and associated benchmarks. Applying the corrections for gage zero movement noted in Figure L-4 resulted in the "normalized" data set shown in Figure L-5.

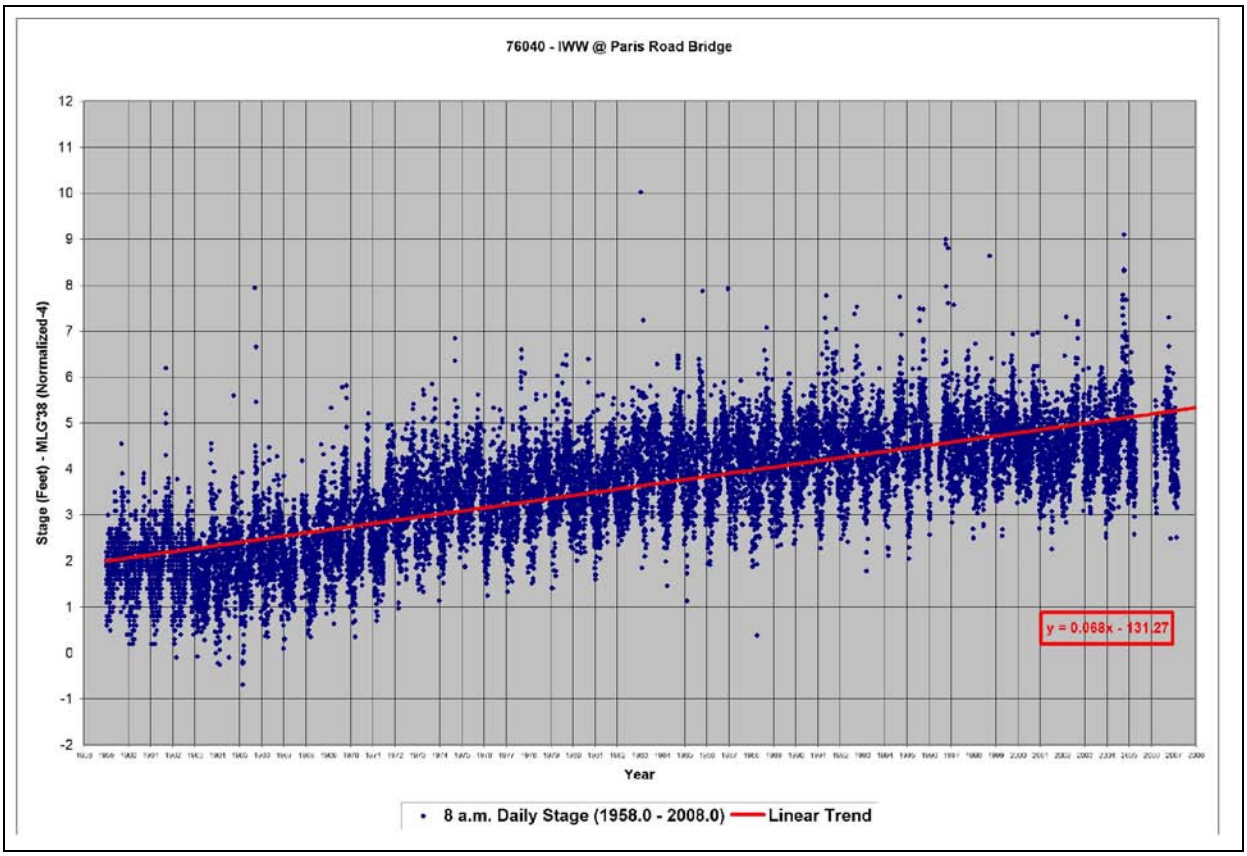


Figure L-5. Normalized gage readings for gage 76040 – IWW @ Paris Road.

a. The review, analysis, and processing steps undertaken with gage 76040, as indicated above in Figures L-4 and L-5, were similarly carried out with respect to the remaining four gages. As a final quality assurance step, all five normalized data sets were differenced against one another (see Figures L-6 through L-15). If all intentional gage zero movement has been accounted for (and if no accidental zero movement or loss of calibration has occurred), then one would expect the graph of the differences to be relatively consistent, smooth and continuous. If subsidence rates were generally the same at any two gages under consideration, the graph would be essentially flat as well. Where rates differ, one would expect that the magnitude of that rate difference would be born out in the slope of the graph.

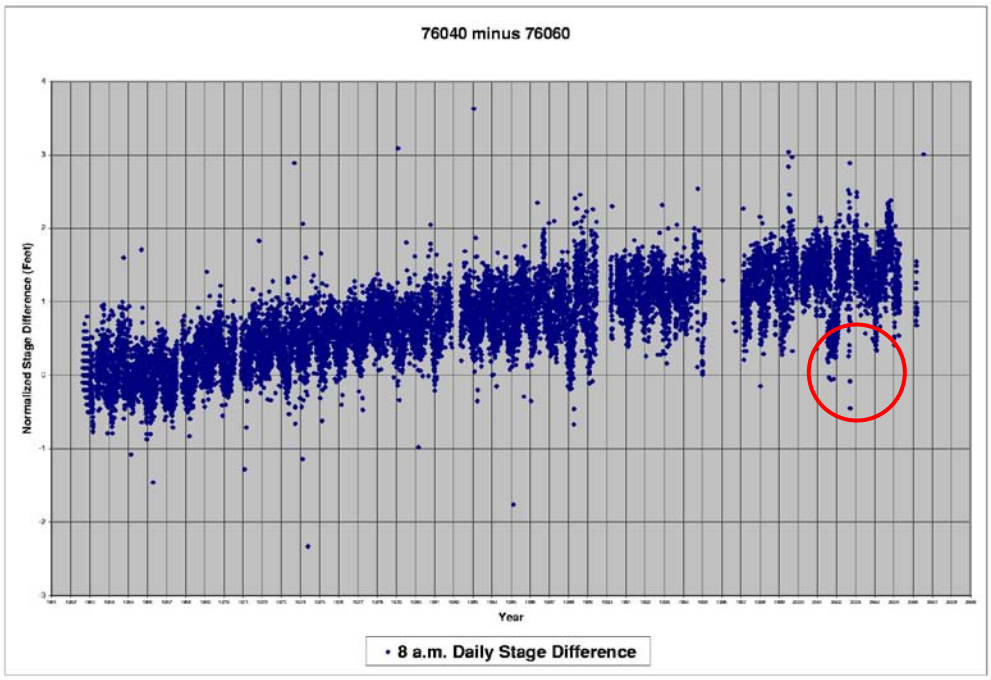


Figure L-6. Normalized gage readings for Gage 76040 – Gage 76060.

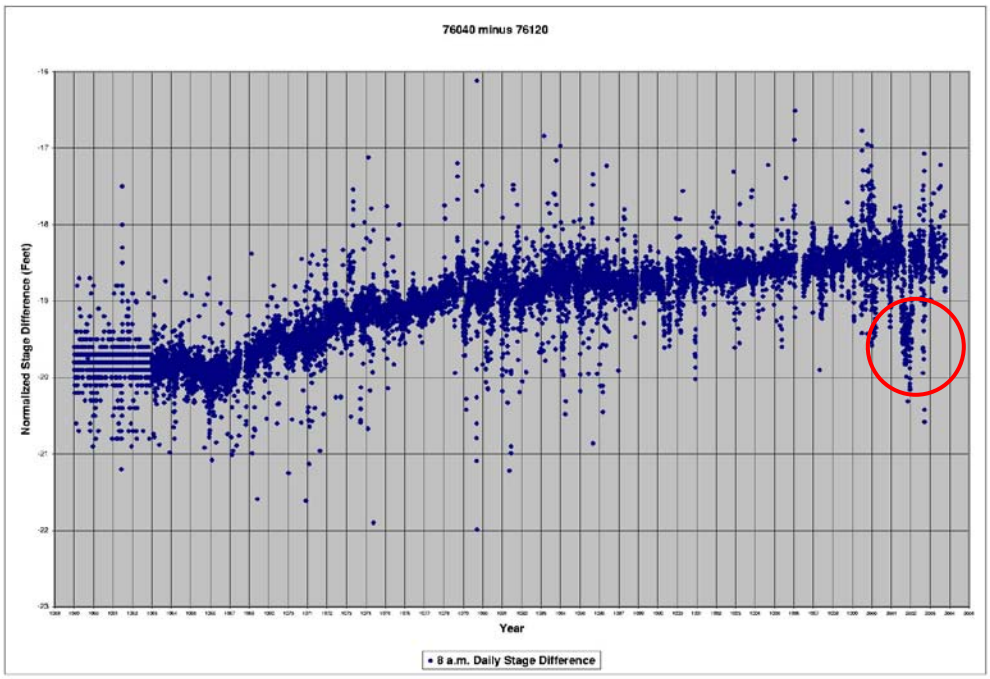


Figure L-7. Normalized gage readings for Gage 76040 – Gage 76120.

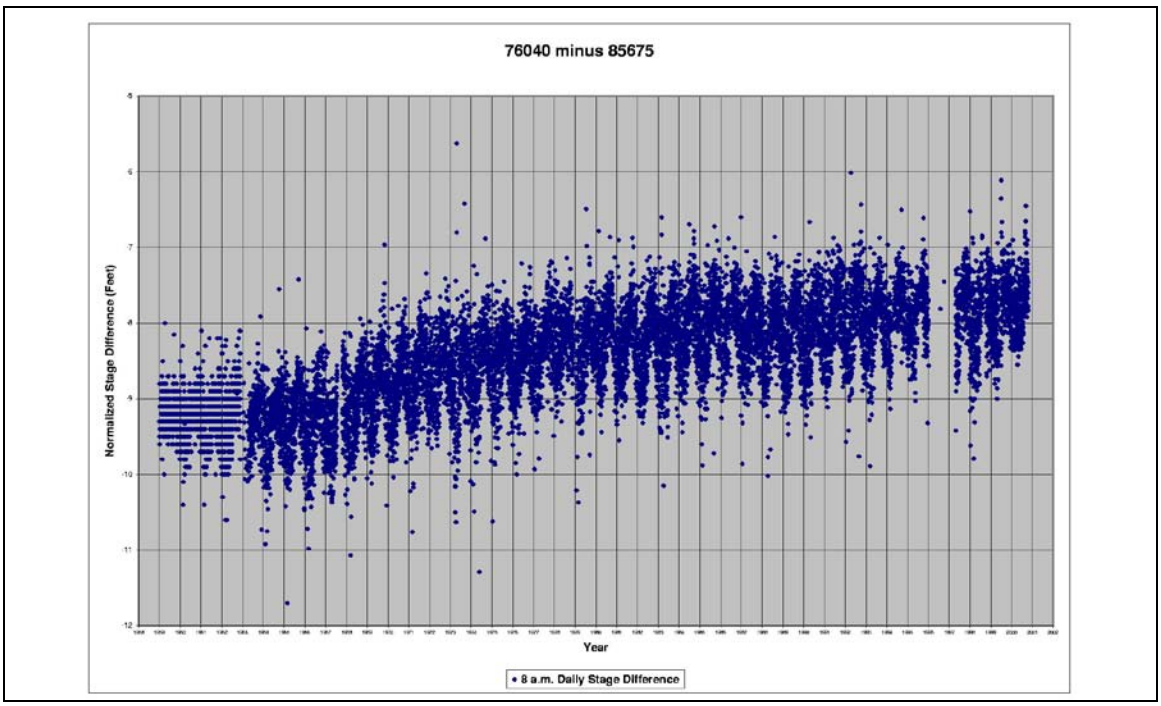


Figure L-8. Normalized gage readings for Gage 76040 – Gage 85675.

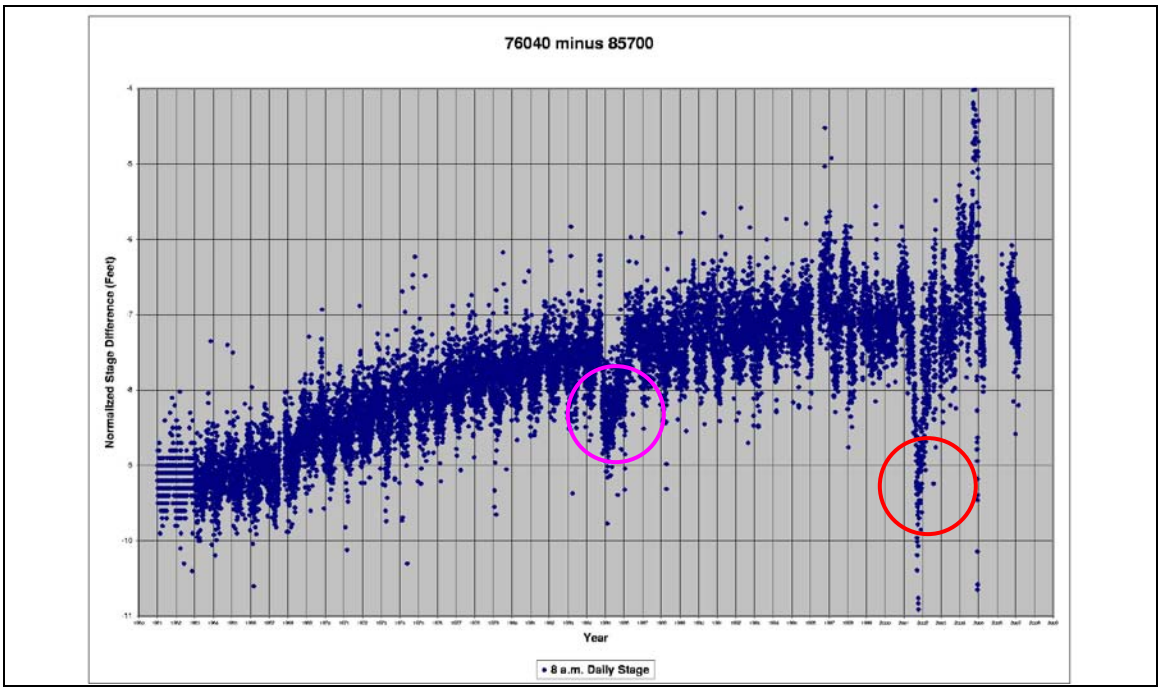


Figure L-9. Normalized gage readings for Gage 76040 – Gage 85700.

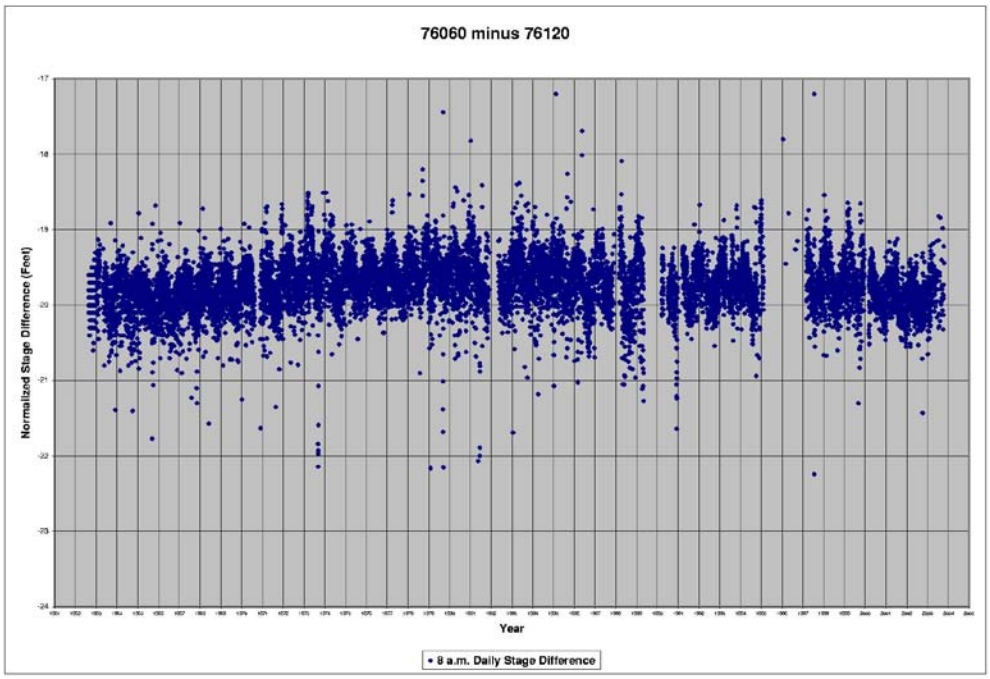


Figure L-10. Normalized gage readings for Gage 76060 – Gage 76120.

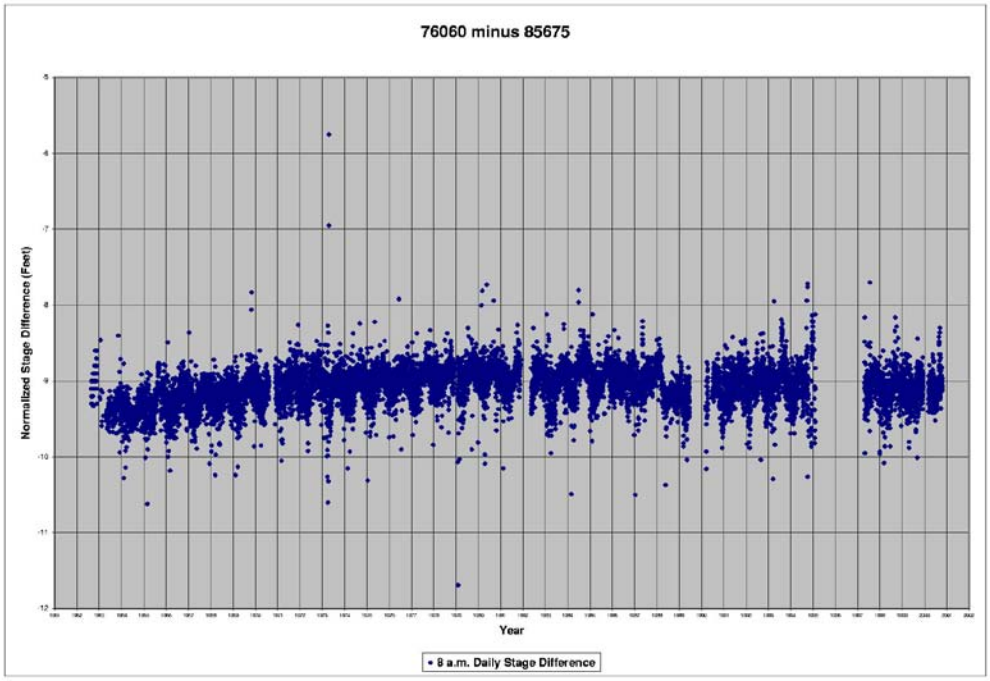


Figure L-11. Normalized gage readings for Gage 76060 – Gage 85675.

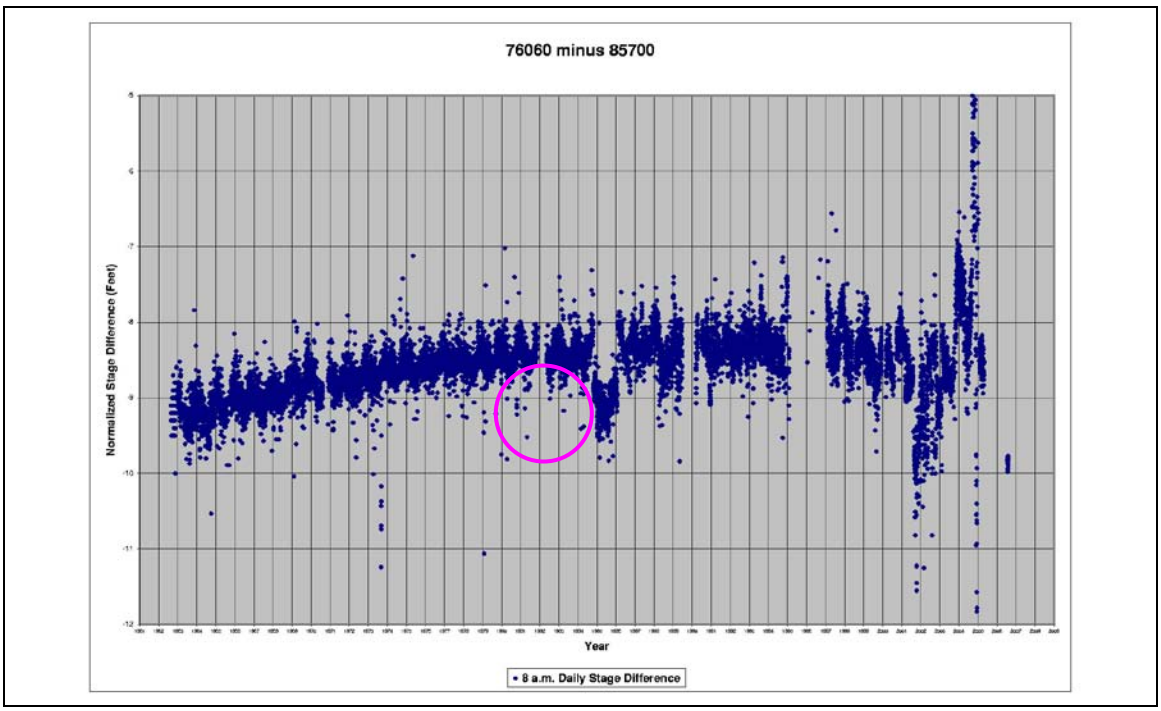


Figure L-12. Normalized gage readings for Gage 76060 – Gage 85700.

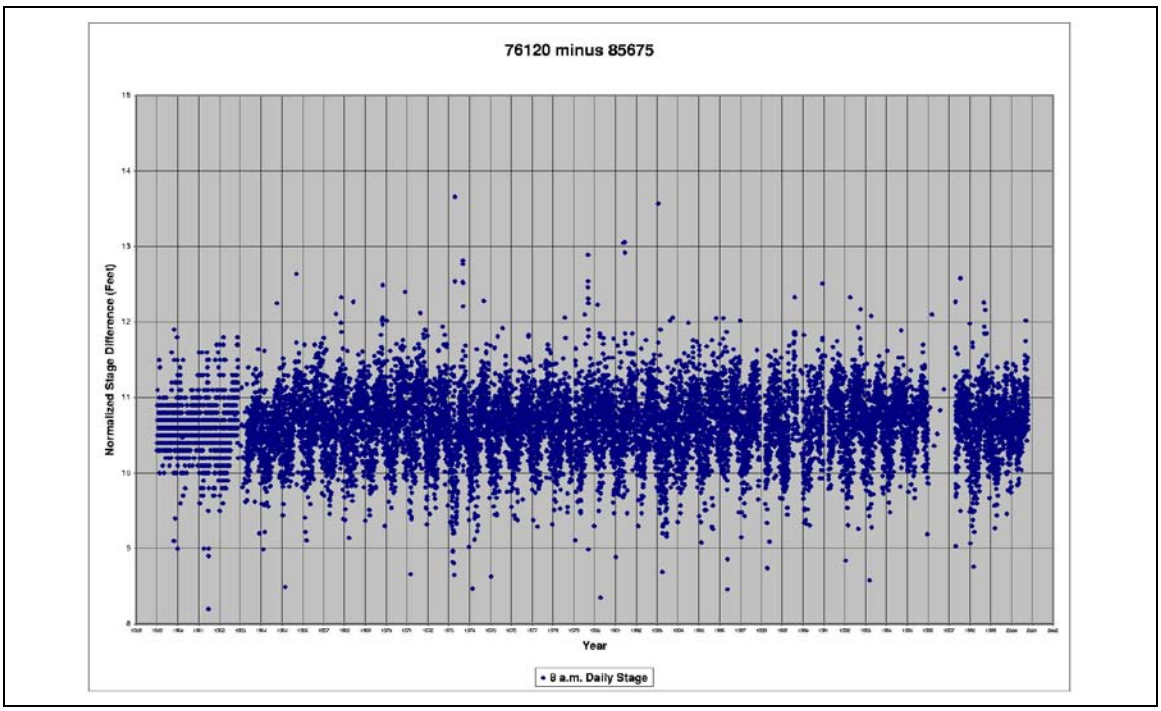


Figure L-13. Normalized gage readings for Gage 76120 – Gage 85675.

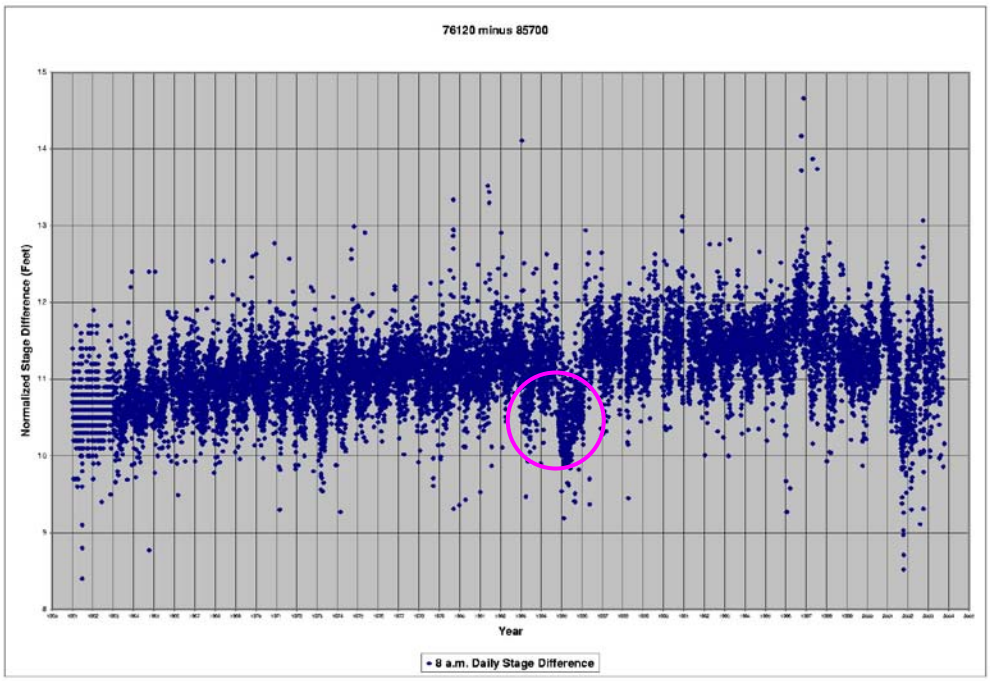


Figure L-14. Normalized gage readings for Gage 76120 – Gage 85700.

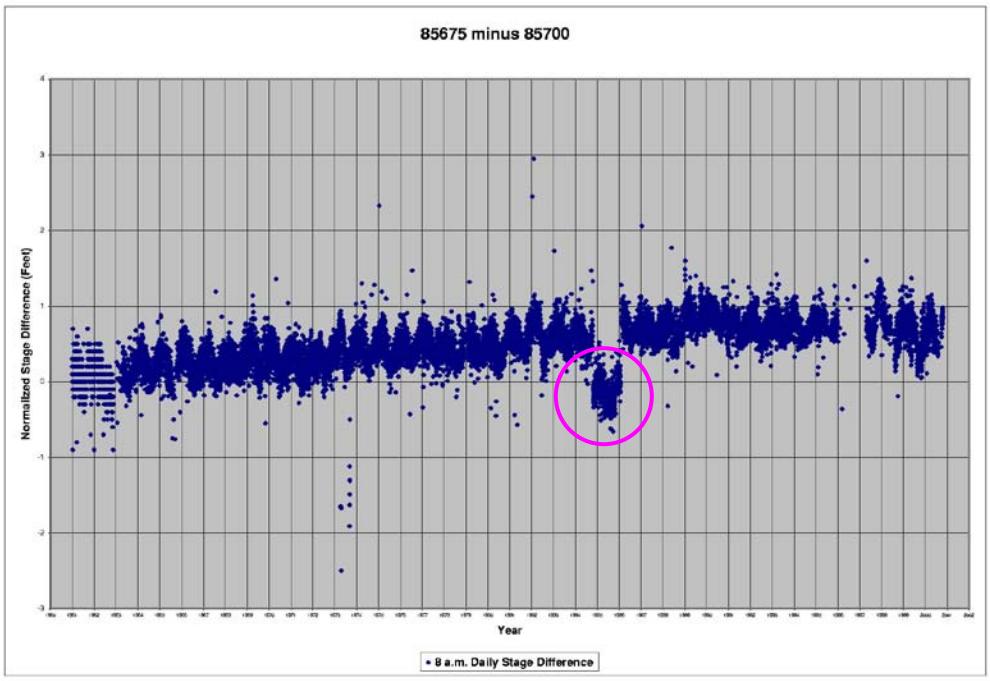


Figure L-15. Normalized gage readings for Gage 85675 – Gage 85700.

b. Figures L-6 through L-15 generally exhibit the anticipated characteristics (i.e., consistent, smooth, continuous) indicating that all intentional vertical movement of the gage

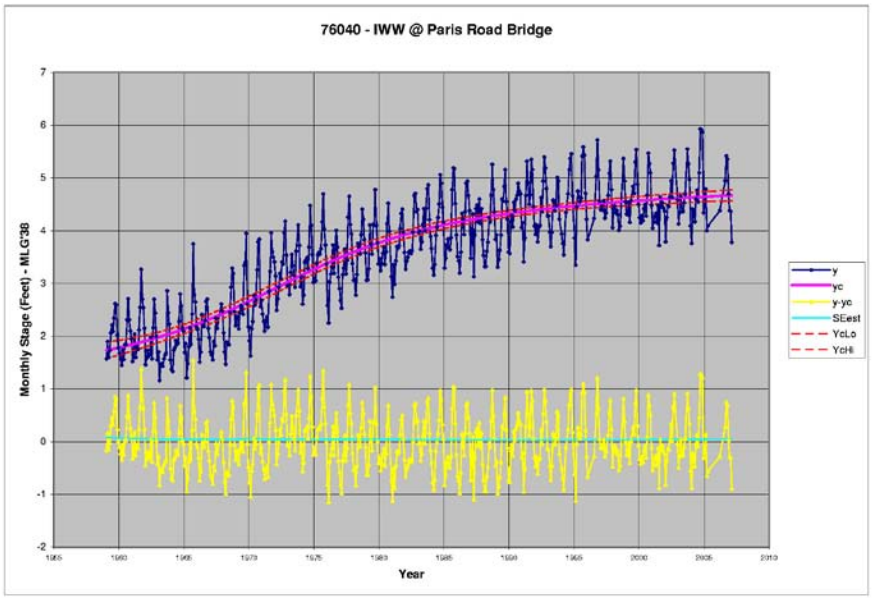
zeros has been accounted for. However, the areas indicated by the red circles suggest that the zero for gage 76040 was disturbed or out of calibration during the latter half of 2001. The areas indicated by the purple circles suggest that the zero for gage 85700 was disturbed or out of calibration during most of 1985. These apparent data problems are noted here but, since their precise cause and magnitude have not been determined and their duration is relatively short lived, the anomalous regions were not removed or altered for subsequent processing. Only the clearly erratic data from mid 2001 forward at gage 85700 has been disregarded in subsequent processing.

L-6. Data Regression. In all of the following discussion, the increase in stage values over time (apparent in Figure L-5 above, for example) is, for simplicities sake, assumed to be attributable solely to subsidence. Although this is almost certainly not the case in reality, it is for the moment, a useful practical assumption. The effects and contribution of eustatic sea level rise will be reintroduced and considered later where necessary. Also, though it may run counter to convention, downward displacement of the land (as reflected by increasing stage readings) is considered positive subsidence (for the purposes of this document, downward displacement of the land and rates of downward displacement will be treated as numerically positive values).

a. A straight-line regression was computed for the 76040 gage data set (see Figure L-5 above). The slope of the line indicates that the average annual apparent subsidence rate over the entire period from 1959 to 2007 is 0.068 feet/year or 21 mm/year, an order of magnitude greater than a commonly accepted estimate for the rate of eustatic sea level rise. This result was essentially duplicated by specialists at NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) using the same normalized data set.

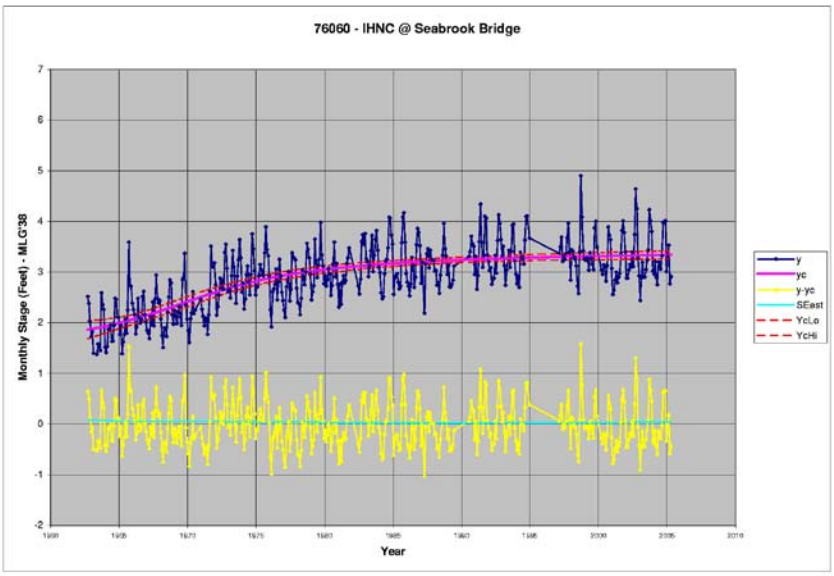
b. It should be noted that CO-OPS has employed basic straight-line regression in order to estimate rates of relative sea level rise at many of its coastal gaging stations, typically using 30 or more years of data (Stolz and Gill, 2005, Zervas 2001). CO-OPS is also responsible for computing National Tidal Datum Epoch (NTDE) mean values for tidal datums (e.g., mean sea level, mean lower low water, mean high water, etc.). The NTDE is the specific 19-year period adopted by NOAA as the official time segment over which tide observations are taken at a given station and reduced to obtain mean values for that station (Gill, et al, 2001). Given the periodic and apparent secular trends in sea level, the NTDE is typically revised every 20 to 25 years. The present NTDE is 1983 through 2001. It should also be noted that while mean sea level is defined as the arithmetic mean of hourly heights observed over the NTDE, a close approximation of mean sea level would be the mid-point of the linear trend (straight line fit via least-squares regression) of monthly means computed from hourly heights observed over the NTDE. The relevance of this point will be made clear subsequently.

c. In Figure L-5, it was apparent that a linear trend line was perhaps not the best model for the USACE gage data sets under consideration. In fact, each gage data set had a distinctly sigmoidal appearance, possibly characterized by a short period of relatively high subsidence preceded and followed by less dramatic rates. For this reason, an attempt was made to fit an arctangent function to the monthly means computed for each of the normalized gage data sets (for months having 20+ days of data). See Figures L-16 through L-20 below.



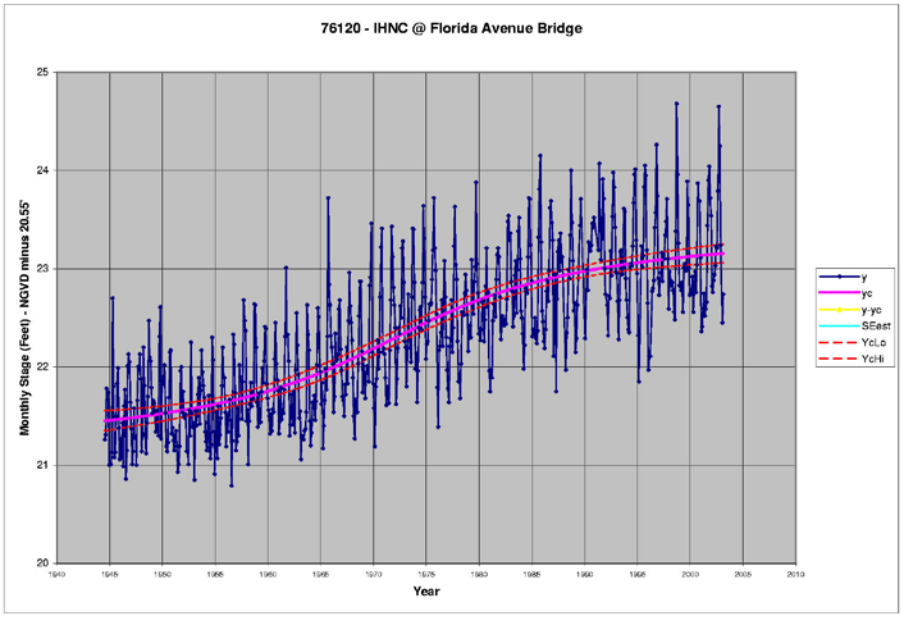
f(x) =	a*ATan(b*(x-c))+d			
a =	1.378155	±0.138453	Corr. Coeff.:	0.88289
b =	0.089980	±0.014565	r^2:	0.779494
c =	1972.207566	±1.119109	RMS Error:	0.512598
d =	2.930489	±0.101659		

Figure L-16. Arctangent function fit to the monthly means for Gage 76040 IWW @ Paris Road Bridge.



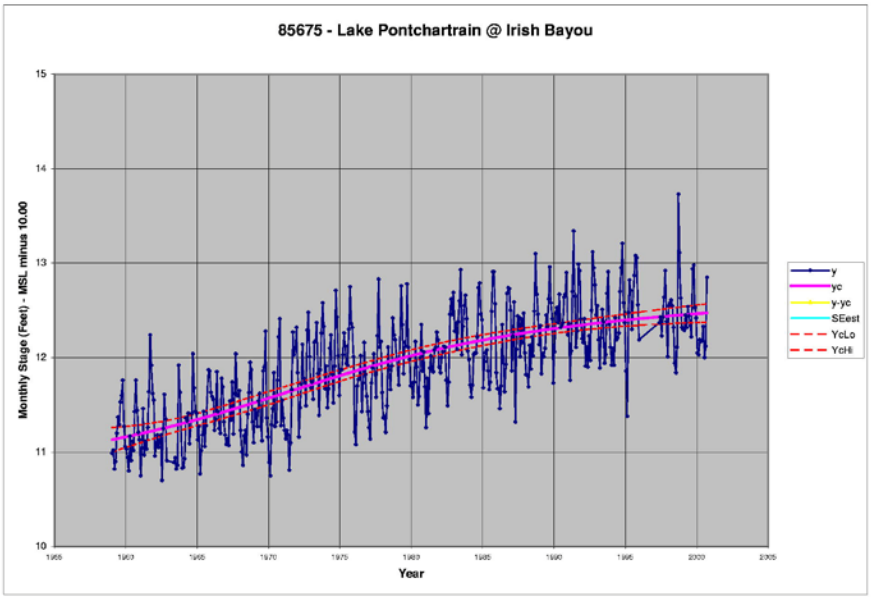
f(x) =	a*ATan(b*(x-c))+d			
a =	0.695612	±0.136575	Corr. Coeff.:	0.720065
b =	0.135400	±0.037931	r^2:	0.518493
c =	1969.704684	±1.896262	RMS Error:	0.433079
d =	2.390207	±0.137857		

Figure L-17. Arctangent function fit to the monthly means Gage 76060 IHNC @ Seabrook Bridge.



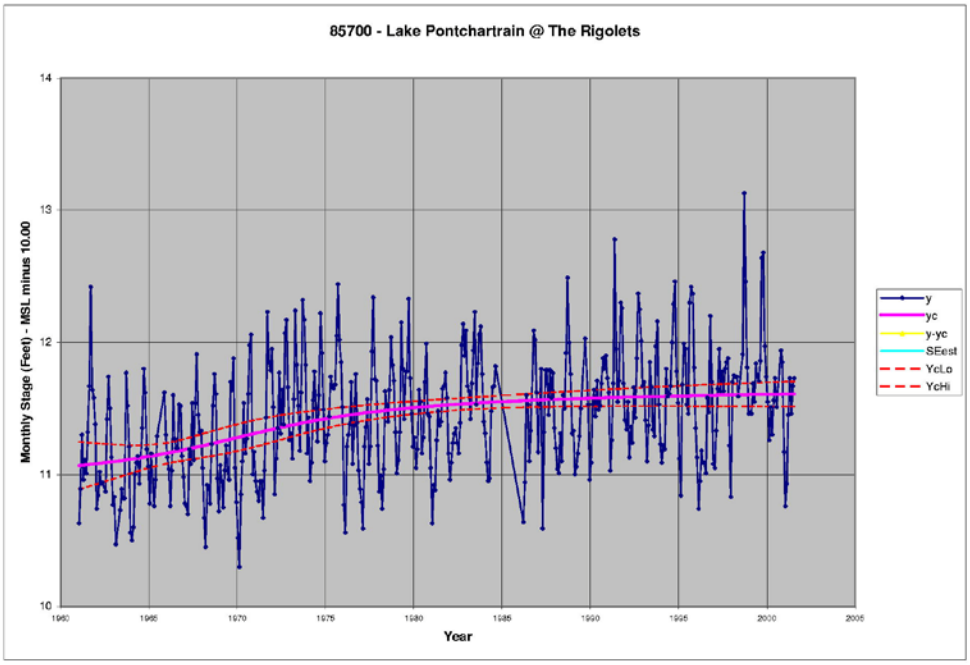
f(x) =	a*ATan(b*(x-c))+d			
a =	0.760559	±0.087261	Corr. Coeff.:	0.777721
b =	0.070699	±0.015234	r^2:	0.60485
c =	1971.786335	±1.298087	RMS Error:	0.482486
d =	22.28285	±0.04282		

Figure L-18. Arctangent function fit to the monthly means for Gage 76120 IHNC @ Florida Avenue Bridge.



f(x) =	a*ATan(b*(x-c))+d			
a =	0.779884	±0.227218	Corr. Coeff.:	0.744277
b =	0.061847	±0.023451	r^2:	0.553948
c =	1971.490714	±3.368383	RMS Error:	0.377163
d =	11.641887	±0.13693		

Figure L-19. Arctangent function fit to the monthly means for Gage 85675 Lake Pontchartrain @ Irish Bayou.

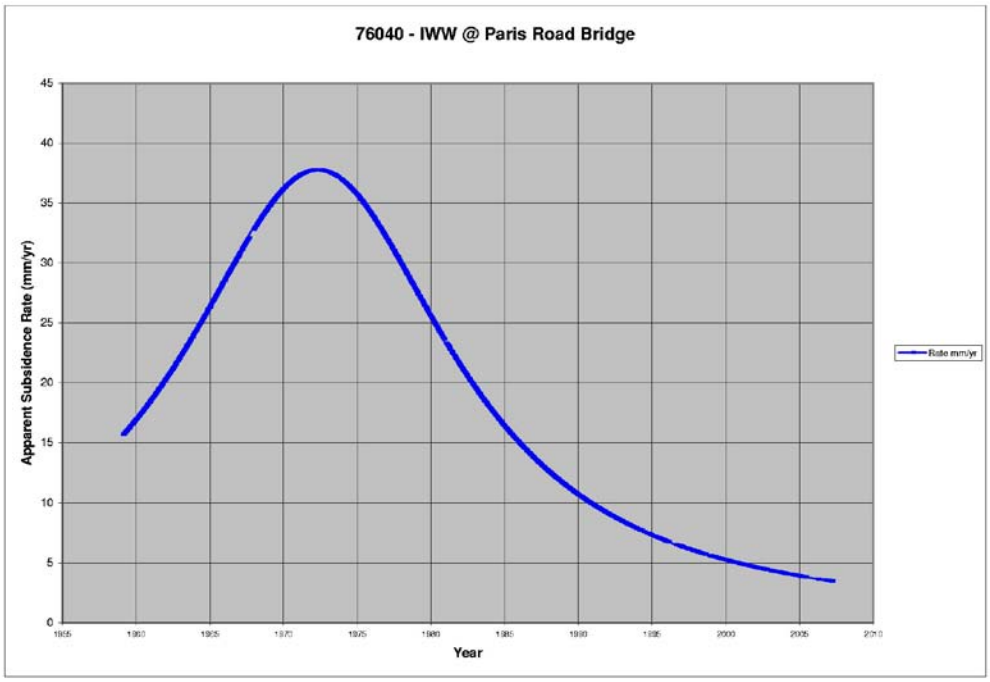


f(x) =	a*ATan(b*(x-c))+d				
a =	0.233812	±0.111057	Corr. Coeff.:	0.387012	
b =	0.144264	±0.09595	r^2:		0.149778
c =	1970.363367	±4.179788	RMS Error:	0.41044	
d =	11.288451	±0.098107			

Figure L-20. Arctangent function fit to the monthly means for Gage 85700 Lake Pontchartrain @ The Rigolets.

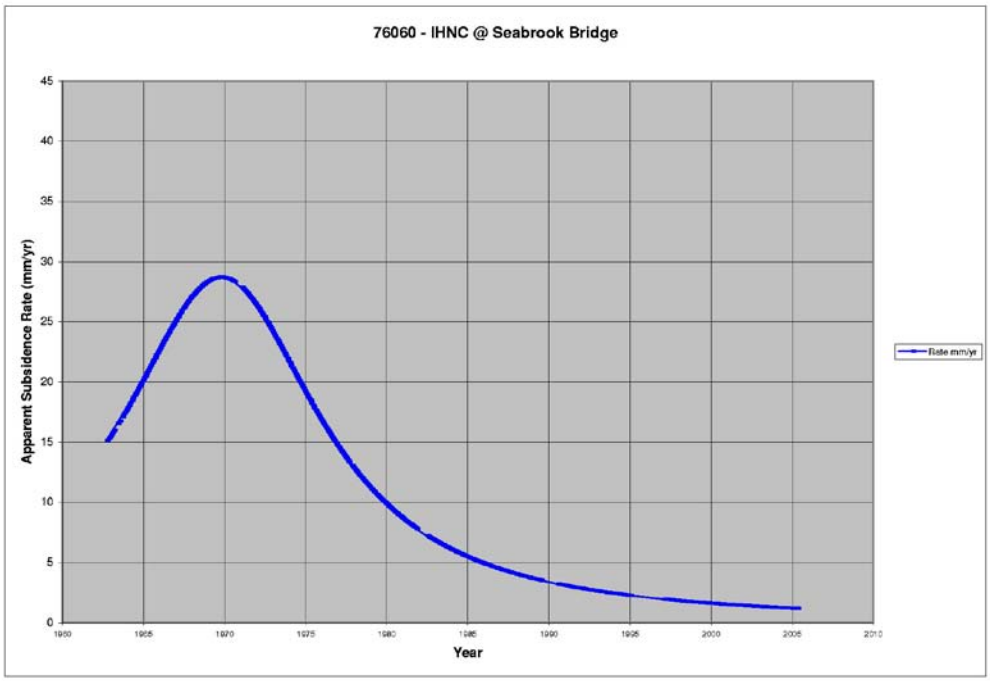
d. In Figures L-16 through L-20, “y” is the observed monthly mean stage computed from the daily 8 A.M. values: “yc” is the estimated mean stage value computed from the arctangent curve fit to the data through iterative, non-linear, least-squares regression; “y-yc” is the residual of observed minus estimated value; “SEst” is the estimate of standard error for each point computed along the curve; “YcHi” and “YcLo” are the upper and lower bounds of the 95% confidence interval of the curve. A notable result of the regression analysis is that the point of inflection, or the point at which the rate of apparent subsidence is at its maximum, occurs at very nearly the same moment in time for each gage site: 1972.2, 1969.7, 1971.8, 1971.5, and 1970.4 for gages 76040, 76060, 76120, 85675, and 85700 respectively. The RMS error, r^2, and Correlation Coefficient were, in all cases, an improvement over the corresponding values produced by straight-line regression. . Note that the graph of mean monthly stages for each gage exhibits (more or less) a seasonal or annually periodic cycle. The phase and amplitude of this apparent seasonal cycle appears to be roughly consistent with estimates for the Average Seasonal Cycle of Monthly Mean Sea Level computed by NOAA for several of their gages along the Louisiana/ Mississippi Gulf Coast (Zervas, 2001).

L-7. Apparent Subsidence Rates. A graph of the estimated instantaneous rate of apparent subsidence, expressed in mm/year rather than ft/year, for each gage was computed from the first derivative of their respective regression models and is shown in Figures L-21 through L-26 below.



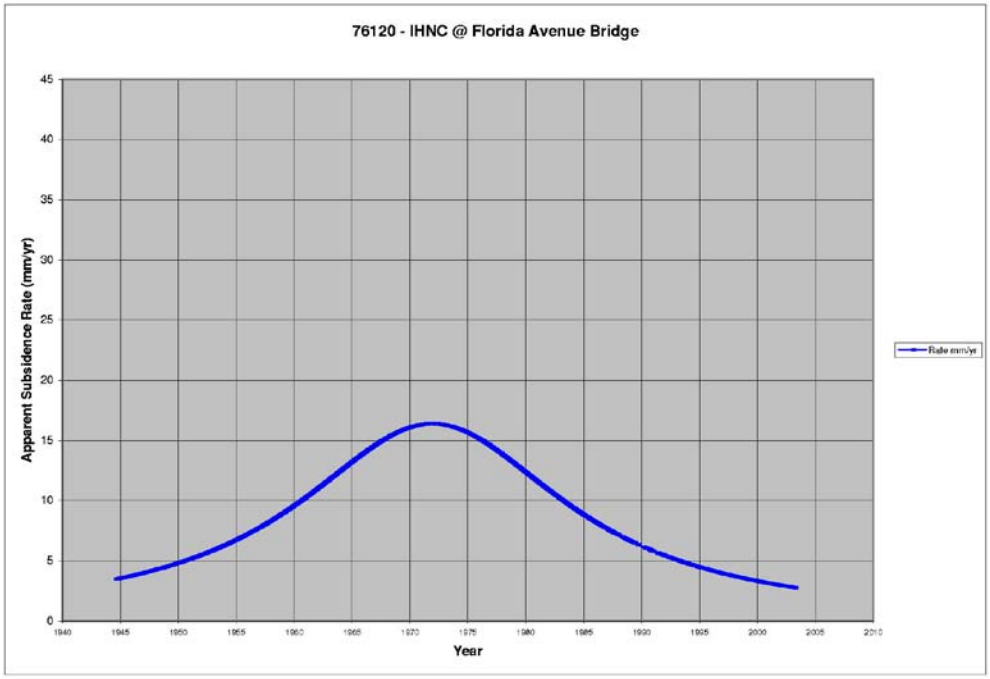
f'(x) = 0.124006/(0.0080964*(x-1972.207566)^2+1)

Figure L-21. Estimated Instantaneous rate of apparent subsidence for Gage 76040 IWW @ Paris Road Bridge.



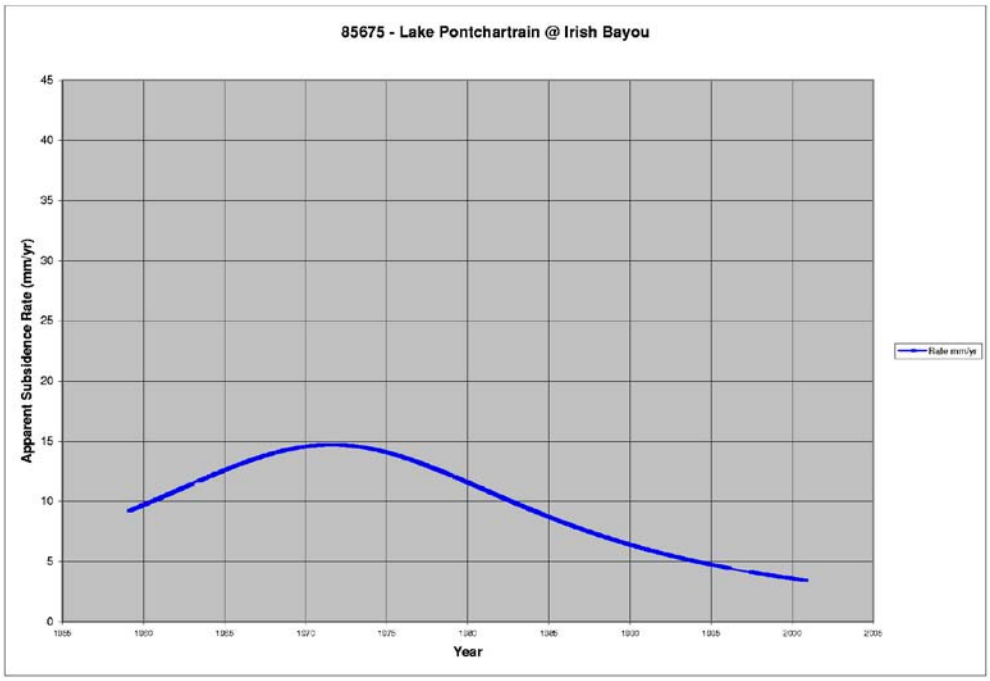
f'(x) = 0.0941859/(0.0183332*(x-1969.704684)^2+1)

Figure L-22. Estimated instantaneous rate of apparent subsidence for Gage 76060 IHNC @ Seabrook Bridge.



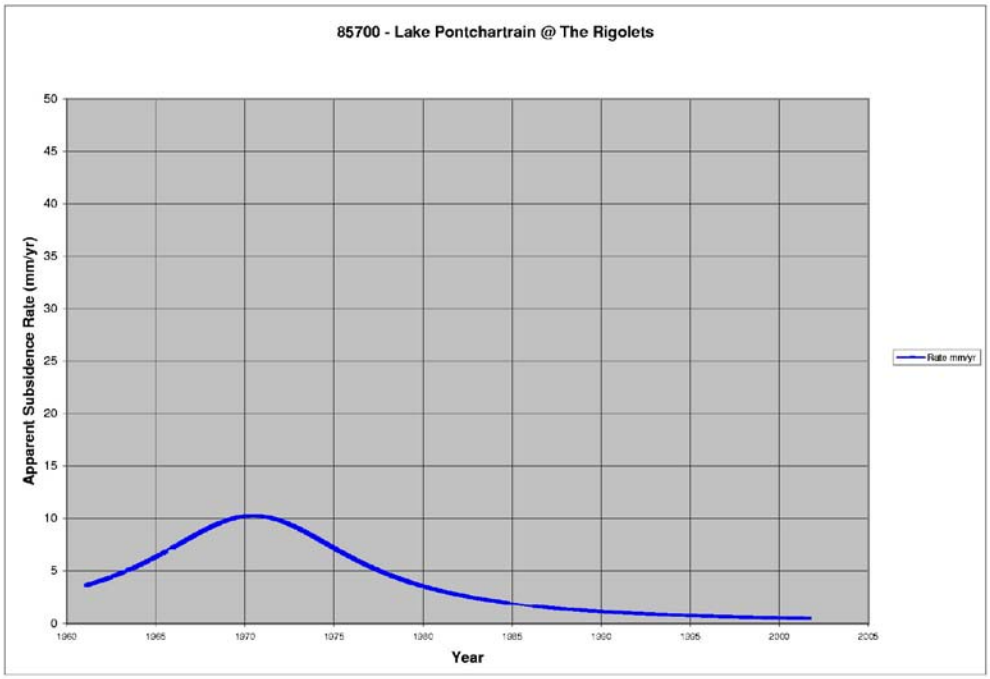
f'(x) = 0.0537708/(0.00499835*(x-1971.786335)^2+1)

Figure L-23. Estimated instantaneous rate of apparent subsidence for Gage 76120 IHNC @ Florida Avenue Bridge.



f'(x) = 0.0482335/(0.00382505*(x-1971.490714)^2+1)

Figure L-24. Estimated instantaneous rate of apparent subsidence for Gage 85675 Lake Pontchartrain @ Irish Bayou.



f'(x) = 0.0337307/(0.0208121*(x-1970.363367)^2+1)

Figure L-25. Estimated instantaneous rate of apparent subsidence for Gage 85700 Lake Pontchartrain @ The Rigolets.

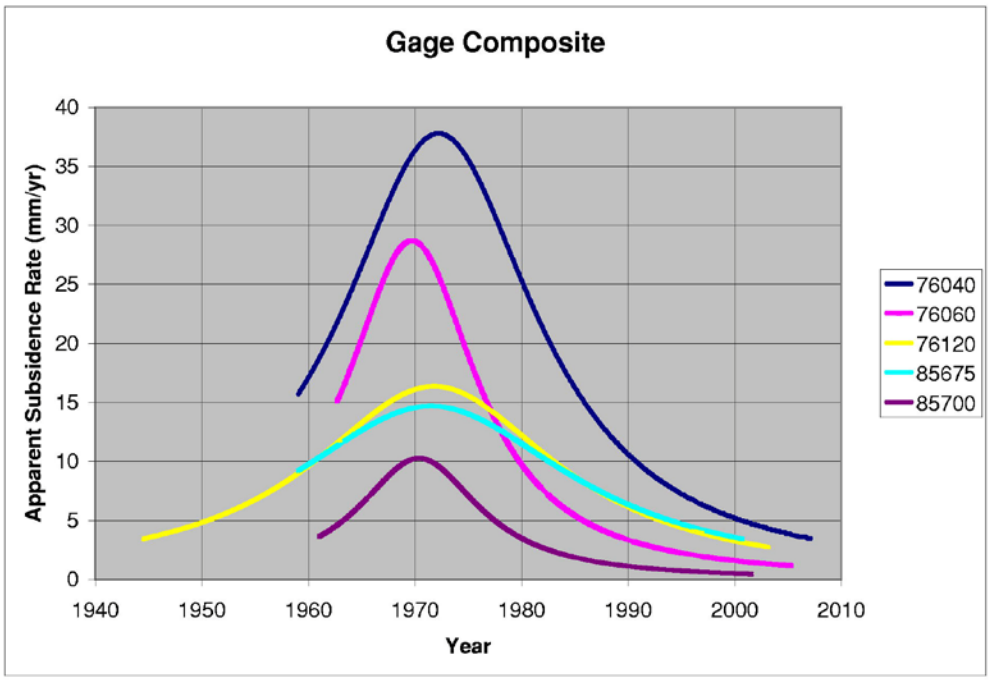


Figure L-26. Composite graph of estimated instantaneous rate of apparent subsidence for all gages.

a. While peak apparent subsidence rates seem to occur nearly simultaneously at all five gage sites, the peak rates themselves vary considerably:

76040 has a peak rate of 37.8 mm/yr at 1972.2
76060 has a peak rate of 28.7 mm/yr at 1969.7
76120 has a peak rate of 16.4 mm/yr at 1971.8
85675 has a peak rate of 14.7 mm/yr at 1971.5
85700 has a peak rate of 10.3 mm/yr at 1970.4

The 76120 rate curve (that is remarkably similar to the 85675 curve) indicates that apparent subsidence at that gage in the 1940s was minimal (± 3 mm/yr) and increased relatively gradually through the 1950s. All of the curves indicate that at some time in the early 1960s rates increased more rapidly, peaking around 1970 to 1972. Thereafter, all of the curves indicate that rates then decreased rapidly over the next ten years and began to flatten out again. All of the curves appear to be converging on a rate of around 2 to 4 mm/yr by 2005.

b. It may be useful to note that the term "apparent subsidence" is simply another way of saying "relative sea level rise." Both are terms used to indicate the combined effect of both *actual* eustatic sea level rise and *actual* subsidence (Stolz and Gill, 2005). Therefore, if all of the above apparent subsidence rate curves are reduced by that portion of the rate thought to be due to eustatic sea level rise (estimated to be 2 mm/yr), the resulting rates should serve as reasonable estimates of *actual subsidence*. The immediate significance here is that the convergence of the apparent subsidence rates in 2005 to 2 to 4 mm/yr suggests that, in fact, the present-day actual subsidence at these gage sites may be negligible (0 to 2 mm/yr).

c. This apparent convergence to zero may be to some extent an artifact of the selected regression function (the arctangent function seeks horizontal asymptotes) and, therefore, overly optimistic. In any event, it would not be wise to use this or any other function fit to the historic stage data as a reliable predictor of future subsidence rates.

L-8. Geodetic – Tidal Datum Comparison. Most of the USACE gage data sets have been connected to one or more nearby permanent bench marks in the national geodetic vertical control network maintained by the NGS. A complete discussion of the history, methods of survey, computation, and adjustment of the elevations of benchmarks in this network is beyond the scope of this work. It is worth noting that a classical vertical datum (e.g., NGVD29 or NAVD88 prior to the advent of Vertical Time Dependant Positioning or VTDP) is, in essence and in the most practical sense for the end user, the physical bench marks and their associated/published elevations.

a. Implicit in this statement is the fact that the final adjusted elevations computed for the physical benchmarks - being influenced by a variety of field and computational factors (choice of control constraints, adjustment methods, classical field survey measurement methods and uncertainties, etc.) - define a network-wide "zero" surface that is irregular and does not precisely coincide with any equipotential surface. It is not, in an absolute geodetic sense, truly or permanently "fixed." It is, in a sense, malleable, meaning that, as the benchmarks go, so goes

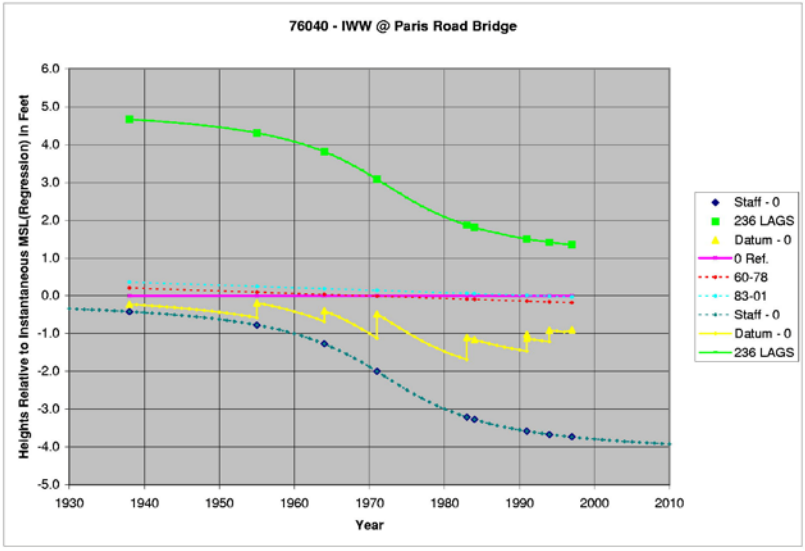
the “zero” surface. As some benchmarks are displaced downward by subsidence and others upward by glacial rebound, for example, so too is the “zero” surface displaced and warped.

b. The “zero” surface is also malleable in the sense that - as new stations and observations are added to the network and other are destroyed or eliminated, and/or as a consequence of the displacements described above – periodic “epoch updates” may be computed for a particular region or portion of an existing vertical datum or a wholesale network-wide re-adjustment may be computed to establish an entirely new vertical datum. An epoch update and/or network-wide datum readjustment essentially results in an entirely new “zero” surface. It may be very similar to the previous “zero” surface in an absolute sense, but it is not precisely coextensive with it (Zilkoski, Richards and Young, 1992).

c. With the advent of GPS, the CORS network,), and more precise geoid models, the problem of defining a truly “fixed” zero reference surface has become more tractable in recent years. However, despite the fact that recent NAVD88 epoch updates in south Louisiana (2004.65 and 2006.81) are based primarily on GPS baseline vector observations, they are still to some degree dependant upon and influenced or otherwise constrained by control point elevations developed conventionally in earlier epoch updates and/or adjustments based on estimated subsidence rates, as well as a geoid model that is subject to further refinement.

d. For these reasons, a means of displaying the relationships among the various geodetic datum epoch “zeros” and the local mean sea level surfaces at each gage location was chosen that may at first seem counter intuitive. The following graphs are based upon the assumption (initially) that the rate of eustatic sea level rise is zero and that the regression curve is the trace of the fixed and unchanging instantaneous mean sea level surface on a gage that is subsiding at the same rate as nearby benchmarks and the land surface to which they and the gage are anchored. By thus defining the regression curve as instantaneous mean sea level (IMSL) or the “fixed” zero reference surface, the vertical displacement of the normalized gage “zero”, the controlling benchmark, and the geodetic datum/epoch “zero” defined by that physical mark may be determined at any moment in time with respect to IMSL.

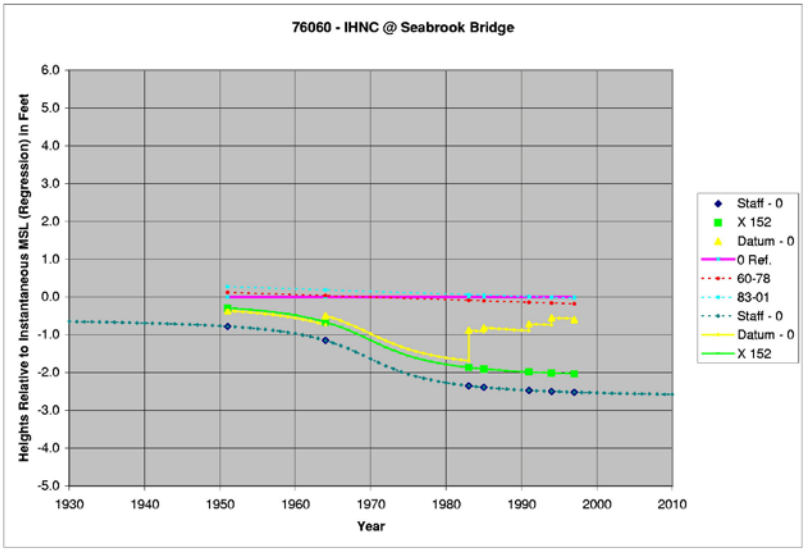
e. Finally, since the rate of eustatic sea level rise is, in fact, estimated to be 2 mm/yr, two lines sloping negatively at the rate of 2 mm/yr (Stolz and Gill, 2005) and intercepting the IMSL zero line at 1969.5 and 1992.5 (these being the respective midpoints of the 1960-1978 and 1983-2001 National Tidal Datum Epochs) have been computed. If the rate estimate for eustatic sea level rise is correct, these lines may be interpreted as the “fixed” tidal datum surfaces corresponding to the height of IMSL at the midpoint of the respective tidal datum epochs (i.e., approximate NTDE MSL). From these lines, estimates of the relationships among the geodetic and tidal datum epochs may be computed (see Figures L-27 through L-30).



NGS Station "236 LAGS"

Year Epoch	IMSL(Reg.) Staff - 0	IMSL(Reg.) 236 LAGS	IMSL(Reg.) Datum - 0	IMSL(Reg.) 0 Ref.	MSL(Reg.) 60-78	MSL(Reg.) 83-01	Stage "MLG'38"	Stage "MSL'38"	NGS Pub Elev.	Vert. Datum
1938	-0.42	4.66	-0.225	0.00	0.207	0.358	1.20	0.42	4.885	"SLD29"
1955	-0.78	4.30	-0.188	0.00	0.095	0.246	1.56	0.78	4.488	"SLD29"
1964	-1.27	3.81	-0.395	0.00	0.036	0.187	2.05	1.27	4.205	"SLD29"
1971	-2.00	3.08	-0.480	0.00	-0.010	0.141	2.78	2.00	3.560	"SLD29"
1983	-3.21	1.87	-1.100	0.00	-0.089	0.062	3.99	3.21	2.970	NGVD29
1984	-3.27	1.81	-1.159	0.00	-0.095	0.056	4.05	3.27	2.969	NGVD29
1991	-3.58	1.50	-1.020	0.00	-0.141	0.010	4.36	3.58	2.520	NGVD29
1991	-3.58	1.50	-1.130	0.00	-0.141	0.010	4.36	3.58	2.630	NAVD88
1994	-3.67	1.41	-0.910	0.00	-0.161	-0.010	4.45	3.67	2.320	NAVD88
1997	-3.73	1.35	-0.900	0.00	-0.180	-0.030	4.51	3.73	2.250	NAVD88

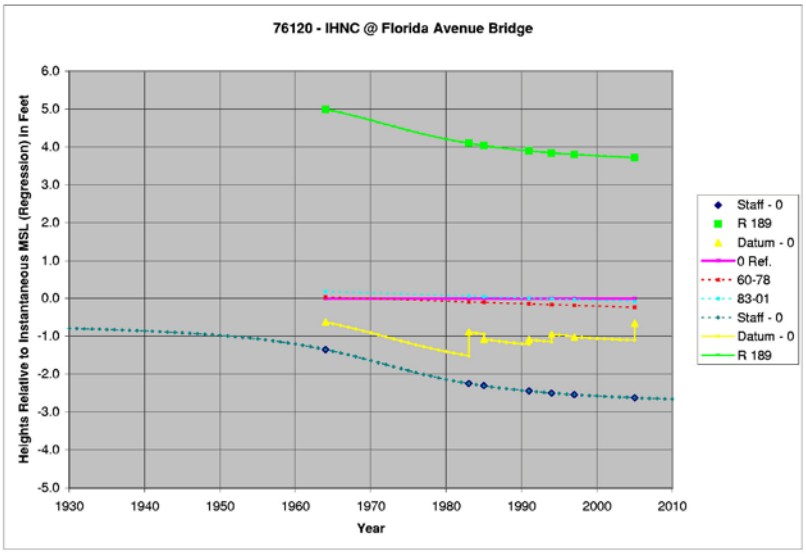
Figure L-27. Estimates of the relationships among the geodetic and tidal datum epochs at Gage 76040 IWW @ Paris Road Bridge.



NGS Station "X 152"

Year Epoch	IMSL(Reg.) Staff - 0	IMSL(Reg.) X 152	IMSL(Reg.) Datum - 0	IMSL(Reg.) 0 Ref.	MSL(Reg.) 60-78	MSL(Reg.) 83-01	Stage "MLG'38"	Stage "MSL'38"	NGS Pub Elev.	Vert. Datum
1951	-0.78	-0.29	-0.363	0.00	0.121	0.272	1.56	0.78	0.072	"SLD29"
1964	-1.15	-0.66	-0.490	0.00	0.036	0.187	1.93	1.15	-0.171	"SLD29"
1983	-2.35	-1.86	-0.880	0.00	-0.089	0.062	3.13	2.35	-0.981	NGVD29
1985	-2.39	-1.90	-0.812	0.00	-0.102	0.049	3.17	2.39	-1.089	NGVD29
1991	-2.47	-1.98	-0.711	0.00	-0.141	0.010	3.25	2.47	-1.270	NGVD29
1994	-2.50	-2.01	-0.551	0.00	-0.161	-0.010	3.28	2.50	-1.460	NAVD88
1997	-2.52	-2.03	-0.591	0.00	-0.180	-0.030	3.30	2.52	-1.440	NAVD88

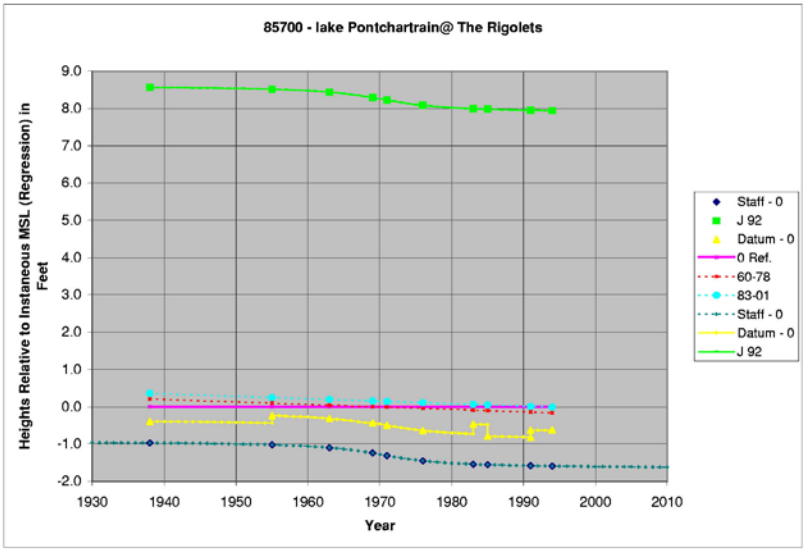
Figure L-28. Estimates of the relationships among the geodetic and tidal datum epochs at Gage 76060 IHNC @ Seabrook Bridge.



NGS Station "R 189"

Year Epoch	IMSL(Reg.) Staff - 0	IMSL(Reg.) R 189	IMSL(Reg.) Datum - 0	IMSL(Reg.) 0 Ref.	MSL(Reg.) 60-78	MSL(Reg.) 83-01	Stage "MSL-20.55"	Stage "MSL"	NGS Pub Elev.	Vert. Datum
1964	-1.35	4.99	-0.620	0.00	0.036	0.187	21.90	1.35	5.610	"SLD29"
1983	-2.24	4.10	-0.883	0.00	-0.089	0.062	22.79	2.24	4.983	NGVD29
1985	-2.30	4.04	-1.075	0.00	-0.102	0.049	22.85	2.30	5.115	NGVD29
1991	-2.44	3.90	-1.090	0.00	-0.141	0.010	22.99	2.44	4.990	NGVD29
1994	-2.50	3.84	-0.950	0.00	-0.161	-0.010	23.05	2.50	4.790	NAVD88
1997	-2.54	3.80	-1.020	0.00	-0.180	-0.030	23.09	2.54	4.820	NAVD88
2005	-2.62	3.72	-0.650	0.00	-0.233	-0.082	23.17	2.62	4.370	NAVD88

Figure L-29. Estimates of the relationships among the geodetic and tidal datum epochs at Gage 76120 IHNC @ Florida Avenue Bridge.



NGS Station "J 92"

Year Epoch	IMSL(Reg.) Staff - 0	IMSL(Reg.) J 92	IMSL(Reg.) Datum - 0	IMSL(Reg.) 0 Ref.	MSL(Reg.) 60-78	MSL(Reg.) 83-01	Stage "MSL-10.00"	Stage "MSL"	NGS Pub Elev.	Vert. Datum
1938	-0.97	8.56	-0.393	0.00	0.207	0.358	10.97	0.97	8.953	"SLD29"
1955	-1.02	8.51	-0.237	0.00	0.095	0.246	11.02	1.02	8.747	"SLD29"
1963	-1.10	8.43	-0.317	0.00	0.043	0.194	11.10	1.10	8.747	"SLD29"
1969	-1.24	8.29	-0.430	0.00	0.003	0.154	11.24	1.24	8.720	"SLD29"
1971	-1.31	8.22	-0.500	0.00	-0.010	0.141	11.31	1.31	8.720	"SLD29"
1976	-1.45	8.08	-0.640	0.00	-0.043	0.108	11.45	1.45	8.720	NGVD29
1983	-1.54	7.99	-0.467	0.00	-0.089	0.062	11.54	1.54	8.457	NGVD29
1985	-1.55	7.98	-0.790	0.00	-0.102	0.049	11.55	1.55	8.770	NGVD29
1991	-1.58	7.95	-0.820	0.00	-0.141	0.010	11.58	1.58	8.770	NGVD29
1991	-1.58	7.95	-0.630	0.00	-0.141	0.010	11.58	1.58	8.580	NAVD88
1994	-1.59	7.94	-0.620	0.00	-0.161	-0.010	11.59	1.59	8.560	NAVD88

Figure L-30. Estimates of the relationships among the geodetic and tidal datum epochs at Gage 85700 Lake Pontchartrain @ The Rigolets.

f. From the perspective of these charts (that again assume that the stage regression lines represent the best approximation of instantaneous mean sea level for any moment in time), one can determine that geodetic datum "zero" for a particular vertical control point at a given gage site has changed over time and at each epoch update and new datum adjustment (i.e., the change from MSL29/ NGVD29 to NAVD88 in 1991) with respect to IMSL and the estimated NTDE MSL values.

g. A chart showing heights relative to IMSL for "85675 – Lake Pontchartrain at Irish Bayou" has not been produced since sufficient documentation of the relationship of the gage zero to a benchmark in the national geodetic vertical network has not yet been obtained. It should also be pointed out that any comparison made to IMSL prior to 1960 for gages 76040, 76060 and 85700 is based upon an extrapolation of the regression curve.

h. As a final effort to clearly convey the apparent relationship among the various geodetic and tidal datum epochs at each gage, graphs that may be more conventional or familiar –

indicating the height differences of IMSL, NTDE'60-'79 MSL and NTDE'83-'01 MSL with respect to the geodetic datum/epoch "zeros" – are shown below (Figures L-31 through L-33, Tables L-2 through L-5).

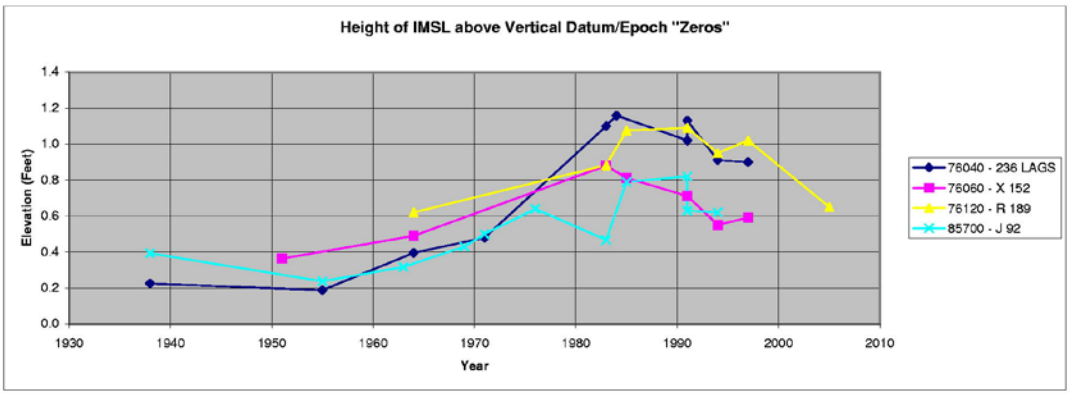


Figure L-31. Elevation of local instantaneous mean sea level with respect to geodetic datum zero as defined by referenced control monuments and associated elevations for given datum and epoch identified in Tables L-2 though L-5.

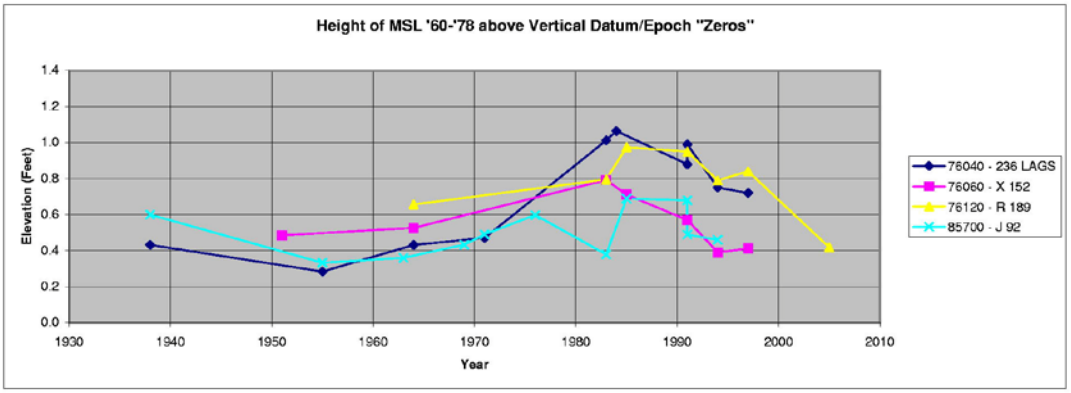


Figure L-32. Elevation of local mean sea level (NTDE 60-78) with respect to geodetic datum zero as defined by referenced control monuments and associated elevations for given datum and epoch identified in Tables L-2 though L-5.

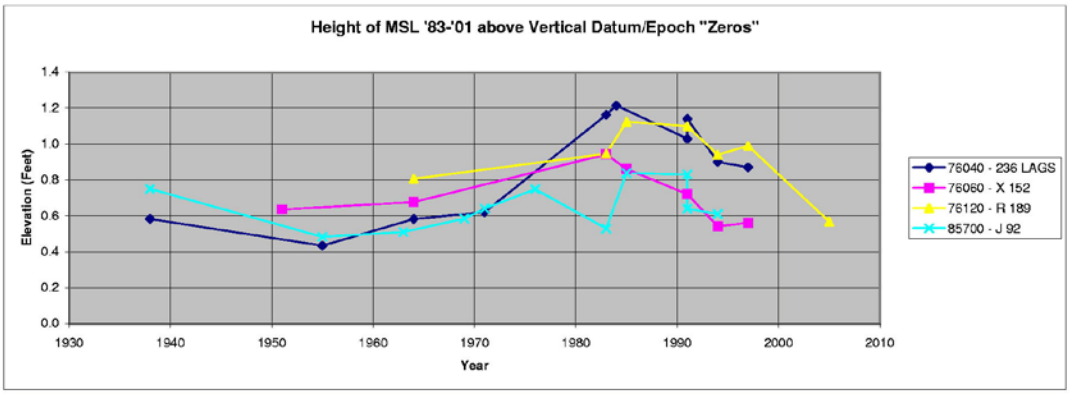


Figure L-33. Elevation of local mean sea level (NTDE 83-01) with respect to geodetic datum zero as defined by referenced control monuments and associated elevations for given datum and epoch identified in Tables L-2 though L-5.

Table L-2. 76040--NGS Station "236 LAGS."

Height (in feet) of IMSL and MSL for 60-78 and 83-01 epochs above various Geodetic Vertical Datum/Epoch "Zeros"
(Assumes Eustatic Sea-Level rise of 0.00656 ft/yr or 2 mm/yr)

Vert. Datum	Year Epoch	IMSL(Reg.) 0 Ref.	IMSL(Reg.) 60-78	IMSL(Reg.) 83-01
“SLD29”	1938	0.225	0.432	0.583
“SLD29”	1955	0.188	0.283	0.434
“SLD29”	1964	0.395	0.431	0.582
“SLD29”	1971	0.480	0.470	0.621
NGVD29	1983	1.100	1.011	1.162
NGVD29	1984	1.159	1.064	1.215
NGVD29	1991	1.020	0.879	1.030
NAVD88	1991	1.130	0.989	1.140
NAVD88	1994	0.910	0.749	0.900
NAVD88	1997	0.900	0.720	0.870

Table L-3. 76060--NGS Station "X 152."

Height (in feet) of IMSL and MSL for 60-78 and 83-01 epochs above various Geodetic Vertical Datum/Epoch "Zeros" (Assumes Eustatic Sea-Level rise of 0.00656 ft/yr or 2 mm/yr)

Vert. Datum	Year Epoch	IMSL(Reg.) 0 Ref.	IMSL(Reg.) 60-78	IMSL(Reg.) 83-01
“SLD29”	1951	0.363	0.484	0.635
“SLD29”	1964	0.490	0.526	0.677
NGVD29	1983	0.880	0.791	0.942
NGVD29	1985	0.812	0.710	0.861
NGVD29	1991	0.711	0.570	0.721
NAVD88	1994	0.551	0.390	0.541
NAVD88	1997	0.591	0.411	0.561

Table L-4. 76120--NGS Station "R 189."

Height (in feet) of IMSL and MSL for 60-78 and 83-01 epochs above various Geodetic Vertical Datum/Epoch "Zeros" (Assumes Eustatic Sea-Level rise of 0.00656 ft/yr or 2 mm/yr)

Vert. Datum	Year Epoch	IMSL(Reg.) 0 Ref.	IMSL(Reg.) 60-78	IMSL(Reg.) 83-01
“SLD29”	1964	0.620	0.656	0.807
NGVD29	1983	0.883	0.794	0.945
NGVD29	1985	1.075	0.973	1.124
NGVD29	1991	1.090	0.949	1.100
NAVD88	1994	0.950	0.789	0.940
NAVD88	1997	1.020	0.840	0.990
NAVD88	2005	0.650	0.417	0.568

Table L-5. 85700--NGS Station "J 92."

Height (in feet) of IMSL and MSL for 60-78 and 83-01 epochs above various Geodetic Vertical Datum/Epoch "Zeros" (Assumes Eustatic Sea-Level rise of 0.00656 ft/yr or 2 mm/yr)

Vert. Datum	Year Epoch	IMSL(Reg.) 0 Ref.	IMSL(Reg.) 60-78	IMSL(Reg.) 83-01
“SLD29”	1938	0.393	0.600	0.751
“SLD29”	1955	0.237	0.332	0.483
“SLD29”	1963	0.317	0.360	0.511
“SLD29”	1969	0.430	0.433	0.584
“SLD29”	1971	0.500	0.490	0.641
NGVD29	1976	0.640	0.597	0.748
NGVD29	1983	0.467	0.378	0.529
NGVD29	1985	0.790	0.688	0.839
NGVD29	1991	0.820	0.679	0.830
NAVD88	1991	0.630	0.489	0.640
NAVD88	1994	0.620	0.459	0.610

L-9. Conclusion. When properly normalized, useful historic subsidence rate data may be extracted from the 8 A.M. daily stages recorded at USACE gages throughout coastal Louisiana. This data may also be helpful in assessing how well previous geodetic vertical datum epoch updates or readjustments by NGS responded to the local effects of subsidence. Finally, south Louisiana appears to be in a region of spatio-temporally varying subsidence. Consequently, straight-line regression applied to stage data recorded at the various USACE gages in this study appears to mask significant subsidence rate variability and captures neither the fact that rates significantly higher than the gage-specific average appear to have occurred during the 1960s and 1970s, nor that these rates appear to have abated to well below the average in recent years.

L-10. References Cited.

Dokka, R. K., 2006, *Modern-day Tectonic Subsidence in Coastal Louisiana*; Geology, v. 34, pp. 281 – 284.

Gill, S. K., Schultz, J. R., et al, *Tidal Datums and Their Applications*; NOAA Special Publication NOS CO-OPS 1, February, 2001.

Gonzalez, J. L., and Tornqvist, T. E., *Coastal Louisiana in Crisis: Subsidence or Sea Level Rise?*; EOS, Vol. 87, No. 45, 7 November 2006.

Shinkle, K., and Dokka, R. K., 2004, *Rates of Vertical Displacement at Benchmarks in the Lower Mississippi Valley and Northern Gulf Coast*; NOAA Technical Report 50, 135 p.

Stolz, A. L., and Gill, S. K., *Relative Long-term Sea Level Trends: How are they determined and what do they tell us?*; Proceedings of the 14th Biennial Coastal Zone Conference, New Orleans, Louisiana, July 17 to 21, 2005.

Zervas, C., *Sea level Variations of the United States 1854-1999*; NOAA Technical Report NOS CO-OPS 36, July, 2001.

Zilkoski, D. B., Richards, J. H., and Young, G. M., *Results of the General Adjustment of the North American Vertical Datum of 1988*; American Congress on Surveying and Mapping, *Surveying and Land Information Systems*, Vol. 52, No. 3, 1992, pp. 133-149.