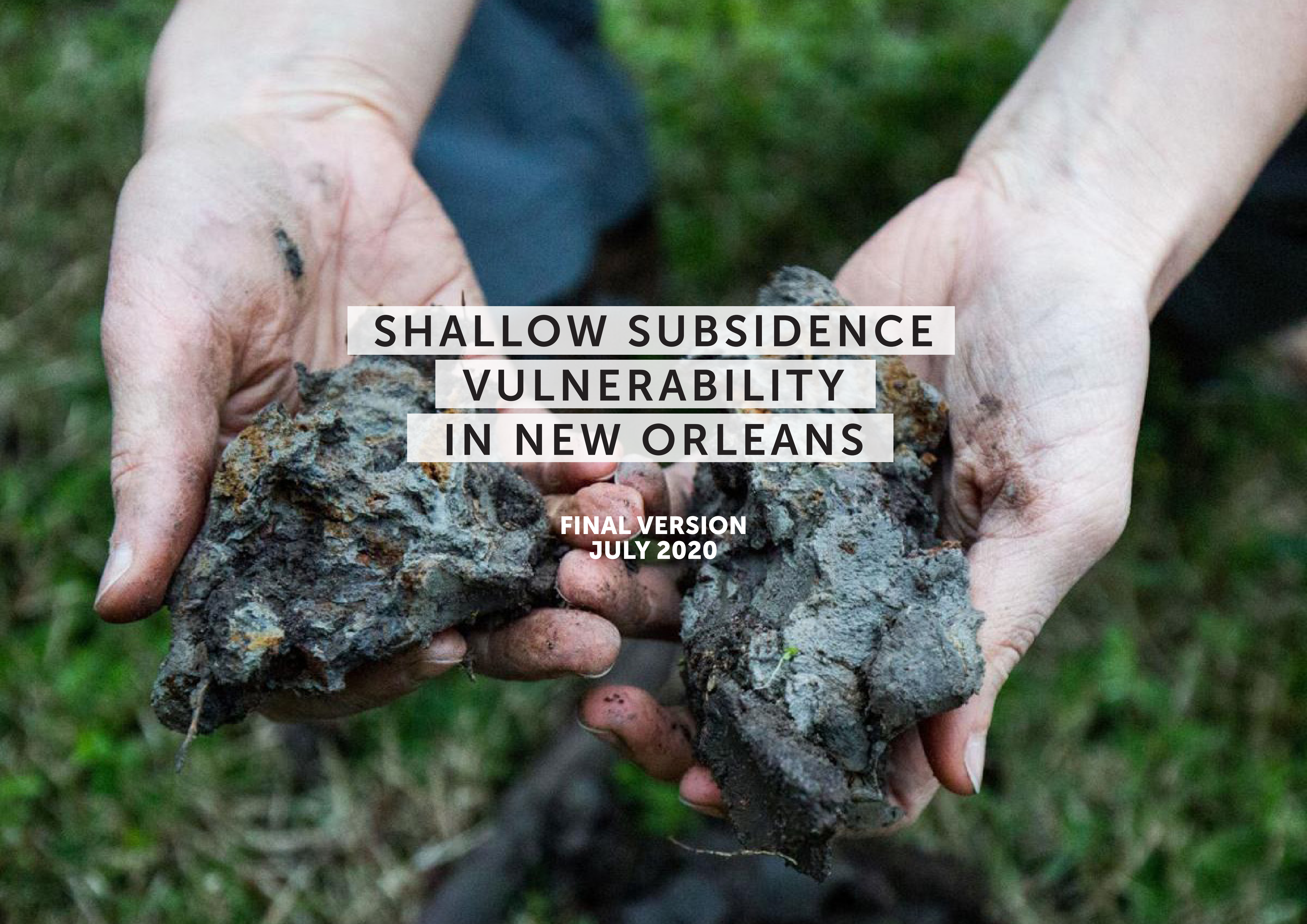

# SHALLOW SUBSIDENCE VULNERABILITY IN NEW ORLEANS

FINAL VERSION
JULY 2020

Authors:

Sanneke van Asselen (Deltares, geology)
Begoña Arellano Jaimerena (Deltares, report editing and urban planning)
Roelof Stuurman (Deltares, groundwater and project organization)

Geology field work team:

Ryan Clarke (Tulane University)
Molly Keogh (Tulane University)
Torbjörn Törnqvist (Tulane University)
Udita Mukherjee (Tulane University)
Nameera Islam (Tulane University)
Alex Kolker (LUMCON)
Gilles Erkens (Deltares)
Marc Hijma (Deltares)
Peter Vos (Deltares)
Chris Rutland (Batture, leveling)

Otto Levelt (Deltares, geographical data analysis)

Tyler Antrup (Former City of New Orleans, project leader. Now, Director of Planning + Strategy at SWBNO )
Mary Kincaid (City of New Orleans, Senior Project Manager)

Utrecht, The Netherlands
July, 2020

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# SHALLOW SUBSIDENCE VULNERABILITY IN NEW ORLEANS

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FINAL VERSION
JULY 2020

Deltares
Enabling Delta Life

Tulane University

CITY OF NEW ORLEANS
MAYOR LATOYA CANTRELL

Resilience + Sustainability
CITY OF NEW ORLEANS

**Gentilly Resilience District**
Planning & Design Convening

# CONTENT

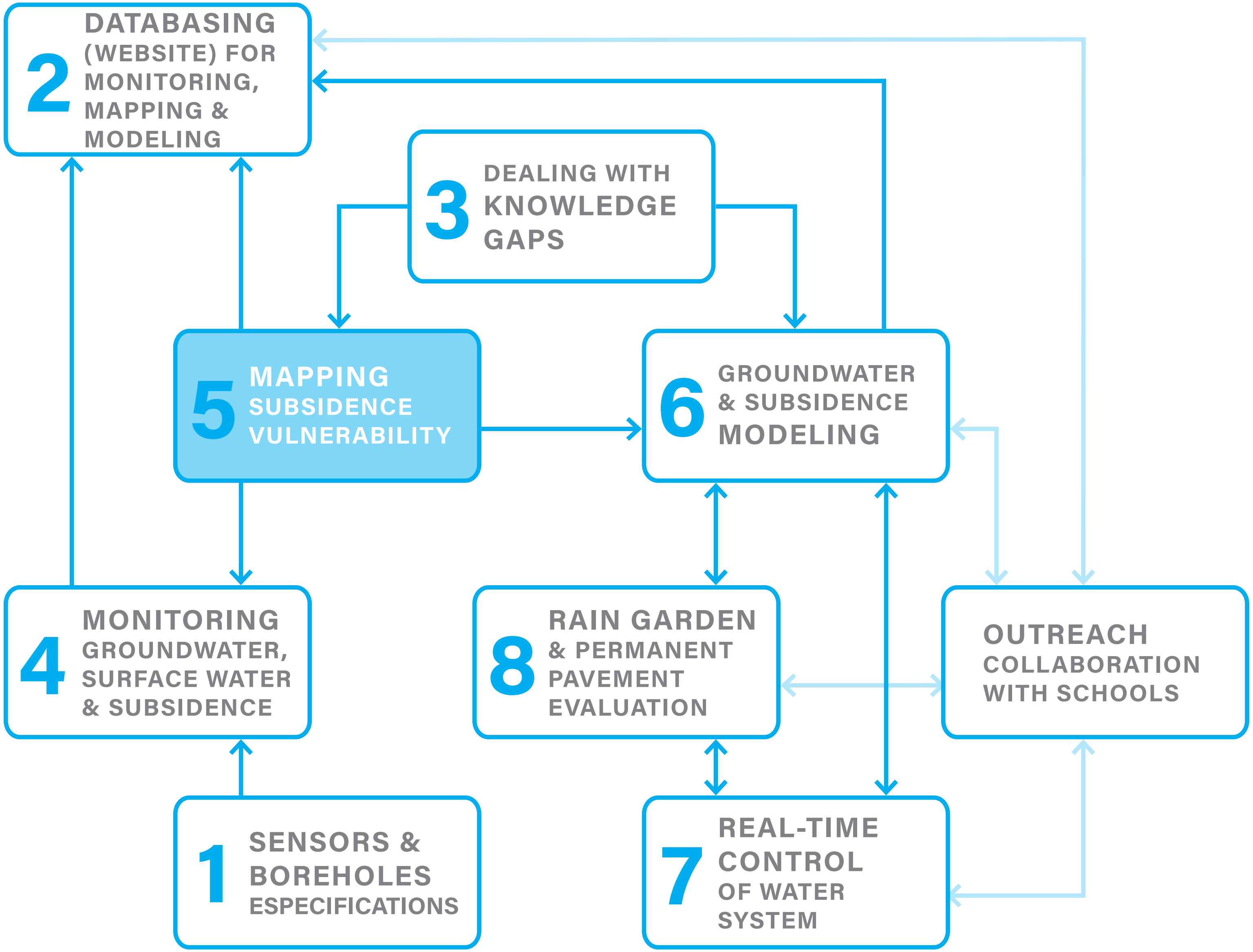


*Figure 1.1. Phases of the project*

# 1.INTRODUCTION

New Orleans is located in the low-lying Mississippi delta and is vulnerable to subsidence, sea-level rise, and in turn, flooding. The oldest parts of the city were built in 1722 on relatively stable and elevated ground formed by natural levees of the Mississippi River. 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 caused land subsidence due to oxidation (degradation) and compaction of soft organic soils (Figure 1.2). Droughts may also cause subsidence due to peat oxidation, when groundwater levels drop and peat is exposed to air. A large part of the city is now below mean sea level (MSL). With ongoing subsidence and sea-level rise on the one hand, and a predicted increased in intensity and frequency of droughts, rainfall events and hurricane systems on the other, the risk of flooding and subsequent societal disruption is increasing. To make the city more resilient to future flooding a new approach to groundwater and subsurface management for New Orleans is needed.

To develop an approach such as this, high-quality and high-resolution subsurface and groundwater data are needed. This information is currently largely lacking and, even if present, is not readily available for the city. Detailed information on geology, hydrology and soil characteristics in the city can be used to effectively design tailor-made measures to limit urban flooding and subsidence. One example of such a measure is installing green infrastructure to increase infiltration of rainwater in the subsurface. Another example is increasing groundwater levels to reduce subsidence by oxidation of organic soils, which occurs mainly above the groundwater level where organic soil is exposed to air.

The project ‘Reshaping the Urban Delta’, funded by the National Disaster Resilience Competition (NDRC), aims to deliver groundwater and subsurface insights and data which will help the planning of initiatives that increase flood resilience and can be used in the design of the same initiatives. The project consists of eight subprojects (see Figure 1.1). A first step towards making New Orleans more resilient to urban flooding is to design a monitoring network to measure water levels, precipitation, water quality and subsidence (**subprojects 1 & 4**). This provides information on spatial and temporal trends in groundwater flows and subsidence, which is needed to design effective measures to limit urban flooding and subsidence. The monitoring data will be stored within a database making all the collected information available for the City and the public (**subproject 2**). Existing knowledge and knowledge gaps on soil conditions and groundwater dynamics in New Orleans will be identified in **subproject 3**. A shallow subsidence vulnerability map will be produced based on geologic and groundwater information collected from shallow boreholes distributed over the entire city (**subproject 5**). In addition to the shallow subsidence, the extraction of groundwater at greater depth (more than 50 meters) is likely to contribute to subsidence as well. A major difference with regards to the shallow component is the scale on which this happens (generally a smaller area is subsiding at greater rates) and the impact it has on all kinds of infrastructure. Therefore, a 3D deep groundwater-subsidence model will be constructed using existing and new cross sections and borehole information (**subproject 6**). This model will be used to analyze groundwater flow, salinization risks, subsidence, climate change impacts, and effects of deep groundwater pumping. **Subproject 7** investigates the potential benefits of real-time control of urban water system using weather forecasting. In **subproject 8** the costs and water storage efficiency of existing rain gardens and permeable pavements will be analyzed. A user-friendly performance quantification tool will be produced.

This report focuses on subproject 5: the design of a shallow subsidence vulnerability map based on geologic and hydrologic information of the shallow subsurface. This information was collected in November 2018 by a team of hydrogeologists of Deltares (NL) and Tulane University (USA). In total, 72 boreholes distributed over the entire city were manually drilled to a maximum depth of 6 m (with an average depth ranging between 3-4 m). Methods used to reveal the subsurface composition, groundwater level information, and dry bulk density and organic matter content characteristics of peat and organic clay are described in Chapter 2. Results of an analysis of historic topographic maps and of digital elevation data are described in Chapter 3 and 4 respectively. Next, geologic and groundwater information collected during the November 2018 field study are described in Chapter 5 and 6 respectively. The subsidence vulnerability map is presented in Chapter 7.

Findings and recommendations for urban planning are provided in Chapter 8 and 9 respectively.

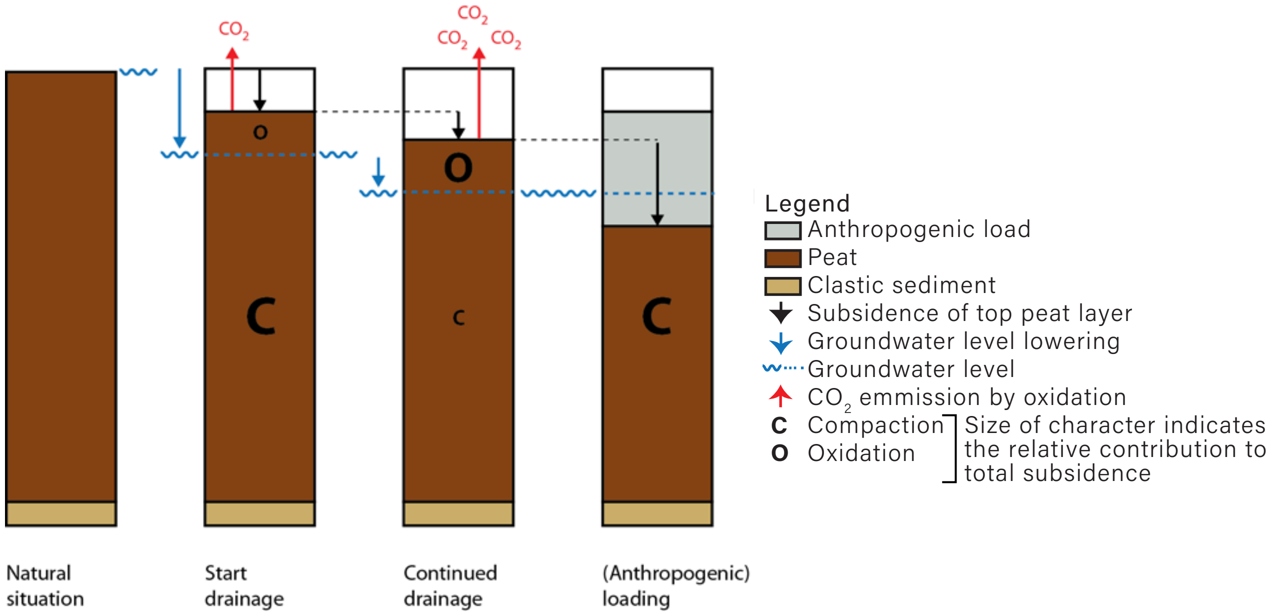


*Figure 1.2. Schematic figure representing land subsidence due to peat oxidation (O) and compaction (C). Just after the start of drainage for land reclamation, the relative share of compaction to total subsidence is large, because the weight of the drained top layer is now fully carried by the underlying organic layer. The relative share of peat oxidation, ocurring mainly above the groundwater level where peat is exposed to air, increases during continued drainage. Peat oxidation results in emmission of* $CO_2$*. If an additional load is added at the surface, subsidence is mainly caused by peat compaction.*

# 2. METHODOLOGY

After collecting and studying existing urban geologic information, the first step in creating a shallow subsidence vulnerability map for New Orleans was to reconstruct the subsurface composition and phreatic (shallow) groundwater level fluctuations. For this, geologic and groundwater data was collected during one-week of fieldwork in November 2018, carried out by Deltares in cooperation with Tulane University. In addition, the history of the subsidence in New Orleans is disclosed based on an analysis of historical topographic maps and related literature. Borehole information collected during fieldwork was then used to construct cross sections of the subsurface and create a map of typical geological sequences. This sequence type map, in combination with groundwater level information, is then used to create a subsidence vulnerability map. The results of the field campaign are compared with subsidence rates derived from recent elevation data (InSAR and LiDAR).

## 2.1 Fieldwork

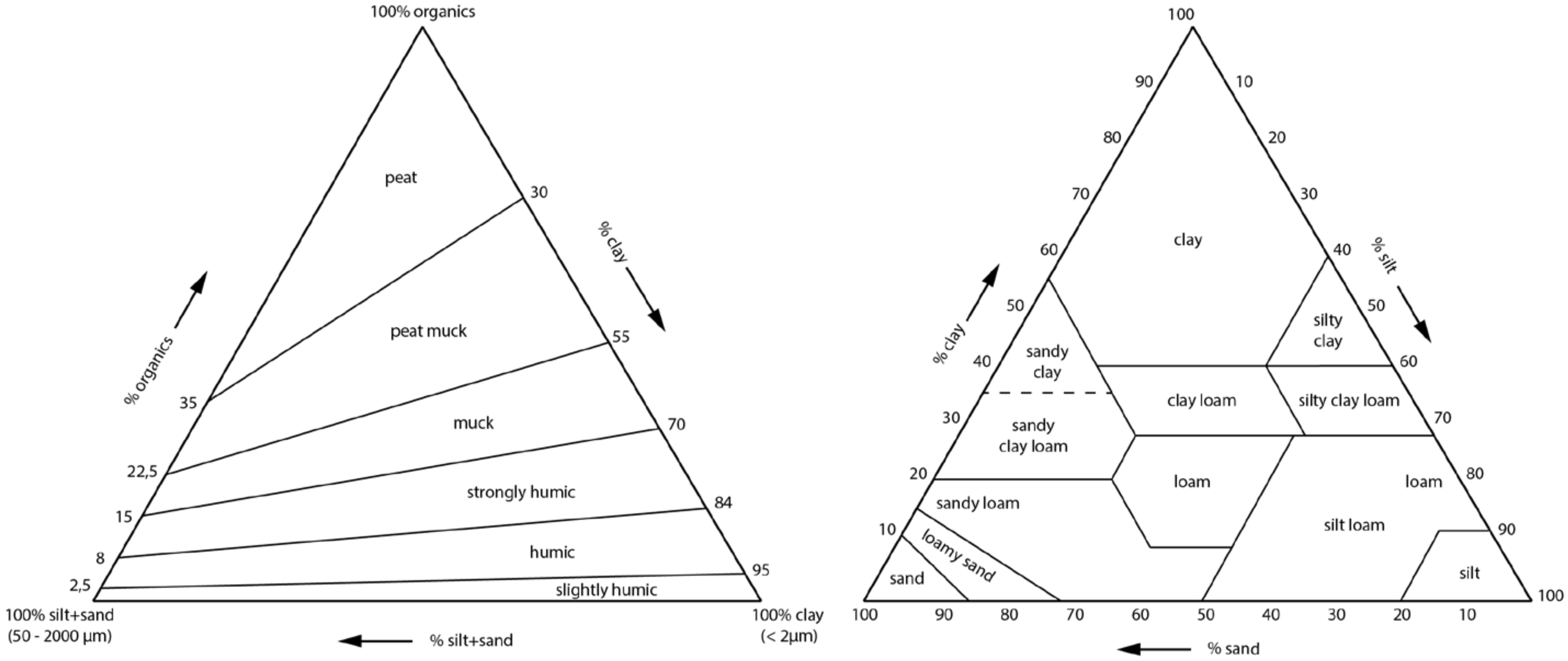
### *Subsurface composition*

To reveal the shallow subsurface composition, 72 shallow boreholes were manually drilled using both Edelman and gouge hand augers. Borehole locations were determined based on topography and accessibility, ensuring an even spatial distribution over the entire East bank of the city. The majority of boreholes are located in low-laying 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 are located at higher elevation locations such as natural levees, crevasse splays, and fills. To circumvent accessibility restrictions, borehole locations were strategically planned in public parks and vacant lots.

Average borehole depths fell within a range of 300 to 400 cm with a maximum depth of 600 cm. Retrieved cores are described at 10 cm intervals. Peat is described based on botanical composition (e.g., wood, sedge and/or reed remains), color and organic-matter content. Within the samples, three organic-matter classes are distinguished: peat, peat muck, and muck. In addition, three humic classes for clastic sediment are distinguished: very humic, humic, slightly humic (Figure 2.1). The organic-matter content was estimated 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 case of peat, smooth in case of clay). Clastic sediments were classified in the field using the USDA texture classification system (Figure 2.1), and later reclassified into grouped classes based off the United Soil Classification System (USCS; Table 2.1). This was done to make results comparable with existing deeper cross sections of the study area already classified using this system. Clastic sediments were described based on presence of plant remains, color, oxidation/reduction characteristics (Figure 2.2), and other relevant properties such as the occurrence of laminations, shell fragments, etc. All borehole locations are levelled (X, Y and Z position, RTK measurements) by a land surveyor from Batture Engineering, using the Louisiana South State Plane Coordinates (epsg: 3452) system and the NAVD88 elevation datum.

### *Groundwater levels*

The land surveyor also measured the actual groundwater table in the borehole using an acoustic groundwater sampler at least 1 day after coring. The lowest and



A

B

*Figure 2.1. Classification of peat and humic clays based on organic matter content (A), USDA texture classification (B)*

| USDA | USCS |
|---|---|
| Peat | Peat |
| Pat muck | Peat |
| Muck | Peat |
| Very humic | Organic |
| Humic | Organic |
| Slightly humic | Organic |
| Clay | Clay |
| Silty clay | Clay silt, silty clay |
| Sandy clay | Sandy clay, clayey sand |
| Clay loam | Clayey silt, silty clay |
| Silty clay loam | Clayey silt, silty clay |
| Sandy clay loam | Sandy clay, clayey sand |
| Loam | Silty sand, sandy silt |
| Silt loam | Silty sand, sandy silt |
| Silt | Silt |
| Sandy loam | Silty sand, sandy silt |
| Loamy sand | Silty sand, sandy silt |
| Sand | Sand |
| Very fine sand | Sand |
| Fine sand | Sand |
| Medium sand | Sand |
| Coarse sand | Sand |
| Very coarse sand | Sand |

*Table 2.1. Translation of USDA classes into 8 grouped USCS classes.*

highest groundwater levels are determined based on oxidation and reduction characteristics observed in the core. 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 (Image 2.1), below surface, indicates the lowest average groundwater level that has occurred at this specific location (Figure 2.2) Above this level, iron oxidation has taken place by oxygen intrusion. Reduction occurs when the soil is waterlogged, and results in greyish-colored stains. The shallowest level where reduction stains occur indicates the highest average groundwater level.

### *Sampling method and compaction calculations*

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 are determined. These intervals are sampled in the field, directly from a gouge auger. The core in the gouge was first cut in half lengthways using a thin wire to allow sampling of the inner, least disturbed, part of the core (Image 2.2). The peat and organic intervals are sampled (max 4 samples per core) using a 1 cm x 1 cm x 5 cm peat sampler. Samples are wrapped in plastic foil and carried to the lab of Tulane University in small cylinder-shaped plastic pots with screw-cap. In the lab, each 5cc sample is oven-dried at 105˚C for 24 hours and weighed on an electronic scale (accuracy of 0.001 g) to determine the dry bulk density (=dry weight / 5 $cm^3$). Subsequently, the samples are heated at 550˚C for 4 hours to determine Loss On Ignition

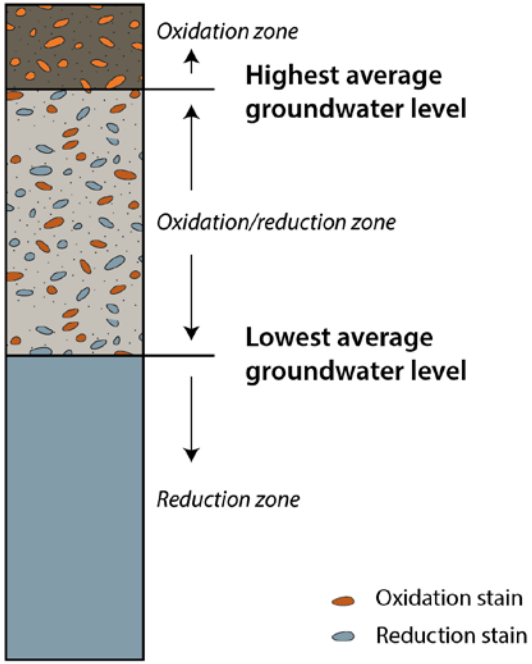


*Figure 2.2. Schematic representation of oxidation and/or reduction zones in the subsoil, used to determine the lowest and highest average groundwater level.*


*Image 2.1. Sample of oxidation in the subsoil.*

(LOI = ((dry weight – ashed weight)/dry weight) x 100%); cf. (Heiri et al., 2001)), which is a measure for the organic matter content.

The amount of compaction of the samples is assessed by comparing the dry bulk density ($\rho$) 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 (Image 2.3 method of van Asselen, 2011). The fresh peat data (n = 139) are derived from the Coastwide Reference Monitoring System (CRMS) project. Both the compacted and fresh peat data series are 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 calculate the dry bulk density for a specific organic-matter content. Next, the amount of compaction of a 5 cc sample can be determined by calculating the decompacted thickness of ($h_{decomp}$) a 5 cc sample, using:

$$h_{decomp} = ((\rho_{comp} / \rho_{fresh})*5),$$

*Image 2.2. Sampling an organic interval using a 1 cm x 1 cm x 5 cm sampler.*

*Image 2.3. Location (red dots) of CRMS sites from which fresh peat data (dry bulk density and organic matter content) are obtained. Source Landsat 7 satellite on April 26, 2000 (next page) >*

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

Compaction = $(h_{decomp} - 5/h_{decomp})*100\%$

## 2.2 Analysis of digital data and literature

### *Historic maps*

The history of drainage development in New Orleans has been visualized based on historic topographic maps from 1800's onwards. Geographic units are derived from the historic maps, mainly showing the development of built-up area and the sinking of parts of the city below mean sea level in time.

### *LiDAR and InSAR elevation data*

Light Detection And Ranging (LiDAR) is a method that uses light (pulsed laser) to measure the distance from a laser scanner attached to a helicopter, aircraft or drone to a target object or surface. The distance is derived from the time needed for a pulse to travel to the target and back to the scanner. Measurements result in a gridded map of surface elevation. Interferometric Synthetic Aperture Radar (InSAR) uses radar images to generate maps of surface deformation by comparing changes in elevation at specific points over time. This method works best over built up urban areas that are exhibiting low rates of deformation over time.

In this study, two existing InSAR studies for New Orleans are analysed (Dixon et al, 2016; Jones et al., 2016), and compared to our field data. Moreover, three LiDAR images from different years (Table 2.2) are compared with ground levelling data from the 2018 field campaign. These brief analyzes give more insight in the relative applicability of the different methods.

| Source | Weblink | Resolution | Vertical uncertainty | Year |
|---|---|---|---|---|
| Atlas Lidar – Louisiana State University | https://maps.ga.lsu.edu/lidar2000/ | 5 m | Accuracy = 1.2 feet (=37 cm) at the 95% confidence level | 2002-2003 (nov-dec) |
| NOAA Digital Coast | https://coast.noaa.gov/digitalcoast/data/ | 1/3 arceconds (ca 10 m) | Accuracy = 0.6 feet (18 cm) at the 95% confidence level | 2012 |
| NOAA Digital Coast | https://inport.nmfs.noaa.gov/inport/item/52969 | 1 m | Network Required Vertical Accuracy = 19.6 cm NVA | Early 2017 |

*Table 2.2. General properties of the LiDAR images used in the analysis. All elevation data used in this study used elevation datum NAVD88.*

# 3.HISTORY

The analysis of the development of the City of New Orleans and its surroundings consisted of the review and interpretation of available historic and topographic maps from 1803 to 2017. The following geographic units have been derived from that data:

- **Built-up area**: area which has been built upon
- **Unbuilt urban area**: area where the grid layout of the streets has already been drawn, but the area seems not to be built upon yet.
- **Cypress swamp**: swamp area covered predominantly by native cypress trees (*Taxodium distichum*)
- **Other wetlands**: all other wetlands and marshes mentioned on the maps
- **Land**: land area not covered by one of the previous units

Legend
■ Built-up area
■ Unbuilt urban area
🟩 Cypress swamp
□ Other marshes
□ Land
🟦 Surface water (large)
🟦 Surface water (small)
▤ Area below sea level

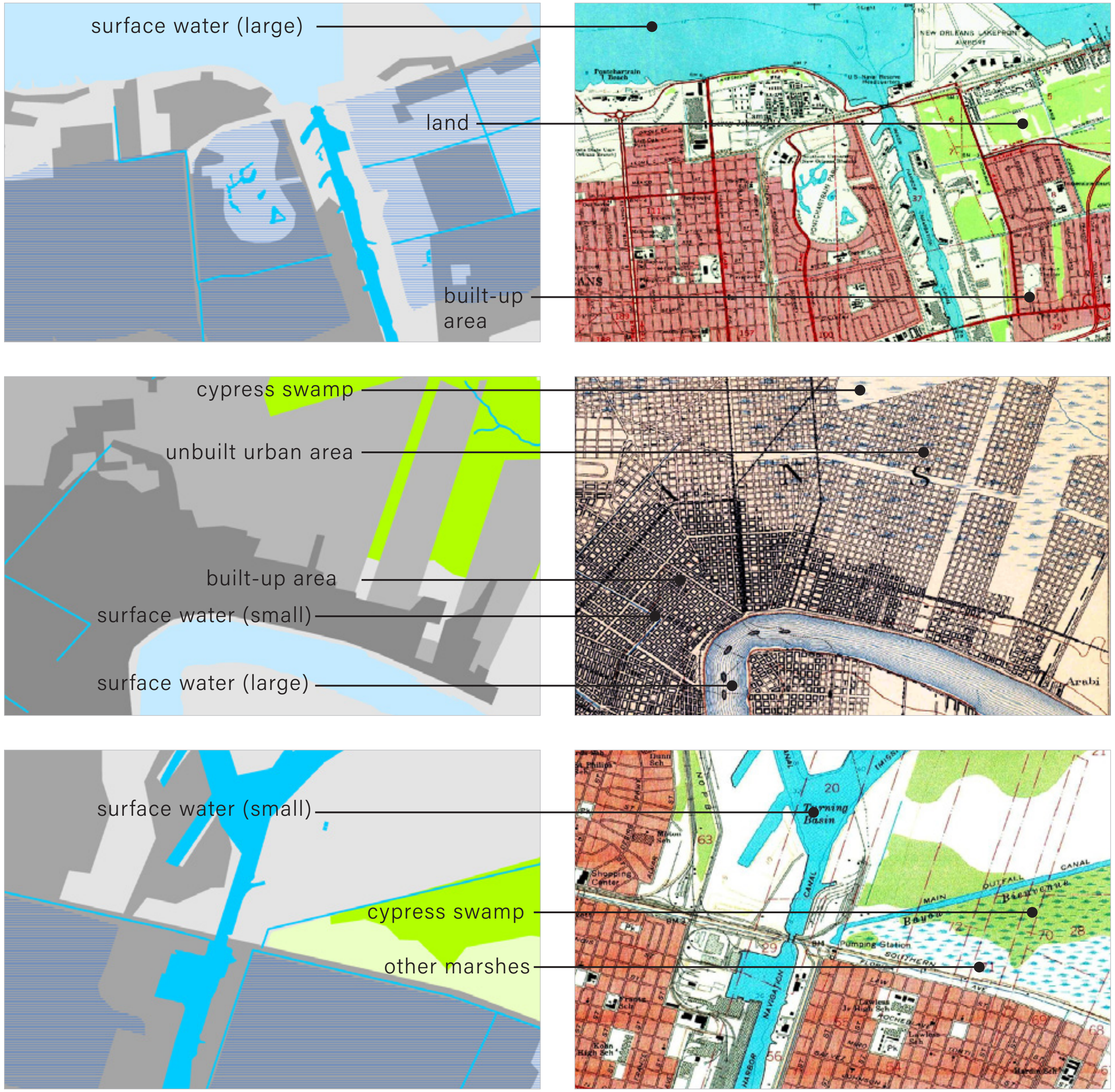


*Figure 3.1. Examples of the process of geographic unit mapping based upon the available topographical maps.*

- **Surface water (large)**: Lake Pontchartrain and the Mississippi River
- **Surface water (small)**: All other surface water
- **Area below sea level**: area below sea level based upon lines of altitude or LiDAR data.

The topographic maps shown in Figure 3.3 describes the area covered by modern day New Orleans as predominantly being covered by cypress swamps (Image 3) around the year 1803. The presence of these swamps with a surface elevation just above sea level, facilitated water infiltration and sediment deposition during overbank flooding. At that time, the main settlements were located next to the Mississippi River. This strategic location allowed for direct access to an important navigational route that connected the state of Louisiana to northern states, and to major cities such as Memphis and St. Louis. In the following years, the city began to grow towards the north, reaching Lake Pontchartrain by 1834. Based on the interpretation of the map from 1891, it is possible that not all the built-up areas indicated in the 1834 map were constructed. This discrepancy (see Figure 3.3, red circle in 1891 map) could be partly explained by the Sauvé's Crevasse flood of 1849 that washed away part of the existing buildings. Regardless, some areas near the Lake Pontchartrain shore may have never been built and it is recommended that this be checked with local knowledge.

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. This coincides with the industrial cypress-logging boom between 1890 and 1925. 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. The distiction between 'cypress swamp' and 'other marshes' appears not to have been made on the different maps, preventing a definitive interpretation based only on this difference. However, it is possible that after the removal of cypress trees, other types of swamps and marshes  were still present in the northern area of the city. 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 stunting the regeneration of cypress trees.

Between 1891 and 1939, the cypress swamps around New Orleans had almost disappeared, and signs of subsidence start to show. This can be seen most prominently in the area between the Metaire-Gentilly Ridge and the Pontchartrain Lake, which at the time was barely urbanized. In the decades to follow, the city continued to grow, first densifying in the higher area along the northeast bank of the Mississipi River that was above sea level, and then in the lower area along Lake Pontchartrain. By 1979, most of this area was urbanized.

The absence of swamps and marshes in and around the City of New Orleans, in combination with levee construction and the subsequent lack of sediment retention might have increased the occurrence of subsidence. It should be noted that the difference in percentage of area below sea level found when using the 1993, 1999 and 2017 maps is not ideal and should be used with caution in future work. Better, more accurate data collection is required.

### *Growth of the area below sea level*

The development of the area below sea level (Figure 3.2) was derived from a historic map analysis.

Between 1939 and 1952 the percentage of area below sea level only rose slightly. In the 1967 map, part of the mapped area

*Image 3. Louisiana cypress swamp*

was already labelled as 5 ft below sea level and between 1967 and 1993 there seems to be no change in the percentage of land below sea level. It is unclear how the area below sea level is mapped during this period or how often it was measured before 1967. LiDAR data was used for the 1999 map and the results of this survey were later published in 2002. The resulting map shows a higher percentage of both area below sea level, and area with a depth greater than 5 ft below sea level. Elevation data from 2010 (5 m grid, Table 2.2.) was used to generate the 2017 map, resulting in even larger percentages of area below sea level.

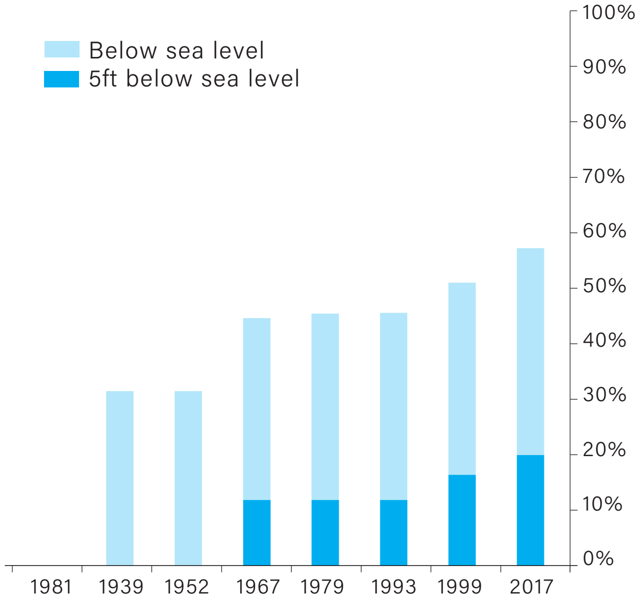


*Figure 3.2. Area below sea level in the urban area of the City of New Orleans*

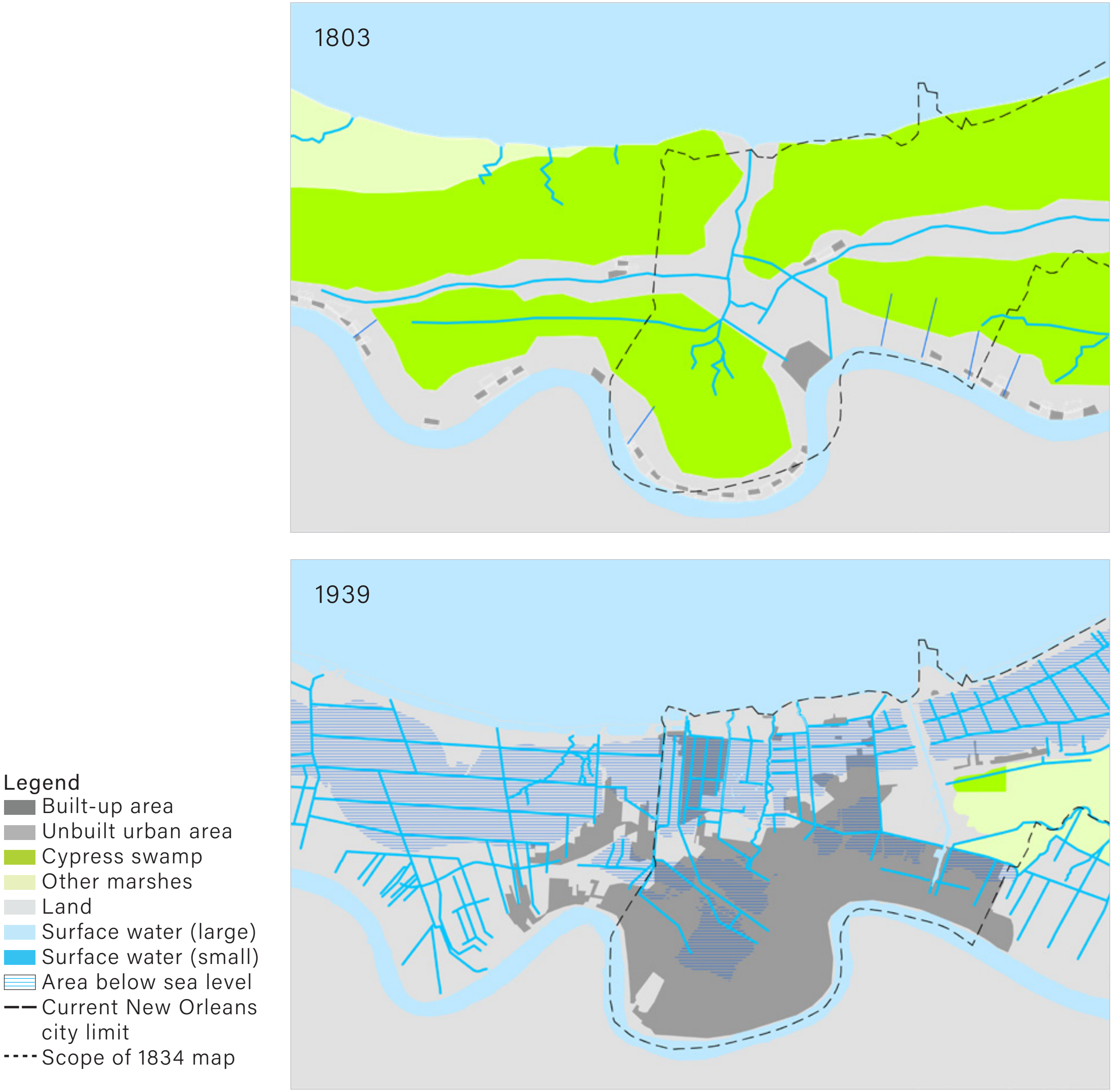
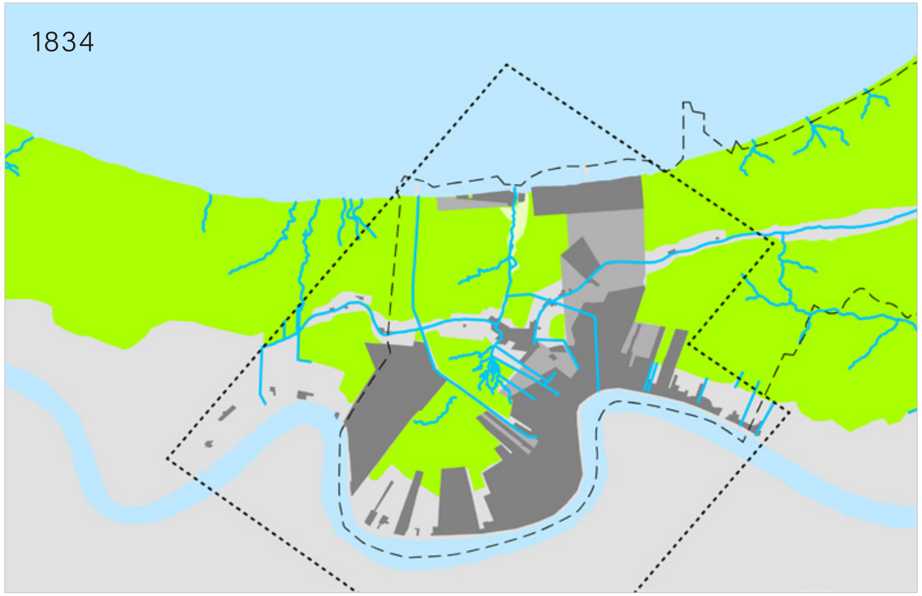
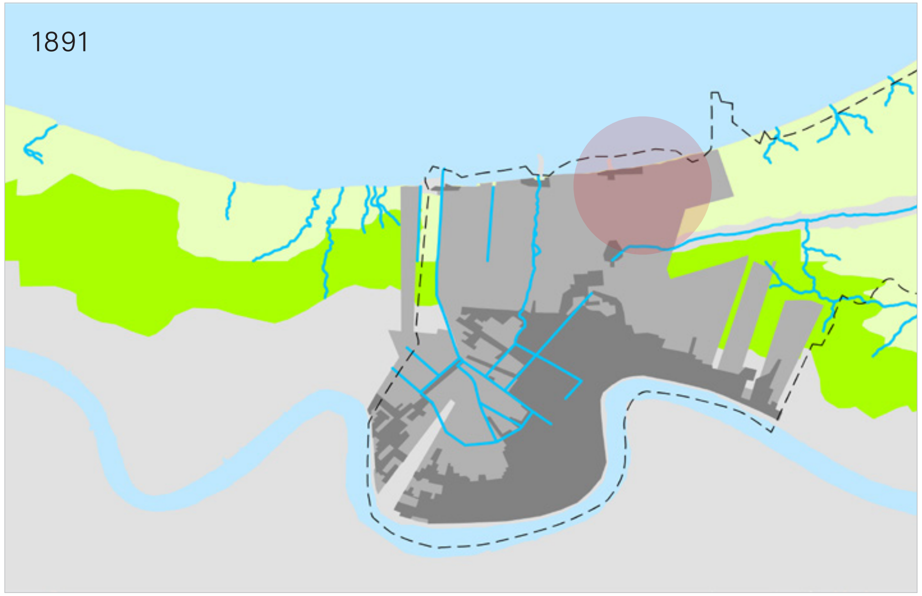
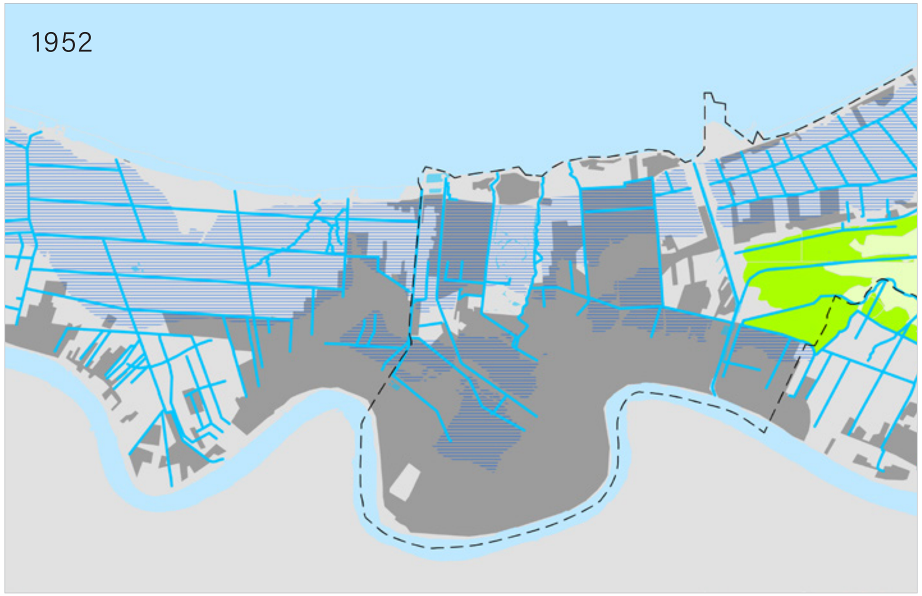
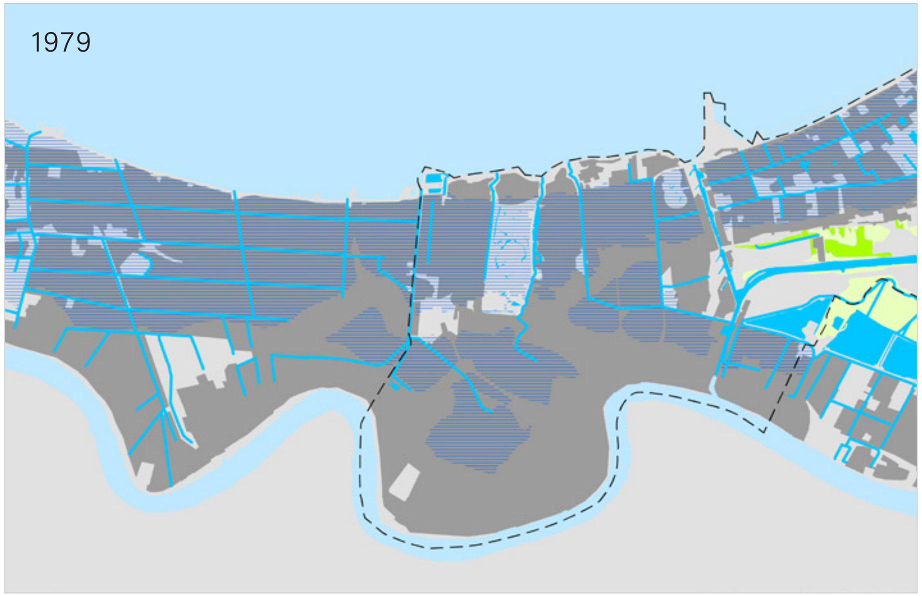


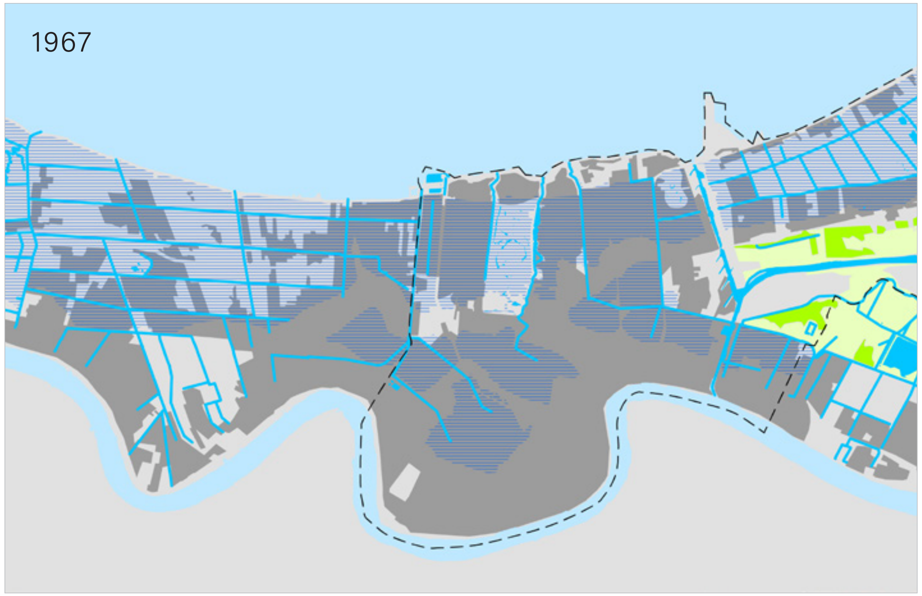
*Figure 3.3. Sequence of maps showing the development of New Orleans and its surroundings for the period 1803-2017, based on available topographic data. Red circle in 1891 map indicates discrepancies in the Built area between in comparison with the 1834 map.*

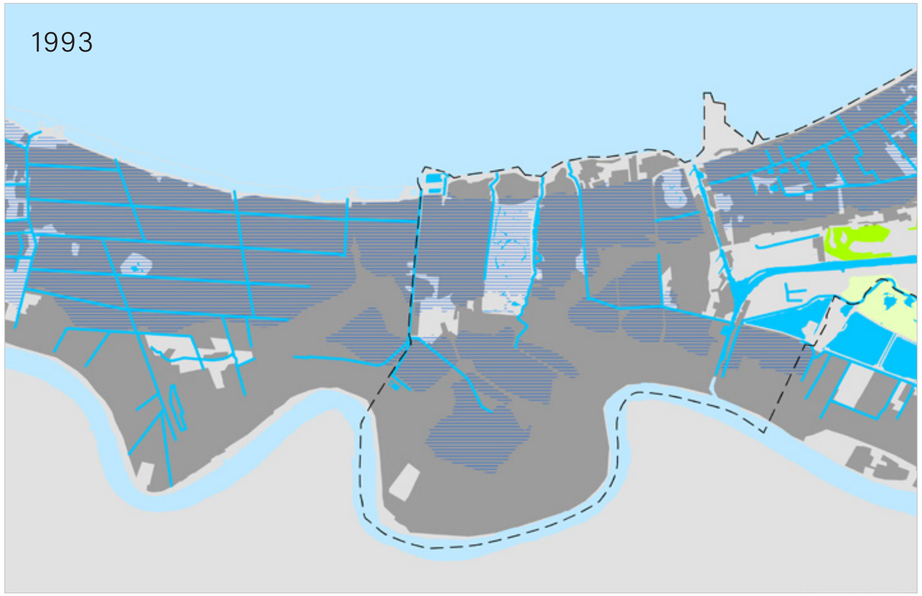

1834

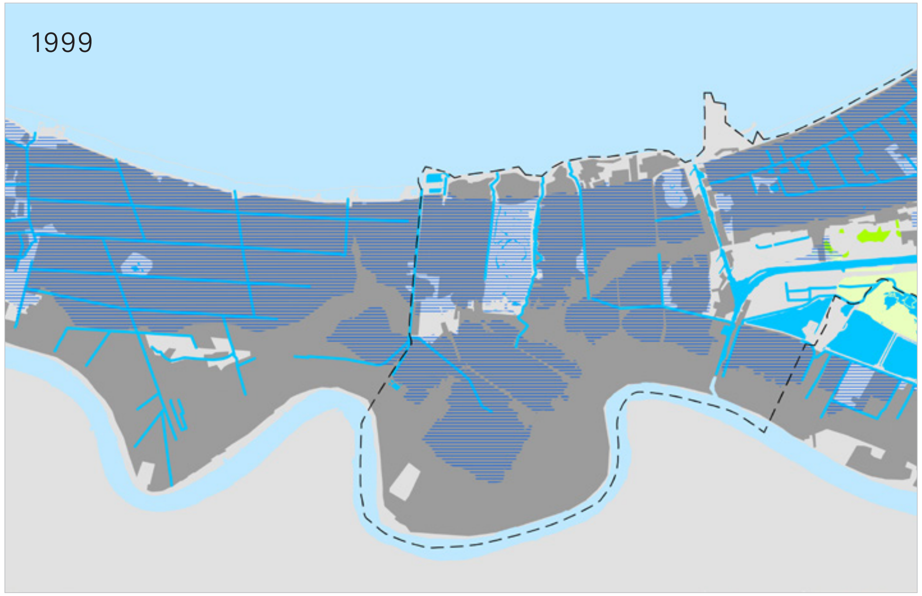

1891

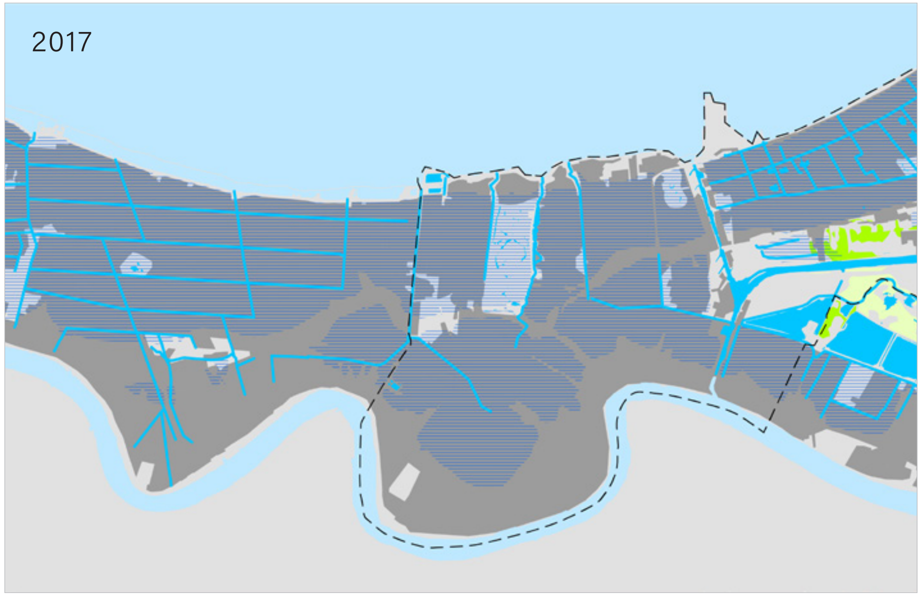

1952


1979


1967


1993


1999


2017

***Anthropogenic topography***

The present topography of New Orleans is partly determined by natural features (natural levees, crevasse splays, abandoned channels), and also partly by anthropogenic activity. Soon after New Orleans was established by the French in 1718 on what it is currently the French Quarter, they began the levee construction along the Mississippi River, to protect the settlement against flooding. Levees were initially constructed on top of the crests of natural levees and were about 6 feet (1.8 m) wide and 3 feet (0.9 m) high (Figure 3.4). In the following years levees were enlarged to 18 feet (5.5 m) wide, 3 feet (0.9 m) high, and extended to protect a larger area. Over the course of time, levees were progressively raised and extended along the Mississippi River, at present reaching heights of up to ~ 9 m MSL. The progressive rise and extension of levees resulted in a progressive decline in sediment supply to the floodplains and swamps, and hence, less sediment accretion.

By the year 1800, a large sand bar had formed by erosion on the east bank of the Mississippi River and aggradation had occurred along the west bank (Figure 3.6). In the lower Mississippi Valley, the term 'Batture' is used to describe such alluvial deposition between the levee and the river. Over time, the city progressively expanded onto the batture where new levees and constructions were built. In the 19th century large anthropogenic fills were constructed, starting with the realization of the Industrial Canal in 1923. Along the canal, dredged sediments were deposited which resulted in an anthropogenic fill of about 25 feet (7.6 m). Between 1926 and 1929 the lakefront reclamation was realized by (hydraulic) pumping of lake sediment and by 1930 the fill was reinforced by a massive concrete seawall. The Shushan airport peninsula was constructed between 1931 and 1933, and the Intracoastal Waterway was realized in 1944. Much of the sediments dredged for the Intracoastal Waterway was deposited north of the canal.

Besides the large anthropogenic constructions and fills, large parts of the city (e.g. residential areas) are raised with a decimeter thick, often sandy, anthropogenic top layer (Figure 3.5). Locations without an anthropogenic fill consist predominantly of parks, areas where sand is found at or close to the surface, or on natural levees. Locally, an anthropogenic fill approximately a meter thick can be found. An example of this is the loamy fill in the residual channel of the Metairie-Gentilly abandoned channel (>5.9 m thick). This abandoned channel appears as a ridge in the landscape and runs from west to east between Lake Pontchartrain and the Mississippi River (Figure 3.3).

Dimensions of cross sections

| Year | Height (ft) | Base width (ft) | Area (sq ft) |
|---|---|---|---|
| 1882 | 9.0 | 53 | 274 |
| 1896 | 15.5 | 120.5 | 951 |
| 1914 | 24.0 | 200.0 | 2455 |
| 1928 | 27.0 | 260.0 | 3645 |
| present | 30.5 | 315.0 | 4956 |

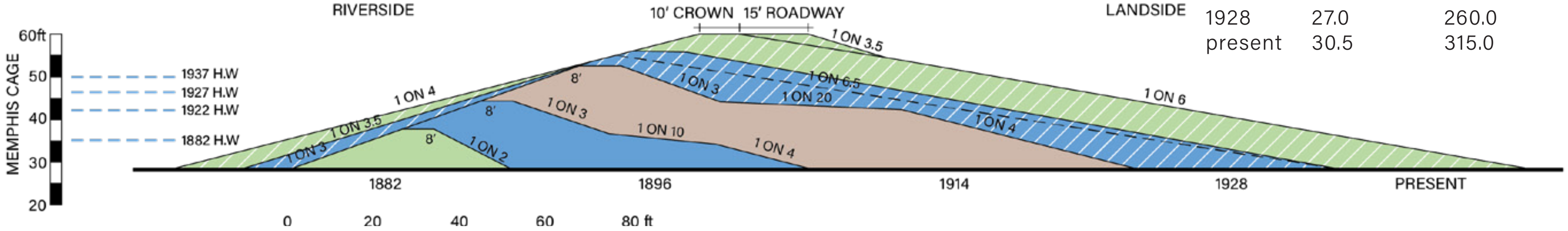


*Figure 3.4. Evolution of Corps of Engineers' standard levee section (1882–1972). Levees were generally heightened sequentially by compacting additional soil on the land side of embankments (Rogers, 2008).*

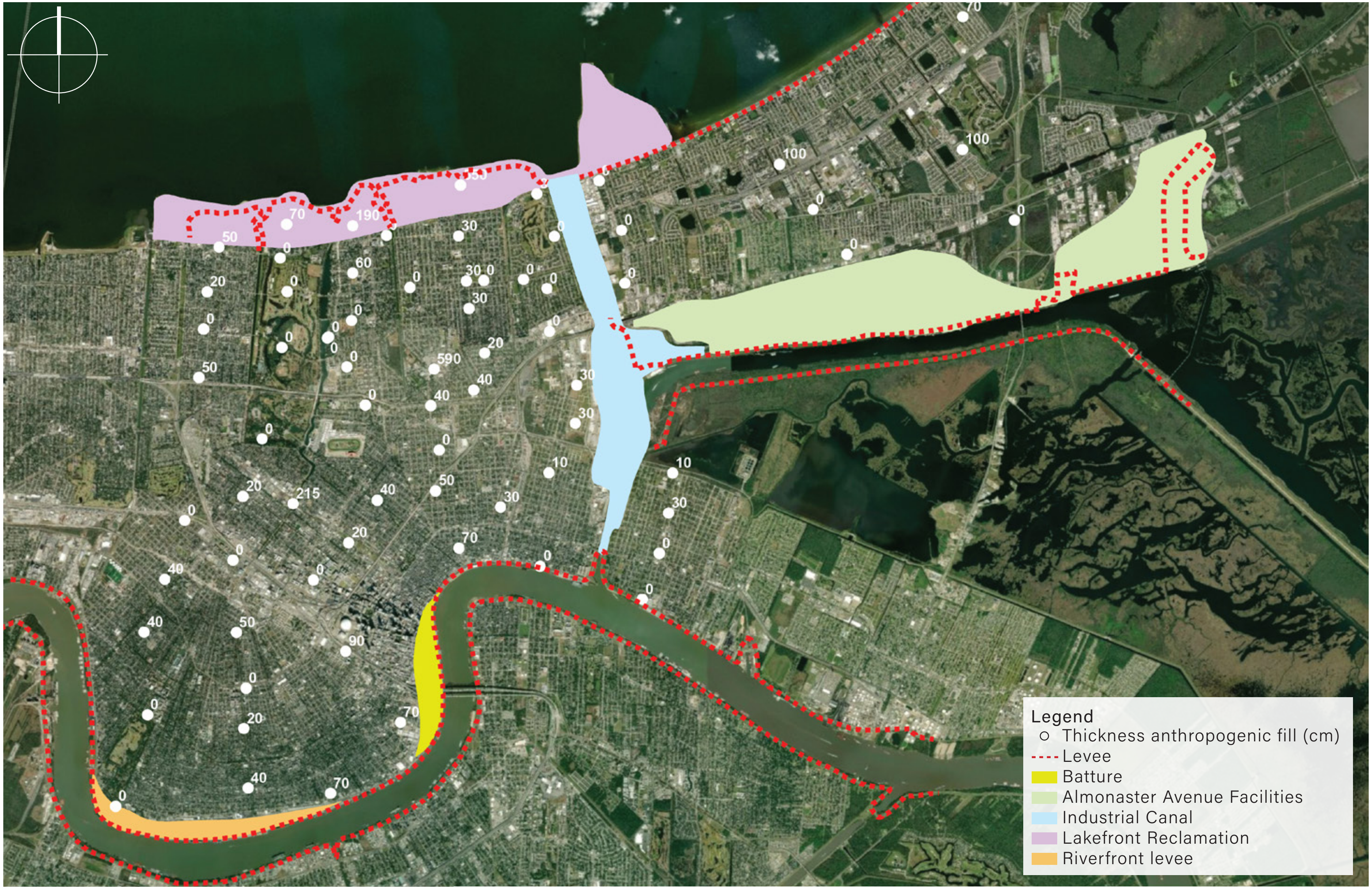


*Figure 3.5. The location of the main levees (red dotted line) and fills in New Orleans. In white the thickness of the anthropogenic fill at the borehole locations is indicated.*

# 4.ELEVATION

## *InSAR*

For surface deformation studies using InSAR, strong signals are recovered from permanent structures as these reflectors tend to provide a high rate of temporal consistency.  Vegetated areas, standing water, or areas with ground movements greater then the phase of the radar signal are tough to process and result in fewer measurement points being available. This is also the case for the studies of Dixon et al. (2006) and Jones et al. (2016). Hence, these maps mainly show movements of buildings and infrastructure, and less of the earth surface itself. If constructions are founded, the InSAR maps represent movements caused by processes acting at and below the foundation level. If constructions are not founded, the maps represent movements caused by all subsidence/uplift processes. Thus, care should be taken in using these images to detect shallow subsidence, which is the focus of this study.

The InSAR-based subsidence maps published by Dixon et al. (2006) and Jones et al. (2016) do not show the same patterns everywhere. For example, the northeast part of New Orleans East is highly subsiding according to Dixon et al. (Figure 4.1), while these areas appear as relatively slow-subsiding areas in the map of Jones et al. (Figure 4.2). According to our field data we would expect these areas to be vulnerable to subsidence due to peat oxidation. Also, parts of the levee and fill along Lake Pontchartrain are subsiding fast according to Dixon et al, while the maps of Jones et al. indicate relatively low subsidence rates in these areas. Based on field data, we would expect low rates of subsidence in these areas because the thick, often sandy fills are not susceptible to oxidation and have already loaded the subsurface for a considerable time. Under these conditions subsidence due to compaction is not expected. Both maps show high deformation rates in parts of the Lower Ninth Ward, an area where high subsidence vulnerability would be expected based on our data, but other boundaries/patterns of high-subsidence areas do not correspond so nicely. Our field data demonstrates that these high subsidence rates are likely to be attributed to the relatively thick peat and humic clay layers found in this area.

Differences between InSAR maps may come from differences in the period covered, technical specifications, data processing technique or reference area used to benchmark the results. For example, Jones et al. used 2 images from 2009 and 2012 respectively and long-wavelength radar from an Uninhabited Aerial Vehicle Synthetic Aperture Radar instrument operated from an altitlude of 12.5 km. Dixon et al. used 33 satellite radar images taken at different times in the period between 2002 and 2005.

## *LiDAR*

The analysis of LiDAR images from 2002 and 2012 suggests that there may be structural deviations when compared with ground levelling data. The LiDAR DEM 2002/2003 elevation data plot shows an average height difference of 0.22m higher than 2018 levelling data at borehole locations with standard deviations of 0.41 m (Figure 4.3). The LiDAR DEM from 2012 elevation data plots on average 0.24 m lower (standard deviation 0.36 m) when compared to the levelling data, suggesting an overall uplift over the last ca 6 years. Since the deviations are large (decimeter scale) and plot either structurally higher or structurally lower compared to the level-

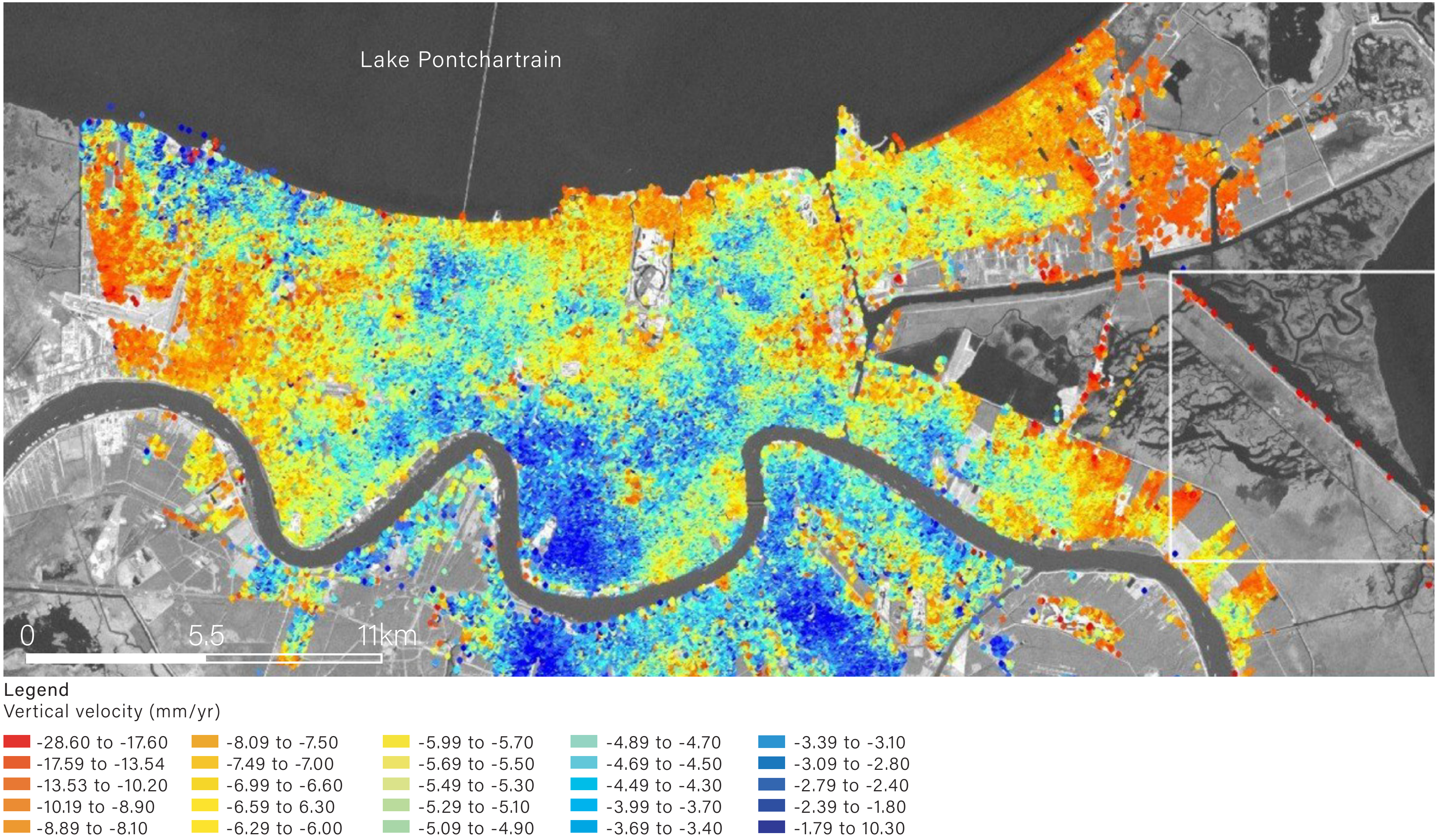
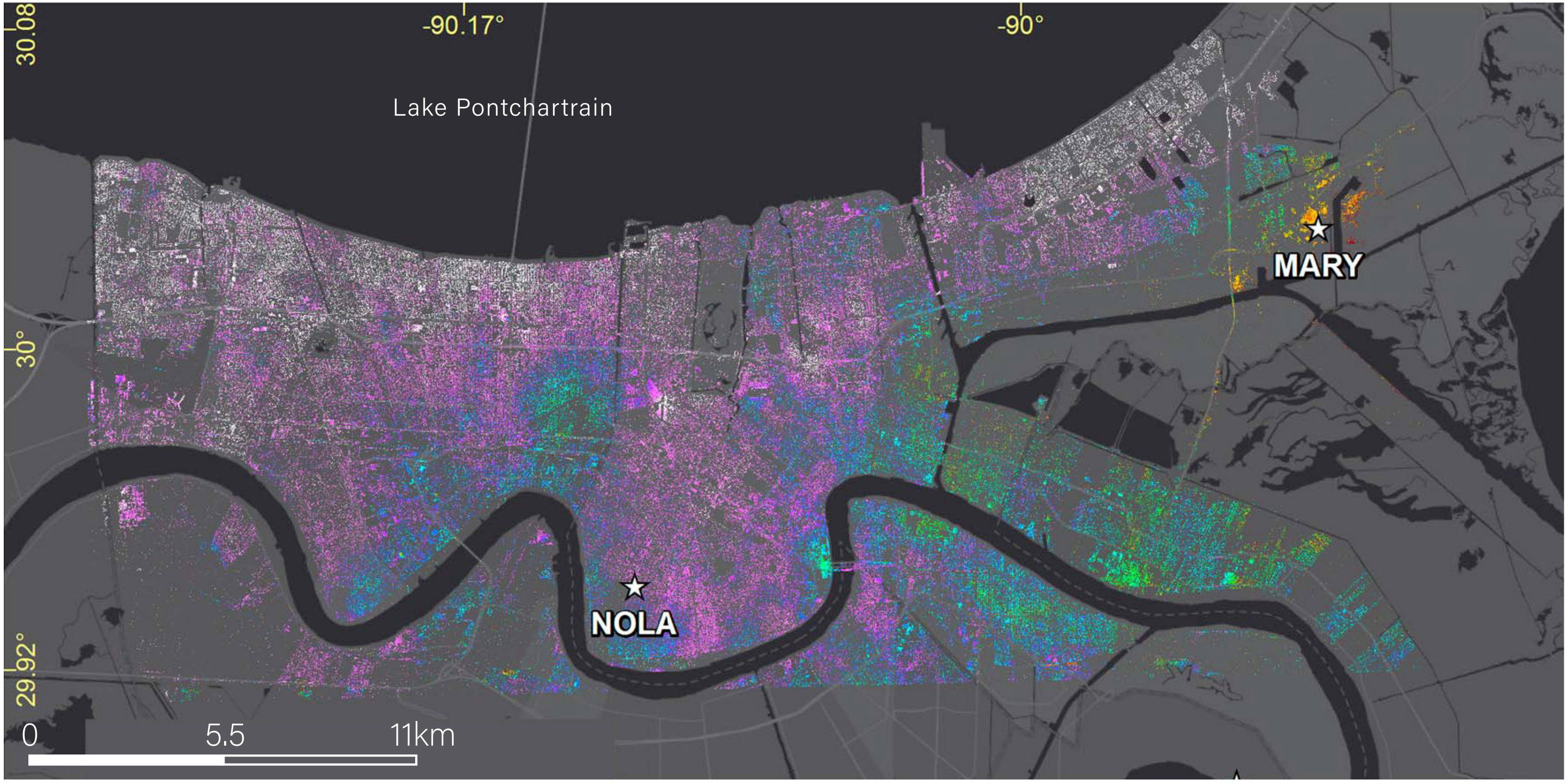


*Figure 4.1. InSAR images from Dixon et al. (2016). Negative values indicate motion away from the satellite, consistent with subsidence*



**Legend**

Vertical velocity (mm/yr)

🟥 <= -35
🟧 -34.9 to -30
🟨 -29.9 to -25
🟫 -24.9 to -20
🟩 -19.9 to -15
🟦 -14.9 to -10
🟦 -9.9 to -6
🟪 -5.9 to -3
🟪 -2.9 to -7
□ > 7

*Figure 4.2. InSAR images from Jones et al. (2016). NOLA and MARY indicate Global Positioning System (GPS) Continuously Operating Reference Station (CORS) Locations.*

ling data, a natural cause of the deviations (i.e. uplift or subsidence of the land surface) is unlikely. More likely, the deviations are caused by data processing, in combination with the fact that LiDAR DEMs are composed of grid cell data, where each grid represents the mean of elevation (point) measurements within that grid cell.

The LiDAR image of 2017 does not show a structural dm-scale deviation when compared to the levelling data, rather levelling data and LiDAR raster data at borehole locations are similar. The levelling data plot is on average 0.036 m lower (standard deviation of 0.07 m) than the 2018 levelling data.

This short analysis of InSAR and LiDAR data demonstrates that care must be taken in drawing conclusions about land subsidence based on rasterized elevation data. For land subsidence studies, high resolution raster elevation data with full coverage (not only constructions) are recommended, in combination with  ground measurements of subsidence and geological surveys to relate subsidence to subsoil processes.

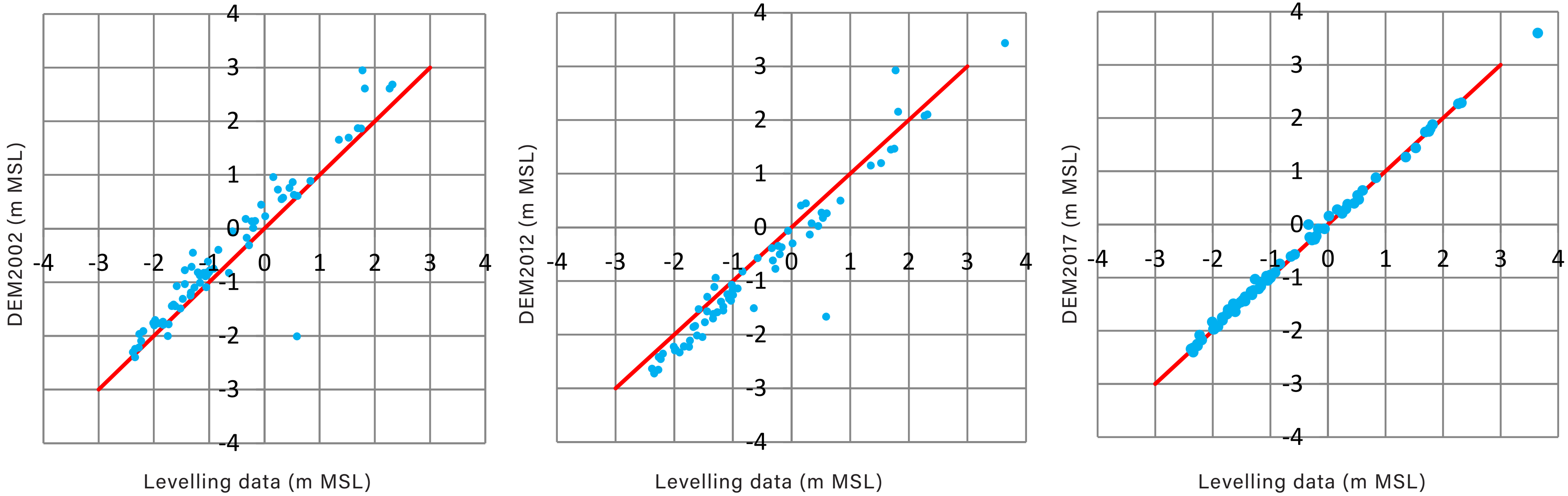


*Figure 4.3. Comparison of LiDAR grid cell values obtained from datasets from 2002 (left) 2012 (middle) and 2017 (right) with levelling data at the 2018 fieldwork borehole locations (blue dots). The red line indicates a 1:1 relation.*

# 5.GEOLOGY

## 5.1 Geology of the shallow subsurface

The locations of boreholes and derived cross sections are visualized in Figure 5.1. The borehole information reveals the geology of the top few meters of the Holocene sequence (Figure 5.5 to 5.9). The total thickness of the Holocene sequence is determined by the depth of the Holocene-Pleistocene boundary. This ranges in New Orleans from between -40 to -100 feet MSL (-12 to -30 m MSL; Figure 5.2) and at its base, the top of Pleistocene can often be found as a stiff paleosol. The general geologic composition of the entire Holocene sequence has been mapped in previous studies (e.g. USACE, 1958 (Figures 5.3 & 5.4).

*Image 5. Sampling during the November 2018 fieldwork*

*Figure 5.1. Borehole locations of the November 2018 field campaign and location of cross sections.*

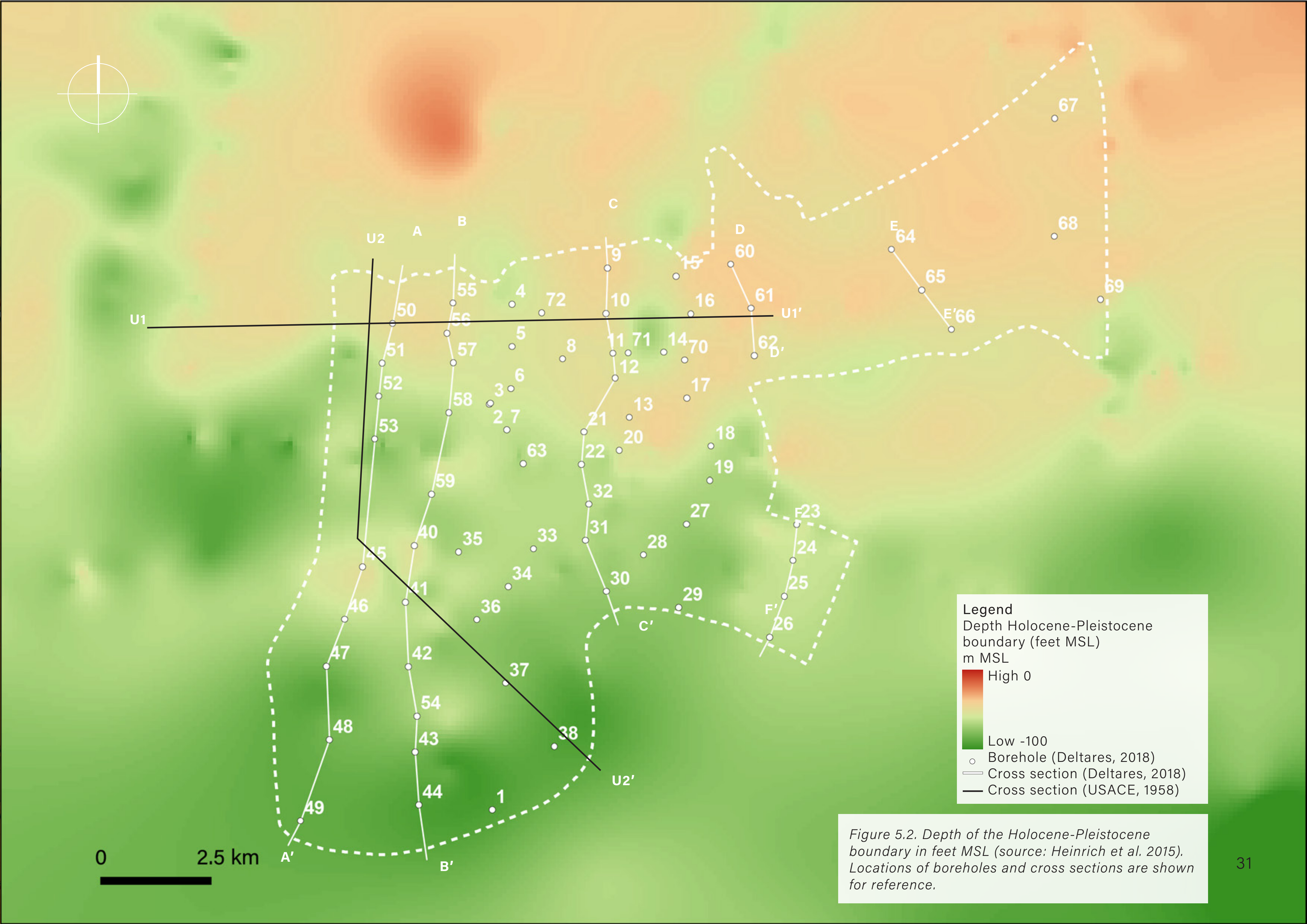


*Figure 5.2. Depth of the Holocene-Pleistocene boundary in feet MSL (source: Heinrich et al. 2015). Locations of boreholes and cross sections are shown for reference.*

### *Paleography*

About 5000 years ago, when the Mississippi River deposition center was located more to the west (Teche Delta Complex), a barrier island chain developed south of the are where Lake Pontchartrain is found today (Otvos & Giardino, 2004; Figure 5.13 & 5.14). Sediments from the smaller Pearl River located to the east of New Orleans, were concentrated into barrier islands and shoals by longshore drift processes creating the Pine Barrier Island trend that is now buried under the northern part of New Orleans (Saucier, 1963; Dunbar and Britsch, 2008) (Image 5.1). About 3800 years ago a major diversion of the Mississippi River created a new course running in a west-east direction south of the present Lake Pontchartrain location, at the same location as the modern Mississippi River (Hijma et al., 2017). The barrier island chain and new Mississippi course enclosed the former bay creating Lake Pontchartrain. The new Mississippi course fed the St. Bernard sub delta and consisted of various river systems that were successively active in the period between ~4000 to ~1900 years ago (Frazier, 1967; Hijma et al. 2017). Another St. Bernard distributary channels is the Bayou Metairie-Gentilly (MG) system, running from west to east through the present City of New Orleans, north of the modern Mississippi. This system started to become active around 2500 years ago (Saucier 1962) and was part of the St. Bernard subdelta. At present, the abandoned channel is expressed at the surface as a ridge running from west to east.

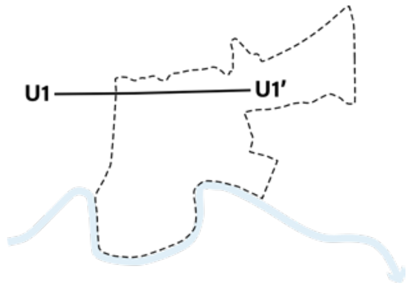
The distributary channels of the St. Bernard sub delta progressively filled the shallow coastal waters in the New Orleans area with fluvial-deltaic sediments. Sediment delivery maintains and increases ground elevation, facilitating the formation of swamps and marshes (Dunbar and Britsch III, 2008). Swamps are fresh water systems that developed close to the rivers in an area that regularly received river water and sediments during overbank flooding. Further away from the rivers brackish and saline marshes developed. About 1000 years ago, the present Mississippi River course came into existence (Figure 5.13)

### *Fluvial deposits*

The Mississippi river brought fluvial sediment to the area of New Orleans. In general, these fluvial deposits consist mostly of clay-silt mixtures. A limited amount of fluvial sand has been deposited in New Orleans. Only in the abandoned channel of the MG system and in natural levee or crevasse splay deposits (very fine) sand-silt mixtures (loamy sand, sandy loam) are found. At greater depths (> 10 m MSL) sandy channel and/or point bar deposits may occur, deposited by precursors of the modern Mississippi River. Close to the river levee, crevasse splay deposits are generally found, containing abundant silt. Further away from a (paleo)river, where floodplain deposits area found, the clay content increases, while the silt-sand content decreases (see for example Figure 5.6 and 5.7).

### *Swamp deposits*

Intercalated with clayey floodplain deposits, peat and humic clays are found that are formed (peat) or deposited (clay) in a swampy environment at some distance from a river. Swamp peat is commonly found in the area between the Mississippi River and Lake Pontchartrain, containing wood and sedge remains. Gyttja, a fine grained organic lake deposit also occurs in the subsurface of this area, indicating the historical presence of paleo lakes and ponds. Existing cross sections from the ‘50s and ‘60s (Figure 5.3 and 5.4) show the occurrence of thick peat layers at shallow depths. The results of the 2018 field campaign demonstrate that much of the shallow peat occurring north of the MG-ridge has partly disappeared or degraded into amorphous, crumbly peat due to oxidation (Figures 5.5, 5.6, 5.7, 5,8 & 5.9). South of the MG ridge, peat and humic clays generally occur at greater depths (mostly between ca 2 to 4 m below surface), and are



overlain by clayey deposits.

### Pine Barrier Island deposits

North of the MG ridge, sands from the Pine Barrier Island trend are found at various depths in the subsurface. The depth to the top of the trend ranges from 50 to 150 cm below surface in parts of Gentilly and Lakeview, as well as in the western part of New Orleans East to more than 150 cm below surface in areas north of the MG the ridge. Pine Barrier Island trend deposits mostly consist of fine to medium grained sands that may contain shell fragments and silty/reworked sections.

### Anthropogenic deposits

The dike constructed along the southern shore of Lake Pontchartrain was built by using lake bed sediments excavated just north of the shoreline and is reflected in the bathymetry of the lake bottom, where a deep hole is present where the excavations took place (up to -10 m MSL; Figure 5.1). The fill consists mainly of loamy sand but may also include clayey-silty intervals. No data has been collected from other fills.

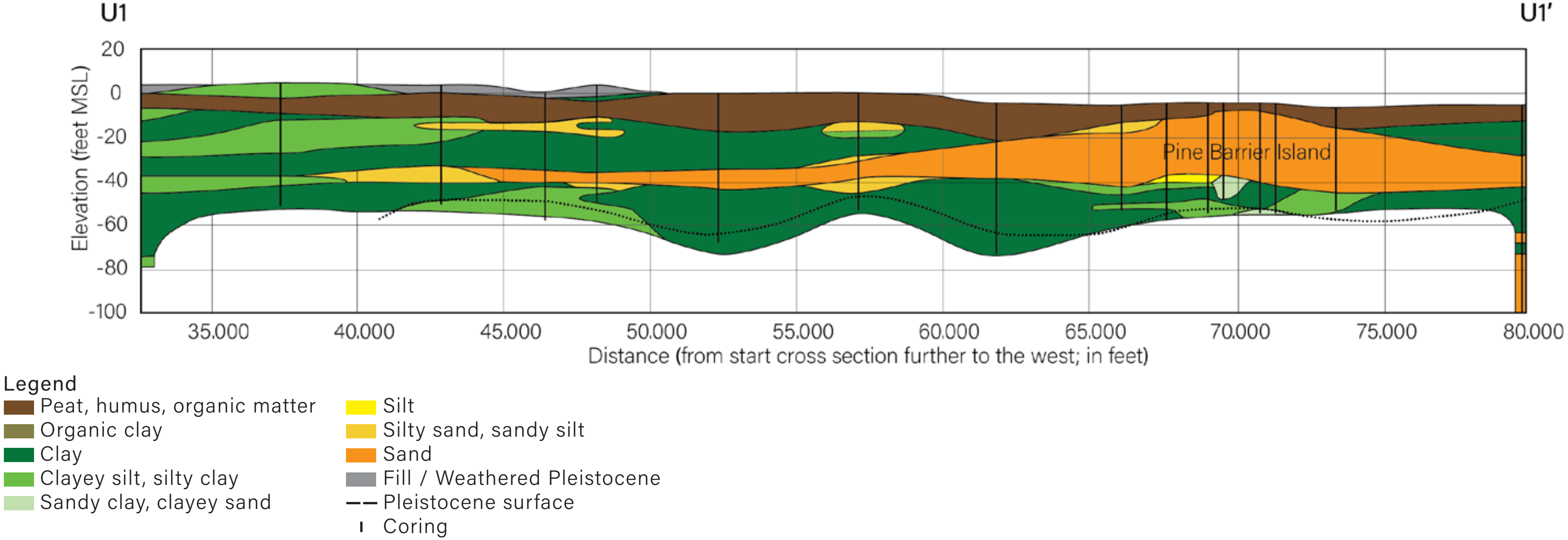
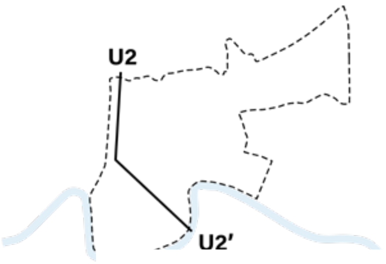


*Figure 5.3. Cross section U1-U1' (see Figure 5.1), showing the east part of the original cross section from USACE B-B' (1958).*



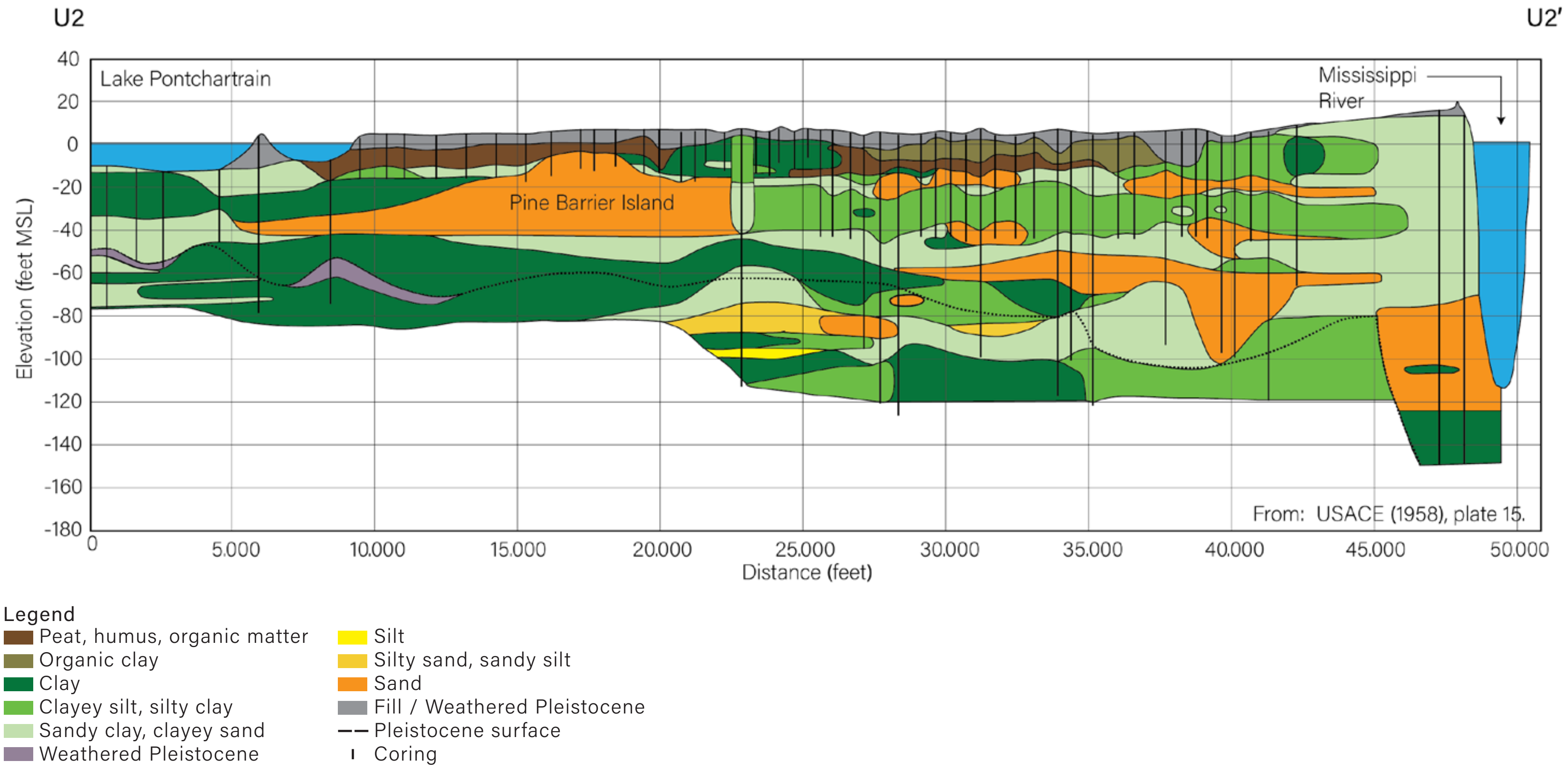


*Figure 5.4. Cross section U2-U2′ (see Figure 5.1; source: cross section USACE D-D′ (1958)). Like in Figure 5.3, this cross section shows a relatively thick shallow peat layer, which at present has partly dissapeared due to peat oxidation.*

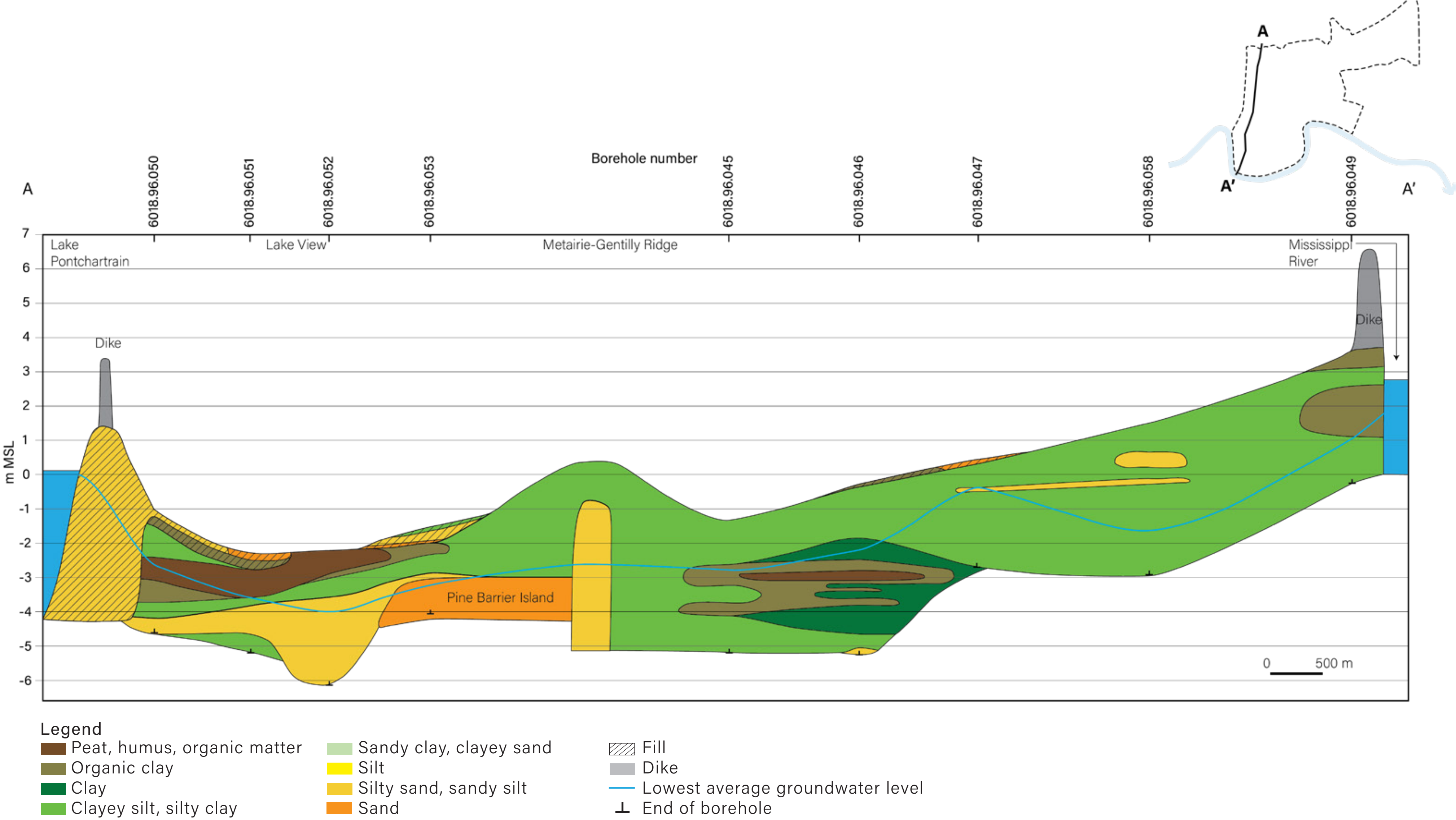


*Figure 5.5. Cross section A-A'. Lake Pontchartrain is bordered by a thick anthropogenic sandy fill with a dike on top of it. The area behind the fill and levee, the Lakeview neighbourhood, has subsided to a present elevation of about 2 m below mean sea level. In this area, peat occurs close to the surface predominantly above the lowest average groundwater level. Consequently, the peat has been exposed to air causing it to degrade and disappear. Further south, sandy and silty sediments of the Pine Barrier Island and abandoned Metairie-Gentilly Ridge are found in the subsurface, which is expressed at the surface as a topographic high. Continuing towards the Mississippi River, the surface has subsided below mean sea level due to compaction of deeper-positioned peat and organic clays below groundwater leve. From here, the surface level gently increases in elevation as you get closer to the natural levee of the Mississippi River.*

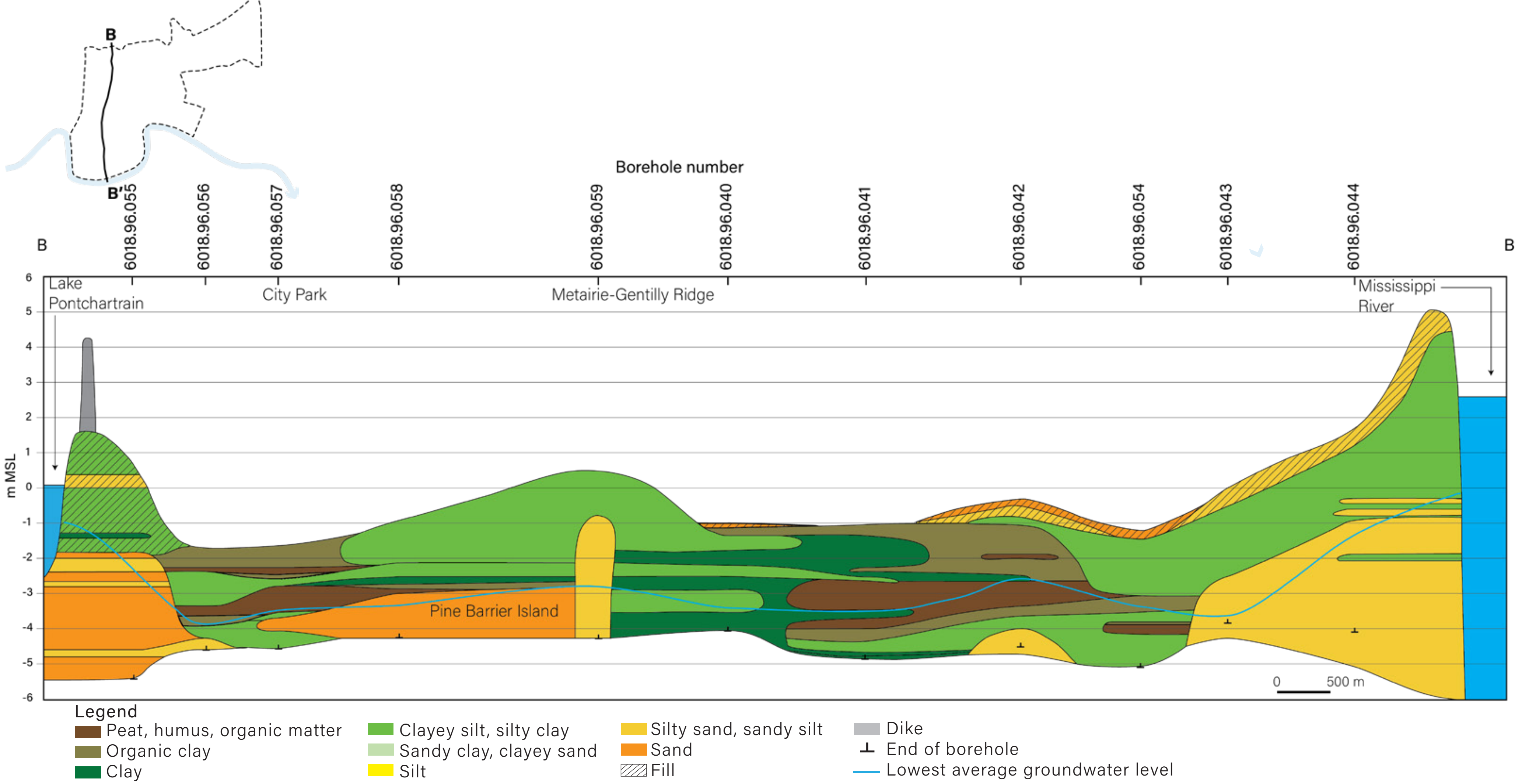


*Figure 5.6. Cross section B-B'. City Park is on the north side (left in cross section) bordered by the anthropogenic fill and levee along Lake Pontchartrain, and on the south side (right in cross section) by the Metairie-Gentilly Ridge. In the subsurface of Metairie-Gentilly Ridge, silty clay (natural levee) deposits overlie silty sand (channel) deposits. At greater depth, the Pine Barrier Island sand occurs north of the ridge. City Park has subsided less than the neighbouring residential areas of Lakeview and Gentilly, to a present elevation of about 1.7 m below mean sea level. The shallow subsurface of City Park is mainly composed of peat and organic clay. Part of these organic layers are present above the lowest average groundwater level, where they are exposed to air, causing subsidence due to peat oxidation. Peat also occurs below the lowest average groundwater level, making the park vulnerable to subsidence due to peat compaction. If the lowest average groundwater level would drop further in this area, non-oxidized peat would be exposed to air and would start to degrade too, causing renewed subsidence. South of Metairie-Gentilly Ridge, the shallow subsurface is largely composed of (organic) clay and peat. Peat mostly occurs just below groundwater level, making this area especially vulnerable to subsidence due to peat compaction. In this area, if the lowest average groundwater level decreased it would also become vulnerable to the effects of subsidence due peat oxidation. Further towards the Mississippi River the subsurface becomes more silty and sandy, and the surface rises upwards towards the highest point of the (natural) levee.*

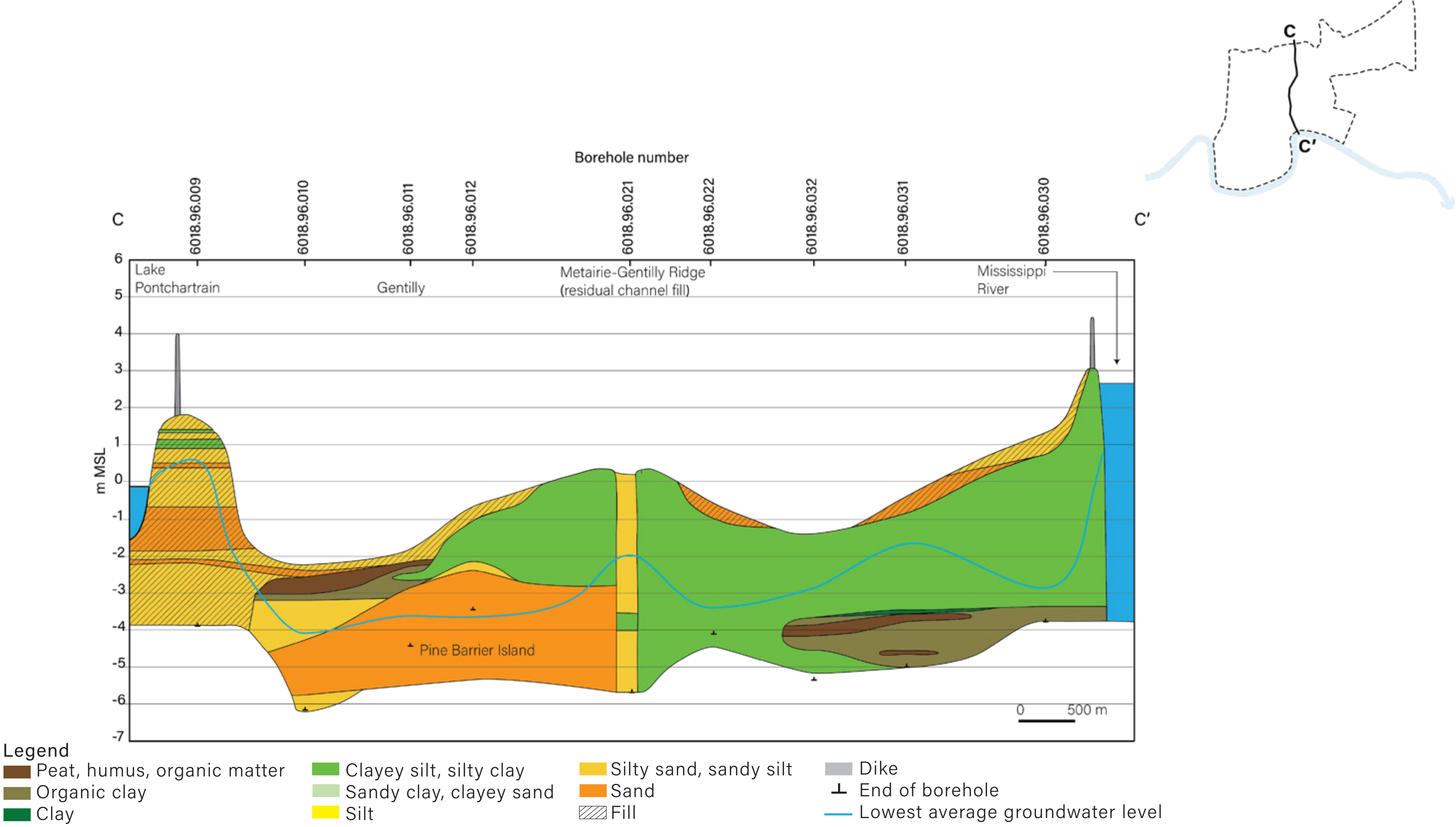
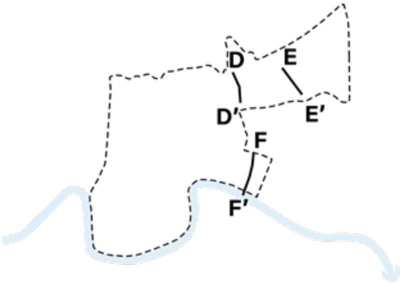
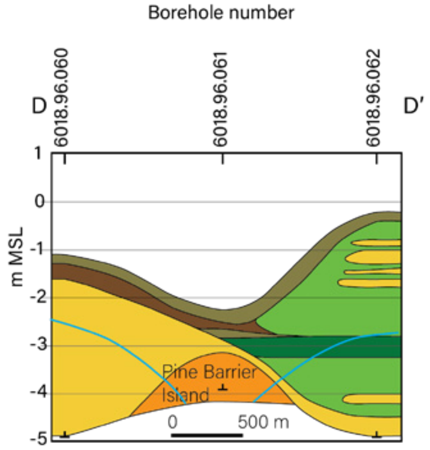
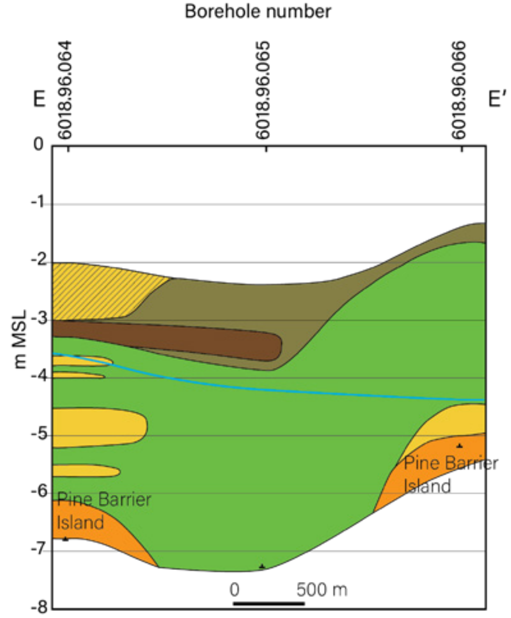
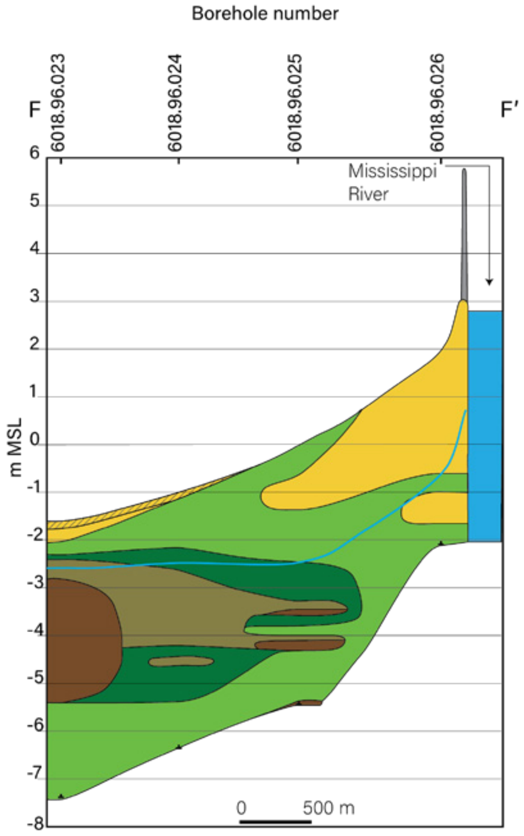


*Figure 5.7. Cross section C-C'. For location see Figure 5.1. Gentilly is located in between two topographic highs on the left of the cross section: the anthropogenic fill and levee along Lake Pontchartrain and Metairie-Gentilly Ridge. The neighbourhood has subsided to a present elevation of about 2 m below mean sea level. Peat occurs close to the surface, above the lowest average groundwater level and therefore has been subjected to oxidation. The Pine Barrier Island sand usually occurs at 1 to 2 meters below surface. The area in between Metairie-Gentilly Ridge and the Mississippi (natural) levee has also experienced subsidence and is at present about 1.4 m below mean sea level. At this location, peat and organic clay occurs at greater depth, below the lowest groundwater table, making this area especially vulnerable to subsidence due to (peat) compaction.*









Legend

| | | | |
|---|---|---|---|
| 🟫 Peat, humus, organic matter | 🟩 Clayey silt, silty clay | 🟨 Silty sand, sandy silt | ⬜ Dike |
| 🟫 Organic clay | 🟩 Sandy clay, clayey sand | 🟧 Sand | ⊥ End of borehole |
| 🟩 Clay | 🟨 Silt | ▨ Fill | — Lowest average groundwater level |

*Figure 5.8. Cross section D-D'. For location see Figure 5.1. A thin top layer consisting of peat and organic clay directly overlies the Pine Barrier Island sand in the north (left in cross section) and clayey / silty fluvial deposits in the south (right in cross section). The peat has been oxidized due to exposure to air.*

*Figure 5.9 Cross section E-E'. For location see Figure 5.1. At this location, Pine Barrier Island sand occurs at greater depth. It is overlain by predominantly fluvial silty clay. The top layer consists of peat and organic clay that has been oxidized due to exposure to air. This has resulted in subsidence to a present elevation of about 2 m below mean sea level.*

*Figure 5.10. Cross section F-F'. For location see Figure 5.1. In the Lower Ninth Ward, abundant peat and organic clay is found in the shallow subsurface, mostly occurring below the lowest average groundwater level. The area has subsided about 1.5 m below mean sea level, mainly due to the compaction of peat and clay. In the northern part of the Lower Ninth Ward, where peat occurs just below the lowest average groundwater level, this area too become vulnerable to subsidence due to peat oxidation, when peat is exposed to air. Towards 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.*

## 5.2 Peat density and organic content

In total, 88 organic samples were analyzed in the Tulane laboratory for dry bulk density and organic-matter content. Samples with an organic-matter content greater or equal than 20% (n=26) are classified as peat. Samples with an organic-matter content lower than 20% (n=62) are classified as humic organic clays (Figure 2.1). The average organic-matter content of the 26 peat samples is 39%, with a maximum value of 67%. Hence, the organic matter content of peat in the subsurface of New Orleans is rather low, indicating a continuous influx of inorganic fluvial sediment during swamp accretion.

Buried peat in the subsurface of New Orleans has on average a higher dry bulk density with a similar organic-matter content (Figure 5.11) compared to fresh peat. Peat in the subsurface of New Orleans has been compacted 31% on average. Relatively high-organic peat tends to be compacted more, although the positive relation between the amount of compaction and organic-matter content of all peat samples is weak ($R^2=0.2$; Figure 5.12). Considering the relatively low average compaction grade, it can be concluded that there is still substantial potential for future subsidence due to peat compaction.

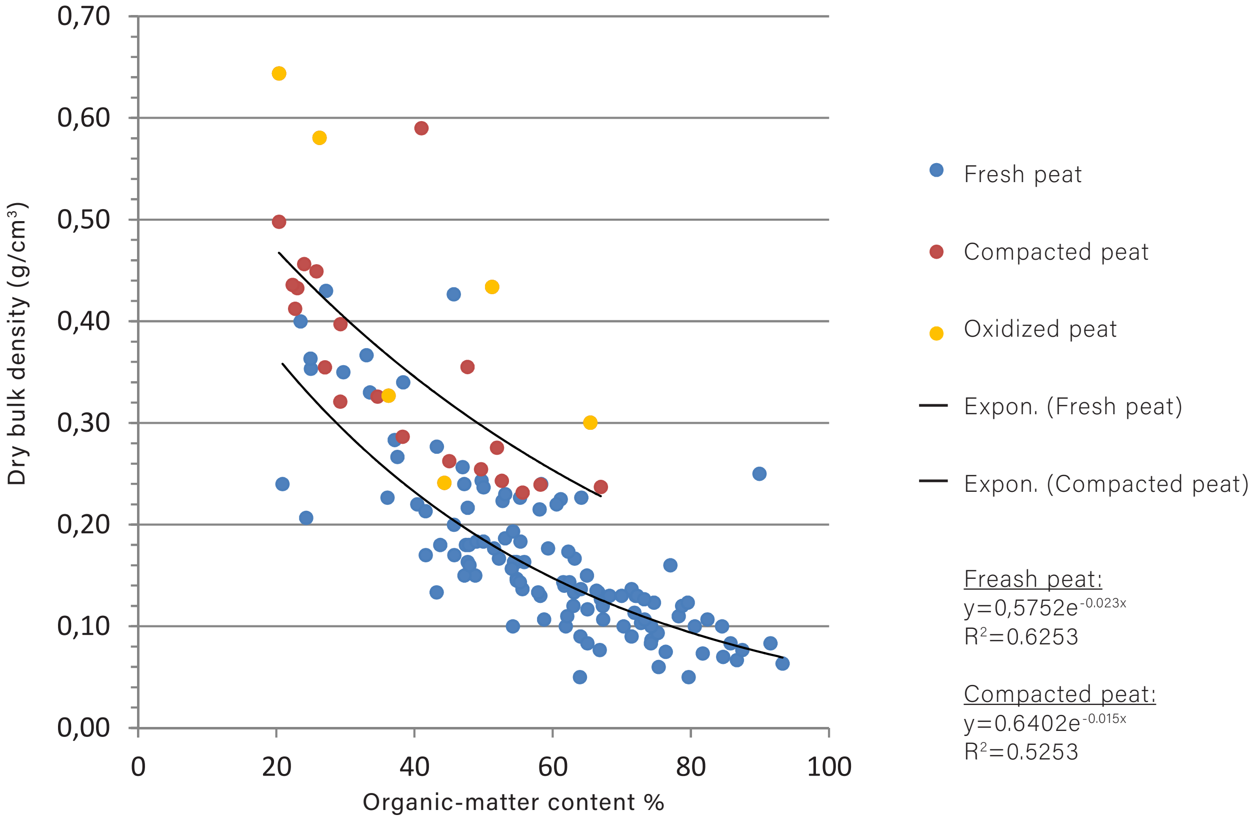


*Figure 5.11. Dry bulk density and organic-matter content of compacted peat and fresh peat obtained from, respectively the subsurface of New Orleans and from surrounding swamps.*

In the areas north of MG-ridge peat occurs at shallow depths. This has caused peat oxidation in the zone above the groundwater table. Degraded peat is much more amorphous, contains fewer fibers, and has a crumbly structure. Yet, lab analyzes show that degraded peat may still have relatively high organic matter content (orange dots in Figure 5.11), comparable to peat that has not yet been degraded (red dots in Figure 5.11). Results also show that the dry bulk density and related compaction grade of degraded peat tends to be higher than that of non-degraded peat (Figure 5.11 & 5.12).

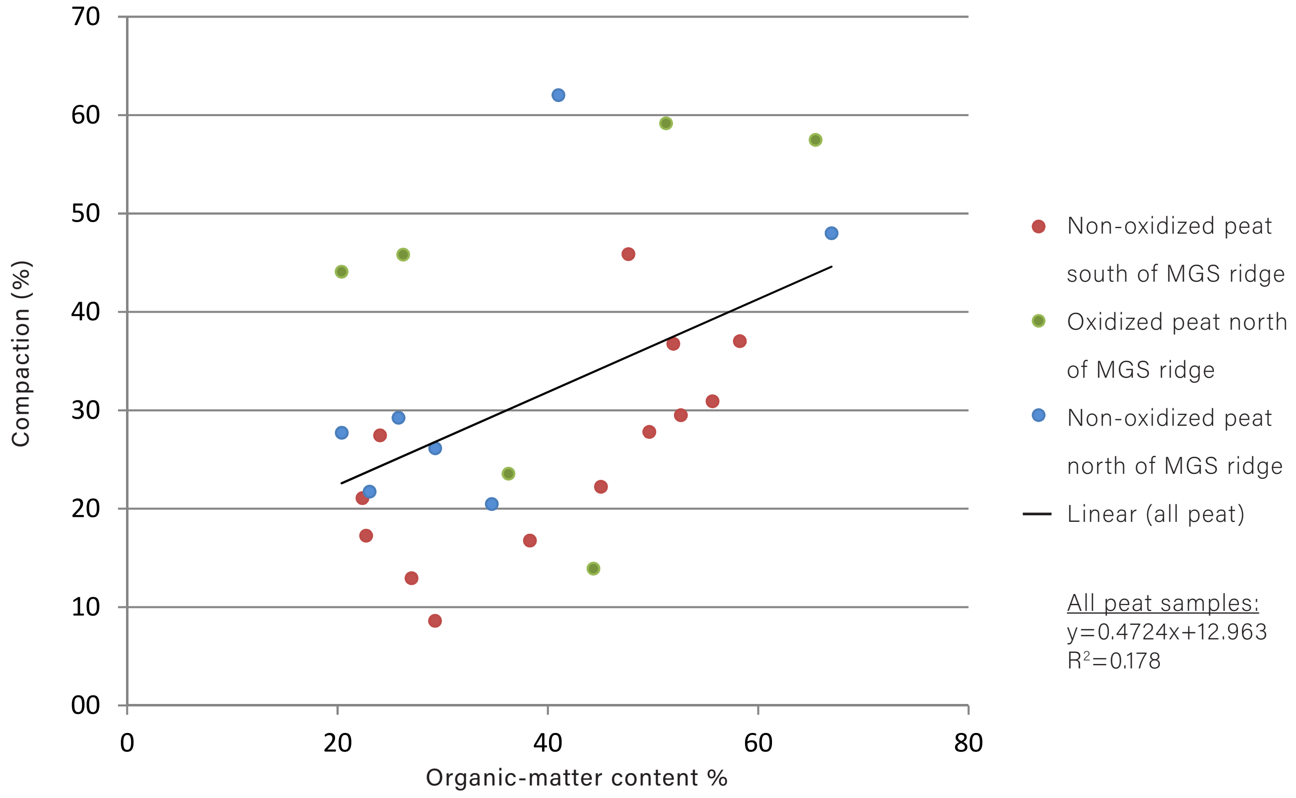


*Figure 5.12. Organic-matter content and compaction grade of different types of peat samples.*

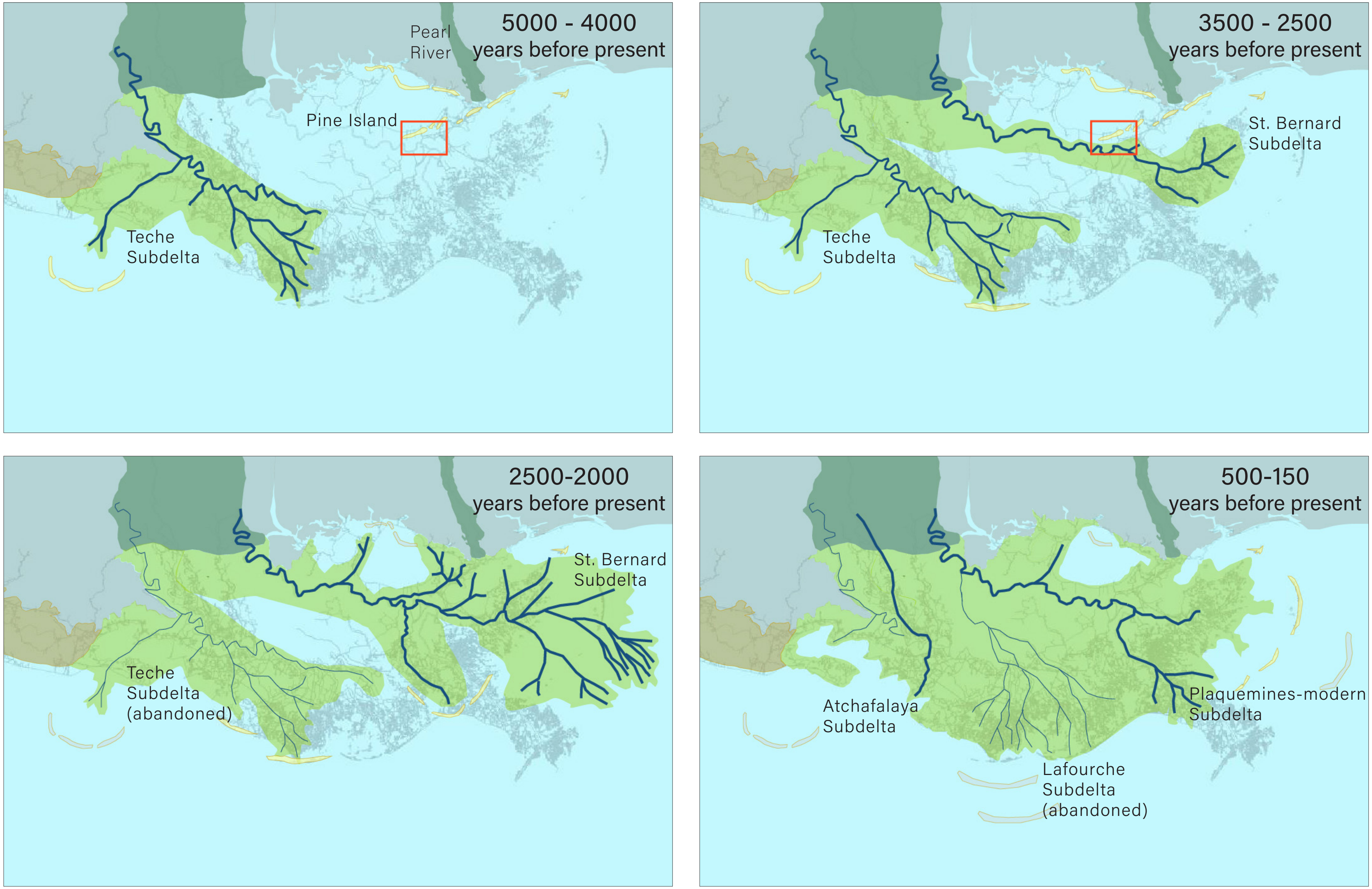
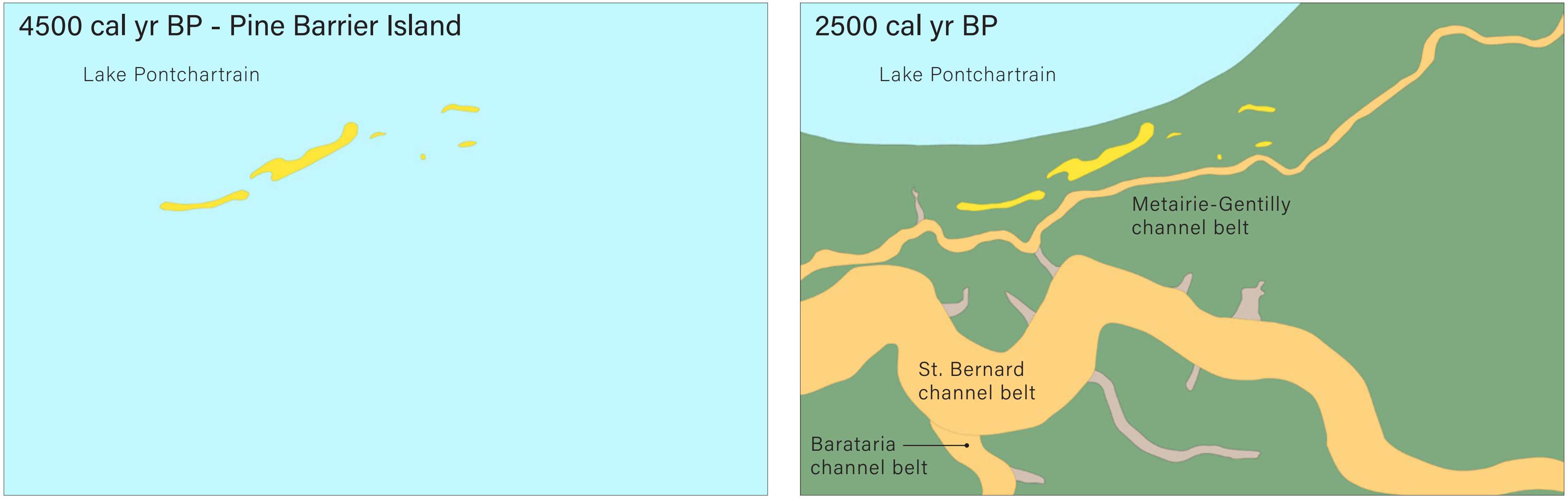
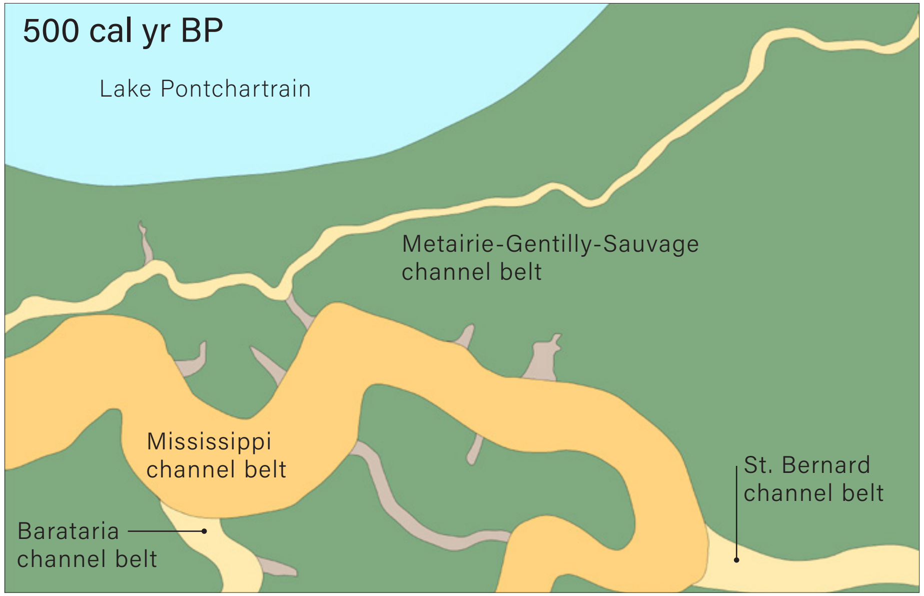


*Figure 5.13. Paleogeographic maps of the delta system in Southeast Louisiana.*





Legend

| | |
|---|---|
| 🟦 Lake | 🟨 Channel belt (inactive) |
| 🟨 Beach barrier island | 🟫 Crevasse |
| 🟧 Channel belt (active) | 🟩 Wetland |

Figure 5.14. Paleogeographic maps of New Orleans. Ages are in calibrated years before present, meaning the radiocarbon measurements used for the paleogeographic reconstructions are corrected for variations in atmospheric radiocarbon concentration.

Image 5.1. Example of Pine Barrier sands

# 6.GROUNDWATER

***Groundwater data collection objectives***
Several subsidence processes are initiated or related to groundwater drainage. In soft soil areas subsidence is often triggered by lowered groundwater levels.

During this study we try to determine the subsidence vulnerability by combining soil and geological information with groundwater information. To counteract the limited data availability relating to the fluctuation of groundwater levels, information relating to groundwater was also collected during the geological borehole campaign. Hydro-morphic soil characteristics (see Figure 2.2) included:

(1) Mean lowest groundwater level (redox boundary):
- below this level is a reduced environment, often grey sand/clay, or brown undecayed peat
- above, signs of oxidization include iron rust or black (decayed) peat.

(2) Mean highest groundwater level
- oxidation - reduction zone marker

Through the acquisition of the above information at the 72 borehole locations, groundwater level fluctuations could be interpreted.

Using the mean lowest groundwater levels markers from each of the boreholes a contour map was generated to aid in the understanding of groundwater flow directions.

Individual borehole grounwater level estimates need to be used with care. For example, it takes time when an oxidized zone becomes reduced again after elevating the groundwater level.

***Groundwater fluctuation***
The results of the groundwater level analysis are presented in the following diagrams and maps. In Figures 6.1 and 6.2 the measurement results are presented (1) below mean sea level, and (2) below surface. In general, the mean highest groundwater level is approximately 50 cm (2 feet) below surface, while the mean lowest groundwater level is around 150 cm (5 feet) below surface. Several outliers exist where the lowest mean groundwater levels are greater then 4 meters below surface while other locations present the highest mean groundwater levels at the surface.

Nearly all groundwater levels (mean high and mean low) are far below sea level (Figure 6.2). The lowest mean groundwater levels are more than 4 meter below sea level. Only a few mean highest groundwater levels are above sea level.

***Mean highest groundwater level (MHG) maps***
In Figures 6.2 & 6.3 the mean highest groundwater levels is presented at the borehole locations in m below surface (Figure 6.2) and in m MSL (Figure 6.3).

***Mean lowest groundwater level (MLG) maps***
Figure 6.4 presents the mean lowest groundwater level below surface. As stated before this groundwater level is often found at approximately 150 cm (5 feet) below surface and corresponds with the approximate depth of the storm-drainage and sewer pipes used for wastewater transport .

Image 6.1. Sampling salinization on the field

The deepest groundwater levels below surface are found near the Mississippi levee at 4.2 meters (13 feet). The deep groundwater levels near the river is likely caused by the deeper pipe infrastructure.

Figure 6.5 presents a map of the mean lowest groundwater level below mean sea level. The locations with the lowest groundwater levels (> 4 meters below mean sea level) are situated in New Orleans East and is likely related to the water level in the canals

***Mean Lowest Groundwater level contours and flow patterns***

When data from the mean lowest groundwater level and surface water levels in the canals, Mississippi, Lake Pontchartrain and the former sand pits in City Park and New Orleans East is combined, a groundwater level contour map can be created (figure 6.7). This map, based on a simple interpolation of available data, presents a good overview of the groundwater level distribution throughout the city. Although a good starting point to better understand the groundwater system within the city, weaknesses in using this map for anything other then a guiding tool may be attributed to the fluctuating nature of the groundwater system itself (i.e. Levels would likely drop very fast parallel to canals or Bayou St. John, towards the

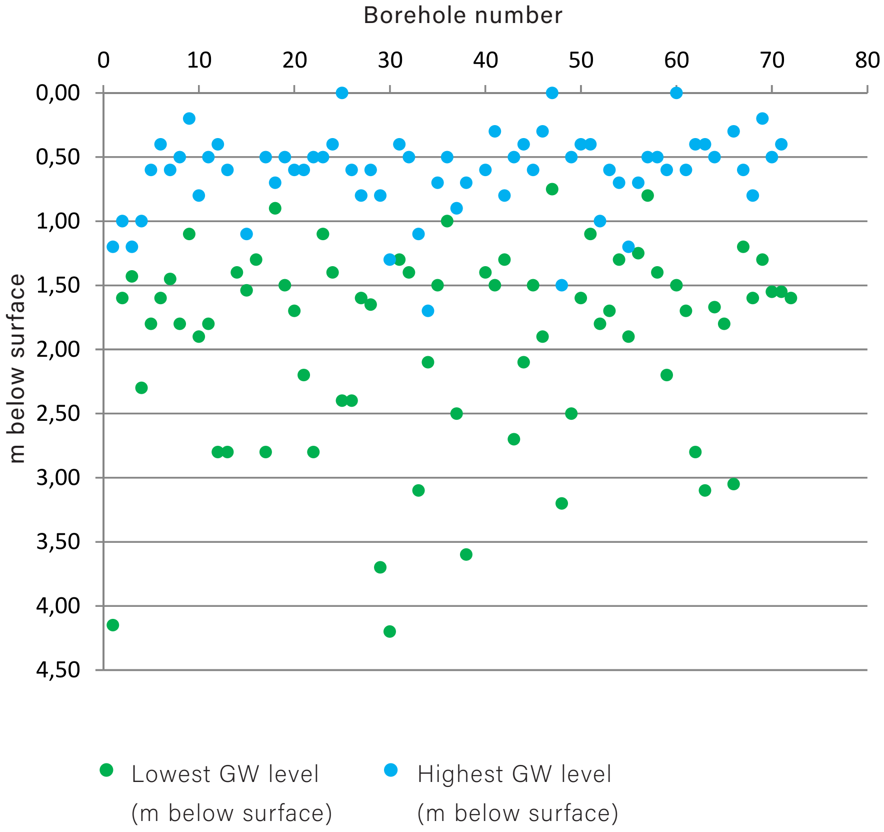


Figure 6.1. Lowest/highest grounwater level (m below surface)

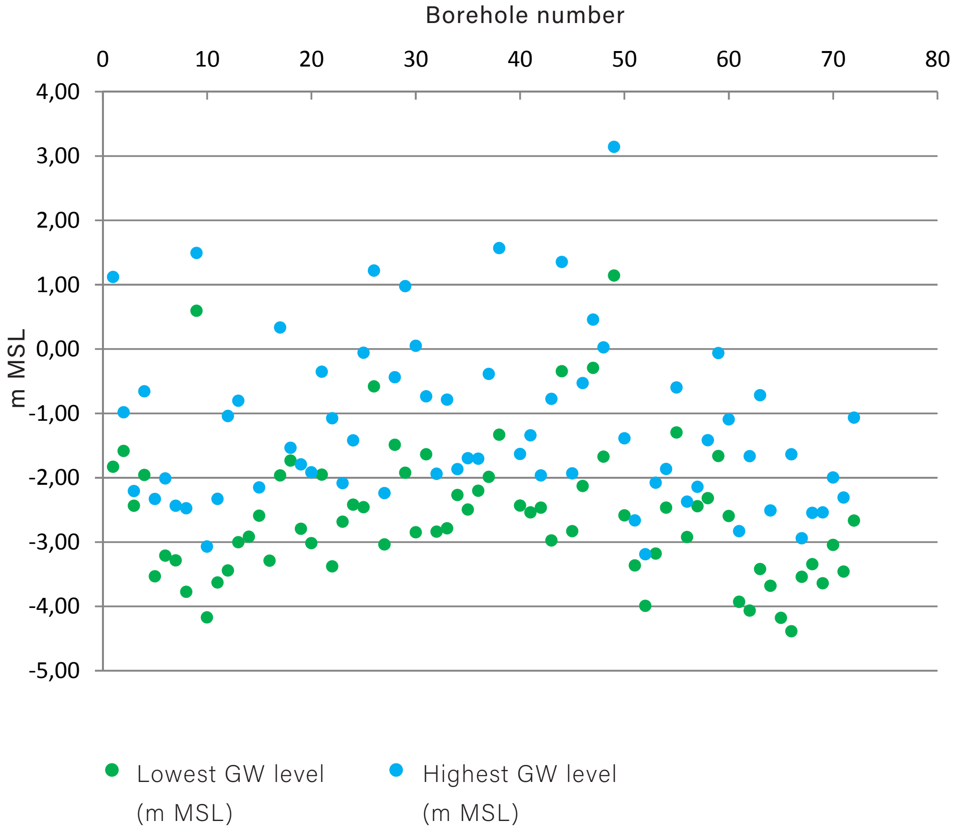


Figure 6.2. Lowest/highest grounwater level (m MSL)

first street and the drainage system below it). Subproject 6 (see introduction) looks to add to the information gained during the borehole logging fieldwork and will improve on this first iteration groundwater contour map.

The contour map presents a clear distribution of the lowest groundwater levels. New Orleans East is an example of an area characterized by very low groundwater levels, but therefore also by steep gradients with the adjacent higher surface water levels (Lake Pontchartrain, Industrial Canal, Inner Harbor Canal and the eastern wetlands). This distribution helps to explain the groundwater flow system: the surrounding surface water system acts as an infiltration (recharge) area and the low (urban) New Orleans East area (Figure 6.7) acts as a groundwater discharge area. The infiltration area contains brackish-salt water, so most of deeper groundwater will be, or become, brackish-salt. The water levels and salinity of the many isolated lagoons are consistent with this analysis: the water levels are nearly a foot higher than canal levels and the salinity is nearly always equal to Lake Pontchartrain salinity. Shallow groundwater and soil moisture is likely to be mostly fresh because of infiltrating rain water. For climate-change and sea level-rise adaptation, in relation to vegetation and infrastructure management, it is important to understand this vertical relation between fresh and salt groundwater.

The other groundwater systems are nearly identical and are also recharged by brackish salt water from; the Industrial canal, London Ave canal, Bayou St. John, Orleans Canal, Canal street Canal, and Lake Pontchartrain around lower groundwater discharge areas. Recharged by fresh water infiltration areas include: the Mississippi and Metairie/Gentilly ridge (infiltrating rain water). Figure 6.7 presents these groundwater flow systems.

***Groundwater salinity measurements***

Groundwater salinity data was also collected during the borehole logging campaign. This was done through the collection of a water sample and an infield Electrical Conductivity (EC) measurement (Image 6.1). If possible, a groundwater sample was also collected from the open boreholes.

Most measurements showed fresh groundwater with EC values of lower than 1000 μS/cm but a number of samples showed a typical (not-disturbed) rain water salinity of around 100 μS/cm. Locations with higher EC measurements can likely be attributed to anthropogenic influences like fertilizers or drainage through the soil oxidation processes. An outlier with regards to salinity levels was recorded in the "bowl area" at the intersection of Napoleon Avenue and Loyola Street. EC levels of 8800 μS/cm were found and through control measurements, high chloride content was named as the defining factor for this anomaly. Further study is needed to explain this high inland measurement as this concentration is much higher than the recorded EC level of Lake Pontchartrain ( ~3000 μS/cm). A full list of the groundwater salinity measurements can be found in Appendix A.

*Figure 6.2. Highest groundwater level (m below surface)*

*Figure 6.3. Highest groundwater level (m MSL)*

*Figure 6.4. Lowest average groundwater level (m below surface)*

*Figure 6.5. Lowest average groundwater level (m MSL)*

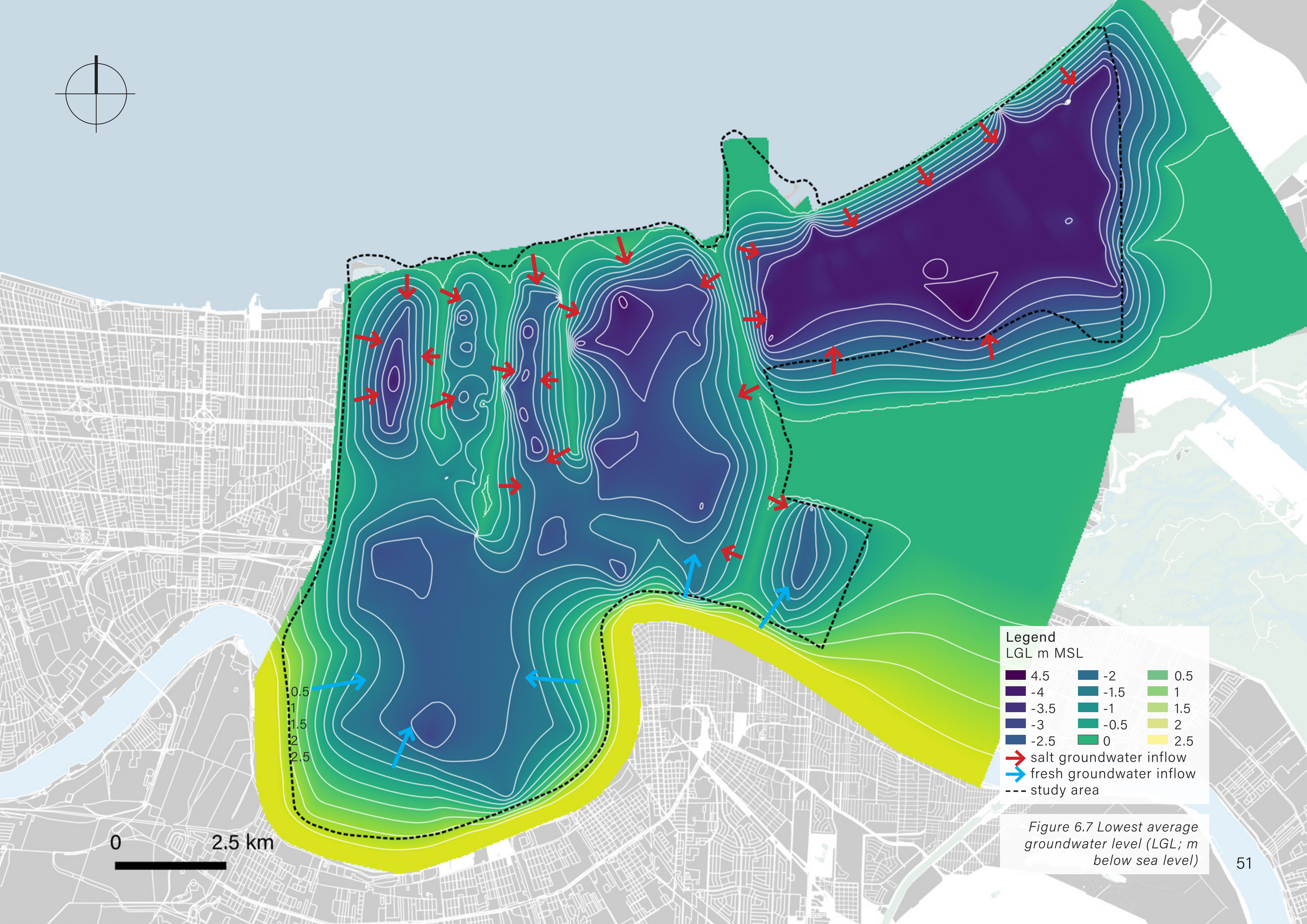


*Figure 6.7 Lowest average groundwater level (LGL; m below sea level)*

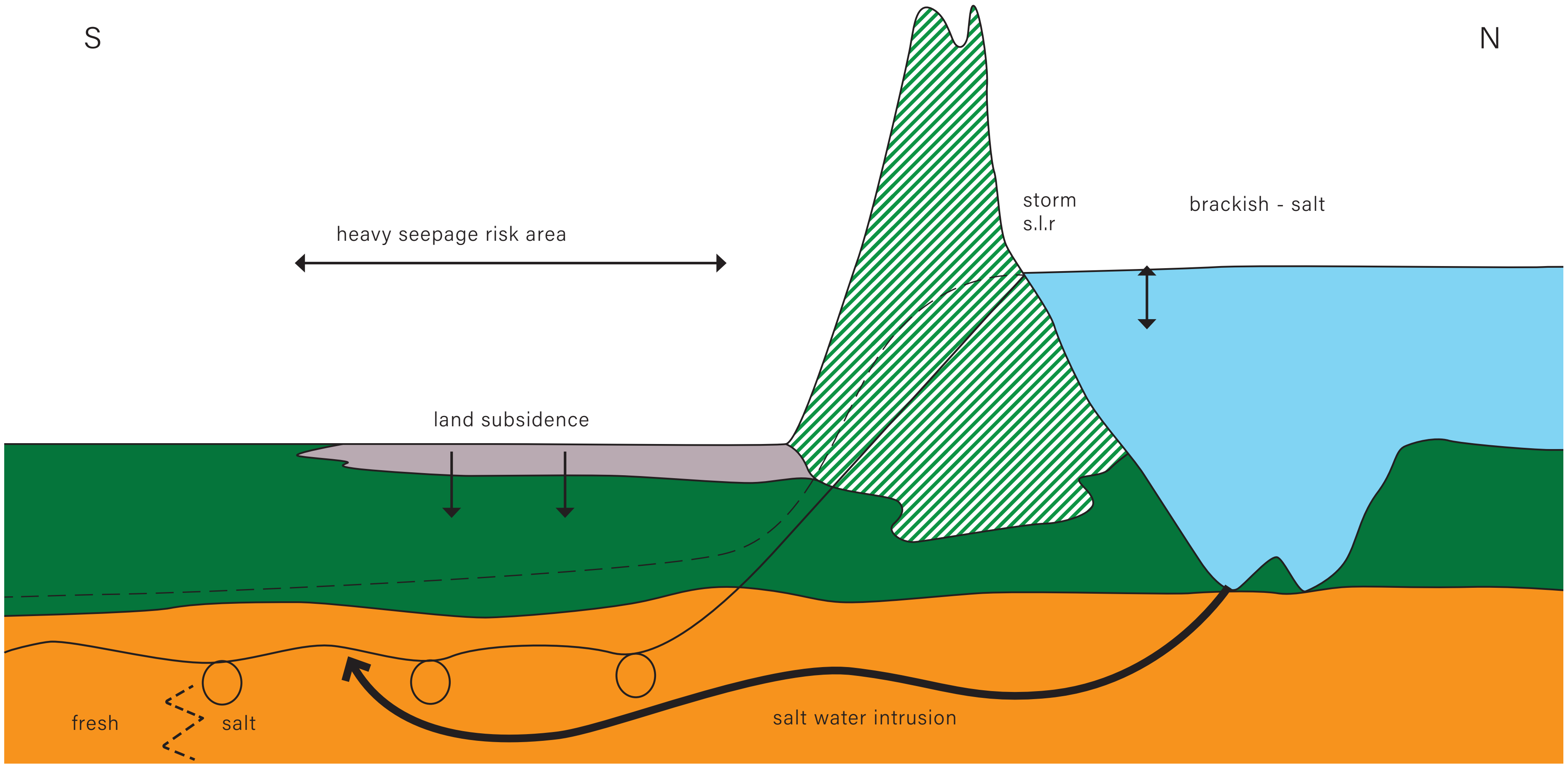


*Figure 6.8. Scheme of groundwater salinization process*

# 7.VULNERABILITY

A subsidence vulnerability map has been constructed based on collected borehole information. The first step in creating this map was to identify typical lithological sequences that present a high risk of shallow subsidence due to peat oxidation and compaction. These sequences can be found summarized in Table 7.1 and have depths ranging from 130 to 600 cm, with an average depth of 390 cm. Next, the delineation of polygons that represent the spatial distribution of the identified sequence types based on the borehole locations, a Digital Elevation Model (DEM) and contours of the top of the Pine Barrier Island was completed. The DEM was used to delineate sequence types (Figure 7.1) that are linked to a morphological surface expression such as natural levees, crevasse splays and fills. The top of the Pine Barrier Island contours were used to subdivide the class '(Organic) clay and/or (oxidized) peat on sand/loam' into a class with sand within 150 cm below surface and a class with sand deeper than 150 cm below surface.

The relative vulnerability for subsidence due to oxidation and/or compaction of the nine different sequence types are described in Table 7.1. The nine classes were then further categorized into three main classes: high vulnerability (red), medium vulnerability (orange) and low vulnerability (green) (Figure 7.2).

In the area north of the MG ridge (Lakeview, Gentilly, New Orleans) peat occurs at shallow depths and is mostly found within 3 m of the surface (with a maximum depth of 4 m below surface). When groundwater levels are lowered, either artificially or naturally during droughts, shallow peat is exposed to air and begins to oxidize, leading to subsidence. This process has already occurred within the area north of the MG ridge and can be seen through the oxidized peat found within 150 cm below surface. Peat found in this area may still be highly organic (see Figure 5.11 and 5.12) and is partly not yet oxidized, hence future subsidence due to oxidation is expected.

At present, the total thickness of peat occurring above the average lowest mean groundwater level (LGL) varies between 10 and 70 cm (Figure 7.3) with its organic matter content falling between 20% and 65%. If all peat above the LGL would oxidize and assuming a residual weight of 5% (not all material degrades during the oxidation process) the total amount of subsidence is estimated to fall between 1 and 40 cm for this area (Table 7.2).

Both north and south of the Metairie-Gentilly ridge peat is found to occur above and below the average LGL (Figures 7.4 & 7.5). In areas where peat occurs just below the LGL (Figure 7.3) lowering of the groundwater level will lead to peat exposure and consequently, to additional subsidence due to peat oxidation (Figure 7.5). In areas where peat occurs just below the LGL (Figure 7.4), lowering of the groundwater level will lead to exposure of this peat, and consequently, to additional subsidence due to peat oxidation.

*Table 7.1. Lithological sequence types, descriptions of sequence types and of their vulnerability for subsidence. Sequence types are grouped into three main classes of vulnerability: high (red), medium (orange) and low (green) subsidence vulnerability.*

| No | Lithological sequence type | Description | Subsidence vulnerability |
|---|---|---|---|
| 🟥 1 | Clay, organic clay, (oxidized) peat on sand/loam<br>1a. sand > 150 cm below surface<br>1b. sand < 150 cm below surface | Floodplain deposits (mainly clay, silty clay, silty clay loam) that are partly organic, intercalated with gyttja and peat layers that are partly oxidized (crumbly, no fibers), on top of sandy and/or loamy deposits of the Pine Barrier Island. The clay is often soft. Oxidized peat thickness < 70 cm (within 150 cm below surface, total peat thickness of 100 cm. A subdivision has been made into locations where the top of the sandy and/or loamy deposits occurs within or deeper than 150 cm below surface. | Vulnerable for subsidence due to oxidation and compaction.<br>- Class 1a, sand > 150 cm below surface<br>- Class 1b, sand < 150 cm below surface |
| 🟥 2 | 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 for subsidence due to compaction when loaded. |
| 🟨 3 | Clay on organic clay and peat | Floodplain deposits (> 200 cm thick; C-SiC-SiCL-CL) on organic clay and peat. | Vulnerable for subsidence due to compaction. Less vulnerable than class 2 because it has already been loaded and less soft clay layers occur. |
| 🟨 4 | Clay and silt on organic clay | Natural levee deposits (>100 cm C-SiC-SiCL-CL-L) on organic clay that may be soft and may include thick (ca 10 cm) wood fragments. | Vulnerable for subsidence due to compaction. Less vulnerable than class 3 because no true peat occurs |
| 🟨 5 | 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 (peaty clay/gyttja may occur) | Vulnerable for subsidence due to compaction. Somewhat less susceptible than class 4 because the overburden is heavier (containing sandy layers), hence more compaction has already occurred. |
| 🟩 6 | Clay | Floodplain deposits (C-SiC-SiCL-CL). Not organic, include both soft and firm clay intervals. | Vulnerable for subsidence due to compaction of soft clay layers. |
| 🟩 7 | 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. | Only clayey intervals are vulnerable for subsidence due to compaction. |
| 🟩 8 | 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. channel deposits). Depth of sand varies between 50 and 470 cm below surface. | Not much vulnerable to shallow subsidence. |
| 🟩 9 | Fill | Anthropogenic fill consisting mainly of sand but may also include clayey to silty layers. | Not much vulnerable to shallow subsidence. |

*C = Clay, Si = Silt, L = Loam, S = Sand*

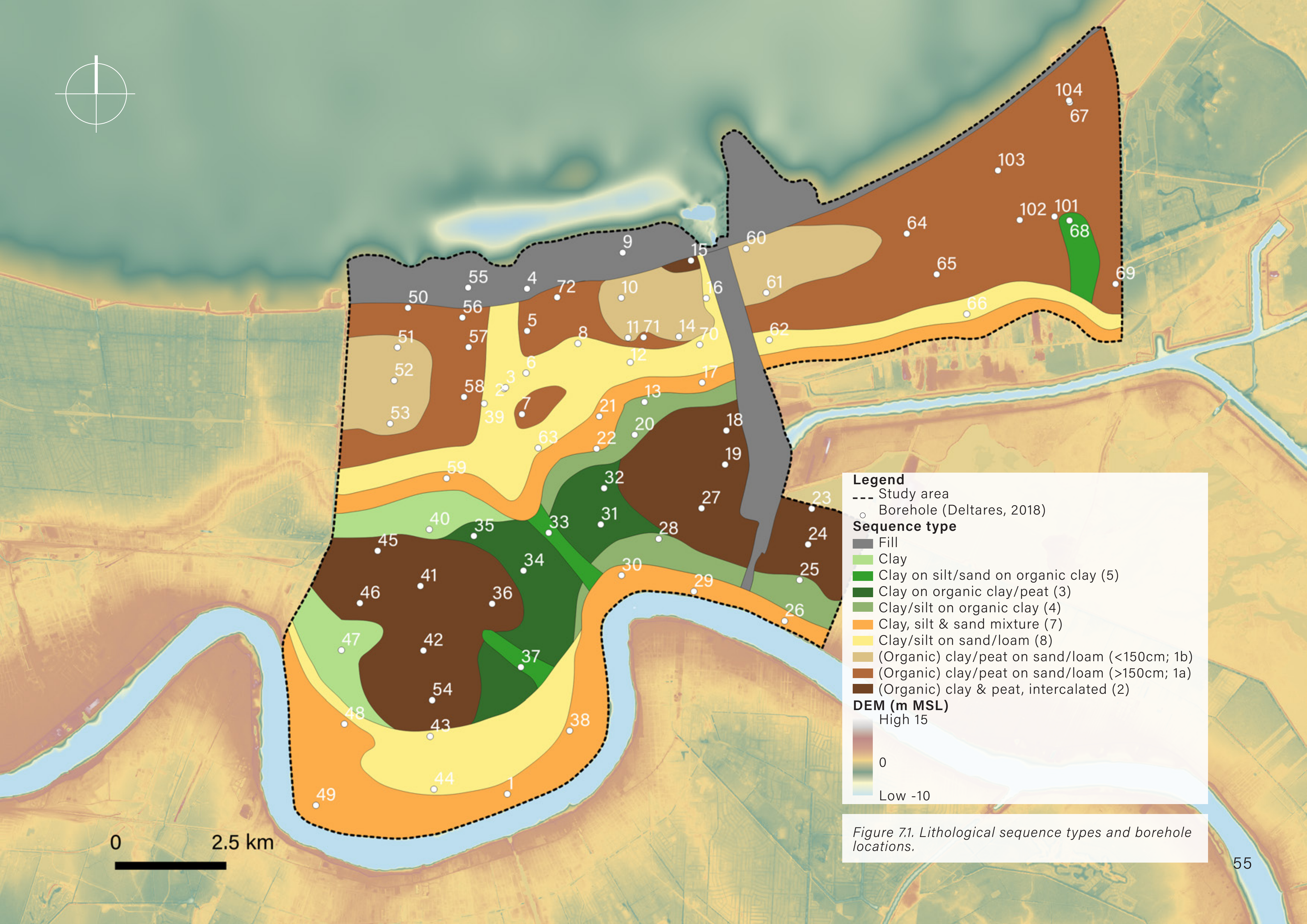


*Figure 7.1. Lithological sequence types and borehole locations.*

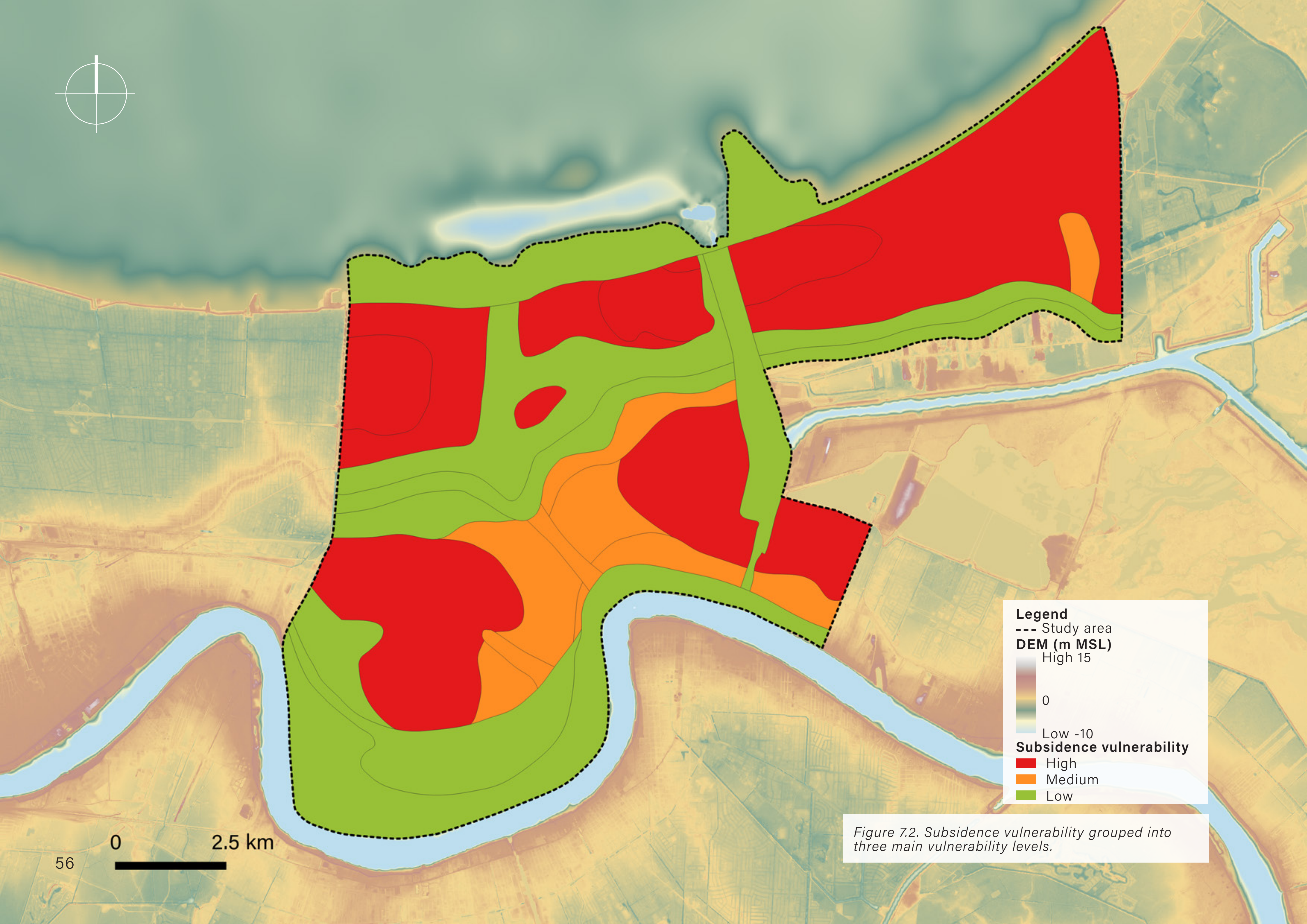


*Figure 7.2. Subsidence vulnerability grouped into three main vulnerability levels.*

*Table 7.2. Estimates of potential subsidence due to peat oxidation, based on borehole information.*

| Peat above LGL (cm) | LOI | LOI minimim (%) | Lost (%) | Subsidence (cm) |
|---|---|---|---|---|
| 10 | 20 | 5 | 15 | 1.5 |
| 30 | 20 | 5 | 15 | 4.5 |
| 50 | 20 | 5 | 15 | 7.5 |
| 70 | 20 | 5 | 15 | 10.5 |
| | | | | |
| 10 | 40 | 5 | 35 | 3.5 |
| 30 | 40 | 5 | 35 | 10.5 |
| 50 | 40 | 5 | 35 | 17.5 |
| 70 | 40 | 5 | 35 | 24.5 |
| | | | | |
| 10 | 65 | 5 | 60 | 6 |
| 30 | 65 | 5 | 60 | 18 |
| 50 | 65 | 5 | 60 | 30 |
| 70 | 65 | 5 | 60 | 42 |

Peat is found to occur below the LGL both north and south of the Metairie-Gentilly ridge (Figure 7.5). In areas where peat occurs just below the LGL (Figure 7.3) lowering of the groundwater level will lead to exposure and consequently to additional subsidence due to oxidation. Furthermore, lowering the groundwater level increases the load carried by the organic subsoil leading to an increased likelihood of subsidence due to compaction by loading. The area south of Metairie-Gentilly ridge is especially susceptible for subsidence due to peat compaction.

The current peat compaction grade in New Orleans varies between 10 and 60% (Figure 5.12), and the total thickness of peat below the LGL varies between 10 to 250 cm (Figure 7.3). Assuming a maximum peat compaction grade of 70%, the expected subsidence is generally in the order of centimeters to decimeters with extreme cases of up to 1.5 m (Table 7.3). In the first decades after loading, subsidence rates due to compaction are mostly in the order of cm/yr. For detailed assessments on future amounts and rates of subsidence due to peat compaction and oxidation, site-specific geologic and hydrologic information is required.

*Table 7.3. Estimates of potential subsidence due to peat compaction, based on borehole information and assuming a maximum compaction grade of 70%.*

| Peat below GLG (cm) | Compaction grade (%) | Max compaction (%) | Subsidence (cm) |
|---|---|---|---|
| 10 | 10 | 70 | 6 |
| 30 | 10 | 70 | 30 |
| 50 | 10 | 70 | 60 |
| 70 | 10 | 70 | 150 |
| | | | |
| 10 | 30 | 70 | 4 |
| 30 | 30 | 70 | 20 |
| 50 | 30 | 70 | 40 |
| 70 | 30 | 70 | 100 |
| | | | |
| 10 | 60 | 70 | 1 |
| 30 | 60 | 70 | 5 |
| 50 | 60 | 70 | 10 |
| 70 | 60 | 70 | 25 |

*Figure 7.3. Depth of the top of the first peat bed below the present lowest average groundwater level at borehole locations*

*Figure 7.4. Total thickness of peat above present lowest average groundwater level at borehole locations.*

*Figure 7.5. Total thickness of peat below present lowest average groundwater level at borehole locations.*

# 8.FINDINGS

The main findings from subproject 5 regarding the subsidence vulnerability assessment for New Orleans based on geologic and hydrologic information of the shallow subsurface are explained below:

- A substantial part of the surficial peat occurring north of Metairie-Gentilly ridge has already been oxidized and has partly disappeared. This is noticeable when comparing profiles created during this study with older USACE profiles from 1958 and the 2003 soil map from NRCS (Figure 8.1). This area still has locations where the total peat thickness may be up to 1 meter thick and occurs above, at or below the lowest mean groundwater level. At these locations peat may still be highly organic and thus, the area is still vulnerable for future subsidence due to peat oxidation and compaction.

- In large parts of the city south of the Metairie-Gentilly ridge peat occurs at greater depths below surface. This area is especially vulnerable to subsidence due to peat compaction.

- Remaining areas are less vulnerable to subsidence and in turn are assigned to an appropriate risk level category. At many places the subsurface contains abundant soft clays, sometimes with intercalated peat layers which are also vulnerable to compaction.

- Peat has been compacted ~31% on average. More subsidence due to peat compaction is expected.

- Care must be taken when drawing conclusions about land subsidence when using InSAR/LiDAR data. For land subsidence studies, high resolution raster elevation data with full coverage (not only constructions) are recommended in combination with ground measurements and geological surveys to relate subsidence to subsoil processes.

- When the French arrived around 1700, the ground elevation where New Orleans is currently located was above sea level. Subsidence started during the 19th century due to cypress tree logging and has continued until present, increasing due to drainage, levee construction and urban development.

- During dry periods groundwater levels drop to ~150cm (5 feet) below surface levels and during wet periods groundwater levels increase to ~50cm (1.5 feet) below surface.

- Shallow groundwater in the northern part of New Orleans is threatened by salinization. This process is the result of the past subsidence processes and can increase in the future due to sea level rise and continuing subsidence.

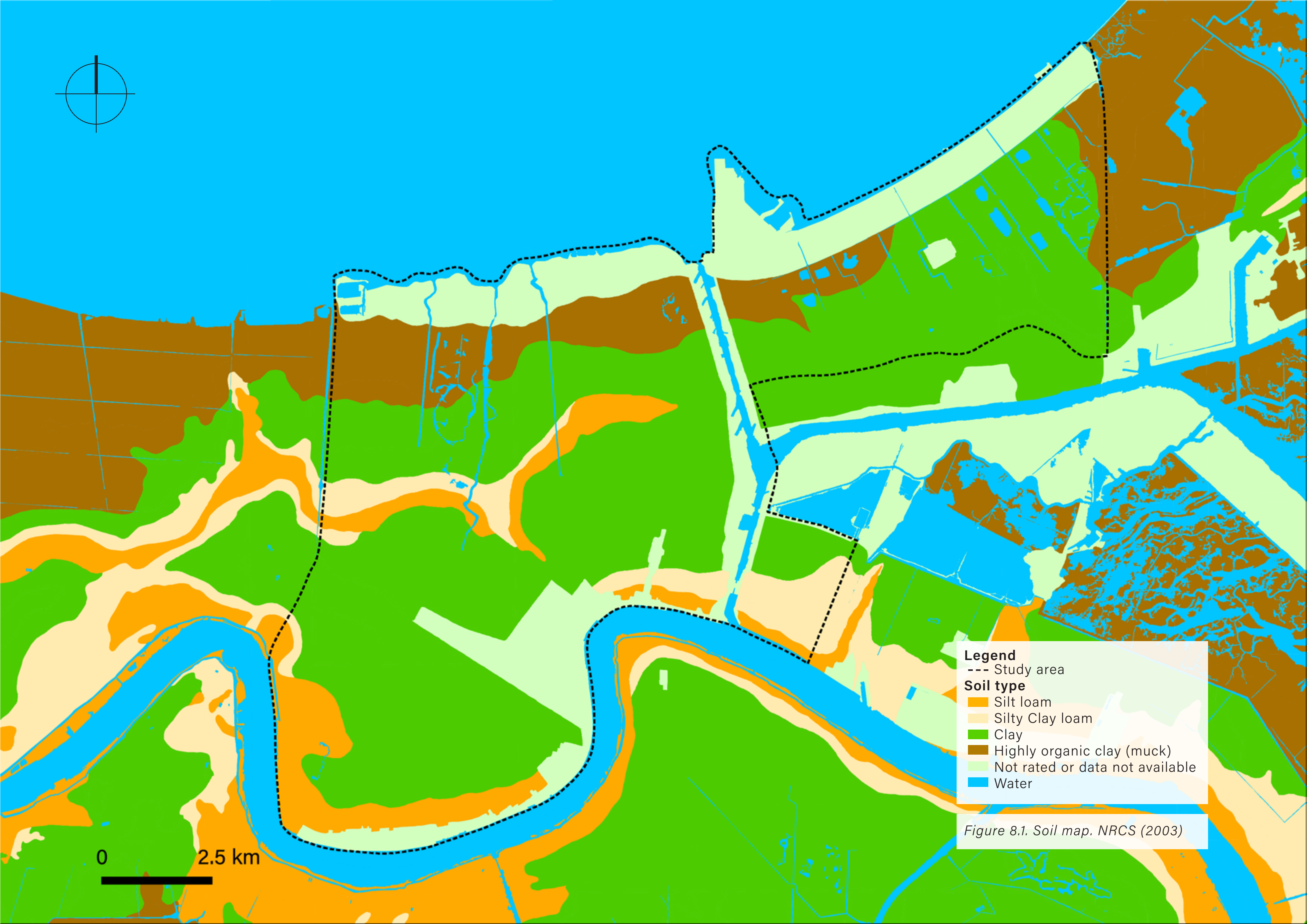


*Figure 8.1. Soil map. NRCS (2003)*

# 9. SUBSIDENCE-SENSITIVE URBAN PLANNING

The following chapter is divided in two sections: the first is comprised of an urban analysis and is followed with a toolbox containing suitable recommendations for subsidence-sensitive urban planning ideas for New Orleans.

## 9.1 Urban analysis

This section of the project defines three scales of action when dealing with shallow subsidence: city, district/neighborhood, and block (see Figure 9.1). The urban analysis addresses these three scales by taking into account specific features that are relevant to the elaboration of the recommendations.

### 9.1.1 City scale

As covered in earlier chapters of this report, the city of New Orleans faces several challenges due to shallow subsidence. In order to face these challenges, it is fundamental that knowledge about subsidence vulnerability is incorporated in urban planning and decision-making, especially regarding both public and private investments in areas with higher shallow subsidence vulnerability. In this regard, information about surface conditions and subsidence risks should be up to date and available for all stakeholders of the City.

The level of subsidence vulnerability (see Chapter 7, Figure 7.2) should be considered when developing or updating land use regulations by defining lower urban densities in areas with higher levels of

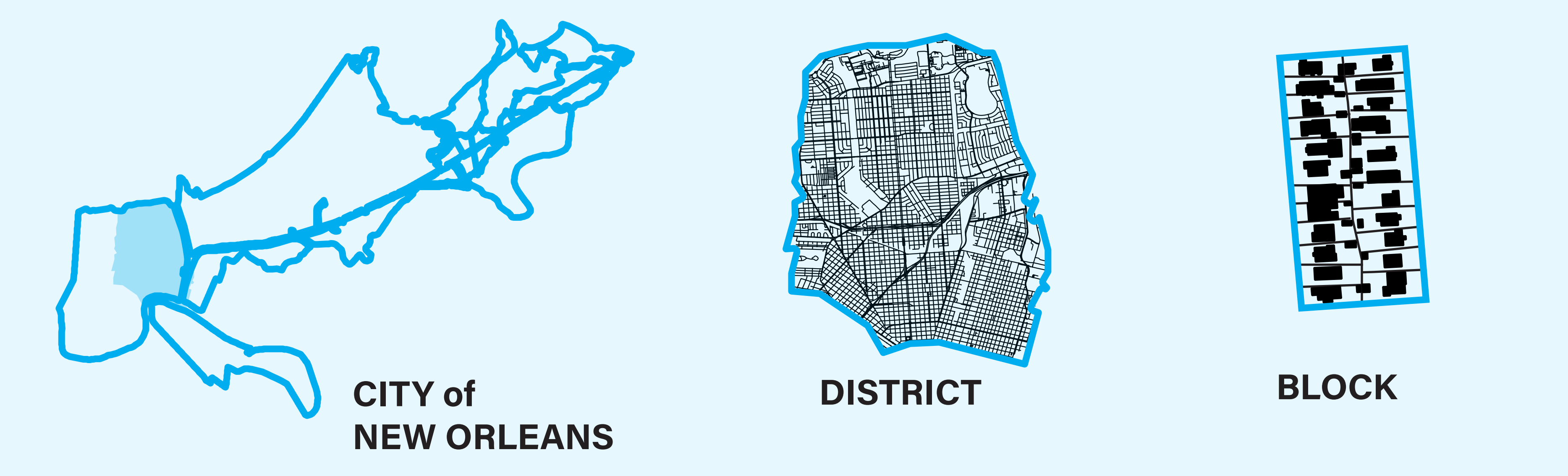


*Figure 9.1. Overview of the three scales of the project: City, district and block.*

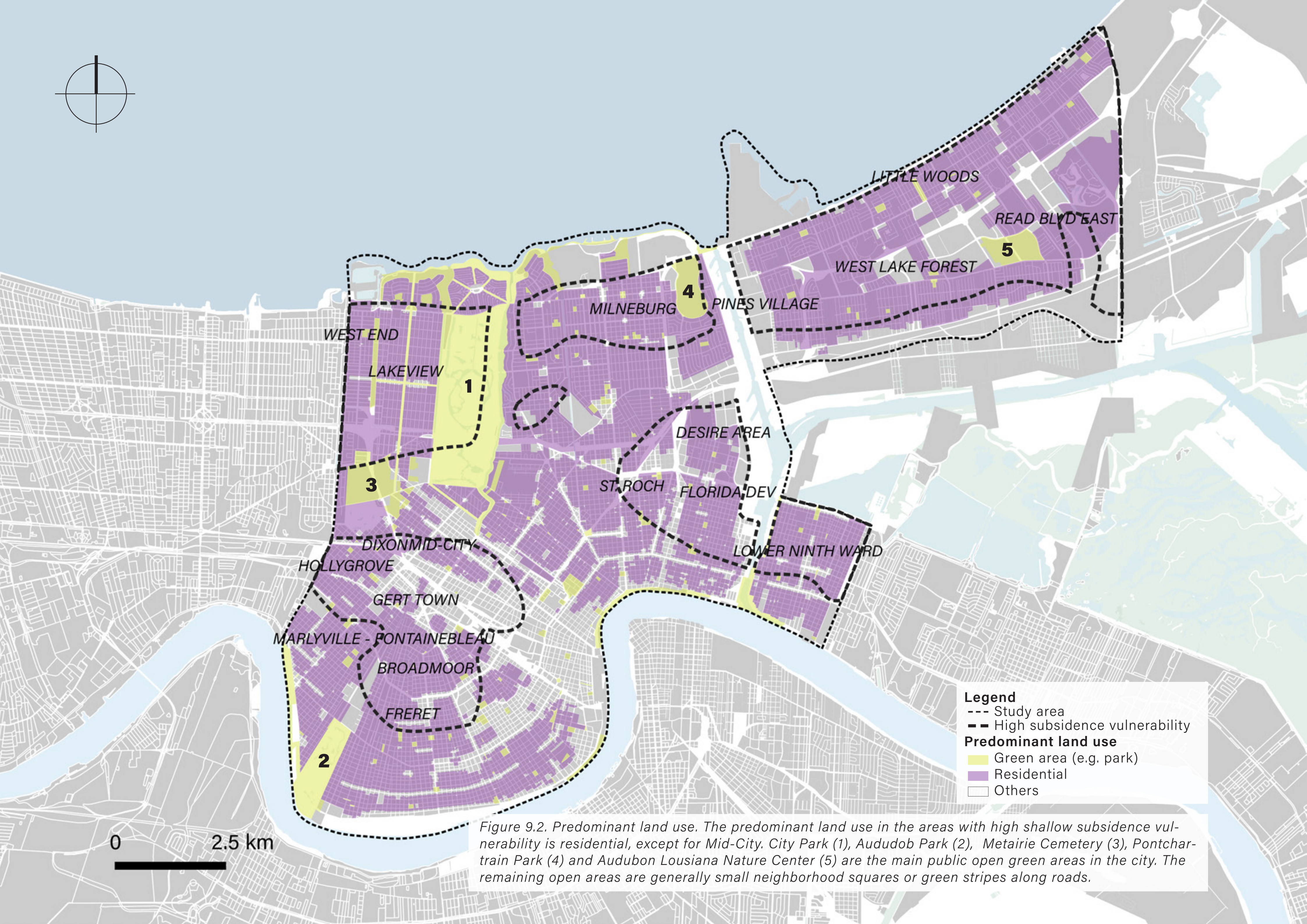


*Figure 9.2. Predominant land use. The predominant land use in the areas with high shallow subsidence vulnerability is residential, except for Mid-City. City Park (1), Aududob Park (2), Metairie Cemetery (3), Pontchartrain Park (4) and Audubon Lousiana Nature Center (5) are the main public open green areas in the city. The remaining open areas are generally small neighborhood squares or green stripes along roads.*

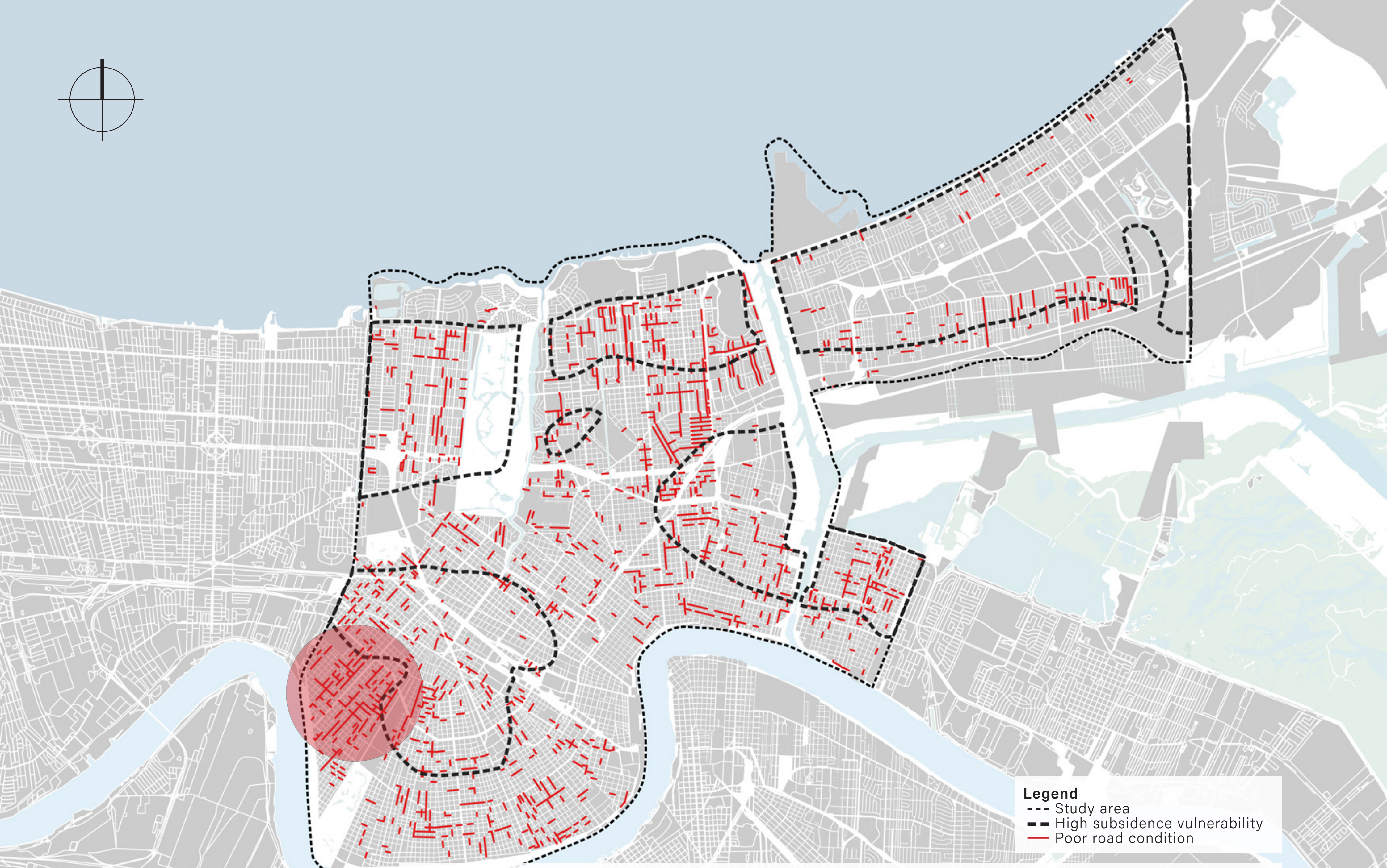


*Figure 9.3. Roads in poor condition, based on the infrastructure improvement project from the Department of Public Works and Sewerage, and Water Board of New Orleans. A road's poor condition could be a sign of subsidence problems, however it might also be influenced by its age and use, among others. The presence of multiple roads in poor condition in an area with low vulnerability to shallow subsidence (red circle) raises questions about a possible additional subsidence problems related to shrink/swell in clay soil that will be analyzed in future phases of this project.*

shallow subsidence vulnerability in order to decrease shallow subsidence due to peat compaction. This can be achieved by either changing the type of land use (e.g. commercial to open green area such as park or wetland, see Figure 9.2) or by limiting the type of construction (e.g. predominantly low-rise buildings). In addition to these steps, the use of lighter materials in the construction of all building types should be promoted (e.g. information, subsidies) and included in building regulations, as well as building on solid ground as oppose to soft soil areas (see Chapter 7, Figure 7.1).

The City's infrastructure presents another opportunity to improve the resilience of the shallow subsurface. Roads and sewerage systems are increasingly and negatively impacted by subsidence (see Image 9.1 and Figure 9.3). Because their design and construction follows standard engineering practices, they cannot adapt to the constant changes in surface conditions. If not already being done, large scale pre-loading should be incorporated into the design and construction of roads. Alternatively, lighter construction material could be used.

It is also recommended that the sewerage and drainage system be constructed with flexible connections to allow for the adaptation of the system within a dynamic subsurface environment. Figure 9.4 highlights the areas where there are both roads in poor condition and repairs in the sewerage system are planned. These highlighted areas may present an opportunity for the implementation of the abovementioned measures.

In addition, it is suggested that water storage measures be increased around the city and groundwater levels should not be lowered. The latter should be supported through the implementation and use of a groundwater monitoring system that allows for the control of groundwater levels. This control may help the city in becom-

*Image 9.1. Pavement in poor condition in Gentilly District. Source Google Street View, retrieved March 26, 2019*

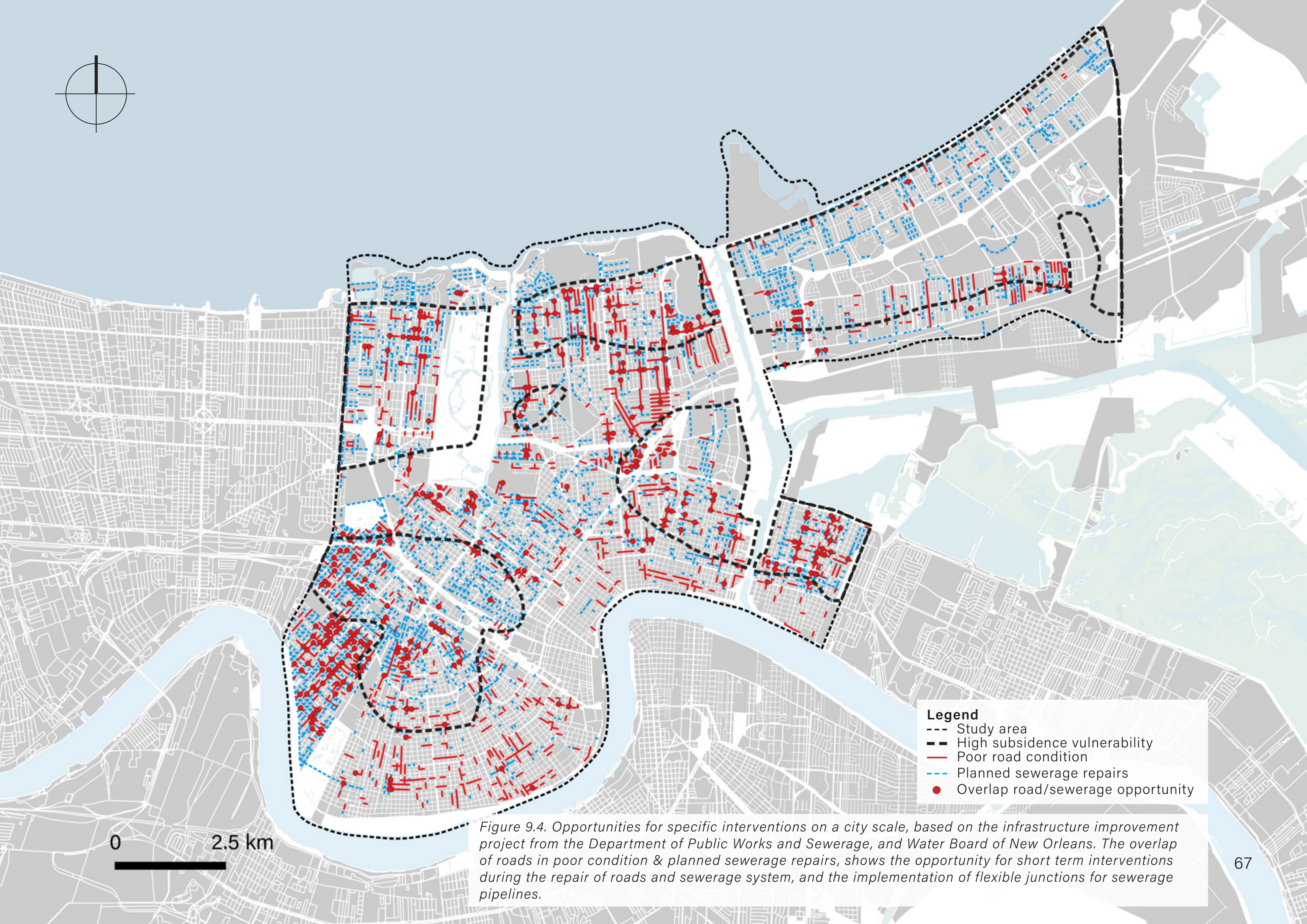


*Figure 9.4. Opportunities for specific interventions on a city scale, based on the infrastructure improvement project from the Department of Public Works and Sewerage, and Water Board of New Orleans. The overlap of roads in poor condition & planned sewerage repairs, shows the opportunity for short term interventions during the repair of roads and sewerage system, and the implementation of flexible junctions for sewerage pipelines.*

ing proactive and take control before the groundwater level fluctuation have additional visible effects on surface conditions in turn affecting infrastructure and buildings.

### 9.1.2 District scale & neighborhood

The different districts in New Orleans have different groundwater and soil characteristics present different degrees of shallow subsidence risks. In neighborhoods with higher vulnerability to shallow subsidence (Figure 9.6) which also tend to be the most recently developed areas (Figure 9.7), groundwater levels should be increased by ~1- 3 feet, especially where organic soils are present above the groundwater level (see Chapter 6). If it’s not possible to increase groundwater levels without incurring groundwater flooding risks, it is recommended to avoid further lowering of groundwater levels in those neighborhoods.

When renovating existing underground pipes, for both waste water and storm drainage, it is recommended to add the commercial equivalent of a French drain at the highest groundwater level (Image 9.2; Figure 9.5) to stop water from rising above this point.

Around the City, vacant lots are available

*Image 9.2. French drain.*

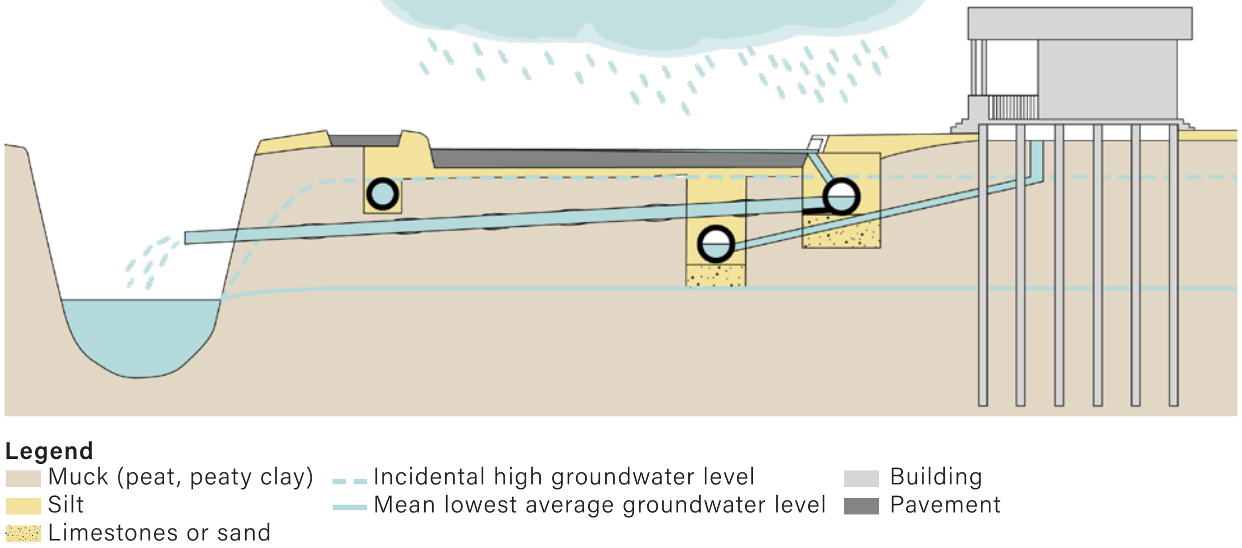


*Figure 9.5. Diagram of a French drain in context.*

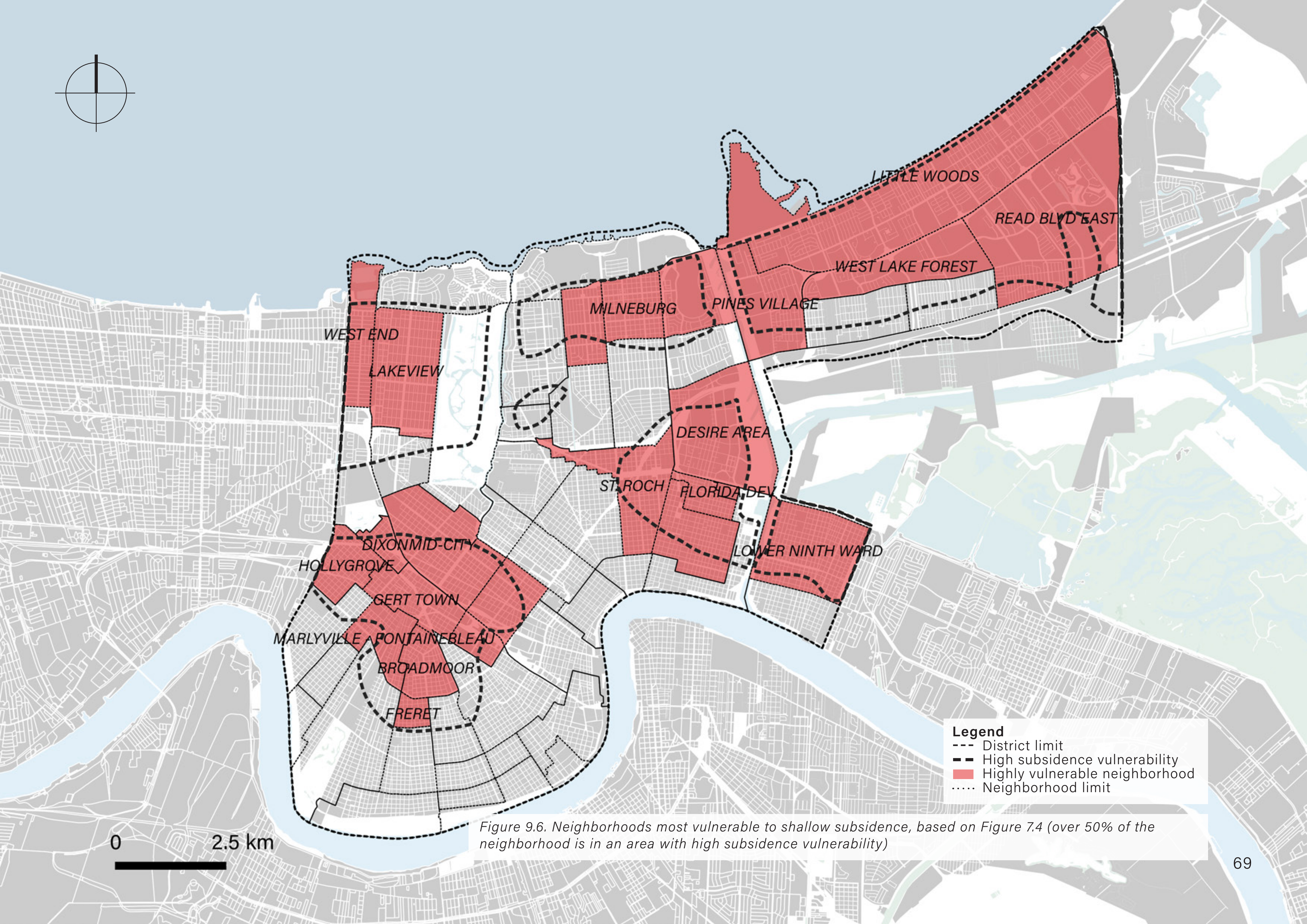


*Figure 9.6. Neighborhoods most vulnerable to shallow subsidence, based on Figure 7.4 (over 50% of the neighborhood is in an area with high subsidence vulnerability)*

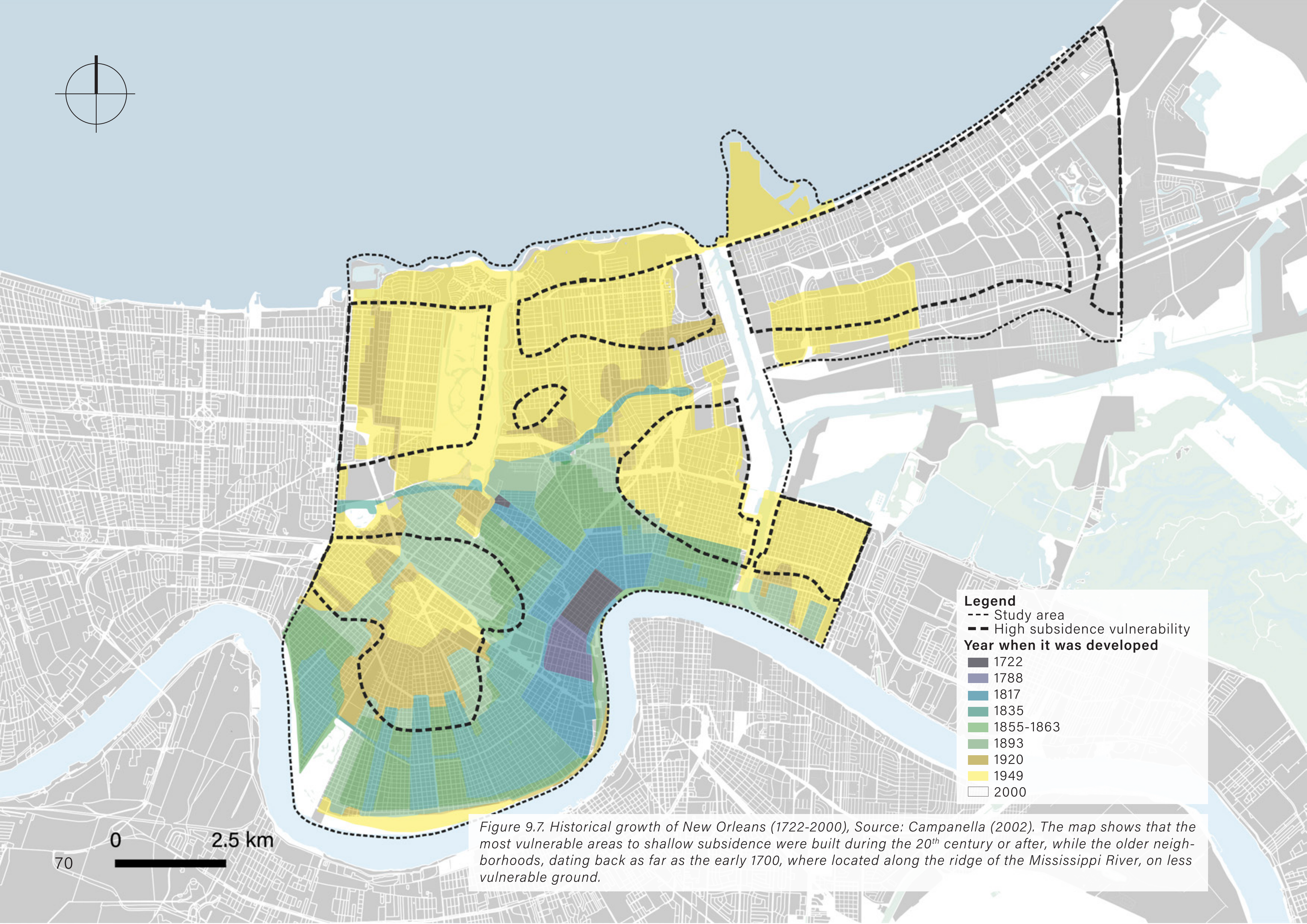


*Figure 9.7. Historical growth of New Orleans (1722-2000), Source: Campanella (2002). The map shows that the most vulnerable areas to shallow subsidence were built during the 20th century or after, while the older neighborhoods, dating back as far as the early 1700, where located along the ridge of the Mississippi River, on less vulnerable ground.*

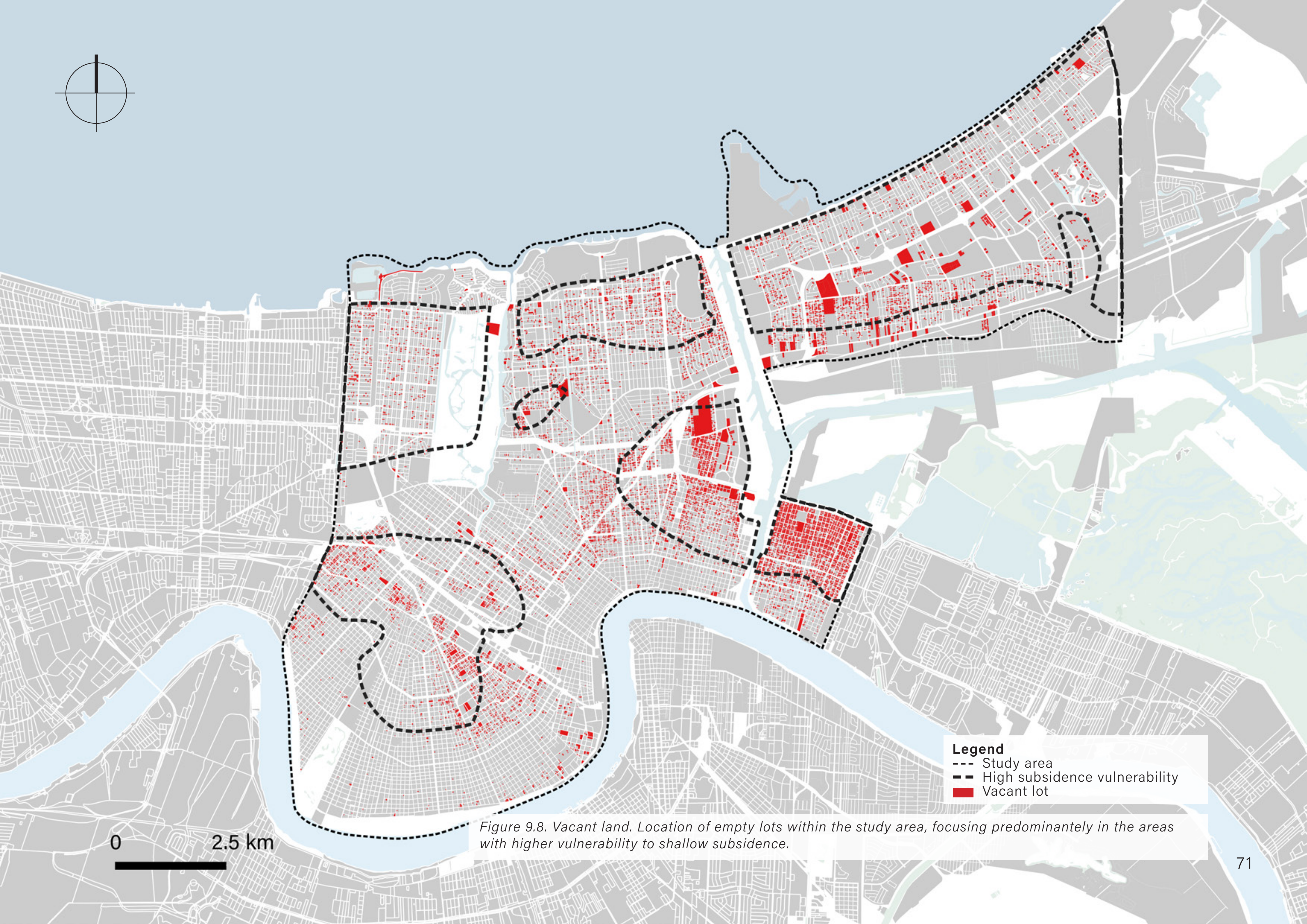


*Figure 9.8. Vacant land. Location of empty lots within the study area, focusing predominantely in the areas with higher vulnerability to shallow subsidence.*

and exist in areas with higher shallow subsidence vulnerability (Figure 9.8). In Lower Ninth Ward ~40% of the district's area is vacant, totaling 412 acres. This district has highest area of vacant lots in the city and presents an opportunity for neighborhood scale green infrastructure measures (e.g. wetland that serves for stormwater storage, infiltration, recreation and biodiversity). In other areas where vacant lots are not cluster together, rain gardens could be implemented (Figure 9.9, Image 9.2) to aid in water infiltration to the subsurface while providing green spaces open to the public for recreation purposes. Indirectly, this would help to improve the urban landscape quality of the area. Along with rain gardens, the use of permeable pavement in public spaces (Image 9.3) is a supporting measure to increase the infiltration of rainfall.

To complement these measures on a district and neighborhood scale, fact sheets could be produced to inform citizens about how to live with subsidence and water in their neighborhoods, the associated risks, and what can be done about them.

### 9.1.3 Block scale & private land ownership

Due to the nature of shallow subsidence, most of the measures recommended refer

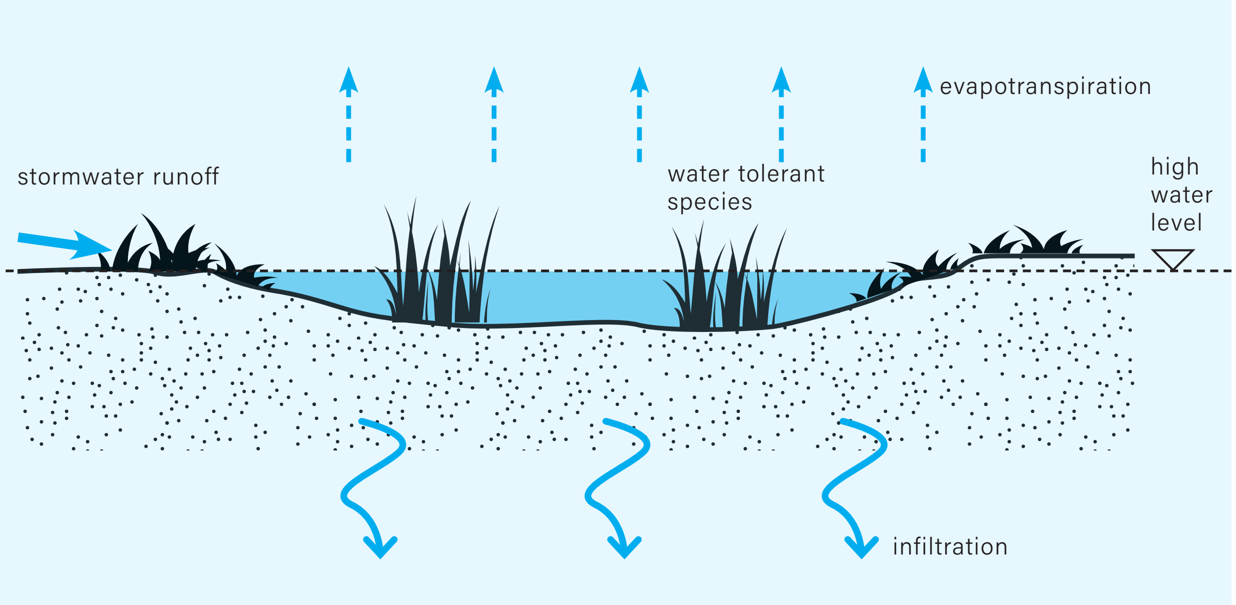


*Figure 9.9. Rain garden diagram*

*Image 9.2. Landesgartenschau, Gießen Germany, by Büro Geskes und Hack Landschaftsarchitekten*

*Image 9.3. Passeig De St Joan Boulevard, Barcelon - Spain, by Lola Domènech. Credits Adriá Goula.*

*Figure 9.10. Overview of built areas and location of relevant urban grid typologies: French Quarter (1), Carrolton (2), Lakeview (3), Milneburg (4) and Lower Ninth Ward (5).*

to larger scale actions. Nevertheless, at the block scale, the most relevant measures with respect to subsidence include (1) awareness raising campaigns and (2) the design and construction of subsidence adaptive housing. Awareness building should focus on private land owners, helping them understand the risks related to subsidence and how to incorporate this knowledge into their design, materials and building techniques.

### 9.1.4 Urban grid typologies

There are several urban grid typologies in New Orleans. On a block scale, the implemented measures and their effectiveness can vary, which is described below. The main grid typologies relevant for this study are summarized in Figure 9.10 and include: 1-French Quarter (Figure 9.11), 2-Carrolton (Figure 9.13), 3-Lakeview (Figure 9.15), 4-Milneburg (Figure 9.17) and 5-Lower Ninth Ward (Figure 9.18).

<u>Typology 1 - French Quarter</u>
Built area per block (app): 70%
Predominant building type: 2 floors
Predominant use: mixed (commercial/Residential)

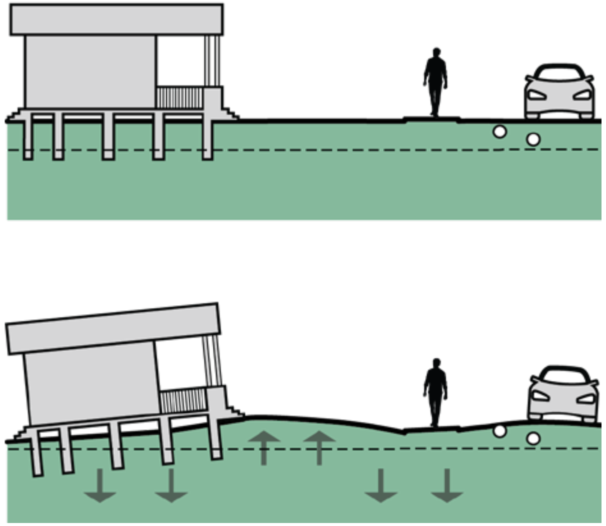
The French Quarter is the historic area of New Orleans (Image 9.4) and many of its structures date back to the early 1700s

*Figure 9.11. Typology 1 - French Quarter*

*Image 9.4. French Quarter. Source: Google Street View, retrieved March 26, 2019*

when building foundations were constructed using untreated wood. Although this neighborhood has not been heavily impacted by shallow subsidence because of its location on the levee of the Mississippi River, it is possible that fluctuations in groundwater levels may adversely affect the old, untreated wooden foundations. It is advisable to replace known, untreated wooden foundations with concrete piles when possible.

Typology 2 - Carrolton
Built area per block (app): 50%
Predominant building type: 1 floor
Predominant use: residential



**Legend**
----- Groundwater level
Type of soil
🟩 Clay

*Figure 9.12. Effect of water fluctuation in clay soils, producing shrink/swell and affecting infrastructure and potentially pooorly founded buildings*

*Figure 9.13. Typology - Carrolton*

*Image 9.5. Carrolton. Source: Google Street View, retrieved March 26, 2019*

Typology 2 is characterized by its relatively even urbanization with predominantly square housing blocks. This urban design planning provides a less efficient house to road ratio than in areas with bigger blocks and provides a greater opportunity for road damage to occur. Although the typology 2 location is outside areas with high subsidence vulnerability as can be seen in Figure 7.2, it presents significant damage to its road and sewerage systems. These

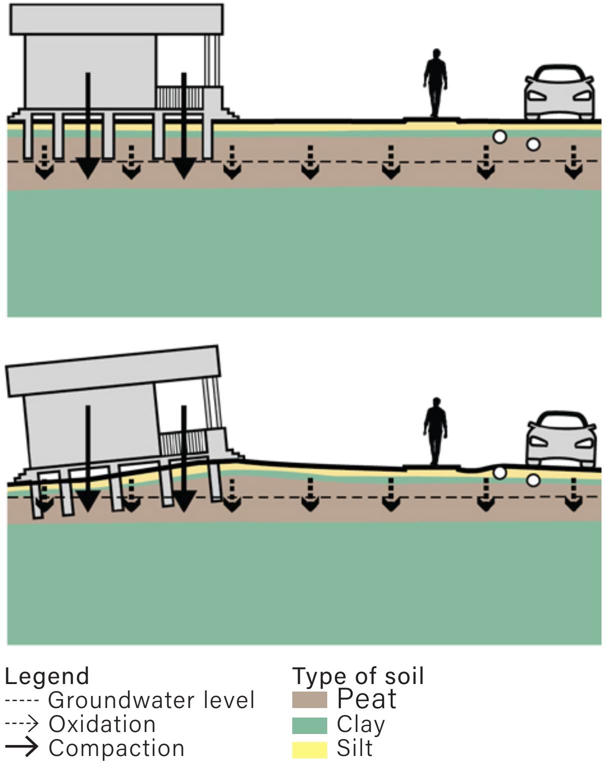


*Figure 9.14. Effect of oxidation on peat soils, producing subsidence.*

*Figure 9.15. Typology 3 - Lakeview*

*Image 9.6. Lakeview. Source: Google Street View, retrieved March 26, 2019*

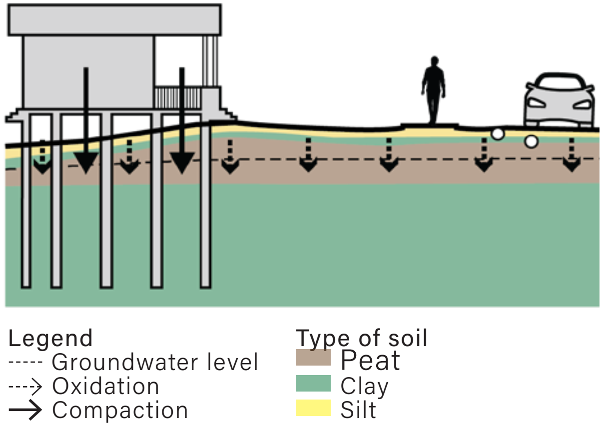


*Figure 9.16. Deeper fundations on solid ground could prevent the negative effects of subsidence on building. In addition, the implementation of private rain gardens could contribute to maintain groundwater levels, preventing further oxidation.*

damages could potentially be explained by the age of the neighborhood or the presence of clay soils that exhibit a shrink and swell property due to fluctuations in groundwater levels (Figure 9.13). It is advisable to reduce storm water drainage on public streets, to promote the use of permeable pavement, and to increase water storage and water infiltration on vacant plots (e.g. rain gardens) and in existing parks.

<u>Typology 3 - Lakeview</u>
Built area per block (app): 30%
Predominant building type: 1 floor
Predominant use: residential

*Figure 9.17. Typology 4 - Milneburg*

*Image 9.7. Milneburg. Source: Google Street View, retrieved March 26, 2019*

Typology 4 - Milneburg
Built area per block (app): 26%
Predominant building type: 1 floor
Predominant use: residential

Both Lakeview (3) (Image 9.6, Figure 9.14) and Milneburg (4) (Image 9.7, Figure 9.15) present similar characteristics with similar land uses and building density. Lakeview has a more efficient house/road ratio which could be related to the difference in road condition when considering both neighborhoods have a similar subsidence vulnerability risk (see Figure 9.3). Additionally, as both neighborhoods are considered in this study to have low building density, more room for green infrastructure measures in both private and public space could be applied (Figure 9.15). Examples include rain gardens in private lots, bioswales along roads and parking lots and infiltration basins in parks.

Typology 5 - Lower Ninth Ward
Built area per block (app): 13%
Predominant building type: 1 floor
Predominant use: residential

The main characteristic of typology 5 is the extremely low building density, smaller lot size and the high lot vacancy. Although it is possible to suggest neighborhood scale green infrastructure measures like in the previous typologies, the amount of

*Figure 9.18. Typology 5 - Lower Ninth Ward*

*Image 9.8. Lower Ninth Ward. Source: Google Street View, retrieved March 26, 2019*

vacant lots presents an opportunity for a larger scale intervention.

Any measures regarding building foundations need to be studied in detail, elaborating first an inventory of the existing types of building foundations and their vulnerability (e.g. concrete piles, wooden piles).

## 9.2 Recommendations for subsidence-sensitive urban planning

The main goal of this project and its proposed measures is to reduce shallow subsidence vulnerability in New Orleans. In Chapter 7 the main causes for shallow subsidence vulnerability were explored. The results point out to two main causes (1) the oxidation and subsequent compaction of peat soils due to the lowering of groundwater levels and (2) the shrink and swell of clay soils due to the fluctuations of groundwater levels. The following general recommendations provide an overview of key aspects that are suggested to be considered in the urban planning stage so the city can face the challenges resulting from subsidence. The general advice is followed by proposed concrete actions, first addressing subsidence prevention and when not possible, presenting adaptation strategies.

### 9.2.1 Integrated Approach and Assessment Framework for Subsidence

The following is a general integrated approach that supports the policy development path cities should follow from problem identification, to planning and implementation of solutions and their evaluation. Currently, New Orleans is in the problem analysis phase which focuses mainly on technical aspects like data collection and analysis. This is a crucial first step in being able to identify the causes of subsidence, begin developing models for the area and make predictions about future impacts. Key governance aspects within this phase are, raising awareness and stakeholder analysis. There are 12 key issues that need to be addressed within this approach in order to be able to deal with subsidence risks (Sinking cities, 2013):

#### 1. Restriction of groundwater extraction

In vulnerable areas, extraction (i.e. pumping) and drainage (i.e. through the use of canals, ditches, French drains, linking of sewerage, etc) of groundwater should be reduced or completely phased out. The following regulatory measures can be considered:

- Appropriate legislation and consistent implementation and enforcement of regulations
- Designation of groundwater regions and critical zones in case of pumping
- Restricted licensing and compliance checking for groundwater well drilling
- Universal groundwater use metering and charges for groundwater use
- Adequate design and maintenance of the underground pipe system (waste water, storm drainage) to avoid unplanned drainage of groundwater.

#### 2. Natural and artificial recharge of aquifers

Increase groundwater recharge at surface level using green infrastructure, permeable pavement, or other techniques. To compensate the negative effects of groundwater pumping, when addressed consistently and effectively, the reduction of groundwater mining can eliminate one of the primary causes of land subsidence. However, the prolonged effects of settlement, possibly taking up to 10 years before effects are seen, are not immediately solved. Natural and/or controlled groundwater recharge may be applied to speed up recovery (e.g. by making use of urban storm water), as well as controlled aquifer storage and recovery (ASR), a practice currently being developed and implemented in Shanghai and Bangkok.

### 3. Development of alternative water supply (instead of groundwater)

Currently, the supply of drinking water comes from the Mississippi while deep groundwater is extracted for industrial use. To meet future (urban) water demand, an alternative water supply for industry and domestic users is required. The process of shifting to an alternative supply should include water demand assessments (water footprint) and cost/benefit analyses. To develop a sustainable alternative water supply, the reduction of surface water pollution is vital.

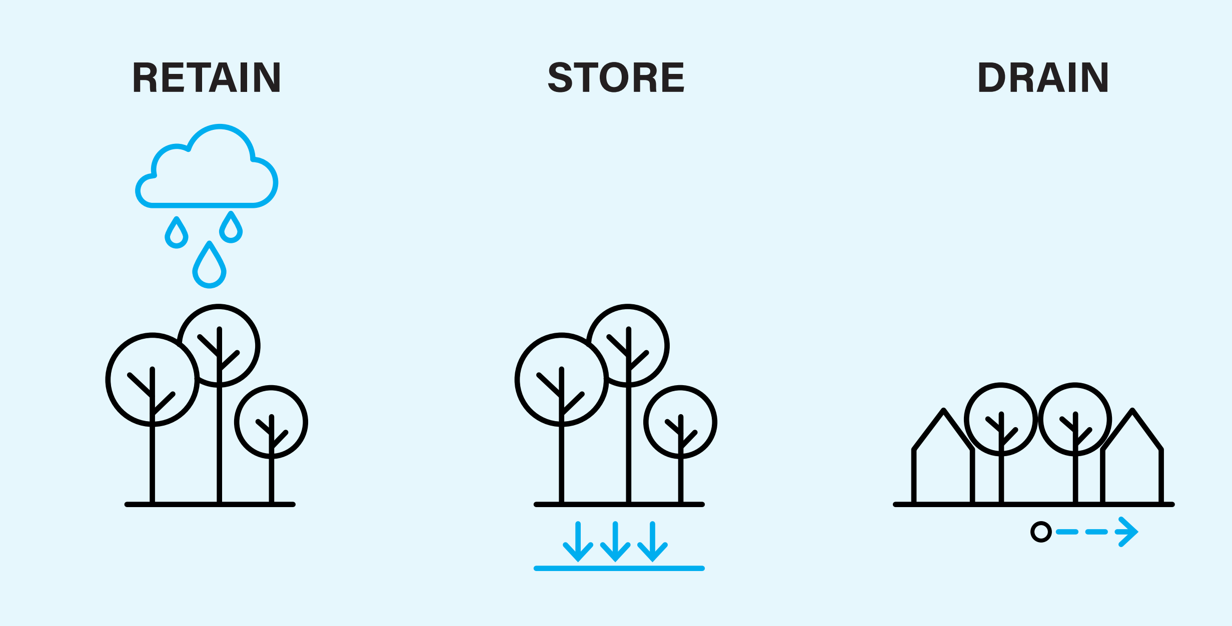


*Figure 9.19. Retain, store, drain diagram*

### 4. Integrated (urban) flood water management

Improved groundwater management and subsidence studies should be part of an integrated urban water resources management strategy that includes the water-subsurface interaction (Figure 9.19). Water resources management should be linked to flood mitigation. Ultimately, land subsidence is closely linked to integrated land and water management, including surface as well as subsurface resources and constraints.

### 5. Improving governance and decision-making

In many cases, governance alone is inadequate in addressing subsidence related issues. Programs realized through an integrated multi-sectoral approach and through the development of sustainable short- and long-term solutions is advisable. This involves public awareness campaigns, the encouragement of public participation, cooperation and coordination between stakeholders at different scales and levels, and enabling good decision-making that is supported by accurate models and decision-making tools.

### 6. Decision support models and tools

To support good decision-making, appropriate models and tools are needed. It is especially important to analyze the relationship between groundwater levels and subsidence, and develop modeling and forecasting capabilities by implementing an integrated groundwater–subsidence monitoring and analytical model. Moreover, it is essential that local agencies have the expertise and tools to conduct these studies and that they are engaged in ongoing capacity building, training, and knowledge exchange. Phases 1 “Sensors & Boreholes” and 6 “Groundwater & subsidence modeling” of this project focus on developing the models and tools needed to this end.

### 7. Appropriate monitoring and database system

Ongoing studies show that a major weakness in efforts to reduce subsidence and related flood risks is access to reliable ground truth data. To strengthen this area of weakness and build a good, reliable database with long time measurements of subsidence and groundwater information, it is necessary to develop and maintain geodetic monitoring networks throughout the metropolitan areas with stable, precisely calibrated benchmarks and periodic leveling surveys. Phases 2 “Databasing for monitoring, mapping & modeling” and 7 “Real-time control of water systems” of this project focus on acquiring the necessary data and designing the monitoring system to realize this step.

### 8. Integration of geotechnical aspects in planning and design of buildings and infrastructure

In the planning and design of heavy buildings and road infrastructure, geotechnical research and modelling of the subsoil should be considered to avoid subsidence problems which may include differential settlements over short and long timescales. This approach will help to avoid considerable damage to the project and reduce the potentially high maintenance costs relating to building infrastructure and foundations. During underground construction activities (ie projects relating to deep parking lots, metro-stations or tunneling), the effects of de-watering should be minimized and, if necessary, monitored and/or mitigated.

### 9. Asset management, financing and public-private-partnerships (PPP)

To minimize damage caused by subsidence, the main financial risks associated with investments and maintenance of assets (buildings, infrastructure) should be assessed. This will lead to improved design options, programming and prioritization of investments, making use of Real Options Theory and Asset Management. This approach involves determining performance indicators, functional specifications, risk mitigation measures and bonus/malus in (innovative) contracts. Moreover PPP and Private Financing approaches that build on sustainable business models should be explored. Cost-benefit analyses are also relevant when assessing different strategies and measures to face subsidence, relating to the feasibility of its implementation.

### 10. Exchange of knowledge and best practices

To minimize damage caused by subsidence, the main financial risks associated with investments and maintenance of assets (buildings, infrastructure) should be assessed. This will lead to improved design options, programming and prioritization of investments, making use of Real Options Theory and Asset Management. This approach involves determining performance indicators, functional specifications, risk mitigation measures and bonus/malus in (innovative) contracts. Moreover, PPP and Private Financing approaches that build on sustainable business models should be explored. Cost-benefit analyses are also relevant when assessing different strategies and measures to face subsidence, relating to the feasibility of its implementation.

Relevant examples of best practices are:

- The Dutch website https://geocontent.rvo.nl/funderingsviewer_storymap/ provides to any interested person, information about soil and subsidence risks, by just searching your zipcode.
- The Association of British Insurers ABI provides home owners with a fact sheet (Apendix 1), where they can find information about subsidence risks,

how to avoid them, and possible solutions in case of subsidence.

- The 2019 Covenant climate adaptive building in South Holland (Apendix 2) provides an overview of technical and economic measures and possibilities to be able to build adaptively to subsidence.
- In the Netherlands, groundwater levels are strictly planned: in urban areas they intend to be deeper than 70cm below surface, but in peat areas they need to be ~30cm below surface to prevent peat oxidation. In agricultural peat areas, the new policy is to keep groundwater levels as high as possible all year, by using infiltration drains.

Currently in the Netherlands, there are two financing schemes related to subsidence:

- The Dutch fund Funderingsherstel https://funderingsherstelfonds.nl/ provides loans to home owners affected by subsidence through their municipalities, only if the municipality is a participant of the fund.

- The Gemeentefonds (municipal funds) are funds provided by the Dutch central government to the municipalities. The funding is based on several factors, one of them being the soil type classification where the city is located.

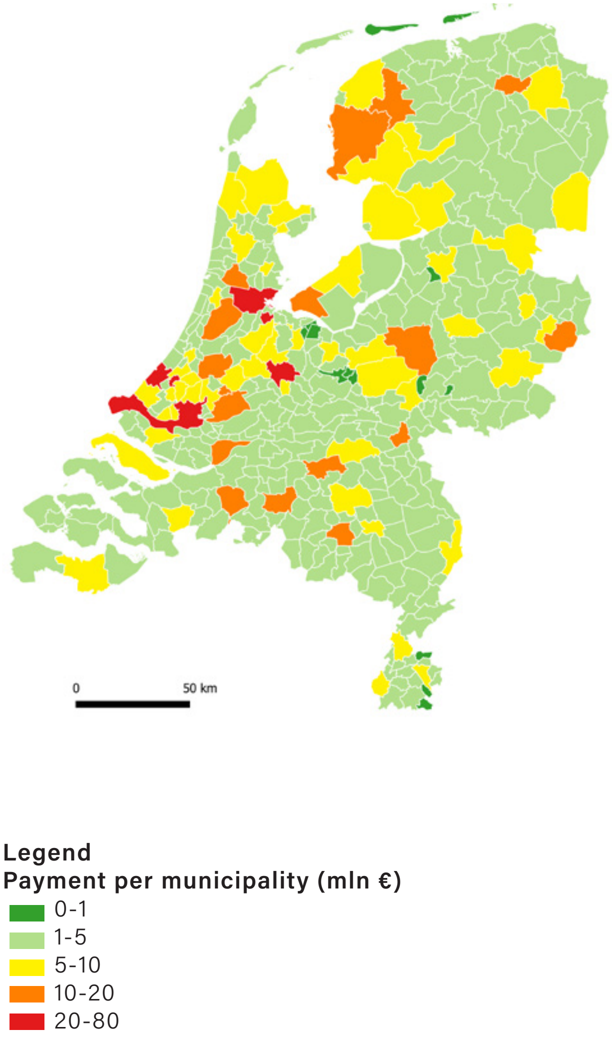


*Figure 9.20. Distribution of Dutch Municipal Fund for subsidence per municipality 2018*

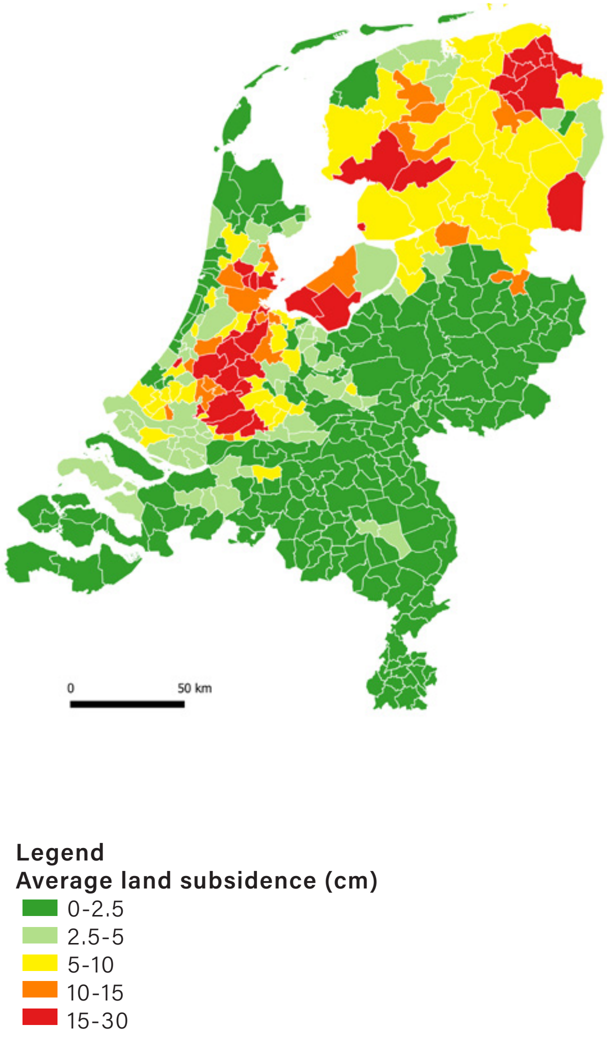


*Figure 9.21. Average land subsidence in the Netherlands per municipality 2016-2050*

According to this classification, soft soils (peat soils) are more vulnerable to subsidence, therefore municipalities on soft soils receive more funds because roads and pipes are more affected by subsidence and need more frequent maintenance (Figures 9.20 & 9.21)

**11. Integration of subsidence knowledge in spatial planning processes.**

Both in urban and rural areas, the processes taking place above ground, have a great impact on the subsurface. This is particularly true in urban areas, where preasures over the use of resources intensify. Land use, for example, can affect rainwater infiltration by making areas of the city more impermeable than others, in turn contributing to the lowering of the groundwater levels. Both buildings and infrastructure can also contribute to the compaction of the soil, exacerbating subsidence. The incorporation of subsidence knowledge and subsurface management is therefore a fundamental aspect of spatial planning (Figure 9.22)

**12. Building with nature**

Building with nature is the ultimate consideration when dealing with subsidence, because it gives room for adaptation in when facing uncertainty.

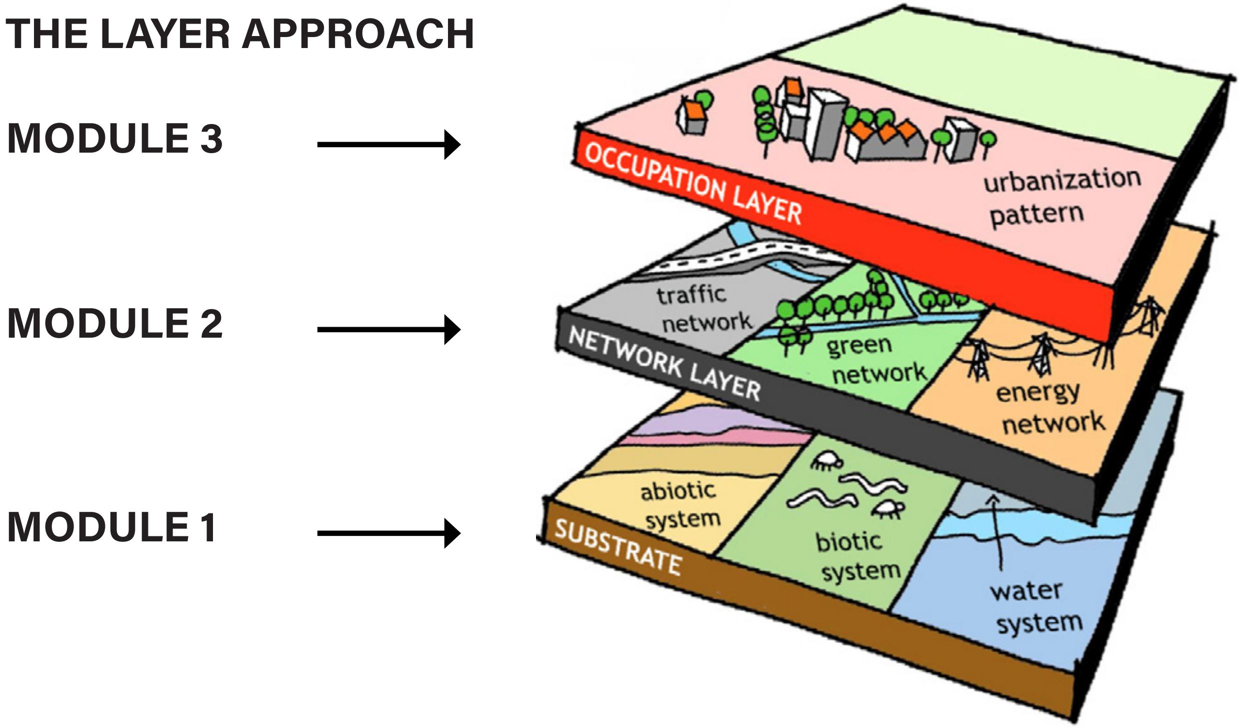


*Figure 9.22. Layer approach diagram*

### 9.2.2 Measures and activities for New Orleans

The following concrete measures and activities are suggested (Table 9.1):

*Table 9.1. Recommended concrete measures to better manage subsidence in New Orleans*

| **Measure** | **Activities** |
|---|---|
| 1. Improve subsidence knowledge<br>**"Living with soft soils"** | ▪ Identify subsidence research gaps to better manage the urban domain of New Orleans.<br>▪ Shrink/swell of shallow clay layers is a very damaging process and needs to be better understood to determine measures to  reduce its negative effects.<br>▪ Improve knowledge about compaction of soft soils<br>▪ Initiate studies, research projects and pilots in close cooperation with city departments (public works, parks and parkways, etc.) and SWBNO to improve maintenance and to reduce subsidence damage costs. |
| 2. Increase and stabilize groundwater levels in subsidence vulnerable areas<br>**"Soft soils need solid management"** | ▪ In vulnerable areas the groundwater level needs to be maintained as high as possible, especially during dry periods.<br>▪ This target level still needs to be substantiated. Too high (shallow) levels can influence the soil storage capacity for rain storms and therefore increase overland flow and urban flooding. This urban groundwater target level can be determined for each neighborhood.<br>▪ Nowadays, low groundwater levels are often 5-6 feet below surface. This target level needs to be 2-3 feet higher.<br>▪ Realizing this level needs to be considered during the design of green-blue infrastructure, like open canals, determining the optimal canal water level.<br>▪ Groundwater level is determined by drinking water loss, and drainage from sewer and storm drainage pipes. The impact on groundwater of the renovation of these systems needs to be understood.<br>▪ During the renovation of infrastructure (sewer, storm drainage) installation of French drains are recommended (approx. at groundwater target level). |
| 3. Prevent future groundwater level decrease | ▪ Better regulate temporally de-watering activities to protect against low groundwater levels<br>▪ Better maintain waste water and storm drainage systems, both the main public pipelines and their connection to private households ("herringbone" structure of groundwater drainage system). This is especially important when the building is founded on piles, because in those cases the connections are often more vulnerable. |
| 4. Increase groundwater and subsidence awareness | ▪ Website about soil characteristics & subsidence risks for land owners<br>▪ Fact sheet with explanation of the subsidence processes and measures against subsidence for land owners<br>▪ Installation of a number of simple, informational and attractive "subsidence monuments", presenting subsidence during the last 300 years.<br>▪ School programs, including school monitoring sites. |
| 5. Consider subsidence vulnerability in urban planning | ▪ Lower densities (e.g. low rise buildings) or alternative land use (e.g. green, water storage) in subsidence vulnerable areas<br>▪ Increase green areas (e.g. rain gardens, squares, parks, etc) to increase infiltration of rainwater |
| 6. Construction considering subsidence knowledge | ▪ Improved building regulations that address subsidence risk<br>▪ Subsidence adaptive building: floating buildings<br>▪ Subsidence resistant building: deeper foundations made of resistant materials (e.g. concrete)<br>▪ Road foundations  made of lighter materials or a series of shallow piles<br>▪ Pre-load roads (Image 9.9) and building locations with sand to avoid later damage due to compaction of the soil<br>▪ Pipe connections with flexible joints (including flexible connections with buildings) |
| 7. Monitor | ▪ Monitor subsidence (satellite every 2-3 years, install shallow extensometers)<br>▪ Groundwater (evaluating existing monitoring network)<br>▪ Monitor sea-level rise and droughts |

Image 9.9. Pre-loading of roads. Credits Rijkswaterstaat beeldarchief

# REFERENCES

**Campanella, R.** (2002) Time and Place in New Orleans: Past Geographies in the Present Day, Pelican Publishing Company.

**Dixon, T.H., Amelung, F., Ferretti, A., Movali, F., Rocca, F., Dokka, R., Sella, G., Kim, S.-W., Wdowinski, S., Whitman, D.** (2016) Subsidence and flooding in New Orleans. Nature 441, 587-599.

**Dunbar, J.B., Britsch III, L.D.** (2008) Geology of the New Orleans Area and the Canal Levee Failures. Journal of Geotechnical and Geoenvironmental Engineering, vol. 134(5), 566-582.

**Frazier, D.E.** (1967) Recent deltaic deposits of the Mississippi River: their development and chronology. Gulf Coast Association of Geological Societies Transactions, vol. 17, 287-315.

**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: Baton Rouge, LA, Louisiana Geological Survey-Louisiana State University for Coastal Protection and Restoration Authority of Louisiana, 140 p., 3 pls.

**Heiri, O., Lotter, A.F., Lemcke, G.,** (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. J. Paleolimnol. 25 (1):101–110. https://doi.org/10.1023/A:1008119611481.

**Jones, C.E., An, K., Blom, R.G., Kent, J.D., Ivins, E.R., Bekaert, D.** (2016) Anthropogenic and geologic influences on subsidence in the vicinity of New Orleans, Louisiana. Journal of Geophysical Research: Solid Earth 121, doi:10.1002/2015JB012636.

**McLindon, C.** (2016). The Geology of New Orleans – Implications for Planners. Online available at https://www.slideshare.net/jkray/the-geology-of-new-orleans.
**Saucier, R.T.** (1963) Recent Geomorphic History of the Pontchartrain Basin. Louisiana State University Press, Baton rouge, USA.

**National Geographic World Map** & World Topographic Map both provided as Basemap in ArcGis Pro. (scale 1: 20.000)

**NRCS** (2003) Soil map. Available at https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.

**Otvos, E. G., & Giardino, M. J.** (2004). Interlinked barrier chain and delta lobe development, northern Gulf of Mexico. Sedimentary Geology, 169(1-2), 47-73.

**Reston, V.A.** (1891-1892). Topographic Quandrangle [map]. (scale 1: 62500)

**Reston, V.A.** (1938-1939). Topographic Quandrangle [map]. (scale 1: 31680)

**Reston, V.A.** (1951-1952). Topographic Quandrangle [map]. (scale 1: 24000)

**Reston, V.A.** (1965-1967). Topographic Quandrangle [map]. (scale 1: 24000)

**Reston, V.A.** (1965-1967)Topographic Quandrangle, photorevised 1972-1979 [map]. (scale 1: 24000)

**Reston, V.A.** (1992 &1967) Topographic Quandrangle, photorevised 1994 [map]. (scale 1: 24000)

**Reston, V.A.** (1998-1999) Topographic Quandrangle [map]. (scale 1: 24000)

**Rogers, J.D.** (2008) Development of the New Orleans Flood Protection System prior to Hurrican Katrina. Journal of Geotechnical and Geoenvironmental Engineering 134 (5). doi: 10.1061/(ASCE)1090-0241(2008)134:5(602).

**USACE** (1958) Geology of the Mississippi River Deltaic Plain, Southeastern Louisiana. Technical report 3-483, Vicksburg, Mississippi.

**Van Asselen, S.,** (2011). The contribution of peat compaction to total basin subsidence: implications for the provision of accommodation space in organic-rich deltas. Basin Res. 23 (2):239–255. https://doi.org/10.1111/j.1365-2117.2010.00482.x.

**Zimpel, C.F.** (1834). Topographical Map of New Orleans and its Vicinity [map]

# APENDIX

## 1. Fact sheet, Association of British Insurers ABI

### Subsidence - Dealing With The Problem

### Introduction

It is the sight every homeowner dreads - cracks appearing in the walls of their home. But don't fear the worst - while there has been an increase in subsidence claims in recent years, most buildings suffer minor cracking at some time so it doesn't mean that there is a subsidence problem.
This information sheet explains:

- What subsidence is and how it can affect a property;
- What signs may indicate there could be a problem with the property;
- What can be done to reduce the risk of subsidence; and
- How household insurers will investigate potential problems and deal with any claim.

What is subsidence?

Subsidence is the downward movement of the ground supporting the building. Particular problems arise when the movement varies from one part of the building to another.

It can be caused by:

- Certain soils - Clay soils are particularly vulnerable to subsidence since they shrink and swell depending on their moisture content.
- Vegetation - Trees and shrubs take moisture from soils causing them to shrink. This is especially so during long periods of dry weather as roots extend in search of water.
- Leaking Drains - Damaged drains can soften or wash away the ground beneath the foundations.
- Less commonly, problems may occur where properties are built over, or close to, mine workings.
- Other types of ground movement, which can result in cracking and structural damage, are:
- Heave - the upward movement of the ground supporting the building.
- Landslip - movement of ground down a slope.

What should you look out for?

The first obvious sign of subsidence is the appearance of cracks. However, not all cracks indicate that there is a problem. Most buildings experience cracking at some time and there is no need to be alarmed by every crack that appears. Cracks are not uncommon in new properties and newly built extensions. They are likely to be the result of the building settling under its own weight. These usually are nothing to worry about, nor are fine cracks that often appear in newly plastered walls as they dry out. Buildings shrink and swell naturally due to changes in temperature and humidity, which can lead to minor cracks where walls and ceilings meet. These too should not normally be anything to worry about.

What should be looked out for are small, usually diagonal, cracks which suddenly appear in plaster work inside and outside bricks at weak points, such as around doors and windows, especially after long periods of dry weather. These may, but not necessarily, indicate movement in the building´s foundations. The cracks will normally be thicker than a 10p coin, and usually be wider at the top. Doors and windows may also “stick” due to the distortion of the building.

Can you do anything to reduce the risk?

Yes. Taking a few simple precautions can help reduce the risk of structural damage.

Trees and shrubs planted too close to a property are a common cause of problems. The attached table indicates the suitable planting distances of various trees from houses, garages or outbuildings. You should also consider the proximity of trees to underground drains and buildings including any belonging to neighbours. Ensure that trees and shrubs are pruned regularly. Expert advice should be sought from an arborist to make sure they are pruned correctly. Regular general maintenance checks should be carried out around a property. Checks should be made for blocked or leaking drains; dirt and leaves cleared from gutters; and pipes checked to make sure there are no splits.

## Cover provided by household insurance

A buildings insurance policy will normally cover damage caused to a property by subsidence, heave or landslip. Damage to walls, gates, fences, patios, drives and swimming pools will not usually be covered unless a home is damaged at the same time and by the same cause. The policy should set out what is and what is not covered. However, if any clarification is required, an agent or the insurer will be happy to help.

Policyholders will normally have to pay the first part of any claim - the excess. This will be detailed in your policy.

If the damage is so serious that a home cannot be lived in, most buildings, and even contents, policies will pay for the cost of comparable alternative accommodation, while the damage is being investigated and the repair work is carried out. This will be subject to a limit which is usually a percentage of the sum insured.

## When should you contact your buildings insurer and what will they do?

As soon as you believe there may be a problem, you should contact your buildings insurer. A policy will normally require the insurer to be advised of any potential claim as soon as possible and, in any event, it is sensible because the sooner the problem is investigated, the quicker everything can be put right the less inconvenience will be caused.

It will first be necessary to identify the cause of the damage and what needs to be done to stop it. Once any movement has been stabilised the necessary repairs can be carried out.

Insurers really do understand and appreciate policyholders' concerns and will do all they can to minimise the worry and inconvenience. Insurers will also keep policyholders informed of developments at every stage.

## Handling a claim

Once they are aware of the damage, the insurer may arrange for a structural engineer and other specialists to carry out detailed investigations to decide the best course of action. These experts will report back to the insurer with their recommendations and then supervise any work that needs to be done.

Alternatively, the insurer may advise the policyholder to contact a structural engineer (it may be able to provide a list of recommended firms) so that the problem can be investigated. Once again, the insurer should then know the cause of the problem and how best to deal with it. Investigations may include digging holes to find out the type of soil, the depth and condition of the foundation and whether roots are causing a problem – this is quite normal.

It may also be necessary to monitor the width of cracks or other signs of movements over a period of time, usually for at least twelve months, so that the extent of the problem can be accurately established. Once all the information has been collected and analysed, then a plan of action can be drawn up to cure the problem.

Today, very few cases of subsidence are likely to require under-pinning - the strengthening or deepening of building foundations. Generally, further damage can be prevented by the professional removal or pruning of trees, repairing drains, or by localised repairs to brickwork. Then internal decorations will be renewed to complete the job.

If a property has suffered coal mining subsidence damage, the Coal Authority or mine owner mining in the area will be responsible for dealing with any claim. If a problem arises contact should be made with the Coal Authority (01623 427162) - as they will be able to provide information regarding the procedure involved. At the same time, the buildings insurer should also be informed.

What happens if you change your insurer?

If you change your buildings insurer and then discover a subsidence related problem, any claim may be dealt with under the Association of British Insurers' Domestic Subsidence Claim Handling Agreement. The agreement sets out which insurers will be responsible for handling any claim. The majority of household insurers subscribe to it. If a claim is made within the first eight weeks of the changeover, the previous insurer will deal with it. Claims between 8 weeks and 1 year will be handled by the new insurer with the cost of settlement shared equally between the two insurers.

Any claims made a year after the changeover means that the new insurer alone will deal with the claim.

Things to remember

If cracks suddenly appear, it does not necessarily mean there is a major problem. Careful attention should be paid to the type, size and distance of any trees and shrubs from a property

While buildings insurance covers damage caused by subsidence, heave or landslip, there will normally be an excess which the policyholder will have to pay – you should check your policy to see what excess you have.

You should contact the buildings insurer as soon as you believe there is a problem. They are there to give help and guidance. If you change insurer and a problem arises, there is an ABI Agreement that sets out which insurer will deal with the claim.

## 2. Covenant climate adaptive building in South Holland

### Why?

- We have to deal with climate change and the consequences of this have a major impact on society. It is of great importance that we build climate adaptively and work together to learn and accelerate.
- The South Holland adaptive delta will become the national leader in climate adaptive building. Here we put the possibilities into practice. Our findings form the “springboard” to a national approach and any sector-wide agreements / standards.
- We acknowledge the assignment and confirm that all parties that play a role in construction in South Holland, both public and private, have a joint responsibility in this and are also the owners.
- That is why we will work together more intensively and at an early stage to make this delta as adaptive as possible.

### How?

- From 4 October we want to build new-build locations, including areas for transformation and explanation, as climate-adaptively as possible and commissioning parties that are part of this ‘Coalition of the Willing’ - including at least the municipalities in the urbanization alliance - are actively asking for this and to send. With regard to possible solutions, attention is paid to, among other things, facades, roofs, foundations and the outside space.
- We strive for:
  1. Less flooding
  2. More biodiversity
  3. Less heat stress
  4. Less prolonged drought and fewer adverse consequences
  5. Less subsidence and fewer adverse consequences
- Then there was prior to the spatial development of the housing plan.
- The participating municipalities work together on this and will apply the same principles.
- We are converting “traditional procurement” into constructive public-private dialogues with the highest possible degree of transparency in order to jointly find solutions.
- We take into account the quality of the living environment, environment, biodiversity, technical, financial and economic aspects and we pay attention to affordability and manageability.
- And we use the stress tests such as municipalities that are (already) required to carry out as an instrument, supplemented with an instrument to be determined for biodiversity, to be able to assess the plans in advance.
- We refer to this in the zoning plans / environmental visions.

### What?

- We prepare a “white paper” with an overview of technical and economic measures and possibilities as we know it now to be able to build adaptively
- Together we ensure that we understand, supplement and where possible improve these measures
- The measures address the challenges: heat stress, prolonged drought, extreme precipitation, subsidence and increasing biodiversity
- We are developing a “climate mortgage” with financiers.

### Awareness & Urgency

- We formulate clear messages, whereby we have formulated the following goals:

1. We make all parties involved aware of their role and importance, and we strike in municipal authorities the bridge between policy and implementation.
2. We help companies to properly “sell” the market opportunities that arise here.
3. We make it clear to owners and end us-

ers why this is to their advantage (or conversely: why not doing this is ultimately more expensive).

- In the coming 1.5 years we will start with the current guide to stress tests and ours to (further) develop an instrument to improve the degree of adaptivity of existing and practical experiences identify new urban environments to be built.
- In the meantime, from the beginning of 2019 we will use a minimum “schedule of requirements” for the climate adaptability of new developments.
- We formulate these minimum requirements together: the water boards, municipalities, managers, designers, property owners, builders, developers, financiers and the province do this together.
- We set up a system of “climate accounting” with financiers in which we assess the financial effects of climate-proof building, for the sake of “awareness” and for the benefit of development of new climate proof financing models.

## 2. Boreholes locations

*Table. Borehole locations using coordinate system Louisiana South State Plane Coordinates (epsg: 3452), ground elevation at borehole location (all elevation measurements use NAVD88), (ground) water level measured one day after coring (Water Elevation) and during coring (GW field) , elevation of the top of permanent water observation pipe, Lowest Groundwater Level (LGL), Highest Groundwater Level (HGL), Electrical Conductivity (E.C.) and pH of groundwater. Detailed geological descriptions of corings will be online available.*

| Bore # | Northing | Easting | Ground Elevation (feet MSL) | Water Elevation (feet MSL) | Bore Location | Top of Observation Pipe | Ground elevation (m MSL) | GLG (m below surface) |
|---|---|---|---|---|---|---|---|---|
| 001 | 518620,695 | 3676308,791 | 7,606 | 2,586 | Chippewa/Pleasant | 7,473 | 2,318 | 4,15 |
| 002 | 548832,086 | 3676085,706 | 0,052 |  | 4532 Bancroft-Rear |  | 0,016 | 1,60 |
| 003 | 548909,217 | 3676179,535 | -3,302 |  | 4532 Bancroft-Front |  | -1,006 | 1,43 |
| 004 | 556287,079 | 3677782,085 | 1,120 |  | Boreas Park |  | 0,341 | 2,30 |
| 005 | 553138,709 | 3677785,810 | -5,687 |  | Cabrini Ct |  | -1,733 | 1,80 |
| 006 | 549997,804 | 3677709,738 | -5,285 |  | Mirabeau/Cartier |  | -1,611 | 1,60 |
| 007 | 546927,123 | 3677402,974 | -6,023 |  | St Bernard/Caton |  | -1,836 | 1,45 |
| 008 | 552201,589 | 3681574,703 | -6,482 |  | Filmore/Wildair |  | -1,976 | 1,80 |
| 009 | 558976,285 | 3684912,254 | 5,558 |  | Live Oaks Park |  | 1,694 | 1,10 |
| 010 | 555605,053 | 3684805,916 | -7,453 |  | Robert E Lee/St Roch |  | -2,272 | 1,90 |
| 011 | 552629,205 | 3685309,230 | -6,003 |  | Filmore/St Roch |  | -1,830 | 1,80 |
| 012 | 550799,319 | 3685476,044 | -2,105 | N/A | Mirabeau/Music |  | -0,642 | 2,80 |
| 013 | 547835,533 | 3686537,953 | -0,666 | -1,978 | Verbena/Iris |  | -0,203 | 2,80 |
| 014 | 552715,327 | 3689101,254 | -4,984 | N/A | St Ferdinand/Press |  | -1,519 | 1,40 |
| 015 | 558390,600 | 3690005,107 | -3,451 | -4,992 | Hayne/Congress |  | -1,052 | 1,54 |
| 016 | 555579,006 | 3691137,113 | -6,532 | N/A | Congress/Prentiss |  | -1,991 | 1,30 |
| 017 | 549282,938 | 3690831,464 | 2,737 | N/A | Chef Menteur/Press |  | 0,834 | 2,80 |
| 018 | 545707,037 | 3692641,371 | -2,741 | N/A | Morice Duncan/Higgins |  | -0,835 | 0,90 |

| GLG (m MSL) | GHG (m below surface) | GHG (m MSL) | GW field (m below surface) | GW field (m MSL) | Water Elevation (m MSL) | EC 1 | EC 2 | EC 2 name | pH | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| -1,83 | 1,20 | 1,12 | 4,00 | -1,68 | 0,788 | | | | 6,0 | |
| -1,58 | 1,00 | -0,98 | 1,30 | -1,28 | | 2370 | 3160 | Bayou | 7,0 | Bayou: EC 3160 |
| -2,44 | 1,20 | -2,21 | 1,45 | -2,46 | | 490 | | | | |
| -1,96 | 1,00 | -0,66 | 2,13 | -1,79 | | | | | 7,0 | |
| -3,53 | 0,60 | -2,33 | 1,60 | -3,33 | | | | | | |
| -3,21 | 0,40 | -2,01 | 1,50 | -3,11 | | | | | 5,0 | |
| -3,29 | 0,60 | -2,44 | 0,90 | -2,74 | | | | | 6,0 | |
| -3,78 | 0,50 | -2,48 | 1,63 | -3,61 | | | | | | |
| 0,59 | 0,20 | 1,49 | 0,15 | 1,54 | | 1207 | | | 6,0 | |
| -4,17 | 0,80 | -3,07 | 1,10 | -3,37 | | | | | | |
| -3,63 | 0,50 | -2,33 | 0,44 | -2,27 | | 300 | | | 4,5 | |
| -3,44 | 0,40 | -1,04 | N/A | N/A | | 106 | | | 5,5 | minimum LGL |
| -3,00 | 0,60 | -0,80 | N/A | N/A | -0,603 | 196 | | | 6,5 | |
| -2,92 | 1,40 | -2,92 | 1,40 | -2,92 | | | | | 5,0 | minimum LGL/HGL |
| -2,59 | 1,10 | -2,15 | 0,20 | -1,25 | -1,522 | | | | | |
| -3,29 | 1,30 | -3,29 | 0,80 | -2,79 | | | | | 5,0 | minimum LGL/HGL |
| -1,97 | 0,50 | 0,33 | 1,12 | -0,29 | | | | | | |
| -1,74 | 0,70 | -1,54 | 0,70 | -1,54 | | | | | | |

| Bore # | Northing | Easting | Ground Elevation (feet MSL) | Water Elevation (feet MSL) | Bore Location | Top of Observation Pipe | Ground elevation (m MSL) | GLG (m below surface) |
|---|---|---|---|---|---|---|---|---|
| 019 | 543172,612 | 3692544,832 | -4,246 | -7,461 | Abundance/Desire |  | -1,294 | 1,50 |
| 020 | 545394,803 | 3685806,367 | -4,322 | -7,931 | Stuart R Bradley School |  | -1,317 | 1,70 |
| 021 | 546764,467 | 3683165,419 | 0,806 | -1,163 | Mount Olivet Mausoleum |  | 0,246 | 2,20 |
| 022 | 544351,411 | 3682965,397 | -1,893 | N/A | St Anthony/I-610 |  | -0,577 | 2,80 |
| 023 | 539883,642 | 3699004,820 | -5,201 | -8,744 | Florida/Choctaw |  | -1,585 | 1,10 |
| 024 | 537211,905 | 3698732,968 | -3,347 | -7,546 | N Johnson/Flood |  | -1,020 | 1,40 |
| 025 | 534551,937 | 3698100,049 | -0,193 | -3,703 | Urquhart/Caffin |  | -0,059 | 2,40 |
| 026 | 531496,952 | 3696984,618 | 5,964 | 3,340 | Flood/N Peters |  | 1,818 | 2,40 |
| 027 | 539910,873 | 3690790,306 | -4,720 | N/A | N Miro/Piety |  | -1,439 | 1,60 |
| 028 | 537620,875 | 3687594,724 | 0,530 |  | Villere/Port | 0,870 | 0,162 | 1,65 |
| 029 | 533707,349 | 3690220,469 | 5,828 | 2,678 | Chartres/Congress |  | 1,776 | 3,70 |
| 030 | 534906,019 | 3684825,095 | 4,434 | -2,554 | Royal/Elysian Fields |  | 1,351 | 4,20 |
| 031 | 538702,694 | 3683277,177 | -1,106 |  | St Anthony/N Roman |  | -0,337 | 1,30 |
| 032 | 541407,239 | 3683525,284 | -4,723 | -7,610 | N Dorgenois/Pauger |  | -1,440 | 1,40 |
| 033 | 538080,005 | 3679397,749 | 1,024 | -5,603 | Esplanade/N Tonti |  | 0,312 | 3,10 |
| 034 | 535254,654 | 3677516,606 | -0,554 | N/A | St Louis/N Miro |  | -0,169 | 2,10 |
| 035 | 537840,909 | 3673818,876 | -3,268 | N/A | Jefferson Davis/Conti |  | -0,996 | 1,50 |
| 036 | 532786,123 | 3675178,848 | -3,948 | N/A | Gravier/Tonti |  | -1,203 | 1,00 |
| 037 | 528059,213 | 3677325,271 | 1,682 | -3,141 | Lasalle/Earhart |  | 0,513 | 2,50 |
| 038 | 523339,439 | 3680955,901 | 7,436 |  | Orange/Annunciation |  | 2,267 | 3,60 |
| 039 | 547716,983 | 3674581,029 | 1,939 | -8,001 | Bayou Oaks bridge |  | 0,591 | N/A |
| 040 | 538328,342 | 3670499,032 | -3,391 | -7,262 | Cleveland/Solomon |  | -1,034 | 1,40 |
| 041 | 534109,579 | 3669834,540 | -3,416 | -5,712 | Telemachus/Palmetto |  | -1,041 | 1,50 |
| 042 | 529297,960 | 3670057,391 | -3,823 |  | General Pershing/S Dupre |  | -1,165 | 1,30 |
| 043 | 522917,666 | 3670558,332 | -0,904 | -4,283 | Napoleon/Loyola |  | -0,276 | 2,70 |
| 044 | 518976,452 | 3670840,744 | 5,754 |  | Napoleon/Camp |  | 1,754 | 2,10 |

| GLG (m MSL) | GHG (m below surface) | GHG (m MSL) | GW field (m below surface) | GW field (m MSL) | Water Elevation (m MSL) | EC 1 | EC 2 | EC 2 name | pH | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| -2,79 | 0,50 | -1,79 | 1,10 | -2,39 | -2,274 | | | | | |
| -3,02 | 0,60 | -1,92 | 0,96 | -2,28 | -2,417 | 718 | | | 7,0 | |
| -1,95 | 0,60 | -0,35 | 0,72 | -0,47 | -0,354 | 3000 | | | 8,0 | |
| -3,38 | 0,50 | -1,08 | 0,20 | -0,78 | | | | | 5,5 | |
| -2,69 | 0,50 | -2,09 | 1,00 | -2,59 | -2,665 | 812 | | | 7,0 | |
| -2,42 | 0,40 | -1,42 | 1,18 | -2,20 | -2,300 | 757 | | | 7,0 | |
| -2,46 | 0,00 | -0,06 | 1,09 | -1,15 | -1,129 | 938 | | | 7,0 | |
| -0,58 | 0,60 | 1,22 | 0,55 | 1,27 | 1,018 | 786 | | | 7,0 | |
| -3,04 | 0,80 | -2,24 | 1,05 | -2,49 | | | | | | |
| -1,49 | 0,60 | -0,44 | 0,85 | -0,69 | | | | | | |
| -1,92 | 0,80 | 0,98 | 1,00 | 0,78 | 0,816 | | | | | |
| -2,85 | 1,30 | 0,05 | 2,20 | -0,85 | -0,779 | | | | | |
| -1,64 | 0,40 | -0,74 | 0,05 | -0,39 | | | | | | |
| -2,84 | 0,50 | -1,94 | 0,65 | -2,09 | -2,320 | | | | | |
| -2,79 | 1,10 | -0,79 | 1,50 | -1,19 | -1,708 | | | | | |
| -2,27 | 1,70 | -1,87 | 1,90 | -2,07 | | | | | | |
| -2,50 | 0,70 | -1,70 | 1,20 | -2,20 | | 570 | | | | |
| -2,20 | 0,50 | -1,70 | 0,80 | -2,00 | | | | | | |
| -1,99 | 0,90 | -0,39 | 1,16 | -0,65 | -0,957 | 1380 | | | 7,0 | |
| -1,33 | 0,70 | 1,57 | 0,89 | 1,38 | | 973 | | | 7,0 | |
| N/A | N/A | N/A | N/A | N/A | -2,439 | | | | | Boring in lagoon |
| -2,43 | 0,60 | -1,63 | 1,20 | -2,23 | -2,214 | | | | | |
| -2,54 | 0,30 | -1,34 | 1,50 | -2,54 | -1,741 | 537 | | | | |
| -2,47 | 0,80 | -1,97 | 1,02 | -2,19 | | 677 | | | 7,0 | |
| -2,98 | 0,50 | -0,78 | 1,08 | -1,36 | -1,306 | 8800 | | | 7,0 | |
| -0,35 | 0,40 | 1,35 | 0,97 | 0,78 | | 1509 | | | 7,0 | |

| Bore # | Northing | Easting | Ground Elevation (feet MSL) | Water Elevation (feet MSL) | Bore Location | Top of Observation Pipe | Ground elevation (m MSL) | GLG (m below surface) |
|---|---|---|---|---|---|---|---|---|
| 045 | 536736,515 | 3666645,383 | -4,370 | -6,732 | Monroe/Palmetto | | -1,332 | 1,50 |
| 046 | 532831,796 | 3665317,946 | -0,752 | -2,654 | Belfast/Dublin | | -0,229 | 1,90 |
| 047 | 529322,949 | 3663946,490 | 1,496 | -1,260 | Hickory/Fern | | 0,456 | 0,75 |
| 048 | 523844,538 | 3664167,522 | 5,007 | N/A | St Charles/Tulane Campus | | 1,526 | 3,20 |
| 049 | 517777,552 | 3662044,753 | 11,947 | 9,093 | Audoban Zoo/River Levee | | 3,642 | 2,50 |
| 050 | 554859,491 | 3668907,144 | -3,238 | -9,898 | Tiara Park | | -0,987 | 1,60 |
| 051 | 551907,891 | 3668121,993 | -7,432 | -10,647 | Louisville/Filmore | | -2,265 | 1,10 |
| 052 | 549432,552 | 3667875,675 | -7,190 | N/A | Harrison/Louisville | | -2,191 | 1,80 |
| 053 | 546227,262 | 3667570,413 | -4,850 | N/A | Kenilworth/Louisville | | -1,478 | 1,70 |
| 054 | 525605,721 | 3670709,184 | -3,825 | -5,957 | General Pershing/Willow | | -1,166 | 1,30 |
| 055 | 556368,311 | 3673392,267 | 1,972 | -1,440 | Breeze Park | | 0,601 | 1,90 |
| 056 | 554136,588 | 3672962,961 | -5,493 | | City Park at Robert E Lee | | -1,674 | 1,25 |
| 057 | 551927,945 | 3673423,439 | -5,388 | -7,685 | Filmore/Golf Course | | -1,642 | 0,80 |
| 058 | 548214,166 | 3673083,653 | -3,011 | -6,423 | Harrison/Diagonal | | -0,918 | 1,40 |
| 059 | 542142,067 | 3671782,668 | 1,762 | N/A | Anseman/Dreyfous | | 0,537 | 2,20 |
| 060 | 559271,742 | 3694113,212 | -3,592 | -4,084 | Downman/Hayne | | -1,095 | 1,500 |
| 061 | 555987,047 | 3695612,749 | -7,316 | -9,941 | Downman/Pines | | -2,230 | 1,700 |
| 062 | 552458,357 | 3695841,635 | -4,153 | -4,809 | Downman/Selma | | -1,266 | 2,800 |
| 063 | 544404,713 | 3678612,353 | -1,047 | -4,328 | Interchange Rdwy/St Bernard | | -0,319 | 3,10 |
| 064 | 560366,296 | 3706088,383 | -6,594 | -10,138 | Bunker Hill | | -2,010 | 1,67 |
| 065 | 557362,369 | 3708316,954 | -7,805 | -9,773 | Tiffin/Edenboro | | -2,379 | 1,80 |
| 066 | 554393,293 | 3710557,436 | -4,389 | -7,342 | Hickerson/Chef Menteur | | -1,338 | 3,05 |
| 067 | 570152,626 | 3718237,516 | -7,681 | | Morrison/Queensway | | -2,341 | 1,20 |
| 068 | 561342,852 | 3718218,629 | -5,731 | | Tanner S Davis | | -1,747 | 1,60 |
| 069 | 556644,384 | 3721652,651 | -7,681 | | Morrison/Queensway | | -2,341 | 1,30 |

| **GLG (m MSL)** | **GHG (m below surface)** | **GHG (m MSL)** | **GW field (m below surface)** | **GW field (m MSL)** | **Water Elevation (m MSL)** | **EC 1** | **EC 2** | **EC 2 name** | **pH** | **Remarks** |
|---|---|---|---|---|---|---|---|---|---|---|
| -2,83 | 0,60 | -1,93 | 1,10 | -2,43 | -2,052 | | | | | |
| -2,13 | 0,30 | -0,53 | 1,20 | -1,43 | -0,809 | | | | | |
| -0,29 | 0,00 | 0,46 | 0,15 | 0,31 | -0,384 | 760 | | | 6,0 | |
| -1,67 | 1,50 | 0,03 | 1,36 | 0,17 | | | | | | |
| 1,14 | 0,50 | 3,14 | 0,80 | 2,84 | 2,772 | | | | | |
| -2,59 | 0,40 | -1,39 | 2,00 | -2,99 | -3,017 | | | | | LLG file empty |
| -3,37 | 0,40 | -2,67 | 0,95 | -3,22 | -3,245 | | | | | |
| -3,99 | 1,00 | -3,19 | 1,10 | -3,29 | | | | | | |
| -3,18 | 0,60 | -2,08 | 1,60 | -3,08 | | 350 | | | | |
| -2,47 | 0,70 | -1,87 | 1,20 | -2,37 | -1,816 | | | | | |
| -1,30 | 1,20 | -0,60 | 1,440 | -0,84 | -0,439 | | | | | |
| -2,92 | 0,70 | -2,37 | 0,05 | -1,72 | | 1600 | | | 6,0 | |
| -2,44 | 0,50 | -2,14 | 0,70 | -2,34 | -2,342 | | | | | |
| -2,32 | 0,50 | -1,42 | 1,300 | -2,22 | -1,958 | 240 | | | | |
| -1,66 | 0,60 | -0,06 | 1,300 | -0,76 | | | | | | |
| -2,59 | 0,00 | -1,09 | 0,120 | -1,21 | -1,245 | 130 | | | 4,5 | |
| -3,930 | 0,600 | -2,83 | 0,760 | -2,99 | -3,030 | 623 | | | 7,0 | minimum GLG |
| -4,07 | 0,40 | -1,67 | 0,200 | -1,47 | -1,466 | 1480 | | | 7,0 | |
| -3,42 | 0,40 | -0,72 | 0,850 | -1,17 | -1,319 | | | | | |
| -3,68 | 0,50 | -2,51 | 0,750 | -2,76 | -3,090 | | | | | |
| -4,18 | 1,50 | -3,88 | 0,350 | -2,73 | -2,979 | | | | | |
| -4,39 | 0,30 | -1,64 | 0,950 | -2,29 | -2,238 | | | | | |
| -3,54 | 0,60 | -2,94 | 0,250 | -2,59 | | | | | | |
| -3,35 | 0,80 | -2,55 | 0,780 | -2,53 | | | | | | |
| -3,64 | 0,20 | -2,54 | 0,20 | -2,54 | | | | | 6,0 | |

| Bore # | Northing | Easting | Ground Elevation (feet MSL) | Water Elevation (feet MSL) | Bore Location | Top of Observation Pipe | Ground elevation (m MSL) | GLG (m below surface) |
|---|---|---|---|---|---|---|---|---|
| 070 | 552119,510 | 3690649,670 | -4,910 | -6,710 | Louisa/Mirabeau |  | -1,497 | 1,55 |
| 071 | 552664,236 | 3686468,794 | -6,265 | -8,758 | Filmore/Franklin |  | -1,909 | 1,55 |
| 072 | 555646,185 | 3680025,598 | -3,501 | -6,028 | Robert E Lee/Pratt |  | -1,067 | 1,60 |
| 101 | 561643,589 | 3717100,757 |  | -12,041 | Lake Bullard |  |  |  |
| 102 | 561384,009 | 3714508,250 |  | -12,628 | Lake Forest |  |  |  |
| 103 | 565081,755 | 3712885,929 |  | -12,202 | Lake Barrington |  |  |  |
| 104 | 570296,494 | 3718179,459 |  | -13,515 | Morrison Canal |  |  |  |

| GLG (m MSL) | GHG (m below surface) | GHG (m MSL) | GW field (m below surface) | GW field (m MSL) | Water Elevation (m MSL) | EC 1 | EC 2 | EC 2 name | pH | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|
| -3,05 | 0,50 | -2,00 | 1,00 | -2,50 | -2,045 | | | | | |
| -3,46 | 0,40 | -2,31 | 0,90 | -2,81 | -2,669 | 243 | | | 5,5 | |
| -2,67 | 0,30 | -1,37 | 0,820 | -1,89 | -1,837 | 472 | | | 7,0 | |
| | | | | | -3,670 | | | | | |
| | | | | | -3,849 | | | | | |
| | | | | | -3,719 | | | | | |
| | | | | | -4,119 | | | | | |