Sea-Level Rise and Subsidence: Implications for Flooding in New Orleans, Louisiana

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Abstract

Global sea-level rise is projected to accelerate two- to four-fold during the next century, increasing storm surge and shoreline retreat along low-lying, unconsolidated coastal margins. The Mississippi River Deltaic Plain in southeastern Louisiana is particularly vulnerable to erosion and inundation due to the rapid deterioration of coastal barriers combined with relatively high rates of land subsidence. Land-surface altitude data collected in the leveed areas of the New Orleans metropolitan region during five survey epochs between 1951 and 1995 indicated mean annual subsidence of 5 millimeters per year. Preliminary results of other studies detecting the regional movement of the north-central Gulf Coast indicate that the rate may be as much as 1 centimeter per year. Considering the rate of subsidence and the mid-range estimate of sea-level rise during the next 100 years (480 millimeters), the areas of New Orleans and vicinity that are presently 1.5 to 3 meters below mean sea level will likely be 2.5 to 4.0 meters or more below mean sea level by 2100.

Subsidence of the land surface in the New Orleans region is also attributed to the drainage and oxidation of organic soils, aquifer-system compaction related to ground-water withdrawals, natural compaction and dewatering of surficial sediments, and tectonic activity (geosynclinal downwarping and movement along growth faults). The problem is aggravated owing to flood-protection measures and disruption of natural drainageways that reduce sediment deposition in the New Orleans area.

Accelerated sea-level rise, the present altitude of the city, and high rates of land subsidence portend serious losses in property in the New Orleans area unless flood-control levees and pumping stations are upgraded. The restoration and maintenance of barrier islands and wetlands that flank New Orleans to the south and east are other adaptations that have the potential to reduce the loss of life and property due to flooding. Accurate monitoring of subsidence is needed to provide calibration data for modeling and predicting subsidence in coastal Louisiana, as well as for support for constructing and maintaining infrastructure and levees. GPS technology is being tested in the New Orleans region as a means for more frequent, less expensive subsidence monitoring.

INTRODUCTION

Accelerated sea-level rise is regarded as one of the most costly and most certain consequences of global warming. If sea-level rise increases at rates projected by the United Nation's Intergovernmental Panel on Climate Change (2001) during the next century, many of the world's low-lying coastal zones and river deltas could be inundated. Several of the world's most heavily populated coastal cities are particularly vulnerable to inundation due to human interactions with deltaic processes. Such is the case in the New Orleans metropolitan area, where more than 1 million people are protected from river floods and storm surge by levees and pumping stations, and where the land is gradually sinking at rates that exceed 20th century sea-level rise.

GEOMORPHOLOGIC SETTING

Most of the present landmass of southeast Louisiana was formed by deltaic processes of the Mississippi River. Over the past 7,000 years, during a period of relatively small fluctuations in sea level, the river deposited massive volumes of sediment in five deltaic

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complexes that now lie in various stages of abandonment (, 1967). The Chandeleur Island chain that lies to the southeast of the city of New Orleans is an erosional feature of one of these ancient deltas. A combination of levees, diversion structures, and reduced suspended sediment discharge have essentially halted the aggradation of the Mississippi River delta in southeast Louisiana.

Levees constructed along the banks of the Mississippi River from Cairo, Ill., to Venice, La., (about 30 km south of New Orleans) prevent the flooding of the adjacent land by sediment-laden river water, halting the depositional processes that naturally maintained the altitude of the land surface in southeast Louisiana above sea level. Three large diversion structures constructed upriver near Simmesport, La., now route up to one-third of the water and sediment load from the Mississippi River westward into the Atchafalaya River to protect New Orleans, Baton Rouge, and many other cities in southeast Louisiana from flooding. The volume of sediment delivered by the Mississippi River to Louisiana has been reduced by almost one-half since 1950 by the construction of reservoirs on the major tributaries of the Mississippi River (Meade, 1995).

Most of the land surface of the New Orleans Metropolitan Statistical Area (MSA), a region that includes all or parts of seven parishes, is sinking or “subsiding” relative to mean sea level. Subsidence of the land surface in the New Orleans region is also attributed to the drainage and oxidation of organic soils (Earle, 1975), aquifer-system compaction related to ground-water withdrawals (Kazmann, 1988), natural compaction and dewatering of surficial sediments (Gosselink, 1984), and tectonic activity (geosynclinal downwarping and movement along growth faults) (Howell, 1960; Jones, 1975).

SUBSIDENCE AND SEA-LEVEL TRENDS

Observations of local subsidence in the New Orleans region were derived from precise leveling data collected by the National Geodetic Survey (NGS) during 1951–55, 1964, 1984–85, 1990–91, and 1995. The subsidence network included a total of 341 benchmarks. Land-surface altitude data sets for each epoch (time period between surveys) were prepared using a minimum constraint least squares adjustment tied to a benchmark in eastern Orleans Parish (Zilkoski and Reese, 1986). Files containing the location of benchmarks and the differences in adjusted heights were converted into ArcView shapefiles and projected into Louisiana State Plane Coordinates, South Zone NAD83, in feet. The annual rate of subsidence at each benchmark was determined by dividing the differences in adjusted heights by the number of years between leveling.

Benchmark locations were integrated with generalized maps of soils and geology covering parts of Orleans Parish, which lies at the center of the New Orleans MSA. It is important to note that the soil and geology data sets were digitized from small-scale, paper, photocopied maps to test the initial concepts of using GIS to support development of a subsidence model (Hart and Zilkoski, 1994). The source of the geology map is “Geology of Greater New Orleans—Its Relationship to Land Subsidence and Flooding” by Snowden and others (1980), and the source of the soils map is the “Soil Survey of Orleans Parish, Louisiana” by the Soil Conservation Service (Trahan, 1989).

Figure 1 shows subsidence rates for 165 benchmarks that were consistently surveyed during the period from 1951 to 1995. Table 1 shows the number of benchmarks surveyed, mean annual subsidence rate, and standard deviation for soils and geologic units for each of the four epochs identified above. The average rate of subsidence among soil types was between 4.0 and 6.0 mm/yr for all but the Aquents soil classification, which makes up about 13 percent of the land area in the Parish (Trahan, 1989). There appears to be a noticeable decrease through time in the mean subsidence rate for the Clovelly-Lafitte-Gentilly soil classification as compared to the others. Also, the overall mean subsidence rate for all soil types increases from the 1951–64 epoch to the 1964–85 and 1985–91 epochs, and then apparent rebound is seen during the 1991–95 epoch. Precipitation was very heavy in the New Orleans region during 1991, which may be related to the apparent high rates of subsidence during 1985–91. Additional correlations may exist between land subsidence and other, more detailed and accurate soil and geology data sets, as well as other environmental factors that may have an effect on subsidence. These other environmental factors include drainage infrastructure, levee locations, drainage pumping-station operations, well locations and withdrawals, ground-water recharge, application of fill and overburden, land use, the history of human settlement and urban development, and the bulk and density of buildings.

The 1951–95 altitude data also showed some interesting differences among survey epochs and

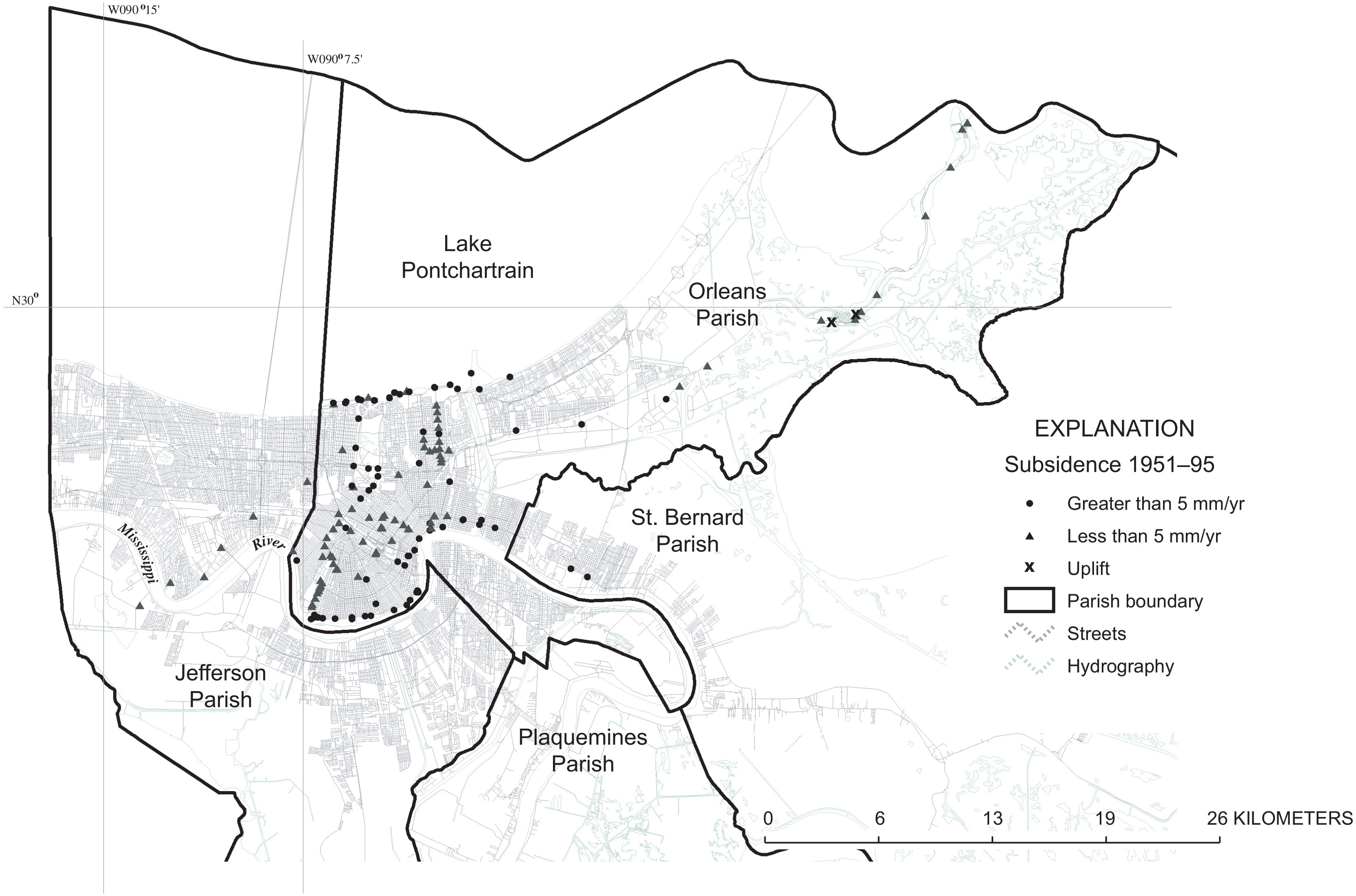

Figure 1. Mean annual local subsidence rates for five soil types and the four major geologic units in the New Orleans region.

Table 1. Mean annual subsidence rates for five soil types and the four major geologic units in the New Orleans region, 1951–95

[mm/yr, millimeters per year; mm, millimeters]

Soil type	1951–64			1964–85			1985–91			1991–95			1951–95		
	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)
Sharkey-Commerce	161	-5.0	4.7	130	-6.4	3.8	176	-8.5	2.4	187	3.9	2.2	87	-4.8	2.8
Clovelly-Lafitte-Gentilly	13	-3.0	1.7	12	-2.2	1.9	17	-1.8	1.8	19	.6	2.3	8	-1.3	.8
Harahan-Westwego	36	-3.3	4.3	33	-3.3	9.2	58	-9.3	5.4	65	2.3	6.7	16	-4.0	3.2
Alemmands, drained—Kenner, drained	14	-5.5	4.3	10	-8.1	5.4	17	-8.5	2.7	17	2.1	4.3	4	-4.0	2.4
Aquents	56	-3.9	3.9	49	-9.4	4.8	66	-9.2	3.2	74	.8	3.3	33	-5.9	2.6
Total	280	-4.5	4.4	234	-6.5	5.4	334	-8.4	3.6	362	2.7	3.9	148	-4.8	2.9

Geologic unit	1951–64			1964–85			1985–91			1991–95			1951–95		
	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)	Number of bench-marks	Average annual difference (mm/yr)	Std. dev. (mm)
Artificial fill	28	-4.8	2.1	26	-10.6	3.5	30	-9.7	1.1	30	2.2	1.8	20	-6.5	1.6
Alluvial soils	63	-3.9	3.4	56	-5.7	7.2	86	-8.6	2.4	98	2.5	5.6	36	-4.6	2.4
Lake fringe deposits	7	-8.1	8.3	3	-13.6	.4	6	-9.5	2.2	7	.5	2.7	3	-9.1	.7
Natural levee deposits	166	-5.6	5.1	124	-6.4	4.5	158	-9.2	3.6	171	4.1	2.4	73	-4.9	3.0
Total	264	-5.2	4.7	209	-6.8	5.5	280	-9.1	3.1	306	3.3	3.8	132	-5.2	2.8

geologic units (table 1). Mean annual subsidence in levee deposits, alluvial soils, artificial fill, and lake fringe deposits ranged from 4.6 to 9.1 mm/yr. It should be noted that one recent analysis of NGS Gulf Coast elevation data by Louisiana State University and NGS (Roy Dokka, Louisiana State University, oral commun., 2003) suggests that the absolute subsidence rates for the New Orleans region could be about 5 mm/yr or higher, but the relative differences would be the same. Relative differences in subsidence rates among the four survey epochs might be explained by a more thorough examination of rainfall data, ground-water extraction and recharge, land-use change, and other factors mentioned previously.

Global sea level has risen about 120 m as a result of melting of large ice sheets since the last glacial maximum about 20,000 years ago (Fairbanks, 1989). The most rapid rise occurred during the late and post-glacial periods followed by a period of relatively stable sea level during the past 6,000 years (Mimura and Harasawa, 2000). During the past 3,000 years, sea level rose at an average rate of about 0.1 to 0.2 mm/yr, but by the end of the 20th century the rate had increased to approximately 1.0 to 2.0 mm/yr or 100 to 200 mm per century (Gornitz, 1995; Intergovernmental Panel on Climate Change, 1996). The Intergovernmental Panel on Climate Change (2001) projects a two- to four-fold acceleration of sea-level rise over the next 100 years, with a central value of 480 mm.

The rate of land subsidence in the New Orleans region (average 5 mm/yr) and the Intergovernmental Panel on Climate Change (2001) mid-range estimate of sea-level rise (480 mm) suggests a net 1.0-m decline in elevation during the next 100 years relative to present mean sea level (fig. 2). A storm surge from a Category 3 hurricane (estimated at 3 to 4 m without waves) (National Oceanic and Atmospheric Administration, 2002) at the end of this century, combined with mean global sea-level rise and land subsidence, would place storm surge at 4 to 5 m above the city's present altitude. The effect of such a storm on flooding in the New Orleans MSA will depend upon the height and integrity of the regional levees and other flood-protection projects at that time.

An additional factor to be considered when evaluating the future vulnerability of New Orleans to inundation is the current altitude of the land surface. Much of the heavily populated area in Orleans and St. Bernard Parishes lies below mean sea level. At the intersection of Morrison Road and Blueridge Court (located in lake fringe deposits of eastern Orleans Parish), for example, which is presently about 2.6 m below local mean sea level, the cumulative effects of land subsidence, sea-level rise, and storm surge from a Category 3 hurricane at the end of this century place storm surge 6 to 7 m above the land surface (fig. 2). Such a storm would exceed the design capacity of the existing flood-protection levees. The storm surge of a Category 5 hurricane, generally greater than 5 m (National Oceanic and Atmospheric Administration, 2002), would pose more serious flooding danger. Hurricane Camille, a Category 5 hurricane that made landfall in Mississippi in 1969, increased water levels in coastal Mississippi by as much as 7 m (U.S. Army Corps of Engineers, 1970). Landfall of a Category 5 hurricane in New Orleans would place the Morrison Road/Blueridge Court intersection at least 9 m below storm-surge level today and, based on the same sea-level rise and land-subsidence trends discussed above, at 10.5 m or more below storm-surge level by the end of the 21st century.

In addition to the decline in land-surface altitude, the loss of marshes and barrier islands that dampen storm surge and waves during hurricanes increases the risks of flood disaster in New Orleans and vicinity. Since 1940, approximately 1 million acres of coastal wetlands have been converted to open water in southern Louisiana as a result of natural and human-induced environmental change (Burkett and others, 2001). The extensive loss of coastal marshes and bald cypress forests that once flanked the hurricane-protection levees of St. Bernard and Plaquemines Parishes has increased the threat of storm-surge flooding for the 94,000 residents in the southern part of the New Orleans MSA. Several barrier island and wetland restoration projects are planned by the State of Louisiana, local governments, and Federal agencies.

ADAPTATIONS THAT MINIMIZE FLOODING

Most of the New Orleans MSA is protected from flooding by levees constructed since 1879 by local sponsors and the U.S. Army Corps of Engineers under five different Congressional authorizations. Levee design heights range from about 4.5 to 6 m above mean sea level. The levees along the Lake Pontchartrain shoreline are designed at a height that exceeds the surge and waves of a Category 3 hurricane. The levee design criteria assume no increase in mean sea level and no subsidence (Alfred C. Naomi, U.S. Army Corps of Engineers, oral commun., 2001). The city of New

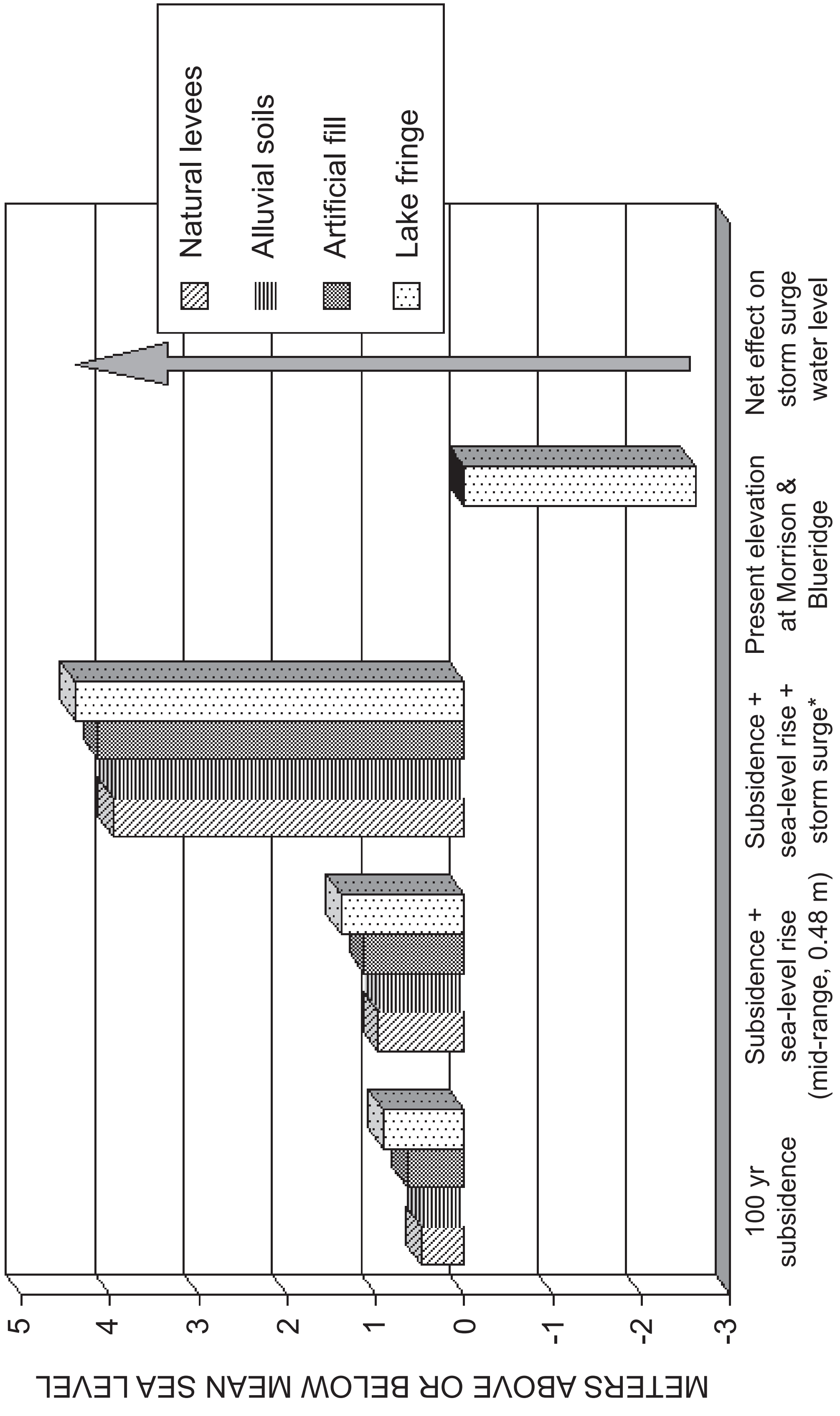

Figure 2. Local subsidence and sea-level projections for New Orleans and vicinity through 2100. Arrow on right represents the cumulative influence of land-surface elevation change and sea-level rise on storm-surge level *(Category 3 hurricane) at the Morrison Road/Blueridge Court intersection, which is presently about 2.6 m below mean sea level.

Orleans is drained by an extensive network of drainage canals (108 km of surface and subsurface canals) with 22 pumping stations. Most of the stormwater drainage is pumped over the flood-protection levees into Lake Pontchartrain (Sewerage and Water Board of New Orleans, 2001).

The following adaptation strategies would aid in reducing, but not eliminate, the vulnerability of the New Orleans MSA to flood disaster:

1. Upgrade levees and drainage systems to withstand Category 4 and 5 hurricanes.
2. Design and maintain flood protection on the basis of historical and projected rates of local subsidence, rainfall, and sea-level rise.
3. Minimize drain-and-fill activities, shallow subsurface fluid withdrawals, and other human developments that enhance subsidence.
4. Improve evacuation routes.
5. Protect and restore coastal defenses.
6. Encourage flood proofing of buildings and infrastructure.
7. Develop flood-potential maps that integrate local elevations, subsidence rates, and drainage capabilities (for use in the design of ordinances, greenbelts, and other flood-damage reduction measures).

GPS SOLUTIONS FOR MONITORING SUBSIDENCE IN LOUISIANA

Accurate monitoring of land subsidence over time is vital to providing data for calibrating models of land subsidence and predicting subsidence, as well as providing information for planning, constructing, and maintaining infrastructure and levees. Historically, geodetic differential leveling has been used to measure subsidence in the New Orleans MSA; it was very accurate but also very expensive. Over the past decade, GPS surveying techniques have proven to be so efficient and accurate that they are now routinely used in place of classical line-of-sight surveying methods for establishing horizontal control. Understandably, interest has also been growing in using GPS techniques to establish accurate vertical control. Progress, however, has been hampered due to difficulties in obtaining sufficiently accurate geoid height differences to convert GPS-derived ellipsoid height differences to accurate orthometric height differences.

These factors have recently been resolved, making GPS-derived orthometric heights a viable alternative to classical line-of-sight geodetic differential leveling techniques for many applications. Additional information is available at the following web sites on the topics of

- completion of the general adjustment of NAVD 88 (http://www.ngs.noaa.gov/PUBS_LIB/NAVD88/navd88report.htm),
- development of NGS guidelines for establishing GPS-derived ellipsoid heights to meet 2- and 5-cm standards (http://www.ngs.noaa.gov/PUBS_LIB/NGS-58.html), and
- computation of an accurate, nationwide, high-resolution geoid model, GEOID99 (http://www.ngs.noaa.gov/GEOID/).

A cooperative study between the Harris-Galveston Coastal Subsidence District (HGCSD) and the NGS is using GPS methods to measure subsidence at a fraction of the cost of the previous method. Due to the magnitude of subsidence in the Houston-Galveston region of southeastern Texas, there are no stable benchmarks in the area. Therefore, stable borehole extensometers were equipped with GPS antennas to provide a reference frame to measure subsidence at other stations in the area. These stations are known as local GPS Continuously Operating Reference Stations (CORS).

The NGS/HGCSD project uses dual-frequency, full-wavelength GPS instruments and geodetic antennas. Data are collected at 30-second sampling intervals and averaged over long periods, generally 24 hours. The goal is to yield differential vertical accuracy of less than 10 mm in a totally automated mode operated by HGCSD personnel. Data have now been collected from the three CORS sites and four portable GPS measuring stations called Port-A-Measures (PAMS), at 20 sites, for more than 4 years in the Houston-Galveston region. Results between CORS and PAMS indicate that some geodetic monuments are subsiding as much as 70 mm/yr and correlate well with extensometer data. The joint NGS/HGCSD GPS subsidence project is described in more detail by Zilkoski and others (p. 13 of these proceedings).

Louisiana's greatest environmental problem is the continuing loss of its coast. To address these problems, NGS in partnership with Louisiana State University through a newly created Louisiana Spatial Reference Center (LSRC) is building a statewide network of GPS CORS similar to the HGCSD network. Like the HGCSD network, the LSRC GPS CORS will be referenced to the National Oceanic and Atmospheric Administration (NOAA) national CORS. The national GPS CORS will provide the framework for the LSRC CORS to measure yearly subsidence rates at the 10-mm level. In addition to the continuously operating GPS CORS and PAMS, specially designed GPS network surveys adhering to NGS guidelines will be performed to estimate the subsidence in local areas.

CONCLUSIONS

Increases in mean sea level, coupled with the current low altitude of the land surface and land-subsidence trends in the region, portend serious losses of life and property in the New Orleans MSA unless flood-control levees and drainage systems are upgraded. The maintenance of barrier islands and wetlands that flank New Orleans to the south, west, and east is another adaptation that will likely minimize the potential loss of life and property due to flooding. The changes in sea level that are predicted to accompany increasing global temperature are statistically and practically significant to those responsible for designing flood-control works and coastal protection strategies for New Orleans, Houston, Amsterdam, and other rapidly subsiding coastal areas. The application of GPS technology for determining orthometric height differences should enhance the utility and cost effectiveness of land-subsidence monitoring in flood-protection design.