



Shallow-subsidence vulnerability in the city of New Orleans, southern USA

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Abstract

Land subsidence in the city of New Orleans (USA) and its surroundings increases flood risk, and may cause damage to buildings and infrastructure and loss of protective coastal wetlands. To make New Orleans more resilient to future flooding, a new approach for groundwater and subsidence management is needed. As a first step in developing such an approach, high-quality and high-resolution subsurface and groundwater information was collected and synthesized to better understand and quantify shallow land subsidence in New Orleans. Based on the collected field data, it was found that especially the low-lying areas north and south of the Metairie-Gentilly (MG) Ridge are most vulnerable to further subsidence; north of the MG Ridge, subsidence is mainly caused by peat oxidation and south of the MG Ridge mainly by peat compaction. At present, peat has compacted ~31% on average, with a range of 9–62%, leaving significant potential for further subsidence due to peat compaction. Phreatic groundwater levels drop to ~150 cm below surface levels during dry periods and increase to ~50 cm below surface during wet periods, on average. Present phreatic groundwater levels are mostly controlled by leaking subsurface pipes. Shallow groundwater in the northern part of New Orleans is threatened by salinization resulting from a reversal of groundwater flow following past subsidence, which may increase in the future due to sea-level rise and continued subsidence. The hydrogeologic information provided here is needed to effectively design tailor-made measures to limit urban flooding and continued subsidence in the city of New Orleans.

Keywords Subsidence · Peat · Urban groundwater · Vulnerability mapping · USA

Introduction

Worldwide, coastal zones including river deltas are subject to land subsidence (e.g., Giosan et al. 2014; Syvitski et al. 2009), which, in addition to eustatic sea level rise, is one of the main drivers of relative sea level rise (e.g., Ericson et al. 2006). Because of their low elevation, many coastal zones are especially sensitive to higher-frequency and more intense storm surges and flooding events induced by climate change (e.g., McCarthy et al. 2001). These pressures increasingly

threaten hundreds of millions of people currently living in coastal areas, while continued population growth and urbanization in coastal zones are expected in the future (Neumann et al. 2015). The city of New Orleans (Louisiana, USA), located in the Mississippi Delta (MD), is one such urban area plagued by subsidence and flooding. Although previous work has examined subsidence in the surrounding wetlands (e.g., Keogh et al. 2021) and used remote sensing to estimate urban subsidence (e.g., Jones et al. 2016), this paper is the first to quantify peat compaction and the potential for continued shallow subsidence within the city, due to processes acting in the top ~5 m, using hydrogeologic field observations.

Land subsidence is caused by both natural and anthropogenic processes (Stouthamer and Van Asselen 2015a; Higgins 2016). Natural causes include tectonics, isostasy, sediment compaction and biogeochemical processes. Natural processes may be accelerated by human activities, like withdrawal of hydrocarbons and groundwater, loading of soft soils, and lowering of the phreatic water table. Human-induced subsidence rates are usually greater than natural

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subsidence rates, but at the same time, human-induced subsidence can be halted, while one cannot reasonably influence natural subsidence (Stouthamer and Van Asselen 2015b). As in many coastal areas, land subsidence in the MD is caused by multiple natural and anthropogenic processes acting at different spatial and temporal scales (e.g., Dixon et al. 2006; Dokka et al. 2006; Meckel et al. 2006; Ivins et al. 2007; Törnqvist et al. 2008; Morton et al. 2009; Dokka 2011; Yu et al. 2012; Jones et al. 2016). However, the specific causes and relative contributions of different processes to total subsidence remain uncertain (e.g., Törnqvist et al. 2008; Jones et al. 2016). Previous studies on measuring subsidence reveal that subsidence rates prior to the twentieth century were dominated by natural causes and are on the order of 1 mm/year or less (Kooi et al. 2019). From 1900 onwards, however, subsidence rates increased due to anthropogenic activities, often to 5–25 mm/year locally (Kooi et al. 2019; Kolker et al. 2011). Kooi et al. (2019) also demonstrated uplift in the northeastern part of New Orleans in recent times, which was attributed to the ceasing of groundwater pumping. This has also been observed in other areas (Chen et al. 2007; Wang et al. 2020).

Like many other deltas in the world, the MD contains abundant peat in the subsurface (e.g., Törnqvist et al. 2008). In peat-rich deltas, a significant part of total land subsidence is usually caused by peat compaction, peat oxidation, irreversible shrinkage and/or peat mining (Deverel and Rojstaczer 1996; Long et al. 2006; Törnqvist et al. 2008; Drexler et al. 2009; Van Asselen 2011; Deverel et al. 2016; Erkens et al. 2016). This paper focuses on shallow subsidence in the city of New Orleans, between the Mississippi River and Lake Pontchartrain, that is caused by peat compaction and oxidation. Here, compaction is defined as a mechanical process of volume reduction due to the expulsion of pore water induced by an increase in effective stress (= overlying weight – pore water pressure; Terzaghi 1943; Paul and Barras 1998). In time, slow rearrangement of the soil particles may cause an additional volume reduction, especially in soft soils. Oxidation is a biochemical process of soil organic matter decomposition by micro-organisms (Neller 1944; Stephens and Johnson 1951; Schothorst 1977). Organic matter is oxidized to CO₂ and H₂O, resulting in a volume reduction of the soil and, hence, subsidence. Peat decomposition rates are especially high in the zone above the phreatic water table, where oxygen—a strong electron acceptor—easily intrudes into the soil and initiates the oxidation process.

The oldest parts of New Orleans were built in 1722 on relatively stable and elevated ground formed by natural levees of the Mississippi River (e.g., Campanella 2002; Van Asselen et al. 2020 and references therein). In later times, large parts of the city were built on soft soils in swamps further away from the river. In these areas,

historical drainage and loading of peat and clay soils has increased land subsidence, due to oxidation and compaction of soft organic soils. Droughts may also cause subsidence due to peat oxidation by causing a lowering of the groundwater level. At present, ~60% of the urban area of New Orleans is located below mean sea level (MSL; Van Asselen et al. 2020). With ongoing subsidence and sea-level rise on the one hand, and a predicted increase in intensity and frequency of droughts, rainfall events, and hurricanes on the other, the risk of flooding and subsequent societal disruption is increasing, as became clear in the aftermath of Hurricane Katrina in 2005. Subsequently, the 2020 Atlantic hurricane season was the most active on record: the previous record of nine hurricanes that made landfall in the contiguous US increased to twelve, including five that struck Louisiana.

Moreover, continued land subsidence causes an increase in pluvial and fluvial flood frequency, inundation depth, and duration, resulting in flood damage. Differential subsidence causes damage to buildings and infrastructure, both at and below the surface (e.g., Cigna and Tapete 2021; Ohenhen and Shirzaei 2022). Land subsidence, whether or not in combination with hurricanes such as Katrina in 2005, may also lead to coastal erosion and loss of protective wetlands (e.g., Day et al. 2007; Törnqvist et al. 2008; Morton et al. 2009). In the case of New Orleans, Hurricane Katrina would likely have caused less damage if the city had previously experienced less land subsidence, in which case the inundation depth would have been less, and water would have drained off more easily from the higher land.

To make New Orleans more resilient to future flooding, a new approach for groundwater and subsidence management for New Orleans is needed. The first step in developing such an approach is collecting high-quality and high-resolution subsurface stratigraphy and groundwater information. Such information is currently largely lacking for New Orleans and, even if present, is not readily available for the city. This study aims to better understand and quantify shallow land subsidence in New Orleans by revealing geologic and hydrologic properties of the shallow subsurface and use this information to delineate areas with typical subsurface hydrogeologic profiles and related vulnerability for specific shallow-subsidence processes, resulting in a subsidence vulnerability map. Such hydrogeologic information may be used to develop subsidence mitigation and adaptation strategies. For example, results of this study may be used to define subsidence hotspots, revealing where action is most urgent, and for gaining insight in where subsidence should be taken into account in urban planning. In general, results of this study are needed to effectively design tailor-made measures to limit urban flooding and subsidence.

Study area

The study area encompasses much of the city of New Orleans between the Mississippi River and Lake Pontchartrain (Fig. 1).

Paleogeographic evolution

About 5000 calibrated (cal) years before present (BP), the Mississippi River deposition center (the Teche Delta Complex) was located west of the modern delta. At that time, sediments from the smaller Pearl River to the east were concentrated into barrier islands and shoals by longshore drift processes. These sediments created the Pine Barrier Island chain south of present Lake Pontchartrain, which is now partly buried under the northern part of New Orleans (Saucier 1963; Otvos and Giardino 2004; Dunbar and Britsch 2008; Van Asselen et al. 2020; Fig. 2a). About 3,800 cal years BP, a major avulsion of the Mississippi River created a new course running in a west-east direction south of

present-day Lake Pontchartrain, near the same location as the modern Mississippi River (Hijma et al. 2017; Fig. 2b). The barrier island chain and new Mississippi course enclosed the former bay creating Lake Pontchartrain. The new Mississippi course fed the St. Bernard subdelta and consisted of various distributary systems that were successively active in the period between ~4,000 to ~1,900 years ago (Frazier 1967; Hijma et al. 2017). One of the St. Bernard distributary channels is the Bayou Metairie-Gentilly (MG) system, which runs from west to east through the present-day city of New Orleans, north of the modern Mississippi (Fig. 3). This system became active ~2,500 years ago (Saucier 1963). At present, the abandoned channel is expressed at the surface as a ridge. The distributary channels of the St. Bernard subdelta progressively filled the shallow coastal waters in the New Orleans area with fluvial-deltaic sediments (Fig. 2c). Sediment delivery maintained and increased ground elevation, which facilitated the formation of swamps and marshes (Dunbar and Britsch 2008). Further away from the rivers, brackish and saline marshes developed. About



Fig. 1 The study area within the city of New Orleans, Louisiana, USA, delineated by the red line or dot. Dark grey indicates surface water

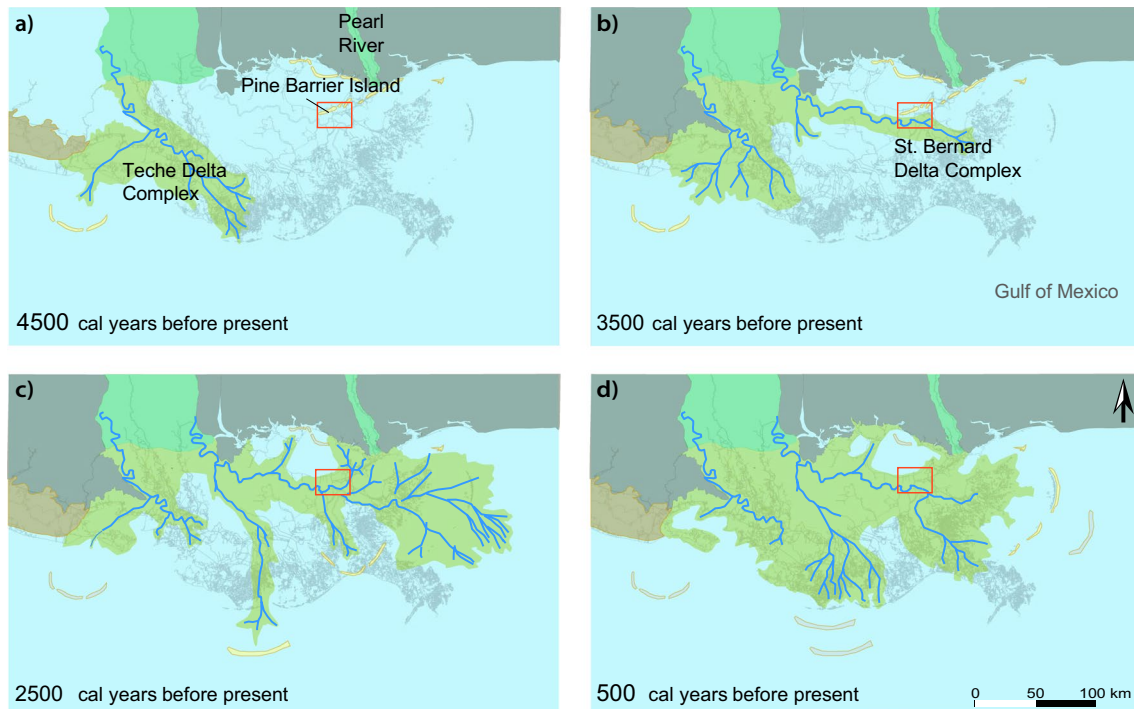


Fig. 2 a–d Schematic representation of the paleogeographic development of the Mississippi Delta system. The red box indicates the approximate location of the area presented in Fig. 3

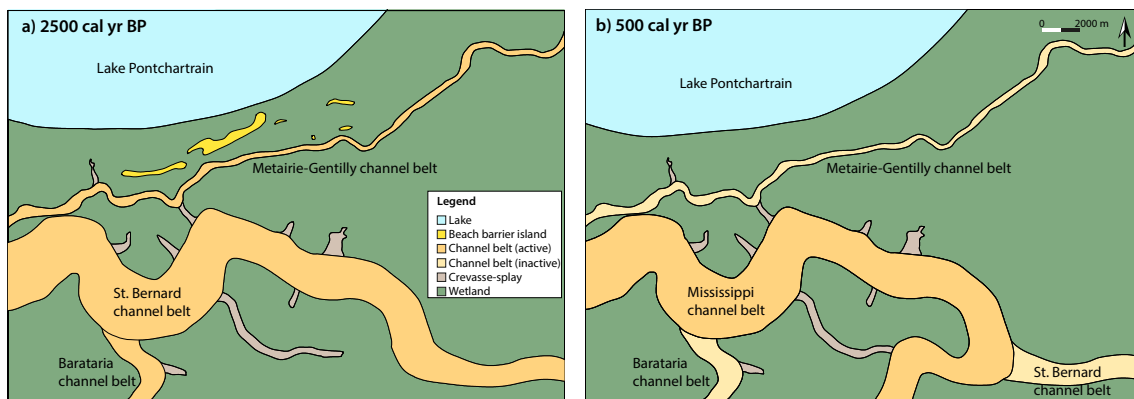


Fig. 3 Schematic representation of the paleogeographic development of the area around present New Orleans (red box in Fig. 2): **a** 2,500 and **b** 500 cal years BP (calibrated years Before Present)

1,000 years ago, the present-day Mississippi River course (Plaquemines-modern) came into existence (Figs. 2d and 3).

Hydrogeology

In the New Orleans urban area, two shallow aquifers can be identified that are relevant for the phreatic groundwater situation: (1) the sandy deposits around the Mississippi River, and (2) the mostly buried sandy Pine Barrier Island in the northern part of the city, which at some places crops

out at the surface. Across most of the city, however, the shallow subsurface consists predominantly of low permeability (organic) clay and peat. The main types of deposits occurring in the study area are described in Text S1 of the electronic supplementary material (ESM). The first aquitard below the Holocene sequence, acting as the hydrogeological basis of the shallow urban groundwater system, is formed by the Pleistocene Prairie Formation, a very impermeable consolidated clay layer that lies 20–30 m below the surface (Prakken 2008).

Historic development

The historical analysis described in this paragraph is based on Van Asselen et al. (2020) and references therein. Around 1803, the area occupied by modern New Orleans was predominantly covered by cypress swamps (e.g., Trudeau 1789; Hardee 1878). These swamps, which had a surface elevation just above sea level, facilitated water infiltration and sediment deposition during overbank flooding. At the time, the main urban development was located on highest ground next to the Mississippi River. In the following decades, the city began to grow towards the north, reaching Lake Pontchartrain by 1834. Along with urban development came intensive cypress tree logging, an important local economic activity during the second half of the 19th century and the first half of the 20th century. The results of this logging caused the cypress swamps to retreat even further, especially in the area surrounding the older urban settlements closer to the Mississippi River. During this period, the construction of canals began as they were necessary to transport the wood generated during the logging activities. These canals, while beneficial for logging, also caused the drainage of shallow groundwater and the intrusion of salt water into the swamps and marshes, disturbing the ecosystem and inhibiting the regeneration of cypress trees. Between 1891 and 1939, the cypress swamps around New Orleans had nearly disappeared, and signs of subsidence started to show. In the decades to follow, the city continued to grow, first densifying in the higher elevation area along the northeast bank of the Mississippi River (in and around the present-day French Quarter) that was above sea level, and then in the lower area along Lake Pontchartrain. By 1979, most of this area was urbanized.

Methods

Hydrogeologic reconstruction

To assess the shallow-subsidence vulnerability of New Orleans, hydrological and geological characteristics of the shallow subsurface were revealed based on boreholes drilled manually in November 2018 using both Edelman and gouge hand augers. Borehole depths ranged from 130 to 600 cm. Borehole locations were determined based on topography and accessibility, ensuring an even spatial distribution over the study area, and partly aligned linearly to facilitate the construction of subsurface cross sections. Most boreholes were located in low-lying former swamps and floodplains, where most subsidence-related problems have occurred. To get a full understanding of the subsurface and groundwater system, the remaining boreholes were located at higher elevation locations such as natural levees, crevasse splays,

and anthropogenic fills. To circumvent accessibility restrictions, borehole locations were strategically planned in public parks and vacant lots.

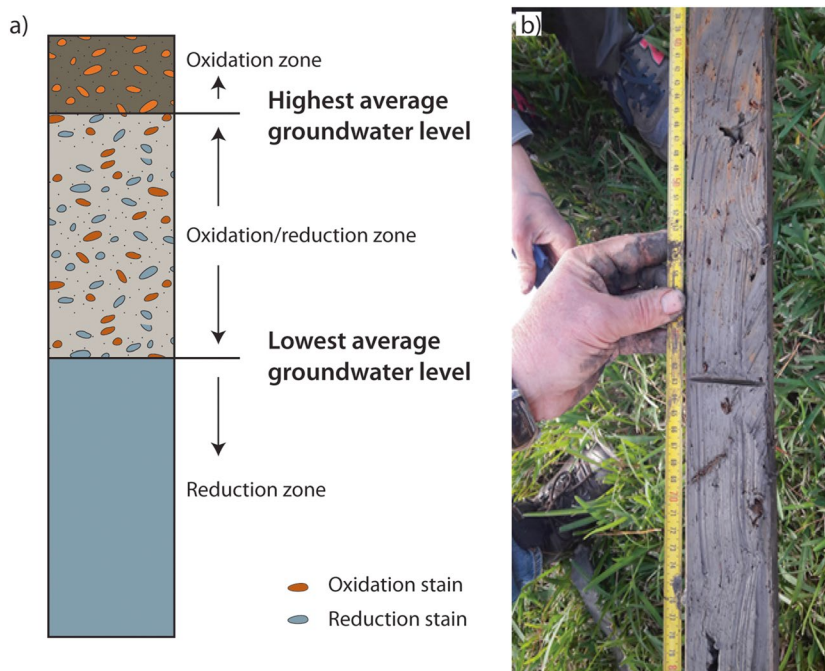
Retrieved cores were described at 10-cm intervals. Peat was described based on the botanical composition (e.g., wood, sedge and/or reed remains), color, and organic-matter content, distinguishing three classes—peat, peat muck, and muck (Fig. S1a in the ESM). The organic-matter content was estimated by experienced geologists in the field by visual inspection of color (brownish or blackish in case of peat, greyish in case of clay) and how it smears in the palm of a hand (friable in the case of peat, smooth in the case of clay). Other relevant observations such as amorphous peat intervals and very soft or stiff intervals were also logged.

Clastic sediments were classified in the field using the US Department of Agriculture texture classification system (Fig. S1b in the ESM), and later regrouped into classes of the Unified Soil Classification System (USCS; Table S1 in the ESM). This was done to facilitate comparison with existing subsurface cross sections of the study area that use the USCS system (e.g., USACE 1958). Clastic sediments were described for the presence of plant remains, color, consistency, and oxidation/reduction characteristics, as well as for other relevant properties such as the occurrence of laminations and shell fragments. Oxidation and reduction characteristics are indicative of the average highest and average lowest groundwater level (Fig. 4). Oxidation of iron occurs when sediment is exposed to air (oxygen) and results in the formation of orange/brownish rust stains. The deepest occurrence of such oxidation stains indicates the lowest average groundwater level that has occurred at this specific location. Reduction occurs when the soil is consistently waterlogged, resulting in greyish-colored stains. The shallowest level where reduction stains occur indicates the highest average groundwater level. All borehole locations were levelled (X, Y and Z position, RTK measurements) by a land surveyor from Batture Engineering, using the Louisiana South State Plane Coordinates (ESPG: 3452) system and the NAVD88 elevation datum.

Compaction estimates

To assess the current degree of compaction of soft soils in the subsurface of New Orleans, the dry bulk density and organic matter content of peat and organic clay intervals were determined. These intervals were sampled in the field, directly from a gouge auger. The sediment core was first cut in half lengthways using a thin wire to allow sampling of the inner, least disturbed, part of the core. A maximum of four samples of peat and/or organic intervals were extracted per borehole using a 1 cm × 1 cm × 5 cm peat sampler (Van Asselen 2011). Samples were immediately wrapped in plastic wrap and delivered to the Quaternary Geology Lab at

Fig. 4 **a** Schematic representation of the oxidation/reduction zones. **b** Oxidation stains, clearly visible above the horizontal cut in the core



Tulane University in small plastic vials with screw-caps. In the lab, each 5 cm³ sample was oven-dried at 105 °C for 24 h and weighed on an electronic scale (accuracy of 0.001 g) to determine the dry bulk density (= dry weight per 5 cm³). Subsequently, the samples were heated at 550 °C for 4 h to determine ‘loss on ignition’ (LOI) = [(dry weight – ashed weight)/dry weight] × 100%; cf. Heiri et al. (2001), which is a measure of the organic matter content.

The degree of compaction was assessed by comparing the dry bulk density (ρ) and organic-matter content of compacted peat samples obtained from the subsurface of New Orleans with the dry bulk density and organic-matter content of fresh swamp peat in the surroundings of New Orleans (Fig. 5; conforming to the method used by Van Asselen 2011). The fresh peat data ($n = 139$, maximum depth 24 cm below surface) were obtained from the Coastwide Reference Monitoring System (CRMS) project. The samples used for this study were all from swamp and freshwater marsh environments, formed in a similar environmental setting as the peat in the New Orleans area (e.g., Dunbar and Britsch 2008; Figs. 2 and 3). Moreover, the fresh peat samples were obtained at similar distances from the main river distributaries as the peat samples in the New Orleans study area (Fig. 5). The fresh peat samples used in this study align well with the bulk density and organic content ranges of uncompacted peat samples collected across the entire MD (Keogh et al. 2021; Fig. S2 of the ESM), as well as with peat from other freshwater marsh environments (e.g., Van Asselen et al. 2011; Morris et al. 2016). Both the compacted and fresh peat data series were plotted in an organic-matter content–dry bulk density diagram. The fresh peat data series

was fitted using an exponential fit, resulting in an equation to assess the dry bulk density of fresh peat for a specific organic-matter content. Next, the amount of compaction of a 5-cm³ sample was determined by calculating the decompacted thickness (h_0) of a 5-cm³ sample, based on the dry bulk density of compacted (ρ_c) and fresh (ρ_0) peat, using:

$$h_0 = (\rho_c / \rho_0) \cdot 5, \quad (1)$$

which was used to calculate the amount of compaction of the sample:

$$\text{Compaction} = (h_0 - 5) / h_0 \cdot 100\%. \quad (2)$$

Subsidence vulnerability map

Core descriptions and analyses were used to construct maps of lithological sequences and shallow-subsidence vulnerability. Typical lithological sequences occurring in the shallow subsurface were identified first based on collected borehole information. Each borehole was attributed with a lithological sequence type. The spatial distribution of borehole sequence types, a digital elevation model (DEM) and the contours of the top of the Pine Barrier Island were subsequently used to delineate polygons representing the spatial coverage of lithological sequence types within the study area. The DEM was used to delineate sequence types that are linked to a morphological surface expression such as natural levees, crevasse splays and fills. The top of the Pine Barrier Island contour map was

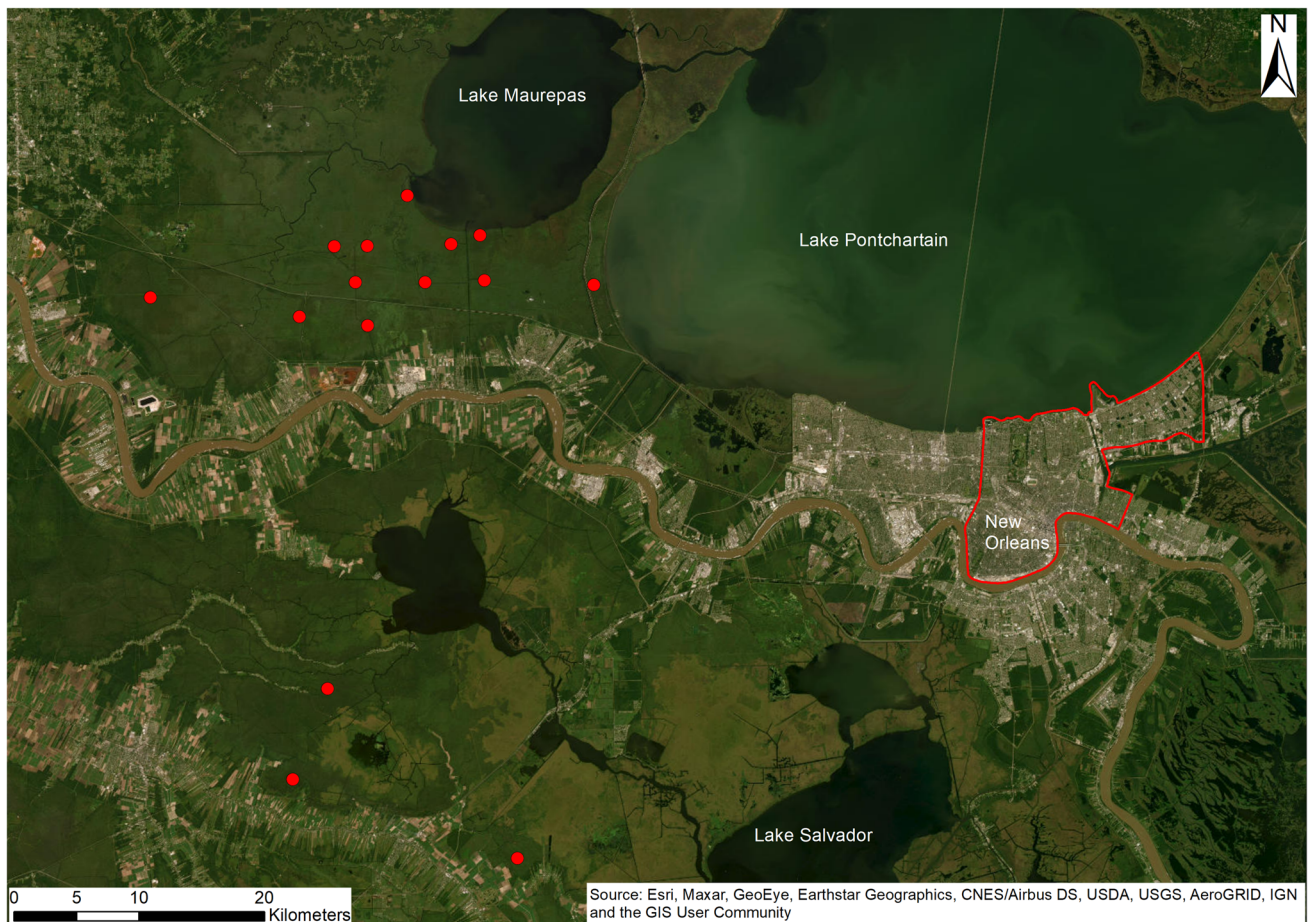


Fig. 5 Location of CRMS sites (red dots) from which fresh peat data (dry bulk density and organic matter content) were used (CPRA 2018). The red outline indicates the study area

used to subdivide classes based on sand depth. The lithological sequence types were described and subsequently attributed a relative vulnerability for subsidence due to oxidation and/or compaction, resulting in the subsidence vulnerability map.

Results

Subsurface composition

In total, 72 boreholes were manually drilled and used to construct 6 cross sections (Fig. 6). The study area has been subdivided into three main geographical units to describe the subsurface composition: the area north of the MG Ridge (between the ridge and Lake Pontchartrain), the MG Ridge itself, and the area south of the MG Ridge (between the ridge and the Mississippi River).

North of Metairie-Gentilly Ridge

Lake Pontchartrain is bordered by a meters-thick, predominately sandy anthropogenic fill with a levee on top (Figs. 7, 8, 9). In the Lakeview and Gentilly neighborhoods, located just south of the fill (see Fig. 1 for neighborhood locations), the ground surface has a present-day elevation of about -2 m MSL (measured during this study at borehole locations in the cross sections presented in Figs. 7 and 9). The DEM indicates even lower elevations, which reach almost -3 m MSL in some areas north of the MG Ridge (most dark green-colored areas in Fig. 6). In Lakeview and Gentilly, peat occurs close to the surface, mostly above the average lowest groundwater level, and is generally amorphous. The ground surface in City Park is somewhat higher, about -1.7 m MSL (Fig. 8). The shallow subsurface of City Park is also mainly composed of peat and organic clay. Part of these organic layers occur above the average lowest groundwater level, where



Fig. 6 Location of manually drilled boreholes and constructed cross sections. The approximate boundary of the abandoned Metairie-Gentilly channel is indicated by the blue lines. Source: digital elevation model (OCM Partners 2017)

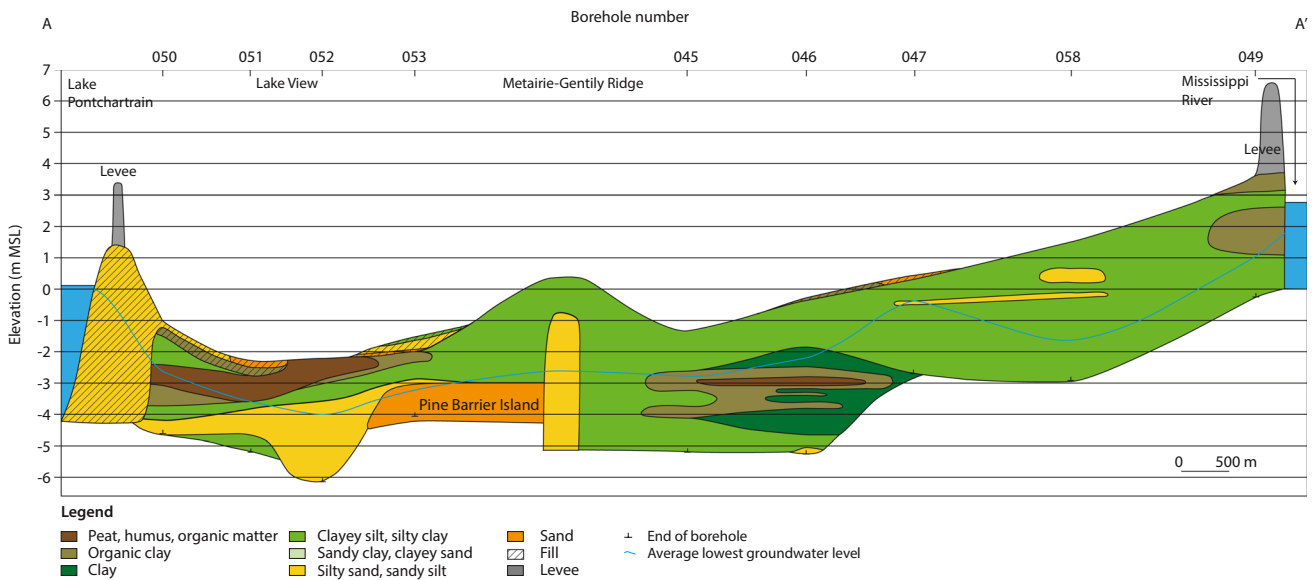


Fig. 7 Cross section A–A'. For location see Fig. 6

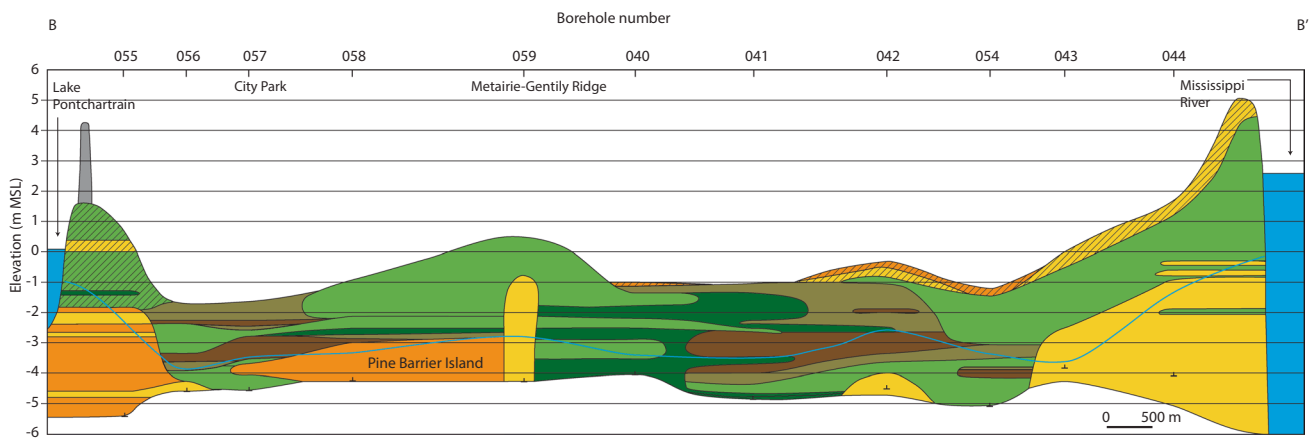
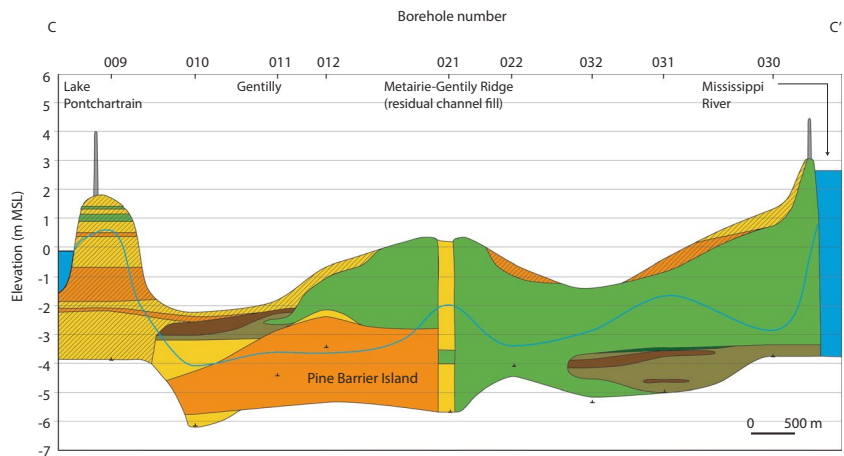


Fig. 8 Cross section B–B'. For location see Fig. 6, and for the legend see Fig. 7

Fig. 9 Cross section C–C'. For location see Fig. 6, and for the legend see Fig. 7



oxidation has resulted in decomposed, amorphous peat. Peat also occurs below the average lowest groundwater level, and these peat layers are still relatively undecomposed. In Lakeview and City Park, the peat layers are underlain by silty clay and (silty) sand. In Gentilly, the peat is directly underlain by (silty) sand deposits of the Pine Barrier Island.

East of the Inner Harbor Navigation Canal, in the western part of the New Orleans East neighborhood (Fig. 1), a thin surface layer consisting of peat and organic clay directly overlies the Pine Barrier Island sand in the north and clayey/silty fluvial deposits in the south (Fig. 10a). The peat has been decomposed by oxidation. Further east, Pine Barrier Island sand occurs at greater depth (Fig. 10b). It is overlain by predominantly fluvial silty clay. The top layer consists of peat and organic clay that have been decomposed by oxidation.

Metairie-Gentilly Ridge

The study area is dissected by the abandoned west–east-oriented Metairie-Gentilly distributary channel. Here, silty and sandy channel deposits occur in the subsurface, bordered by natural levee deposits consisting mostly of silty clay (Figs. 7, 8 and 9). At present, the former channel is expressed as a topographic high at the surface. The top of the former channel is generally elevated a few decimeters above MSL, roughly 2 m higher than the surrounding area.

South of Metairie-Gentilly Ridge

South of the MG Ridge, peat occurs at greater depth below the surface than north of the MG Ridge, generally below the average lowest groundwater level, and is overlain by floodplain deposits consisting of organic and/or silty clays

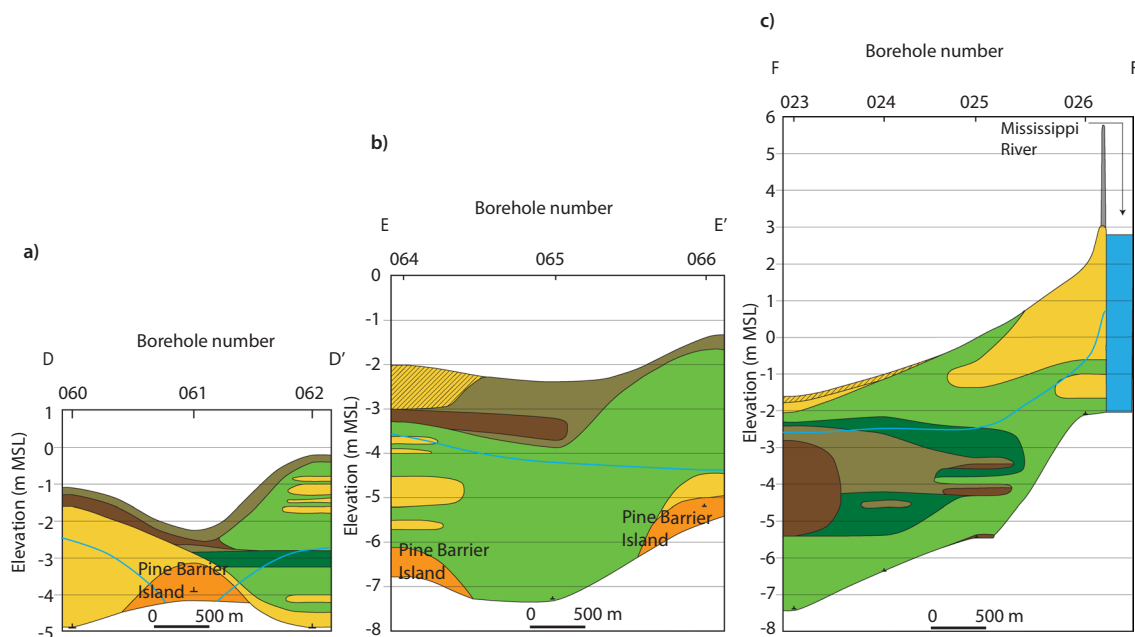


Fig. 10 Cross sections **a** D–D', **b** E–E' and **c** F–F'. For locations see Fig. 6, and for the legend see Fig. 7

(Figs. 7, 8 and 9). The present lowest surface elevation in this area, measured along the cross sections, is about -1.4 m MSL at borehole 032 (Fig. 6). From there, the ground surface gently increases in elevation towards the natural levee of the Mississippi River, where the shallow subsurface becomes increasingly silty and sandy. Some relatively small lower-elevation areas occur also south of the MG Ridge (for example, elevations of -2.0 to -2.5 m MSL occur between boreholes 019, 020 and 027, and between boreholes 042 and 054; Fig. 6), but in general the area south of the MG Ridge is elevated higher than the area north of the MG Ridge.

East of the Inner Harbor Navigation Canal, in the Lower Ninth Ward, abundant peat and organic clay is found in the shallow subsurface, mostly occurring below the average lowest groundwater level (Fig. 10c). The area has subsided to about -1.5 m MSL (measured at borehole 023). Close to the Mississippi River, more silt and sand is found in the subsurface, and the surface rises upwards to the highest point on the (natural) levee.

Peat compaction

In total, 88 organic samples were analyzed for dry bulk density and organic-matter content, of which 26 samples had an organic-matter content greater than or equal to 20% and were classified as peat (conforming to Van Asselen et al. 2011; Erkens et al. 2016). The remaining samples, which have an organic-matter content lower than 20% ($n = 62$) were classified as humic clays, and in this paper are excluded from subsequent quantitative analyses that are developed specifically

for peat soils. The average organic-matter content of the 26 peat samples is 39%, with a maximum value of 67%.

The dry bulk density of fresh peat samples (from CRMS sites, Fig. 5) is on average lower than the dry bulk density of the buried peat in the subsurface of the city of New Orleans (Fig. 11). For each (compacted) peat sample, the amount of compaction was calculated using Eqs. (1) and (2). An exponential equation fit to the fresh peat data (blue line in Fig. 11) was used to estimate the original uncompacted dry bulk density of compacted peat with a specific LOI. The R^2 of this equation is 0.63, indicating a rather high natural variability in dry bulk density, which is expected because peat commonly has a heterogeneous structure composed of different amounts and types of fibers (Van Asselen 2011). This natural heterogeneity, in addition to uncertainties that arise from the sampling procedure, introduces an uncertainty in the calculated amount of compaction that is difficult to estimate but is considered to be on the order of 15% (cf. Van Asselen 2011). Peat in the subsurface of New Orleans has been compacted 31% on average, with a maximum of 62% (Table 1). Relatively high-organic peat tends to be compacted more, although the positive relationship between the amount of compaction and organic-matter content of all peat samples is weak ($R^2 = 0.2$; Fig. 12).

In the areas north of the MG Ridge, peat occurs at shallow depths. This has caused peat oxidation in the zone above the average groundwater level, forming decomposed peat. Generally, decomposed peat is amorphous, contains few fibers, and has a crumbly structure. Yet, lab analyzes show that decomposed peat may still have relatively high organic

Fig. 11 Dry bulk density plotted against organic matter content (LOI) of buried samples from the subsurface of New Orleans (red and yellow), as analyzed in this study, and of fresh peat samples from CRMS sites (blue; see Fig. 5). The trendline is fitted on the fresh peat samples, used to estimate the uncompacted dry bulk density of compacted peat

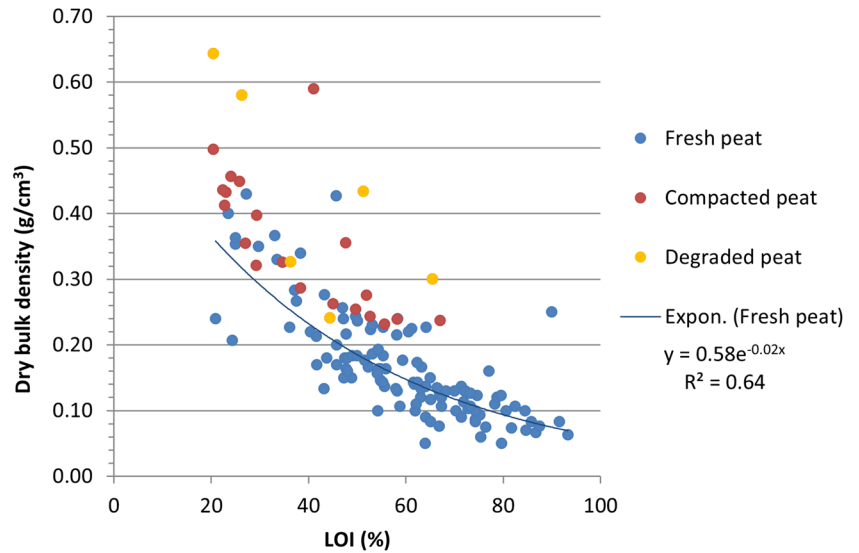


Table 1 Depth, organic matter content (LOI), measured dry bulk density of compacted peat, estimated original dry bulk density of uncompacted fresh peat, and the calculated amount of compaction of the compacted peat samples

Area	Borehole No.	Depth range (m)	LOI (%)	Measured dry bulk density (g/cm ³)	Estimated uncompacted bulk density (g/cm ³)	<i>h</i> ₀ (cm)	Calculated compaction (%)
South of Metairie-Gentilly Ridge	018	103–108	48	0.36	0.19	9.24	46
	027	251–256	52	0.28	0.17	7.91	37
	027	340–345	58	0.24	0.15	7.94	37
	027	375–380	56	0.23	0.16	7.24	31
	031	336–341	24	0.46	0.33	6.89	27
	032	252–257	45	0.26	0.20	6.43	22
	032	295–300	29	0.32	0.29	5.47	9
	034	257–262	22	0.44	0.34	6.34	21
	041	290–295	53	0.24	0.17	7.09	30
	042	275–280	38	0.29	0.24	6.01	17
	042	160–165	27	0.36	0.31	5.74	13
	045	250–255	23	0.41	0.34	6.04	17
	054	285–290	50	0.25	0.18	6.93	28
	North of Metairie-Gentilly Ridge	005	139–144	28	0.45	0.32	7.07
005		103–108	65	0.30	0.13	11.76	57
050		172–177	41	0.59	0.22	13.17	62
051		75–80	26	0.58	0.31	9.23	46
051		113–118	44	0.24	0.21	5.81	14
051		183–188	36	0.33	0.25	6.54	24
056		175–180	35	0.33	0.26	6.29	20
057		127–132	23	0.43	0.34	6.39	22
058		190–195	20	0.50	0.36	6.92	28
064		115–120	51	0.43	0.18	12.25	59
069		115–120	20	0.64	0.36	8.94	44
072		175–180	67	0.24	0.12	9.62	48
072		195–200	29	0.40	0.29	6.77	26

Fig. 12 Amount of compaction of peat samples plotted against the organic matter content (LOI)

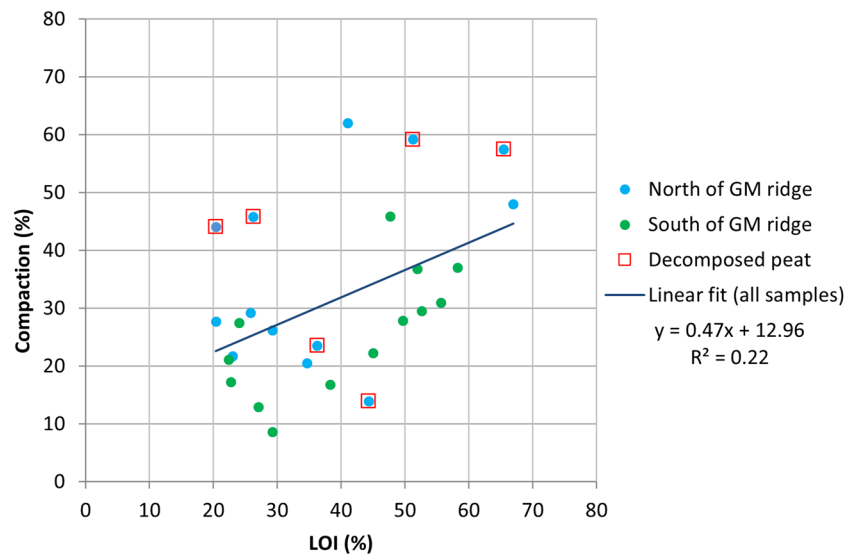


Table 2 Hypothetical subsidence scenarios based on peat thickness above the average lowest groundwater level (LGL), loss on ignition (LOI) and the calculated amount of subsidence due to peat oxidation ($= LOI_{lost}/100 \times \text{peat thickness}$)

Peat above LGL (cm)	LOI	LOI minimum (%)	LOI _{lost} (%)	Subsidence (cm)
10	20	10	10	1
30	20	10	10	3
50	20	10	10	5
70	20	10	10	7
10	40	10	30	3
30	40	10	30	9
50	40	10	30	15
70	40	10	30	21
10	65	10	55	6
30	65	10	55	17
50	65	10	55	28
70	65	10	55	39

matter content (red squares in Fig. 12), comparable to peat that has not yet been decomposed. Results also demonstrate that the dry bulk density and related compaction grade of decomposed peat tends to be higher than that of nondecomposed peat (Figs. 11 and 12).

At present, the total thickness of peat occurring above the average lowest groundwater level varies between 10 and 70 cm. The organic matter content (i.e., LOI) of the sampled peat varies between 20 and 65% (Table 1). The potential amount of subsidence by peat oxidation has been estimated, using the relationship in Table 2, for different hypothetical combinations of peat thickness above the average lowest groundwater level and organic matter content, assuming a residual weight of 10% after decomposition. By

using the lowest groundwater level, this calculation produces a maximum potential compaction value. The value of 10% residual is based on previous LOI laboratory determinations that demonstrate maximum LOI values of ~95% (e.g., Van Asselen 2011; Erkens et al. 2016): in the authors' experience, burning peat samples at 550 °C leaves some residual ash, even for high-organic peat. Assuming the burning process in an oven decomposes more organic material than the peat oxidation process in the field, a residual weight of 10% is estimated and used to calculate potential maximum subsidence by peat oxidation.

The estimated amount of subsidence due to peat oxidation varies between 1 and 39 cm for this area (Table 2). Both north and south of the Metairie-Gentilly Ridge, peat is also found to occur below the average lowest groundwater level. In areas where peat occurs just below this level, further lowering of the groundwater level will lead to additional subsidence due to oxidation of the fresh peat that becomes exposed to oxygen.

The potential amount of subsidence due to compaction of peat below the average lowest groundwater level was also estimated. The current peat compaction grade in New Orleans varies between ~10 and 60% (Fig. 12). The total measured thickness of peat below the average lowest groundwater level varies between 10 and 250 cm. Assuming a maximum peat compaction grade of 70% (estimate based on this study, unpublished data from the main author, and similar studies, e.g., Van Asselen 2011; Van Laarhoven 2016; Keogh et al. 2021), the expected subsidence due to future peat compaction, for different combinations of peat thickness and current compaction grade, is generally on the order of centimeters to decimeters with extreme cases of up to ~150 cm.

The calculations presented in Tables 2 and 3 are estimates suggesting the orders of magnitude of subsidence that may

Table 3 Potential subsidence due to compaction of peat for different hypothetical combinations of peat thickness below the average groundwater level (column A) and present compaction grade (column B), using the formulas $C = A / [1 - (B/100)]$, $E = [1 - (D/100)] \times C$, and $F = A - E$

A	B	C	D	E	F
Peat below LGL (cm)	Current compaction (%)	Initial thickness (cm)	Max potential compaction (%)	Thickness after 70% compaction (cm)	Potential subsidence (cm)
10	10	11	70	3	7
50	10	56	70	17	33
100	10	111	70	33	67
250	10	278	70	83	167
10	30	14	70	4	6
50	30	71	70	21	29
100	30	143	70	43	57
250	30	357	70	107	143
10	60	25	70	8	3
50	60	125	70	38	13
100	60	250	70	75	25
250	60	625	70	188	63

occur in the study area. For detailed assessments of future amounts and rates of subsidence due to peat compaction and oxidation, additional site-specific geologic and hydrologic information is required.

Lithological sequence types

Based on the borehole information, nine typical lithological sequence types are distinguished in the study area. Each sequence type is described in terms of lithological composition, depositional environment, and vulnerability to shallow subsidence (Table 4). The sequence-type polygons (Fig. 13) are subsequently grouped into larger polygons reflecting three different classes of subsidence vulnerability: low, medium, and high vulnerability (Table 4; Fig. 14).

Hydrogeology

The oxidation and reduction characteristics demonstrate that, in general, the average highest groundwater level is ~0.5 m below the surface, while the average lowest groundwater level is ~1.5 m below the surface (Fig. 15). Several exceptions occur, for example on the Mississippi River levee in the southern part of the study area (boreholes 1, 29, 30, 38; Fig. 6) where the average lowest groundwater levels may be more than 3.5 m below surface level. At some locations further from higher ground (e.g., borehole 60, Fig. 6), the average highest groundwater level is at surface level. Most of the recorded average high and average low groundwater levels are below mean sea level (Fig. 16). In general, going from south (Mississippi River) to north (Lake Pontchartrain) in the study area, phreatic groundwater levels decrease relative to mean sea level (Fig. 16), reflecting the general decrease in surface elevation going from south to north in the study area.

Based on the groundwater levels recorded at each borehole, a contour map of the average lowest groundwater levels has been constructed by using a simple linear interpolation (Fig. 17). New Orleans East is an example of an area characterized by very low groundwater levels, and therefore also by steep gradients with the adjacent higher surface water levels (Lake Pontchartrain, Inner Harbor Navigation Canal, and the eastern wetlands). This contour map helps to explain the groundwater flow system of New Orleans: in general, surface-water systems surrounding the city (Lake Pontchartrain, the main canals/bayous, and the Mississippi River) act as infiltration (recharge) areas and the low, subsided areas in New Orleans (below mean sea level: New Orleans East, Lakeview, Gentilly, low-lying area south of MG Ridge, i.e. ‘the Bowl area’) act as regions of groundwater discharge. More specifically, New Orleans may be subdivided into six hydrogeological groundwater flow zones (Saucier 1994; Stuurman 2014; Table 5).

Lake Pontchartrain has not always been an infiltration area but has become one as a result of subsidence. The related decrease in groundwater level caused a 180° turn in the groundwater flow direction over the last century. Consequently, brackish salt water started to flow into the city of New Orleans. The outfall canals have also become infiltration areas. Consequently, most deeper groundwater is, or will become, brackish to salty (Fig. 18). The water level and salinity of the many isolated lagoons (former sand pits) in New Orleans East are consistent with this analysis: the water level in these sand pits are nearly a foot (30 cm) higher than canal levels and the salinity is nearly always equal to Lake Pontchartrain salinity (R. Stuurman, Deltares Research Institute, Netherlands, unpublished report, 2017).

Table 4 Descriptions of lithological sequence types and corresponding subsidence vulnerability (C clay, MSiC silty clay, SiCL silty clay loam, CL clay loam, LS loamy sand, SL sandy loam, L loam, S sand). Colors indicated in the far-left column indicate vulnerability to shallow subsidence and correspond with Fig. 14.

Litho-sequence No.	Lithological sequence type	Description	Subsidence vulnerability
1 (red)	Clay, organic clay, (decomposed) peat on sand/loam. 1a. sand > 150 cm below surface 1b. sand < 150 cm below surface	Floodplain deposits (mainly C–SiC–SiCL) that are partly organic, intercalated with gyttja and peat layers that are partly decomposed (crumbly, no fibers), on top of sandy and/or loamy deposits of the Pine Barrier Island. The clay is often soft. Decomposed peat thickness < 70 cm (within 160 cm below surface), total peat thickness < 100 cm	Vulnerable to subsidence due to oxidation and compaction (in general, the maximum subsidence potential is less for 1a compared to 1b, due to a thinner layer of the soft/organic material above the sand)
2 (red)	Clay, organic clay and peat, intercalated	Floodplain deposits (C–SiC–SiCL–CL) that are partly organic, intercalated with peat and gyttja layers. Clay layers are often soft. Peat occurs in most cases deeper than 150 cm below surface, with a maximum total thickness of 160 cm	Vulnerable to subsidence due to compaction
3 (orange)	Clay on organic clay and peat	Floodplain deposits (> 200 cm thick, consisting of C–SiC–SiCL–CL) on organic clay and peat. Total peat thickness < 40 cm	Vulnerable to subsidence due to compaction. Less vulnerable than sequence type 2 because the peat is generally thinner and more compacted already
4 (orange)	Clay and silt on organic clay	Natural levee deposits (> 100 cm, C–SiC–SiCL–CL–L) on organic floodplain deposits (C) that may be soft and may include thick (~ 10 cm) wood fragments, as well as thin (cm) peaty layers	Vulnerable to subsidence due to compaction. Less vulnerable than sequence type 3 because only thin peat layers occur
5 (orange)	Clay on silty/sandy deposits on organic clay	Floodplain deposits (100–200 cm; C–SiC–SiCL–C) on levee/crevasse deposits (LS–SL–S) on clay (C–SiC–SiCL) that is partly organic (thin layers of peaty clay/gyttja may occur)	Vulnerable to subsidence due to compaction. Somewhat less susceptible than sequence type 4 because the overburden is heavier (including sandy layers), hence more compaction has already occurred
6 (orange)	Clay	Floodplain deposits (C–SiC–SiCL–CL). Not organic, include both soft and firm clay intervals	Vulnerable to subsidence due to compaction of soft clay layers
7 (green)	Clay, silt and sand mixtures/intercalations	Natural levee and/or crevasse splay deposits (SiC–SiCL–CL–SiL–SL–L–LS). Predominantly loamy deposits. Organic clay intervals may occur	Some clay intervals may be vulnerable to subsidence due to compaction
8 (green)	Clay and silt on sand/loam	Natural levee and/or floodplain deposits (C–SiC–SiCL–CL–SiL–L) on Pine Barrier Island sand or other sandy loamy deposits (e.g. top of channel deposits). Depth of sand varies between 50 and 470 cm below surface	Low vulnerability to shallow subsidence
9 (green)	Fill	Anthropogenic fill consists mainly of sand but may also include clayey to silty layers	Low vulnerability to shallow subsidence

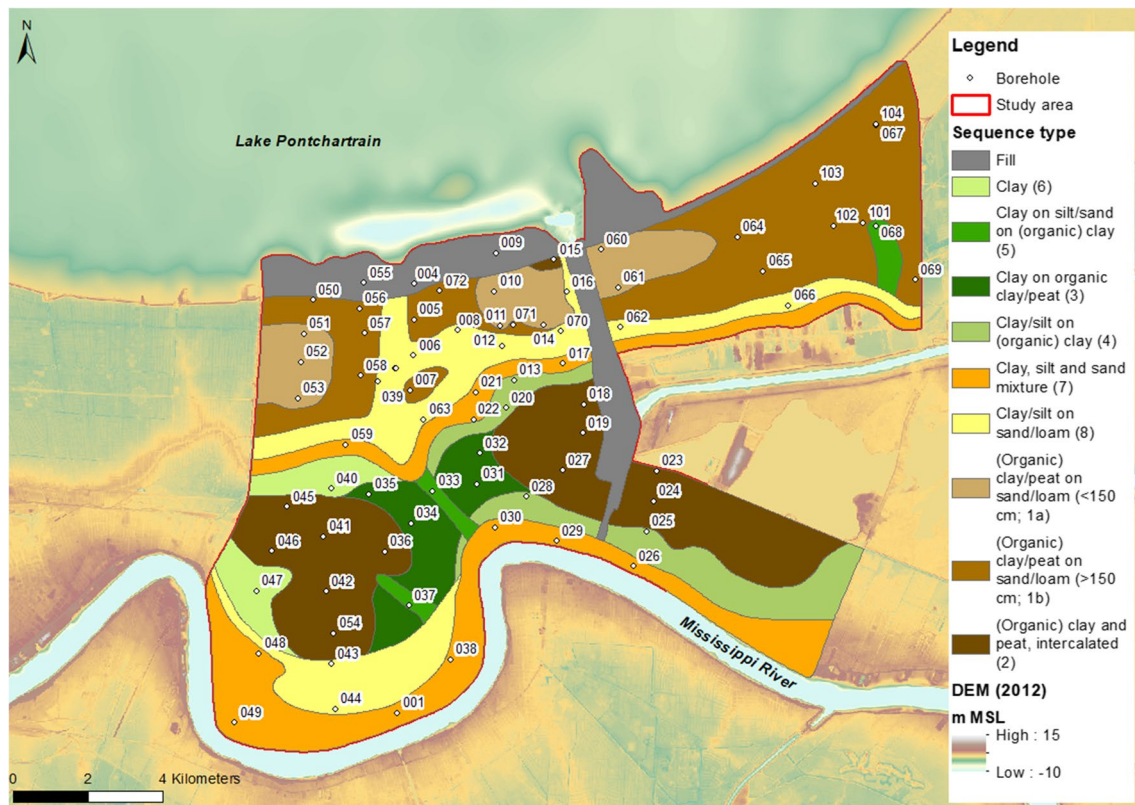


Fig. 13 Lithological sequence types, determined based on borehole information. The numbers in the legend correspond with sequence type classes in Table 4. Source: digital elevation model (OCM Partners 2017)

Discussion

Subsidence and subsidence vulnerability

The primary causes and rates of land subsidence in New Orleans vary in time and space (an overview is given by Kooi et al. 2019). Land subsidence rates in New Orleans and surroundings have been inferred from different data types including geological data (e.g., Törnqvist et al. 2008; Yu et al. 2012), geodetic leveling data (e.g., Shinkle and Dokka 2004; Dokka 2006, 2011), tide gauge and water level gauge data (e.g., Dokka 2011), GPS data (e.g., Dokka et al. 2006; Karegar et al. 2015), InSAR (Dixon et al. 2006; Jones et al. 2016; Kooi et al. 2019), extensometry, or surface elevation tables (SETs) data (Jankowski et al. 2017), and geophysical modelling (e.g., Wolstencroft et al. 2014). These studies, which primarily use data from rural and natural areas, demonstrate that land subsidence rates caused by natural processes, including isostasy, tectonics, and natural compaction of Holocene strata, are generally on the order of 10^{-1} to 10^0 mm/year. Anthropogenic-induced subsidence due to hydrocarbon and groundwater extraction, drainage, and surface loading is often an order of magnitude higher, locally causing rates up to ~50 mm/year (Kooi et al. 2019).

Human-induced subsidence rates estimated in the present study are consistent with these earlier findings (further explained in the next sections). Regarding subsidence vulnerability, two main areas have been distinguished that, noting their present elevation below MSL, have already experienced substantial land subsidence: north of the MG Ridge, where peat and humic clay occur especially close to the surface, and south of the MG Ridge, where peat and humic clay generally occurs at greater depth.

Area north of Metairie-Gentilly Ridge

Comparing the detailed lithostratigraphic cross sections constructed in this study with older lithostratigraphic cross sections constructed in the 1950s (USACE 1958; an example is given in Fig. S3 in the ESM) reveals that a substantial proportion of the shallow peat in the area north of the MG Ridge has disappeared over the last several decades. For example, in ~70 years, the surface level of Lakeview has subsided about 2.2 m: from about 0 m MSL in the 1950s (Fig. S3 in the ESM; approximately the midpoint of the cross section), to a present elevation of ca. -2.2 m MSL (boreholes 51 and 52 in Fig. 7). The peat layer has reduced in thickness from about 3 m in the 1950s to a present thickness of

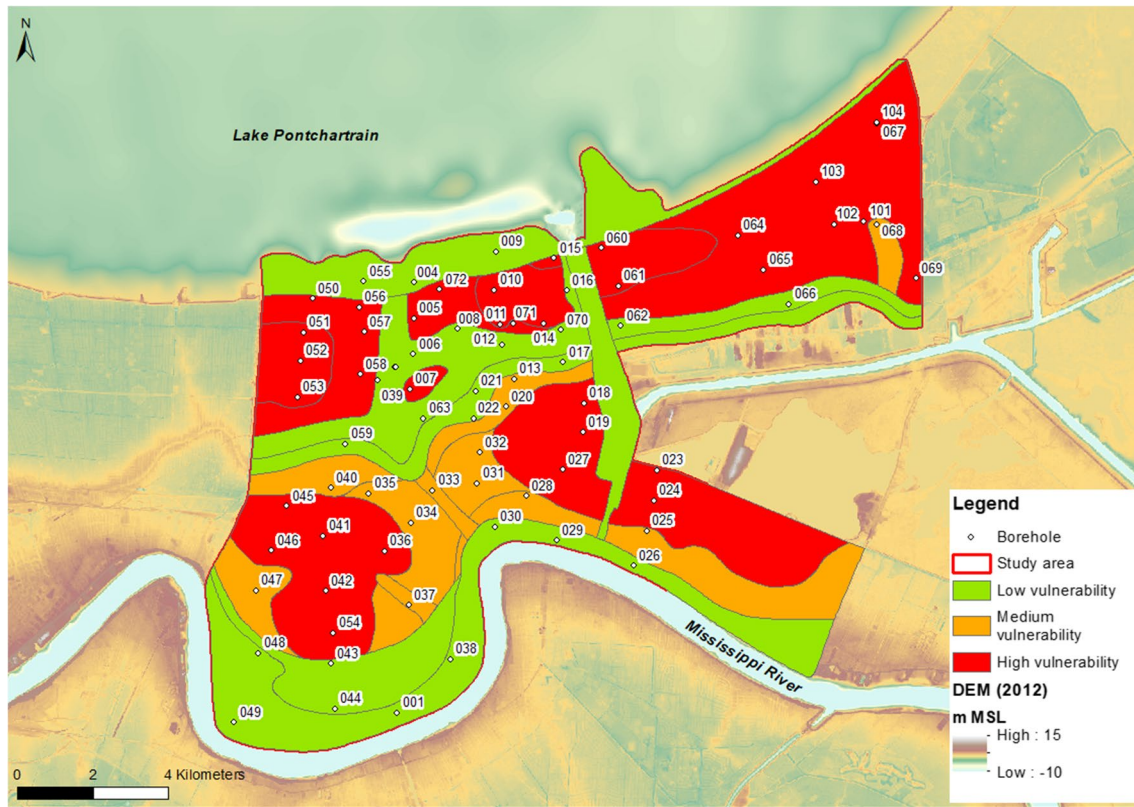
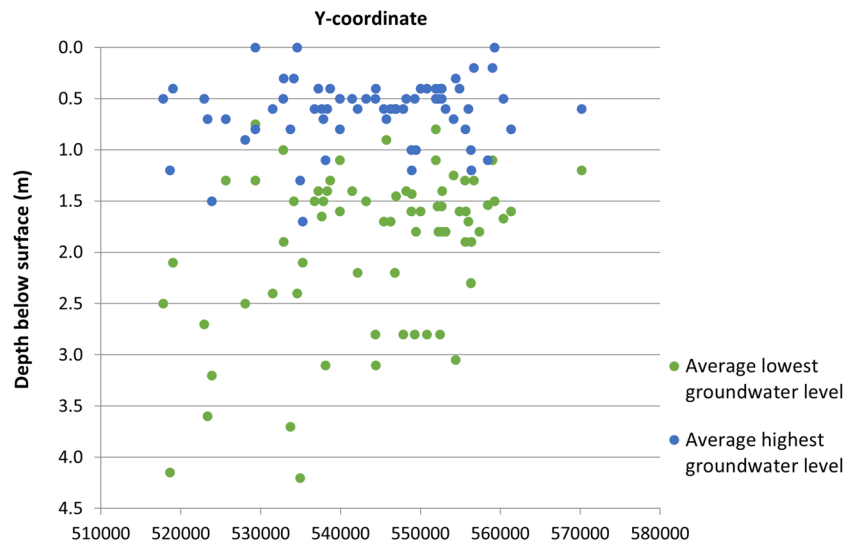


Fig. 14 Shallow-subsidence vulnerability, determined based on the lithological sequence type (Fig. 13 and Table 4). Red = litho-sequences 1 and 2; orange = litho-sequences 3–6; green = litho-sequences 7–9. Source: digital elevation model (OCM Partners 2017)

Fig. 15 Average lowest and highest groundwater levels relative to surface level recorded for each borehole. The X-axis gives the Y-coordinate (indicating the north–south position in study area) of the borehole, using the Louisiana South State Plane Coordinates (EPSG: 3452)



~0.7 m (Fig. S3 in the ESM and Fig. 7, respectively). The loss of elevation corresponds with an average subsidence rate of ~30 mm/year, which is much higher than earlier-reported natural land subsidence rates but is in accordance with previously presented human-induced subsidence rates (e.g., Kooi et al. 2019). Presumably, the elevation loss has

largely been caused by peat oxidation in this area where peat occurs at shallow depth and therefore is highly susceptible to oxidation following drainage. Peat oxidation is an important process causing shallow land subsidence in many other peat-rich deltas as well, both in rural and urban areas. For example, for the rural areas of the Rhine-Meuse

Fig. 16 Average lowest and highest groundwater levels relative to mean sea level (MSL) recorded for each borehole. The X-axis gives the Y-coordinate (indicating the north–south position in study area) of the borehole, using the Louisiana South State Plane Coordinates (EPSG: 3452)

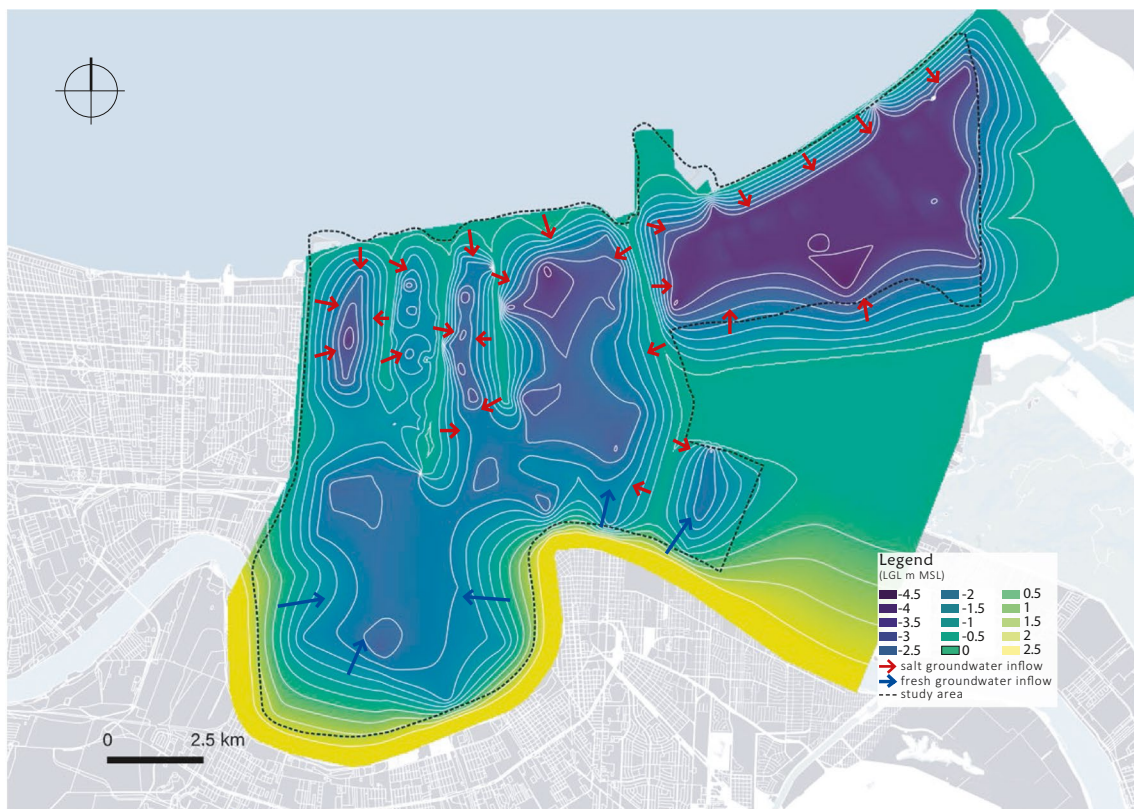
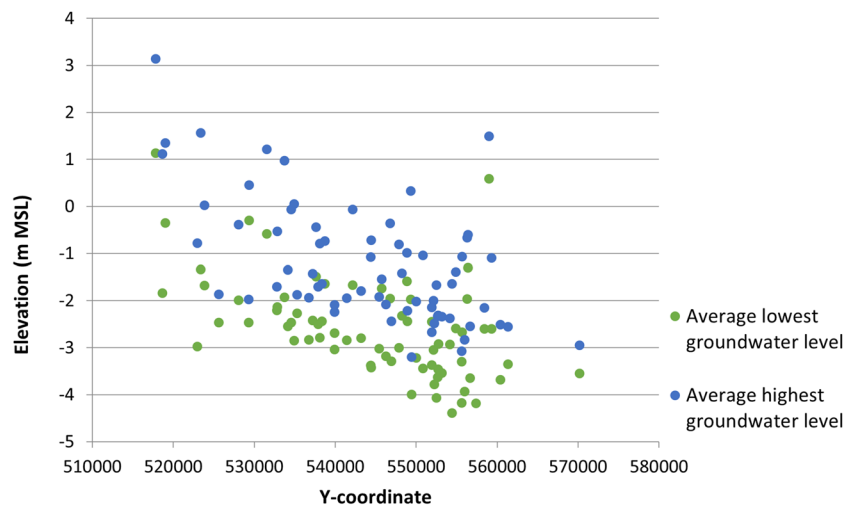


Fig. 17 Average lowest groundwater level and directions of salt and freshwater flow (LGL average lowest groundwater level)

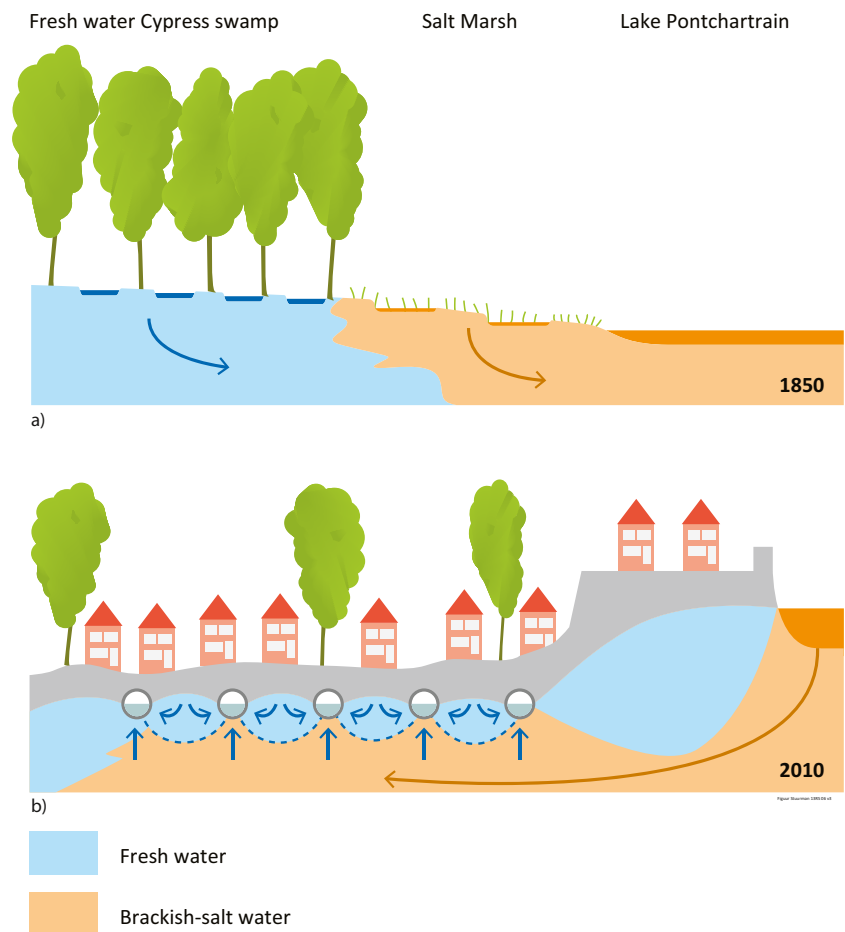
Delta (the Netherlands) with peat soils, a spatially averaged total subsidence due to drainage of 1.9 m over the last millennium was estimated by Erkens et al. (2016). Of this total subsidence, 70% was ascribed to peat oxidation. In the Sacramento-San Joaquin delta (USA), drainage and cultivation of delta soils since 1850 has resulted in subsidence on over 60 islands, with magnitudes ranging from 1 to over 8 m due to oxidation, consolidation and shrinkage (Deverel and

Leighton 2010; Deverel et al. 2016). In built-up areas, previous studies demonstrated that peat oxidation may cause part of the land subsidence in peat-rich areas (Van Asselen et al. 2018). The observed subsidence is likely also caused in part by compaction of peat and clay following a reduction in pore water pressure due to phreatic groundwater-level lowering. Lowered pore water pressure causes a higher effective stress in the soil profile (= total weight – water pressure; Terzaghi

Table 5 Six hydrogeological groundwater flow zones of New Orleans

Zone no. (recharge/discharge area)	Zone description	General characteristics	(Ground-)water flow
1 (recharge)	Mississippi River	The navigable channel is 12–15 m deep, with local depths of up to 60 m. The water level at New Orleans city is on average 3.5 m above mean sea level. The lowest and highest river water levels measured are ~0.3 and 6 m NGVD (National Geodetic Vertical Datum of 1929; RiverGages.com). These water levels are always higher than the groundwater levels in the adjacent urban zones	The sandy Mississippi channel body is an important (freshwater) infiltration area for the urban shallow and deeper groundwater system of New Orleans. The relative high river level determines the hydraulic head in the silty and clayey natural levee zone along the river
2 (recharge)	Mississippi natural levee zone	The natural levee zone adjacent to the river is elevated up to ~5 m above mean sea level and is ~1.5–3 km wide and generally covered by a (silty) clay layer. Northwards, the surface level gradually falls.	Local infiltrated rainfall is drained by the leaking sewer and storm drainage pipes. Perforation of the covering clay layer that occurred during construction activities may cause groundwater flooding, especially during high river water level (only close to the relatively high Mississippi level)
3 (discharge)	Lower basin-shaped ('the Bowl') area between Mississippi levee and Metairie-Gentilly ridge	This zone is partly below mean sea level. The soil consists mainly of peaty freshwater marsh deposits. The 'bowl' morphology has increased through time due to subsidence, causing this zone to be vulnerable to urban flooding	This is mostly a groundwater discharge area. Infiltrated rainwater, drinking water loss, and groundwater discharge are drained by leaking wastewater and storm drainage pipes
4 (recharge)	The Metairie-Gentilly Ridge	An abandoned natural river channel that is visible as a long ridge in the landscape but forms a barrier for surface-water drainage of the area to the south	This zone acts as a (shallow) groundwater infiltration area. Infiltrated rain (and drinking water) flows largely in the northern direction and exfiltrates in the southern part of zone 5
5 (discharge)	Lakeview, Gentilly, New Orleans NO	Located largely below sea level with peat-like ground and sandy Pine Barrier deposits located mostly below the surface. In predrainage times, most parts of this zone were covered by freshwater cypress swamps. The north part was salt-brackish marsh. The area subsided several meters during urbanization over the last 100 years, especially directly after the onset of drainage	A groundwater discharge area. Along the canals and Lake Pontchartrain this groundwater discharge is brackish-salt. Infiltrated rainwater, drinking water loss, and groundwater discharge is drained by leaking wastewater and storm drainage pipes. In New Orleans East, open canals also support groundwater drainage. This zone is highly vulnerable to pluvial flooding
6 (recharge)	Lake Pontchartrain, Bayou St. John, Inner Harbor Canal and outfall canals	Lake Pontchartrain is 3–4 m deep on average. It is linked directly to the Gulf of Mexico and thus is brackish/saline (2,500–5,500 mg/L chloride). The city's (outfall) canals are in open connection with the lake	Lake and canals are infiltrating bodies. Brackish salt groundwater flows towards the city. Most of this water is drained by the leaking pipes below the streets adjacent to the shore and canals and back into the lake

Fig. 18 Reversing of the groundwater flow direction in New Orleans. Consequently, deeper groundwater is becoming brackish to saline. Scenarios in **a** 1850 and **b** 2010



1943) and therefore soil compaction: the weight of the soil above a certain subsurface level is carried less by pore water and more by the soil matrix. In general, the relative contribution of peat compaction and oxidation to subsidence varies in time and space (Van Asselen et al. 2018): if a peatland is drained, the drop in pore water pressure in the top layer will initially mainly cause compaction, due to a sudden increase in effective stress. Through time, the rate of compaction slows down as overpressured pore water is expelled, after which compaction is mainly caused by creep, a soil mechanical process of densification due to rearrangement of soil particles over long time periods. Continued drainage results in the contribution of oxidation being larger than compaction. In built-up areas, however, substantial anthropogenic loading has caused a shift to relatively more subsidence due to compaction.

The area north of the Metairie-Gentilly Ridge is still especially vulnerable to subsidence due to peat oxidation because of the occurrence of several decimeters-thick peat layers occurring at shallow depths, above, at and just below the average lowest groundwater level. These peat layers are already partly decomposed by oxidation but may still have a relatively high organic content (Figs. 11 and 12). Subsidence

due to oxidation of up to ~40 cm is estimated based on thicknesses of peat layers presently occurring above the average phreatic groundwater levels (Table 2). However, there may be centimeters to decimeters more subsidence if groundwater levels are further lowered in the future due to droughts, groundwater level lowering, or continued drainage by leaking pipes. Continued subsidence is expected to occur in areas where substantial peat occurs at shallow depth and where (Pine Barrier) sandy or loamy deposits occur at relatively great depth or are lacking (sequence type 1b in Fig. 13). Additionally, anthropogenic loading may further increase subsidence in this area.

Area south of Metairie-Gentilly Ridge

In the area south of the MG Ridge, peat and organic clay mostly occur at greater depth, generally below the average lowest groundwater level. As a result, these soils are less prone to oxidation compared to organic soils north of the MG Ridge. Instead, shallow subsidence in this area has largely been caused by peat and clay compaction due to loading in combination with an increase in effective stress following groundwater level lowering. One of the 1950s

cross sections (D–D'; USACE 1958; not included in this paper) runs east–west and crosses the study area in the vicinity of borehole 41 (Fig. 6). The present surface elevation at this borehole location is about -1 m MSL (Fig. 6), while the surface elevation in the 1950s was about 1.5 m MSL (cross section D–D' in USACE (1958) and Van Asselen et al. (2020)). This change in elevation implies a similar subsidence rate in this area as was estimated for the area north of the MG Ridge: ~ 35 mm/year.

The area south of the MG Ridge still is especially susceptible to subsidence due to peat (and clay) compaction, caused by the weight of overlying organic and sediment layers and by anthropogenic loading. The estimated average compaction grade of 31% (for the entire study area) indicates that there is still substantial potential for future subsidence due to peat compaction in the study area (centimeters to decimeters, Table 3). Further lowering of the groundwater level increases the load carried by the soil matrix leading to soil compaction. In addition, peat positioned just below the average groundwater level is also vulnerable to oxidation in case the groundwater level is lowered further.

In addition to organic layers, soft clay layers occur throughout New Orleans' most vulnerable areas. Soft clay is generally found at depths greater than 1 m below surface level. The thickness of soft clay layers varies between 0.2 m and more than 4.5 m. These layers are also vulnerable to compaction due to loading, and hence, contribute to the overall vulnerability to subsidence due to compaction.

Land subsidence in relation to (geo)hydrology

This study demonstrates that past and present water management in the city of New Orleans has been an important factor contributing to shallow land subsidence. Historical drainage for logging and city development as well as present drainage by leaking (storm drainage and sewage) pipes has caused land subsidence due to peat oxidation and compaction. To resist negative effects of soil movement, most pipes are connected using flexible geotextile slabs (Waggoner and Ball 2013; Stuurman 2014), which protect against the inflow of sand but are permeable for groundwater. Consequently, during the time that the groundwater level is above the depth of the pipes, which are mostly situated ~ 1.5 m below surface, this system drains groundwater. Moreover, many pipes, including wastewater and drinking water pipes (Nougues 2021; Nougues and Stuurman 2022) are damaged due to soil movement and insufficient maintenance, and hence are leaking, meaning the drinking water losses are a source of groundwater recharge, but a large part of this lost drinking water is drained by the adjacent sewer and stormwater drainage pipes. During rain storms or rain periods, groundwater levels may increase several decimeters up to more than 1 m, but are usually quickly lowered to prerin groundwater levels

as a result of the effective drainage system (Fig. S4 in the ESM). On a larger scale, land subsidence has affected the hydrological system by causing a reversal of the groundwater flow direction, which resulted in the salinization of the deeper groundwater level (Fig. 18).

Perspectives for subsidence-sensitive urban planning

In this study, the potential for future subsidence of centimeters to decimeters has been assessed. Continued subsidence will make the city of New Orleans even more vulnerable to flooding, especially as sea-level rise accelerates. To deal with shallow subsidence, both adaptation and mitigation strategies may apply outcomes of this study—for example, the subsidence vulnerability map (Fig. 14) identifies areas that have high and low risk for shallow subsidence. This information, and underlying subsurface (sequence type) information, may be used to decide which areas are suitable for new building projects (firm sandy soils), and which are not (soft peat and clay soils). Moreover, results of this study indicate hotspot subsidence areas, where mitigation strategies could be applied, which may include raising the phreatic groundwater level through drainage system improvement.

This study identified spatially variable causes of subsidence in the city of New Orleans, quantified subsidence, and made a first assessment of the vulnerability for future subsidence. Measuring subsidence and understanding mechanisms are crucial first steps to address land subsidence, following the 6M policy cycle approach (Erkens and Stouthamer 2020). This 6M approach provides guidance for decision makers on how to deal with land subsidence and its negative impacts. These first steps are also important for raising awareness about land subsidence (Deltares 2013). The next steps of the 6M policy cycle are *modelling* of subsidence, *cost-benefit analysis* ('money'), *implementing measures*, and *monitoring effects* of subsidence measures. Key issues to be addressed to deal with subsidence are proposed in Van Asselen et al. (2020, see also Deltares 2013).

Conclusions

Based on the present study it is concluded that:

- A substantial part of the surficial peat occurring north of the MG Ridge has been oxidized since the 1950s, driving average subsidence rates of 30 mm/year. The total remaining peat thickness in this area is generally <1 m. Peat above the average lowest groundwater level is largely decomposed but may still have a relatively high organic content. Peat occurs above, at, or just below the average lowest groundwater level, making

this area still vulnerable for future subsidence due to peat oxidation and, to a somewhat lesser extent, peat compaction due to loading and/or a drop in pore water pressure following groundwater level lowering.

- In large parts of the area south of the MG Ridge, peat occurs at greater depths below surface. This area is therefore especially vulnerable to subsidence due to peat compaction and is less prone to subsidence due to peat oxidation as compared with the area north of MG Ridge. Here, subsidence rates of ~35 mm/year have occurred over the last 70 years.
- Areas where the subsurface contains abundant soft clays, possibly with intercalated peat layers, remain vulnerable to subsidence due to compaction. Sandier areas are less vulnerable to subsidence and in turn are assigned a lower risk level category.
- In the city of New Orleans, peat has been compacted ~31% on average, with a range of 9–62%. Continued subsidence due to peat compaction is expected.
- During dry periods, average groundwater levels drop to ~150 cm below surface levels and during wet periods, average groundwater levels increase to ~50 cm below surface.
- Past and present water management in the city of New Orleans has been an important factor contributing to shallow land subsidence: drainage for logging and city development, and drainage by (leaking) stormwater drainage, wastewater, and drinking water pipes have resulted in land subsidence. Subsequently, land subsidence affected the hydrological system by reversing the groundwater flow direction and thereby causing salinization of the deeper groundwater level.
- This study is a crucial first step to address urban land subsidence, and provides support for decision makers in dealing with subsidence risks.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10040-023-02762-y>.

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Declarations

Conflict of interest statement Conflict of Interest: The authors declare that they have no conflict of interest.

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