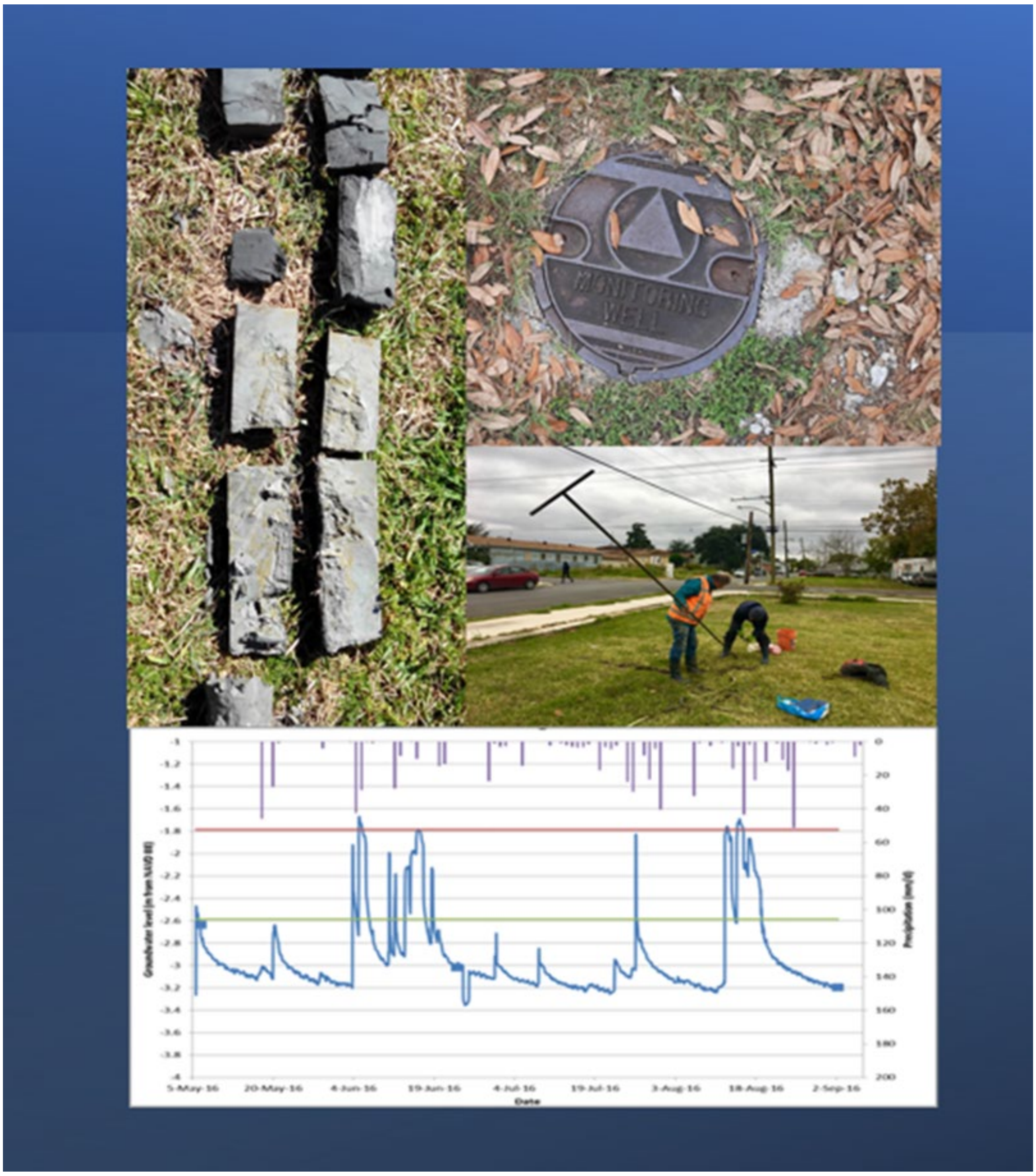
Monitoring Water and the Urban Environment
New Orleans Water Monitoring Vision and Elaboration

DRAFT REPORT

Author(s)
Roelof Stuurman
Geoff Zimmel
Jelle Buma



Monitoring Water and the Urban Environment
New Orleans Water Monitoring Vision and Elaboration

Client	City of New Orleans
Contact	Mary Kincaid (Director, Stormwater and Green Infrastructure)
Reference	
Keywords	New Orleans, groundwater monitoring, subsidence

Document control	
Version	0.1
Date	25-05-2023
Project nr.	11200801-000
Document ID	11200801-000-BGS-0004
Pages	99
Classification	
Status	draft This is a draft report, intended for discussion purposes only. No part of this report may be relied upon by either principals or third parties.

Author(s)		
	Roelof Stuurman	
	Geoff Zimmel	
	Jelle Buma	

The allowed use of this docuemnt is limited to check the correct order-performance by Deltares USA. Any other client-internal-use and any external distribution is not allowed.

Doc. version	**Author**	**Reviewer**	**Approver**
0.1	Roelof Stuurman	Roel Melman	Henriette Otter
	Geoff Zimmel		Edwin Welles
	Jelle Buma		

Deltares

Summary

Introduction

Based on an in-depth study of urban groundwater monitoring and experiences in the Netherlands the locations of urban monitoring wells are proposed. The substantiation of these choices is reported in (draft) report Monitoring water and the Urban Environment, New Orleans Water Monitoring Vision and Elaboration (Deltares, 2023 draft). This memo presents a summary of this report and presents the monitoring objectives and the proposed locations and operational monitoring aspects. This project is part of a larger NDR project focused on subsurface, groundwater and subsidence (figure 1.1).

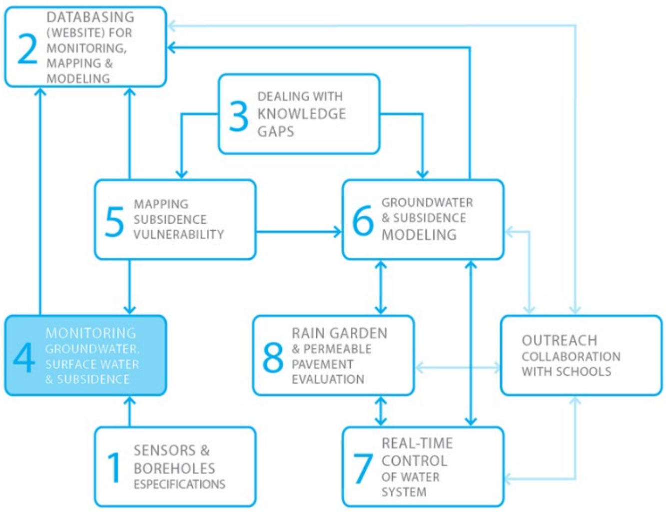


Figure 1.1: All subprojects of this NDR groundwater project

“The main objective of this urban monitoring network is to understand the actual and future shallow groundwater fluctuation in relation to rainfall, evaporation, surface water levels and drainage (and/or recharge) by underground infrastructure. Of course, also changes due to climate change, sea level rise and subsidence are considered”.

This monitoring design should support urban water management for a long period.

The proposed monitoring network is also designed to better understand the relation between deep groundwater and shallow groundwater. The deeper hydraulic heads (“water pressure”) at approximately 20-60 feet depth are related to river level and Lake Pontchartrain level. Therefore, also deeper observation screens are proposed. Shallow screens are approx. 9 feet deep. Deeper screens are approx. 20-60 feet deep. These deeper observation wells are proposed for the Pine Barrier Sands near Lake Pontchartrain and sandy (“point bar”) deposits near the river (see figure 1.2). In addition, existing very deep (> 300 feet) USGS wells are studied.

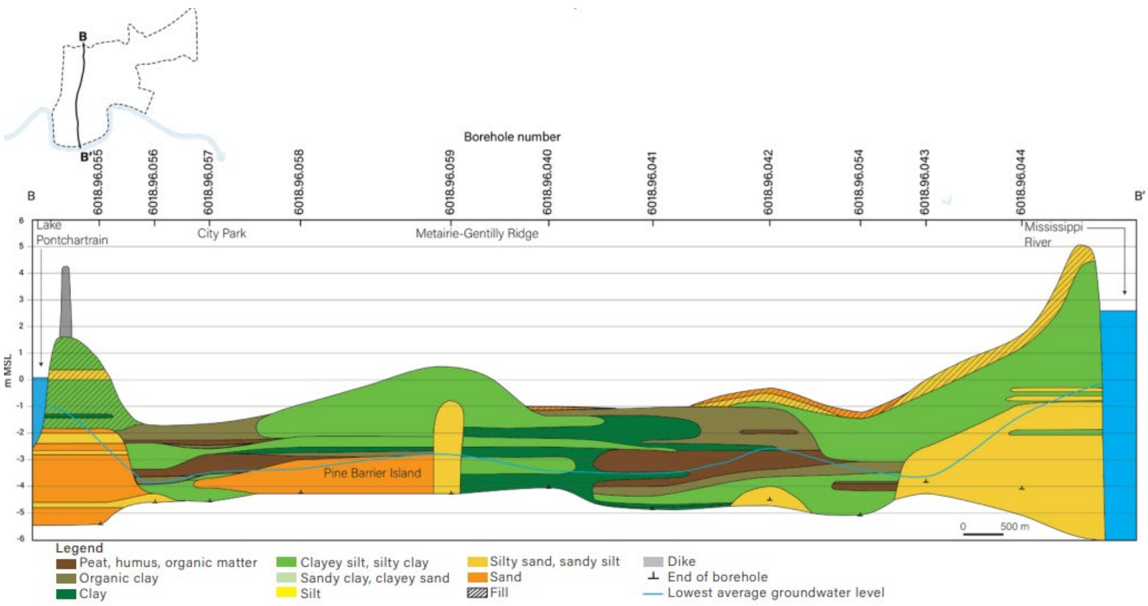


Figure 1.2: Example of a north-south geological cross-section Constructed and reported in sub-project 5 (Shallow subsidence vulnerability in New Orleans, Sanneke van Asselen et al., 2019).

Monitoring objectives

The groundwater impacts and processes in New Orleans inform the following 12 monitoring objectives:

1. To define which groundwater regimes, occur in subsidence-prone clay and peat areas. Can changes be made to groundwater levels to reduce subsidence?
2. To define the extent which wooden foundation piles have emerged above groundwater. Untreated piles are vulnerable to rotting processes. This can be a risk for heritage buildings.
3. To define the extent to which groundwater levels are influenced by water levels in the canals.
4. To define the extent to which groundwater levels are influenced by subsurface infrastructure. Often the storm drainage and wastewater transport pipes drain groundwater, while the drinking water system discharges water into the ground. What will happen with the groundwater situation in future after these systems are renovated?
5. Determine to what extent shallow groundwater levels and deep hydraulic heads interact. Understanding the impact of deep groundwater pumping on shallow groundwater levels.
6. Better understand the relationship between groundwater levels and the influence of the Mississippi River and/or Lake Pontchartrain. Are groundwater levels influenced by Mississippi River or Lake Pontchartrain water levels? This information can become important in relation to sea level rise, and or construction activities (like channel deepening).
7. Determine the storm water (rain) storage capacity of local soils. When is this capacity exceeded? At what point will ponding and overland flow occur?
8. Determine if there is a salinization risk for freshwater-dependent land use functions.
9. Better understand and define the relationship between sub-regional groundwater flow (flow system) in the urban area between the Mississippi River / Lake Pontchartrain. This can help to understand the transport (risks) of salt and/or polluted water.
10. Discuss the potential climate change scenarios and the effect on the future groundwater situations. Determine how a monitoring system can help track changes.

11. Create groundwater and subsidence awareness (See Figure 2.1).
12. Set up temporary monitoring networks in vulnerable areas to observe the local effects of dewatering (e.g. subsidence, dry fall of untreated wooden foundation piles). To mitigate damage caused by dewatering, a monitoring protocol is advised. Groundwater level thresholds should be determined (at what groundwater level is risk deemed to be unacceptable to the local infrastructure or environment). If these thresholds are reached, projects plans should continue (or stop) accordingly.

Figure 2.1. Example of raising public awareness of groundwater monitoring: a floater on top of groundwater allows groundwater levels and fluctuations to be visible above ground. The transparent tube delineates the ranges where groundwater levels are too low (red) and fair (green). This New Orleans monitoring project will present the results on a public available website.

Groundwater monitoring and action perspective

It's not simple to quantify the benefits of a groundwater monitoring network. The cities of Amsterdam (921,000 inhabitants, 2500 observation wells) and Rotterdam (589,000 inhabitants, 2000 observation wells) report the yearly groundwater monitoring costs for each city are approximately $750,000. The groundwater monitoring network does indeed cost a lot of money, but it is considered an essential part of each city's groundwater care obligation.

A monitoring network in New Orleans can help to reduce damage to the public domain as well as to the private sector, including to homeowners. The main groundwater related risks in New Orleans are:

1. Building and road damage due to subsidence in areas with organic subsoils caused by too low groundwater levels,
2. Road and building damage in relation to temporally high groundwater levels,
3. Road and building damage during dry periods (too low groundwater levels) caused by shrink-swell of shallow clay deposits and/or peat oxidation,
4. Foundation risks, especially for historical buildings constructed on wooden piles. Low groundwater levels can stimulate wood rot.
5. Groundwater flooding. This can arise by:
    a. Increasing rainfall amounts (climate change)
    b. Renovation of storm drainage and wastewater transport pipes. Now these pipes are draining (and therefore lowering) groundwater.
6. Groundwater and soil salinization. A potential risk for trees and other vegetation. This risk is related to droughts and the groundwater flow of brackish-salt groundwater from Lake Pontchartrain (and outfall canals) towards the lower parts of Gentilly and New Orleans NE.
7. Tree damage due to (1) drowning (too high groundwater levels), (2) dryness and (3) salinization.

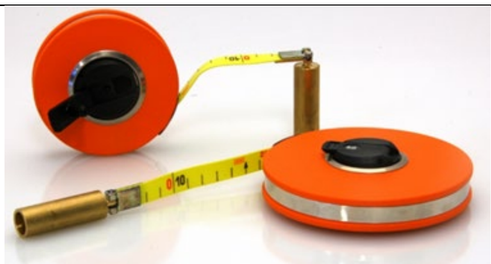
Of course, these risks have different risk-owners. For example, protecting historical buildings on wooden piles is the responsibility of the owners. They could install groundwater observation well around there property (like the termite's observation networks).

Measurement methods and frequencies

A conceptual understanding of the groundwater system, its periodic fluctuations and defining the purpose of the system itself is an important first step in selecting an appropriate sampling method and frequency. The sampling frequency should be sufficiently high enough to capture the periodic fluctuations within the natural system or the effects caused by human activities. Manual data collection (6 times/year) like in the Amsterdam provides a low cost, time intensive solution to measuring gradual seasonal changes but would not be able to capture the rise in groundwater associated with rainfall events. To capture changes to groundwater level after high intensity rainfall events, it is suggested that hourly recordings be taken.

Reason for Measurement	**Frequency Requirement**
Storage capacity	Hourly
Groundwater subsidence	Daily
Surface water – Groundwater	Hourly
River water – Groundwater	Hourly to Daily
Street infrastructure – Groundwater	Hourly
Wooden piles – Groundwater	Twice per month

We propose the use of 4 types of sensors and hand measurement equipment.

Divers ❑ Interval 1 hour ❑ Sensor costs $ 600	Divers are high-quality pressure sensors from Schlumberger that allow the user to convert pressure head to groundwater depth. The sensors also provide temperature data. 
CTD diver ❑ Interval 1 hour ❑ Cost $ 1600	It autonomously measures conductivity, pressure and temperature and records them in its internal memory
Telemetry ❑ Interval 30 minutes ❑ Daily storage ❑ Costs $ 2000 per location	For example, by using Solinst LevelSender telemetry system of University of California. The LevelSender 5 is simple, of modem design to send data wirelessly from Solinst data loggers in the field, via cellular communication, to multiple emails and an SMS receiver. You can receive the data directly on your smart device. 
Hand measurements ("plopper" in Dutch for plunger)	

Locations

Table 5.1 provides a summary of our proposed well locations along with the monitoring objective.

Table 5.1: Information proposed monitoring sites: (a) approx. 9 feet deep, (b) approx. 20-40 feet deep. In orange the locations with real-time available data. These locations need to be protected. In yellow proposed locations if it becomes necessary to reduce the number of sites and sensors.

Groundwater observation well		
Num-ber	***Location***	***Monitoring Objective***
1 a+b	Harlequin Park (North Shore)	Effect water level Lake Pontchartrain (LP) on groundwater flow towards urban area (incl. salinization)
2 a+b	Allain Toussaint Blv. - City Park	
3 a+b	Allain Toussaint Blv- Pratt (P)	
4 a+b	Live Oaks Park	
5 a+b	New Orleans Mosquito, Termite and Rodent Control Board	
6 a+b	Hayne Blv - Burke Ave	
7 a+b	East Dr. Audubon Park	Effect Mississippi river water level on groundwater situation southern part New Orleans.
8 a+b	Clay Square Park	
9 a+b	Park Washington Square	
10 a	Samuel Square Park	Phreatic groundwater level and salinity (at this location we measured salt groundwater (remarkable).
11 a	Gen. Pershing - Dupre	Phreatic groundwater level in relation to peat layer at resp. 30, 10, 40, 10 cm below Mean Lowest Groundwater level**. Subsidence risk.**
12 a	Telemachus - Palmetto	
13 a	Gravier - Tonti	
14 a	Florida Ave.	
15 a	Claiborne Ave.	Subsidence risks, effect subsurface unfractured on groundwater
16 a	Tillford Rd. - Edenboro Rd.	
17 a	Mount Olivet Mausoleum	Water level at groundwater divide (Metairie-Gentilly ridge)
18 a	Buddy Deuterive Park	Phreatic groundwater to understand impact underground infrastructure, seepage and precipitation/evaporation
19 a	Milne	
20 a	Lake View (approx.)	
21 a	Filmore City Park (Existing: Eustis P-5)	Subsidence control (peat just below lowest groundwater level).
22 a	St. Claude	Phreatic groundwater to understand impact underground infrastructure, seepage and precipitation/evaporation
23 a	French Quarter	
24 a	Metairie Road	Water level at groundwater divide (Metairie-Gentilly ridge)
25 a+b	Mirabeau (existing)	Understanding relation shallow groundwater and deeper (Pine Barrier) groundwater.
26 a	Lafitte Greenway (existing shallow well P-3)	Phreatic groundwater to understand impact underground infrastructure, seepage and precipitation/evaporation

Surface water observation well		
SW 1	Audubon Park	Discharge into St. Charles urban drainage system (quantity and quality/salinity)
SW 2	City Park	Water levels and salinity
SW 3	City Park	
SW 4	Lagoon Pontchartrain Park	Water levels, salinity in relation to weather conditions and Lake Pontchartrain water level.
SW 5	Lake Willow	
SW 6	Lake Bullard Ave	

Citizens science network

In addition, we propose the development of a public citizens network. For example, starting at schools, but also at properties of interested individuals. See below instructions. https://www.deltares.nl/en/expertise/areas-of-expertise/subsidence/measuring-groundwater-yourself

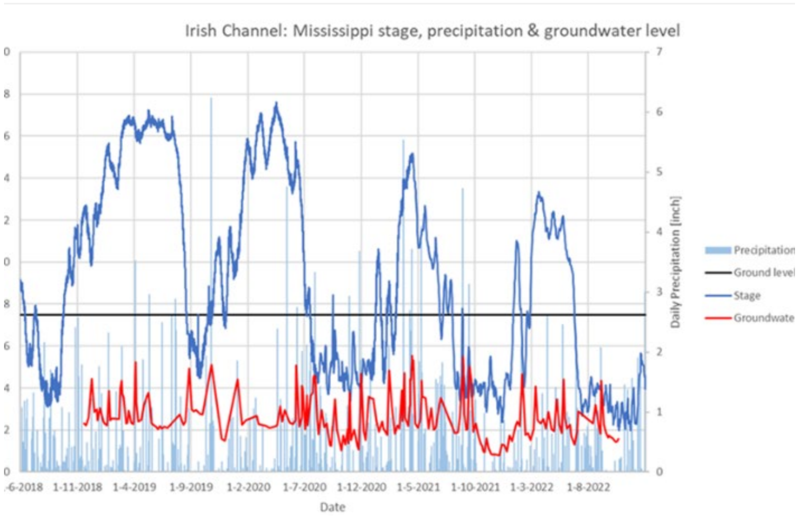


Figure 5.1: In the garden of a private property at the Irish Channel neighbourhood a shallow groundwater observation well is installed during the summer of 2018. Since then the residents monitor the groundwater levels, more or less weekly, by hand. In figure 5.19 the results are compared with the water level of the Mississippi river (approx. 0,25 miles south). This river level is always higher than the groundwater level. Often more than 5 feet.

Supporting time series groundwater analysis SWBNO pumping station discharges and Water treatment Plant inflow

With support of the SWBNO Nougues and Stuurman (2022) estimated an integrated groundwater balance for New Orleans (figure 5.2). These numbers are based on discharge measurements at the pumping stations and the Waste water Treatment Plant. The following conclusions were drawn from the desk study: 1) the rainwater drainage system accounts for most of the total groundwater drainage (58 per cent); 2) 50 per cent of the influent of the WWTP is groundwater, which is a large unnecessary load for the treatment process; and 3) 55 per cent of the drinking water produced infiltrates the soil during distribution, which means that the drinking water losses are a larger groundwater replenishment than the annual precipitation surplus

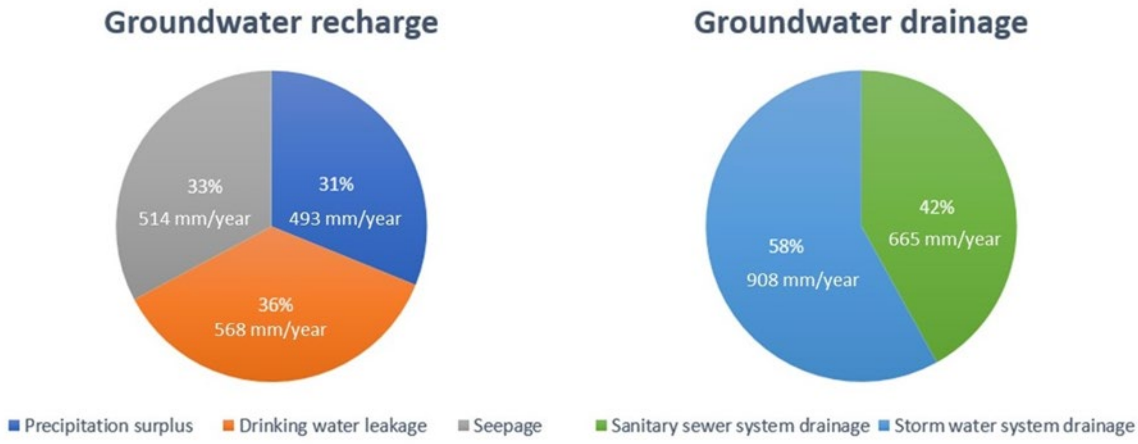


Figure 5.2: The proportions and quantities of the various fluxes in the period 2018-2020 (precipitation 1,782 mm/year and evaporation about 1,289 mm/year).

Recently Deltares, in cooperation with SWBNO installed a CTD-diver (Salinity, temperature and water level) at Pumping Station 4 (Gentilly, 1-hour frequency). A decade ago, we also installed a CTD-diver (Salinity, temperature and water level) at Pumping Station 1 (see figure 5.3). These measurements help to better understand groundwater drainage by leaking infrastructure.

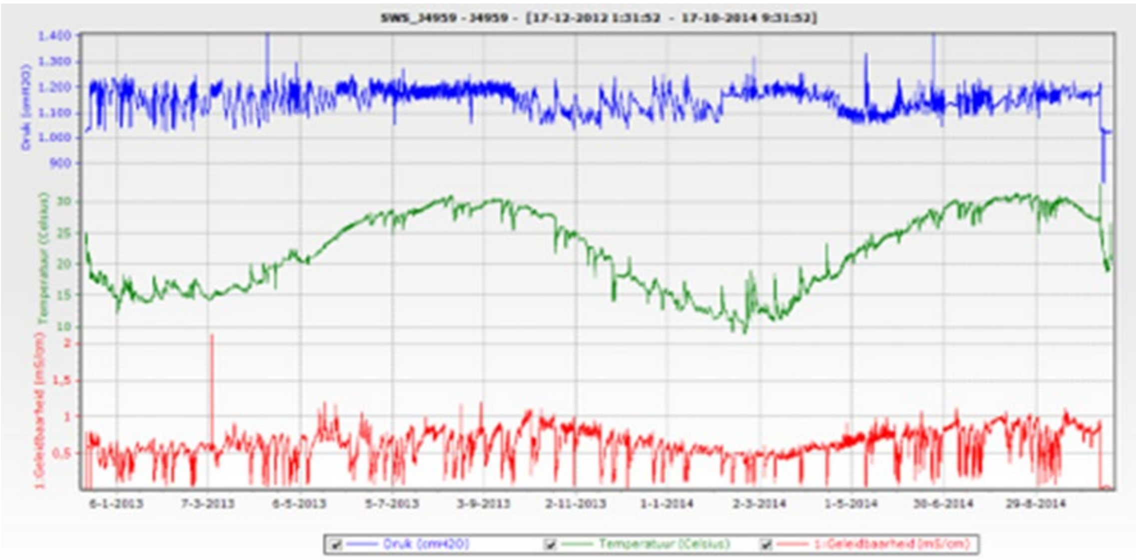


Figure 5.3: 18 months (2013-2014) of monitoring storm drainage components (temperature, salinity and water level) at Pumping Station 1, using CTD-sensor (Van Essen). The salinity (EC) shows a mean value of ca. 0.5 mS/cm and a reduction during rainfall. This is an indication of groundwater drainage.

<u>Conclusion:</u> the groundwater monitoring network delivers more local information about the groundwater system. Using the pumping station data (extended with salinity measurements) supporting city wide information about groundwater changes can be monitored.

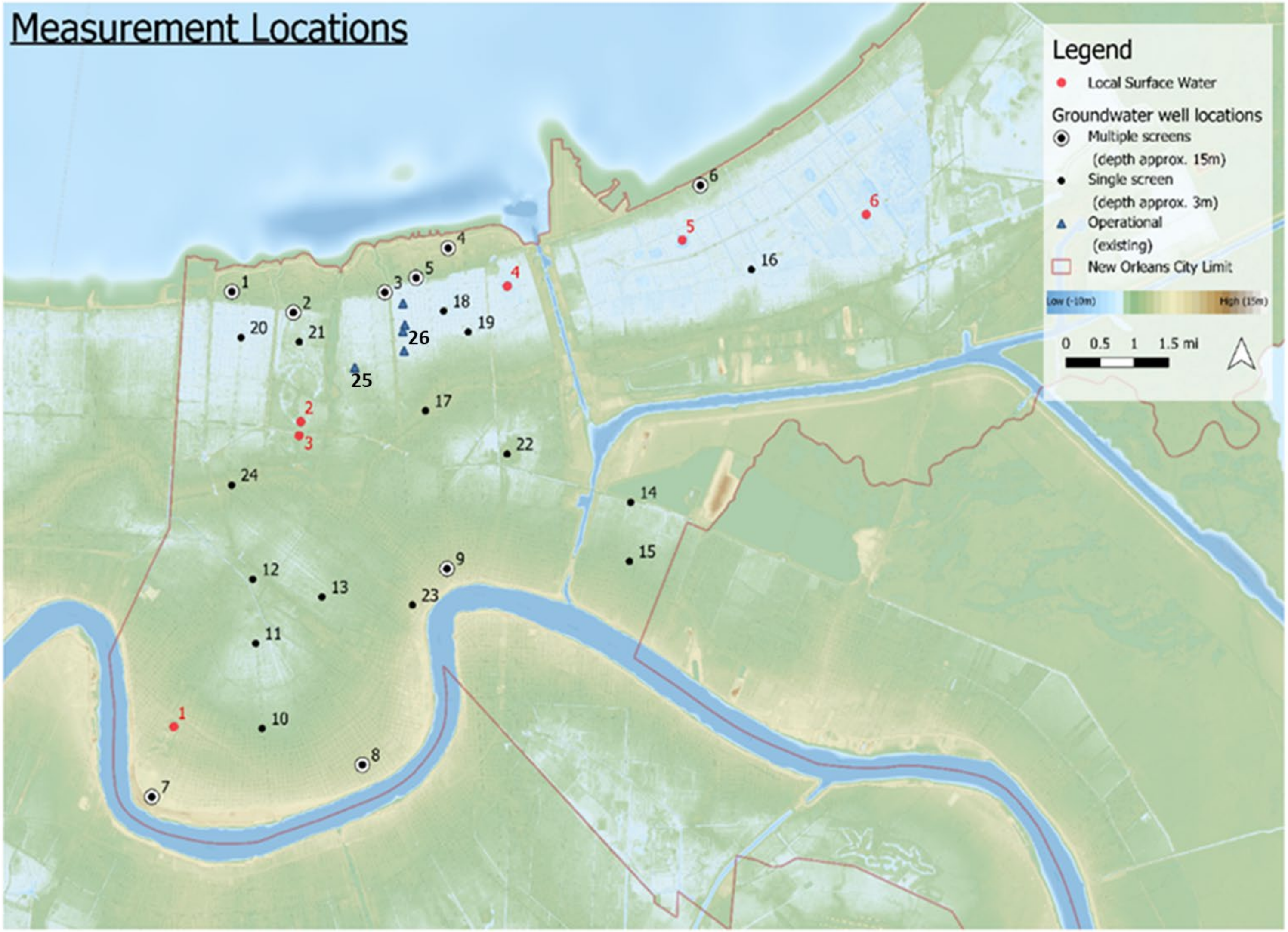
Practical Considerations

During the installation we will cooperate with:

- Tulane University (geological borehole descriptions).
- Groundwork New Orleans (technical support).
- Batture (surface elevation levelling).
- Eustis or other geotechnical consultant (deeper wells).

Approximately 6 months after installation the first results will be presented in a comprehensive report and at our public database. The method of reporting will be simple to copy during the coming years by local consultants or institutions.

We advise to cooperate with SWBNO, especially in relation to the groundwater analysis of pumping station data.


Measurement Locations
Legend
Local Surface Water
Groundwater well locations
Multiple screens (depth approx. 15m)
Single screen (depth approx. 3m)
Operational (existing)
New Orleans City Limit
Low (-10m)
High (15m)
0 0.5 1 1.5 mi
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26

Contents

1 Introduction and problem conceptualization

1.1 General project introduction

New Orleans has been actively subsiding for decades and a large part of the city is below sea level. Frequently flooded streets resulting from high intensity rainfall events and an expected increase in tropical storms as a result of warming climatic conditions are cause for concern. A solution to help the city better cope with urban water and subsidence challenges could be to invest in spatial planning initiatives to become more resilient to extreme weather events and changing environmental conditions. Before solutions are implemented however, it may be advantageous to organize a suite of monitoring tools to provide both a baseline dataset as well as a way to quantify the results of implemented solutions.

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 in- formation (**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 4**. Therefore, first information was collected about monitoring objectives and monitoring operation of urban groundwater monitoring world-wide. Secondly, based on information of the New Orleans subsurface and urban water system a monitoring network was designed.

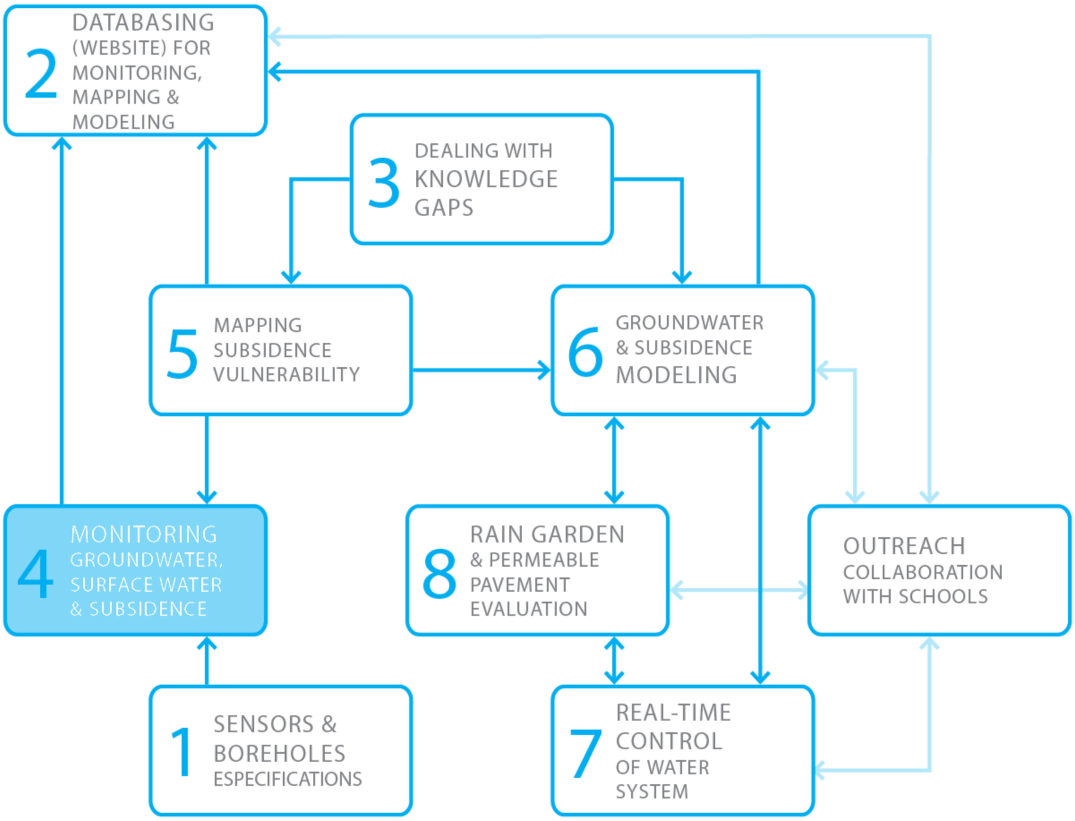


Figure 1.1 Deltares NDRC project diagram

1.2 Groundwater monitoring

Data collection and monitoring of the urban water environment throughout the city of New Orleans could help with building onto existing flood risk reduction knowledge, subsidence vulnerability understanding and operational water management efficiencies to the toolbox of decision makers. Currently, data is distributed (if available at all) through various sources making it difficult to draw conclusions from the information itself. In combining surface water, groundwater, subsidence and weather-related datasets into one location, risk reduction and fact-based decision making could become more easily integrated into the operational and decision-making procedures that are currently in place.

This document provides a collection of examples from the US and Europe relating to groundwater monitoring and database storage solutions, outlining both high-tech and low-tech solutions satisfying the project objectives at each of the locations. These brief examples are provided to outline the importance of program objectives and highlight the different monitoring programs that may be possible. Later in the report possible monitoring ideas are discussed and coupled with existing surface and subsurface infrastructures within New Orleans.

“***You can’t manage what you don’t know***” is an unfortunate, yet true statement that is echoed in urban water management meetings around the globe. Efficient, resilient monitoring systems are possible and will undoubtably provide stakeholders with confidence in knowing that the urban water data they collect and distribute can positively affect the safety of the residents and stability of structures within the City of New Orleans.

1.3 Project execution and deliverables (Activity C: Water Monitoring Network Design)

According to the project proposal the following results are proposed.

1. Project Inception → executed in 2019.
2. Stakeholder Interaction & Design → executed by Teams meetings and by face-to-face meetings in New Orleans.
3. Cost-Benefit Analysis → part of this report.
4. Comments on Final Network Design → part of the review of the draft version of this report.
5. Final Monitoring Strategy→ Part of this final (reviewed) report.
6. Installation 20 groundwater monitoring sites→ spring 2023.
7. Data Collection → 6 months after installation.
8. First Monitoring Report → 9 months after installation.
9. Lessons Learned Workshop → spring 2024.

2 Urban groundwater monitoring: experiences from Europe

2.1 The Netherlands

The Dutch have been pumping to reclaim livable land for hundreds of years and continually upgrade and maintain the necessary civil works to protect the approximately 9 million inhabitants who would be in immediate danger if major water infrastructures were to fail. 23 water authorities and 342 municipalities share in these responsibilities together with the provinces and central government.

Operational groundwater management and the care of groundwater quality is in large part the task of the water authorities. However, permitting for large withdrawals (industrial withdrawals, drinking water supply and ‘soil energy systems’) is the responsibility of the provincial governments who deal with the drinking water supply alongside the ten water supply companies that are treated as semi-public organizations.

In general, municipalities are responsible for hydrologic measures within public areas that will reduce, as much as possible, negative effects the groundwater level has on structures and local land use. Popular trends have included permanent municipal monitoring networks to identify high risk areas that were paired with interviews about the negative local effects relating to structural damages. From the results of these studies, areas were identified where measures may need to (or not) be implemented. More attention was given to areas where high groundwater was seen but special attention is being paid to areas where water levels were reduced during the 2018 summer dry period.

2.1.1 Amsterdam – Historic canals, a modern-day solution?

Amsterdam is the most populated city in the Netherlands and provides a world class example of urban water management. Known for its canal structure, classic Dutch architecture and biking culture, Amsterdam regularly places high on many ‘best cities in the world’ lists. But what keeps the city stable and above water is a combined national, provincial and local integrated water management plan. Throughout the 17th century the development and expansion of the canal network allowed traders and merchants to carry their goods to every corner of the city. Today, the historic canal structure of Amsterdam is recognized as a UNESCO world heritage site and as discussions on global warming and its effects on sea level rise continue, the over 400-year-old city planning, and construction effort is being looked at today as a viable, reproducible solution to modern day challenges elsewhere.

Monitoring the water levels of approximately 2500 groundwater measurement locations (in Amsterdam and surrounding areas) is completed by hand, six times a year and is made publicly available through a web-based interface (Figure 2.2). The water level at these locations measures the phreatic water level in the top layer of soil from 0 to 4 meters below surface and does not consider deeper aquifers within this framework. In addition, several hundred observation wells are monitored by sensors (frequency 1 hour).

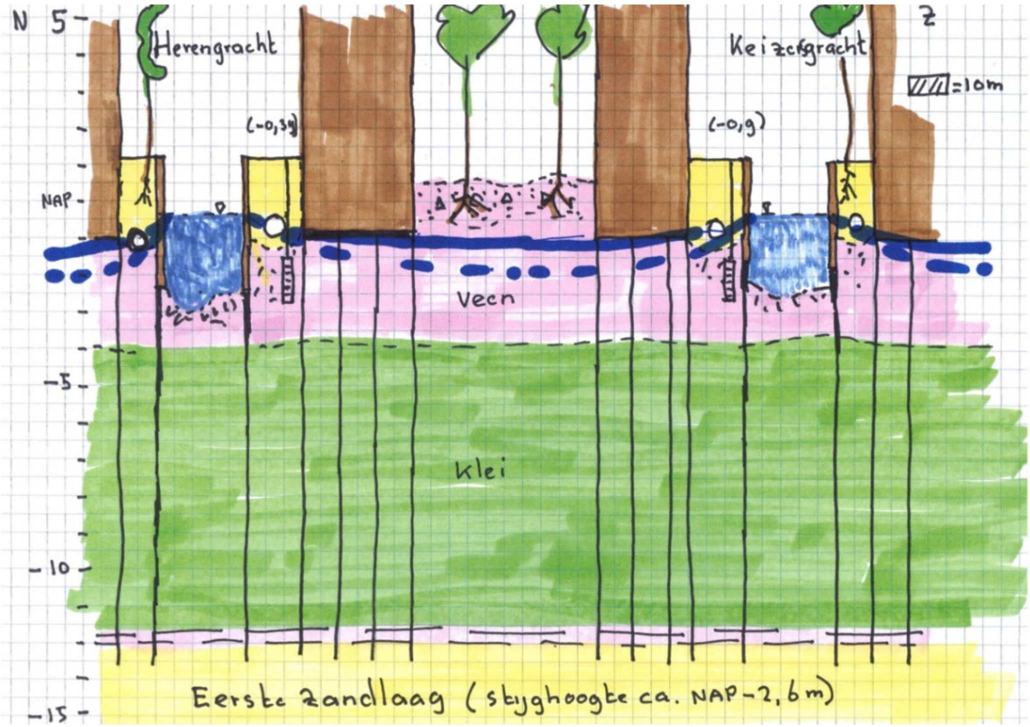


Figure 2.1 A cross section sketch of the lithology and canal structure through the City of Amsterdam. Peat (veen), Clay (Klei) and Sand (Zand) layers are expressed in pink, green and yellow respectively. Resulting groundwater levels as an artifact of canal water levels can be seen in blue. The effects of pipe leakage and evapotranspiration from trees should also be noted.

Groundwater and canal levels in Amsterdam are something that is important to get correct. With a phreatic water level that is close to the surface, an increase in groundwater level may cause low elevation gardens and crawlspaces / basements to become moist or flood. During periods of drought, a dropping water level could contribute to the rotting of wooden piles that the houses are built upon. Managing the canal water level ensures a stable groundwater level and reduces the risk of flooding. The canals are managed by pumping stations and water is discharged during times of heavy rain (to lower the water level) and added during drier periods (to raise the water level). Both actions take the local environment into consideration including the types of vegetation, land use and structures nearby, all of which may be affected by a change in groundwater level.

Originally, the monitoring network was designed to control the negative effect of sewer pipe leakage on the groundwater levels. Nowadays, it is also used to study the effect of sewer system renovation (often causing increasing groundwater levels) and canal bank renovations.

The yearly total operation costs of this monitoring network are approx. Euro 800,000 per year[1].
Based on a rough estimate the yearly costs per observation well are approximately Euro 320.

[1] Rotterdam: 2000 observation wells, yearly costs approx. Euro 700.000.

Deltares

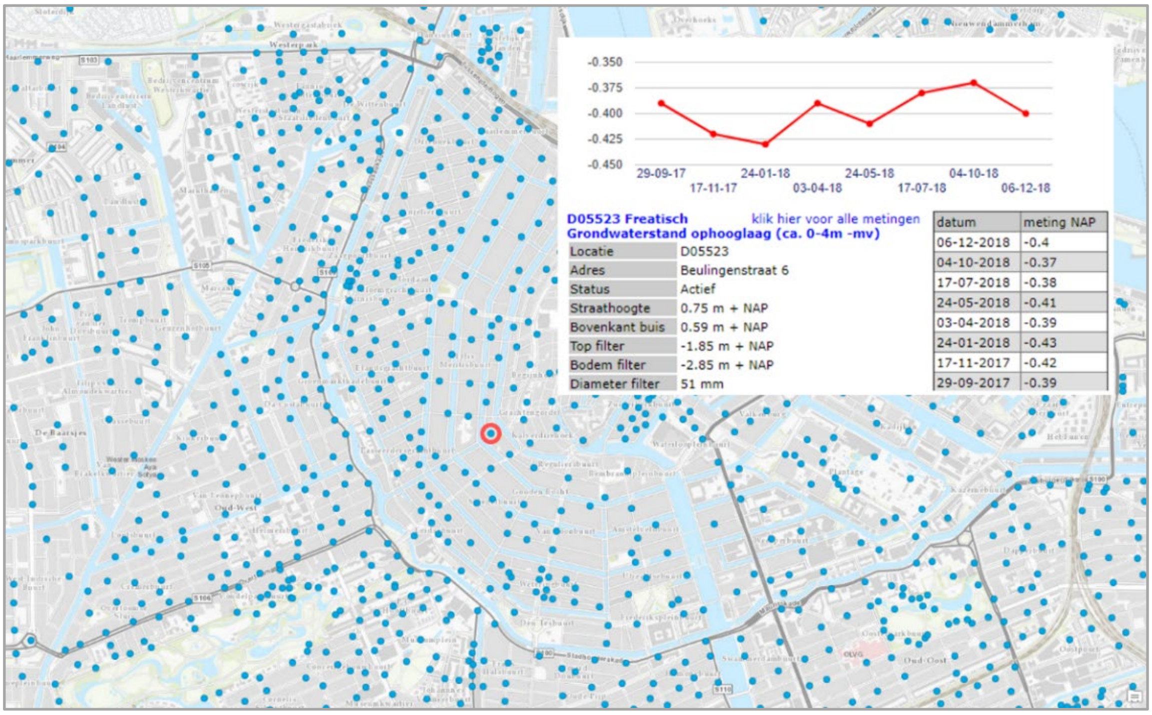


Figure 2.2 A selection of groundwater monitoring network measurement locations in Amsterdam Centrum and surrounding areas (from Waternet online data portal (https://maps.waternet.nl/kaarten/peilbuizen.html?).

2.1.2 Delft – stakeholder engagement and understanding the system

The municipality of Delft takes a similar approach when it comes to its groundwater monitoring network, and for similar reasons - concerns about groundwater levels affecting public safety, nearby structures and the environment. All municipal action is aimed at preventing damage and monitoring provides a way to develop a baseline dataset and track deviations when implemented measures take place.

Delft's Groundwater Interest Group has collected a great deal of information over its 25-year existence and was founded after residents reported moisture problems due to high groundwater levels. The committee, municipality and the local water authority come together to discuss and collaborate in solving problems relating to subsidence (structural issues), flooding (canal spillovers) and potential issues relating to changes in groundwater levels.

The monitoring network solution implemented by the City of Delft is a modern-day example when compared to that of Amsterdam. Delfts automated system is provided by an independent operator who installs and maintains both the monitoring devices and database. Measurements are recorded twice daily and sent through a cellular enabled device to a secure cloud-based storage system. As with Amsterdam, data is also made publicly available through an online portal (*Figure 2.3*).

A bi-daily measurement frequency is important in Delft as the City and local water board watch closely the effects of a decision reduce the amount of water being withdrawn by an industrial water user (very comparable with the Michoud, New Orleans situation). Concerns for the city stem from the idea that the rebound of groundwater levels will disturb the steady state created during the long term, high volume abstraction of the industrial user. Risk associated with groundwater related issues is reduced by increasing the frequency of monitoring events. Additionally, understanding the speed of the aquifer system helps determine operational requirements built into the system.

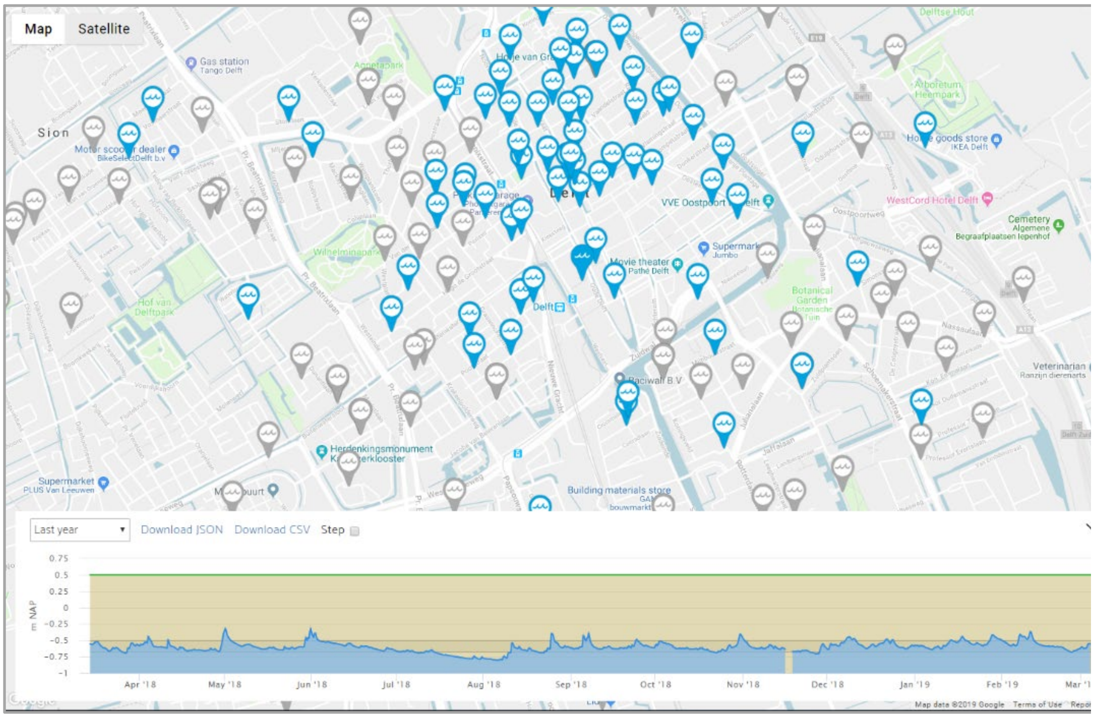


Figure 2.3 Location and distribution of groundwater monitoring locations within the city of Delft, NL. Data made publicly available by the municipality of Delft through (https://opendata.munisense.net/).

2.1.3 Gouda – towards accountability and transparency

Subsidence relating to the consolidation of soft peat and clays in the city center of Gouda is often blamed on the steady reduction of groundwater levels over the past centuries. The historic homes built between the 16th and 20th centuries were not constructed on foundations, so they are subsiding as well. As a proof of concept combining groundwater monitoring, Internet of Things (IoT) monitoring devices, and blockchain technology, a small group of wellbores were fitted with a groundwater level monitoring device that records and transmits data directly to a distributed blockchain ledger. With no single point of storage and no human interference within the system, residents can be assured that data manipulation is not taking place within this closed system. As a second step towards insuring transparency, the blockchain protocol was built to check the recorded and stored data against the values that the water utility provider posts online, allowing users to monitor recorded data against what is being shown to the public.

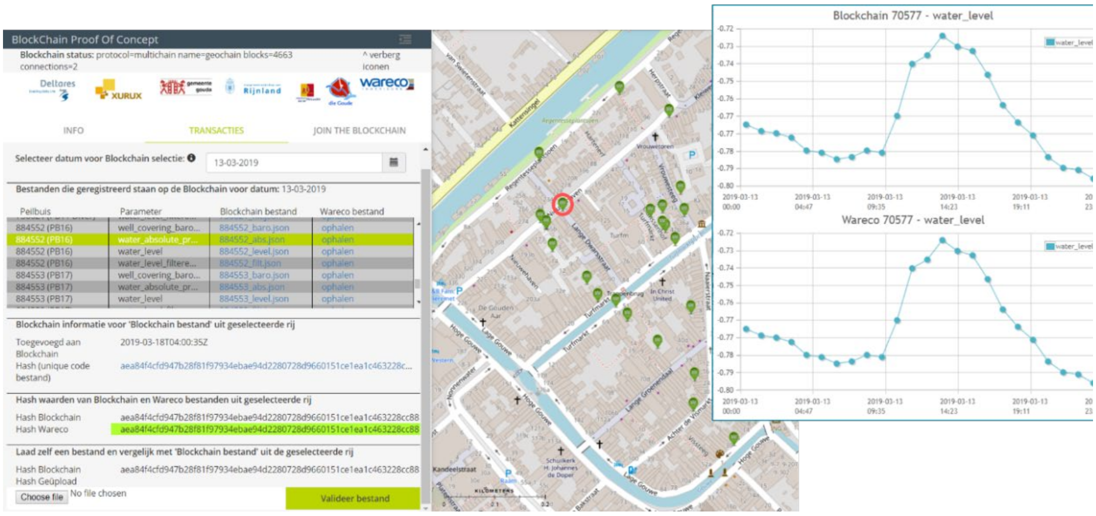


Figure 2.4 Small scale Blockchain proof of concept groundwater monitoring network in Gouda. Each green marker represents the location of a web interfacing recording device. The device measures the water level and transmits it directly to the blockchain ledger and compares the recorded measure with the data being presented on the water company's websites

2.2 Other examples from Europe

From subsidence to groundwater flooding, risk identification, infiltration opportunities or urban planning, the reasons *why* (or how) a city would want to undertake the installation of a groundwater monitoring network is dependent on the location. The following subsections briefly describe the monitoring networks in Hamburg, Oslo, Dresden and Antwerp.

2.2.1 Hamburg (Germany)- for a secure water supply

Hamburg is a city 100% reliant on groundwater for its public water supply and a good example of how through optimizing a groundwater monitoring network it is possible to reduce operational costs without sacrificing data quality or reliability (groundwater quality and quantity data). As a first step towards their program implementation, an in depth understanding of the geological and hydrogeologic systems to be monitored was put forefront. Understanding and prioritizing what they wanted to monitor allowed the involved decision makers to reduce the monitoring network from over 1000 monitoring borehole locations to 539 in the shallow aquifer and 109 locations within the deep aquifer. The shallow aquifer took priority over its deeper counterpart because of its susceptibility to contamination and potential impact of flooding if groundwater levels become too high. In addition to the shallow and deep groundwater level recording devices, 157 boreholes were selected as locations to collect groundwater quality information and were divided between both the shallow and deep aquifers.

Sampling method and frequency were also altered. By implementing a combination of dataloggers and telemetry devices, fast paced changes to groundwater levels resulting from tidal influence and precipitation events trigger an automated alert system so the appropriate response measures can be taken in time. Something that would not have been possible if they were still using their previous system of manual measurements twice per month. The updated monitoring network increases the amount of information received by city planners, response teams and planners while reducing maintenance costs and providing the public with a tool to better understand the groundwater related risks within the area.

2.2.2 Dresden (Germany) – in preparation for, and in response to flood risk management

Groundwater flooding is likely a significant contributor to overland flooding where hydrologic and hydrogeologic conditions permit - occurring when groundwater levels rise above ground level (i.e. in depressions / topographic lows). When this happens, the subsurface system cannot drain infiltrating waters fast enough and the resulting pooled body of water on the surface will remain in place until evaporated, pumped or drained naturally when storage within the phreatic groundwater system becomes available. This relatively poorly acknowledged flooding type has gained the attention of scientists, water managers, and insurance agencies over the past few years and is gaining recognition as serious contributor to flood related damages.

Dresden's groundwater monitoring network records and transmits daily level measurements and through their online portal allows the public to see how close the groundwater level is to the surface. Map symbols in *Figure 2.5* show multiple pieces of information; the organization responsible for the monitoring device is indicated by the symbol shape, while the risk at the defined location is indicated by its color. Dresden provides different maps to show groundwater information, precipitation data, flood forecasting and river flood risk maps at different alarm levels.

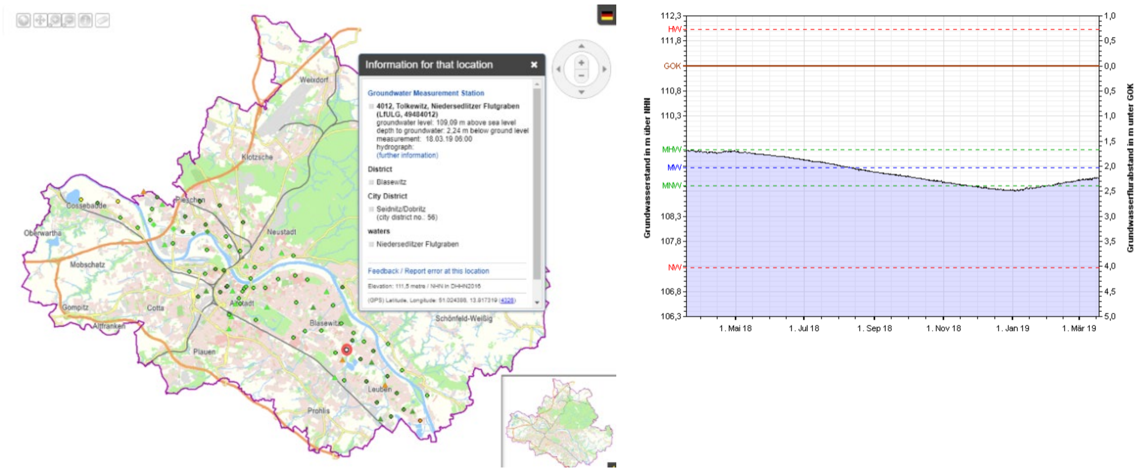


Figure 2.5 (left) Locations and levels of selected groundwater monitoring location from multiple different monitoring departments (right) Raw hydrograph data as recorded by the measurement device and displayed with the high/low water level (HW/NW) as well as the means of the high / low groundwater level and the median (MHW, NHW, MW) data available to the public at: https://www.dresden.de/de/stadtraum/umwelt/umwelt/messwerte-online/Grundwasser.php

Groundwater monitoring locations record a daily water level when river stages and precipitation events are considered normal. Frequency is increased to several daily recordings during periods of intense rainfall and elevated river levels to better understand the situation and manage the associated risk.

2.2.3 Antwerp (Belgium) – identifying risk and urban planning

Antwerp acknowledges the prosperity that water has brought to the region but also its inconveniences. In 2013 supplementary monitoring wells were installed to bring the total network size to 150, covering the nine districts of the city. The main directive of the monitoring networks is for comparison between current levels and historic datasets, looking for abnormalities and potential 'sensitive' zones where flooding, subsidence or negative environmental effects may be caused by groundwater level fluctuations.

From an ecological and parks/environment perspective, the monthly data stream has built up to where seasonal trends are emerging. This information proves helpful to city planners and urban architects who are selecting what type of trees or vegetation should be planted in new developments. Understanding the seasonal fluctuation of water depth helps them to select plants with root depths penetrating deep enough to tap into the groundwater source, reducing the maintenance costs of the department.

Additionally, infiltration opportunities could be observed from the dataset, potentially allowing for land use classification and rezoning to take place if the land type is considered high risk for flooding. *Figure 2.6* presents a collection of maps made publicly available through the external portal of the city of Antwerp.

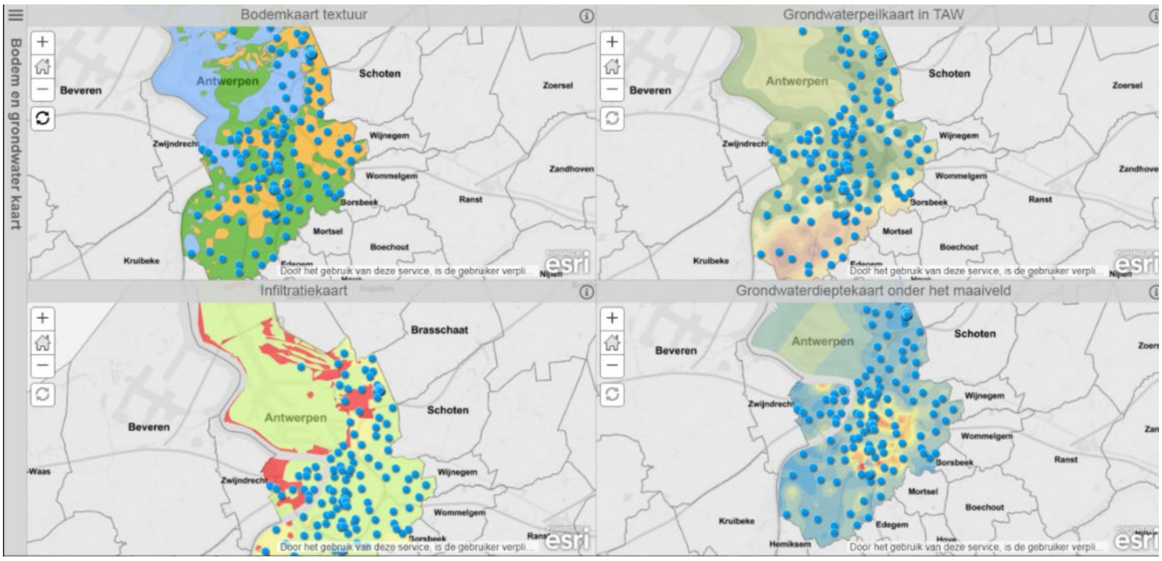


Figure 2.6 Location of boreholes overlaid with different layers. (top left) soil texture map, (top right) groundwater level map, (bottom left) Infiltration capacity, (bottom right) groundwater depth chart. From the city of Antwerp website (http://stadantwerpen.maps.arcgis.com/home)

2.2.4 Oslo (Norway) – a national water well database

Through the Norwegian geological survey, a national registry nicknamed GRANADA (the national groundwater borehole database) stores and makes available a national collection of groundwater knowledge. This includes well data and reports on groundwater investigations and pumping locations for water and boreholes drilled for energy needs.

The Database acts as a publicly accessible repository for drilling records and is currently not set up to compare or analyze the data within the framework in which it is displayed. Many states or state agencies within the United States have similar standalone datasets available on their websites.

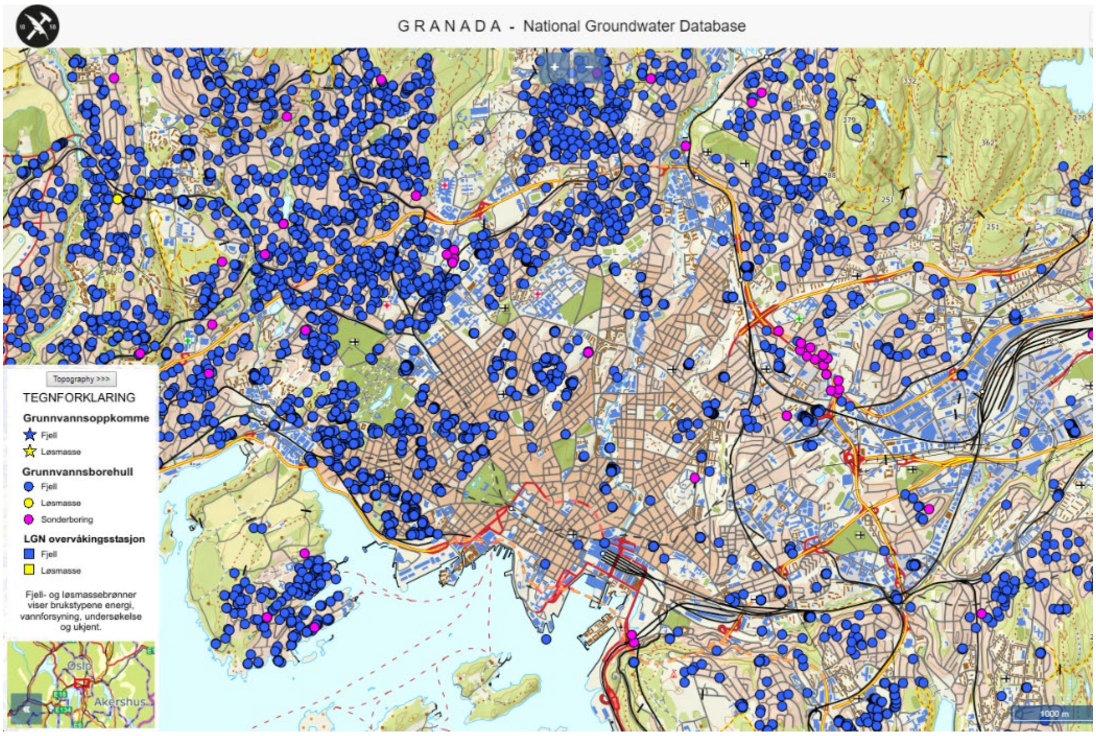


Figure 2.7. Groundwater bore hole locations in Oslo, Norway. Borehole information stored at each location includes location, depth and additional drilling information if available (http://geo.ngu.no/kart/granada/).

2.3 Concluding observations

Although out of sight, groundwater should not be out of mind. Within the correct geologic setting, an aquifer's ability to provide a high-quality water source to domestic, agricultural or industrial consumers in a way that is safe for the users and the environment has been proven to be feasible for centuries. From the examples above, a realization that each system was built around specific requirements for the city (or adapted to new challenges), country or area of interest should be apparent. Depending on what is sought after by the client, may it be water quality, record keeping, or a real-time groundwater level monitoring system, a network can be developed and optimized to meet the desired function.

A publicly available (and easily searchable) information data-source is ideal, not only for operators & regulator transparency, but also for the distribution of information during emergency situations and educational opportunities for the community. With the current state of database management for operational systems and spatial plotting within dashboards, a smooth display with multiple layers of data is achievable.

3 Urban groundwater monitoring - experiences in the USA

A 2001 report commissioned by the USGS on groundwater level monitoring and the importance of long-term water level data outlines crucial pieces of information needed to develop a successful monitoring network but focuses on regional (basin or state scale) case studies. While the concepts needed to define such a monitoring network are the same, differences in scale should be considered when implementation on a more local scale and within an urban setting is to take place.

Additionally, the American Geosciences Institute (AGI) provides an interactive map of groundwater monitoring information, including over 7000 groundwater wells collected from state and federal agencies. Each interactive wellbore provides information on well construction and lithology, allowing for a high-level overview of aquifer health but too few details to be able to make decisions at a local level.

The vastness of the United States makes monitoring on a national level with insight into local systems within urban centers unviable. State based water resource acts, such as that in California, place ownership of water monitoring and management on the water districts, municipalities and cities themselves where local knowledge of the surficial and subsurface systems can be implemented more efficiently. Through this appropriate use of local systems knowledge as well as the individual problems linked to each urban center a much more efficient monitoring and management plan can be realized.

3.1 San Francisco groundwater management program

In 2016 the San Francisco Public Utilities Commission prepared an urban water management plan for the City and Country of San Francisco in response to the drought and corresponding local state of emergency where at the time, represented the driest period in the hydrologic record. This plan considers (among other points) the local water supply and demand dynamics, shortage contingencies and climate considerations. The plan requires all its urban water suppliers to update and prepare their urban water management plans every five years and these (and the overall program itself) need to fall in line with the 1983 California Urban Water Management Planning Act. The purpose of the act is “to assure water suppliers plan for long-term reliability, conservation and efficient use of California’s water supplies to meet existing and future demands”.

Included as a section within the Urban Water Management Plan, The Groundwater Management Program is in itself one third of the total groundwater program which also consists of the San Francisco Groundwater Supply Project and the Regional Groundwater Storage and Recovery Project. The program looks at providing data and advice to prevent overdraft, pollution or contamination in any of the 7 groundwater basins in San Francisco and is devised in line with the urban water management plan.

Groundwater monitoring within the area of interest provides both chemical properties and physical water levels within the area of interest. When combined with pumping information from key locations (ie. San Francisco Zoo, local groundwater supply projects and regional groundwater and storage recovery projects) changes may be correlated to certain actions, driving a better understanding of the subsurface system. Surface water and storm water systems are also included within this plan and the link between the systems is not missed.

3.2 Nassau County groundwater monitoring program

Nassau County in New York State is home to 1.3 million people and relies on groundwater as a source for 100% of the drinking water delivered to its residents. Commissioned by the Nassau County Department of Public Works (DPW) their groundwater monitoring objective is clear; “to ascertain the overall condition of the groundwater resource and behavior of the aquifer system on a countywide scale through an extensive network of monitoring wells”. In doing so, information is measured to study the system trends in water use, quality, levels and any relationships they may have with weather patterns. Although all work pertaining to sample collection, measurements, data interpretation and reporting is done by the DPW, a cooperative working partnership with the USGS has existed for over 65 years. The data and reports generated are protected under the freedom of information act and distributed to any person or business who may be interested.

Monitoring components consist of 620 wells spread over ~1000 km^2 county with screen depths targeting different aquifers depending on the well locations. Located at (and surrounding) a groundwater divide, multiple wells were placed and are visited monthly to record the water levels at this site. Because of this location’s high natural groundwater level and its susceptibility to fluctuations in response to climate conditions, these wells act as a drought indicator for the rest of the county. Piezometric levels are also recorded and when evaluated against historical information, trends with respect to the behavior of the hydraulic system may be interpreted.

3.3 USGS Groundwater Watch – Groundwater monitoring on a National and State level

The United States Geological Survey (USGS) provides an active network of over 17,000 wells across the country that are measured at least once a year (1,744 are monitored in real time and another 1,280 at a daily timestep). Additionally, a national database of 850,000 wells is kept, maintained and is searchable through the waterdata.usgs.gov website. These networks are used for state and local monitoring projects and hydrologic research. Each state is searchable and from there, each country and individual wells. Site statistics, groundwater level data and site description are all available in downloadable format.

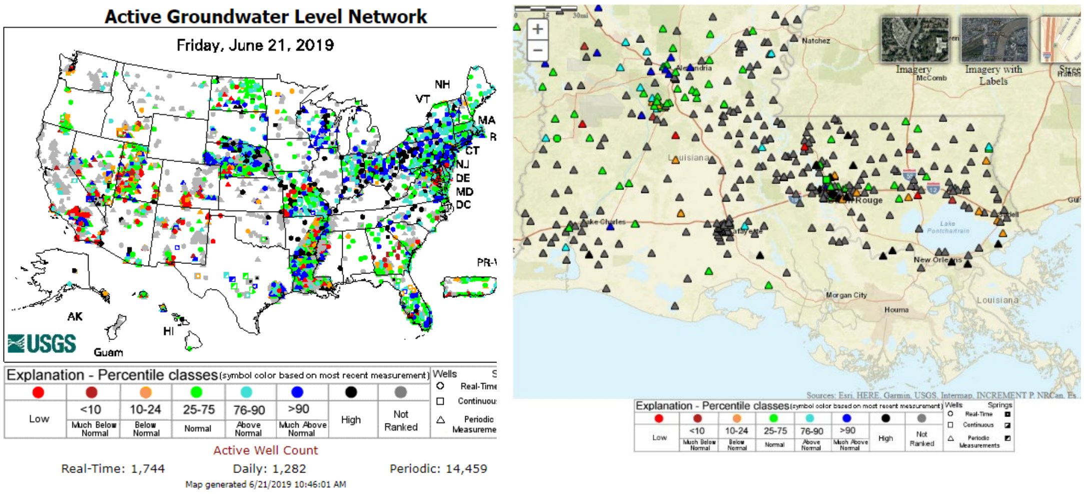


Figure 3.1 (left) United States Active groundwater level network map and (right) Louisiana groundwater well monitoring locations. From (https://groundwaterwatch.usgs.gov/default.asp)

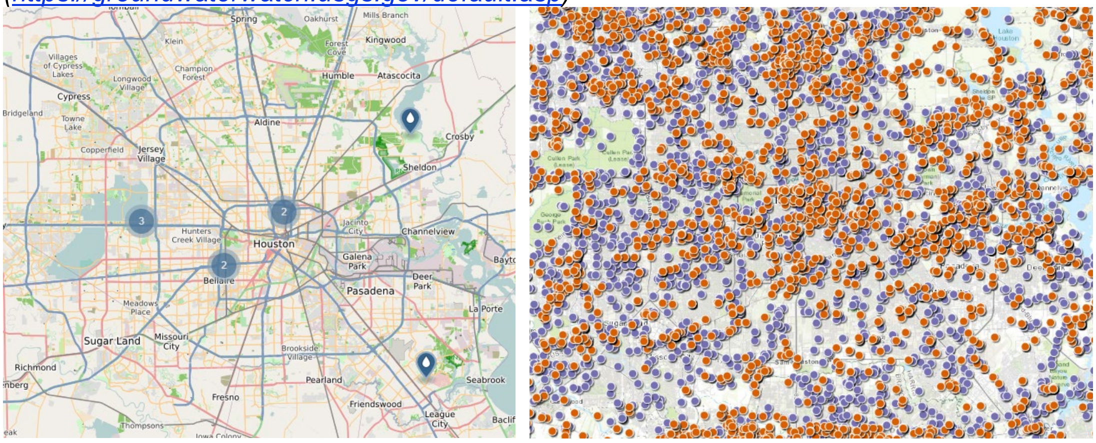


Figure 3.2 (left) locations of automatic recording devices actively monitoring the groundwater levels within the aquifer of interest. (right) All well locations listed as "water supply wells / pumping (purple)" or "monitoring wells (orange)" over the city of Houston. (from: https://www2.twdb.texas.gov/apps/WaterDataInteractive/GroundWaterDataViewer)

State wide water agencies, such as the "Water Data for Texas" group (a subproject of the Texas Water Development Board) also provide publicly available information on the current levels of reservoirs and groundwater, as well as drought, evaporation and rainfall data. The groundwater level measuring projects is a cooperative effort between 50 groundwater conservation districts with the intent to have at least 1 well per 25 sq/miles within minor aquifers and 1 well per 125 sq/miles for major aquifers (left). Figure 3.2 (right) shows the well density over the same area, orange wells are labelled in the well report as "Proposed use – monitoring" whereas wells highlighted in purple are intended for the "withdrawal of water". Only wells from the left image provide hydrograph data and well information. Locations from the right image from the interactive water data site only provide information pulled from the submitted drillers well report.

Figure 3.2 (left) shows wells that are transmitting real time groundwater levels and can also be found in the active National/State monitoring network provided by the USGS (Figure 3.1). The locations from (Figure 3.2) however, which do not include locations where data is recovered and charted periodically, provides a good example of the network density that may be present and may have the potential for use if “re-worked” into a denser monitoring network.

3.4 Concluding observations

With the exceptions of the examples provided earlier, the public distribution of urban groundwater monitoring information was difficult to find at a local level. Information relating to water quality was generally present in the form of an annual water quality report, but supporting information was not found. If the information is present and being used to guide water related decisions, then a natural step towards a transparent system is presenting the data within the public domain. If, however, groundwater related decisions are taking place by a group that does not have the proper tools and knowledge at their disposal, they are putting the environment, infrastructure and the local population at undue risk.

4 A vision on monitoring water and the urban environment

4.1 An INTEGRATED monitoring network

Groundwater is only a single component within a complex system of interrelated parts. Figure 4.4.1 provides an abstracted, generalized example of how groundwater levels interact with other natural and anthropogenic systems. This figure is provided to help raise awareness of the complicated and interrelated process at play as well as inspire discussions about leveraging current (and emerging) technologies to monitor interrelated urban water systems.

"an INTEGRATED monitoring network for the region would ensure that water management strategies could be targeted precisely when and where needed"

- Greater New Orleans Water Plan – Urban Design

The merging of currently independent (if available) parts such as surface and groundwater levels, water chemistry, subsidence, precipitation, and storm system information could help to provide insights into inter-related parts of the system. In doing so, the potential to better understand water related risks would increase.

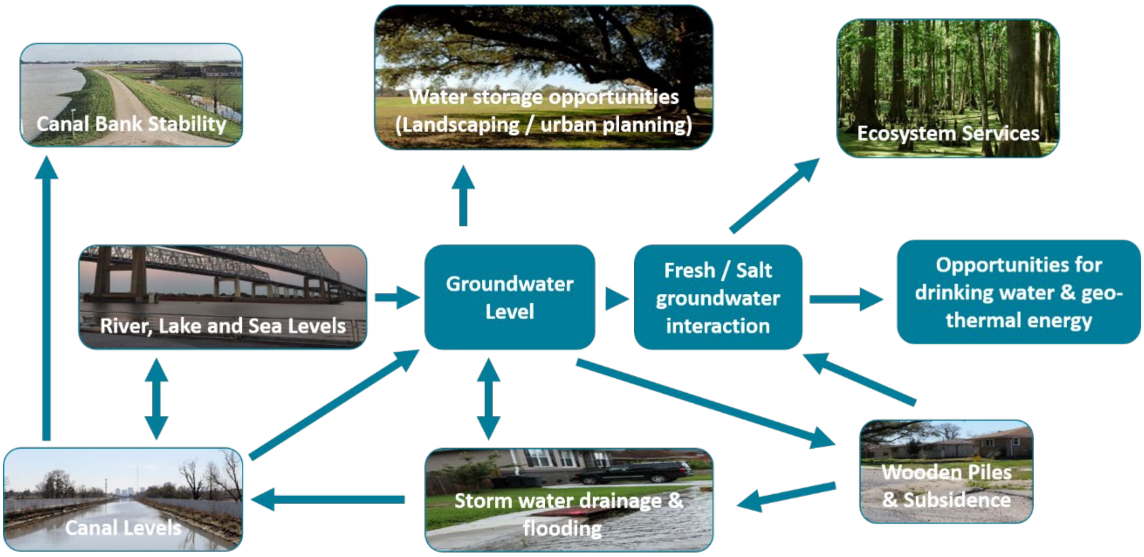


Figure 4.4.1 An example of how groundwater levels may interact with natural and anthropogenic systems.

4.2 The monitoring cycle

Figure 4.2 presents a possible approach towards an iterative integrated water resource management (monitoring) plan and helps to visualize the cyclical nature of the process itself.

Building from an understanding of the project objective, defining the information to be collected is an important second step.

A monitoring strategy follows and includes a conceptualization of the “what”, “where” and “how”. The network design advances and materializes the monitoring strategy, installing hardware solutions and creating or implementing software solutions where needed. Processing the data and data analytics can be an automated process, either built into the system or as a standalone repository that stores raw data that can then be made available to whoever is granted access. Decisions on how the data is then reported, distributed and utilized should be outlined in the vision and decided upon through communications with stakeholders at the start of the project.

Integrated water management strategies are no different than other process that need to evolve with changing technologies, methods and thought processes. Hence the cyclical nature of the process itself. An evaluation of if the process is providing decision makers with information they require and in a more general sense, if the program is satisfying the objectives and scope set during the conceptualization phase.

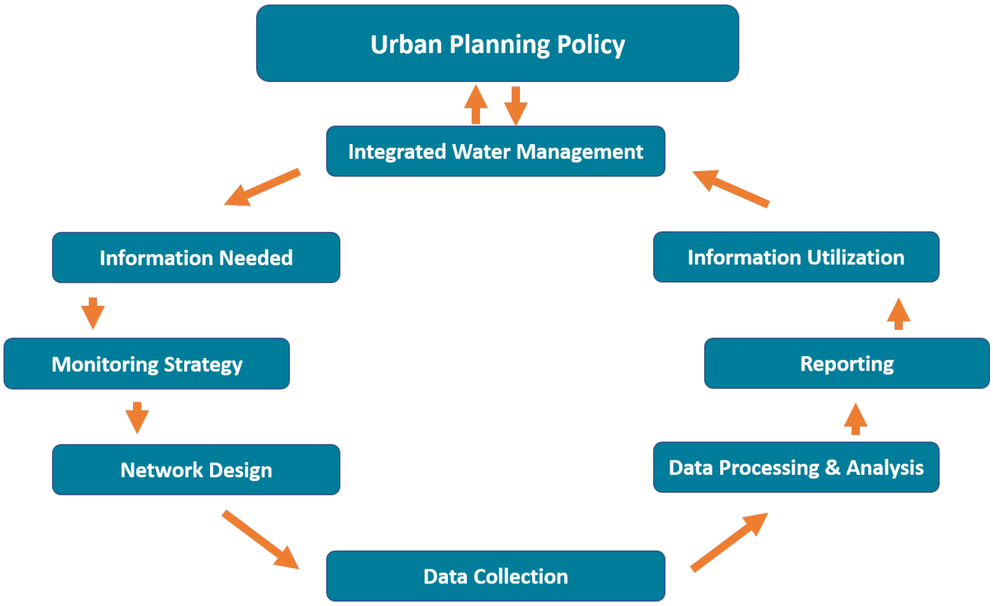


Figure 4.2 Integrated water management monitoring cycle steps and its relationship with urban planning policy decision makers.

To complete the cycle, a re-evaluation of the entire process and its deliverables should be undertaken at regularly scheduled intervals or as needs change. Are there new tools or processes that should be changed or adapted to? Do stakeholders / decision makers require new or different forms of information? Is there information being created that is no longer relevant, out of date or redundant? These are all examples of relevant questions that may be asked to help better understand if a review of the project cycle is needed.

Section 4.3 breaks down the integrated water management monitoring cycle into its parts and couples each action with parts of the figure from section 4.1. These images can be found in Annex 1.

4.3 From design to implementation – Examples of possible solutions

In table below the steps of the monitoring cycle (figure 4.2) are filled up for different monitoring goals.

	**Gw Level // River, Lake & Sea levels, Water storage opportunities**	**Gw level // water storage opportunities // storm drainage and flooding // wooden piles & subsidence (**	**Canal bank stability // canal levels // gw level // fresh and salt groundwater interaction // wooden piles & subsidence/**	**Gw levels // fresh & salt gw interaction, ecosystem, opportunities for drinking water // subsidence**
Integrated Water Management	Rain water infiltration to reduce pluvial flooding & damage	Optimize strategy to reduce pluvial flooding and subsidence	Mid / long term management strategy of outfall canals	Mid / long term management strategy of deep groundwater
Information Needed	How do rivers and lakes influence infiltration opportunities?	Where is removing pavement / infiltration recommended, and where should repairs to storm water drainage take place?	What are the risks of infiltration from? Is subsidence occurring below the canals?	Opportunities and risk of deeps groundwater for wetland ecology, freshwater supply, energy storage and groundwater logging
Monitoring Strategy	Determine influence of river and lake on; (1) surface elevation / lithology and (2) on deep, then shallow groundwater levels (hourly)	Determine interaction between groundwater, storm water drainage, subsidence and land use	Determine interaction between canals, subsurface and groundwater	Determine interaction between deep and shallow groundwater, fresh / salt distribution and subsidence
Network Design	Lithological profiles, well transects, surface water gauges, rainfall	Lithological profiles, well transects, sewer inspections, land use types (paving), rainfall, surface elevation	Lithological profiles, well transects, canal water levels, salinity in canals, groundwater salinity, wetland ecology	Lithological profiles, well transects (shallow / deep), groundwater salinity, wetland ecology, surface elevation
Data Collection	Data Collection	Data Collection	Data Collection	Data collection
Data Processing & Analysis	Graphs / Statistical analysis	Graphs / Statistical analysis	Statistical analysis, groundwater modelling	Statistical analysis, groundwater modelling
Reporting	Zonation map Groundwater depth x lithology = Infiltration potential	Zonation maps: causes and impacts of low groundwater & pluvial flooding	Risk zonation maps: seepage / waterlogging, salinization, subsidence	Zonation maps: opportunities and risks of deep groundwater
Example Information Utilization	Prioritization of infiltration measures	Prioritization: un-paving vs storm water repair	Management strategy: maintain or reduce infiltration from canals	Management strategy: enhance freshwater buildup, no drill zones, masterplan for deep groundwater

5 Water quantity monitoring

5.1 Introduction – “You can’t manage what you don’t know”

To help combat frequently flooded streets, subsidence, salt water intrusion and other potential effects linked to more frequently occurring high intensity weather events, the City of New Orleans could look toward initiating an integrated water resource monitoring plan combining subsurface, surface and weather-related measurement types to help determine a baseline dataset and work towards understanding the relationship between different variables.

Error! Reference source not found. presents a data collection, storage and analytics workflow that would be appropriate for the New Orleans East.

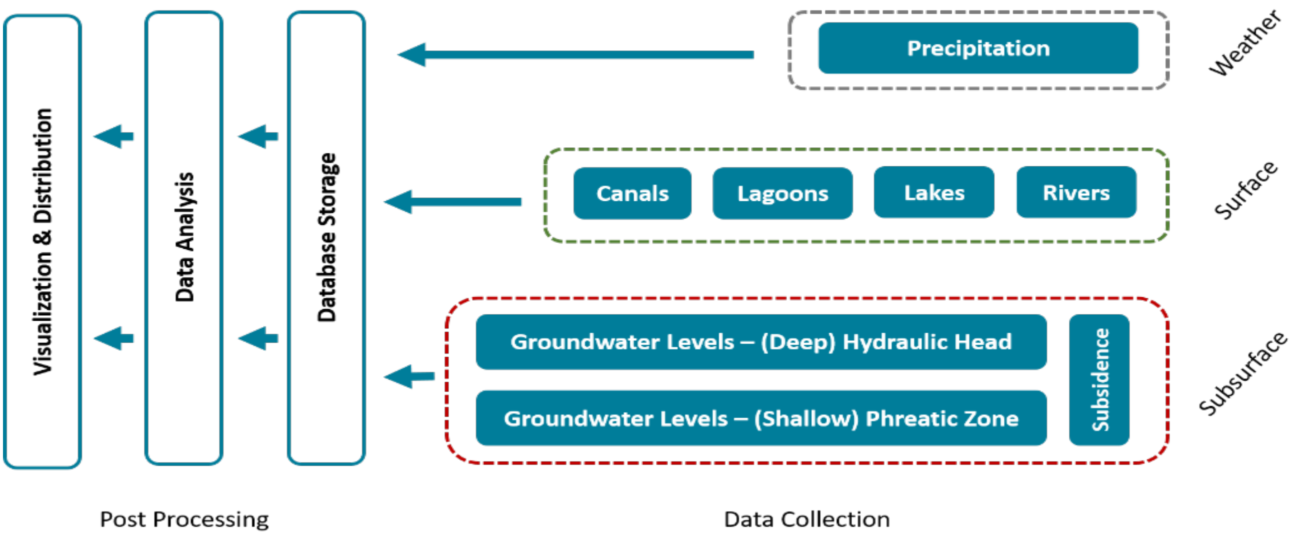


Figure 5.1 An example of different data sources that may be combined in coming up with an urban water monitoring program for New Orleans.

5.2 Monitoring objectives

Setting actionable, attainable, and quantifiable monitoring objective(s) that include manual and technology enabled recording devices distributed over the area of interest is a key step prior to moving into the monitoring cycle. The defined monitoring objectives & resulting action plan is achievable in a cost-effective manner while providing enough data so valid relationships may be seen.

Figure 5.2. One objective could be to safeguard the Heritage Live Oak trees. Rising and sustained groundwater levels may drown and suffocate the root system.

The preceding description of groundwater impacts and processes in Greater New Orleans informs the development of the following 12 monitoring objectives:

1. To define which groundwater regimes occur in subsidence-prone clay and peat areas. Can changes be made to groundwater levels to reduce subsidence?
2. To define the extent to which wooden foundation piles have emerged above groundwater. Untreated piles are vulnerable to rotting processes.
3. To define the extent to which groundwater levels are influenced by water levels in the canals.
4. To define the extent to which groundwater levels are influenced by subsurface infrastructure. Often the storm drainage and waste water transport pipes drain groundwater, while the drinking water system loses water into the groundwater. What will happen with the groundwater situation in future after these systems are renovated?
5. Determine to what extent shallow groundwater levels and deep hydraulic heads interact. Understanding the impact of deep groundwater pumping on shallow groundwater levels.
6. Better understand the relationship between groundwater levels and the influence of the Mississippi River and/or Lake Pontchartrain. Are groundwater levels influenced by Mississippi River or Lake Pontchartrain water levels?
7. Determine the storm water (rain) storage capacity of local soils. When is this capacity exceeded? At what point will ponding and overland flow occur?
8. Determine if there is a salinization risk for freshwater-dependent land use functions.
9. Better understand and define the relationship between sub-regional groundwater flow and Mississippi River / Lake Pontchartrain.
10. Discuss the potential climate change scenarios and the effect on the future groundwater situations. Determine how a monitoring system can help track changes.
11. Create groundwater and subsidence awareness (*Figure* 5.3).

12. Set up temporary monitoring networks in vulnerable areas to observe the local effects of dewatering (e.g. subsidence, dry fall of untreated wooden foundation piles). To mitigate damage caused by dewatering, a monitoring protocol is advised. Groundwater level thresholds should be determined (at what groundwater level is risk deemed to be unacceptable to the local infrastructure or environment). If these thresholds are reached, projects plans should continue (or stop) accordingly.

Figure 5.3. Raising public awareness of groundwater monitoring: a floater on top of groundwater allows groundwater levels and fluctuations to be visible above ground. The transparent tube delineates the ranges where groundwater levels are too low (red) and fair (green).

5.3 Water system analysis overview

In 1717 a decision was made in Paris to begin construction of a settlement in North America to be named New Orleans. Engineers charged with this task likely began clearing underbrush in early 1718 and were met with wet, marshy conditions between the Mississippi river and lake Pontchartrain. Between the early 18th and 20th centuries, the land was transformed to keep pace with a growing population that swelled from the initial few hundred settlers to over two hundred thousand inhabitants. This shift and had a dramatic effect on the subsurface water system and the evolution of the fresh – salt water dynamic shift is presented below in Figure 5.4(a – d). The following section provides a very brief overview of the shallow and deep groundwater systems.

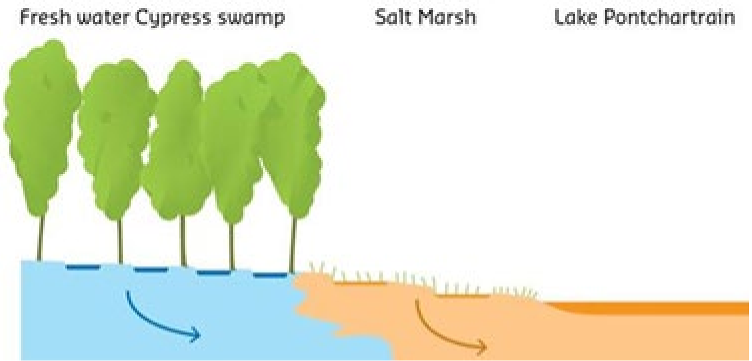
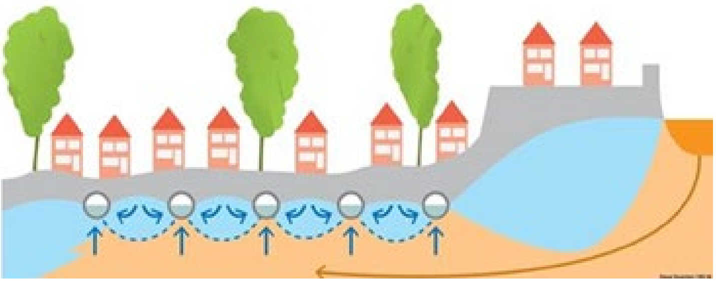


Figure 5.4 (a) Stage 1 - Original ecosystem dynamic between the freshwater cypress swamp (now New Orleans) and Lake Pontchartrain. Fresh water flows from the South to the north (from swamp to lake), following the elevation and pressure gradients through the salt marsh system.

Figure 5.5 (b) Stage 2 – Anthropogenic activities begin. A water retaining structure is built protecting the inland area from the lake waters. No change to subsurface flow patterns occur at this step.

Figure 5.6 (c) Stage 3 – Civil structures and water management practices begin to transform the local ecosystem, reclaiming land by draining a section of the cypress swamp and inducing a flow reversal in the process. Now, the salty groundwater system stemming from Lake Pontchartrain now drains towards the freshwater of the cypress swamp.

Figure 5.7 (d) Stage 4 – Freshwater lenses develop over time as an equilibrium is reached in the new subsurface flow system. Less dense freshwater sits on top of the more dense saltwater originating from the Lake. Drains and sewer systems remove water from the urban groundwater environment.



5.3.1 Shallow groundwater flow

Figure 5.8 depicts an image of the shallow flow system model completed by Deltares/Tulane in 2019 (Van Asselen et all, 2019) over New Orleans East. Groundwater flows from levels of higher elevation (green) to areas of lower elevation (purple) and in doing so allows for the mixing of the older subsurface waters with newer waters from the surface, canals, lakes, lagoons or river. Freshwater is drawn into the underground system from the Mississippi (blue arrows) and more saline water can be seen flowing from the canals in the direction of the red arrows.

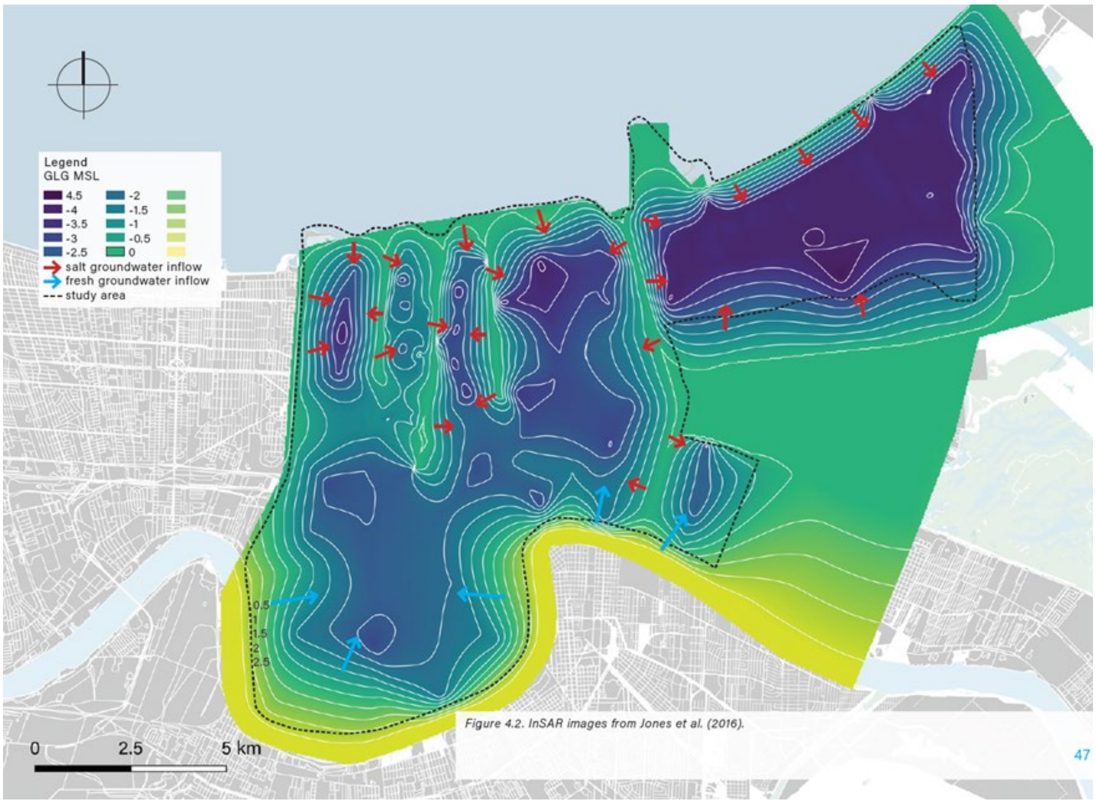


Figure 5.8 Estimated groundwater head level map over New Orleans. Groundwater flows from areas of higher levels (yellow / green) to areas of lower levels (blue / purple) and water type is dependent on the source. Freshwater is fed to the system from the Mississippi river (blue arrows) whereas the canals and water sourced from Lake Pontchartrain is more saline (red arrows).

A conceptual cross section profile trending East to West in the NE quadrant of the city can be seen below in Figure 5.9. This image provides an example of the way the groundwater system interacts with the canals, pipes, parks and subsurface lithology. Hand drawn water level estimates from the sketch can be compared with the modelled results from Figure 5.8.

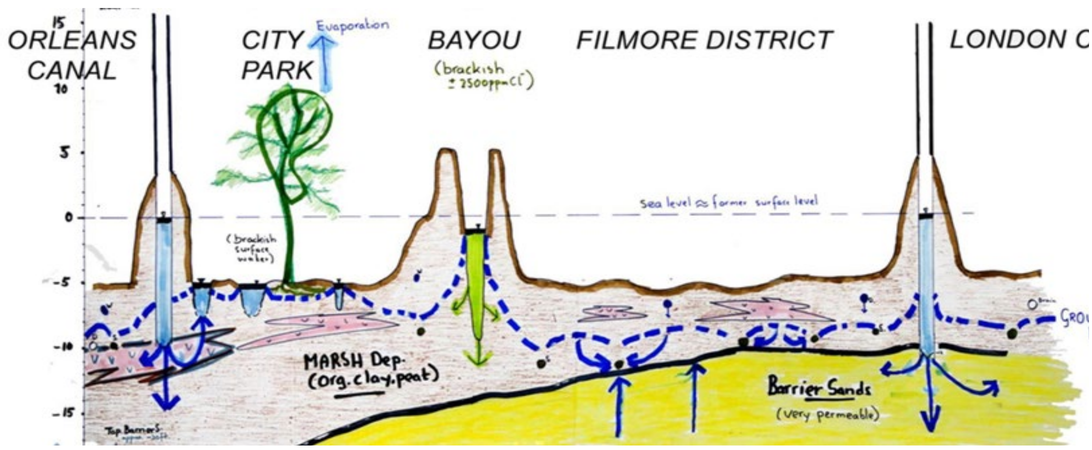


Figure 5.9 A conceptual sketch representing a cross section trending approximately E-W through the Orleans Canal, City Park, Bayou canal / river, the Filmore District and London Canal. Lithology (organic deposits and Sand layers are represented in brown and yellow, respectively) and the theoretical flow lines and groundwater levels are represented as solid and dashed blue lines.

Groundwater flow lines can be seen in the sketch of Figure 5.9 as solid blue arrows and flow from canals into lithologic layers of higher hydraulic conductivity (sands and lenses within the clay/peat). Leaking underground pipes can both add water to the system as well as remove it depending on pipe pressure, amount of structural damage (cracks), and permeability.

Like the sketch presented in *Figure 5.9*, the image below (*Figure 5.10*) provides a conceptual drawing of the flow systems between the Mississippi river and Lake Pontchartrain, trending in a North – South direction. Flow fines can be seen moving away from areas of higher piezometric head (the lake, river and higher zones of elevation) towards lower lying discharge areas. The infiltration from these two sources would provide freshwater infiltration from the Mississippi and saline water from lake Pontchartrain as described above and represented in *Figure 5.8* by the blue and red arrows.

Groundwater abstractions and depletion of the deeper confined aquifer has lowered the hydraulic head over time. This change increases subsidence risk by reducing the counteracting force acting on the downwards overburden from above. The red arrows below also highlight a current lack of understanding with respect to the amount of water that is leaving the system as recharge.

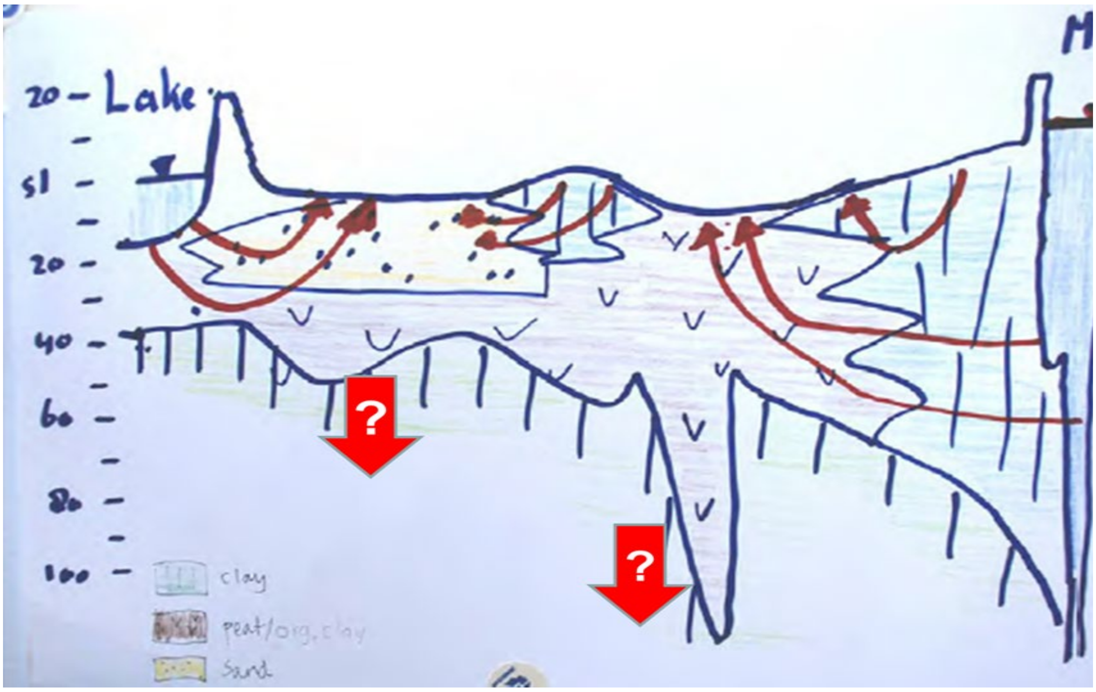


Figure 5.10 A conceptual sketch trending approximately North – South between Lake Pontchartrain and the Mississippi River in the eastern section of New Orleans. Groundwater flow lines are shown as solid red (hand drawn) arrows and lithologies such as sand, peat and clays are represented by blue, purple and yellow colors respectively.

5.3.2 Groundwater Drainage

Until recently, no information existed about the behavior of shallow groundwater in New Orleans. To fill this gap, 73 shallow soil bore holes were drilled (see New Orleans Subsidence Vulnerability report, Van Asselen et all, 2019) and a few high frequency groundwater monitoring wells were installed. Both systems delivered valuable new information about the fluctuation of the shallow groundwater system and led to the conclusion the groundwater level is strongly controlled by the sewage and stormwater drainage network below the roads and sidewalks.

As can be seen in the (conceptual) image of Figure 5.11 (top), the solid blue line representing the mean lowest groundwater level corresponds to the base of wastewater drainage infrastructure during normal weather conditions. During extreme storm events however, groundwater levels can increase with a range between several decimeters (2 feet) up to nearly 2 meters (6 feet) as can be seen in the groundwater hydrograph shown in the bottom left image of Figure 5.11. The groundwater level rises rapidly during precipitation events but returns to the pre-rainfall event groundwater level at a slower rate as the added groundwater drains off and returns to its steady state.

Figure 5.11 also presents a conceptualization of how the stormwater and sewer systems are aligned within the New Orleans subsurface and potentially helps with the explanation of the groundwater drainage processes. Storm drainage pipes and sewage pipes are placed in a subsurface trench filled with gravel and sand, this helps to protect the pipes against the negative effects of subsidence or other ground movements. Additionally, the pipes are joined with geo textile slabs allowing for a flexible joint at the pipe connection. These slabs protect against the inflow of sand into the system but are permeable to groundwater. The permeability of this connection, its degradation over time, and cracked and broken pipes allow groundwater to enter the drainage system and be removed from the area. The infill materials used during the construction process also create a high permeability/porosity preferred flow network for the groundwater to follow. If the groundwater level rises and water pressure of the groundwater system is greater than the water pressure within the pipes, groundwater will enter the drainage system. Groundwater levels will then be limited to the elevation of drainage network itself. Interestingly, if broken pipes are replaced, a rise in groundwater level should be expected within the vicinity surrounding where the replacement is taking place.

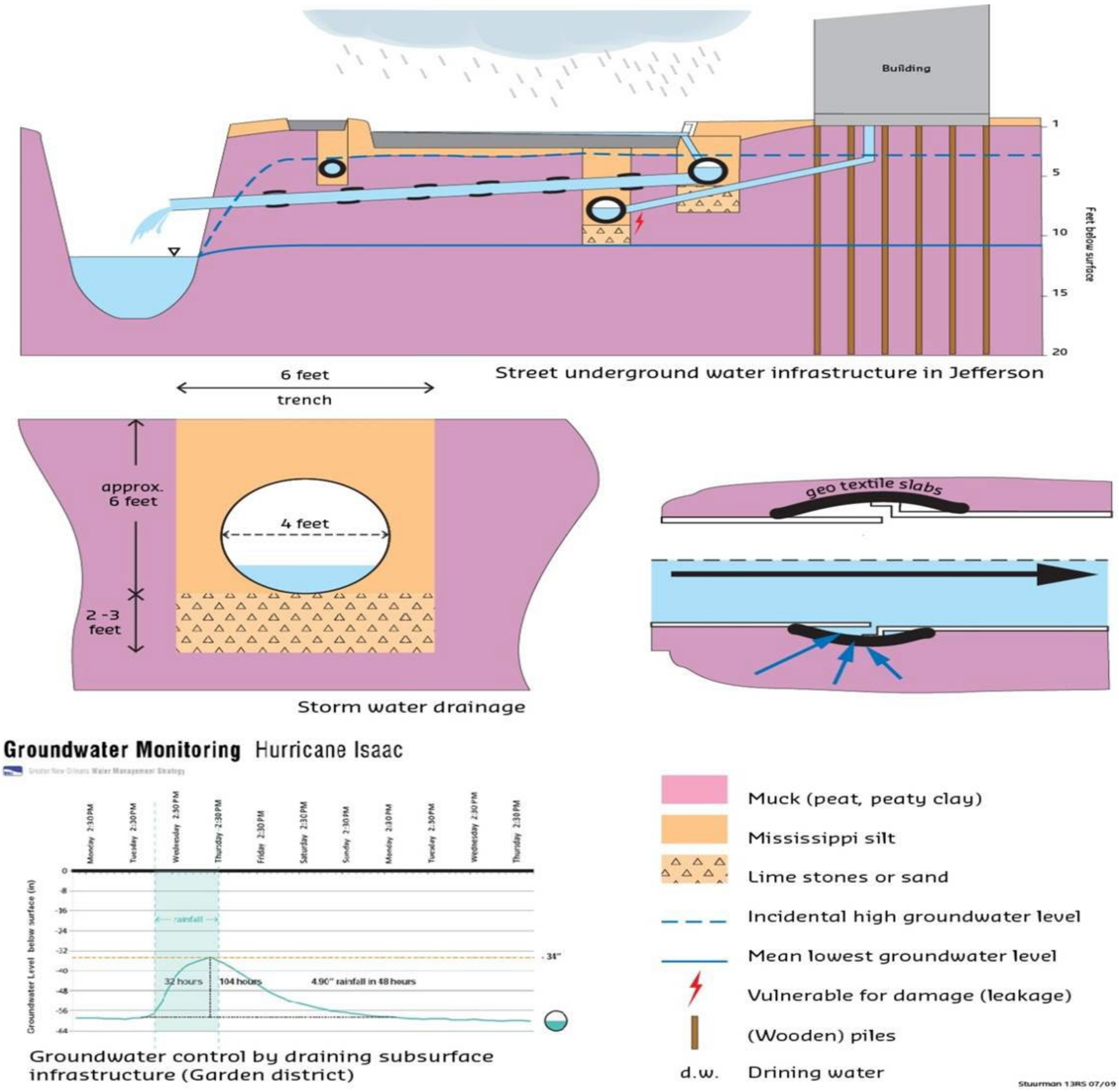


Figure 5.11 A collection of images describing the influence of underground water infrastructure on the shallow groundwater system. (top) A conceptual schematic of the depth and placement of stormwater and sewer systems and their relationship to the incidental high and mean lowest groundwater levels. (mid left) a cross sectional view of the pipe and surrounding sediment types. (mid right) A conceptual drawing of the use of geo textiles as joint connectors. (bottom left) a hydrograph showing the relationship between the Hurricane Isaac rainfall event and the groundwater level increase.

5.3.3 Deep groundwater flow

The New Orleans East deep groundwater aquifer system was used primarily for industrial purposes for most of the 20th century with the main groundwater extraction site located at the Michoud (Entergy) plant as highlighted in Figure 5.12 with purple. The facility used the groundwater for cooling purposes, later discharging it back into the canal system. Prolonged pumping at rates greater than the rate of recharge let to a significant drop in hydraulic head at the abstraction location and is highlighted by the ‘bulls’ eye’ pattern targeting the plant (Figure 5.12). The deep aquifers main recharge zone is in the hilled area north of Lake Pontchartrain (Figure 5.13) and the deeper aquifers contain both salt and fresh water systems. Due to the length of flow path system, it is suggested that the fresh groundwater aquifer below New Orleans is thousands of years old.

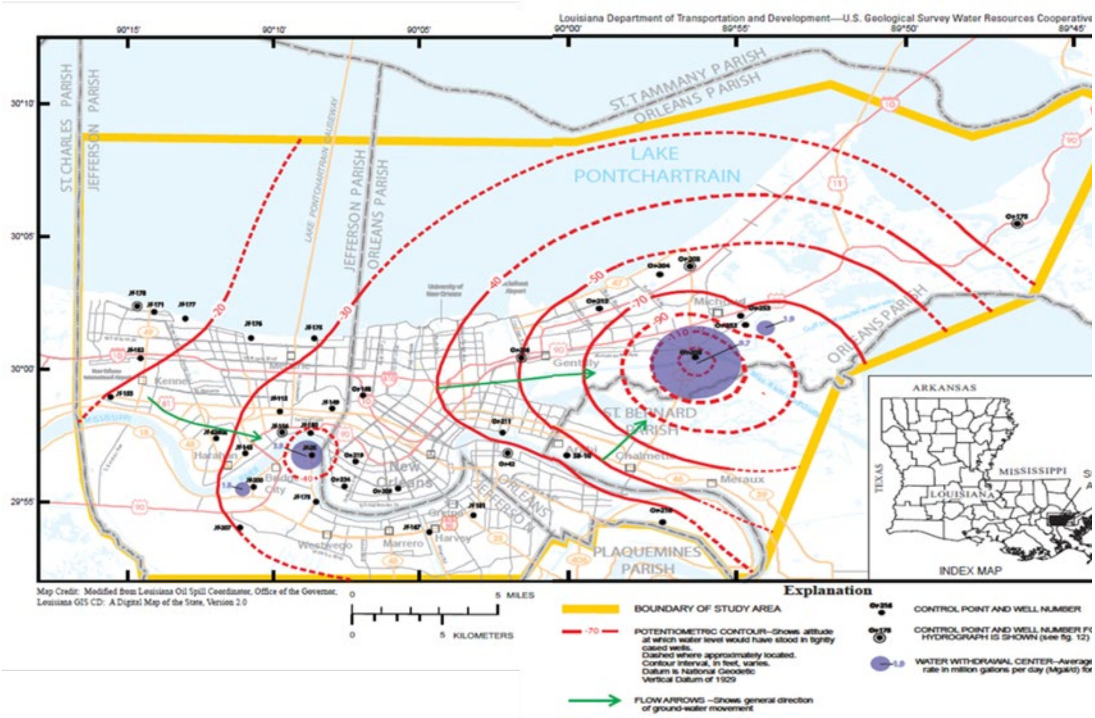


Figure 5.12 Contours of equal hydraulic heads in and around New Orleans (USGS/Prakken, 2009). The figure displays the impact of groundwater pumping at the Michoud Entergy plant site on groundwater flow in the deep Gonzales aquifer.

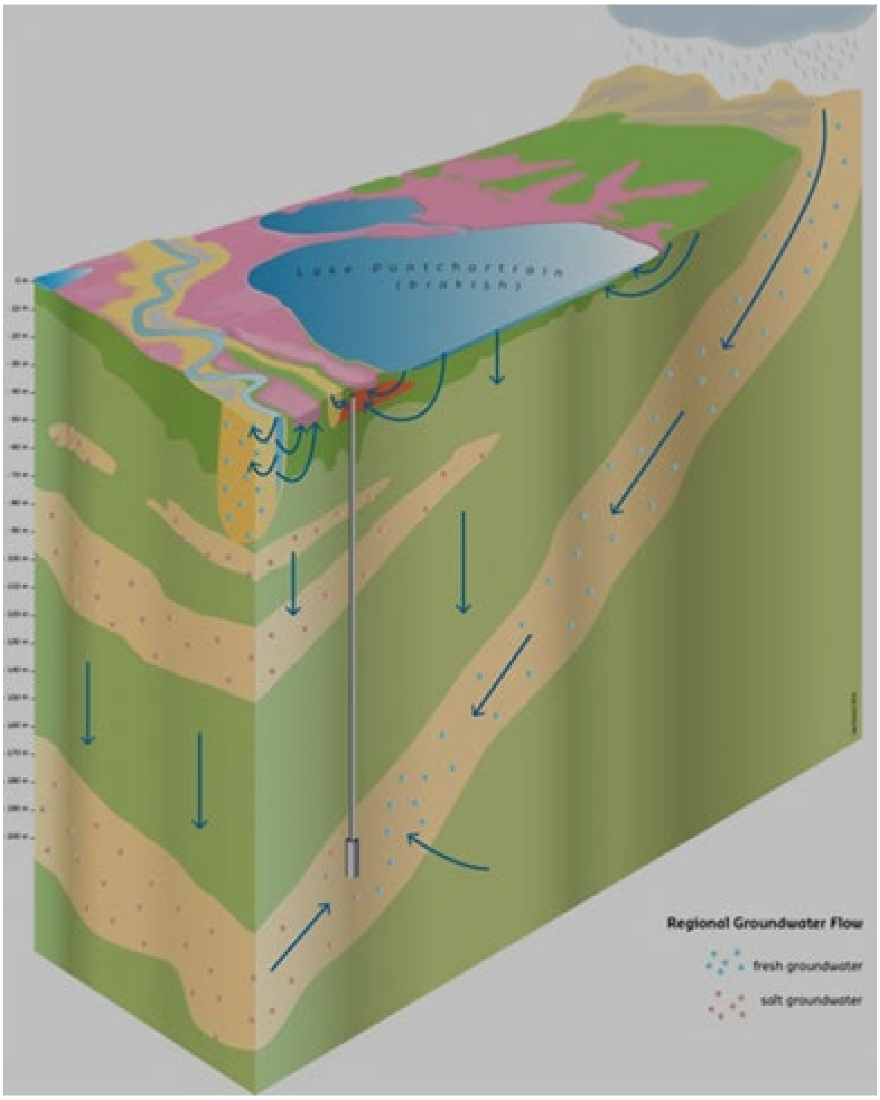


Figure 5.13 Schematization of the regional groundwater system around New Orleans

5.4 Precipitation and evaporation

The use of existing local meteorological information to enhance the understanding of how rain and evaporation influence groundwater levels, storm water runoff and urban surface water levels are key benchmark indicators that are identified as important to better conceptualize the urban hydrologic cycle. It is suggested that between 1 and 3 stations be installed and maintained, having the data fed into the main storage database (locations: e.g. New Orleans NE, Gentilly, Garden District). Additionally, radar and soil moisture maps could be added thus allowing for potential insights with respect to vegetation health and precipitation to occur.

Currently, there exists a lack of evapotranspiration information over New Orleans. As reliable and high-resolution ground-based evaporation measurements are not available for the study area, evapotranspiration can be estimated using the Makkink-method (Eilander et al., 2023) applied to the ERA5 global climate dataset, which provides climate data on a global scale including temperature, humidity, wind speed, and net radiation (Hersbach et al., 2023). The resulting estimates of evapotranspiration are rather consistent per year and vary for period

2010-2020 between 1012 mm in 2013 and 1117 mm in 2011. It is advised to install a few (3-4) field observation sites as validation of the ERA5 data.

5.5 Existing shallow monitoring wells

5.5.1 2200 Prytania Street (Waggonner & Ball)

In 2012 a shallow groundwater observation well was installed in the garden of the WB office, approx. 30 feet from the street. Deltares added a sensor (so-called “diver”) measuring groundwater levels at a 1-hour interval (figure 5.14). Although the soil consisted of low-permeability heavy clay, the decrease of the groundwater level after a rainstorm was remarkable. During rainstorms the groundwater levels rose instantaneously 16-25 inches (40-63 cm) but dropped afterwards in a very short period (days). This decline can only be explained by drainage of the underground infrastructure below the street, supported by secondary permeability of the shallow subsurface. Probably, this secondary permeability layer is formed by roots (fresh and dead) of shrubs and trees, in combination with filled drought cracks.

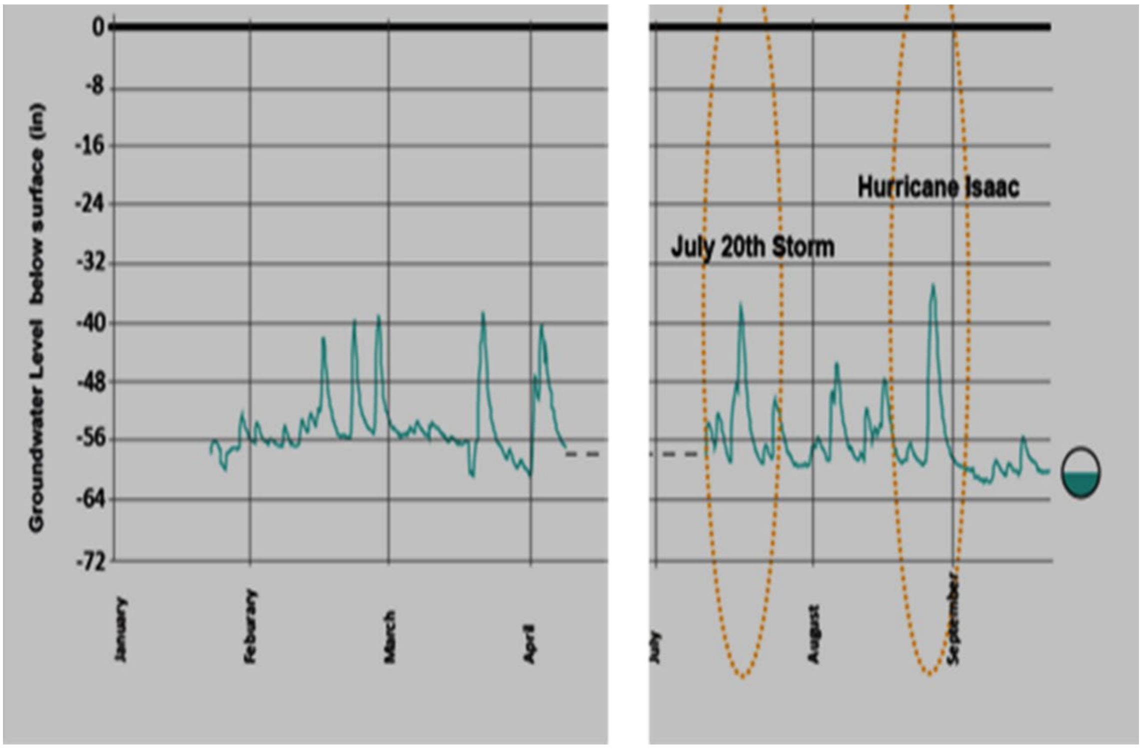


Figure 5.14: Time series of the 2012 high frequency monitoring results at WB office.

5.5.2 Lafitte greenway

There are few active shallow observation wells in New Orleans East. 4 sites in the Lafitte Greenway project present an excellent local example of what could be expected from a city-wide network. Figure 5.15 presents the recent measuring results, showing steep rises (often 2 feet) slightly lagging rainfall events and returning to its relatively stable (mean lowest) groundwater level over a longer period of time. At these locations, the lowest groundwater levels sit ~ 7.5 to 9 feet below sea level.

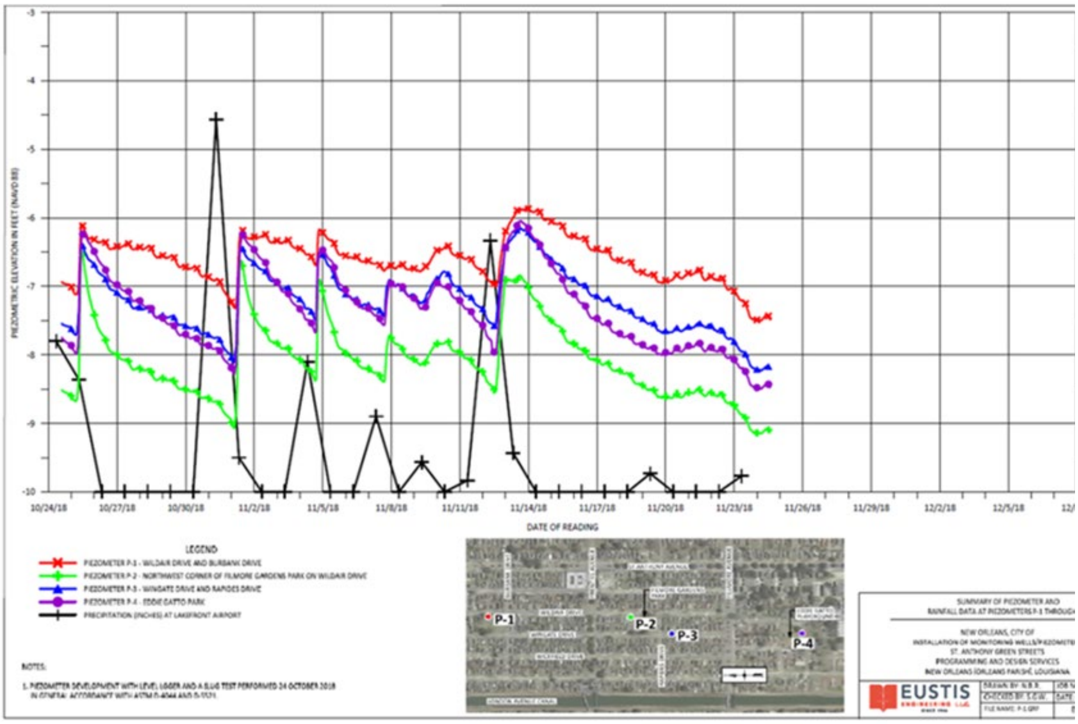


Figure 5.15 Hydrograph lines from 4 operational borehole locations in the Gentilly District. Precipitation is included as the black line. Notice the response in recorded shallow groundwater levels to precipitation events.

5.5.3 Lake Vista (information based on Eustis data report No.5 & 6)

Eustis Engineering in cooperation with Batture presented piezometer measurements from three piezometers installed for the proposed drainage improvements associated with the City Park water storage project.

The scope of this monitoring service with Batture included installation of three open standpipe piezometers and one year of monitoring reported on a monthly basis. Piezometers were to be installed at the 10-ft. depth below existing ground surface to evaluate long term ground water elevations (figure 5.16). Phreatic (shallow) groundwater levels and salinity was monitored. These data were collected to make informed decisions for potential future green infrastructure associated with transferring stormwater drainage from the adjacent Lake Vista neighborhood into City Park.

Figure 5.15: Locations of shallow groundwater monitoring wells at Lake Vista

Ground water level fluctuations and larger conductivity fluctuations appear to be event-based with rainfall (figure 5.16). Approximately 3 to 4 inches of rainfall was measured at the project rain gauge from 22 October to 17 November 2020. This is reflected in the readings of piezometers P-2 and P-3 (closer to the lagoon) where groundwater levels increase when rainfall is recorded at the site. At Piezometer P-1, we recorded relatively consistent groundwater levels. This is because the area of Piezometer P-1 is located at higher grades and does not pool rainwater. Piezometer P-1 shows relatively consistent conductivity levels whereas conductivity levels are rising at P-2 and P-3.

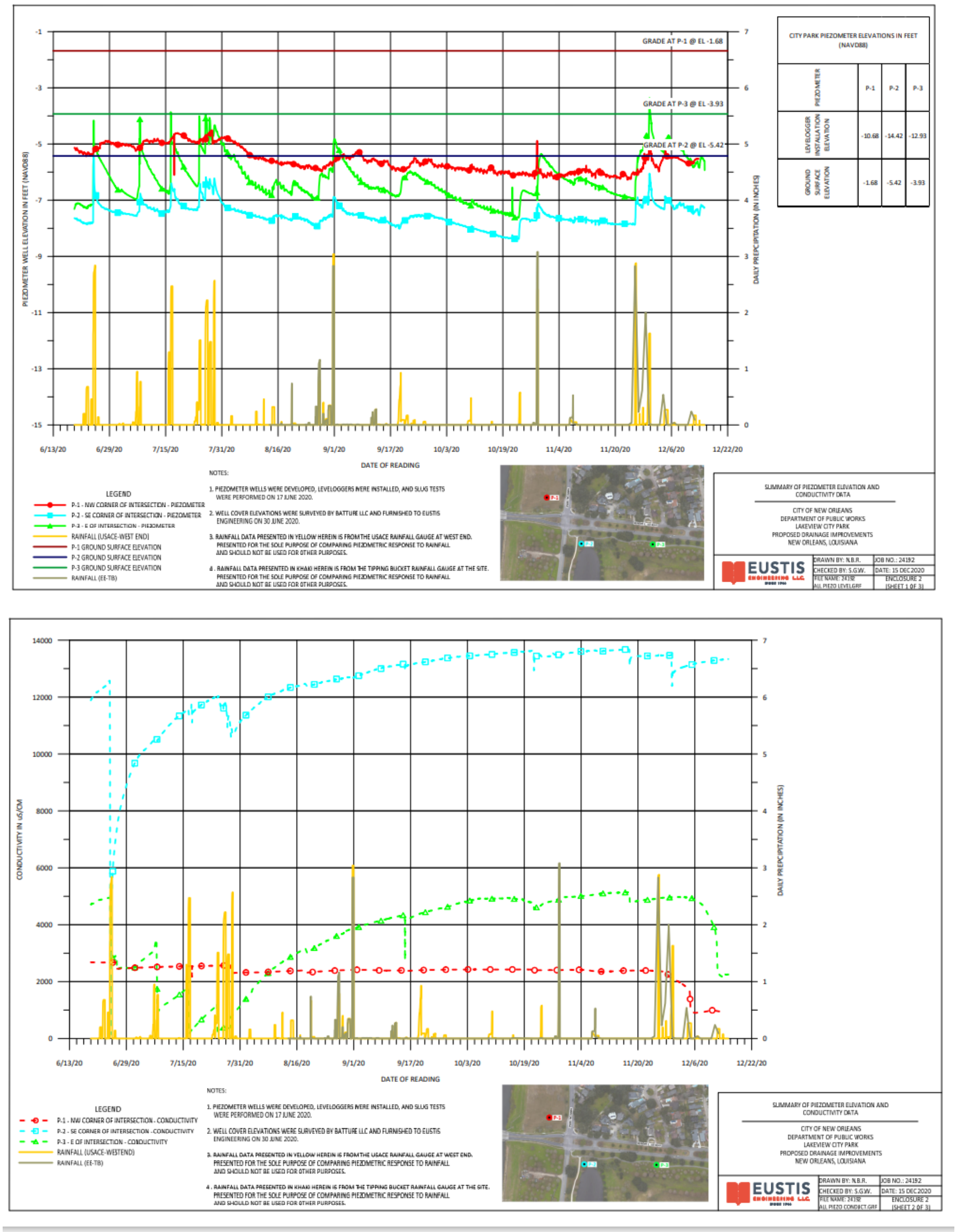


Figure 5.16: Groundwater monitoring results Lake Vista

5.5.4 (Inside) City Park groundwater monitoring network

Between June 2020 and February 2021 fifteen direct push borings using a Geoprobe® rig were performed, collecting fifteen hand piston samples and the installation of fifteen open well standpipes with fifteen Solinst Levelogger® piezometers to collect one year of piezometric data (figure 5.17). Soil mechanics laboratory tests, performed on samples obtained from these borings, were used to assist with classifications (Eustis, 2022).

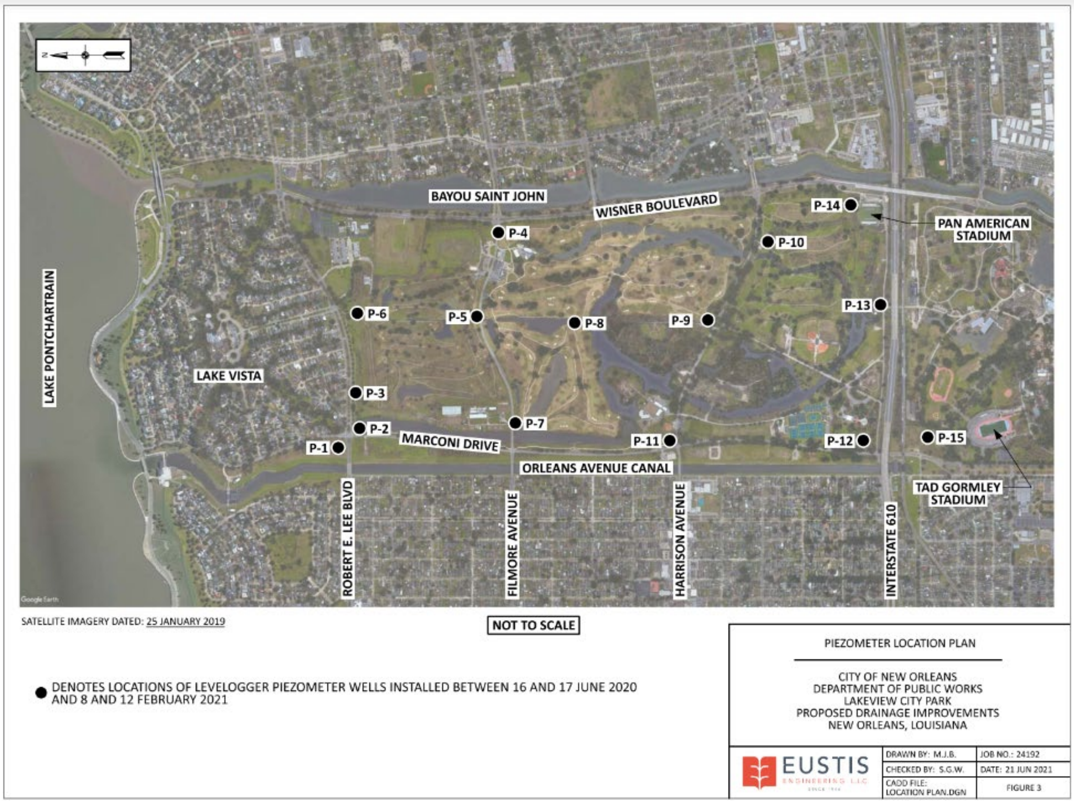


Figure 5.17: Locations of shallow groundwater monitoring wells at City Park.

The piezometers consist of 2-inch diameter Schedule 40 PVC risers that extend slightly above the ground surface. A 5-ft screen with 0.010-inch opening was installed at the base of each borehole. For each piezometer, 20/40 filter sand pack material was placed around the screen extending 3 feet above the screen. A 1-ft thick bentonite seal overlies the sand pack. The remainder of each bore hole was then sealed with a cement-bentonite grout to the surface per guidelines described in ASTM D5092 (figure 5.18). These piezometers will serve for ground water level monitoring for the 12-month period. The wells are not suitable, nor intended for ground water quality testing.

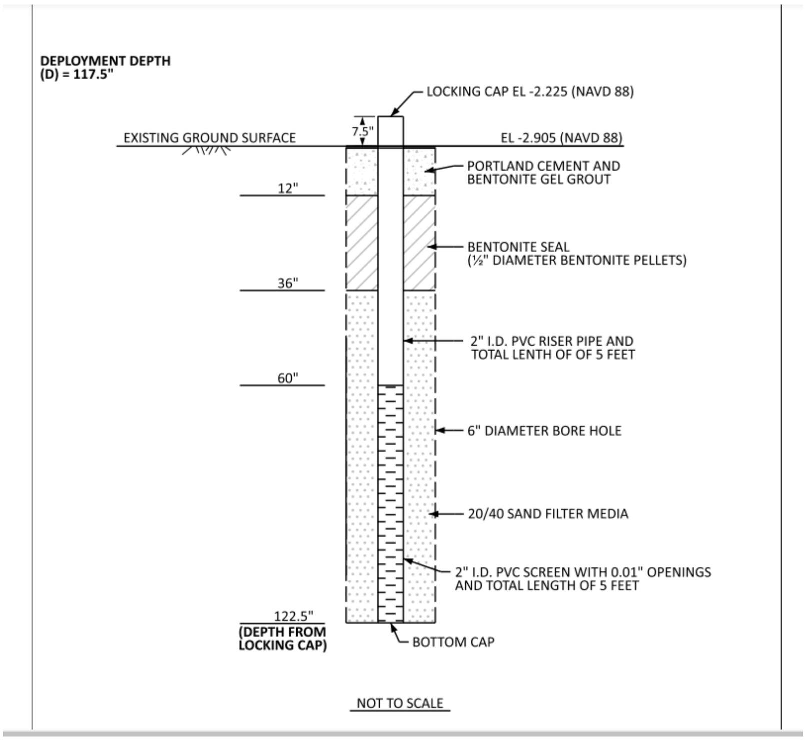


Figure 5.18: Design of groundwater observation wells in City Park.

5.5.5 Irish Channel

In the garden of a private property at the Irish Channel neighborhood a shallow groundwater observation well was installed during the summer of 2018. Since then, the residents have monitored the groundwater levels, more or less weekly, by hand. In figure 5.19 the results are compared with the water level of the Mississippi river (approx. 0,25 miles south). This river level is always higher than the groundwater level. Often more than 5 feet.

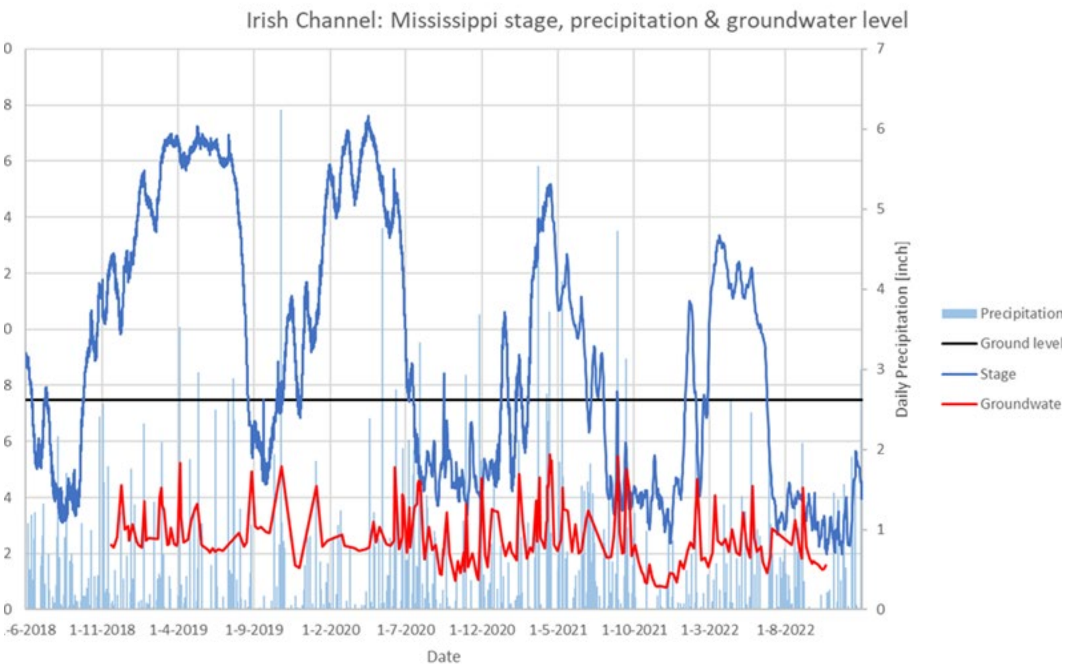


Figure 5.19: Handmade groundwater monitoring results at private property Irish Chanel compares with Mississippi levels.

5.5.6 Army Corps of Engineers

It is likely that several unused groundwater monitoring points exist. For example, installed during the work around the outfall channels after 2005. Also an unknown observation well was found at pumping station 4 (see picture below). Deltares will obtain information.

Unknown monitoring well next to the entrance of Pumping Station 4.

5.5.7 Mirabeau

In recent years, shallow groundwater has been monitored at the Mirabeau Avenue site. On the north side of Mirabeau, 4 observation wells were installed near each other at different depths (9): (1) in the top of the Pleistocene (90 ft), (2) at the basis of the Pine Barrier sands, (3) at the top of the Pine Barrie sands and (4) in the covering clay layer (figure 5.20). The measurements in the deepest filter showed a constant (linear) hydraulic head (approx. equal to surface level). The measurements in the filters in the Pine Barrier sands (2 and 3) were equal and show a fast response to rainfall events.

Figure 5.21 shows a times series recorded from the observation well in the center of the Mirabeau park area. The filter was placed approximately 7 feet below surface level within the Pine Barrier sands formation. Along with water level depth and precipitation, the graph also shows the surface elevation and the depth of the top of the sands. The high frequency measurements show a very fast reaction (rise in ground water level) during rainstorms and occasionally records levels at or above surface level. In the following hours/days after a precipitation event, the groundwater level drops in an exponential manner back to the mean lowest groundwater level. This level likely coincides with the depth of drainage systems below surface level and could likely be attributed to the leaking/permeable storm drainage and waste water sewer system in the adjacent streets.

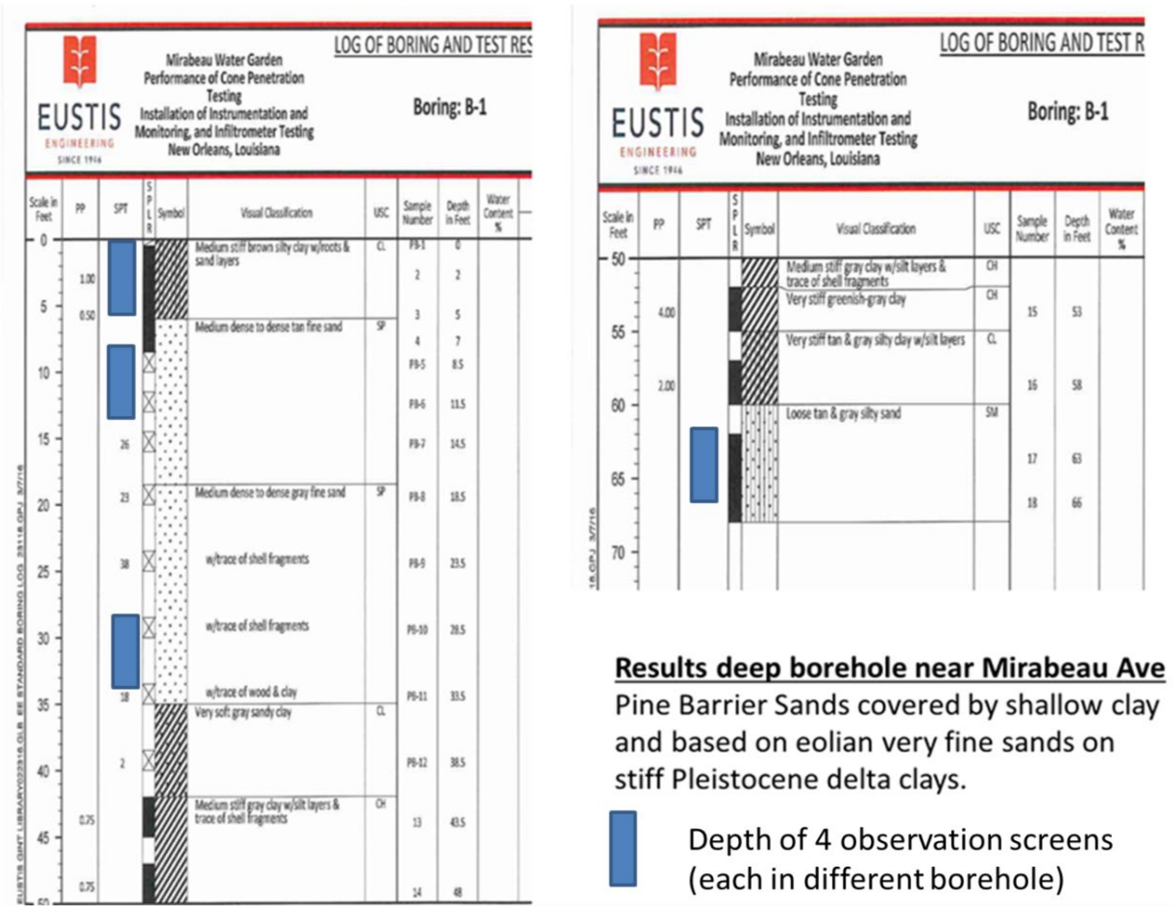


Figure 5.20 Borehole description and groundwater observation screens at the Mirabeau multi-screen monitoring site (near Mirabeau Ave).

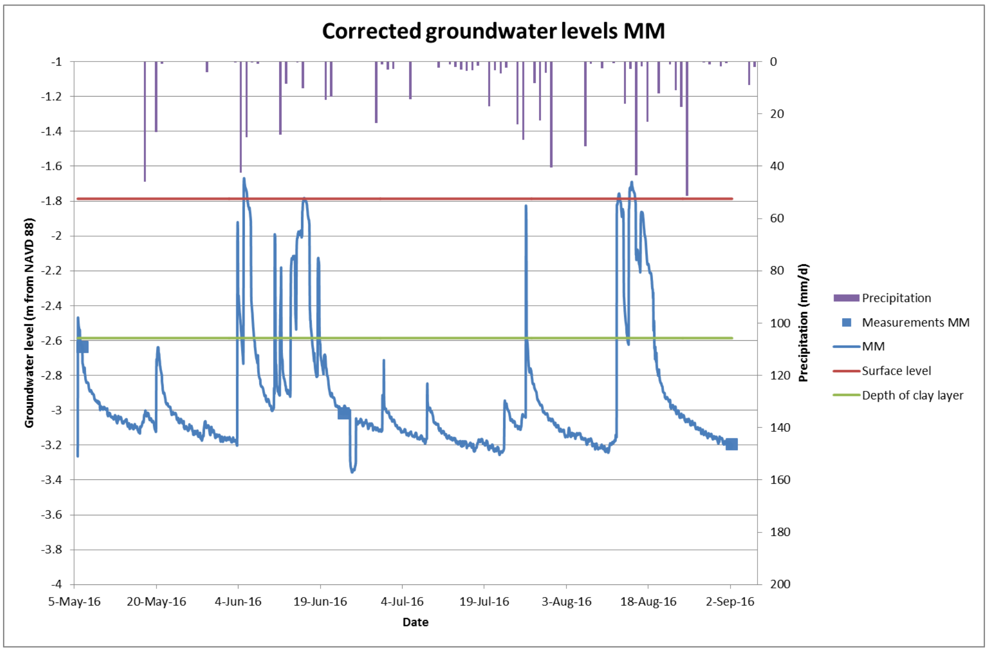


Figure 5.21 Groundwater fluctuation in an observation well in the center of Mirabeau

5.6 Existing deep groundwater observation wells

There are currently a number of relevant deep observation wells in and around New Orleans (see Table 5.1, figure 5.22). Nearly all (5 out of 6) are monitoring the hydraulic head (groundwater pressure) in the confined Gonzales New Orleans Aquifer. The monitoring results (*Figure 5.*) show extreme changes over time. During the Seventies the hydraulic head fluctuated around 120 ft below sea level (Or-42), and 175 ft below sea level (Or-206). This is an extremely unnatural situation as deep groundwater wells drilled here during the 19th Century presented artesian conditions (see figure 5.23). With this observation and due to deep groundwater pumping, the hydraulic head dropped more than 185 feet (> 60 meter).

Well number Or-179, located in Petites Coquilles hosts a deeper observation well within the Abita aquifer (below the Gonzales A.). The time series from this well (figure 5.24) reaches back to 1965 and has recorded a 60-foot drop in hydraulic head between then and 2010. It has since stabilized around 50ft above the NGVD 1929 sea level datum.

Table 5.1 Information of main New Orleans deep groundwater observation wells.

Number	**Start**	**Depth (ft.)**	**Aquifer**
Or – 175	1963	499	Gonzales
Or – 179	1965	2434	Abita
Or – 203	1981	453	Gonzales
Or – 263	1972	647	Gonzales
Or – 42	1948	775	Gonzales
Jf – 156	1974	780	Gonzales

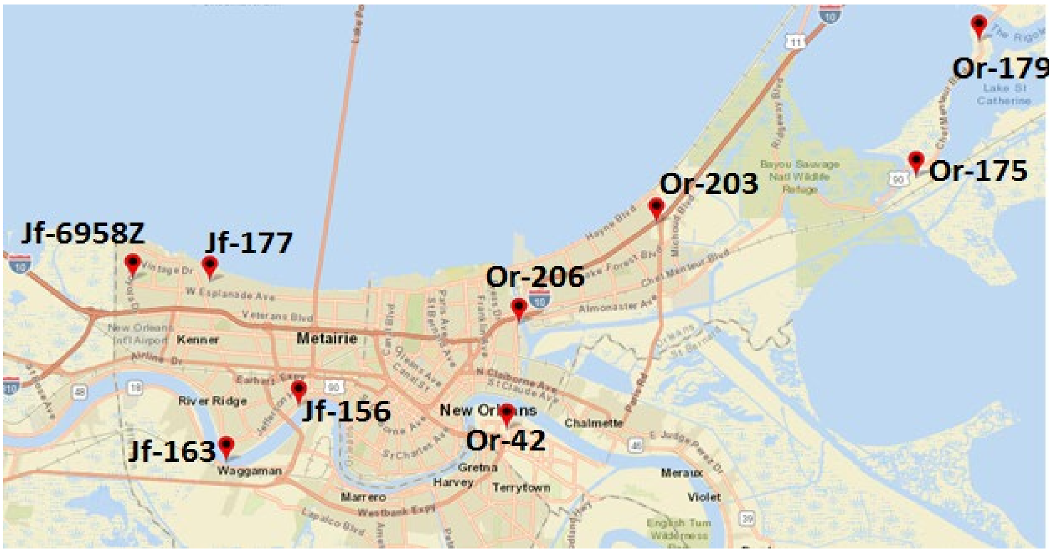


Figure 5.22. The locations of USGS maintained (active) deep groundwater observation wells in and around New Orleans. All sites, accept Or-179 are in the Gonzales New Orleans aquifer. This aquifer is, or was, used for groundwater pumping. The Or-179 is situated in the deeper Abita aquifer.

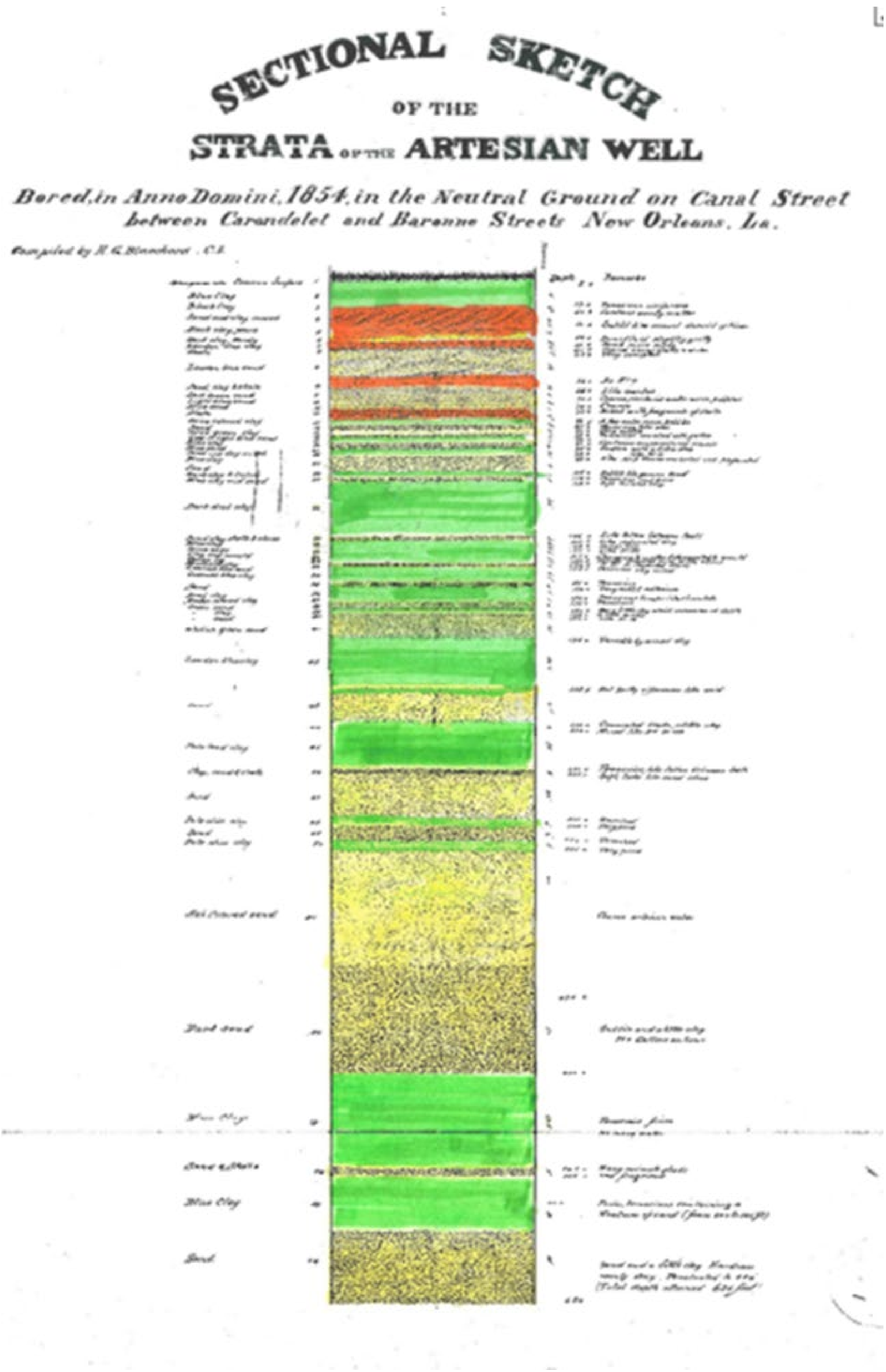


Figure 5.23 This old borehole description showed an artesian hydraulic head in 1854 in the French Quarter.

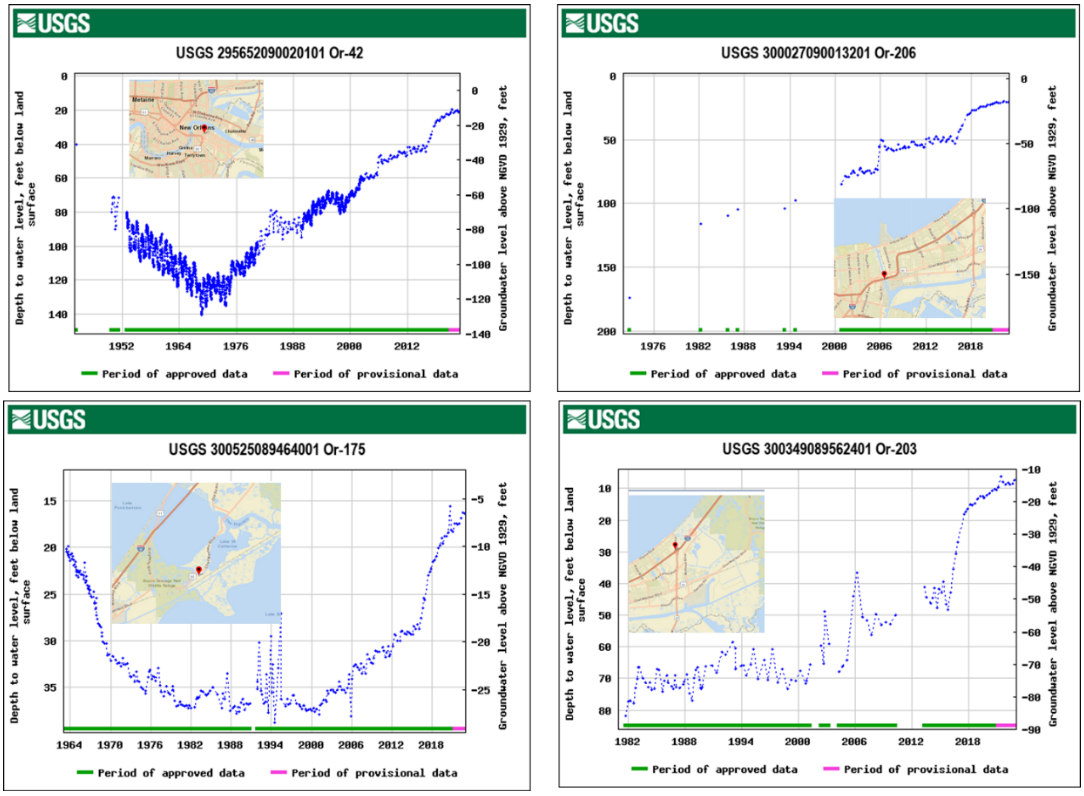


Figure 5.24 Long year time series of deep hydraulic heads (Gonzales aquifer) in and around New Orleans (until 2022). The hydraulic heads dropped dramatically low in the last century. Since 1970 the hydraulic head has restored slowly. The last 3 years the restoration accelerated due to the extraction stop at Michoud.

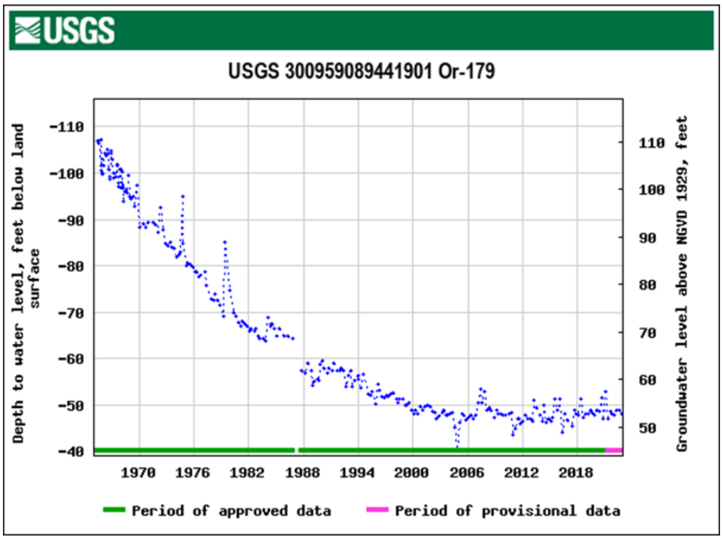


Figure 5.24b The hydraulic head in the Abita aquifer (approx. 2500 feet below surface) dropped approx. 60 feet between 1965-2006. The cause is not clear, but one possible explanation for the decline in hydraulic head could be the groundwater pumping north of Lake Pontchartrain (well at Chef Menteur Blv. New Orleans NE)

Monitoring deep groundwater is meaningful in relation to the following:

1. Lowering of the hydraulic head can cause “deep” subsidence that also lowers the surface elevation. Lowered hydraulic heads starts 2 processes:
    a. Inelastic (irreversible) drainage of the clay deposits below and above the pumped aquifer.
    b. Elastic (reversible) processes by compaction/concentration of the grains in the sand aquifer. After pumping stops this can (partly) restore (see Kooi et al, 2023).
2. Knowledge of deep groundwater systems can offer opportunities with respect to future drinking water sources. Deep aquifers could be useful in providing the city of New Orleans with an underground reservoir capable of storing a water protected from surface events in case of emergency situations. Additionally, treating the deep brackish water system may prove to be more economic than alternative water sourcing options.
3. Deep aquifer injection and storage could be used as a possible solution for urban storm water management, helping to reduce urban flooding while at the same time helping to restore the lowered hydraulic head.

5.7 Surface water as a groundwater monitoring tool

In East New Orleans, there are several man-made lagoons remaining from sand mining operations that were developed in the 1960s’ during highway construction (figure 5.25). The lagoons are not connected with the local canal system although some lagoons have overflow constructions built in to discharge water into the urban storm drainage system when a critical threshold is reached. Water within these systems is brackish or salt and these lagoons act (more or less) as an open-air groundwater monitoring site. Normally, the lagoons are recharged by rain and seepage, and loose water by (open water) evaporation. Monitoring these sites could also produce more insight into New Orleans evaporation as well as groundwater level measurements and salinity information. We propose monitoring 2-3 lagoons for the indicators mentioned above.

Figure 5.25 Example of isolated lagoons in New Orleans North-East. The fluctuation of these (brackish-salt) lagoons is related to rainfall and evaporation but also related to the water level of Lake Pontchartrain.

5.8 Existing surface water monitoring sites

The water levels of the Mississippi, Lake Pontchartrain, canals and Wetland Triangle are important constraints for groundwater flow. With the exception of the drainage canals and ponds in the North East quadrant of New Orleans, all surface water levels are higher than the groundwater levels in the urban area. Understanding the relationship between water levels and water quality of the surrounding bodies of water and urban groundwater is important for: (1) understanding seepage (groundwater discharge) in the urban area, (2) understanding salinization of urban groundwater, (3) understanding heave risks and (4) addressing potential environmental or health risks. There are several relevant and active monitoring sites maintained by USGS, USACE and NOAA (figure 5.26).

Figure 5.6 Active surface monitoring sites around New Orleans.

The results for the most relevant sites (Mississippi, Lake Pontchartrain and Bayou Bienvenue) are presented in figure 5.27. The last years water levels of the Mississippi fluctuated between 2-17 feet, while the water level at the other side of the city (Lake Pontchartrain) in general fluctuates between -1 and 2 feet, with incidental extremes of 4 feet.

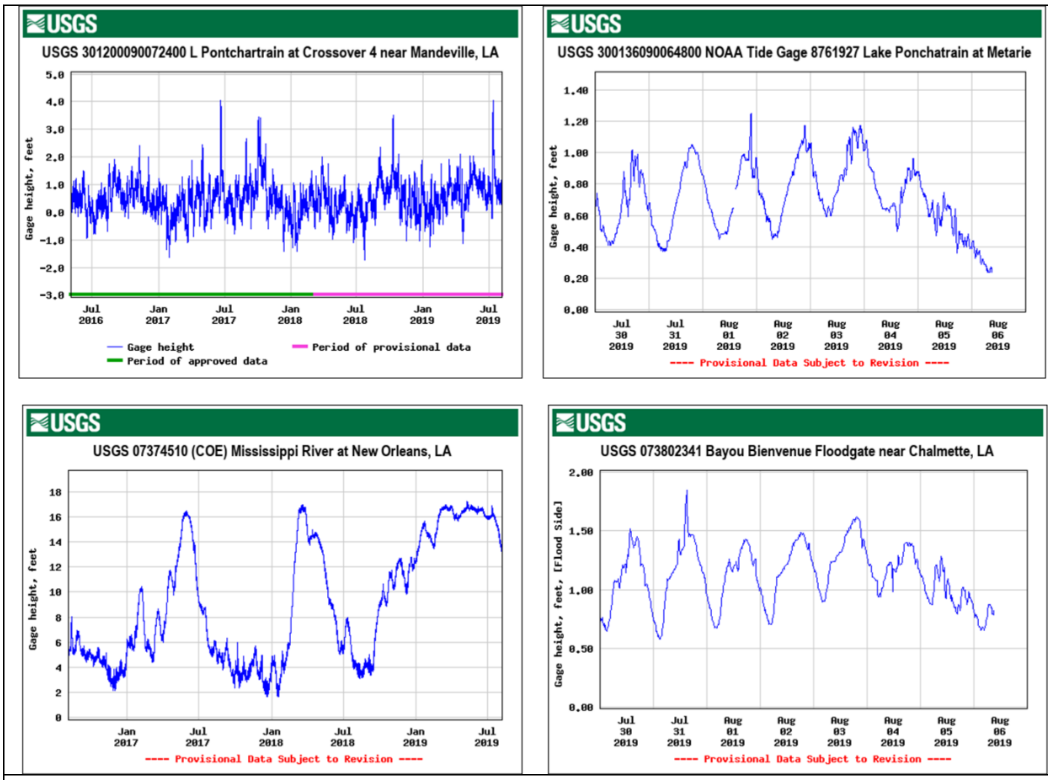


Figure 5.27: Examples of surface water monitoring.

A holistic and overarching view of the New Orleans East urban water system should include information on both surface and groundwater systems where both water levels and water quality are recorded.

6 Water quality monitoring

Monitoring the water quality within an urban water framework is essential to maintaining an understanding of the system and allows for evidence-based decision making while protecting surface and groundwater sources. Compliance with government mandated guidelines set within the Clean Water Act and Safe Drinking Water Act and regulated by the Environmental Protection Agency (EPA) gives water users the assurance that they are protected from poor water quality around them. Failure to maintain acceptable water quality standards has social and environmental consequences as recently seen in the Flint, Michigan lead contamination case. https://water.usgs.gov/owq/WhyMonitorWaterQuality.pdf

6.1 Lake Pontchartrain

For nearly 20 years the Lake Pontchartrain Basin Foundation (LPBF) has been sampling and analyzing surface water quality along the lake's coastline on a weekly or bi-weekly basis. Locations 2, 3, 4, 5 and 11 as seen in *Figure 6.1* presents the relevant locations to New Orleans East and provides information relating to pH, salinity, electrical conductivity, oxygen content, temperature and fecal coliform. Observing all monitoring locations would add to the overall knowledge of the lake system health.

A key measure recorded at each location is electrical conductivity. This parameter measures the ease with which water passes an electrical current and is a proxy indicator for the presences of inorganic dissolved solids. Pure water is a poor conductor and therefore dissolved anions and cations dictate the conductivity. Increases in salinity or the presence of ions in sewage discharges are examples that would increase conductivity readings. *Figure 6.2* shows a time series of specific conductivity values between now and the early 2000's and can be interpreted as linearly related to salinity. The graph indicates a trend of decreasing salinity over the last decade.

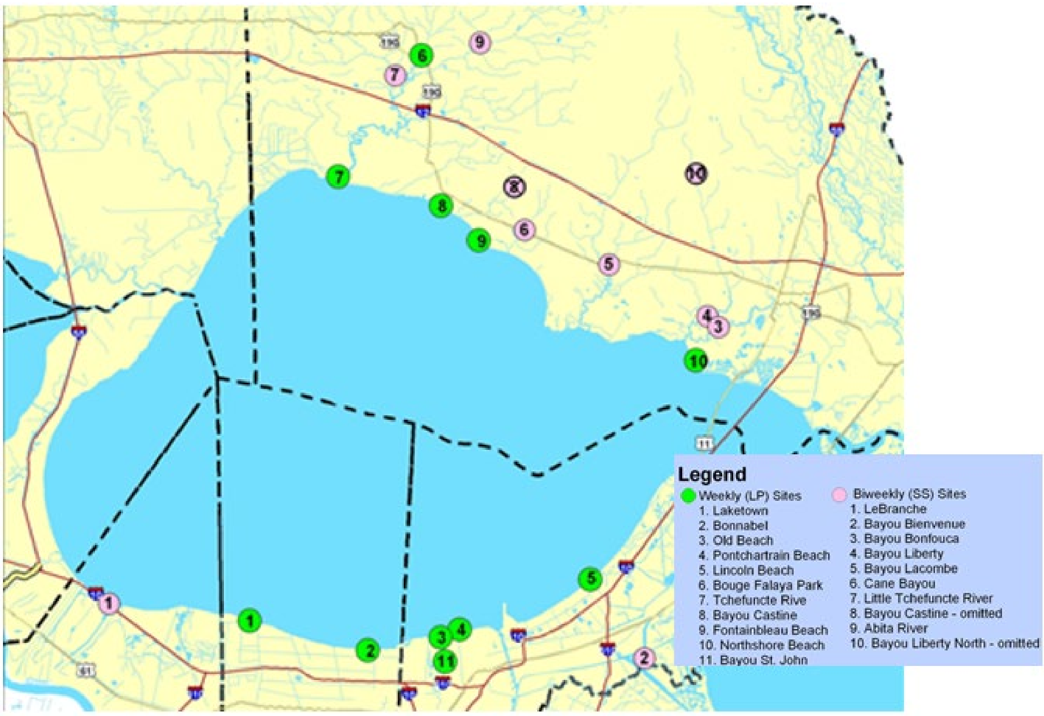


Figure 6.1 Weekly and biweekly sample sites around Lake Pontchartrain

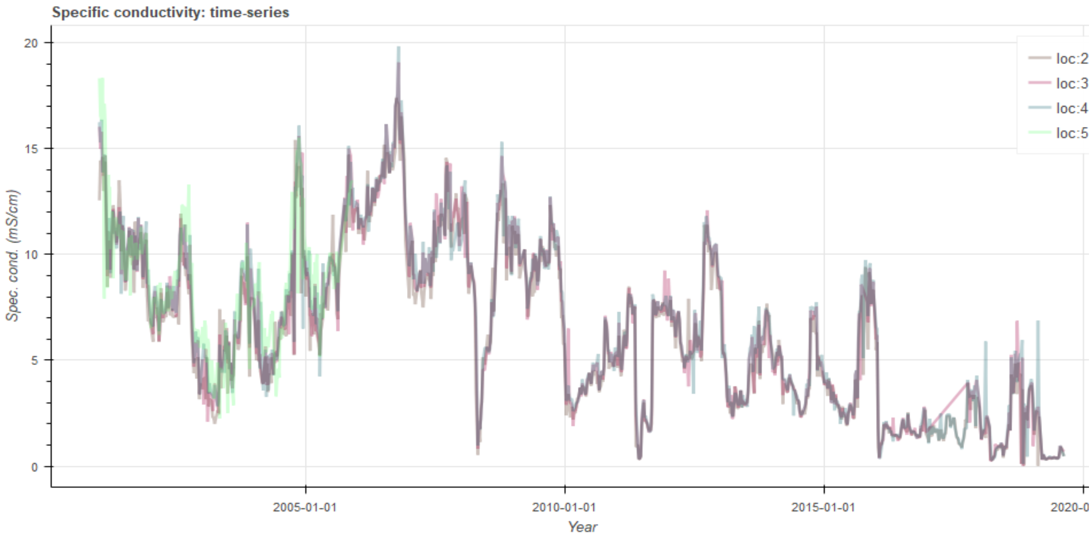


Figure 6.2 Example of a specific conductivity timeseries at locations 2,3,4 and 5 surrounding Lake Pontchartrain

6.2 Urban water quality monitoring (SWBNO, LPBF)

The LPBF as commissioned by the Sewage and Water Board of New Orleans (SWBNO) started sampling and analyzing urban drainage water in New Orleans East. Nowadays, there are 18 observation locations, 10 of which are located at drainage pumping sites (*Figure 6.3*). Results are presented annually (see Brady Skaggs, Will Pestoff, Justin Summer, 2019) with parameters consisting of temperature, dissolved oxygen (DO), specific conductance, salinity, pH, turbidity, ammonia (NH3), Total Kjeldahl Nitrogen (TKN), nitrate (NO3), nitrite (NO2), total phosphorus and orthophosphate (PO4).

Figure 6.3 Locations of SWBNO water quality measurement stations within New Orleans East. Locations that recover the sample at a pumping station lists the name of the station in brackets (i.e. DPS7)

The results are presented in statistical box plots but are not analyzed in relation to weather or hydrological storm water data (i.e. amount of discharge or water level). Deltares and Waggonner Ball installed an ECT-sensor (Electrical conductivity, water level and temperature) at Pumping station 1 between the period 2013-2014. The results showed clear relations between water levels (rainfall), temperature and electrical conductivity (salinity). During rain storms the EC dropped to 50-60 µS/cm, while during dry periods a range of 600-1000 µS/cm is considered normal. This small experiment provides evidence that during dry periods groundwater is slightly more saline and drainage may have an impact on water quality parameters.

Salinity measurements at pumping station 4 (DPS 4) between 2011 and 2016 also showed a clear relationship between storm drainage water quality (salinity, EC) and weather events. During dry periods salinity rises, in part because drainage of salt groundwater in the areas near Lake Pontchartrain and canals becomes more relevant.

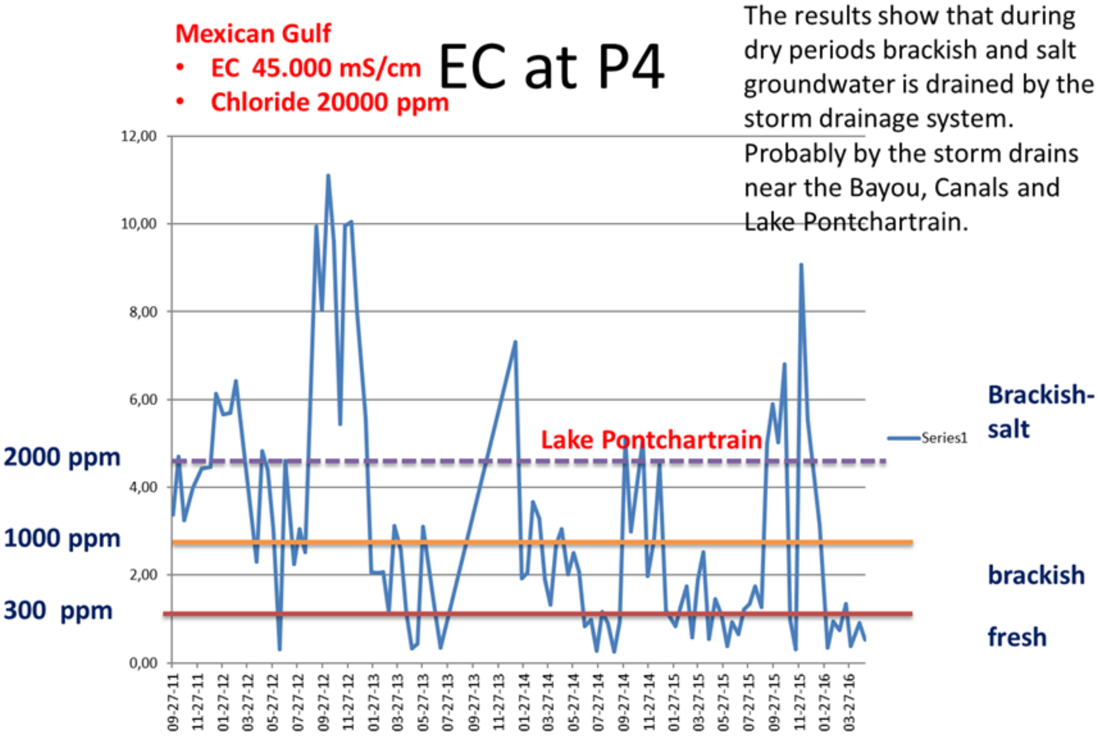


Figure 6.4 The salinity fluctuation at pumping station 4.

6.3 Storm Drainage monitoring

New Orleans began to develop its two-part drainage system over 100 years ago and consists of (1) a waste water system and (2) a storm water system. Increased levels of storm water drainage during precipitation events are one of the city's major problems. If the climate change predictions of more frequent, high intensity rainfall events are assumed to be correct, then obtaining a better understanding of the current storm drainage transport system and identifying the right information to improve this system is of great importance.

To do so, it is suggested that a better understanding and analysis of pumping data take place using time series analysis and system modelling. In addition, spatial information will improve understanding in three ways: (1) provide the operational status of the main system, (2) provide the operational status of the drainage basins, and (3) present the known locations where regular flooding takes place within the city.

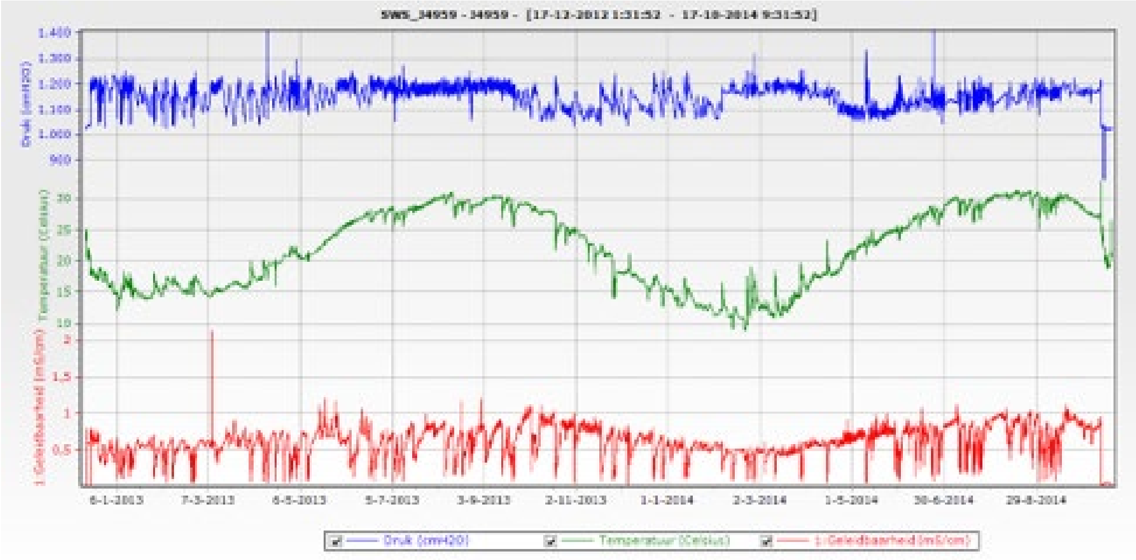
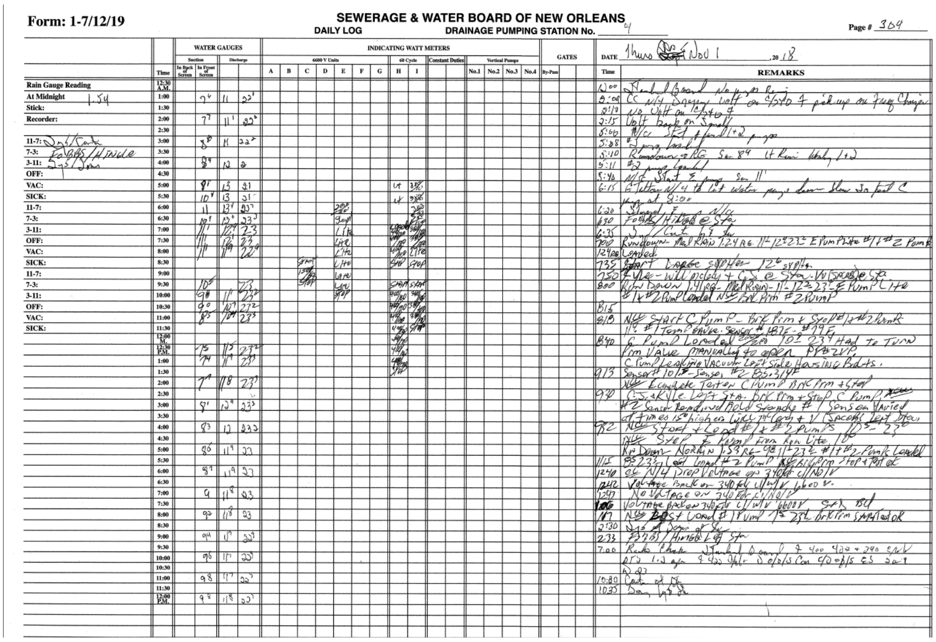


Figure 6.5: 18 months (2013-2014) of monitoring storm drainage components (temperature, salinity and water level) at Pumping Station 1, using CTD-sensor (Van Essen).

The storm drainage system is an unintended but important factor in groundwater management as the system likely drains groundwater at many locations. During a period (2013-2014) of experimental monitoring in the water basement at pumping station 1 this groundwater drainage could be observed (figure 6.5). Normally, the salinity (EC) at Pumping Station 1 is equivalent to the salinity of drinking water, and/or Mississippi water. Drinking water is produced from Mississippi water, so salinities are equal. During rain storms the salinity drops because of the storm drainage (rain possess a very low salinity). If only storm drainage water was discharged, the discharge and salinity would be much lower than current measurements.

Pumping stations are also operational during ‘dry-weather’ flow periods or periods without rainfall to maintain a base canal level. A modernization of the current system could help with the optimization of the system itself, lead towards a better understanding of how the drainage system is linked with precipitation events and groundwater / surface water levels, and in turn, provide a reduced risk to the citizens and potential cost saving measures to the operators. Some information on pump station location, pump capacity, and number of pumps at the station location can be found on the SWBNO website but is siloed in relationship to other data sources.


Form: 1-7/12/19

SEWERAGE & WATER BOARD OF NEW ORLEANS

DAILY LOG

DRAINAGE PUMPING STATION No.

Page #

WATER GAUGES — INDICATING WATT METERS — GATES — DATE — REMARKS

Rain Gauge Reading

At Midnight

Stick:

Recorder:

11-7:

7-3:

3-11:

OFF:

VAC:

SICK:

Figure 6.6. An example of the current system the SWBNO uses to monitor drainage of their systems. Digitization of this process could unlock potential cost saving measures through optimization and unlocking trends in the data.

The main monitoring objectives for the drainage pumping stations is to better understand the relationship between station pumping activity, precipitation events and the effects both have on water quality and water level. Information on salinity, quality, quantity and dry / wet weather water transfer will be recorded and over time, a system baseline will be established. Figure 6.7 highlights the names and locations of major pumping stations within New Orleans East. Although it would be advantageous to monitor every pumping station, we recommend starting with the four locations represented by blue symbols in central New Orleans (DPS 3, DPS 4, DPS 17, DPS 19). The following list of suggestions are also made available to the reader:

- Make available hourly pumping rates for each station within New Orleans East.
- If not currently available, add sensors at the pumping station to monitor water level, temperature and salinity.
- Make available daily pumping quantities of constant duty pumps.
- Organize monitoring of urban flooding (where and when water on the streets) during different rainfall intensities.
- Complete a periodic “complete” hydro chemical analysis (e.g. as a start 6 samples/year → 3 during dry and 3 during wet periods).

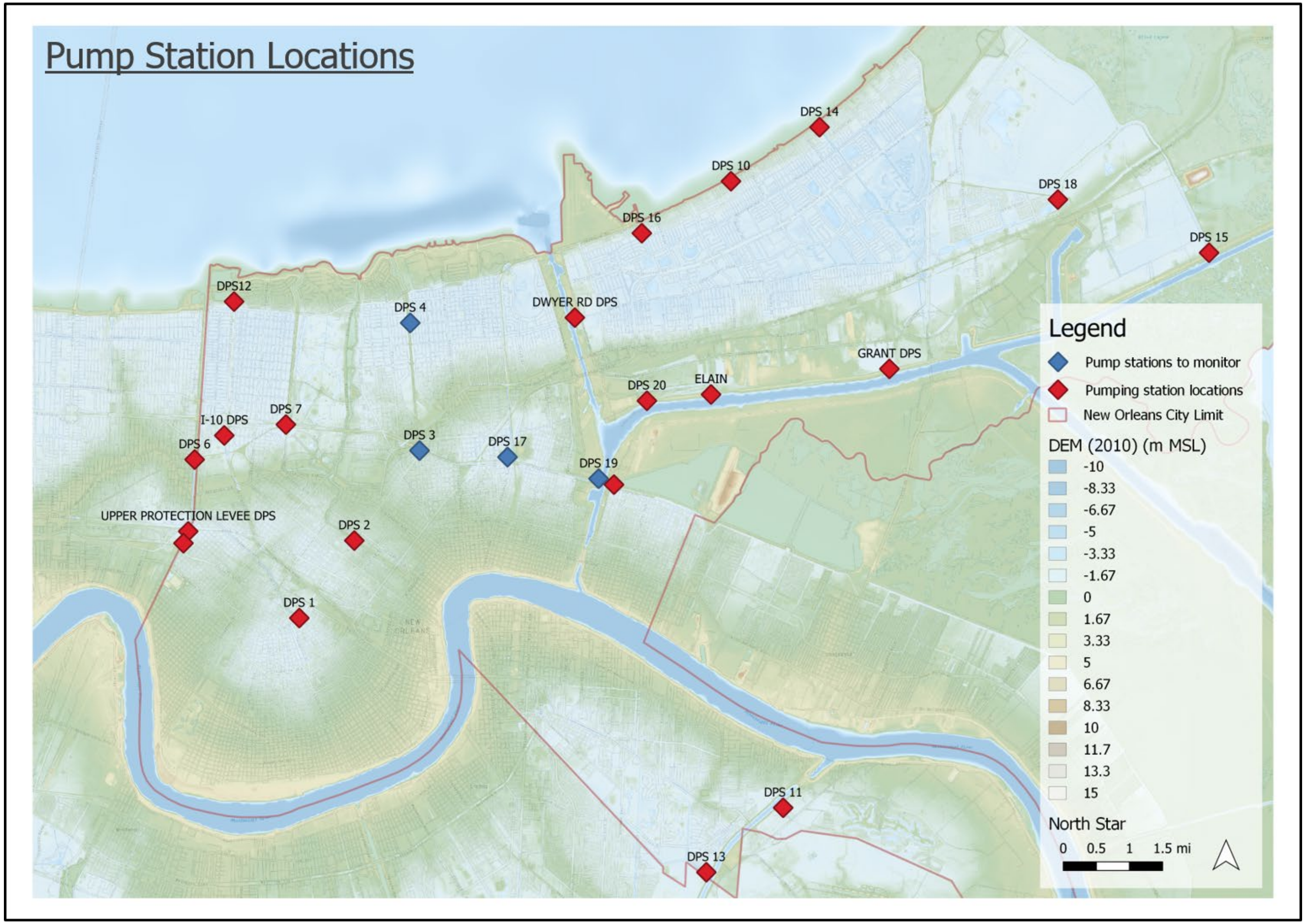


Figure 6.7. New Orleans pump station locations and proposed monitoring sties.

6.4 Waste water

An understanding of the waste water system is important as all water balance items should be accounted for within the system. Doing so also adds a dataset to the overall study and breaks down the compartmentalized current state of the current system. This may also lead to more accurate model predictions and in turn better risk estimations. As described earlier in this chapter, New Orleans East has separated storm drainage and waste water systems. In its simplest form, the amount of treated waste water should be less than produced drinking (minus real losses) but the reality for the city is that more water is treated then is put into the system (figure 6.8). This highlights a common problem for utility companies, groundwater being drained by the wastewater system through broken pipes, permeable geotextile joints, and sometimes by design[2].

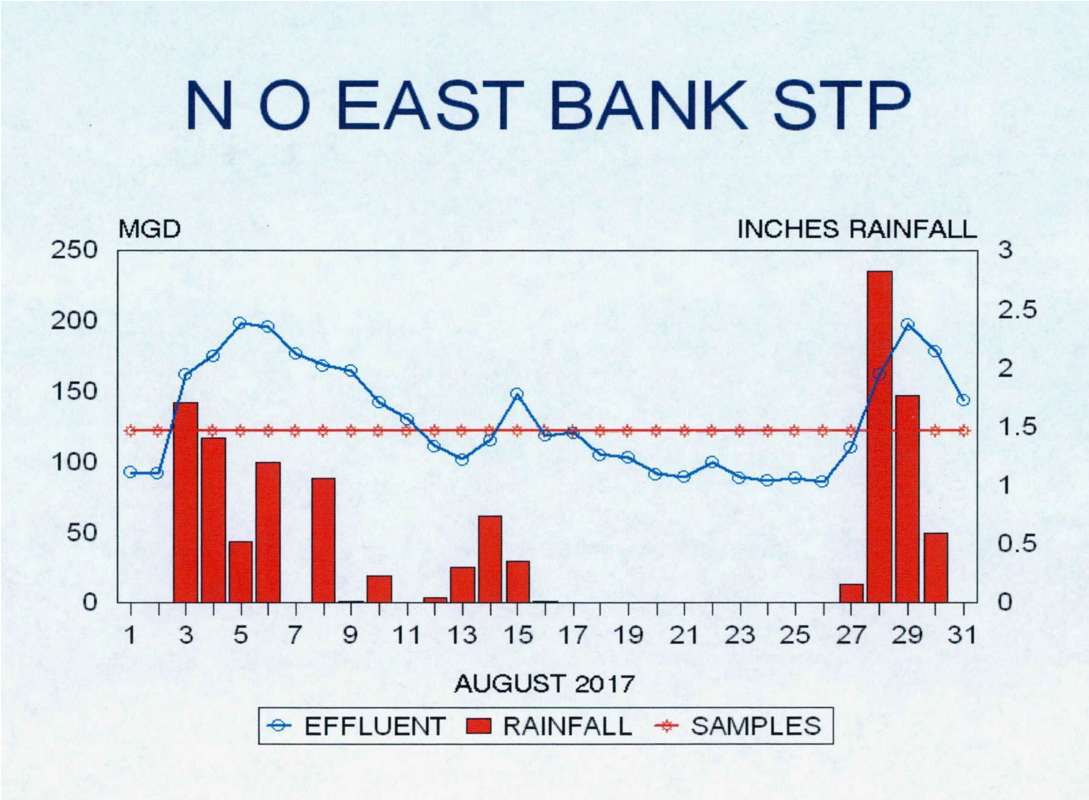


Figure 6.8 A 2017 chart showing the relationship between rainfall events and amount of effluent recorded. The correlation between parameters hints at a 'leaky' system (diagram from SWBNO).

This drainage system provided by the wastewater network helps to control the groundwater level artificially, lowering it (in theory) to the height of the buried pipes. Over time an equilibrium is reached and groundwater levels fluctuate in relation to the rate of water entering the system, and water being removed. At locations where pipes are being replaced, an increase in groundwater level is cautioned as the drainage network is removed. Advice on what parameters would be helpful to include in a dataset:

- Daily monitoring of water quantities at wastewater treatment plants (arrived, treated).
- Daily monitoring of the quantity of pumped water at the local pumping stations.

[2] Long time ago this was happening in the French Quartier.

- Continuous water quality monitoring of waste water selected parameters to better understand the water origins (e.g. salt-water parameters like chloride and sodium)
- A temporal project monitoring project using (natural) tracers to better understand the origins of waters.

6.5 Drinking water

The Mississippi river has been providing residents of New Orleans with its drinking water for over a hundred years. As the urban environment is built up over time and the installation of drinking water pipe networks occurs, the local groundwater system may be altered as an anthropogenic preferential drainage network is formed in the coarse-grained, high transmissivity trench infill material of which the pipe network is constructed (as described earlier in the storm and waste water networks).

A second and opposite relationship that should be noted is the effect of groundwater recharge from losses in the drinking water distribution network. These losses are most often negligible and do not affect the local groundwater levels. If leakage is abundant and drainage in the area is low, a localized effect may be observed if a high-density groundwater monitoring network is operational. Within the Netherlands the total loss of produced drinking water is ~ 5% and considered one of the lowest rates of losses in the world. This loss also includes illegal tapping (e.g. grow houses) and deliberately flushing to clean the pipe system. In the Dutch system, drinking water loss to the subsurface (artificial groundwater recharge) accounts for approximately 50% of the overall loss (or ~2.5 % of produced drinking water).

More than half of New Orleans S&WB's water lost to leaks, costing millions, audit reveals

BY JEFF ADELSON | JADELSON@THEADVOCATE.COM MAR 15, 2019 - 6:58 PM

Advocate photo by Matthew Hinton -- The Sewerage & Water Board's Carrollton water treatment plant.

Buy Now

Figure 6.9 Online news article clipping from 2019, reporting on the SWBNO audit finding 50% of treated and distributed water is lost to leaks.

In comparison, New Orleans drinking network water losses are estimated at more than 50% (figure 6.9). To address water loss attributed to leaking pipelines, S&WB has undertaken a strategic water loss control program including flow monitoring and a leak detection program to accurately and reliably identify water leaks (August et all, 2009).

Table 6.1 Drinking water losses according study of Nora freeman (2019)

FY	Total	-	Apparent Losses	=	Real Losses	/	Uarl	ILI*
2008	31072.71	-	393.09	=	30679.62	/	1.83	46
2009	32891.34	-	405.12	=	32486.22	/	1.91	46.6
2010	28642.8	-	450.45	=	28192.35	/	1.84	41.9
2011	31892.56	-	438.87	=	31453.69	/	1.93	44.7
2010	31786.54	-	428.01	=	31358.53	/	1.99	43.2
2013	28844.17	-	450	=	28394.17	/	2.11	36.8
2014	29373.89	-	437	=	28936.89	/	2.13	37.1
2015	27848.6	-	459	=	27389.6	/	2.16	34.7
2016	30977.8	-	383.16	=	30594.64	/	2.22	37.5
2017	30633.7	-	462.24	=	30171.46	/	2.23	36.9

Recently, the SWBNO conducted a water audit update (Nora Freeman, 2019). The real water losses in 2017 amounted to 30171 million gallon per year (83 million gallon/day, see Table 6.1). Based on this information and divided by the land surface of New Orleans (Wikipedia: 439 km2), we calculate a mean groundwater recharge by leaking pipes of approx. 0.7 mm/day. This is nearly equal to the natural recharge (rain minus evaporation) of the Netherlands, and even more than the natural recharge in New Orleans. New Orleans mean daily rainfall is ~ 4 mm/day, but daily (open-pan) evaporation is ~ 4.5 mm/day. The drinking water loss at this moment is a very significant factor in N.O.'s groundwater recharge, and renovation of the infrastructure is most likely to have an impact on both the groundwater levels and vegetation health.

It's still unclear how drinking water loss is distributed spatially. A better understanding of this information could improve modelling results of the urban groundwater system, including the understanding of groundwater impact of water main renovation. Recovered from the SWBNO website, figure 6.10 presents the age of water mains in New Orleans. It's conceivable that loss is related to age, but it can also be argued that younger mains are constructed in softer soil areas and are therefore more vulnerable. It is also suggested that the seasonal shrink-swell soil processes are also considered during new renovation activities. The following items are suggested components of the drinking water system data flow that should be continued and made available for analysis:

- Continue the yearly water audit to determine real losses.
- Obtain a better understanding of the impact drinking water loss on groundwater levels, soil stability, erosion and groundwater quality.
- Design a salinity risk monitoring network in the Mississippi to understand possible salinization of the drinking water intake location(s).

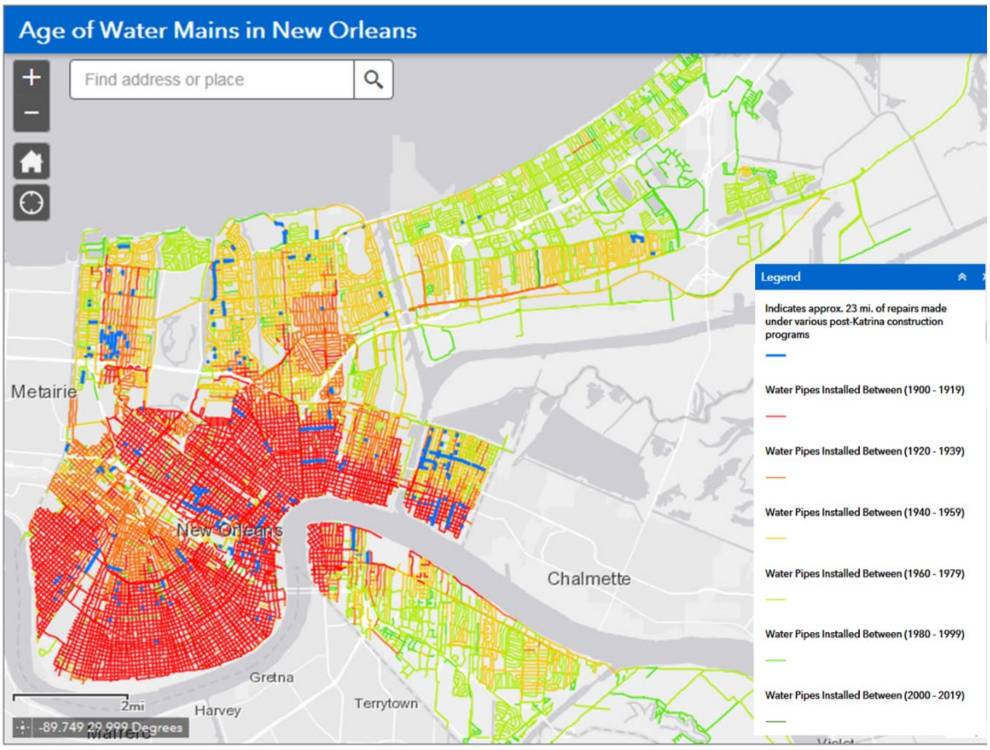


Figure 6.10 Age and distribution of the New Orleans water main network from the SWBNO website.

6.6 Urban water balance

Nougues and Stuurman (2022) estimated an integrated groundwater balance for New Orleans. Considering recharge by rainfall minus evaporation, recharge by infiltrating river, Lake Pontchartrain and outfall canals, recharge by drinking water loss and drainage by underground infrastructure. The following conclusions were drawn from the desk study: 1) the rainwater drainage system accounts for most of the total groundwater drainage (58 per cent); 2) 50 per cent of the influent of the WWTP is groundwater, which is a large unnecessary load for the treatment process; and 3) 55 per cent of the drinking water produced infiltrates the soil during distribution, which means that the drinking water losses are a larger groundwater replenishment than the annual precipitation surplus (see Figure 6.11).

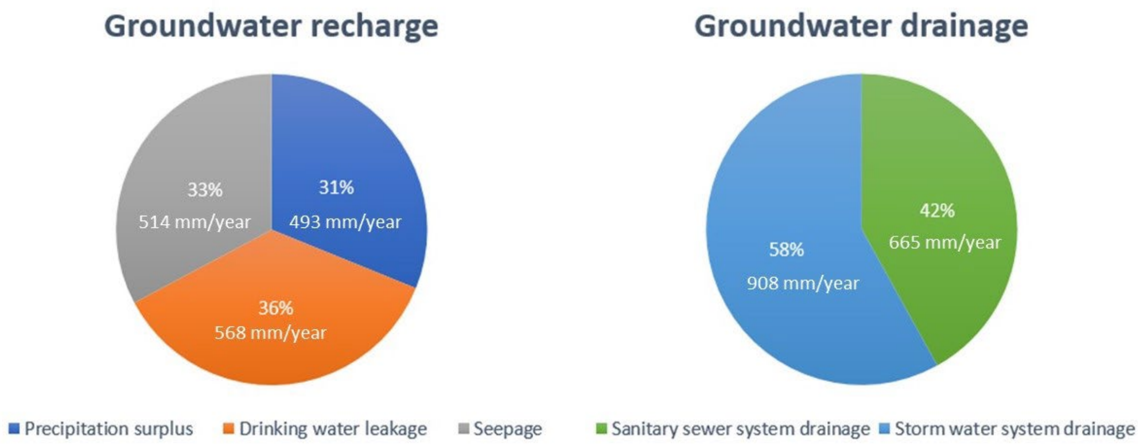


Figure 6.11: The proportions and quantities of the various fluxes in the period 2018-2020 (precipitation 1,782 mm/year and evaporation about 1,289 mm/year).

6.7 Mississippi salt water intrusion

It is obviously important the protection of the freshwater intake for the drinking water supply should be maintained. Less apparent however is the effect that decreased water quality (i.e. increased salinity) would have on other environmental forms as the river water infiltrates into adjoining spaces. During decreased periods of river discharge and as a result of sea level rise, a salt water wedge can “travel” upstream (*Figure 6.5*). Exceedance of the EPA water protection act chloride concentration of 250 ppm is found to occur 15-20 miles downstream from the toe of the wedge. This process is monitored by the United States Army Corps of Engineers during low discharge periods and can be combated through the construction of a sand sill along the river bottom. Conservative estimates show that the sill would need to be constructed an average of about once every five years as the sill is eroded over time. Since completion of the 45-ft. channel, a sill has been constructed three times, first in 1988, in 1999, and in 2012. Monitoring devices or spot testing should be completed along the river bed to pinpoint the location of the intrusion wedge toe (*Figure 6.7*). It is suggested that monitoring devices be installed in this fashion at structures crossing the Mississippi or a monitoring plan be devised at frequent sampling intervals as to avoid the necessity for the installation and maintenance of permanent equipment.

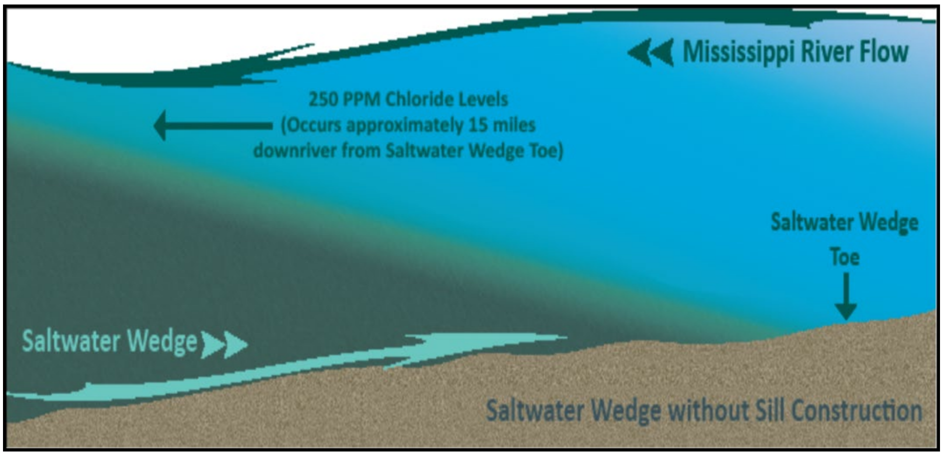


Figure 6.5 Saltwater wedge conceptual diagram shown intruding upstream into the Mississippi River. More dense saline water wedge sits underneath the freshwater river flow.

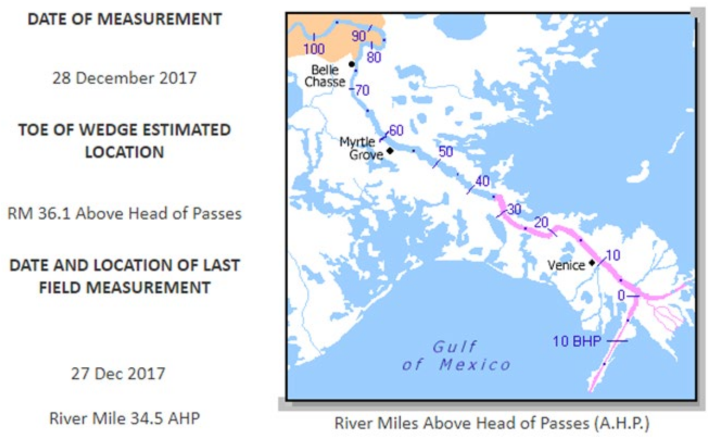


Figure 6.6 Saltwater wedge monitoring results along the Mississippi as of 28 December 2017.

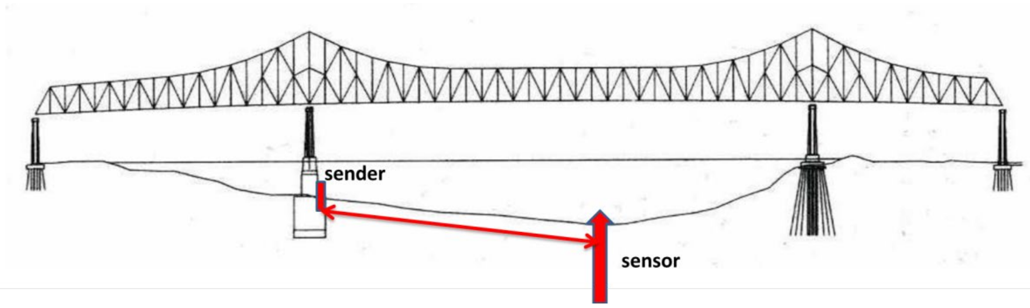


Figure 6.7 Proposed monitoring location of salinity recording devices along structures crossing the Mississippi. Devices placed along the river bed will be first to record the advance of the salt water wedge.

7 Additional monitoring parameters

7.1 Ecology

Ecological monitoring infrastructure within and surrounding New Orleans East is currently not aligned with groundwater and subsidence monitoring locations. The structure and species composition of vegetation in metro New Orleans East is highly variable. Lewis et al. (2017) demonstrated that management policies, land abandonment, and elevation are useful predictors of this variation. Less understood is how soil properties, nutrient flows, drainage efficiency, and surface and groundwater interact with the urban ecosystem and produce or respond to this variability. Much of the existing relevant data is collected and managed by different municipal and parish entities, requiring data gathering and synthesis to ascertain hydrological and potential pan-GNO ecological linkages. A more integrated and comprehensive understanding of the role of vegetation and urban ecosystems in hydrology and soil properties would empower land managers to manage the urban ecosystem strategically in line with other regional and proposed project goals for mitigating subsidence, flooding risk, and coastal land loss.

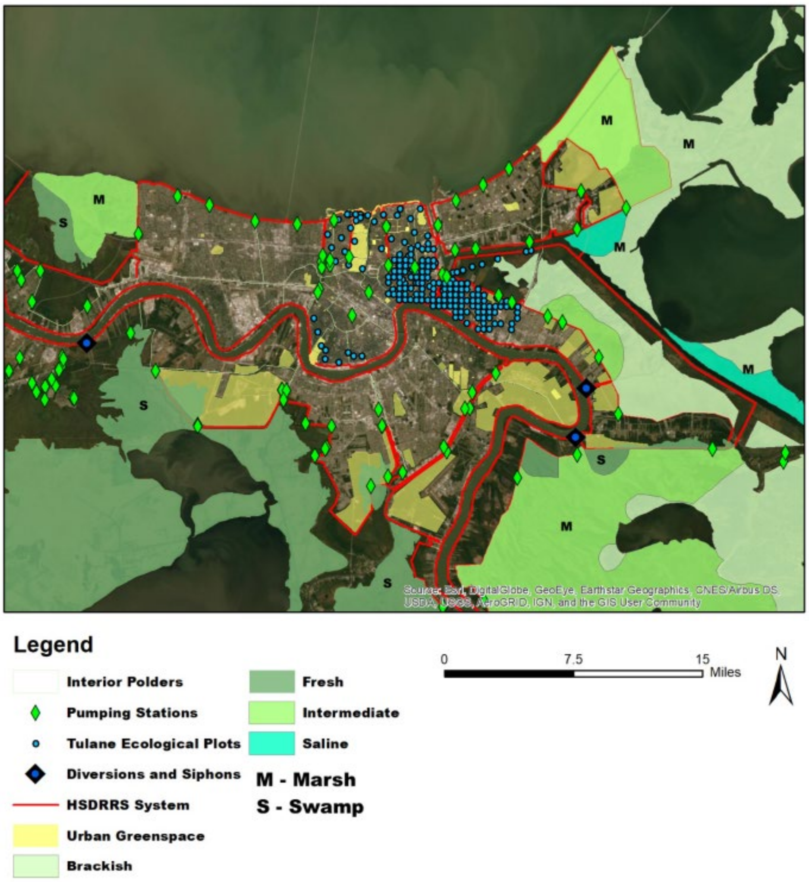


*Figure 7.1 Ecosystem information map for Greater New Orleans with the existing ecological monitoring sites from Tulane *Lewis at all, 2017).*

7.2 Shrink – Swell and Subsidence

Subsidence occurs most often in response to one of two situations. 1) through the decrease in pore pressure and resulting collapse in matrix space due to overburden pressure (ie. as a result of over abstracting groundwater from a confined aquifer), and 2) From the oxidization of peat as a result of lowering the shallow groundwater table. Both result in damage to local infrastructure and both are situations where knowledge of the local soil and subsurface groundwater system helps aid in risk reduction.

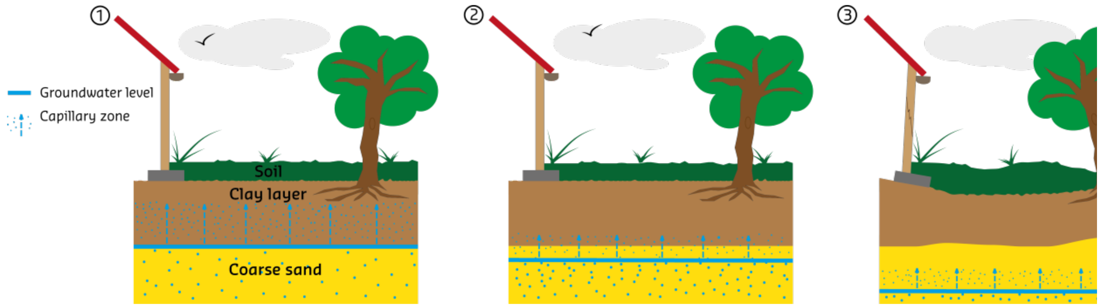


Figure 7.2 A conceptual demonstration of the relationship between groundwater level, capillary rise, evapotranspiration and their effect on the shrink / swell property of clays.

The sequence of images shown above (Figure 7.2) highlights the increased capillary rise through clay sediments and its subsequent reduction as groundwater levels drops into the sandy zone affecting the groundwater distribution through the clay zone. The clay sediment will dry over time if recharge does not occur through surface recharge or groundwater level rise. As water is continuously removed from the system by the vegetation through the process of evapotranspiration, the combination of a lower water level, lack of rainfall and continuous evapotranspiration leads to the contraction (shrinking) of the clay sediments. When this reaction happens in reverse, the clay particles adsorb water and swell in size. This shrink swell process is not uncommon as seasonal as dry summers cause clays to shrink and the reprieve during a rainfall event or wet season causes the clays to swell. Control of the groundwater level can be maintained through the proper operation of canal and levee systems.

Subsidence is another ground deformation factor that takes place as alterations to the subsurface (either natural or manmade) take place. Figure 7.3 provides a subsidence risk map that was generated after the shallow borehole field campaign took place in 2018 (see the full shallow subsidence report for more information). Soil types were distinguished, recorded and grouped based on their risk to subsidence.

Technology and computing power are enabling satellite-based earth observation techniques to help define where subsidence is taking place in near real time. Interferometric Synthetic – Aperture Radar, more commonly referred to as InSAR is the process of decoding and comparing active radar images that are sent and received from satellites to show relative changes in ground, or structure level over time. Figure 7.5 is a processed InSAR image using a standard definition Sentinal-1 dataset between January 2016 and April 2019. This image is controversial in a few ways. Green areas represent a stable environment and pose no risk or concerns, red and blue areas represent subsidence and uplift at a magnitude of greater than 5mm/year respectfully. These areas should be flagged as potential areas of concern.

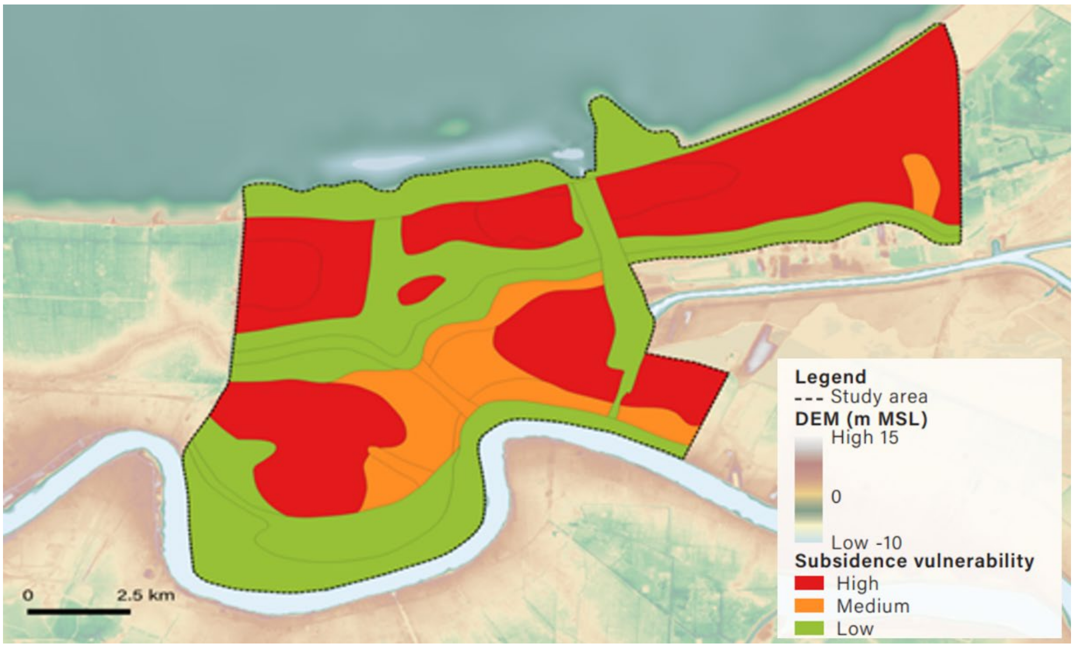


Figure 7.3 Subsidence vulnerability map from the Deltares 2019 shallow subsidence report.

The blue area in NW New Orleans East was an initially surprising result until the data was cross referenced with a ground-based GPS station that is operated by the US government and confirmed the trend. Groundwater level measurements from the National groundwater monitoring network give an indication of *why* this uplift is occurring. Deep groundwater monitoring sites Or-206 and Or-203 (Figure 5.22) show a rise in the deep groundwater level of the Gonzales Aquifer with an epicenter of the surficial rebound at the location of the Michoud Entergy plant extraction site (Figure 7.4). The reduction of water extraction at this location increases the water pressure with the confined aquifer (increasing the water level) and causing uplift at the surface. This situation is similar to that described in section 2.1.2 where the City of Delft automated groundwater monitoring program was designed to observe the gradual, stepwise reduction in pumping rate, so groundwater level changes did not adversely affect residents.

Sites subsiding at a rate of over 5mm/year are highlighted by the red locations occur most prominently along the dike systems at the edge of the Lake Pontchartrain Causeway, as well as the dike along the canal near Lake Borgne. A third site in the Warehouse District and the French Quarter District are most likely caused by dewatering operations that are taking place at numerous construction projects within this area. More information on subsidence can be found within the 2019 Deltares Subsidence report.

Proposed subsidence monitoring objectives include:
- Classification of vulnerable “at risk” areas with respect to subsidence and uplift.
- Locate and Quantify the amount of subsidence or uplift occurring within New Orleans. (Historic and current).
- Continue research on the potential causes of subsidence and uplift.
- Define a monitoring program and action strategy during dewatering periods of civil works projects.
- Define a monitoring program and action strategy after time the completion of pipe network upgrades.

- Work with the city water and road departments to design a maintenance program based on a weighted, multi – criteria analysis including (subsidence, soil type, pipe age, construction type, pipe material, etc.).
- Continuation of InSAR monitoring with 2-year intervals and consideration of purchasing a high-resolution dataset.

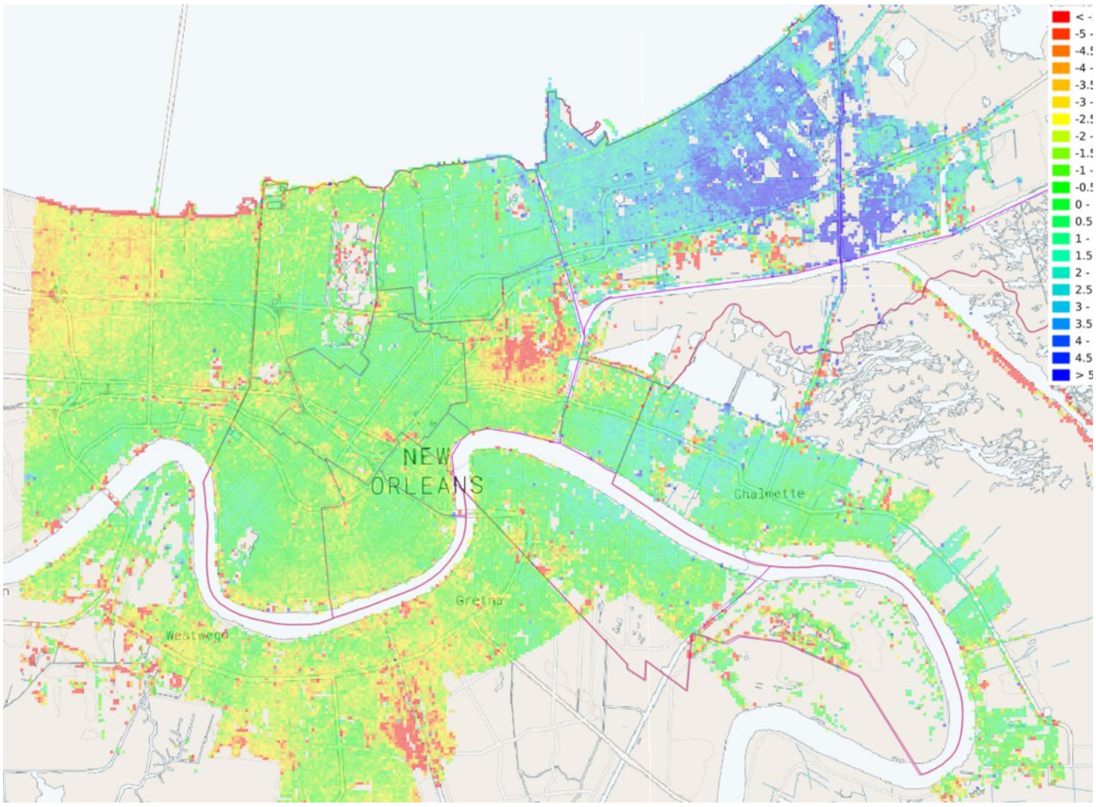


Figure 7.5 Standard resolution InSAR results over New Orleans at a -5 to +5mm/year deformation rate scale. Blue areas signal uplift, red areas signal subsidence.

8 Monitoring network design: Surface and Groundwater water locations

In total, 29 measurement locations are suggested to satisfy four major program objectives (Figure 8.1):

1) To study groundwater levels in relation to subsidence vulnerability (especially at locations with organic layers just below the known lowest groundwater level).
2) To understand the risk of groundwater flooding during precipitation events.
3) To study groundwater levels in relation to high lake and river levels.
4) To understand the relation between (leaking) street infrastructure and groundwater levels.

Of the 30 recommended sites, 15 locations measure information from a shallow single point below surface level (1 screen) and 9 locations were selected as sites where 2 measurement depths (2 screens) are recommended. Placing multiple measurement devices at a single location is done to recover information pertaining to the shallow phreatic zone and deep hydraulic heads from the Pine Barrier sands (or deep regional aquifer system).

Placement of wells parallel to Lake Pontchartrain were recommended to grow the understanding of the relationship between lake and groundwater level, salinity and geo-technical risks (i.e. heave and bursting clay layers due to overpressure within deeper aquifers). Observation well locations were also selected parallel to the Mississippi river to help develop a better understanding of water level gradient and geotechnical risks in the south of the city.

In addition, 6 surface water monitoring locations are advices. These locations support understanding of the groundwater – surface water interaction.

The scope of this project includes integrating and building on the knowledge that others have gained through previous work in the area. Five locations (represented by blue triangles) show the locations of operational projects to be added to the proposed database. More information on monitoring objectives at each location can be found in table 8.1.

Frequency and method of observation is a combination of high frequency telemetric devices and manual measurements. For the latter, public engagement opportunities within schools and neighborhoods can be built into the system allowing for educational and social program integration within the project. Manual measurements can be taken using a measuring tape / plunger or electronic water level tape. Pressure sensors (Divers) would allow for water level measurements to take place at hourly, daily or other predetermined intervals dependent on location. These devices can be coupled with cellular data transmission units, reducing the need for manual data collection.

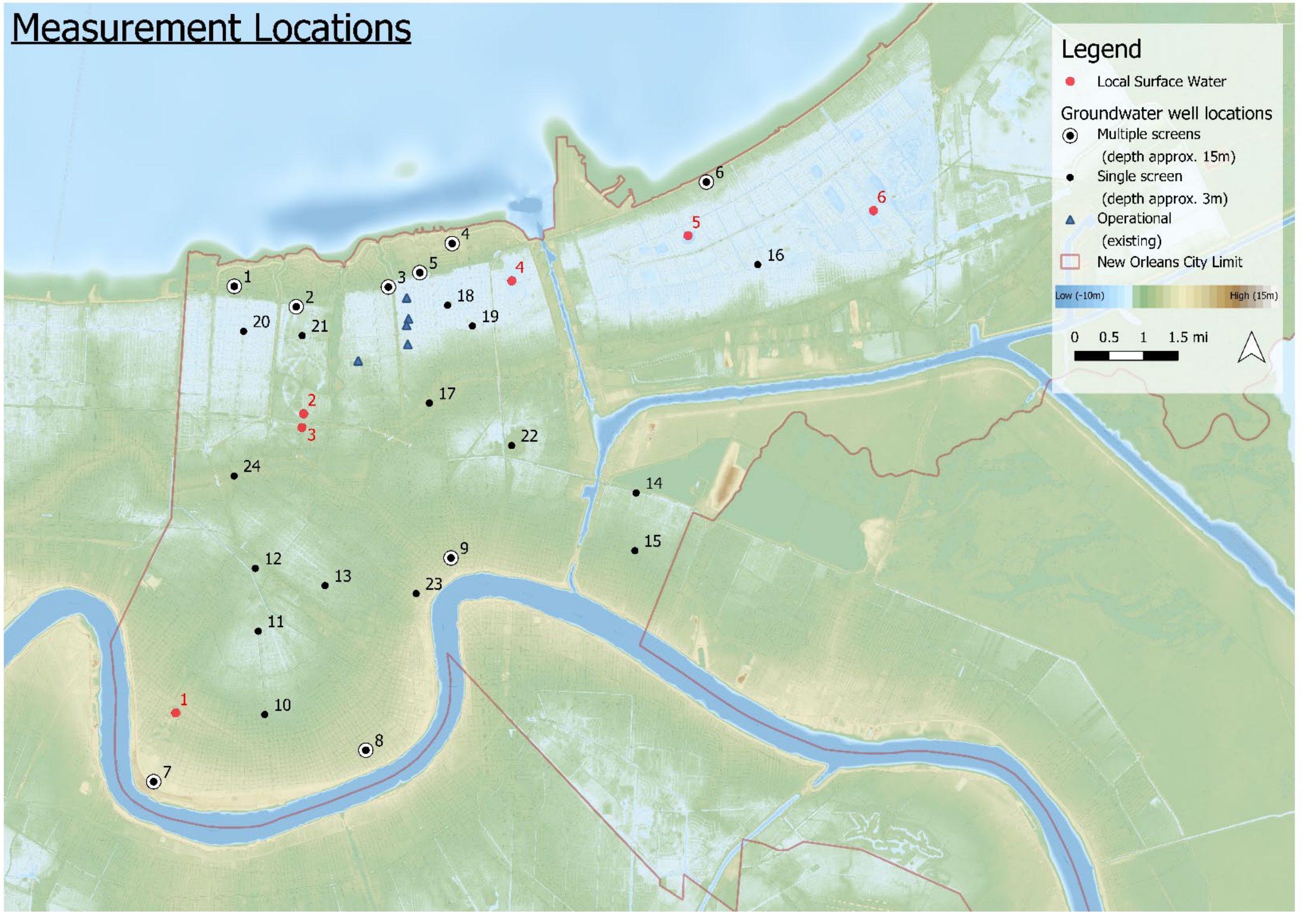


Figure 8.1 Locations of recommended surface and groundwater monitoring locations within New Orleans. Wellbore 20 & 22 represent the approximate installation location of the monitoring device.

Table 8.1: *Information proposed monitoring sites: (a) approx. 9 feet deep, (b) approx. 20-40 feet deep. In orange the locations with real-time available data. These locations need to be protected. In yellow proposed locations if it becomes necessary to reduce the number of sites and sensors.*

Groundwater observation well		
Num-ber	***Location***	***Monitoring Objective***
1 a+b	Harlequin Park (North Shore)	Effect water level Lake Pontchartrain (LP) on groundwater flow towards urban area (incl. salinization)
2 a+b	Allain Toussaint Blv. - City Park	
3 a+b	Allain Toussaint Blv- Pratt (P)	
4 a+b	Live Oaks Park	
5 a+b	New Orleans Mosquito, Termite and Rodent Control Board	
6 a+b	Hayne Blv - Burke Ave	
7 a+b	East Dr. Audubon Park	Effect Mississippi river water level on groundwater situation southern part New Orleans.
8 a+b	Clay Square Park	
9 a+b	Park Washington Square	
10 a	Samuel Square Park	Phreatic groundwater level and salinity (at this location we measured salt groundwater (remarkable).
11 a	Gen. Pershing - Dupre	Phreatic groundwater level in relation to peat layer at resp. 30, 10, 40, 10 cm below Mean Lowest Groundwater level**. Subsidence risk.**
12 a	Telemachus - Palmetto	
13 a	Gravier - Tonti	
14 a	Florida Ave.	
15 a	Claiborne Ave.	Subsidence risks, effect subsurface unfractured on groundwater
16 a	Tillford Rd. - Edenboro Rd.	
17 a	Mount Olivet Mausoleum	Water level at groundwater divide (Metairie-Gentilly ridge)
18 a	Buddy Deuterive Park	Phreatic groundwater to understand impact underground infrastructure, seepage and precipitation/evaporation
19 a	Milne	
20 a	Lake View (approx.)	
21 a	Filmore City Park (Existing: Eustis P-5)	Subsidence control (peat just below lowest groundwater level).
22 a	St. Claude	Phreatic groundwater to understand impact underground infrastructure, seepage and precipitation/evaporation
23 a	French Quarter	
24 a	Metairie Road	Water level at groundwater divide (Metairie-Gentilly ridge)
25 a+b	Mirabeau (existing)	Understanding relation shallow groundwater and deeper (Pine Barrier) groundwater.
26 a	Lafitte Greenway (existing shallow well P-3)	Phreatic groundwater to understand impact underground infrastructure, seepage and precipitation/evaporation
Surface water observation well		
SW 1	Audubon Park	Discharge into St. Charles urban drainage system (quantity and quality/salinity)
SW 2	City Park	Water levels and salinity
SW 3	City Park	
SW 4	Lagoon Pontchartrain Park	Water levels, salinity in relation to weather conditions and Lake Pontchartrain water level.
SW 5	Lake Willow	
SW 6	Lake Bullard Ave	

8.1 Temporary (project) groundwater monitoring networks

During construction projects and installation of subsurface infrastructure, temporary groundwater extractions are often needed to dewater the construction site. These extractions create decreased groundwater levels, accelerate local subsidence, and may cause structural damage to build infrastructure nearby. To mitigate this damage, a monitoring protocol is advised:

- In vulnerable areas, temporary monitoring networks should be installed.
- Groundwater thresholds should be determined for projects in vulnerable areas. If these thresholds are reached, projects should be stopped immediately, and mitigation measures taken.

9 Practical considerations

9.1 Determination of the detailed field location

In theory, the exact placement for a monitoring well should be dictated by the monitoring objectives of the program itself. Reality, however, complicates the exact placement of wellbores and locations are selected that fit within the existing community structure and project budget.

The objectives as mentioned earlier, focus on the general groundwater levels that can then be analyzed against different parameters. These measurements require a groundwater level that has limited influence from drainage pipes, artificial infiltration or drainage canals. Although these systems have been present for many of years, it is preferred that observation wells are installed at an equidistance between streets and with some distance between the well locations and canals. Local land use needs to be considered. Comparison of data will become more difficult (with relatively few monitoring locations) when land use is varied.

9.2 Ten Commandments for the placement of groundwater observation wells

1. A vertically level tube that consists of a perforated section (filter screen) and a blank riser tube. The greater the tube diameter, the better: 36 millimeters is common. The top of the filter screen must correspond to the average highest groundwater level. The bottom is set least half a meter (2 feet) below the average lowest groundwater position.
2. The average highest and lowest groundwater levels can often be determined on the basis of soil characteristics. The zone below the average lowest groundwater position is always grey, and peat is brown (oxidized peat above the lowest groundwater level is black). Between the highest and lowest water levels, rust stains are often discernible. Unfortunately, these characteristics are not documented during normal drilling procedures. Have a geologist onsite who can properly classify drill cutting or log cored materials.
3. Placement of level tubes during the dry season reduces the likelihood of dry falling.
4. In the case of clay or peat layers, make special considerations where the measurement is going to be most meaningful: below or above the disturbing layer, or both. In the latter case, make two separate drill holes.
5. Backfill perforations in contact with clay or peat layers with bentonite chips, to seal the aquifer. Add a filter stocking and coarse sand filter around the filter screen.
6. Avoid inflow of rain water along the tube by choosing favorable locations (i.e. not placed in local depressions), by using an impermeable well cover and by adding bentonite chips (swelling clay) around the tube at ground level.
7. The top of the tube should be sealed with a perforated cap for ventilation and a robust protective sleeve.
8. Placement of the measuring point is preferably located above ground level. Adjustments should be made to prevent tampering or accidental damage.
9. Do not place observation wells next to a tree or close to surface water unless the specific measuring objective demands this.
10. Has the contractor installed the well according to the design? Unknown adjustments to the well design can limit the functionality of the well itself.

9.3 Installation of monitoring wells

It must be ensured that the monitoring well is correctly recording the water table or the hydraulic head at the specified depth. Therefore, the well will have to be properly installed and developed. Checks include the tightness of its casing (e.g. the positions and tightness of the annular sealants). Rehabilitation of a monitoring well may be required after a certain time and therefore, the functionality of the monitoring well should be checked at regular intervals. The well casing and screen material should meet the specified requirements. Requirements listed by EPA may be used as reference (EPA, 1994):

- The materials should maintain their structural integrity and durability in the environment in which they are used over the entire operating lifetime.
- They should be resistant to chemical and microbiological corrosion and degradation in contaminated and uncontaminated waters.
- They should be able to withstand the physical forces acting upon them during and following their installation, and during their use.
- They should not chemically alter groundwater samples.
- They should be easy to install during the construction of a monitoring well and the material itself or its stability (tensile strength, compressive strength, and collapse strength) should not alter after installation.

Figure 9.1: Production of shallow borehole

Filter packs need to be placed in such a way that the top of the filter pack aligns with the water level between the saturated zone and aquifer or formation boundary if lithology changes. At greater depths the use of a prepacked filter is recommended, this way it is ensured that the filter pack is properly installed.

The filter pack material used must be safe and should not introduce any bacteria to the subsurface during installation. Any wellbore contamination must be avoided. The chosen gravel pack size depends on the aquifer material (sieve analysis results will dictate the correct material size) and influences the slotted screen size (figure 9.2). Top and bottom formation seals must be properly installed to avoid water movement outside of the casing. Centralizers can be used to keep the well centered in the wellbore during installation and should be installed at proper distances. This will ensure the functioning of seals and gravel packs are guaranteed.

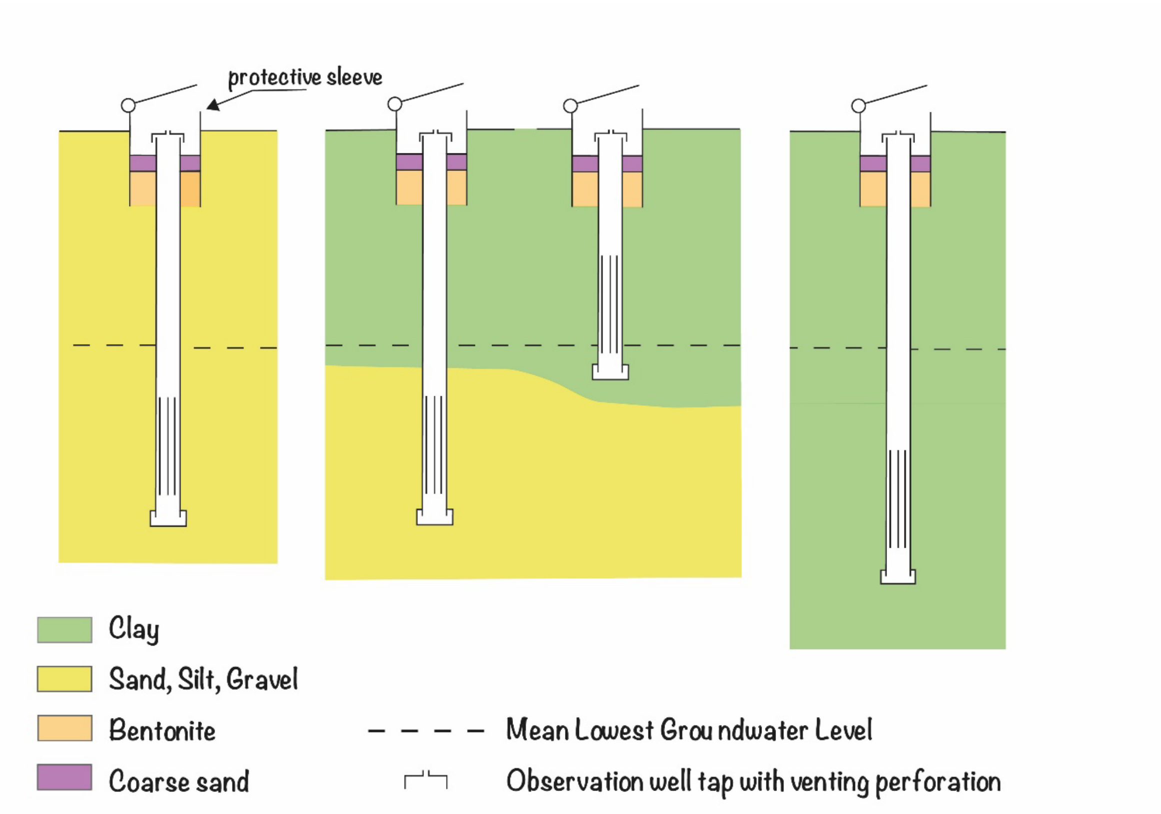


Figure 9.2: Installation of shallow wells under different geological (lithological) situations.

9.4 Well completion

This section contains some practical suggestions that may be useful when completing the well installation (figure 9.3).

- Make sure that the outside surface of the piezometer tube, including the joints, is as smooth as possible to ease its installation.
- Use centralizers to keep (non-prepacked) screens in the center of the borehole.
- Make sure that the inside surface of the piezometer tube is as smooth as possible to prevent measuring equipment from getting stuck.
- In case several piezometers are placed in one borehole, the tops of the piezometer tube above surface level should indicate the depth of its screen (the deeper a piezometer, the lower its top). The piezometer tubes may be cut at heights differing by 5 cm, for instance.
- Do not use a screw-top to close a tube.
- Give each tube a unique number and place a unique identification label on the monitoring well.
- Construct a cement surface seal above surface level for stability and to prevent surface water from entering the well directly.

- A steel casing will protect from vandalism and water from entering the well.
- Fix a lock to prevent unauthorized access to the well, if necessary, in combination with a fence around the monitoring well.

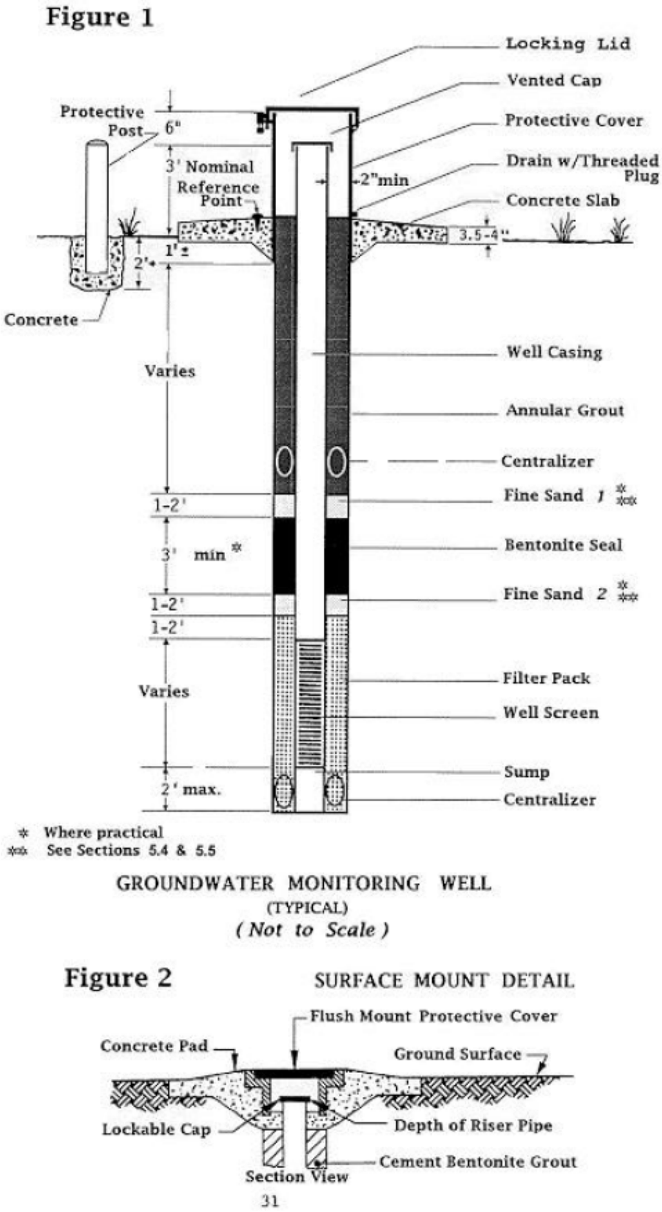


Figure 9.3 (left) Typical wellbore schematic of a groundwater monitoring well and surface mount detail. (right) Flush mounted, city works covers. An example for how the street level may look on top of a groundwater observation well.

9.5 Measurement Methods and Frequencies

A conceptual understanding of the groundwater system, its periodic fluctuations and defining the purpose of the system itself is an important first step in selecting an appropriate sampling method and frequency. The sampling frequency should be high enough to capture the periodic fluctuations within the natural system or the effects caused by human activities. Manual data collection like in the Amsterdam case provides a low cost, time intensive solution to measuring gradual seasonal changes but would not be able to capture the rise in groundwater associated with rainfall events. It should be mentioned however, that the knowledge of canal water levels in Amsterdam provides sufficient control of groundwater elevation understanding, so the long-term trend of the phreatic system is of main importance. To capture changes to groundwater level after high intensity rainfall events, it is suggested that hourly recordings be taken.

Table 9.1 Reason for measurement and frequency requirement comparison

Reason for Measurement	Frequency Requirement
Storage capacity	Hourly
Groundwater subsidence	Daily
Surface water – Groundwater	Hourly
River water – Groundwater	Hourly to Daily
Street infrastructure – Groundwater	Hourly
Wooden piles – Groundwater	Twice per month

Manual measurements occur less frequently and are prone to recording, record keeping, or calculation errors (see figure 9.4 for an example of measuring devices). Automation solves these problems and can be implemented in a cost-effective manner. Additionally, technology driven solutions will provide a sampling frequency that is high enough for monitoring networks covering large areas and where abrupt changes to the environmental conditions are present (i.e. the effect of precipitation, tidal influence or water pipe ruptures). As seen in the Dresden case, internet connected devices allow the collection frequency to be altered (or set) to the operators' preference or based on environmental conditions (i.e. lots of precipitation).

Figure 9.4 (left) low tech water level tape and plunger vs (right) water level tape with water sensor and light and sound indicators. Both accurately measure groundwater level depth from surface.

Dataloggers or "abandoned" measurement devices are an in between solution that provide the accuracy and frequency of an automated device but require an operator to download the data. These groundwater level recording devices have built storage capabilities but not the ability to transmit the information that is stored within the unit itself (figure 9.5). Integrated and third-party hardware providers convert data loggers into telemetry devices, providing cellular and satellite capable data streams.

Figure 9.5 Divers are high-quality pressure sensors from Schlumberger that allow the user to convert pressure head to groundwater depth. Different measurement parameters are also available (ie. EC and temperature)

Technology is enabling more frequent measurements to occur while cellular or satellite-based transmission services and offsite data storage provide safe, secure and cost-effective ways of recording the dataset. Ultimately, understanding and defining the reason for the monitoring network and conceptualizing the speed at which the system is moving are important aspects to consider when selecting a network that is appropriate for the city. Often, a mixed system made up of multiple measurement types (telemetry, hand measurements, interested citizen scientists and dataloggers) may produce the best results.

9.6 Maintenance

Wellbore and device maintenance should be conducted at regular intervals and integrated into data collection retrievals and manual groundwater level measurements. A visual equipment inspection and cleaning should be completed at least twice per year and wellbore site inspection looking for vandalism, pooling water around the wellbore or other signs of tampering at least once per year. Well flushing should be done every few years to make sure the filter pack and screen do not become clogged with fine grain sediments.

9.7 Post processing & ‘Data-basing’

Data storage and visualization has been advancing rapidly over the past 5 years. Cloud storage solutions provide an added layer safety against data losses that could occur on a local system. If a local storage solution is preferred, there are many options in this space as well. Distributed systems, where data is stored among a network of computers or computer nodes is another data storage solution design. Although not the purpose of this document, database storage structure should be considered during the initial phases of a project to incorporate current information and potential future growth of the network. A smart system should be fully digital and compiled in an efficient, smart, and searchable way.

From a visualization perspective, dashboard software packages with mapping capabilities are becoming more and more prevalent as companies like Microsoft, Tableau and ESRI are all competing for market share. Dashboards allow data to take on a new life as interactive graphs, charts, slicers, maps and other custom visuals provide creators with ample creative license and viewers to see the data in a more friendly way. Figure 9.6 presents an example of a dashboard created in Microsoft PowerBI where borehole, groundwater and chemical timeseries information is presented in an online, interactive method.

Figure 9.6 A screen capture of DiscoverEI's interactive "Synthetic water quality" Dashboard created in Microsofts PowerBI

10 Cost Benefits of groundwater monitoring

10.1 Introduction

Little is written (studied) about the costs and benefits of groundwater monitoring. Kim and Kim (2019) estimated the cost-benefits for the Korean groundwater monitoring network. The total cost including installation, maintenance and servicing over the next 50 years is estimated to be US$ 0.79 billion, while the benefits are valued at US$ 2.31 billion (292% of the costs).

The World Bank (Tuinhof et al, 2004) presented the following statements about cost-effective groundwater monitoring:

- Effective groundwater monitoring is characterized by two key requirements:
    - it should be driven by a specific objective—monitoring for its own sake often leads to inefficient use of manpower and budgets.
    - the data collected should be systematically stored for future use—there are far too many cases of monitoring data being 'lost along the way'.

- Groundwater monitoring is often considered expensive—the main components of expenditure include the capital cost (of network installation), sampling costs (for instrumentation, personnel and logistics) and analytical costs (for laboratory, data processing and storage). Moreover, the return on initial investment is not likely to be evident immediately. Yet, in the longer run, this return can be substantial where monitoring represents an integral part of a management process and avoids loss of valuable groundwater sources, the introduction of costly treatment or the need for expensive aquifer remediation. Awareness of these factors increases if cost-benefit analysis is included in the design phase of groundwater monitoring programs.

- The effectiveness of groundwater monitoring can be considerably increased by careful attention to network design, system implementation and data interpretation, and by:
    - making best use of data collected by past monitoring activities;
    - selecting monitoring stations that, as far as possible, are easily accessible;
    - making fullest use of indicator determinants to reduce analytical cost;
    - promoting complementary self-monitoring amongst water users;
    - incorporating quality control and quality assurance procedures.

An inquiry at the cities Rotterdam and Amsterdam provided the following information:
- The benefits cannot be expressed in monetary terms. A groundwater monitoring network does indeed cost a lot of money, but they consider it an essential part of their interpretation of the groundwater care obligation.
- Rotterdam (589.000 inhabitants, land surface 79.53 sq. miles) possesses approx. 2000 observation wells of which:
    - 450 are equipped with high frequency sensors and,
    - 1550 are measured by hand (1x per year).
    - Total costs Euro 700,000 per year.
    - So, yearly costs per observation well is approx. Euro 350.
- Amsterdam (921,000 inhabitants, land surface 64.00 sq. miles) possesses 2500 observation wells of which:
    - Most are hand-logged (6x per year).
    - Several hundred using sensors.

    - Costs (exclusive maintenance) are approx. Euro 800,000.
    - So, yearly costs (exclusive maintenance) per observation well is approx. Euro 320.
- Hellevoetsluis (40,312 inhabitants, land 15.87 sq. mi)
    - Installation costs Euro 1300 per observation well.
    - Yearly costs per observation well: Euro 300.

Based on these Dutch number's operational costs (including maintenance, data storage and data visualization at website) will be approx. $ 300-350 per observation well (location) per year. Regular reporting (for example at 2-3 years interval) is not included and will cost approx. 1-2-week work for 1 person.

10.2 Potential benefits of an urban groundwater monitoring network in New Orleans

A monitoring network can help to reduce damage for the public domain as well as for the private sector, including home owners. The main groundwater related risks in New Orleans are:

1. Building and road damage due to subsidence in areas with organic subsoils caused by too low groundwater levels (for road damage processes, see appendix C),
2. Road and building damage in relation to temporally high groundwater levels,
3. Road and building damage during dry periods (too low groundwater levels) caused by shrink-swell of shallow clay deposits and/or peat oxidation,
4. Foundation risks, especially for historical buildings constructed on wooden piles. Low groundwater levels can stimulate wood rot.
5. Groundwater flooding. This can arise by:
    a. Increasing rainfall amounts (climate change)
    b. Renovation of storm drainage and waste water transport pipes. Now these pipes are draining (and therefore lowering) groundwater.
6. Groundwater and soil salinization. A potential risk for trees and other vegetation. This risk is related to droughts and the groundwater flow of brackish-salt groundwater from Lake Pontchartrain (and outfall canals) towards the lower parts of Gentilly and New Orleans NE.
7. Tree damage due to (1) drowning (too high groundwater levels), (2) dryness and (3) salinization.

Of course, these risks have different risk-owners. For example, protecting historical buildings on wooden piles is the responsibility of the owners. They could install groundwater observation well around their property (like the termite observation networks).

11 Recommendations for the use of monitoring results in urban (water) planning

11.1 Introduction

Urban planning requires a unique mixture of technical and political skills, both of which require fact-based inputs so informed decisions can be made with a mindset backed by a current and appropriate dataset. An urban water monitoring plan that includes, groundwater, surface water, soil information, pumping rates, precipitation and subsidence rates could also be termed an integrated water monitoring program and will help to provide clarity to answers relating to water resources. Programs of this nature are iterative, non-static, require a large amount of foresight, optimization, expert local knowledge as an inputs and direction from stakeholders.

The use of monitoring results is as wide ranging as the creativity of the user. Urban planners could use the dataset to look at current events and future modelled scenarios to understand how risk associated with natural events may change over time, and how the implementation of risk reduction measures may protect the people and infrastructure within the areas of interest. Departments linked to sewage, water and transportation may also be able to use the data from this system to implement cost savings through program optimization of their maintenance schedules or the operation of mechanical stations themselves. Emergency services could the system information to help strategically allocate resources and provided data to first responders in relation to flood risk (ground or surface) or in case of mechanical failure of a key piece of equipment. By providing this system to the public, operators be able to provide useful pieces of information to concerned or inquisitive citizens and aid in their own understanding of the city's water network.

The monitoring results are also essential to calibrate (validate) the urban groundwater model of the city. This urban groundwater model can produce city-wide groundwater level maps and groundwater flow maps.

Last, but not least: the availability of groundwater monitoring will help to understand how groundwater works. You can't manage what you don't understand. Making the results public available will also create more awareness for understanding of the impact of climate change.

11.2 Dealing with actual and changing groundwater levels

Understanding the actual groundwater level fluctuation can support the design of roads, infrastructure and buildings. The determination of "<u>target groundwater levels</u>" can help. For example: at what depth groundwater levels become damaging? What is the optimal groundwater level? It's clear that in zones with peat layers (e.g. Lakeview) the groundwater level should stay above the top of these peat layers. In the French Quartier the target levels should be protect the (untreated) wooden piles of historical buildings. In other areas, too high groundwater level can reduce the availability of rain water storage, causing extra vulnerability for flooding.

In the Netherlands the monitoring results are most times used in discussions with the citizens. For example, during discussions about groundwater related flooding. In New Orleans this monitoring network can help to collect "lessons learned": understanding the effect of infrastructure renovations and climate change.

We recommend determining target levels for every groundwater monitoring site.

12 Literature

August, Rudy, David W. Kurtz, Griff Machinski, 2009: Sewerage and Water Board of New Orleans: Water Loss Control Program. **Pipelines Specialty Conference 2009**

Eilander et al., (2023). HydroMT: Automated and reproducible model building and analysis. Journal of Open Source Software, 8(83), 4897, https://doi.org/10.21105/joss.04897

Eustis, 2022: Geotechnical instrumentation installation report. Lakeview City Park proposed drainage improvements. New Orleans, Louisiana Eustis Engineering project no. 24192.

Kim, Sun G., Gyoo-Bum Kim (2019): Are Groundwater Monitoring Networks Economical? Cost-Benefit Analysis on the Long-Term Groundwater Supply Project of South Korea. Water 2019 *11*(4).

Nora Freeman, Freeman LLC, 2019: Water audit update. Sewerage and Water Board of New Orleans, **Fiscal Years 2008 – 2017**

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.bd0915c6 (Accessed on 4-April-2023)

IGRAC, 2008: Guideline on: Groundwater monitoring for general reference purposes.

CONSTRUCTION OF GEOTECHNICAL BOREHOLES AND GROUNDWATER MONITORING SYSTEMS HANDBOOK. PREPARED BY THE LOUISIANA DEPARTMENT OF ENVIRONMENTAL QUALITY AND LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT, DECEMBER 2000

Stuyfzand, P.J. 2012. Hydrogeochemcal (HGC 2.1), for storage, management, control, correction and interpretation of water quality data in Excel (R) spread sheet. KWR Watercycle Research Institute, KWR-report BTO.2012.244(s), updated in Feb.2015, 82p.

STOWA, 2012: Report 50. HANDBOEK METEN VAN GRONDWATERSTANDEN IN PEILBUIZEN (Handbook measurements groundwater levels in observation well: STOWA is the knowledge centre of the Dutch water boards)

R. Taugs, L. Moosmann, N. Classen & P. Meyer (March 2016) Hamburg TU1206 COST Sub-Urban WG1 report.

Nguyen01 (April 5, 2017). Peilbuizen Waternet V1.0. Retrieved May, 2019, from https://maps.waternet.nl/kaarten/peilbuizen.html

Gemeente Delft and Munisense (Unknown). Munisense open data portal. Retrieved May, 2019, from https://opendata.munisense.net/

City of Dresden (Unknown) Dresden Themenstadtplan. Retrieved May, 2019 from, http://stadtplan2.dresden.de

City of Antwerp (Unknown) Stand Antwerpen. Retrieved May, 2019 from, http://stadantwerpen.maps.arcgis.com/home

Geological Survey of Norway, NGU (Unknown) The national groundwater database GRANDA, Retrieved May, 2019 from, http://geo.ngu.no/kart/granada/.

Nougues, Laura and Roelof Stuurman (2022). Groundwater drainage in New Orleans. Water Matters (https://www.h2owaternetwerk.nl/water-matters/wmjun2022)

Prakken, L.B., 2009, Groundwater resources in the New Orleans area, 2008: Louisiana Department of Transportation and Development Water Resources Technical Report no. 80, 36 p.

The San Francisco Public Utilities omission (April, 2016) 2015 Urban Water Management Plan for the City and County of San Francisco. Retrieved May 2019 from, https://www.sfwater.org/Modules/ShowDocument.aspx?documentID=8839

Skaggs, Brady, Will Pestoff, Justin Sumner (2019). Statistical assessment canal sampling 2018. LPBF, March 2019.

Suozzi, T. (2005) Nassau County Groundwater monitoring program (2000 – 2003).

Tuinhof et al (2004): Groundwater monitoring requirements for managing aquifer response and quality threats. GWMate Briefing notes series. World bank.

Groundwater Watch, Office of Groundwater (May 2019) Active groundwater level network, U.S. Department of the interior. Retrieved May, 2019, from https://groundwaterwatch.usgs.gov/default.asp

Adelson, J. (2019, March 15). More than half of New Orleans S&WB’s water lost to leaks, costing millions, audit reveals (News Article). Retrieved July, 2019 from: https://www.nola.com/news/article_16496297-02ec-5c8e-9033-c040525ceb72.html

Myers, D. (Unknown). *Why monitor water quality?* Retrieved September, 2019 from: https://water.usgs.gov/owq/WhyMonitorWaterQuality.pdf

Jackson, J. (2019, August 2). New Orleans. *Encyclopedia Britannica*. Retrieved September, 2019 from: https://www.britannica.com/place/New-Orleans-Louisiana/Cultural-life

https://groundwaterwatch.usgs.gov/default.asp

NEW:

https://www.usgs.gov/science-explorer-results?es=Groundwater+Monitoring&classification=map

http://www.twdb.texas.gov/innovativewater/index.asp

A Monitoring interactions

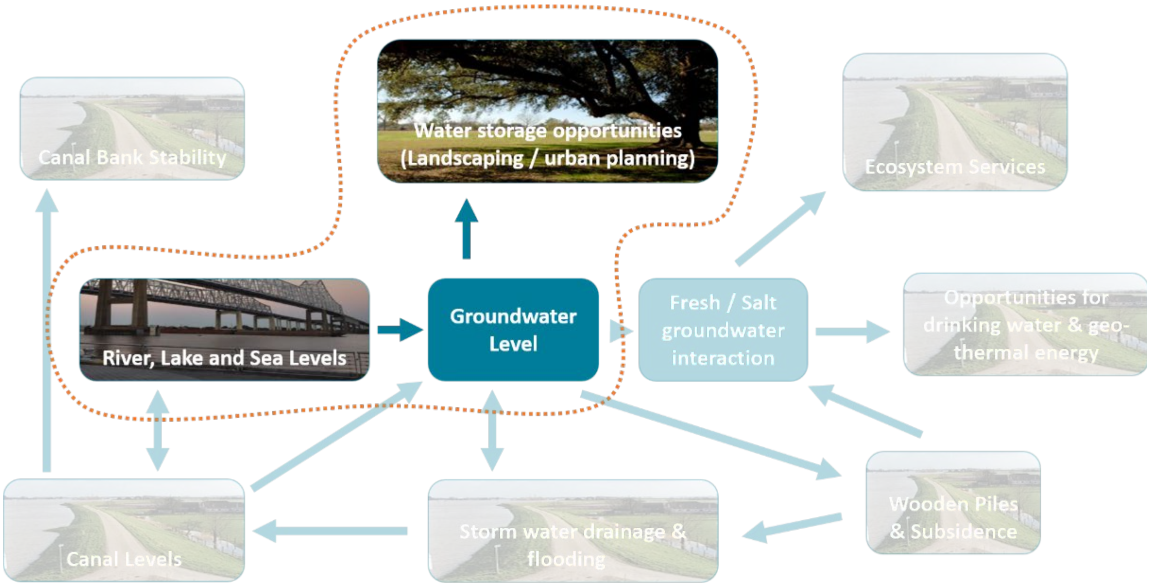


Figure 12.1 – Highlighted interactions between groundwater levels, groundwater level and natural surface water systems within the context of the integrated monitoring system vision as presented in Figure 4.4.1.

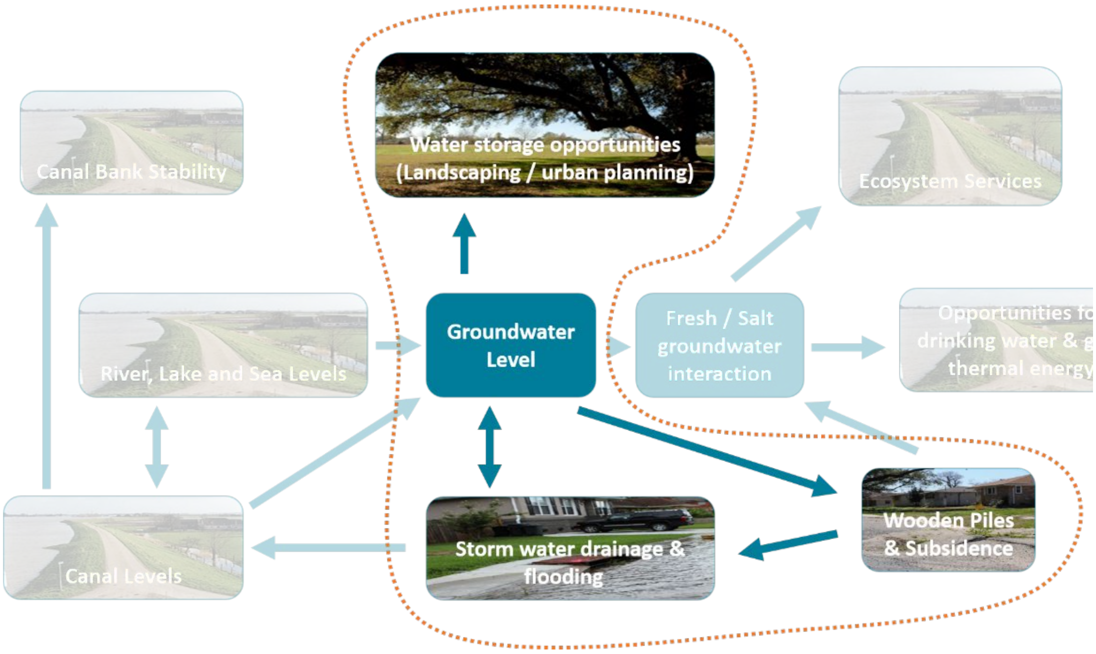


Figure 12.2 - Highlighted interactions between groundwater levels, water storage opportunities, storm water drainage and flooding, and wooden piles and subsidence within the context of the integrated monitoring system vision as presented in Figure 4.4.1.

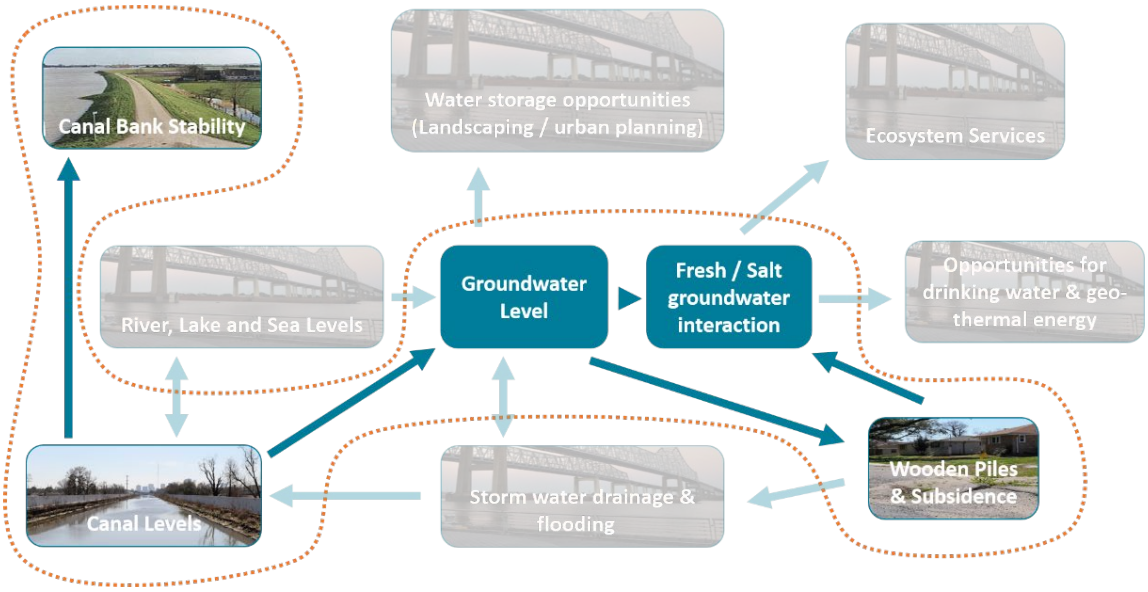


Figure 12.3 - Highlighted interactions between groundwater levels, canal bank stability, canal levels, fresh / salt water (groundwater) interactions and wooden piles and subsidence systems within the context of the integrated monitoring system vision as presented in Figure 4.4.1.

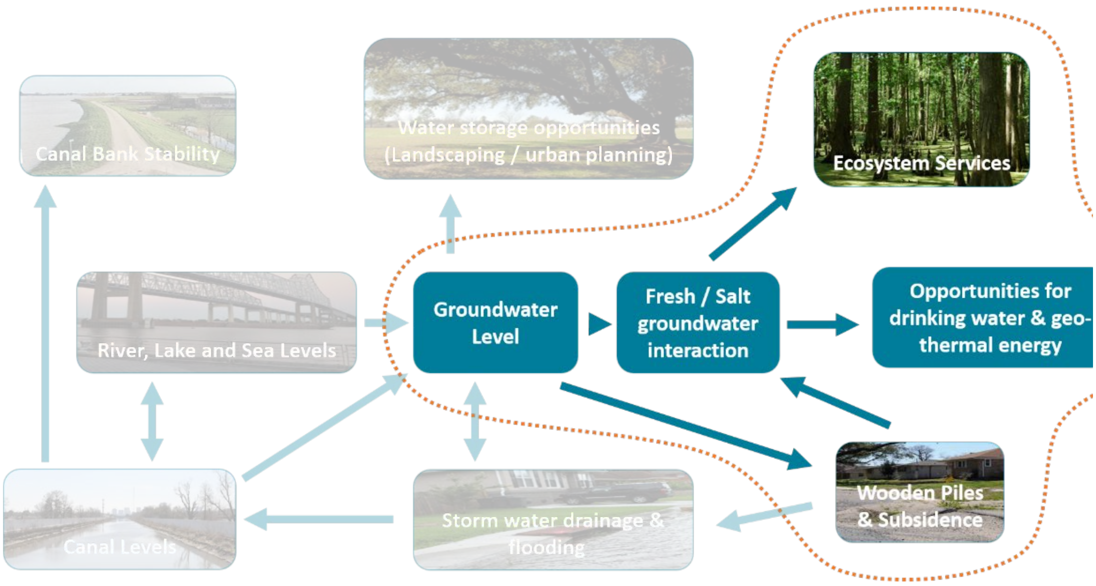


Figure 12.4 - Highlighted interactions between groundwater levels, fresh / salt water (groundwater) interaction, ecosystems, opportunities for drinking water & geothermal energy and wooden piles and subsidence systems within the context of the integrated monitoring system vision as presented in Figure 4.4.1

B Borehole locations

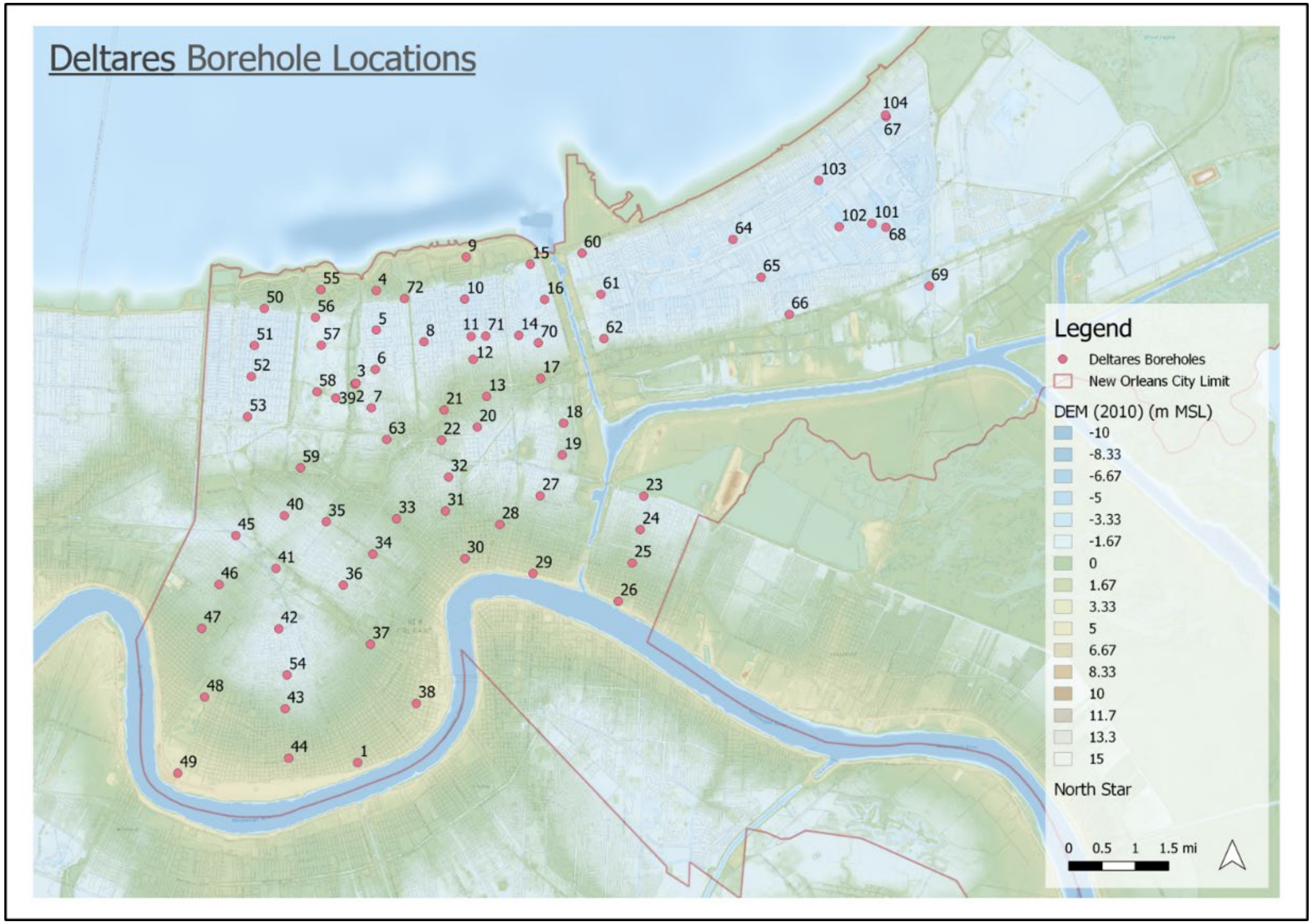


Figure 12.5 Deltares borehole locations located within the Greater New Orleans boundary.

C Street damage, subsurface and monitoring

1. Soil stability vulnerability
   - Soil type (shallow geology): e.g. sand is less compressible than clay (muck).
   - Soil moisture:
     - muck, (silty) clay can shrink during dry periods and swell after wet periods.
     - After heavy rain periods (and/or urban flooding) the top soil can become saturated and lose stability.
     - After long dry periods brick covered streets on a (low quality) sand fill are often damaged
   - Loading by (heavy) traffic; differential pressure distribution in relation to soil characteristics causes damage
   - Salinization (also flooding by salt water) can destabilize clay minerals and cause soil collapse
   - Post-construction subsidence; depending on the quality of artificial pre-loading
   - Transition zones & service pipe connections : damage at the transition with piled buildings, bridges etc.
2. Horizontal movement (creep)
   - Often caused by geomechanical forces along canals (or other depressions) and embankments
3. Groundwater level;
   - Causing differential subsidence in areas with organic soils,
   - Increased groundwater levels can put pressure on (empty) underground transport pipes and lift them
     - After repair of the damaged subsurface infrastructure a new raised groundwater level may develop!
   - What is the optimal groundwater level for each soil type? (can be managed by “French” drains)
4. Damage state of the storm drainage pipes, sewer pipes and tap water pipes:
   - Broken sewer and storm drainage pipes drain water and sediment. Streets lose foundation.
   - Broken tap water pipes cause local soil saturation and therefore soil instabilities
5. Trees: Extensive root growth is an important factor in street damage
   - Root structure is related to soil type and groundwater level. Root structure of new trees can easily managed (photo). How to handle existing (heritage) trees?
   - Groundwater depressions around trees (trees suck up a lot of water)

6. *Gas pipes and corrosion damage risks.*
   - *Corrosion is determined by water quality and subsurface bacteria.*
   - *Gas pipes can break because of soil instabilities caused by differential subsidence*
   - *Leaking methane can cause explosions.*
   - *Methane gas kills tree roots. Rotting roots create instable soil conditions.*

D Salinity classification

	Chloride mg/L	Salinity %	Salinity ‰	Electrical Conductivity µS/cm	TDS ppm	*remarks*
Oligohaline-fresh	<30	< 0.04	< 0.4	<500	<400	Rainwater (EC = 40-60 µS/cm) or water with high rainwater percentage
Fresh	30 -300	0.04 – 0.1	0.4 – 1.0	500 – 1,100	400 – 1,000	Mississippi river water, tap water New Orleans.
Brackish	300 – 1,000	0.1 – 0.2	1.0 – 2.0	1,100 – 2,750	1,000 – 2,000	Higher than 300 ppm chloride becomes tasted. Often useful for irrigation.
Brackish-salt	1,000 – 10,000	0,2 – 1.8	2.0 - 18	2,750 – 24,000	2,000 – 18,000	Range of Lake Pontchartrain, Bayou St. John (EC 4500 µS/cm,= approx. 2,000 mg/l chloride)
Saline	10,000 – 20,000	1.8 – 3.6	18 - 36	24,000 - 47,500	18,000 – 36,000	Coastal sea water (Mexican Gulf) has salinity of 32 ‰, open sea 36-36.5 ‰
Hypersaline	> 20,000	> 3.6	>36	> 47,500	>36,000	Groundwater in contact with salt formations, or marshlands with local high evaporation rates.
Brine	>45,000	>10	>100	106,000	>100,000	Groundwater in contact with salt formations

Table: Estimated conversion of different salinity indicators. Note that TDS is in mg/kg water (ppm) and Cl in mg/L. Conversion of mg/L to mg/kg is by multiplication with solute density^{-1}. Brine definition via TDS, according to Davis & De Wiest 1966. EC at 20^{o}C. (Based on Stuyfzand (2012) regarding chlorinity classes and equations to convert Cl into EC and EC into TDS. EC and most TDS values have been rounded off).

E Monitoring network design

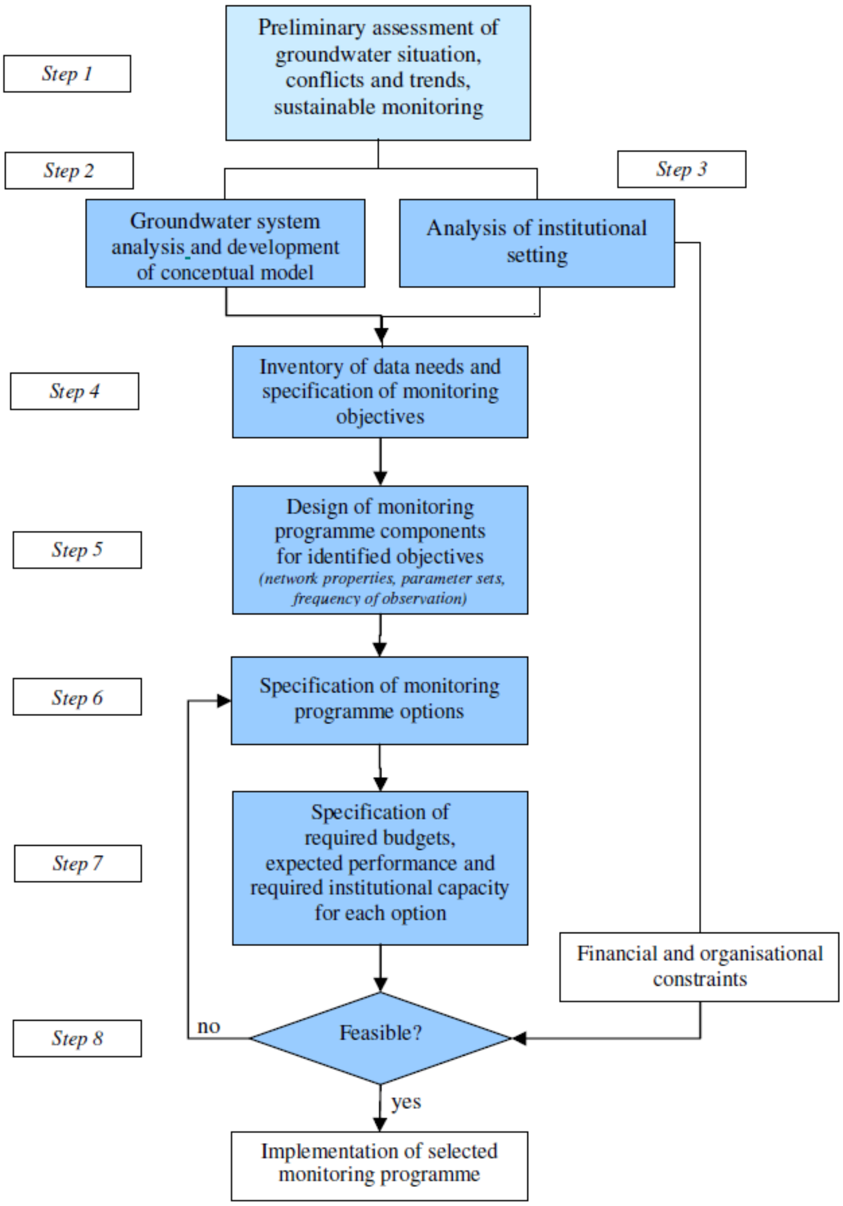
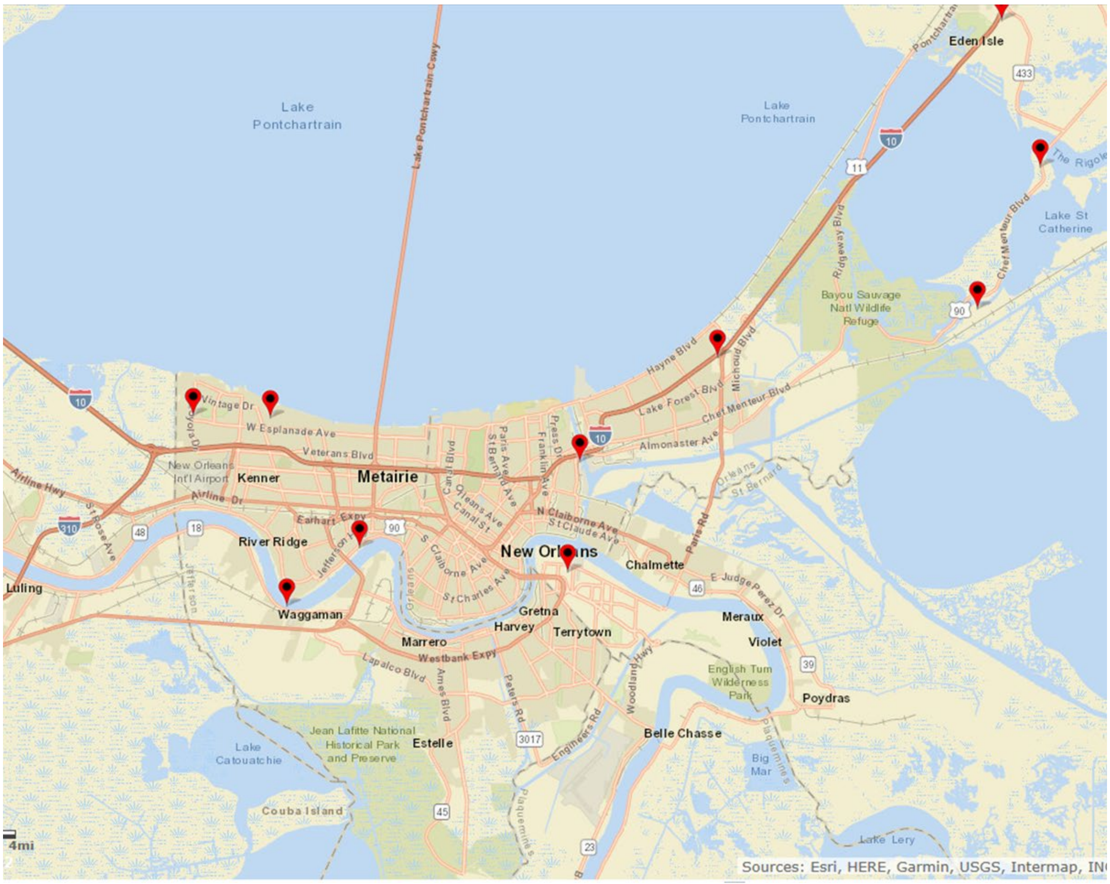


Figure 2.2: Scheme for design of a groundwater monitoring programme

F Locations deep (active) USGS groundwater monitoring wells



Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares