Geo-Marine Letters (2019) 39:265–278
https://doi.org/10.1007/s00367-019-00573-3

TECHNICAL PAPER

Recent subsidence rates for Barataria Basin, Louisiana

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Received: 22 December 2018 / Accepted: 17 May 2019 / Published online: 27 May 2019
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Abstract

Subsidence in south Louisiana is a fundamental process and major source of uncertainty influencing restoration planning and design and wetland habitat resilience. The primary goal of this study was to conduct an analysis of recent subsidence rates within the Barataria Basin. High-resolution geodetic GPS elevation measurements at 19 benchmarks were used to determine recent subsidence rates for the Barataria Basin. Net elevation changes at all stations equaled or exceeded predicted measurement uncertainties based on session duration. Water elevation change from two gauges in the southern part of the basin supplemented survey data, resulting in a range of subsidence velocities at 21 locations from about 2 to 7 mm/year. These data record short-term subsidence trends (6- to 16-year time series) that are expected to be representative of conditions at proposed restoration sites over the next 20 to 50 years. Foundation/rod depths for benchmarks ranged from near surface to about 30-m deep. None of these foundations/rods were sleeved or anchored and thus were not isolated from surrounding consolidating sediment and associated downdrag forces. Therefore, subsidence rates at these sites were considered representative for the entire sediment column. Subsidence rate comparisons for nearby deep and shallow rod benchmarks support this conclusion. Spatial variability in subsidence indicates a compelling relationship between subsidence rates and the age, composition, and thickness of Holocene deltaic deposits. The Coastal Protection and Restoration Authority of Louisiana intends to use this same approach to continue refining subsidence rates throughout coastal Louisiana to support coastal restoration planning and design.

Introduction

Subsidence in south Louisiana is a primary factor influencing restoration planning and design and wetland habitat resilience. Subsidence is defined as a downward movement of the earth's surface relative to a vertical datum such as sea level, which includes localized impacts of settling due to overburden and marsh consolidation associated with hydrologic changes. Natural subsidence processes include consolidation of Holocene, Pleistocene, and Tertiary age sediments (Dokka 2009); fault-induced elevation changes due to basin tectonics (Dokka 2006; Dokka et al. 2006; Dokka 2011); and downwarping of the Gulf Coast geosyncline due to sediment loading (Blum et al. 2008; Yuill et al. 2009). Human-induced subsidence processes include lowering of the groundwater table through forced drainage of saturated organic soils (marsh and swamp), causing measurable shrinkage of the soil column (oxidation of organic matter) (Jones et al. 2016); overburden associated with flood protection levees; and marsh surface settling resulting from alterations to natural marsh hydrology (Yuill et al. 2009). Subsurface fluid withdrawal has been identified as a localized cause of subsidence (Morton et al. 2006); however, the geographic extent and vertical contribution to the subsidence signal is difficult to quantify based on a variety of reservoir characteristics and geologic controls impacting the degree to which surface changes may occur (Chan and Zobak 2007; Mallman and Zobak 2007). Further, Olea and Coleman (2014) reported that oil and gas production plays only a minor role relative to subsidence, with sediment loading and normal faulting dipping basinward accounting for > 90% of the signal. Subsidence rates vary widely across south Louisiana due to the age and complexity of deltaic deposits, underlying geologic controls, and human alterations to wetland habitat.

Consolidation of fine-grained, deltaic Holocene deposits with high water content is considered the principal contributor

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to subsidence in the Louisiana coastal zone (Kolb and Van Lopik 1958; Roberts 1985; Roberts et al. 1994; Törnqvist et al. 2008; Jankowski et al. 2017). Primary consolidation occurs as soil volume is reduced due to dewatering under the weight of overlying sediment. Oxidation of organic matter through chemical reactions also reduces soil volume. Thicker sediment deposits contain more interstitial water available for removal, which leads to high rates of subsidence as they consolidate. Older deltaic deposits have undergone primary consolidation for a longer period and therefore should exhibit lower subsidence rates than recently deposited sediments. Keucher (1994) and Keucher et al. (2001) have indicated that early consolidation of highly organic and clay-rich facies within a newly deposited delta is a primary component of subsidence. In other words, areas of the deltaic plain overlying thick Holocene deposits within the entrenched Mississippi River valley are expected to subside at higher rates than areas outside the valley where Holocene sediment thickness is less (Roberts 1985).

Although Dokka (2006, 2011) identified deep seated subsidence (upper Pleistocene and older) as a primary contributor to subsidence on the delta plain, he assumed that all measured elevation changes reflected movement below the base of pilings or rods in consolidating Holocene clay, thereby ignoring the potential impact of downward drag forces (e.g., Endo et al. 1969; Bozozuk 1972; Blanchet et al. 1980; Fellenius 1984; Tran and Nguyen 2003; Fellenius 2006; El-Mossallamy et al. 2013; Abdrabbo and Ali 2015) caused by settling of Holocene sediment through which a pile or rod was driven. In geotechnical terms, shear stresses that act downward on a pile or rod within a consolidating sediment column are called negative skin friction (Davisson 1993; Briaud and Tucker 1996; Huang et al. 2015; Fellenius 2018). This downward force on a pile or rod from the surrounding sediment is called downdrag. Unless coatings or sleeves are applied during the installation of piles or rods in consolidating sediments, downdrag forces will act to pull piles or rods downward as the sediment subsides (Floyd 1978; Chao et al. 2006; Fellenius 2018).

Understanding the causes and rates of subsidence across the Louisiana coastal zone is critical to successful planning and implementation for State Coastal Master Plan projects. Estimates of subsidence have been made by comparing benchmark leveling data (e.g., Shinkle and Dokka 2004), tide gauge measurements (e.g., Penland and Ramsey 1990; Kolker et al. 2011; USACE 2015), and radiometric dating of buried peat horizons (e.g., Roberts 1985; Kulp 2000; Dokka 2009). Estimates of recent subsidence rates generally are derived from data obtained from sites on or near engineered structures (e.g., roads, bridges, buildings). Therefore, resulting subsidence rate estimates may not fully reflect natural marsh subsidence processes unrelated to the confounding effects of human disturbances. Given the geologic complexity and diverse processes contributing to subsidence, it has been difficult for the Coastal Protection and Restoration Authority of Louisiana (CPRA) to generalize subsidence rate estimates over spatial scales ranging from 10 to 10^4 km^2 (i.e., project scale). In this regard, the 2012 Coastal Master Plan developed plausible ranges of subsidence identified during an expert advisory panel meeting in September 2010 that subsequently were adopted as part of the 2017 Coastal Master Plan (Fig. 1; Reed and Yuill 2016).

The primary goal of the present study was to conduct an assessment of recent subsidence rates (velocities) within the Barataria Basin (Fig. 2). In particular, campaign-style geodetic GPS (global positioning system) elevation measurements (8- to 24-h continuous measurements for a minimum of two separate days) were evaluated for CPRA/National Geodetic Survey (NGS) secondary benchmarks and Continuously Operating Reference Station (CORS) elevations (primary survey markers). These data record short-term subsidence trends (6- to 16-year time series) from direct survey measurements and are expected to be indicative of conditions at proposed restoration sites over the next 20 to 50 years. Further, the US Army Corps of Engineers (USACE), US Geological Survey (USGS), and National Oceanic and Atmospheric Administration (NOAA) water-level gauge measurements were evaluated for documenting subsidence relative to eustatic sea-level rise estimates for the northern Gulf of Mexico (GoM). Because Holocene geology and sediment consolidation are primary factors controlling subsidence, defining the geological setting of the Barataria Basin was deemed critical for understanding local geological controls and their impact on observed subsidence velocities.

Physical setting

During the last glacial advance, the Late Wisconsinan, continental ice accumulation caused sea level to be lowered approximately 125 m below its present level (Clark et al. 2009; Yokoyama et al. 2018). As a result, the Louisiana shoreline was as far as 160 km south of its present position (Kolb and van Lopik 1958). Lowered sea level led to incision by gulfward-flowing streams and their tributaries into the newly exposed Pleistocene Prairie Formation. Entrenchment of the ancestral Mississippi River into the Prairie Formation formed an alluvial valley with branching tributary valleys approximately 16- to 40-km wide. With the onset of glacial melting, sea level rose and glacial outwash formed substratum sand and gravel deposits in the entrenched valley. Sea level continued to rise until between 4000 and 7000 years ago, when an approximate stillstand of sea level occurred slightly lower than the present level (Nummedal 1983; Coleman et al. 1991; Milliken et al. 2008). The Mississippi River began building a series of lobate deltas, displacing Gulf waters that had extended up the Mississippi River alluvial valley. As such, the deltaic plain is composed of active and several inactive

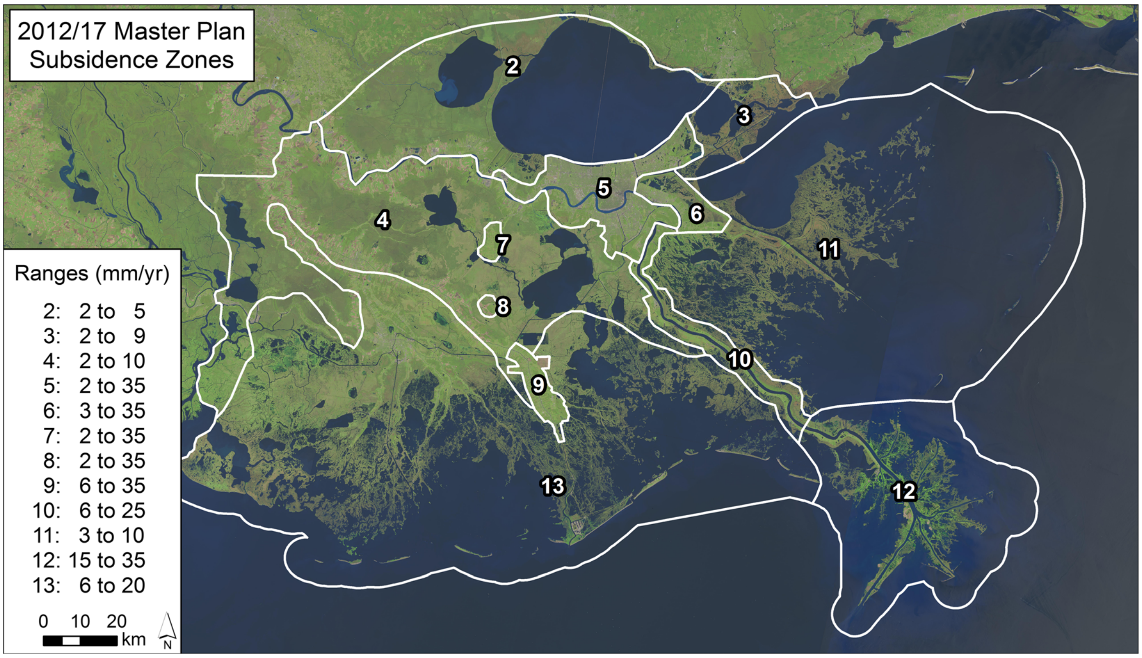

Fig. 1 Subsidence rate ranges used as input to 2017 Coastal Master Plan modeling efforts. The ranges depict plausible subsidence rates estimated to be indicative of conditions over the next 50 years (modified after Reed and Yuill 2016)

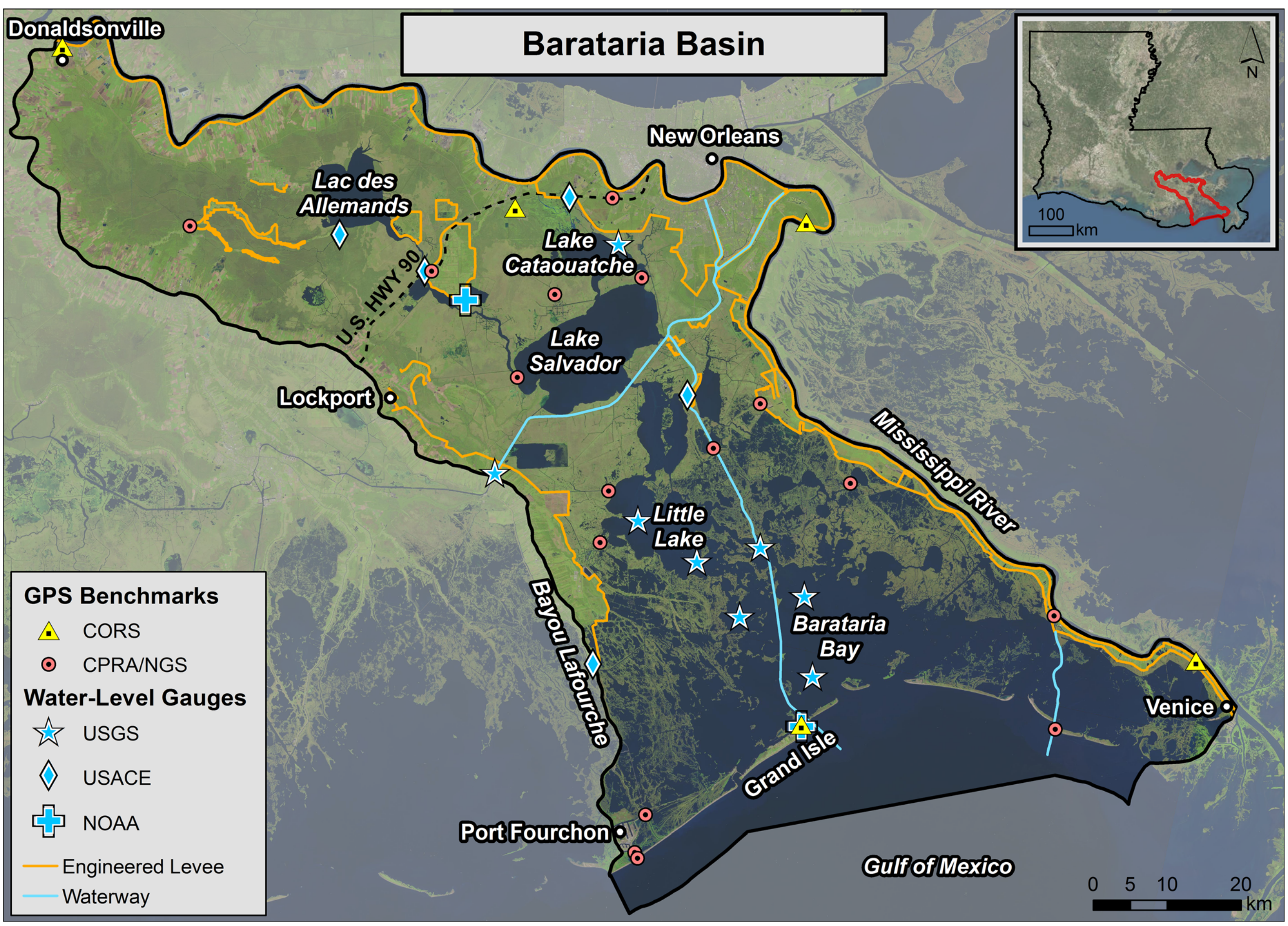

Fig. 2 Satellite image (Landsat 8 OLI/TIRS) illustrating the hydrologic boundary and physiographic features for the Barataria Basin, as well as GPS benchmark and water-level gauge locations for evaluating subsidence

delta complexes, including from oldest to youngest, the Maringouin, Teche, St. Bernard, Lafourche, Plaquemines/Modern (Frazier 1967), and the Atchafalaya/Wax Lake complexes (Fig. 3).

Delta building over the past 7000 years has resulted in a thick sequence of fine grained deposits filling the ancestral Mississippi River valley (Frazier 1967; Coleman 1988; Roberts 1997; Kulp et al. 2005). These deltaic deposits reach a maximum thickness of 130 m at the mouth of the present Mississippi River and about 60 m in the ancestral valley near Grand Isle (Dunbar et al. 1994; Heinrich et al. 2015). Since the early 1900s, engineering activities have had a major influence on many of the key elements controlling the delta cycle. The Old River Control Structure has disrupted the delta switching process by maintaining the Mississippi River in its present course. Flood protection levees built beginning in the late 1700s confined the flow of the Mississippi River, eliminating overbank flooding of nutrients and sediments that accompany floods (Davis 2010). Further, suspended sediment load of the Mississippi River declined by approximately 50% between the 1930 to 1952 period and the 1963 to 1982 period (Kesel 1988; Blum and Roberts 2009). This decline has been attributed to erosion control measures such as bank stabilization by revetments and to dams constructed on the Missouri River and other large tributaries. As the natural delta-building process became constrained, the impact of Holocene sediment consolidation (subsidence) became more pronounced as relative sea-level rise and erosion began to dominate the coastal landscape, accelerating wetland vegetation changes and land loss.

The Barataria Basin, which encompasses approximately 7100 km^2, is located west and south of the Mississippi River, east of Bayou Lafourche, and is bounded at its southern extent by barrier islands fronting the GoM (Fig. 2). The basin is approximately 110-km long and widens southward from the junction of Bayou Lafourche and the Mississippi River at Donaldsonville. The widest part of the basin is along the barrier islands at the GoM, between the mouth of Bayou Lafourche and the Mississippi River. Elevations are highest on natural levees bordering the Mississippi River, reaching approximately 4 to 5 m, and lowest in the marshes where they are slightly above sea level (outside the polders and flood protection systems). From north to south, habitats transition from swamp to freshwater marsh to intermediate marsh to brackish marsh to salt marsh and mangroves. Major physiographic features include natural and artificial levees of the Mississippi River and Bayou Lafourche, the Gulf Intracoastal Waterway (GIWW), US Highway 90, Lac des Allemands, Lake Cataouatche, Little Lake, Lake Salvador, a swamp zone in the upper basin, a central marsh landmass, a beach ridge complex, and a chain of barrier islands. The USACE maintains three navigation channels in the basin: (1) Barataria Bay Waterway, which runs from Barataria Pass at Grand Isle to the GIWW east of Lake Salvador; (2) the GIWW, which runs east-west through the central reaches of the basin; and (3) the Empire Waterway, which runs from the GoM to the Mississippi River (Fig. 2).

The Barataria Basin is characterized by a complex history of delta development due to multiple episodes of delta lobe progradation. The basin filled with deltaic sediment reaching thicknesses of approximately 60–90 m near the coast, beneath which lie substratum sands reaching 45–50 m thick below Grand Isle (Dunbar et al. 1994; Heinrich et al. 2015). According to the delta cycle (Roberts 1997), erosional headlands and barrier islands, separated by tidal inlets at the southern extent of the Barataria Basin, are the result of subsidence and erosion due to delta abandonment. All of the island and

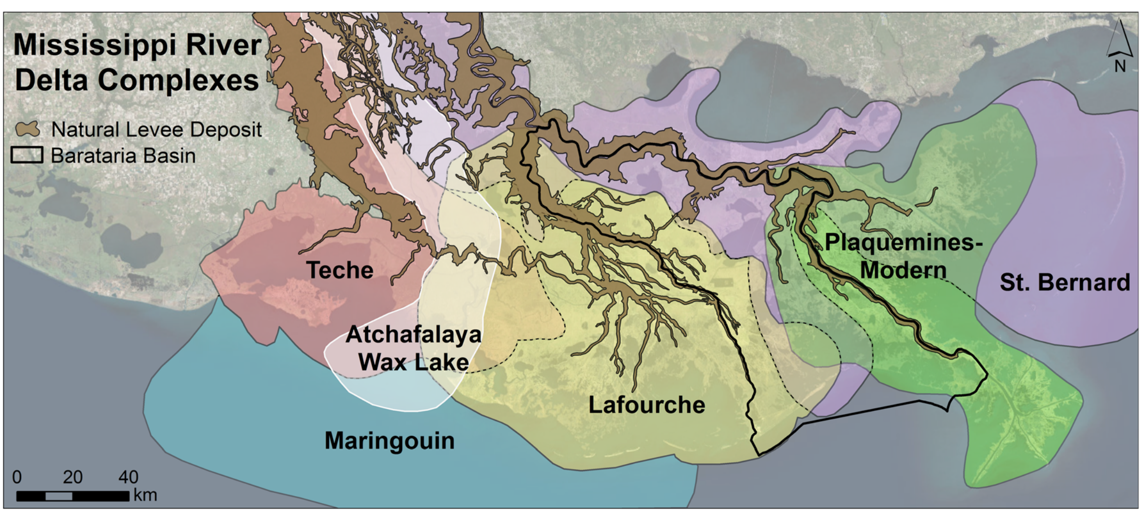

Fig. 3 Mississippi River delta complexes (modified after Frazier 1967), including natural levee deposits from the 1984 Geologic Map of Louisiana. Although not illustrated, multiple delta lobes often are present within delta complexes (see Frazier 1967). Within the Barataria Basin, St. Bernard delta lobes range in age from about 4500 to 2000 years BP; Lafourche delta lobes range from about 2000 to 300 years BP; and Plaquemines delta lobes range from about 1000 years to present

headland segments, except Grand Isle, are migrating landward. Island segments are associated with two periods of Holocene deltaic progradation and abandonment. The western beaches are associated with development of the Lafourche Delta complexes, and the eastern islands are remnants of the Plaquemines Delta Complex (Fig. 3). As each delta lobe was abandoned, erosion and subsidence became the dominant processes reshaping marginal landforms. Erosion, reworking, and redistribution of coarser deltaic sediment led to development of barrier islands and headland beaches. These beach and island environments play a critical role in protecting interior marshes from erosion and saltwater intrusion from the GoM. Overall, wetland environments in the Barataria Basin are currently in the transgressive phase of the delta cycle, with erosion and subsidence dominating landscape change.

Methods

Three independent survey data sets were used to estimate variations in short-term subsidence rates within the Barataria Basin. These included (1) NOAA, USACE, and USGS water-level gauges; (2) CORS primary benchmarks; and (3) CPRA/NGS secondary benchmarks. Because we were most interested in determining subsidence rates or velocities associated with the general location of coastal restoration sites (primarily natural marshes, swamps, and barrier islands), our main focus was with secondary benchmarks and water-level gauges. Although many potential survey locations were identified within the basin, time series length and data quality dictated the final number of sites used to describe variations in subsidence rates throughout the basin.

Fifteen water-level gauges were available for evaluation within the Barataria Basin. An additional water elevation time series was evaluated for Cedar Key, Florida, to determine the eustatic sea-level change signal for the northern GoM at a stable location (Fig. 4). Although relative sea-level change for the Pensacola gauge is often considered representative of eustatic sea-level change for the northern GoM (e.g., Penland and Ramsey 1990; Kolker et al. 2011), Zervas et al. (2013) indicated that land movement at Cedar Key was closest to zero (stable) for all NOAA gauges in the northern Gulf. As such, sea-level change for the 105-year water-level record at Cedar Key (2.1 mm/year) was considered most representative of eustatic changes for the northern GoM.

Elevation time-series data were compiled for 20 benchmarks within the Barataria Basin. Data observation periods of 13 to 24 h were analyzed for five CORS primary benchmarks, resulting in sub-centimeter measurement accuracy for determining subsidence velocities (Eckl et al. 2001; Snay et al. 2002; Soler et al. 2006). Fifteen CPRA/NGS secondary benchmarks provided discrete elevation measurements that contained 8- to 24-h observation periods, which indicated measurement accuracies of sub-centimeter to 2 cm (Snay et al. 2002).

High-resolution vertical measurements (static GPS) for each CPRA/NGS secondary site were collected by licensed surveying firms or federal agency personnel. Historical raw GPS datasets (RINEX files) for locations within the Barataria Basin between 2003 and 2019 were compiled, including three surveys completed as part of this study. These surveys followed protocols for data collection, processing, and adjustments for acquiring ellipsoid heights to sub-centimeter-level accuracy (session durations ≥ 13 h; Snay et al. 2002). Prior to performing static GPS observations, all 2-m-fixed height tripods were calibrated for correct antenna height measurements and checked for vertical accuracy. After field surveys were completed, all survey files were processed using Trimble Business Center software (Fenstermaker 2017). The IGS Precise Ephemeris was downloaded from the NGS website for each day the GPS data were collected. CORS locations that were selected as the primary reference frame were also downloaded from the NGS website and post-processed with static GPS data.

Several adjustment scenarios for all primary and secondary benchmarks were evaluated using a variety of CORS locations, after which, the adjustment for the GPS network was minimally constrained to the published adjusted NAD83 (2011) Epoch 2010.00 and published ellipsoid height at the antenna reference point for CORS benchmark LMCN. Once an initial adjustment was performed, all baseline outliers were disabled and the network readjusted until all outliers were removed (Fenstermaker 2017).

Linear regression was used to calculate subsidence rates (elevation change with time) associated with water level and elevation measurements for all survey locations in the Barataria Basin. A derived general linear model predicts the trend of a series of data points and establishes an equation that minimizes the distance between the fitted line and data points (Clark and Hosking 1986). When evaluating the difference between observed values and predicted values, the coefficient of determination (R^2) is used to estimate goodness-of-fit or the percentage of response variation that is explained by the linear model (Taylor 1997). Generally, the higher the R^2 value, the better the linear model fits the data.

While R^2 provides an estimate of the strength of a relationship between model and response variables, it does not address whether the relationship is statistically significant. To test the overall significance for a regression model, an F-test is used to evaluate the model derived using specific data to a model with no predictors (null hypothesis is the two models are equal) (Clark and Hosking 1986). A low P value indicates the relationship between the linear model and data points is statistically significant. R^2 and P values were calculated for each statistical model to assess goodness of fit and significance between data points and the model trend.

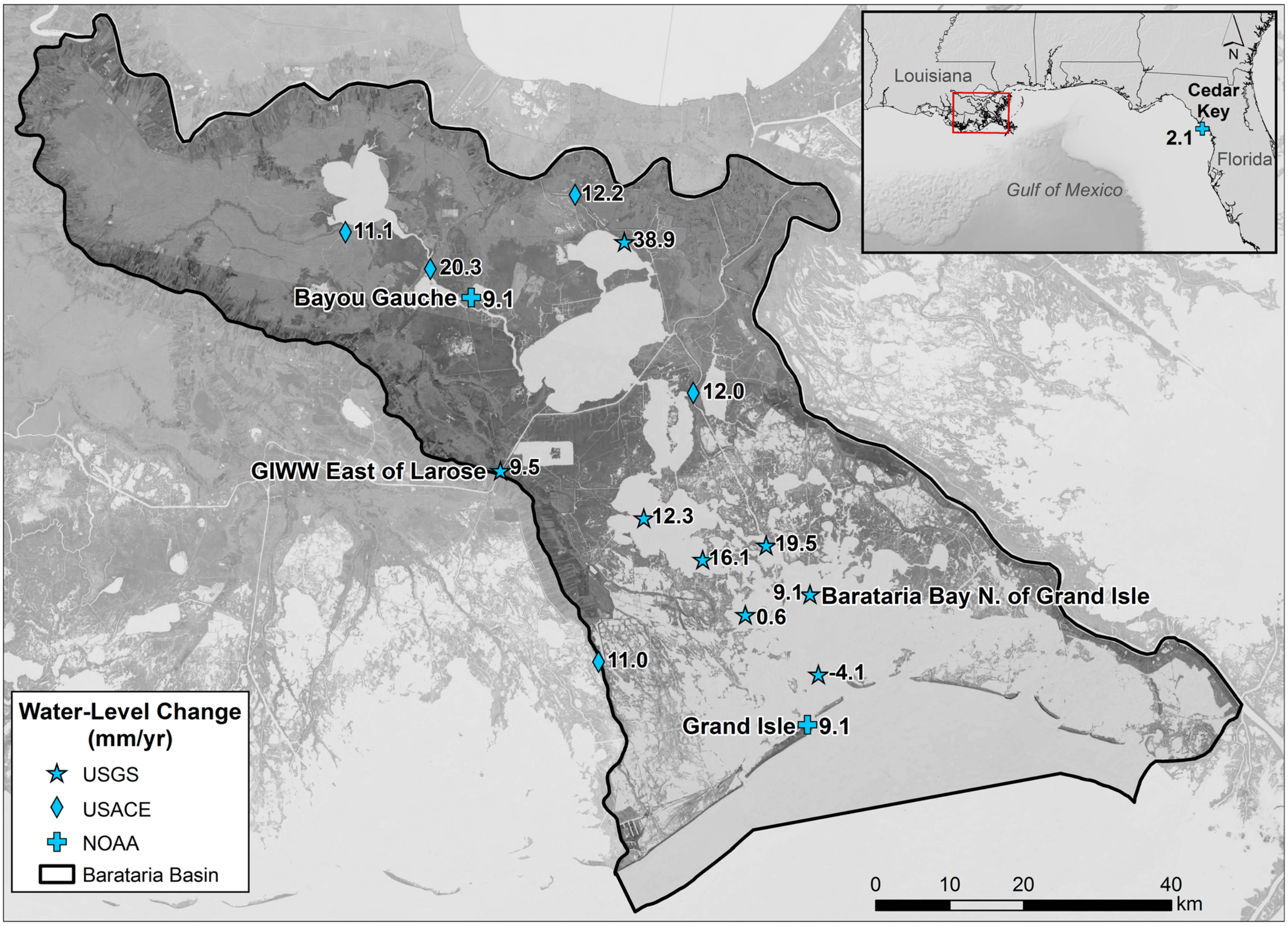

Fig. 4 Water-level change rates within Barataria Basin and at Cedar Key, Florida

Results

Subsidence rates (velocities) derived from geodetic GPS elevation surveys at benchmarks and water-level change trends indicate a range between approximately 2 and 7 mm/year for the Barataria Basin. The upper end of this range is less than half that reported for earlier estimates (2 to 20 mm/year; Reed and Yuill 2016). Differences may be because previous estimates of subsidence velocities were based primarily on subsidence derived from water-level change estimates and expert opinion (Reed and Yuill 2016), whereas the present study relied mainly on campaign-style geodetic GPS elevation surveys to derive subsidence velocities, a more direct measurement of elevation changes.

Water-level change trends Data for 15 water-level gauges documented elevation change trends for time series that encompassed approximately 14 years to greater than 70 years. Analyzed water-level changes within the Barataria Basin ranged from less than zero to 38.9 mm/year (Fig. 4; Byrnes et al. 2018). The longest period of record was the NOAA Grand Isle gauge (8761724) where a relative sea-level rise rate of 9.1 mm/year was documented. The Grand Isle gauge is located on the thickest sequence of Holocene sediment within the basin (~ 60 m) and is maintained by NOAA, the agency responsible for tidal records around the USA. As such, its trend is the standard by which all other water-level trends were evaluated. All measurements were adjusted where datum shifts were specified in agency data files. Two USGS stations show negative to very low water-level rise rates, indicating possible gauge installation or recording problems. Nine of the remaining gauges illustrate markedly greater water-level rise rates than Grand Isle, suggesting that measured trends may be influenced by hydrologic processes within the basin other than sea-level rise and fall. Higher relative sea-level rise rates would not be expected at interior marsh water-level gauges because water-level changes at these locations are subjected to lags in hydrologic flow due to friction from the presence of natural marsh ecosystems (Inoue et al. 2008). Further, human alterations to the marsh landscape related to water management and flood control, including roads, hurricane protection levees, locks, navigation channels, and others, have strong influence on surface water ingress and egress that affects water-level change rates at interior marsh locations

(Bracken et al. 2013). As such, only four of the 15 water-level gauges illustrated reasonable trends of relative sea-level rise: (1) NOAA Grand Isle, 9.1 mm/year; (2) NOAA Bayou Gauche, 9.1 mm/year; (3) USGS Barataria Bay North of Grand Isle, 9.1 mm/year; and (4) USGS GIWW East of Larose, 9.5 mm/year.

Based on water-level time series length and observed benchmark elevation changes adjacent to water-level stations, two of the four records were used for estimating subsidence velocities. NOAA Grand Isle and USGS Barataria Bay North of Grand Isle were located in areas that had direct contact with open-water marine environments (Fig. 4), and thus provide water elevations unaffected by anthropogenic hydrologic controls (e.g., roads, flood control and hurricane protection structures, navigation waterways) in the basin. Further, both gauges had time-series lengths of at least one tidal epoch, the minimum time required to account for cycles of 18 to 19 years in tidal amplitude and phase, as well as averaging meteorological effects (NOAA 2000). For both stations, the eustatic sea-level rise signal for the northern GoM (2.1 mm/year from the NOAA Cedar Key gauge) was subtracted from the relative sea-level rise trend to determine subsidence rates.

GPS-derived subsidence rates High-resolution geodetic GPS elevation measurements recorded at 20 locations within the Barataria Basin documented subsidence rates ranging from 0.7 to 7.1 mm/year. (Fig. 5). All elevation measurements were made to an accuracy of 1–2 cm. As such, benchmark G365 was eliminated from our analysis because only 1-cm vertical change was recorded at this location. Further, the relationship between the trend line and data points for G365 was not significant (Table 1). It should be noted that G365 was the only benchmark with a sleeved rod (9-m-long sleeve) where the base of the benchmark rod was in Pleistocene sediment. All other stations recorded at least 1.7-cm total change for their respective measurement periods; elevation change ranged from − 1.7 to − 10.2 cm. Record length also varied from 6 to 16 years, with the longest period recording the greatest change.

Five subsidence velocities were determined using CORS data, with velocities ranging from about 2.0 to 7.1 mm/year (Table 1). All but station GRIS were located along the eastern and northern margins of the basin (Fig. 5). Four of the five CORS benchmarks were located on existing concrete structures and one was located on a tower on a concrete pad (ENG5). After investigating each CORS location using NGS site descriptions and photos of the structures upon which the stations were attached, it was concluded that all associated foundation depths likely were within approximately 6 m of the ground surface. This indicated that the base of all footings or piles was located in slowly consolidating Holocene sediment.

Conversely, rod depths were known for all but one (BA23 SM02) CPRA/NGS secondary benchmark; rod depths ranged from 1 to 33 m. The common assumption has been that subsidence rates recorded at these locations represent velocities for depths greater than rod lengths (Keogh and Törnqvist 2019). However, unless benchmark rods are sleeved and/or anchored, downward forces exerted by consolidating sediment will influence elevation changes at the rods (Fig. 6). Floyd (1978), Dunnicliff (1993), Chao et al. (2006), and USACE (2012) provide detailed descriptions of the use of sleeves as a means of shielding benchmark rods from the forces associated with consolidating sediment. As such, all elevation changes for benchmarks monitored in the Barataria Basin include the effects of subsidence throughout the entire sediment column.

For the 14 secondary benchmarks (not including G365), subsidence velocities ranged from about 4.3 to 6.1 mm/year. All trends had high coefficients of determination and showed a statistically significant relationship between the model (trend line) and data points at $P < 0.07$ (Table 1). Although subsidence estimates at BA15 SM 01, BA34 SM 04, and BA-SCOFIELD2 could not be analyzed statistically because only two measurements were available for calculating a subsidence rate, subsidence velocities determined at these sites were consistent with adjacent benchmarks, supporting regional subsidence trends within the basin (Fig. 5). Finally, even though the subsidence trend at benchmark G365 was not considered statistically significant, the 12.4-year elevation change time series from a partially sleeved benchmark rod driven into indurated Pleistocene sediment suggests that subsidence below the rod base (deep subsidence) is approximately an order of magnitude less than recorded for overlying Holocene deltaic deposits.

Discussion

Spatial variability in subsidence velocities within the Barataria Basin illustrates a compelling relationship between subsidence and age, composition, and thickness of Holocene deltaic deposits. In the northern Barataria Basin, where modern deltaic deposits are shallower than approximately 20 m (Heinrich et al. 2015), velocities generally are less than 3 mm/year (Fig. 7). This area is characterized by the oldest deposits from the St. Bernard deltaic complex adjacent to the main river channel (Fig. 3), where sediment texture is coarser and more consolidated than finer grained, more recent deposits in the southern basin (Kolb and Van Lopik 1958; May et al. 1984; Dunbar et al. 1994; Heinrich 2005). Where subsidence rates increase to about 5 to 7 mm/year (southern basin), deltaic deposits are younger and thicker (40 to 70 m), resulting in greater consolidation potential. The relationship between age and thickness of deltaic deposits and resulting rates of

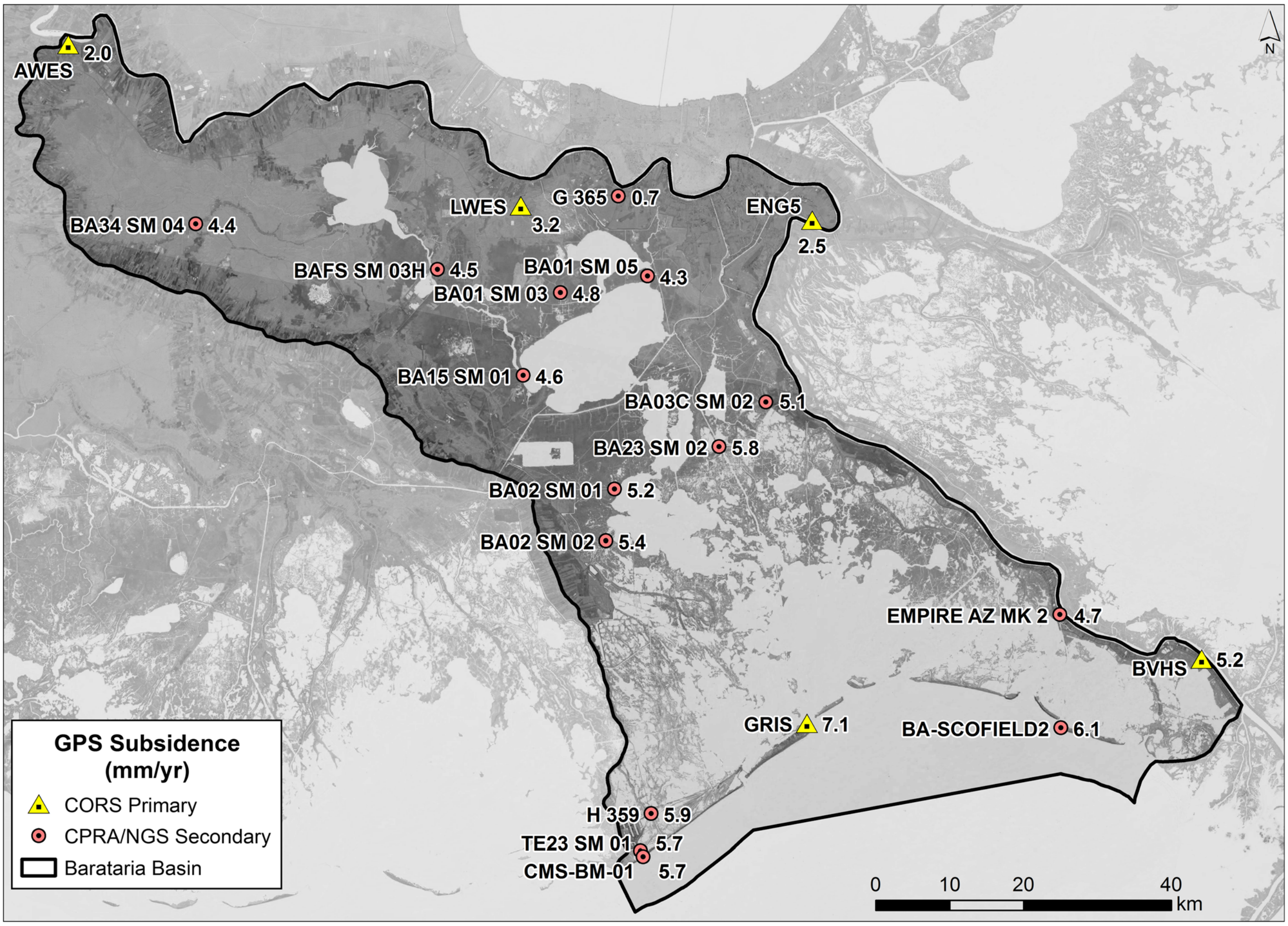

Fig. 5 Subsidence rates for primary (CORS) and secondary benchmarks (CPRA/NGS) in Barataria Basin

subsidence has been described previously by Kolb and Van Lopik (1958), Penland and Ramsey (1990), Keucher (1994), Roberts et al. (1994), Kulp (2000), and Törnqvist et al. (2008). Although time series of high-resolution geodetic GPS elevation surveys were not available prior to the early 2000s, the relationship between magnitude of subsidence and Holocene sediment composition and thickness developed prior to this time appears to be substantiated by our results.

In a recent study, Jankowski et al. (2017) and Nienhuis et al. (2017) suggest that variations in subsidence throughout coastal Louisiana may contradict established relationships between subsidence velocities and characteristics of Holocene deltaic deposits. Their analyses relied upon Coastwide Reference Monitoring System (CRMS) vertical accretion and surface elevation change measurements to derive shallow subsidence rates across the Louisiana delta and chenier plains. CRMS vertical accretion and surface elevation monitoring documents marsh surface processes such as erosion/accretion, growth/decay, and shrink/swell (Cahoon et al. 2011). However, in consolidating Holocene clays, differencing vertical accretion and surface elevation change to derive a process called shallow subsidence is not valid for stations where the reference rod associated with surface elevation measurements is not anchored and sleeved to create stability and isolate the rod from settlement forces between the marsh surface and base of the rod (Floyd 1978; Dunnicliff 1993; Chao et al. 2006; USACE 2012; see Fig. 6). Cahoon (2015) recognized the importance of a stable foundation upon which a rod base should rest (i.e., ideally set on bedrock) for estimating subsidence. To determine total subsidence for each CRMS location, Jankowski et al. (2017) combined CORS velocities (assumed to be estimates of deep subsidence) with their shallow subsidence estimates. However, even if CRMS rod surface elevation table (RSET) rods were installed with anchors and sleeves, rod depths associated with surface elevation measurements generally are deeper than CORS foundations/rods. As such, summing shallow subsidence estimates and CORS velocities will always overestimate their total subsidence.

When evaluating subsidence at any CORS, water level, benchmark, or CRMS RSET station, one must consider the influence consolidating sediment may have on foundations and/or rods. Concrete buildings in south Louisiana, upon which CORS instruments often are mounted, are supported by footings and/or piles. The depth to which foundations

Table 1 Summary of subsidence velocities for GPS benchmarks in Barataria Basin

Station	Foundation/rod depth (m)	Period	Years	Net elevation change (cm)	Subsidence velocity (mm/year)	R^2	*P*
AWES (CORS)	1 (as per NGS; concrete building)	Sep 2010–Mar 2019	8.47	− 1.7	2.0	0.85	0.009
BVHS (CORS)	Unknown (concrete school building)	Feb 2003–Mar 2019	16.15	− 10.2	5.2	0.95	0.000
ENG5 (CORS)	~ 3 (steel tower)	July 2008–Mar 2019	10.70	− 2.9	2.5	0.69	0.000
GRIS (CORS)	Unknown (pile-driven building)	Oct 2006–Mar 2019	12.42	− 9.1	7.1	0.95	0.000
LWES (CORS)	Unknown (concrete school building)	July 2008–Mar 2019	10.70	− 4.3	3.2	0.81	0.000
BA01 SM 03	15.85	Feb 2003–Jan 2018	14.97	− 7.3	4.8	0.99	0.031
BA01 SM 05	15.85	Jan 2003–Mar 2019	16.15	− 7.3	4.3	0.93	0.009
BA02 SM 01	19.51	Jan 2003–Mar 2018	16.15	− 8.0	5.2	0.99	0.006
BA02 SM 02	15.85	Feb 2003–Jan 2018	14.97	− 8.4	5.4	0.92	0.043
BA03C SM 02	14.63	Jan 2003–Jan 2018	15.01	− 7.8	5.1	0.98	0.011
BA15 SM 01[ab]	14.63	Feb 2003–Jun 2014	11.34	− 5.2	4.6	N/A	N/A
BA23 SM 02	Unknown (likely > 3 m)	Jan 2003–Jan 2018	15.01	− 8.9	5.8	0.99	0.034
BA34 SM 04[ab]	14.63	Oct 2006–Jun 2014	7.66	− 3.4	4.4	N/A	N/A
BAFS SM 03H	15.85	Jan 2003–Jan 2018	15.03	− 7.6	4.5	0.88	0.064
BA-SCOFIELD2[a]	20.73	Aug 2007–Feb 2017	9.49	− 5.8	6.1	N/A	N/A
CMS-BM-01	1	Feb 2013–Mar 2019	6.08	− 3.9	5.7	0.87	0.002
EMPIRE AZ MK 2	~ 2	May 2004–Sep 2016	12.35	− 5.8	4.7	0.99	0.014
G365	Sleeved to 9 m; 32.92	May 2004–Sep 2016	12.36	− 1.0	0.7	0.09	0.695
H359	24.38	May 2004–Apr 2018	14.81	− 9.5	5.9	0.98	0.000
TE23 SM 01	29.27	Jul 2008–Apr 2018	10.70	− 9.4	5.7	0.89	0.005

[a] only two elevation measurements were available for calculating subsidence velocity

[b] January 2018 elevation measurements were inconsistent with previous measurement trends, suggesting possible benchmark disturbance

The bases of all benchmark rods are in Holocene sediment, except for G365 where the rod base is in Pleistocene sediment

extend into Holocene sediment likely varies but most of these structures are located on relatively stable levee deposits, and it is unlikely that foundations extend deeper than required by modern construction guidelines (about 6 m; FEMA 2011). Because the base of all foundations and/or rods within the Barataria Basin resides in consolidating Holocene clays and no coatings or sleeves were indicated for any CORS foundations or rods, forces acting on piles or rods by consolidating sediment slowly drag piles and rods downward with consolidating sediment. Downdrag is a well-defined process in geotechnical literature associated with pipes and pilings in unconsolidated fine grained environments where the settlement rate of soils surrounding a pile is greater than the settlement rate of the pile (Bozozuk 1972; Fellenius 1984; Tran and Nguyen 2003; Fellenius 2006; Abdrabbo and Ali 2015; Huang et al. 2015; Kiprotich 2015). This consolidation force is caused by negative skin friction on a pile or rod. As an example, Bozozuk (1972) documented this force acting on a 49-m-deep open-ended pipe (test pile) surrounded by marine clay (comparable with a small diameter rod surrounded by fine grained deltaic silt and clay) and found that settling clays surrounding the pipe dragged the pipe slowly downward. Based on settling measurements at the top of the pipe (1.54 ft) relative to settlement of the original ground surface (1.77 ft) over a five-year period, approximately 87% of ground movement was reflected in test pile settlement. These results imply that velocities, measured with instruments mounted to buildings or relative to benchmark rods driven into consolidating Holocene sediment, record subsidence for the entire sediment column, not just for sediment deposits deeper than the base of a pile or rod.

Downdrag forces on a rod in consolidating clays are well-recognized for benchmark installation as well. Chao et al. (2006) discuss design and installation of benchmarks and the need for sleeved and/or anchored benchmark rods to attain stability and avoid downdrag forces associated with consolidating sediment. Subsiding Holocene deltaic sediment is the type of soil for which sleeves were designed to isolate benchmark rods from the effects of consolidating sediment above the base of the rod. Although most secondary benchmarks evaluated as part of our study recorded velocities for rods between 14 and 30 m long, to our knowledge, none of these

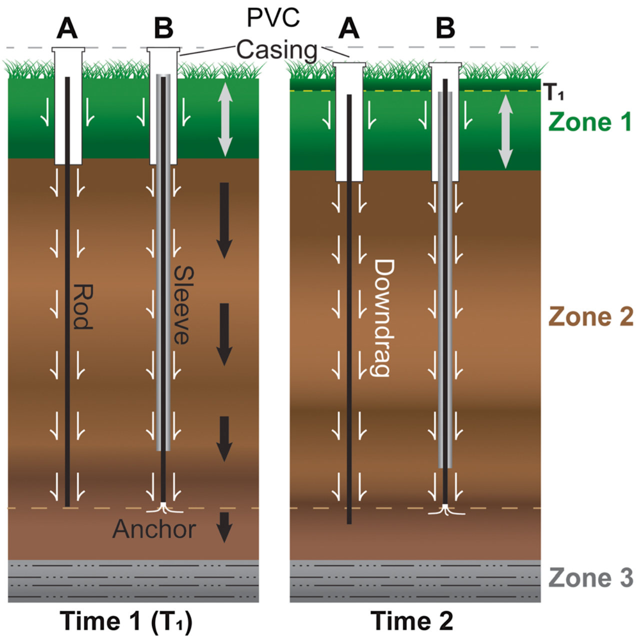

Fig. 6 Illustration of downdrag force exerted on a benchmark rod (with and without anchor and sleeve) due to consolidating Holocene deltaic sediment. When there is no separation (anchor/sleeve) between the rod and consolidating sediment, rod elevation change between Times 1 and 2 records subsidence throughout the entire sediment column. An anchored and sleeved rod is protected from consolidation forces and records subsidence below the base of the anchor. Zone 1 is the active marsh where surface shrink/swell, accretion/erosion, and organic growth/decay processes impact marsh evolution under relative sea level (RSL) change. In our depiction, the marsh surface keeps pace with RSL rise between Times 1 and 2. Zone 2 represents consolidating Holocene deltaic sediment. Zone 3 represents consolidated sediment

benchmark rods were installed using sleeves and anchors. Consequently, friction on a rod by consolidating sediment includes subsidence forces throughout the entire sediment column, as recorded by elevation measurements.

A side-by-side comparison for shallow- and deep-rod benchmarks within the Barataria Basin, to confirm unanchored rods within consolidating Holocene deltaic sediment record subsidence for the entire sediment column, does not presently exist; however, subsidence velocities for CMS-BM-01 (1-m rod depth; 5.7 mm/year) and H359 (24.4-m rod depth; 5.9 mm/year) are comparable and within 6 km of each other (see Fig. 5). Further, benchmark TE23 SM 01, located between CMS-BM-01 and H359, and within 860 m of CMS-BM-01, documents a subsidence velocity of 5.7 mm/year (29.3-m rod depth), similar to adjacent benchmarks. To the east but in the same general proximity as these benchmarks, CORS station GRIS and the Grand Isle water-level gauge record nearly equivalent subsidence velocities (7.1 and 7.0 mm/year, respectively), although their foundation/rod depths vary (< 6 m and 19.8 m, respectively), indicating spatial variability for the area of approximately ± 1 mm/year. Based on these observations, and contrary to the conclusions of Keogh and Törnqvist (2019), it appears that elevation changes for unanchored and unsleeved benchmarks monitored in the Barataria Basin include the effects of subsidence throughout the entire sediment column. Although the degree to which downdrag forces acting upon rods and/or foundations in Holocene deltaic sediment in south Louisiana may be expected to vary depending on the geotechnical properties of consolidating sediment, observations from the present study indicate that benchmarks record total subsidence.

Additionally, benchmark anchors used to quantify consolidation settlement associated with beach restoration on Caminada Headland (Byrnes et al. 2015) were installed with sleeves to isolate variations in settlement at specific subsurface layers and avoid downdrag forces caused by settling soil above the rod base. Varying subsidence velocities were recorded for each consolidating layer within which a Borros anchor was installed, resulting in greater surface displacement for shallow anchors versus deep anchors (Fig. 8). In other words, consolidating sediment above deep anchors that were sleeved settled at a greater rate, resulting in an increased distance between the top of rod and the ground surface relative to the PVC casing lid. This phenomenon was not documented for any benchmarks analyzed for the present subsidence study, and the authors are not aware of other unsleeved and unanchored benchmarks in south Louisiana marsh environments where this process of differential settlement has been noted.

Subsidence estimates derived using direct measurements of elevation from high-resolution GPS surveys as part of the present study, as well as variability in rates, are lower than those determined by Jankowski et al. (2017) and illustrated by Nienhuis et al. (2017). Within our most rapidly subsiding zone of the southern Barataria Basin, data from Jankowski et al. (2017) yielded an average total subsidence rate of 10.3 ± 6.7 mm/year (n=30), whereas our analysis recorded average subsidence of 5.8 ± 0.7 mm/year (n=13). Even with the removal of two outliers from their data set, large variability in subsidence likely reflects data noise associated with marsh surface processes recorded by CRMS measurements. Comparison of CRMS surface elevation and vertical accretion measurements provides a valuable indicator of surface erosion/deposition processes as a function of hydrologic variations (e.g., water level, currents, waves, storms) within and between sites. Surface physical processes, and their spatial variations, often result in changing sedimentation and erosion patterns over short distances (Butzeck et al. 2015). Further, small-scale variations in vegetation growth and decay, as well as bioturbation, impact vertical accretion and surface elevation change. Differencing these parameters to derive shallow subsidence assumes no spatial variation in marsh density, vegetation type, and growth and decay processes at a given site. However, marsh surface changes vary widely over short distances, creating an undulating and variable marsh surface (Rogers et al. 2005), even within CRMS locations. Subsidence does impact the active marsh zone, but surface

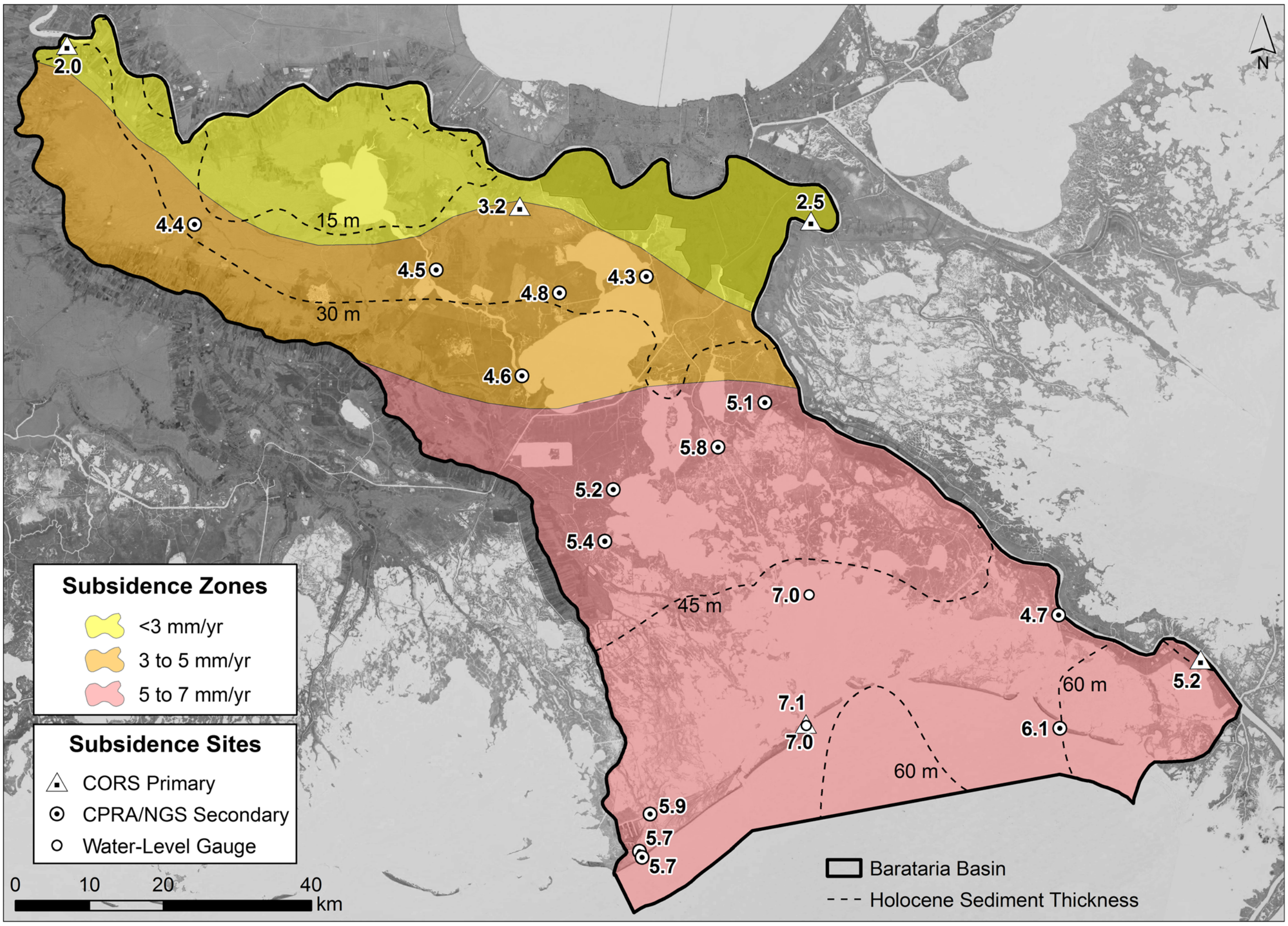

Fig. 7 Subsidence zones identified for Barataria Basin based on high-resolution elevation change measurements at benchmarks and water-level gauges. Holocene sediment thickness contours illustrate a general decrease in sediment thickness from south to north corresponding to a general decrease in subsidence rates

processes associated with marsh elevation changes (e.g., floods and droughts, variations in tidal flow throughout the marsh due to small-scale gradients in surface elevation and vegetation density, storm impacts, percent organic versus mineral sediment, vegetation growth/decay, spatial variation in sedimentation/erosion) have the greatest impact on marsh elevations (Kemp et al. 1999; Cahoon et al. 2011). Consequently, a derived subsidence quantity from a comparison of surface elevation and vertical accretion measurements is not reasonable for coastal Louisiana.

Fig. 8 Shallow (**a**) and deep (**b**) benchmark rod tops illustrating differential subsidence relative to rod depth. Both rods were installed at the same time, with the same distance from top of rod to casing cover, and both rods were anchored and sleeved

Finally, no geographic pattern with subsidence throughout south Louisiana was detected by Jankowski et al. (2017), indicating no apparent relationship to the primary factor influencing subsidence in south Louisiana—consolidation of Holocene deltaic sediment (Kolb and Van Lopik 1958; Törnqvist et al. 2008). This anomaly was recognized by Jankowski et al. (2017) as an inconsistency relative to existing studies, but discussion regarding marsh surface processes recorded in CRMS data, unrelated to subsidence, and its impact on subsidence calculations was not included. Subsidence trends for the present study are consistent with variations in Holocene deltaic sediment thickness and time of deposition; younger and thicker sections within the ancestral Mississippi River valley record largest subsidence velocities (Fig. 7).

Conclusions

High-resolution geodetic GPS elevation measurements at 19 benchmarks were used to determine recent subsidence velocities for the Barataria Basin. Elevation change time series encompassed 6- to 16-year periods. Net elevation changes at all stations equaled or exceeded predicted measurement uncertainties based on session duration. Water elevation change at two gauges in the southern part of the basin supplemented the survey data, resulting in a range of subsidence velocities at 21 locations from approximately 2 to 7 mm/year. Foundation/rod depths for benchmarks ranged from near surface to about 30 m. However, none of these foundations/rods were isolated from the surrounding consolidating sediment and associated downdrag forces. As such, subsidence velocities at these sites were considered representative for the entire sediment column. Subsidence velocity comparisons for deep and shallow rod benchmarks within about 6 km of each other support this conclusion (CMS-BM-01 rod depth = 1 m and velocity = 5.7 mm/year; H359 rod depth = 24.4 m and velocity = 5.9 mm/year; TE23 SM 01 rod depth = 29.3 m and velocity = 5.7 mm/year).

Maximum subsidence rates were recorded in the southern portion of the basin where Holocene sediment thickness is greatest, deltaic sediment is youngest, and subsurface sediment composition is primarily fine grained. Velocities ranged from about 5 to 7 mm/year in this region. Mid-basin subsidence rates ranged from 3 to 5 mm/year, and those to the north where Holocene sediment is relatively thin and overlapping delta lobes are common, velocities generally were less than 3 mm/year. These data indicate that subsidence rate ranges used in the 2017 Coastal Master Plan for Barataria Basin can be refined from 2 to 20 mm/year to approximately 2 to 7 mm/year. Presently, the second phase of this study is focused on evaluating subsidence trends east of the Mississippi River and Lake Pontchartrain, as well as further assessing the influence of Holocene sediment consolidation on downdrag forces for benchmark rods of varying depths. Future evaluations are expected to extend westward from Bayou Lafourche through Terrebonne Basin and the Chenier Plain.

Acknowledgements Technical discussions with CPRA personnel including Richard Raynie, Ed Haywood, and Angelina Freeman provided valuable insight regarding subsidence issues in south Louisiana. Thanks to Darin Lee (CPRA), Jim Pahl (CPRA), Leigh Anne Sharp (CPRA), and Jamie Bartel (formerly CDM Smith) for providing valuable technical review comments on earlier drafts of this manuscript. Survey measurements and data collected by Ricardo Johnson (Fenstermaker & Associates) under a separate contract with CPRA were the primary source of elevation measurements for determining recent subsidence rates. We also thank Rob Hollis (Applied Coastal) for the figure preparation depicting sediment consolidation forces acting on benchmark rods with and without sleeves and anchors. Special thanks to anonymous reviewers for making helpful suggestions that improved the manuscript.

Funding information This work was financially supported by the Coastal Protection and Restoration Authority of Louisiana with funding from the National Fish and Wildlife Foundation (NFWF).

References

Abdrabbo FM, Ali NA (2015) Behavior of single pile in consolidating soil. Alexandria Eng J 54:481–495

Blanchet R, Tavenas F, Garneau R (1980) Behavior of friction piles in soft sensitive clays. Can Geotech J 17:203–224

Blum MD, Tomkin JH, Purcell A, Lancaster RR (2008) Ups and downs of the Mississippi Delta. Geology 36:675–678

Blum MD, Roberts HH (2009) Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nat Geosci 2: 488–491

Bozozuk M (1972) Downdrag measurements on a 160-ft floating pipe test pile in marine clay. Can Geotech J 9:127–136

Bracken LJ, Wainwright J, Ali GA, Tetzla G, Smith MW, Reaney SM, Roy AG (2013) Concepts of hydrological connectivity: research approaches, pathways and future agendas. Earth Sci Rev 119:17–34

Briaud JL, Tucker LM (1996) Design and construction guidelines for downdrag on uncoated and bitumen-coated piles. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, DC

Butzeck C, Eschenbach A, Gröngröft A, Hansen K, Nolte S, Jensen K (2015) Sediment deposition and accretion rates in tidal marshes are highly variable along estuarine salinity and flooding gradients. Estuar Coasts 38:434–450

Byrnes MR, Hedderman C, Hasen M, Roberts HH, Khalil SM, Underwood SG (2015) Differential sediment consolidation associated with barrier beach restoration: Caminada Headland, South Louisiana. In: Proc coastal sediments. World Scientific, Hackensack, New Jersey, p 2015

Byrnes MR, Britsch LD, Berlinghoff JL, Johnson R (2018) Determining recent subsidence rates for Barataria Basin, Louisiana: Implications for engineering and design of coastal restoration projects. Applied coastal research and engineering final report to the coastal protection and restoration authority of Louisiana, Baton Rouge, LA

Cahoon DR (2015) Estimating relative sea-level rise and submergence potential at a coastal wetland. Estuar Coasts 38:1077–1084

Cahoon DR, Perez BC, Segura BD, Lynch JC (2011) Elevation trends and shrink-swell response of wetland soils to flooding and drying. Estuar Coast Shelf Sci 91:463–474

Chan AW, Zobak MD (2007) The role of hydrocarbon production on land subsidence and fault reactivation in the Louisiana coastal zone. J Coast Res 24:771–786

Chao KC, Overton DD, Nelson JD (2006) Design and installation of deep benchmarks in expansive soils. J Surv Eng 132(3):124–131

Clark WAV, Hosking PL (1986) Statistical methods for geographers. John Wiley & Sons, New York

Clark PU, Dyke AS, Shakun JD, Carlson AE, Clark J, Wohlfarth B, Mitrovica JX, Hostetler SW, McCabe AM (2009) The last glacial maximum. Science 325:710–714

Coleman JM (1988) Dynamic changes and processes in the Mississippi River delta. Geol Soc Am Bull 100:999–1015

Coleman JM, Roberts HH, Bryant WR (1991) Late Quaternary sedimentation. In: The geology of North America, volume J, the Gulf of Mexico. Geological Society of America, pp 325–352

Davis DW (2010) Washed away? The invisible peoples of Louisiana's wetlands. University of Louisiana Lafayette Press, Louisiana

Davisson MT (1993) Negative skin friction in piles and design decisions. Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, pp 1793–1801

Dokka RK (2006) Modern-day tectonic subsidence in coastal Louisiana. Geology 34:281–284

Dokka RK (2009) Comparison of methods used to measure modern subsidence in southeastern Louisiana. Trans Gulf Coast Assoc Geol Soc 59:225–242

Dokka RK (2011) The role of deep processes in late 20th century subsidence of New Orleans and coastal areas of southern Louisiana and Mississippi. J Geophys Res 116:B06403. https://doi.org/10.1029/2010JB008008

Dokka RK, Sella GF, Dixon TH (2006) Tectonic control of subsidence and southward displacement of southeast Louisiana with respect to stable North America. Geophys Res Lett 33:L23308. https://doi.org/10.1029/2006GL027250

Dunbar JB, Blaes M, Dueitt S, Stroud K (1994) Geological investigation of the Mississippi River Deltaic Plain, Report 2 of a Series. Technical Report GL-84-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Dunnicliff J (1993) Geotechnical instrumentation for monitoring field performance. John Wiley & Sons, United States

Eckl MC, Snay R, Soler T, Cline MW, Mader GL (2001) Accuracy of GPS-derived relative positions as a function of interstation distance and observing session duration. J Geod 75:633–640

El-Mossallamy YM, Hefny AM, Demerdash MA, Morsy MS (2013) Numerical analysis of negative skin friction on piles in soft clay. HBRC J 9:68–76

Endo M, Minou A, Shibata T (1969) Negative skin friction acting on steel pipe pile in clay. 7th international conference on soil mechanics and foundation engineering 2:85–92

Fellenius BH (1984) Negative skin friction and settlement of piles. Second international seminar, Pile foundations, Nanyang Technological Institute, Singapore

Fellenius BH (2006) Results from long-term measurement in piles of drag load and downdrag. Can Geotech J 43:409–430

Fellenius BH (2018) Basics of foundation design. Pile Buck International, Inc., Vero Beach, Florida

Federal Emergency Management Agency (FEMA) (2011) Coastal construction manual: principles and practices of planning, siting, designing, constructing, and maintaining residential buildings in coastal areas – chapter 10: designing the foundation

Fenstermaker (2017) Surveying and analysis services – Barataria Basin area CORS and benchmark subsidence study using static GPS observations. Final Report to the Coastal Protection and Restoration Authority of Louisiana, Baton Rouge, LA

Floyd RP (1978) Geodetic bench marks, NOAA manual NOS NGS. National Ocean Service, Rockville, Maryland, p 1

Frazier DE (1967) Recent deltaic deposits of the Mississippi River: their development and chronology. Trans Gulf Coast Assoc Geol Soc 17: 287–315

Heinrich P (2005) Review of the engineering geology of St. Bernard Parish, Louisiana. NewsInsights 15:6–11, Louisiana Geological Survey, Baton Rouge, Louisiana

Heinrich P, Paulsell R, Milner R, Snead J, Peele H (2015) Investigation and GIS development of the buried Holocene-Pleistocene surface in the Louisiana coastal plain. Louisiana geological survey final report to the coastal protection and restoration Authority of Louisiana, Baton Rouge, LA

Huang T, Zheng J, Gong W (2015) The group effect on negative skin friction on piles. Procedia Eng 116:802–808

Inoue M, Park D, Justic D, Wiseman WJ (2008) A high-resolution integrated hydrology–hydrodynamic model of the Barataria Basin system. Env Modelling & Software 23:1122–1132

Jankowski KL, Törnqvist TE, Fernandes AM (2017) Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. Nat Commun 8:14792. https://doi.org/10.1038/ncomms14792

Jones CE, An K, Blom RG, Kent JD, Ivins ER, Bekaert D (2016) Anthropogenic and geologic influences on subsidence in the vicinity of New Orleans, Louisiana. J Geophysic Res B: Solid Earth 121: B012636. https://doi.org/10.1022/2015B012636

Kemp GP, Day JW, Reed DJ, Cahoon DR, Wang M (1999) Sedimentation, consolidation and surface elevation change in two salt marshes of the Mississippi River Deltaic Plain: geotechnical aspects of wetland loss. In: Recent Research in Coastal Louisiana: Natural System Function and Response to Human Influence. Louisiana Sea Grant College Program, Baton Rouge, LA, pp 15–34

Keogh ME, Törnqvist TE (2019) Measuring rates of present-day relative sea-level rise in low-elevation coastal zones: a critical evaluation. Ocean Sci 15:61–73

Kesel RH (1988) The decline in suspended load of the lower Mississippi River and its influence on adjacent wetlands. Environ Geol Water Sci 11:271–281

Keucher GJ (1994) Geologic framework and consolidation settlement potential of the Lafourche Delta, Topstratum Valley Fill: implications for wetland loss in Terrebonne and Lafourche Parishes, Louisiana. Dissertation, Louisiana State University, Baton Rouge, LA

Keucher GJ, Roberts HH, Thompson MD, Matthews I (2001) Evidence for active growth faulting in the Terrebonne Delta Plain, south Louisiana: implications for wetland loss and the vertical migration of petroleum. Environ Geosci 8:77–94

Kiprotich N (2015) Modelling of negative skin friction on bored piles in clay. MS thesis, Chalmers University of Technology, Göteborg, Sweden

Kolb CR, Van Lopik JR (1958) Geology of the Mississippi River Deltaic Plain, Southeastern Louisiana. US Army Engineer Waterways Experiment Station Technical Report 3–483, Vicksburg, Mississippi

Kolker AS, Allison MA, Hameed S (2011) An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. Geophys Res Lett 38:L21404

Kulp M (2000) Holocene stratigraphy, history, and subsidence: Mississippi Delta Region, North-Central Gulf of Mexico. Dissertation, University of Kentucky

Kulp M, Penland S, Williams SJ, Jenkins C, Flocks J, Kindinger J (2005) Geologic framework, evolution, and sediment resources for restoration of the Louisiana Coastal Zone. J Coast Res SI44:56–71

Mallman EP, Zobak MD (2007) Subsidence in the Louisiana coastal zone due to hydrocarbon production. J Coast Res SI50:443–449

May JR, Britsch LD, Dunbar JB, Rodriguez JP, Wlosinski LB (1984) Geological investigation of the Mississippi River deltaic plain. Technical Report GL-13-84, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Milliken KT, Anderson JB, Rodriguez AB (2008) A new composite Holocene sea-level curve for the northern Gulf of Mexico. In: Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise, Geological Society of America Special Paper 443, 1–11, doi: https://doi.org/10.1130/2008.2443(01)

Morton RA, Bernier JC, Barras JA (2006) Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. Environ Geol 50:261–274

National Oceanic and Atmospheric Administration (NOAA) (2000) Tidal datums and their applications. NOAA special publication NOS CO-OPS. Center for Operational Oceanographic Products and Services, Silver Spring, Maryland, p 1

Nienhuis JH, Törnqvist TE, Jankowski KL, Fernandes AM, Keogh ME (2017) A new subsidence map for coastal Louisiana. GSA Today 27:58–59

Nummedal D (1983) Rates and frequencies of sea-level changes: a review with an approach to predict future sea levels in Louisiana. Trans Gulf Coast Assoc Geol Soc 33:361–366

Olea RA, Coleman JL (2014) A synoptic examination of causes of land loss in southern Louisiana as related to the exploitation of subsurface geologic resources. J Coast Res 30:1025–1044

Penland S, Ramsey KE (1990) Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908-1988. J Coast Res 6:323–342

Reed DJ, Yuill B (2016). 2017 Coastal Master Plan: attachment C2-2: subsidence. Coastal Protection and Restoration Authority of Louisiana, Baton Rouge, LA

Roberts HH (1985) A study of sedimentation and subsidence in the south-central coastal plain of Louisiana. Final report to U. S. Army Corps of Engineers, New Orleans District, LA

Roberts HH (1997) Dynamic change of the Holocene Mississippi River deltaic plain: the delta cycle. J Coast Res 13:605–627

Roberts HH, Bailey A, Keucher GJ (1994) Subsidence in the Mississippi River delta: important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis. Trans Gulf Coast Assoc Geol Soc 44:619–629

Rogers K, Saintilan N, Cahoon D (2005) Surface elevation dynamics in a regenerating mangrove forest at Homebush Bay, Australia. Wetl Ecol Manag 13:587–598

Shinkle KD, Dokka R (2004) Rates of vertical displacement at benchmarks in the lower Mississippi Valley and the northern Gulf Coast. NOAA Tech Report, NOS/NGS 50, National Oceanic and Atmospheric Administration, Silver Spring, Maryland

Snay RA, Soler T, Eckl M (2002) GPS precision with carrier phase observations: does distance and/or time matter? Professional Surveyor 22:20–24

Soler T, Michalak P, Weston ND, Snay RA, Foote RH (2006) Accuracy of OPUS solutions for 1- and 4-h observing sessions. GPS Solutions 10:45–55

Taylor JR (1997) An introduction to error analysis, the study of uncertainties in physical measurements. In: University science books. Sausalito, California

Törnqvist TE, Wallace DJ, Storms JEA, Wallinga J, Van Dam RL, Blaaum M, Derksen MS, Klerks CJW, Meijneken C, Snijders EMA (2008) Mississippi delta subsidence primarily caused by compaction of Holocene strata. Nat Geosci 1:173–176

Tran TX, Nguyen TM (2003) Negative skin friction on concrete piles in soft subsoil on the basis of the shifting rate of piles and the settlement rate of surrounding soils. Slovak J Civil Eng 3:13–20

U.S. Army Corps of Engineers (USACE) (2012) Survey markers and monumentation. In: Engineering manual EM-1110-1-1002. USACE, Washington, DC

USACE (2015) Updated atlas of U.S. Army Corps of Engineers historical daily tide data in coastal Louisiana. USACE, New Orleans District, LA

Yokoyama Y, Esat TM, Thompson WG, Thomas AL, Webster JM, Miyairi Y, Sawada C, Aze T, Matsuzaki H, Okuno J, Fallon S, Braga J-C, Humblet M, Iryu Y, Potts D, Fujita K, Suzuki A, Kan H (2018) Rapid glaciation and a two-step sea level plunge into the last glacial maximum. Nature 559:603–607

Yuill B, Lavoie D, Reed DJ (2009) Understanding subsidence processes in coastal Louisiana. J Coast Res SI54:23–36

Zervas C, Gill S, Sweet W (2013) Estimating vertical land motion from long-term tide gauge records. NOAA Technical Report NOS CO-OPS 065, National Ocean Service Center for Operational Oceanographic Products and Services, Rockville, MD

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