Internship Report

Groundwater drainage in New Orleans
An internship at Deltares

Laura Nougues

Company Supervisor: Roelof Stuurman
University Supervisor: Frans van de Ven

TU Delft

Deltares

Abstract

The goal of this study was to get a better understanding of the current groundwater drainage in New Orleans, Louisiana. Firstly, the behaviour of the groundwater fluctuation at three different locations within the study region was analyzed: the park on Mirabeau Avenue, the St. Anthony neighbourhood, and the Irish Channel neighbourhood. This was done by examining daily rainfall data and groundwater level fluctuations.

Next, an analysis was conducted on the interactions between groundwater drainage and different water infrastructure systems like: the sanitary sewer system, the storm water drainage system, and the drinking water system. Due to the age of these networks, damage caused during natural disasters like Hurricane Katrina, the ground movement sensitivity of the region and the existing land subsidence, these networks are in poor shape. To quantify the groundwater drainage component of each system, an existing QGIS wastewater model was used along with different time series, including hourly and daily data for precipitation and sewer station influents, and a storm drainage analysis based on pumping station data.

The following notable conclusions per water system were made: 1) 50% of the total water treated in the wastewater treatment plant is groundwater, adding a large amount of unnecessary stress to the treatment process, 2) the storm water drainage system is the largest groundwater drainage component contributing to 58% of the total groundwater drainage and 3) 55% of the produced drinking water is lost during distribution, meaning the drinking water losses are a larger groundwater recharge than the annual precipitation surplus. A large part of this lost drinking water is then drained by the adjacent sewer and storm water drainage pipes. The final groundwater balance can be seen in Figure 1 as well as the groundwater flux ratios in Figure 2.

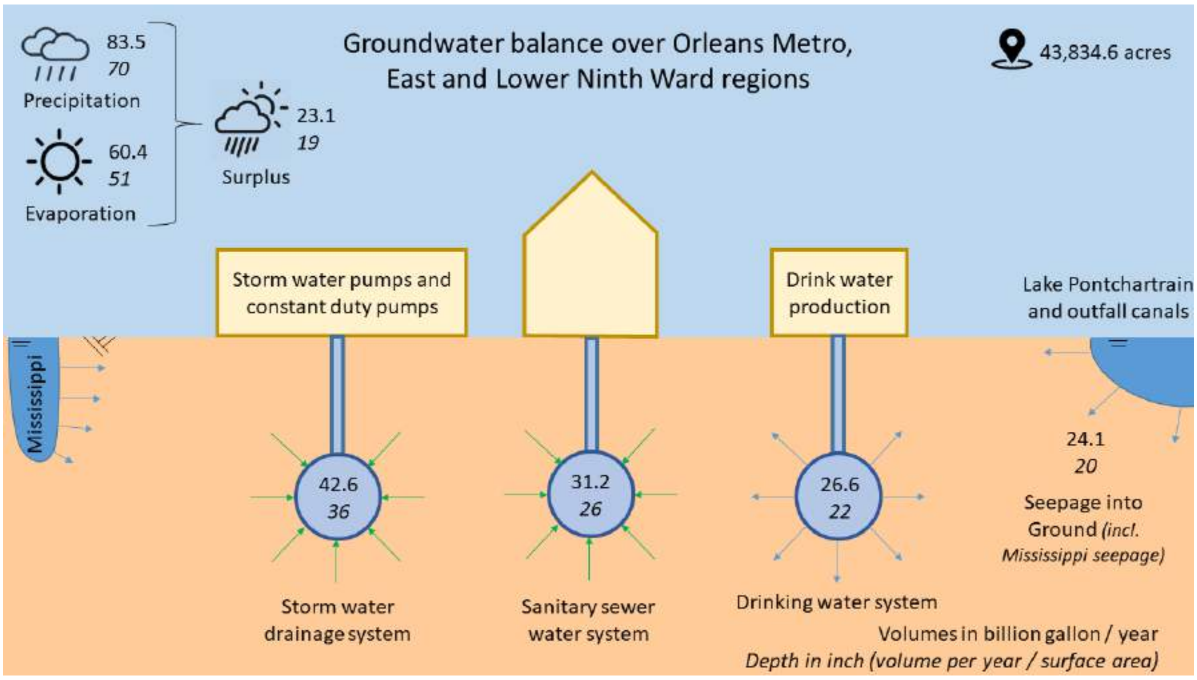

Figure 1: Groundwater balance for the study region. Groundwater is recharged by the precipitation surplus, the drinking water leakages and the seepage from Lake Pontchartrain, the outfall canals and the Mississippi River. Groundwater is drained by the sewer system and the storm water system.

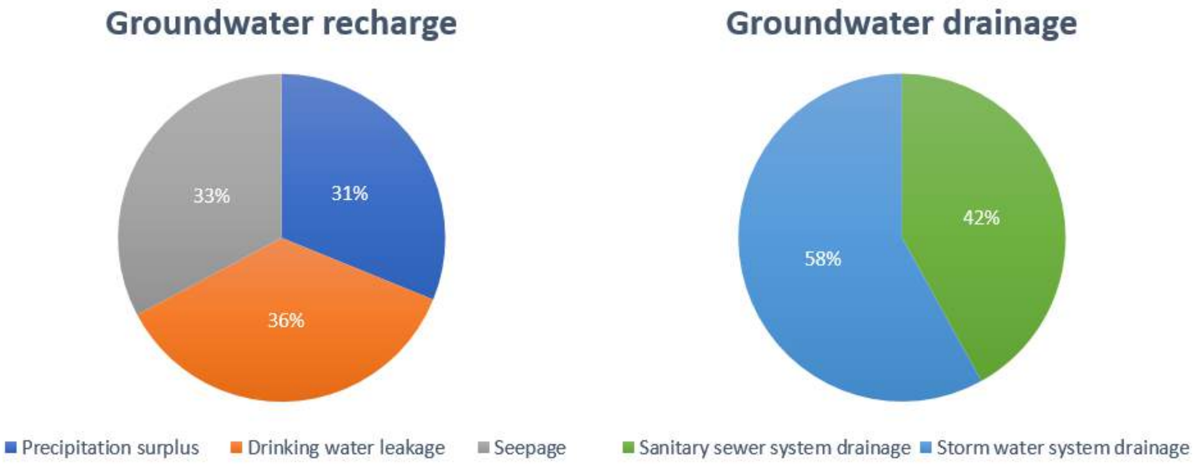

Figure 2: Ratio of the different groundwater recharge and drainage fluxes

Within the study, certain uncertainties and assumptions must be noted. the potential evaporation was used instead of the actual evaporation. Much of the data collected and analysed covered different time periods. It was assumed that the fluctuation in sewer flow was fully caused by extra groundwater drainage and that the constant duty pumps working on dry days were only pumping drained groundwater.

The most important recommendations for future studies are to monitor the water quality of the wastewater influent and pumping station discharges to find the water origin and to get a better understanding of the influences of the different groundwater fluxes and the consequences of possible future renovations.

Preface

This report is the product of a three month internship at Deltares done as part of my Water Management masters degree at the Delft University of Technology. Despite not being able to go to New Orleans nor being able to work from the Deltares office, I am extremely happy with my internship experience. I got to get a taste of the professional world, while working on a topic that greatly interests me. Ending this internship on such a positive note would not have been possible without the help and support of the following people.

To start off, I would like to thank my two internship supervisors: Roelof Stuurman and Frans van de Ven. Roelof and Frans, thank you for the great opportunity and for the support along the way. I learned a lot and I am very pleased and proud of the outcome.

Further, I would like to thank Frans Roelofsen from Deltares for all his QGIS support, as well as Daan Rooze for always making time for my questions and Paul Baggelaar from PB Icasat for the help in analysing some of the data.

From the Sewerage and Water Board of New Orleans, I would like to thank Adam Kay and Tyler Antrup for all their data and explanations.

I would like to thank Bob Mora and Jennifer Snape from Batture LLC for all their monitoring well data and for getting me in touch with Sean Walsh from Eustis Engineering LLC, who I would also like to thank for his contribution to my internship.

Finally, I would like to thank Christopher Sanchez from Stantec for all his time helping with the QGIS waste water model and Tor Tornqvist for the Irish Channel groundwater data.

Laura Nougues
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Abbreviations and definitions

Billion gallon (BG)

Drainage pumping station (DPS)

Inner Harbour Navigation Channel (IHNC)

Million gallon per day (MGD)

Sewer pumping station (SPS)

Sewerage and Water Board of New Orleans (SWBNO)

Wastewater Treatment Plants (WWTP)

Base flow - the dry weather groundwater drainage into the sewer system.

Drainage - the flow of groundwater from the subsurface into the water infrastructure systems.

Drainage level - a groundwater steady state level which is influenced by neighbouring drainage infrastructures.

Groundwater drainage rate - the daily precipitation intensity of a rain peak divided by the number of days needed for the groundwater level to return to the drainage level.

Hydrograph - a graph showing the discharge rate caused by a specific precipitation event, in relation to time.

Invert level - the bottom level of the inside of a drainage pipe.

Lag time - the difference in time between the occurrence of the precipitation peak and of the discharge peak in a hydrograph.

Leakage - the flow of water from the the water infrastructure systems into the subsurface.

Potential evaporation - the amount of evaporation that would occur if sufficient water were available.

Precipitation surplus - the difference between precipitation and evaporation.

River stage - the water level in a river with respect to a chosen reference level.

Wet weather groundwater drainage - the wet weather groundwater drainage through the sewer system.

Contents

1
Introduction

Within the Greater New Orleans, Louisiana, three parishes can be identified: Orleans Parish, Jefferson Parish, and St. Bernard Parish. These parishes are almost completely surrounded by water: Lake Pontchartrain to the north, the Mississippi River to the south, Lake Borgne to the east, and wetlands to both the east and west. These wet borders along with the fact that half of the land between these water bodies are below sea level [Sneath, 2019], create major flooding and drainage concerns. Due to the bowl like shape of these parishes, virtually all rainfall that falls within this region must be removed through pumping or evaporation.

To accommodate this, New Orleans is equipped with a dense network of effective pumping stations. These stations however, unintentionally drain groundwater through the storm drainage system in both wet and dry days. The pumps ensure that, during dry periods, there is a low water level in the culverts and pipes, in preparation for future rain events. When a certain minimum water level is reached in the pumping station basins, the pumps are activated. In dry periods, the low water level in the pipes and culverts drain groundwater and in wet periods, the rapid groundwater rise increases the pressure on the pipes causing extra groundwater drainage through the storm system.

Groundwater drainage lowers the groundwater level which in turn causes the peat and clay subsurface soil to dry out and settle resulting in the subsidence of the ground surface level [Stuurman, 2020b]. This process has now turned into a destructive cycle in which pumping causes subsidence which then necessitates increased pumping capacities in order to keep the land dry, leading to further subsidence. As subsidence occurs at different rates throughout the region depending on soil and groundwater conditions, many fractures, cracks and sinkholes can be found in roads, parking lots and patios [Living With Water Blog, 2020].

It is known that next to the groundwater - storm drainage system interaction, there is also an interaction between groundwater and other water infrastructures like the sanitary sewer system and the drinking water network. Due to the age of the sewer network as well as damage caused during hurricane Katrina, the system suffers from draining lines [Stuurman et al., 2013]. A significant portion of the wastewater treatment plant influent is groundwater drained through sewer pipes enhancing the ground subsidence and also burdening the wastewater treatment plant. The interaction between groundwater and drinking water is opposite as to the ones explained so far. Here, drinking water leaks into the ground, wasting a portion of the produced water and money.

The goal of this study is to get a better understanding of the current groundwater drainage in New Orleans. This will be achieved by studying the interactions between groundwater and other systems and then quantifying the groundwater drainage within these interactions.

In Chapter 2, an overview of the study region and its characteristics will be given after which the groundwater behaviour of several groundwater monitoring wells will be mapped out in Chapter 3. The following four chapters will analyze the interaction between groundwater and a specific process. Chapter 4 will look at the groundwater - sanitary sewer system interaction, Chapter 5 at the interaction between groundwater and the storm water drainage system and finally, Chapter 6 will examine the groundwater and drinking water interaction. The research will be concluded in Chapter 7, in which a quantitative overview will be given with the groundwater drainage processes and a brief recommendation for future studies will be given.

2
Research area

The three parishes of the Greater New Orleans can be split up into five different basins: the Jefferson Basin, the Hoey Basin the Orleans Metro Basin, the Orleans East Basin, and the St. Bernard Basin, see Figure 2.1. Each basin having their own water systems and urban typologies [Stuurman et al., 2013]. Within these basins, there are more than 40 sub-basins separated by both hydraulic and hydrologic boundaries [Dolman, 2013].

Within this study, only three parts of the Greater New Orleans will be analysed: Orleans Metro, Orleans East, and the western part of St. Barnard; the Lower Ninth Ward and Holy Cross neighbourhoods (further referred to as Lower Ninth Ward). The location and size of these catchments can be seen in Figure 2.2. These regions, as well as the Algiers neighbourhood on the West Bank of the Mississippi, are under the responsibility of the Sewerage and Water Board of New Orleans (SWBNO). Algiers will however not be examined in this study as most data collected concerns only the East Bank.

The Orleans Metro basin stretches between the 17th Street Canal in the west till the Inner Harbour Navigation Channel (IHNC) in the east. The water system in this basin is made up of a network of underground canals and culverts in which seventeen pumping stations are in charge of draining the region [Dolman, 2013].

The Orleans East basin is surrounded by the Intracoastal Waterway to the south and the Bayou marshlands to the east. The Orleans East basin contains a series of open canals and nine pumping stations which drain water into the lake or into the Intracoastal Waterway [Dolman, 2013].

The final, smallest catchment, the Lower Ninth Ward, is a section of the St. Bernard basin which is part of the Orleans Parish and, like the Orleans Metro basin, has underground pipes and culverts that drain the water into the IHNC. The rest of the St. Bernard basin, pumps water into the Central Wetlands Unit through open canals. There are eight pumping stations in the whole St. Bernard basin [Dolman, 2013].

Figure 2.1: Catchments of Greater New Orleans

Figure 2.2: Catchments being analyzed in this study

Within the Greater New Orleans, sandy deposits from the Mississippi River form a shallow aquifer near the river. Another important shallow aquifer is found in the northern part of the city and is formed by buried beach sand, the Pine Island Barrier. The first aquitard found under the aquifer is an impermeable consolidated clay layer that lies about 65 to 100 feet (20m to 30m) below the Mississippi River surface and rises to a depth of 50 feet (15m) towards the lake. It is formed by the Prairie Formation. On the north shore of the lake, the Prairie Formation tapers out as it moves inland [Stuurman et al., 2013]. See Figure 2.3 to see the north-south geological transect.

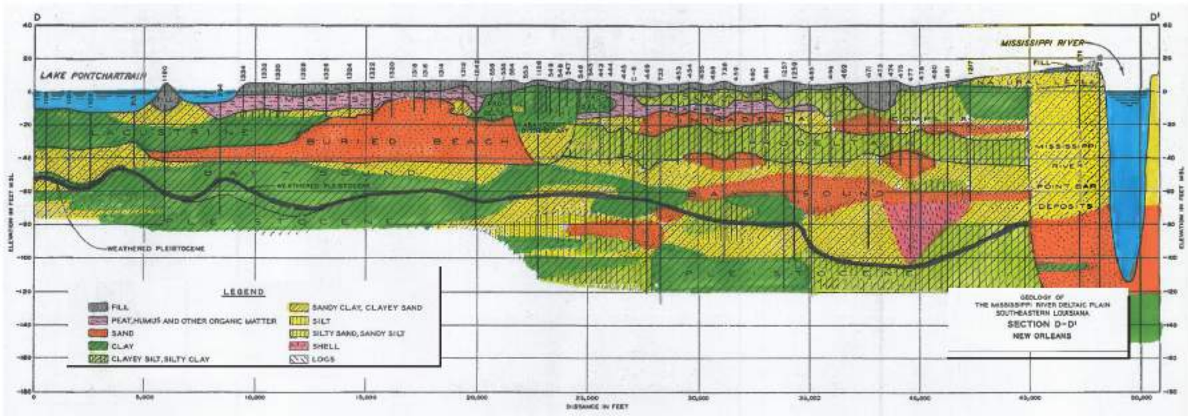

Figure 2.3: Detailed north-south geological transect [USACE, 1958] *color overlay by Deltares*

2.1. Precipitation

Using data obtained from the the National Oceanic and Atmospheric Administration's database [NOAA, 2020], the total yearly precipitation between the years of 2015 and 2020 were found, see Table 2.1.

Year	Precipitation [inch/year]	Precipitation [mm/year]
2015	71.34	1812.04
2016	70.34	1789.94
2017	72.42	1839.47
2018	61.59	1564.39
2019	62.53	1588.26
2020	71.75	1822.45

Table 2.1: Yearly precipitation values

2.2. Evaporation

To get an idea of how much evaporation occurs in the system, the Thornthwaite equation for potential evaporation was used. Due to the lack of availability of radiation data, it was not possible to use another method to estimate daily evaporation. The Thornthwaite equation is a simple method which does not need many input variables. The variables needed for this equation are daily average temperatures and the average monthly day length. Furthermore, the Thornthwaite equation has been found to work best for climates similar to the one where it was created, eastern USA, which is fairly appropriate for New Orleans [Karlsson and Pomade, 2006].

The Thornwaite potential evaporation equation gives monthly evaporation in mm and is as follows:

$$E_P = 16 \times \frac{L}{12} \times \frac{N}{30} \times \left(\frac{10 \times T_d}{I}\right)^{\alpha} \tag{2.1}$$

In which L is the average day length of a certain month in hours, N the number of days in that month, Td the average daily temperature of the month in degrees Celsius, I the yearly heat index shown below, and α a constant also shown below.

$$I = \sum_{i=1}^{12} \left(\frac{T_d}{5}\right)^{1.514} \tag{2.2}$$

$$\alpha = \left(6.75 \times 10^{-7}\right) \times I^3 - \left(7.71 \times 10^{-5}\right) \times I^2 + \left(1.792 \times 10^{-2}\right) \times I + 0.49239 \tag{2.3}$$

The daily average temperatures measured at the New Orleans Lakefront Airport between January 2015 until December 2020 were gathered from the National Oceanic and Atmospheric Administration's database [NOAA, 2020]. The hourly average day lengths per month were found on a weather site [Weather Atlas, 2020] and are:

January	February	March	April	May	June	July	August	September	October	November	December
10.50	11.20	12.00	12.90	13.70	14.10	13.90	13.20	12.30	11.40	10.70	10.20

Table 2.2: Average day length per month in hours [Weather Atlas, 2020]

Using the equations and data mentioned above, the monthly potential evaporation values were found. In Table 2.3 an overview of the Thornthwaite values and the sum of the monthly evaporation values can be seen for each year. The average yearly potential evaporation is then 50.71 inches or 1,288.08 mm and can be rewritten to a daily evaporation of 0.14 inches or 3.53 mm.

Year	Heat Index [-]	Alpha [-]	Ep [inch/year]	Ep [mm/year]
2015	122.02	2.76	54.31	1379.42
2016	113.57	2.52	47.79	1213.92
2017	118.07	2.64	49.26	1251.09
2018	118.02	2.64	51.48	1307.50
2019	117.33	2.62	50.88	1292.43
2020	118.58	2,66	50.56	1284.11

Table 2.3: Yearly Thornthwaite potential evaporation values

It must be kept in mind that this is a potential evaporation, which means that it is the evaporation which would occur if a sufficient amount of water were available. This means that the calculated evaporation will overestimate the actual evaporation due to a smaller water availability in dry periods.

2.3. Precipitation surplus

Now that the yearly precipitation and potential evaporation are known, the minimum precipitation surplus can be found. This is equal to the yearly precipitation minus the yearly potential evaporation. The surplus represents the amount of rainwater that will need to be pumped out of the study region on stored in water bodies and the ground. In Table 2.4, the yearly surpluses can be found.

Year	Precipitation surplus [inch/year]	Precipitation surplus [mm/year]
2015	17.03	432.62
2016	22.68	572.02
2017	23.16	588.38
2018	10.11	256.89
2019	11.65	295.83
2020	21.19	538.34

Table 2.4: Yearly precipitation surplus

Over the six years of data, the average yearly precipitation surplus is equal to 17.64 inches (448.01mm). This is a huge amount of precipitation that needs to be processed by the pumping stations and the subsurface storage.

3
Groundwater behaviour

The groundwater system in the Greater New Orleans is recharged naturally by both surface waters and precipitation and artificially by leakages from the drinking water system [Stuurman et al., 2013]. In the northern part of the Orleans Metro catchment, groundwater recharge comes from Lake Pontchartrain and canals in open connection to the lake; the London Avenue Canal, the Orleans Canal, the IHNC, and the 17th Street Canal. A share of this groundwater is brackish, due to the brackish nature of Lake Pontchartrain and the resulting brackish nature of the connected canals, see Figure 3.1. In the southern part of the catchment, the groundwater is recharged by the fresh watered Mississippi River.

Within the whole catchment, shallow groundwater is drained through underground pipe systems, both storm water and sanitary sewer systems (further referred to as sewer systems) and through evaporation [Stuurman, 2020a]. Due to this drainage, the groundwater will drop down to a drainage level; a groundwater steady state level which is controlled by leaking storm water and sewage pipes. Groundwater enters the pipes at pipe connections, open connections, passing through geotextile slabs or through cracks [Stuurman et al., 2013]. See Figure 3.2.

The three pipe networks; drinking water network, sewer network, and storm water drainage network, are located at different depths. The drinking water network is in general the shallowest. The storm water drainage pipes and the sewer pipes are found relatively close together deeper in the ground, with the sewer system usually being located the deepest [Stuurman, 2016].

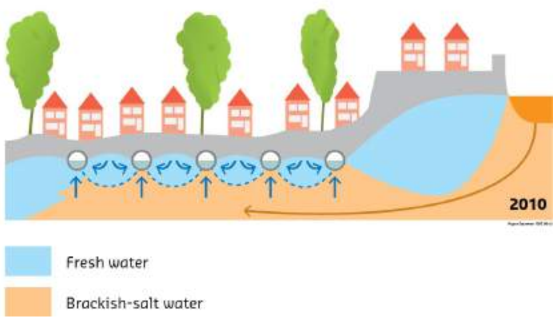

Figure 3.1: Brackish groundwater flowing from the lake towards the lower Gentilly area [Stuurman et al., 2013]

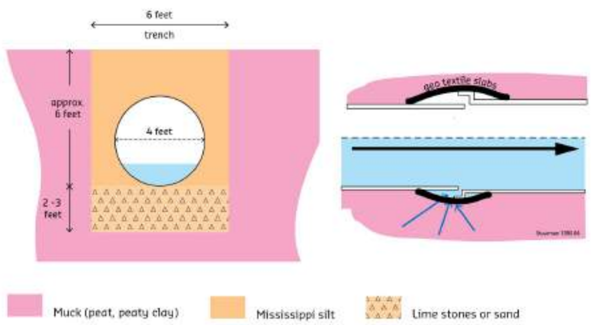

Figure 3.2: Groundwater drainage through sewage and storm water drainage pipes [Stuurman et al., 2013]

How fast groundwater drains is currently unknown and is critical information needed in order to analyze the impact of water storage on the surrounding area [Stuurman, 2020a]. A better understanding of the drainage mechanism can be found by examining the influence of groundwater drainage in relation to underground infrastructure proximity. Furthermore, studying the homogenousness of groundwater drainage rate due to precipitation events of varying intensities is crucial in getting a better understanding of the drainage mechanism. During rainstorms, the groundwater levels will quickly rise, after which, the level will drop down again to the drainage level influenced by the drainage systems, as can be seen in Figure 3.3. During high groundwater levels, there is more drainage into the underground infrastructure and as the groundwater levels subside, the groundwater drainage also drops back down to the base flow. In 2012, hourly groundwater level measurements were taken in the Garden District, see Figure 3.4. In this graph, the rapid groundwater rise and fall can clearly be seen as well as a drainage level.

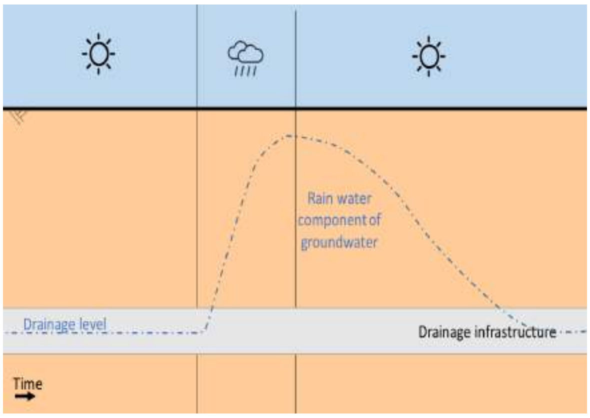

Figure 3.3: Groundwater variation due to precipitation and groundwater drainage

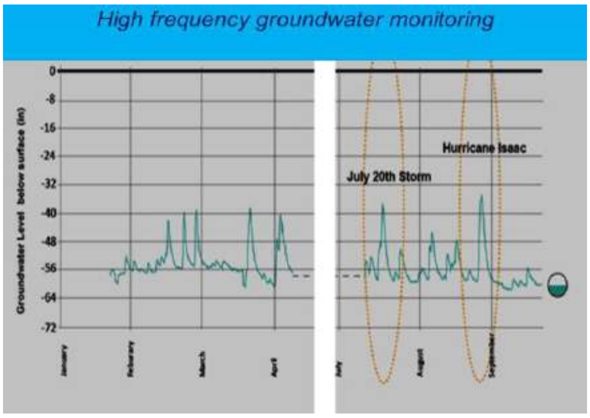

Figure 3.4: Groundwater fluctuation in monitoring well in the Garden District from 2012 [Stuurman, 2021b]

3.1. Method

In this section, groundwater level time series for numerous monitoring wells by the park on Mirabeau Avenue, the St. Anthony neighbourhood, and in the Irish Channel neighbourhood will be analysed during different precipitation events. The location of the different monitoring wells can be seen in the Figure 3.5. Each of the three locations have different attributes. The Mirabeau Avenue wells are located in a park and so surrounded by a large green area, the St. Anthony wells are located in a tightly built up area and the Irish Channel well is found at close proximity to the Mississippi River.

During the precipitation event, the groundwater level will increase after which it will start descending back to the drainage level, due to groundwater drainage. For the three locations, different, independent, precipitation events will be examined and for each event the following characteristics will be identified:

- the intensity of the precipitation event,
- the maximum groundwater level during the precipitation event,
- the time needed for the groundwater to return to the drainage level,
- the rate at which the groundwater returns to the drainage level.

Using these characteristics, along with the depth of the groundwater drainage level, the depth of the storm drainage infrastructure and the distance between the monitoring wells and the existing drainage infrastructure, it will be possible to make a conclusion about the significance of the infrastructures influence on groundwater drainage. If it turns out that there is a homogeneous relationship between the drainage behaviours, a hydraulic formula will be made linking the time needed for the ground level to return to the drainage level and the precipitation events of varying magnitudes.

3.2. Results

The characteristics gathered for each monitoring well can be seen in Table 3.1. These characteristics include the distance to the closest drainage system, the groundwater drainage level, the ground surface level, and the invert level of the storm water drainage pipes. The invert level is the bottom level of the inside of the drainage pipe. The sewer system depths will not be examined as the exact depths are unknown, however, the sewer system is generally located deeper than the storm drainage system [Stuurman, 2016].

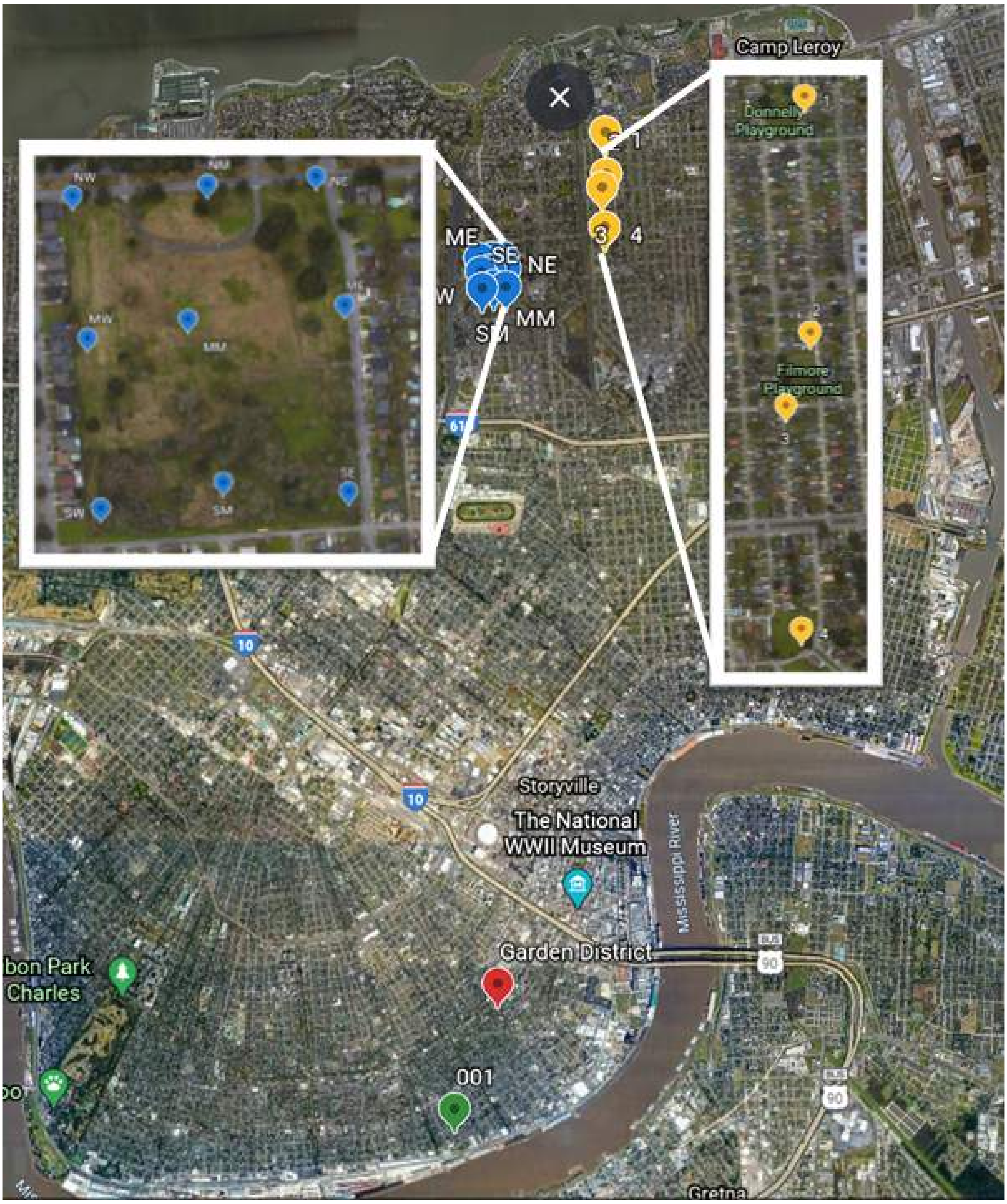

Figure 3.5: Location of the monitoring wells

Well location	Well name	Distance to middle of street [m]	Distance to middle of street [ft]	Closest drain direction	Ground surface level [ft NAVD 88]	Lowest groundwater level [ft NAVD 88]	Drainage level [ft NAVD 88]	Invert level storm drainage pipe [ft NAVD 88]
Mirabeau	NW	15	49,21	N	-8,04	-11,88	-11,15	-10,99
	NM	15	49,21	N	-5,51	-11,84	-11,48	-11,71
	NE	15	49,21	N	-5,91	-12,47	-11,81	-10,00
	MW	50	164,04	W	-5,25	-10,00	-10,00	-10,60
	MM	160	524,93	W	-5,91	-10,99	-10,50	-10.60
	ME	15	49,21	E	-5,41	-11,15	-11,15	-10,00
	SW	20	65,62	S	-3,77	-9,68	-9,68	-9,74
	SM	50	164,04	S	-4,10	-10,17	-9,19	-7,68
	SE	15	49,21	E	-3,44	-10,66	-10,17	-9,84
Irish channel	001	24	78,74	SE	7,47	1,50	2,30	3,97
St. Anthony neighbourhood	1	8	26,25	W	-7,25	-12,5	-12,00	-9,35
	2	13	42,65	E	-6,33	-13,00	-12,50	-12,89
	3	5	16,40	W	-7,12	-13,00	-12,50	-12,24
	4	10	32,81	SE	-5,71	-11,50	-11,00	-9,32

Table 3.1: Monitoring well characteristics

3.2.1. Mirabeau Avenue Park

At the intersection between Mirabeau Avenue and Saint Bernard Avenue there is a large grass field with nine groundwater monitoring wells, see the blue dots in Figure 3.5. For each well, different precipitation events have been identified which had a significant effect on groundwater fluctuation. For each event, the time needed for the groundwater to return to the drainage level, as well as the intensity of the precipitation peak was recorded. See Figures 3.6 till 3.14 for the peak groundwater fluctuations over time and Table 3.2 for the final, numerical, overview.

When looking at Table 3.2, it can be said that in general, the largest stabilization rates occur after the largest precipitation events. However, there is no clear pattern to be found across all precipitation events and monitoring wells linking precipitation intensity to stabilization rate.

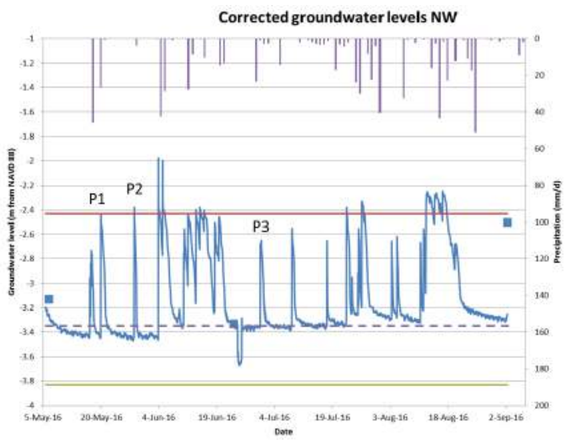

Figure 3.6: NW [Stuurman, 2016]

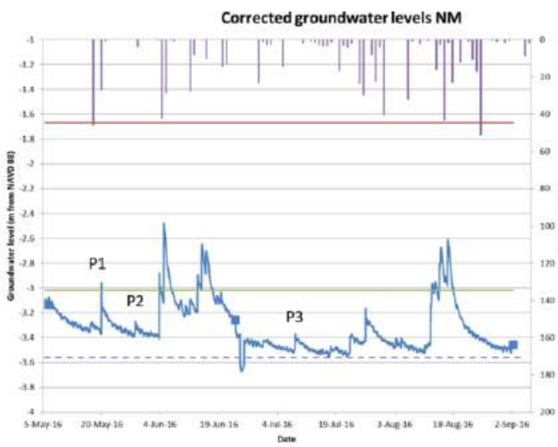

Figure 3.7: NM [Stuurman, 2016]

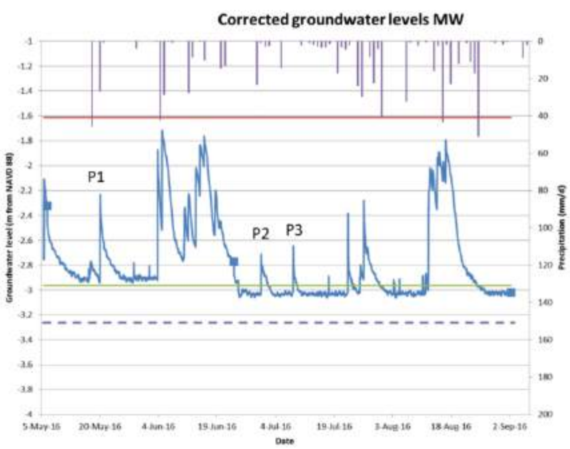

Figure 3.8: MW [Stuurman, 2016]

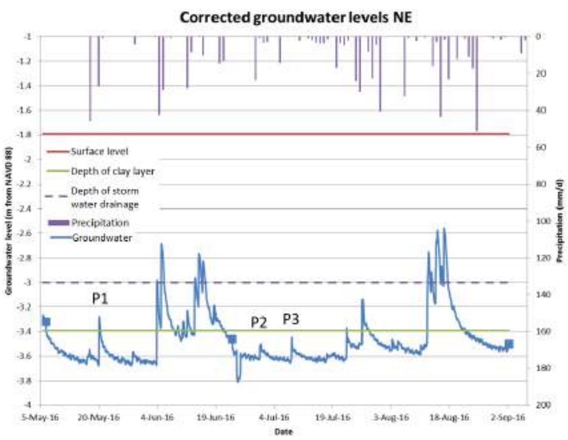

Figure 3.9: NE [Stuurman, 2016]

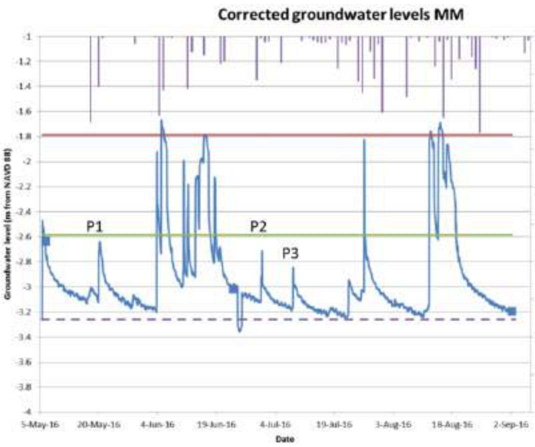

Figure 3.10: MM [Stuurman, 2016]

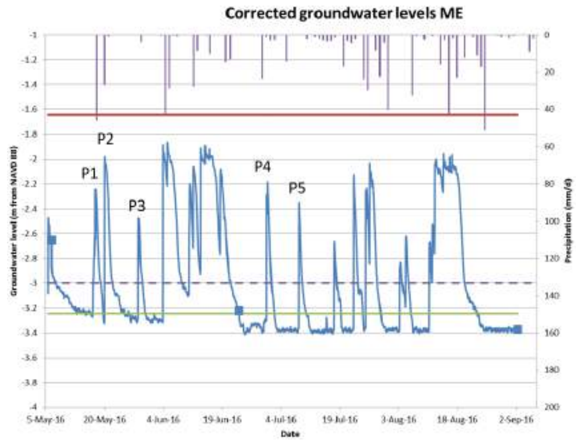

Figure 3.11: ME [Stuurman, 2016]

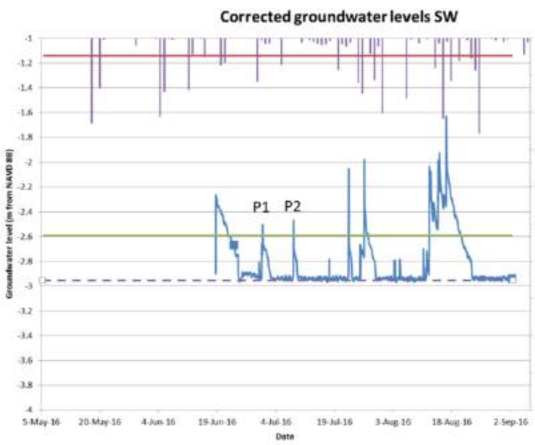

Figure 3.12: SW [Stuurman, 2016]

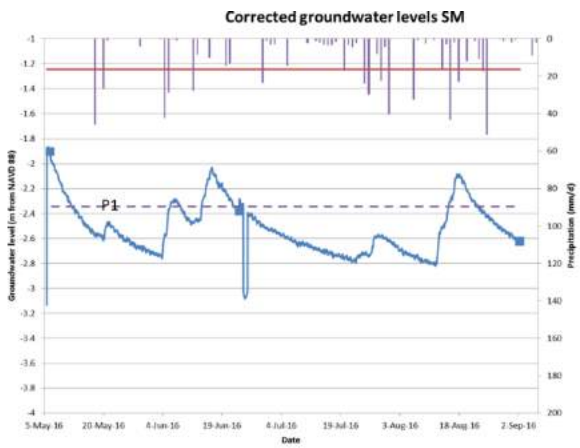

Figure 3.13: SM [Stuurman, 2016]

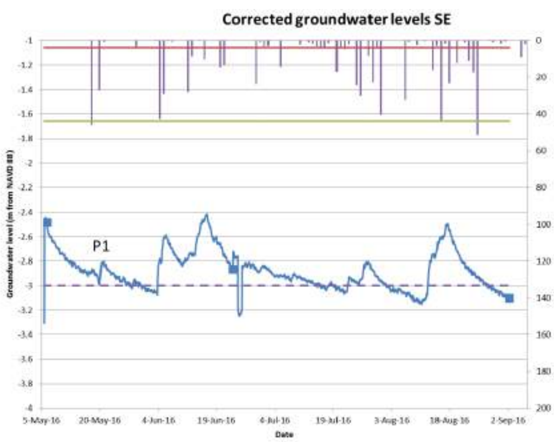

Figure 3.14: SE [Stuurman, 2016]

NW

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,06	27	-7,97	5	0,21
P2	0,16	4	-7,78	1,25	0,13
P3	0,91	23	-9,06	3,75	0,24

NM

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,06	27	-9,68	8,75	0,12
P2	0,16	4	-10,93	3,38	0,05
P3	1,18	30	-11,06	6,5	0,18

NE

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,06	27	-10,73	8	0,13
P2	0,91	23	-11,45	3,5	0,23
P3	0,59	15	-11,25	5	0,11

MW

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,06	27	-7,28	7,5	0,14
P2	0,91	23	-8,89	2,5	0,36
P3	0,59	15	-8,63	2	0,30

MM

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,06	27	-8,63	7,87	0,14
P2	0,91	23	-8,89	7,5	0,12
P3	0,59	15	-9,78	8,25	0,07

ME

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,77	45	-7,35	2,25	0,79
P2	1,06	27	-6,5	6	0,18
P3	0,16	4	-8,1	2,63	0,06
P4	0,91	23	-7,15	2,25	0,40
P5	0,59	15	-7,68	3	0,20

SW

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	0,91	23	-8,17	2,25	0,40
P2	0,59	15	-8,07	1,13	0,52

SM

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,06	27	-8,1	13,75	0,08

SE

	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,06	27	-9,19	7,5	0,14

Table 3.2: Peak rainfall events and the time needed for the groundwater to return to its drainage level for the Mirabeau monitoring wells

3.2.2. Irish Channel Neighbourhood

The Irish Channel is located in the south western part of the city along the Mississippi river, at about 0.4 miles (600m) away from the river, see the green dot in Figure 3.5. Compared to the other two groundwater monitoring regions, the Irish Channel neighbourhood has a much higher ground surface elevation. At the Irish Channel monitoring well, the groundwater level and hourly Mississippi River stage fluctuations were monitored over a time span of about two and a half years, see Figure 3.15. For the groundwater level data points, irregular hand measurements were done.

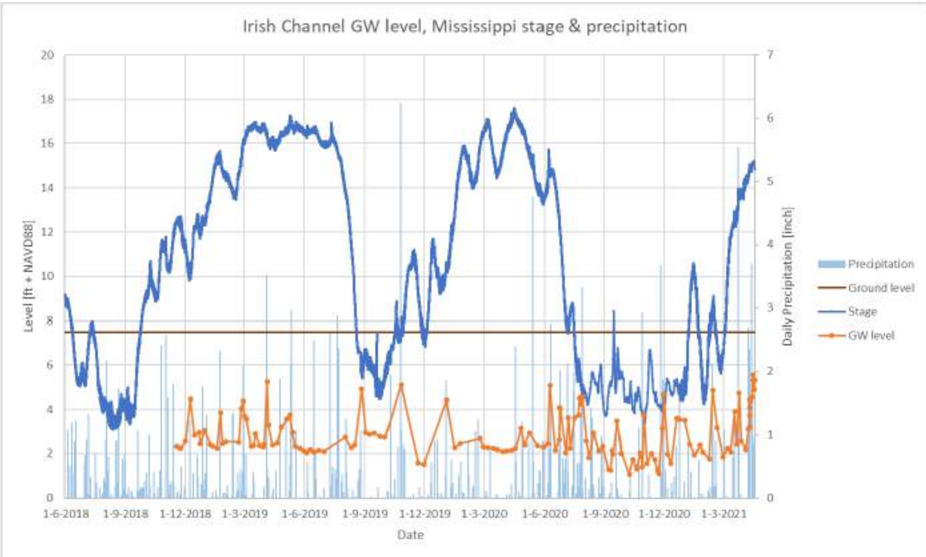

Figure 3.15: Irish Channel ground level, groundwater level, storm drainage depth, river stage (on left axis) and precipitation (on right axis)

The river stage shows seasonal variations, where there is a low level around August and September and a high level around April. When comparing the stage fluctuations to the groundwater level fluctuations, no clear relation can be seen, however, the groundwater levels are always lower. The low groundwater levels that occur around June to July 2019 and March to April 2020, coincide with high river stages. This would suggest that the river stage does not influence the groundwater fluctuation and that only precipitation does. In Figure 3.16, a closer look is taken at the groundwater and precipitation data.

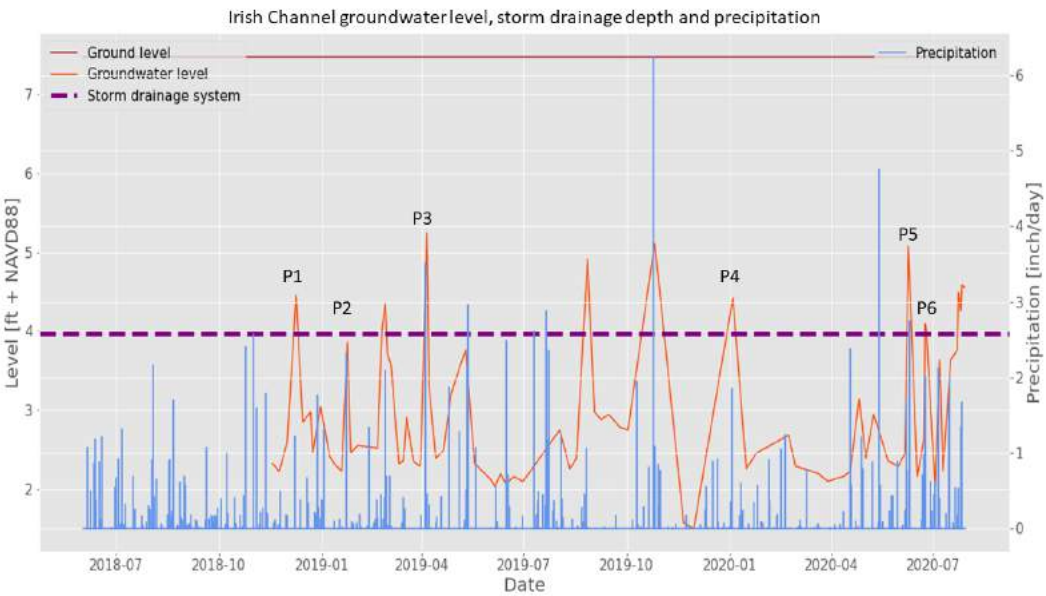

Figure 3.16: Irish Channel ground level, groundwater level, storm drainage depth (on left axis) and precipitation (on right axis)

In the figure, six groundwater peaks can be identified ranging between the 9th of December 2018 till the 6th of July 2020. The numerical overview of the peaks can be seen in Table 3.3.

	001				
	Peak intensity [inch]	Peak intensity [mm]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,22	30,99	4,45	41	0,03
P2	2,32	58,93	3,86	3	0,77
P3	3,52	89,41	5,24	8	0,44
P4	1,85	46,99	4,42	12	0,15
P5	2,75	69,85	5,08	7	0,39
P6	2,01	51,05	4,09	9	0,22

Table 3.3: Peak rainfall events and the time needed for the groundwater to return to its drainage level for the Irish Channel monitoring well

In the Irish Channel, it takes much longer for the groundwater to return to the drainage level compared to the other monitoring well locations. This can be explained by the lack of daily groundwater fluctuation data. For the other two locations it was possible to see exactly when the groundwater level reached the drainage level. For the Irish Channel, as not all data is known, it could be possible that within the time periods assumed in Table 3.3, there were another, earlier moments in which the groundwater reached its drainage level which were not measured.

3.2.3. St. Anthony Neighbourhood

The St. Anthony Neighbourhood is located in the northern part of New Orleans and contains four monitoring wells. The exact location of the wells can be seen in Figure 3.5, when zooming into the orange dots. As opposed to the Mirabeau monitoring wells, here, each well had a significant groundwater fluctuation peak during the same seven precipitation events. The intensity of these peaks and the time needed for the groundwater to return to its drainage level can be seen in Figure 3.17. What stands out when looking at the table and the visual representation of the groundwater fluctuations, is that all four monitoring wells have very similar responses to precipitation.

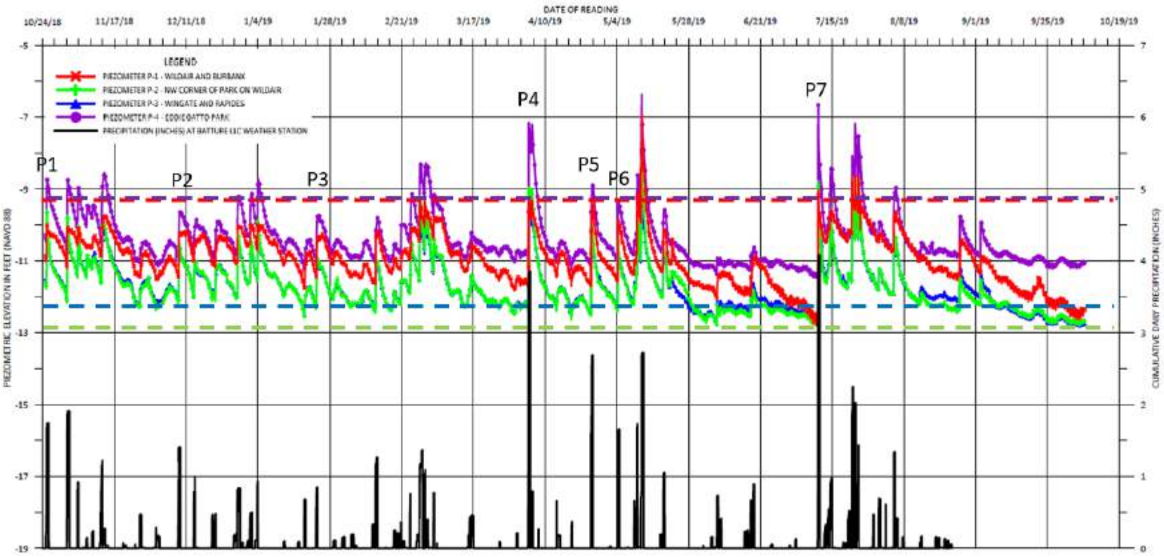

Figure 3.17: St. Anthony groundwater level fluctuation, storm drainage depth and precipitation [Walsh, 2020]

			1			2			3			4		
	Peak intensity [inch]	Peak intensity [mm]	Peak ground water level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]	Peak groundwater level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]	Peak ground water level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]	Peak ground water level [ft NAVD 88]	Time to return to drainage level after peak [days]	Stabilization rate [inch/day]
P1	1,76	44,70	-9,89	5,76	0,31	-9,64	6,72	0,26	-10,12	6,72	0,26	-8,67	6,72	0,26
P2	1,40	35,56	-10,18	3,84	0,36	-10,67	4,8	0,29	-10,85	4,8	0,29	-9,63	3,84	0,36
P3	0,84	21,34	-10,33	3,84	0,22	-10,94	4,8	0,18	-11,05	4,8	0,18	-9,71	4,8	0,18
P4	3,88	98,55	-9,29	8,64	0,45	-8,96	8,64	0,45	-9,27	8,64	0,45	-7,15	8,64	0,45
P5	2,78	70,61	-9,41	7,68	0,36	-9,94	7,68	0,36	-10,54	7,68	0,36	-8,86	7,86	0,35
P6	1,68	42,67	-9,85	4,8	0,35	-10,4	4,8	0,35	-10,75	4,8	0,35	-9,3	4,8	0,35

Table 3.4: Peak rainfall events and the time needed for the groundwater to return to the drainage level for the St. Anthony monitoring wells

3.2.4. Groundwater behaviour

In this final section, the groundwater behaviour will be analysed. At the three locations, the peak intensities and days needed for the groundwater to return to the drainage level were used to find the groundwater drainage rate. The drainage rate is defined as the daily precipitation intensity of the peak divided by the number of days needed for the groundwater to subside back to the drainage level. The groundwater drainage rate and rainfall intensity relationship can be seen in Figure 3.18. Further, the distance between the monitoring wells and the underground drainage infrastructure in the adjacent streets can also be seen in the figure.

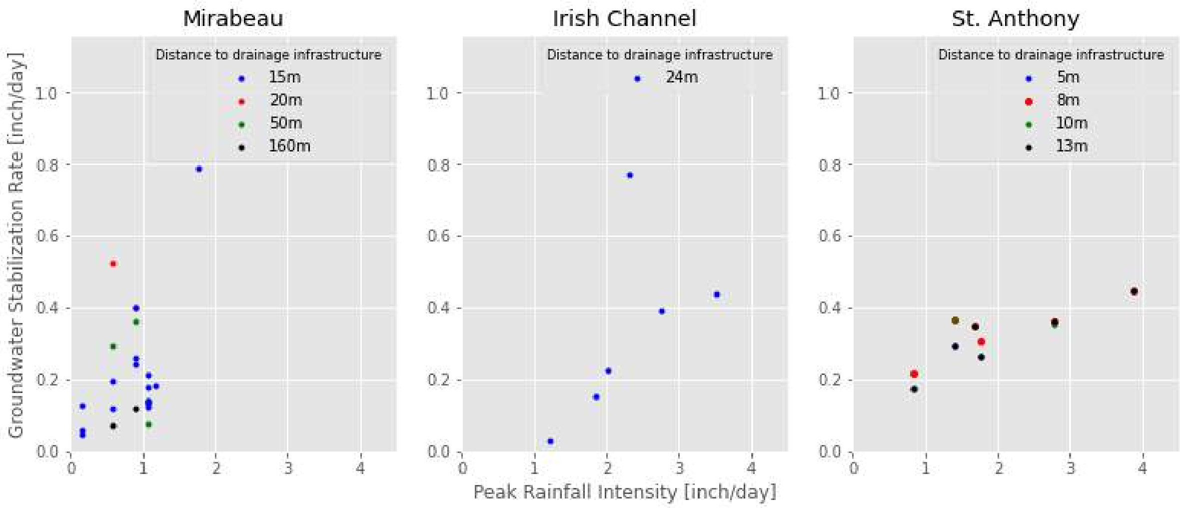

Figure 3.18: Groundwater stabilization rate in relation to peak precipitation events and in relation to distance between monitoring wells and underground drainage infrastructure

Initially two trends were to be expected. Namely:

1. The larger the precipitation event, the higher the groundwater level and so the higher the groundwater stabilization rate.
2. The closer a monitoring well to an adjacent street, the higher the groundwater stabilization rate.

The first point was expected as the larger precipitation event, the higher the groundwater will rise and the greater the pressure will be acting on the drainage pipes, increasing the stabilization rate. For the second point, it was expected that a monitoring well located closer to a street and therefore a drainage system, would drain faster as the groundwater would have to travel a smaller distance.

In Mirabeau, these two trends are not very apparent. Here, the two most elevated points match the expected trends in the sense that the fastest stabilization rate happens during high precipitation events and is measured in monitoring wells located the closest to drainage systems. However, the rest of the points seem to be quite random. For the Irish Channel monitoring well plot, an increase in stabilization rate can be seen for increasing precipitation, however, it would be rash to validate this trend, as there are so few data points available.

When looking at the St. Anthony monitoring wells, there is a clearer relation between stabilization rate and rainfall intensity, however, there is no clear relation between stabilization rate and distance to drainage pipes. Many peak precipitation events have similar groundwater stabilization rates, independent of their proximity to drainage pipes. Though, for each of the four monitoring wells, the distances to the closest streets differ much less than the distances between the Mirabeau wells and the streets.

It can therefore be concluded that the proximity to underground infrastructure does not have a pronounced effect on the stabilization rate of groundwater. There is probably a zone with a high groundwater drainage rate right around the drainage systems after which the groundwater stabilization rate then attenuates and equalises over a short distance.

As stated in Section 3.1, the relationship between the groundwater drainage levels and the depth of the storm drainage infrastructure would also be compared. In Table 3.5, a few of the monitoring well characteristics have been highlighted and the differences between the drainage levels and the depth of the drainage infrastructures have been added. The negative differences signify that the drainage infrastructures are located underneath the groundwater drainage levels.

Well location	Well name	Distance to middle of street [ft]	Invert level storm drainage pipe [ft NAVD 88]	Drainage level [ft NAVD 88]	Difference [ft NAVD 88]
Mirabeau	NW	49,21	-10,99	-11,15	0,16
	NM	49,21	-11,71	-11,48	-0,23
	NE	49,21	-10,00	-11,81	1,81
	MW	164,04	-10,60	-10,00	-0,60
	MM	524,93	-10,60	-10,50	-0,10
	ME	49,21	-10,00	-11,15	1,15
	SW	65,62	-9,74	-9,68	-0,06
	SM	164,04	-7,68	-9,19	1,51
	SE	49,21	-9,84	-10,17	0,33
Irish channel	001	78,74	3,97	2,30	1,67
St. Anthony neighbourhood	1	26,25	-9,35	-12,00	2,65
	2	42,65	-12,89	-12,50	-0,39
	3	16,40	-12,24	-12,50	0,26
	4	32,81	-9,32	-11,00	1,68

Table 3.5: Difference between groundwater drainage level and depth of drainage infrastructure

It must be kept in mind that this difference is between the drainage level and the invert level of the pipe. The tertiary storm drainage pipes have a diameter varying between 1ft (0.30m) to 2.5ft (0.76m) [Stuurman, 2016]. So, for all the boreholes where the invert level of the closest drainage pipe is located under the drainage level (with a negative difference in Table 3.5), the groundwater drainage levels coincide with a section of the drainage pipe.

For all the positive differences in Table 3.5, the bottom of the drainage system is higher than the drainage level. The largest difference between the drainage level and the storm drainage infrastructure is 2.65ft (0.81m), which occurs in the St. Anthony neighbourhood by monitoring well 1. In these situations, the drainage levels are probably lowered by the influence of the sewer systems, which as mentioned previously, lie deeper than the storm drainage systems.

There does not seem to be a relationship between the proximity of the nearest drainage system to the monitoring wells and the difference between the drainage system depth and groundwater drainage level. Monitoring well MM is located the furthest away from a drainage system, but has a very small difference in depth between the pipe and the drainage level. Oppositely, for monitoring well 1, the well is located relatively close to the drainage system, but the difference in depth is large.

An explanation for this is the presence of other storm drainage systems located at other depths. The differences in Table 3.5 are in relation to the closest drainage system, however the groundwater level will also be affected by other drainage systems located further away. This explains why for some monitoring wells which are located close to a drainage system, there is still a large difference between the drainage level and the drainage system depth. There are then more neighbouring drainage systems affecting the drainage level.

To conclude, it can be said that the groundwater drainage level is not only influenced by the depth of the nearest drainage system, but by all of those located near by.

In Section 3.1, it was mentioned that if a homogeneous relationship between the peak precipitation events and the time needed for the groundwater level to return to the drainage level was seen, a hydraulic formula would be made linking these two factors. As mentioned at the beginning of the Groundwater behaviour section, in Mirabeau, there is no clear homogeneous trend between the data points. For the Irish Channel and the St. Anthony points, a clearer trend is seen, with the correlation between the data points being 0.58 and 0.85 respectively. The hydraulic formula for the Irish Channel can be seen in Equation 3.1 and that for St.

Anthony in Equation 3.2.

$$\text{Groundwater drainage Irish Channel [inch/day]} = 0.193 \times \text{precipitation [inch/day]} - 0.1042 \tag{3.1}$$

$$\text{Groundwater drainage St. Anthony [inch/day]} = 0.0709 \times \text{precipitation [inch/day]} + 0.1785 \tag{3.2}$$

The variations between Equations 3.1 and 3.2 show that the sub-surface soil composition has an influence on the groundwater stabilization rate. The soil compositions of both locations displayed in Stuurman [2016] and Walsh [2020] indeed show varying ground compositions.

3.3. Conclusion

The groundwater drops down to the drainage infrastructure depth, but the groundwater drainage level is not only influenced by the depth of the nearest drainage system, but by all of the systems located near by. Additionally, the proximity of drainage infrastructure does not have a strong influence on the stabilization rate of groundwater. In the area directly surrounding the drainage pipes, there is a region with a higher drainage rate, but this quickly attenuates and equalises, making groundwater stabilization rates independent of distance from the drainage systems.

4
Sewer system

There are numerous wastewater treatment plants (WWTP) in the Greater New Orleans region. As explained before, in this study, only the Orleans Metro basin, Orleans East basin, and the Lower Ninth Ward are examined. The wastewater produced in these three regions flows into the East Bank WWTP. The sewer system is a gravity collection system in which the sewage flows through the mains under gravity. Throughout the system, there are various sewer pumping stations (SPS) that lift the sewage back up to a higher level for continued gravity flow towards the treatment plants. The wastewater pumping stations are both automatically and manually operated [SWBNO, 2017]. In Figure 4.1, the East Bank WWTP, as well as the sewer pipelines and the SPS can be seen.

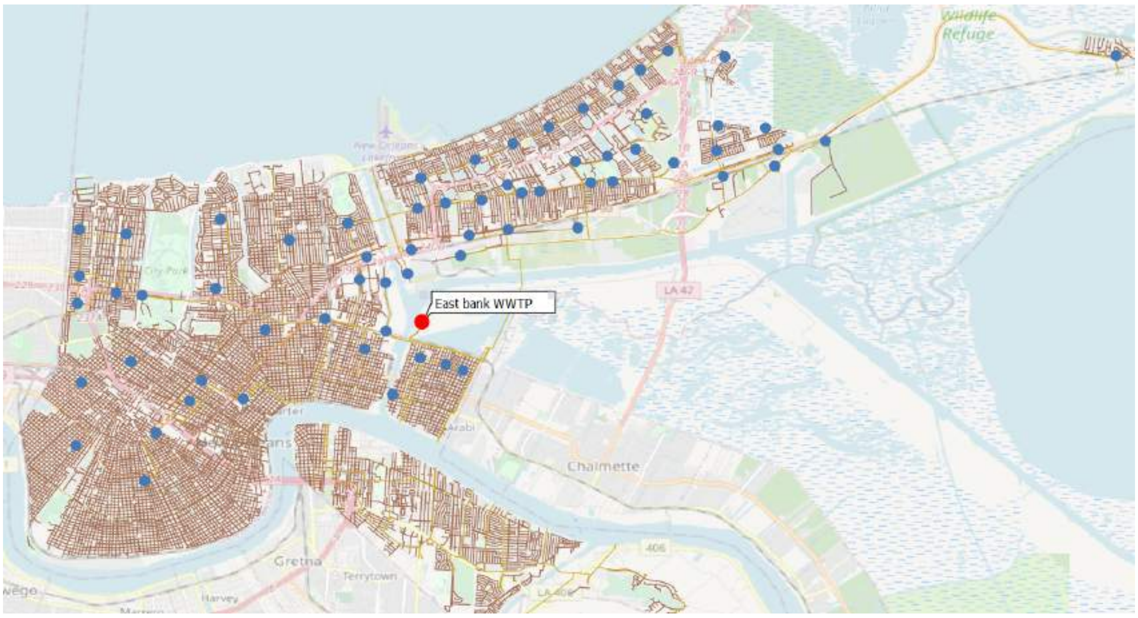

Figure 4.1: East Bank sewer system map

Ideally, the sewer system would only transport industry and household wastewater and there would be no groundwater drainage into this system. However, the New Orleans sewer system is in poor condition. The system suffers from draining lines, insufficient pumping capacity, and deteriorating equipment. During wet days, the treatment plants treat considerably more influent than during dry periods, due to the extra groundwater pressure acting on the sewer pipes and draining into the system [Stuurman et al., 2013]. In addition, illicit connections and damages to the pipe system contribute to this phenomena. In this study however, it is assumed that the larger influent during wet days is related to extra groundwater drainage.

In this chapter, the dry weather and wet weather groundwater water drainage through the East Bank WWTP sewer system will be examined and evaluated.

4.1. Method

To start off, a QGIS model of the East Bank WWTP sewer system developed by Stantec will be used to look at the dry weather scenario. The dry weather groundwater flow entering the sewer system per sub-catchment is programmed in the model. From here on out, this dry weather groundwater flow will be referred to as the base flow.

By plotting the daily WWTP influent received from the SWBNO, the dry weather WWTP influent will be found. This will be equal to the lowest occurring influent value over the two years of data. This dry weather influent has two components: 1) the groundwater base flow and 2) the sanitary flow. In reality, there will be a daily and seasonal variation to both these flows and the dry weather flow will fall within a certain range, however, in this study the estimated dry weather influent will be taken as the lowest occurring influent value.

To find the amount of extra groundwater drained through the sewer system during wet periods, the dry weather influent needs to be subtracted from the measured influent values:

$$\text{Wet Weather Groundwater Flow} = \text{WWTP Influent} - \text{Dry Weather Influent} \tag{4.1}$$

The wet weather groundwater flow is caused by storm water leaking into the sewer system via manholes, illicit connections and damaged pipes.

4.2. Results

Using the QGIS sewer model, the base flow for each catchment within the study region was found. Across the three catchments, this was equal to a total of 43.81 MGD or 15.99 billion gallon per year (60.5 million m^3/year). The distinction of base flows per catchment can be seen in Figure 4.2.

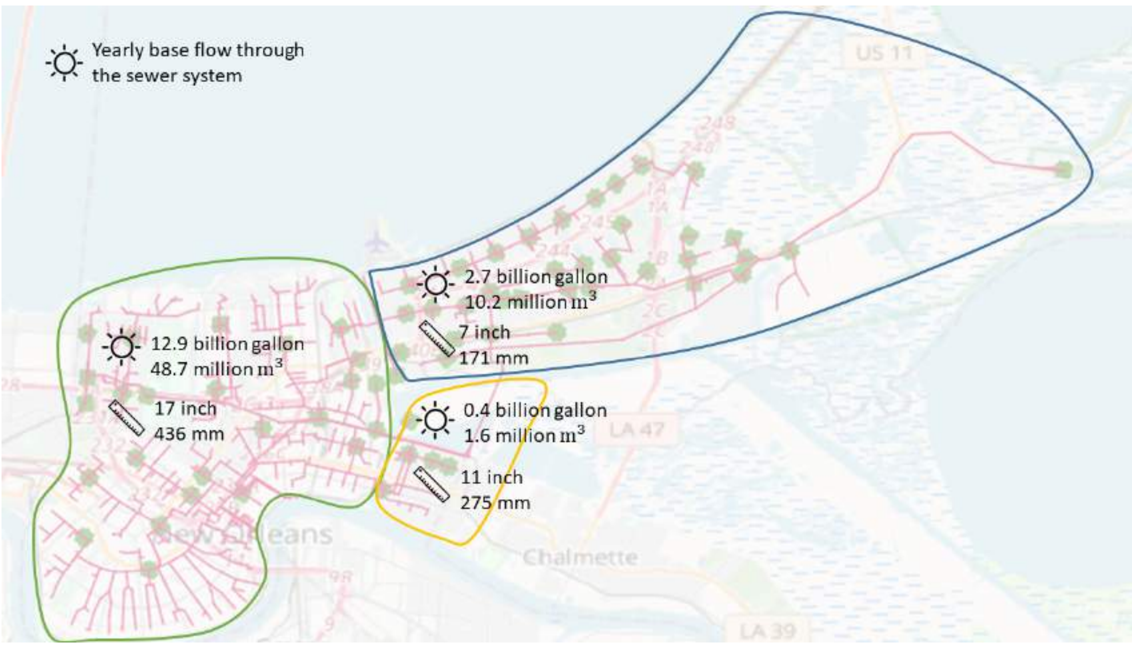

Figure 4.2: Yearly base flow to the East Bank WWTP based on Stantec model

In Figure 4.3, the data received from the SWBNO was plotted and the daily East Bank WWTP influent along with the measured daily precipitation over a time span of two years can be seen. It can be seen that there is a distinct influent fluctuation, implying a strong response in the WWTP influent to precipitation. In other words, during wet periods, the water entering the sewer system increases as explained above due to extra water pressure on the sewer pipes.

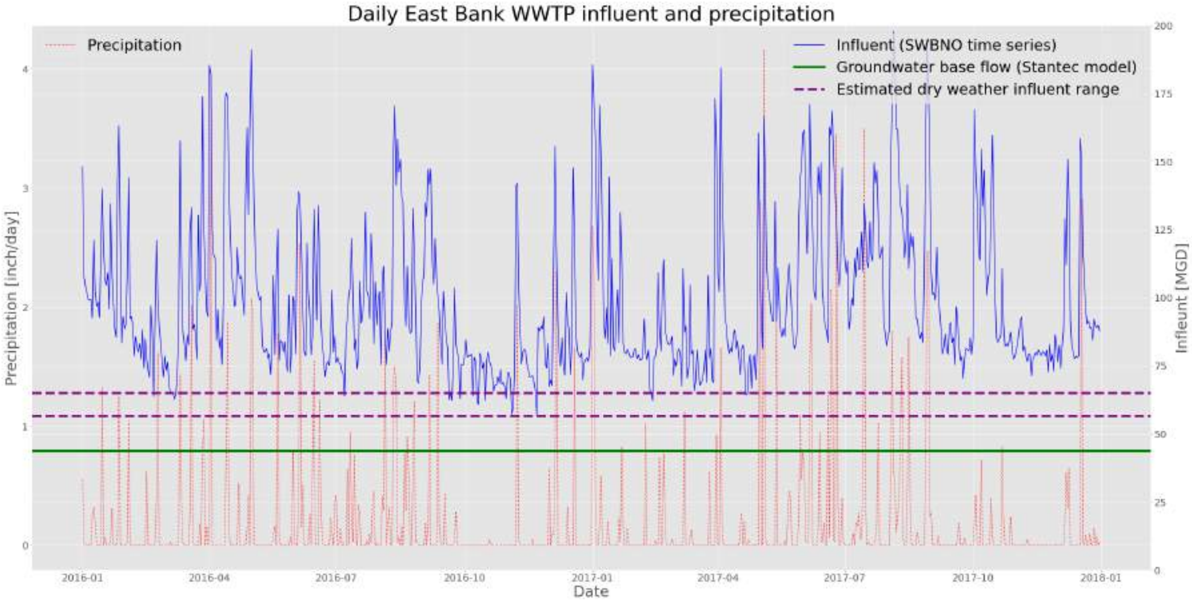

Figure 4.3: Daily WWTP influent and daily rainfall

The range between the purple lines in Figure 4.3 represents the average dry weather influent and the green line the modeled base flow. As stated above, the groundwater drainage in this study will be calculated in terms of the lowest estimated dry weather influent value. The difference between the WWTP influent values and the lowest dry weather influent line is the groundwater drainage that occurs during wet periods. Across 2016 and 2017, this adds up to about 30,000 million gallons, which is an average of 41.62 MGD or 15.19 billion gallons per year (57.5 million m^3/year). The distribution per region can be seen in Figure 4.4.

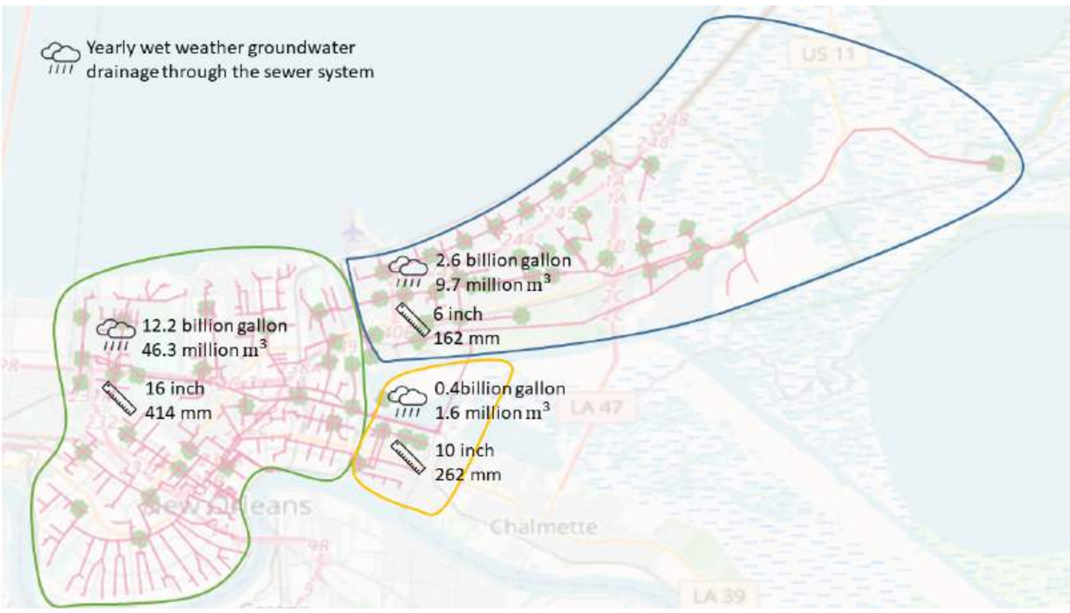

Figure 4.4: Yearly wet weather groundwater drainage

When zooming into a dry period, small daily fluctuations can be seen, see Figure 4.5. These fluctuations can be explained by the daily variation in sanitary flow. On the 8th of November 2016, a large jump in the WWTP influent can be seen and can clearly be linked to the precipitation that occurred that day. The rapid response between precipitation and WWTP influent can also clearly be seen when zooming into a wet period, see Figure 4.6. Here, the WWTP influent fluctuations are much more substantial than the ones seen in Figure 4.5.

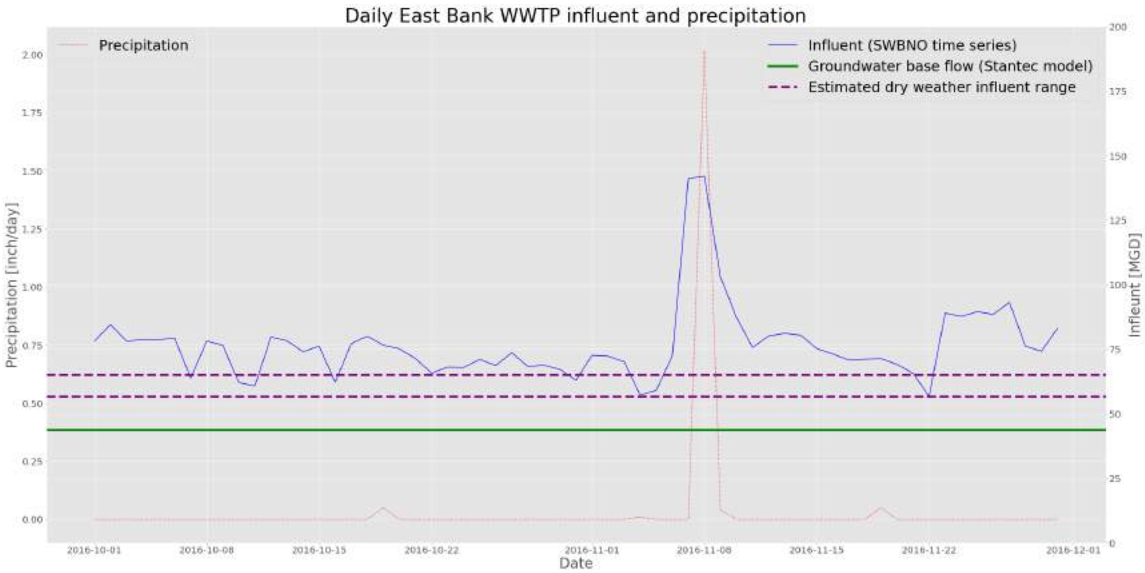

Figure 4.5: Daily WWTP influent during a dry period

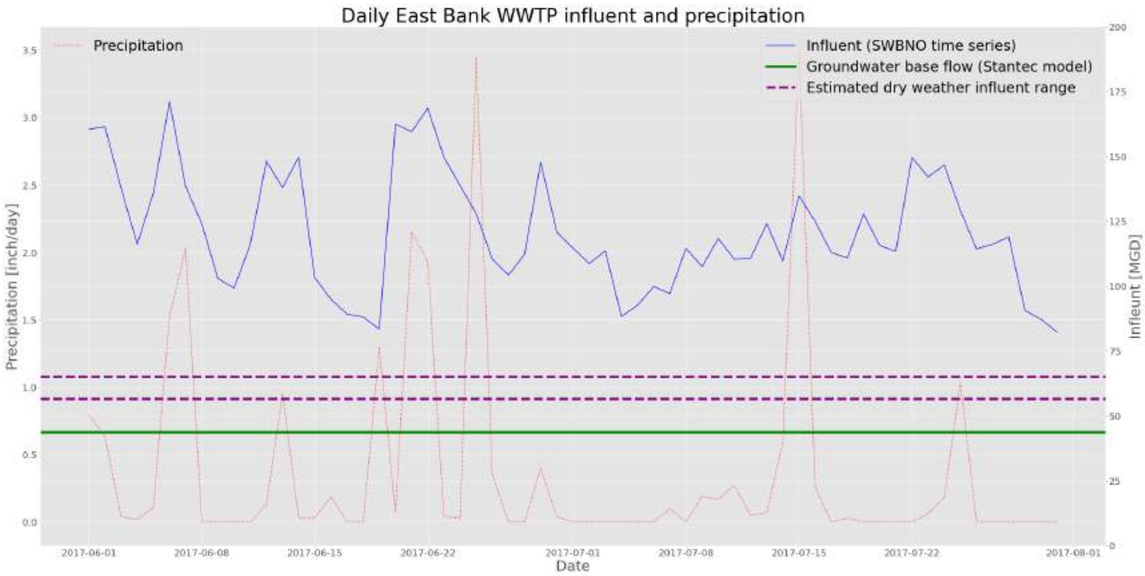

Figure 4.6: Daily WWTP influent during a wet period

4.3. Conclusion

In total, the yearly base flow and wet weather groundwater flow add up to 31.18 billion gallons (115 million m^3/year) of groundwater drained through the sewer system per year. The numerical overview of the different flows can be seen below in Table 4.1. This is a huge amount of water which is transported to the WWTP, adding unnecessary stress to the treatment system. In some cases, during exceptionally large storms, wastewater is discharged without treatment [Stuurman et al., 2013]. The permitted WWTP capacity is 122 MGD (461,829 m^3/day) [SWBNO, 2017].

Region	Yearly base flow				Yearly wet weather groundwater drainage				Yearly total groundwater flow			
	[billion gallon]	[million m3]	[inch]	[mm]	[billion gallon]	[million m3]	[inch]	[mm]	[billion gallon]	[million m3]	[inch]	[mm]
Orleans Metro	12.86	48.68	17.16	435.94	12.22	46.26	16.31	414.25	25.08	94.94	33.47	850.19
Orleans East	2.70	10.22	6.73	170.85	2.56	9.69	6.38	161.99	5.26	16.60	13.10	332.84
Lower Ninth Ward	0.43	1.63	10.84	275.21	0.41	1.55	10.33	262.41	0.84	3.18	21.17	537.62
Total study region	15.99	60.53	13.43	341.19	15.19	57.50	12.76	324.12	31.18	114.72	26.19	665.31

Table 4.1: Overview of different sewer system flows per catchment

5
Storm water drainage system

Storm water drainage is very important in New Orleans due to the city's bowl like shape and the vast area covered in pavement. Nearly all precipitation falling into the city has to be directly pumped out as it cannot naturally drain out of the area through gravity and the paved surfaces cannot soak up and store rain. This results in rain water quickly flowing into the drainage systems. Currently, rain water is drained into catch basins, which is then transported through drainage pipes to the closest interior drainage pumping station (DPS) by storm water pumps [Adelson, 2017]. When it is not raining, constant duty pumps remove "dry weather flow" which can be due to [SWBNO, 2021a]:

- forecasted rain,
- run-off from irrigation,
- run-off from outdoor residential use,
- drainage ingress from water leaks.

Before a big forecasted storm, the constant duty pumps are turned on to lower the basin level and increase storage capacity within the storm water drainage system. Within the study region there are nine constant duty pumps on the East Bank: eight within the Orleans Metro catchment and one in the Lower Ninth Ward. At the smaller pumping stations, constant duty pumps are automated, while the constant duty pumps at the larger pumping stations are manually controlled by operators [SWBNO, 2021a].

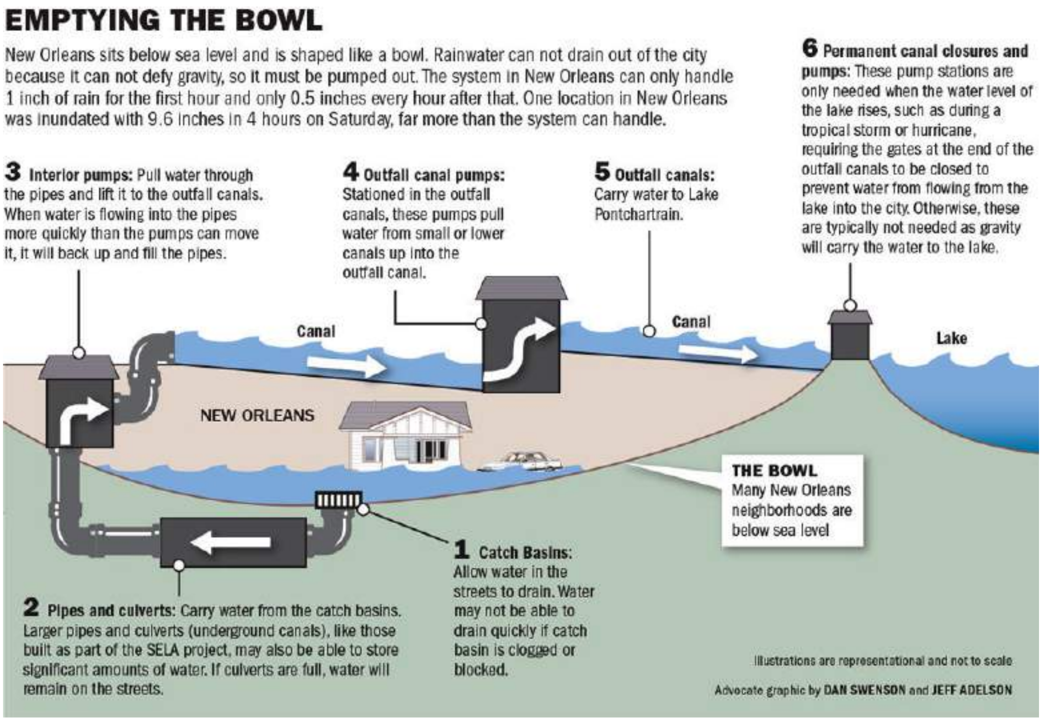

Figure 5.1: Explanation of storm water drainage system [Adelson, 2017]

In Orleans Metro, the DPS's either send water through outfall canals directly to Lake Pontchartrain or to the IHNC. In Orleans East, the northern part of the catchment discharges storm water into the lake and the southern part into the Intracoastal Waterway. Then finally, the Lower Ninth Ward discharges its storm water into the IHNC [Stuurman et al., 2013]. In Figure 5.1 a graphical overview is given of the storm water drainage system. Most of the constant duty pumps send water to a station in the middle of the city, via small canals and pipes, which then pumps that water to the river [SWBNO, 2021a].

The DPS's are manually operated. As water levels in the basins rise due to precipitation, the operators turn on the pumps to lower the water level. The operators of each pumping station choose which pumps to turn on and for how long depending on the severity of the precipitation [Mixed Media, 2019]. In Figure 5.2, data has been collected for the DPS 1 basin. The blue line shows the fluctuation regime of the pressure in the basin. From this line it is clear that the operators try to keep a constant water level in the basin as there are small fluctuations around a certain base level. The green line shows the temperature variation of the water in the basin. A clear seasonal trend can be seen here, where the water is colder during the winter months. Lastly, the red line represents the conductivity of the water. The average water conductivity is around 0.5mS/cm, revealing the presence of water with an origin other than rainwater. Rainwater has a lower conductivity of about 50 μS/cm or 0.05 mS/cm [Zolotkov, 2021].The conductivity in the basin then normally corresponds to the conductivity of groundwater. When it rains, the basin conductivity goes down due to the lower conductivity of rain. These downward facing peaks during rain events can be seen in the figure.

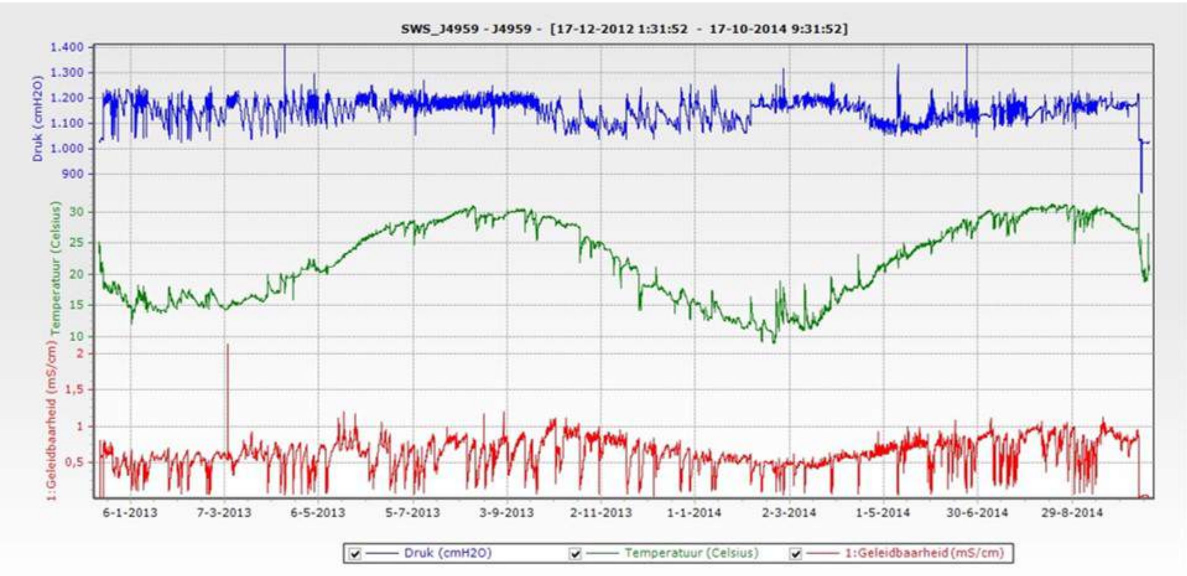

Figure 5.2: Storm water basin characteristics of DPS 1. From top to bottom: Pressure [cm water], temperature [°c] and salinity [mS/cm], [Stuurman, 2021a]

Due to both the damaged state of the drainage system pipes and the method of construction, the storm water drainage system drains a significant amount of groundwater [Stuurman et al., 2013]. This continuous groundwater drainage, as explained earlier in the report, results in land subsidence. In this chapter, a closer look will be taken at the storm drainage processes of DPS 1 and 4, both situated in Orleans Metro, see Figure 5.3. An estimate will be made of the amount of groundwater drained by the storm drainage system within the whole study area. In this chapter, a distinction will be made between groundwater drained through the storm water pumps and through the constant duty pumps.

5.1. Method

Firstly, the storm water discharges of DPS 1 and 4 will be examined. Using data-sets provided by SWBNO with daily pumping station discharges between the 5^{th} of May 2018 till the 22^{nd} of September 2020, the precipitation-discharge relationship will be analysed. This will include the use of hydrographs to find the run-off response rate, as well as using an impulse-response relation to justify the discharge from the precipitation.

Figure 5.3: Drainage pumping stations across study region

In this chapter, it will be assumed that only precipitation falling on paved surfaces enters the storm water drainage system, with the rest being stored within the system. In reality, during heavy rain events, the unpaved areas also contribute to the storm water run-off. However, over the two years of available rainfall data, 85% of the hourly precipitation is smaller than 0.18 inch per hour (4.57mm/hour), which can be classified as a moderate rain event [American Meteorological Society, 2012]. Using the total area would be more realistic for the 15% highest rain events. This would however, overestimate the yearly storm water run-off contribution, as during the majority of the rainy days there is a moderate amount of precipitation in which only the paved areas contribute to the storm water run-off.

Then, the ideal storm water drainage discharges of the pumping stations will be compared to their actual discharges. Here, the ideal storm water discharge is defined as the pumping station discharge that is caused only by precipitation that has fallen onto paved surfaces. The comparison will be visualised by plotting the ideal and actual discharges against precipitation for each pumping stations. The formula that will be used to calculate the ideal storm water drainage is:

$$\text{Pumping station discharge} = \text{Paved area} \times (\text{Daily rain - Daily evaporation}) \tag{5.1}$$

As shown in Chapter 2, the average daily evaporation was found to be 0.14 inches per day (3.53mm/hour). Rewriting Equation 5.1 so that the discharge is expressed in million gallon gives:

$$Q = \frac{A \times 43560 \times (R - 0.14) \times 0.083 \times 7.48}{10^6} \tag{5.2}$$

In which Q is the daily storm water pump discharge in million gallon, A the paved area in acres, and R the daily rainfall in inches. The paved areas belonging to each pumping station can be seen in Appendix A. In order to find the amount of groundwater seeping into the system through the storm water pumps, the differences between the measured discharges and the ideal discharges for all data points will be summed up.

Finally, the constant duty pumps of DPS 1 and 4 will be examined in order to make conclusions about the behaviour of the constant duty pump systems. An estimate will then be made across the study region of the amount of groundwater drained by the constant duty pumps.

In order to differentiate between rainwater and the other water fluxes that cause the constant duty pumps to turn on, only constant duty pump discharges occurring on dry days will be examined. These discharges will then be made up of:

$$\text{Dry period discharge} = \text{Groundwater drainage} + \text{Irrigation run-off} + \text{Residential run-off} \tag{5.3}$$

Unfortunately, with the data currently available, it will not be possible to make a distinction between the three components shown in Equation 5.3. Only an indication of the groundwater drained by the constant duty pumps can be given as the sum of the dry weather discharges. It must be kept in mind that in reality, the groundwater drained by the constant duty pumps will be lower.

5.2. Results

In Figure 5.4 and 5.5, the daily storm water pump discharges can be seen as well as the daily constant duty pump discharges and daily precipitation for DPS 1 and 4 respectively. The individual yearly plots can be found in Appendix B and Appendix C. At first glance, there seems to be a significant correlation between precipitation and discharge. Most high rainfall events are followed by a high storm water discharge period for both pumping stations. However, when taking a closer look, there are some discrepancies. For DPS 1, there is a dry period between February and March 2019 in which the storm water pumps are on. It was later found that during this period, the constant duty pumps which normally regulate the water level in the drainage canals were under maintenance meaning that they had to be compensated by the storm water pumps [SWBNO, 2021a]. For DPS 4, the tendency of using the storm water pumps during dry periods is also seen, to a lesser extent, between June and July 2019 and July and August 2020. This suggests that the storm water pumps are also pumping water from different sources which could be: irrigation run-off, residential outdoor run-off or drained groundwater.

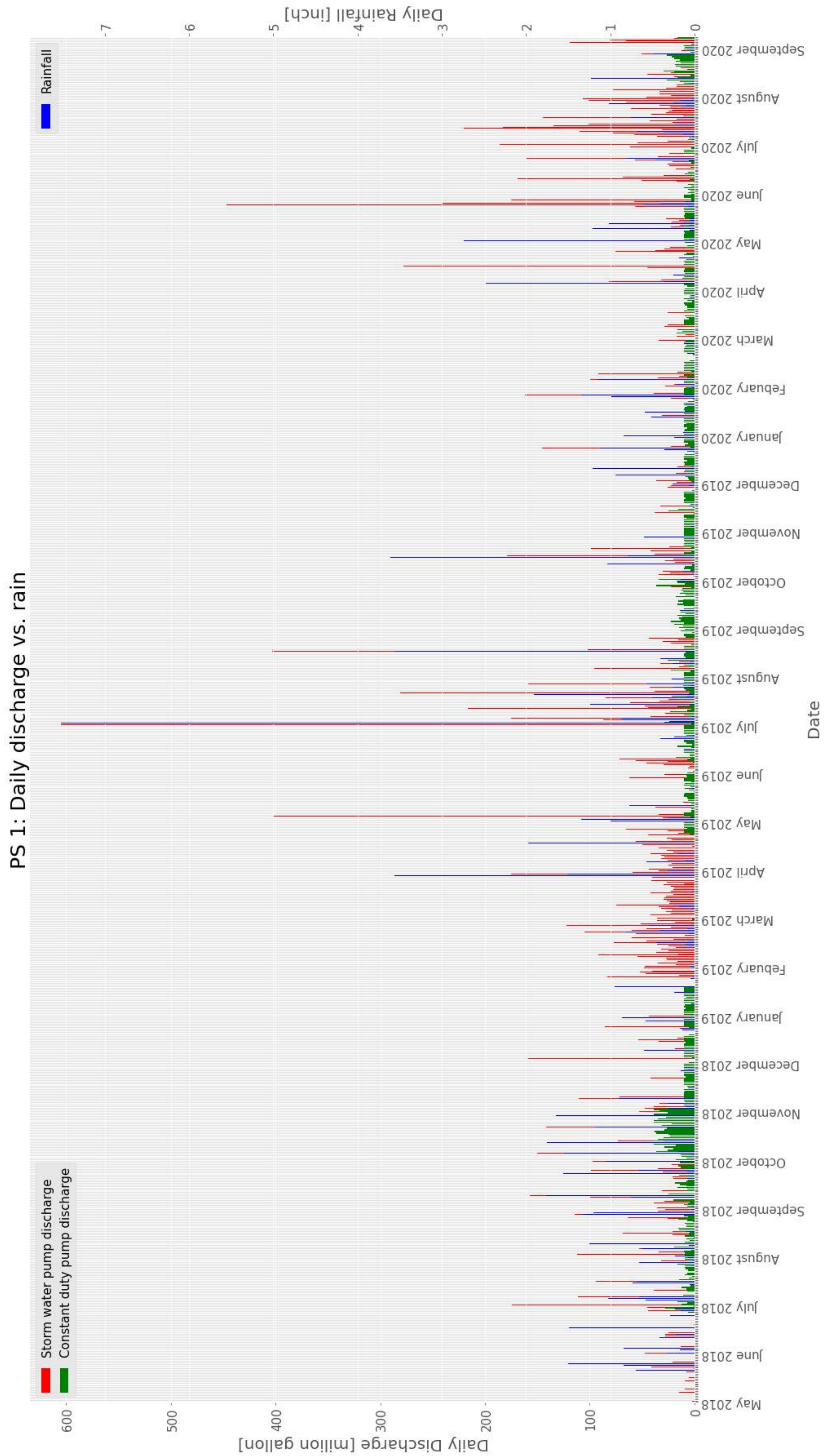

Figure 5.4: DPS 1 storm water pumps discharge, constant duty pumps discharge and rainfall time series

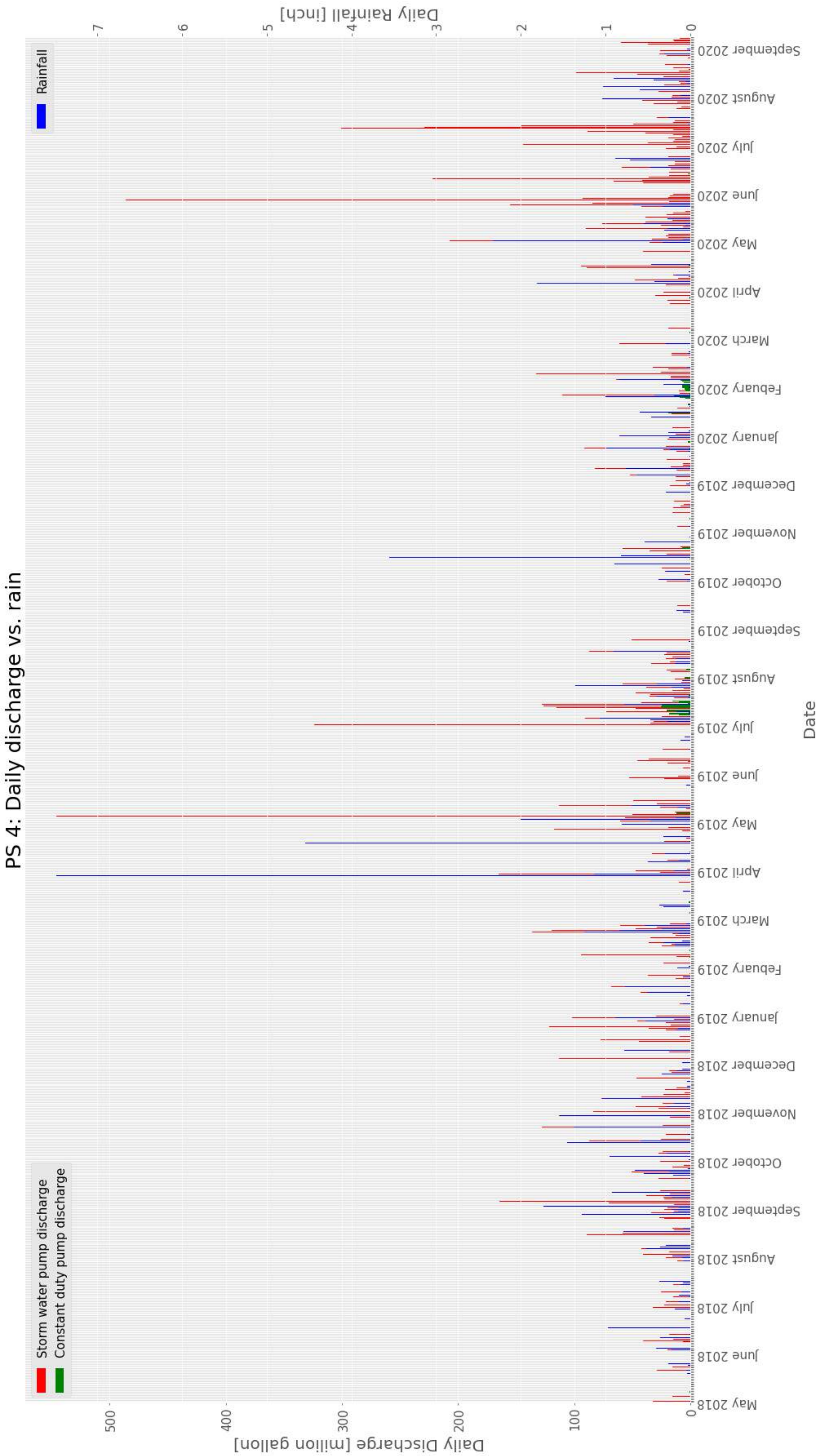

Figure 5.5: DPS 4 storm water pumps discharge, constant duty pumps discharge and rainfall time series

5.2.1. Precipitation - discharge relationship

In Figure 5.6, the daily storm water discharge for DPS 4 can be seen, aligned with the daily groundwater fluctuations of one of the St. Anthony monitoring wells and daily precipitation. Visually, there seems to be a significant link between the three plots. High hourly pumping station discharges occur on days with relatively high rain intensities and high groundwater levels. During some periods, it can be seen that the groundwater level is steadily decreasing when the pump is turned off, for example in October 2019.

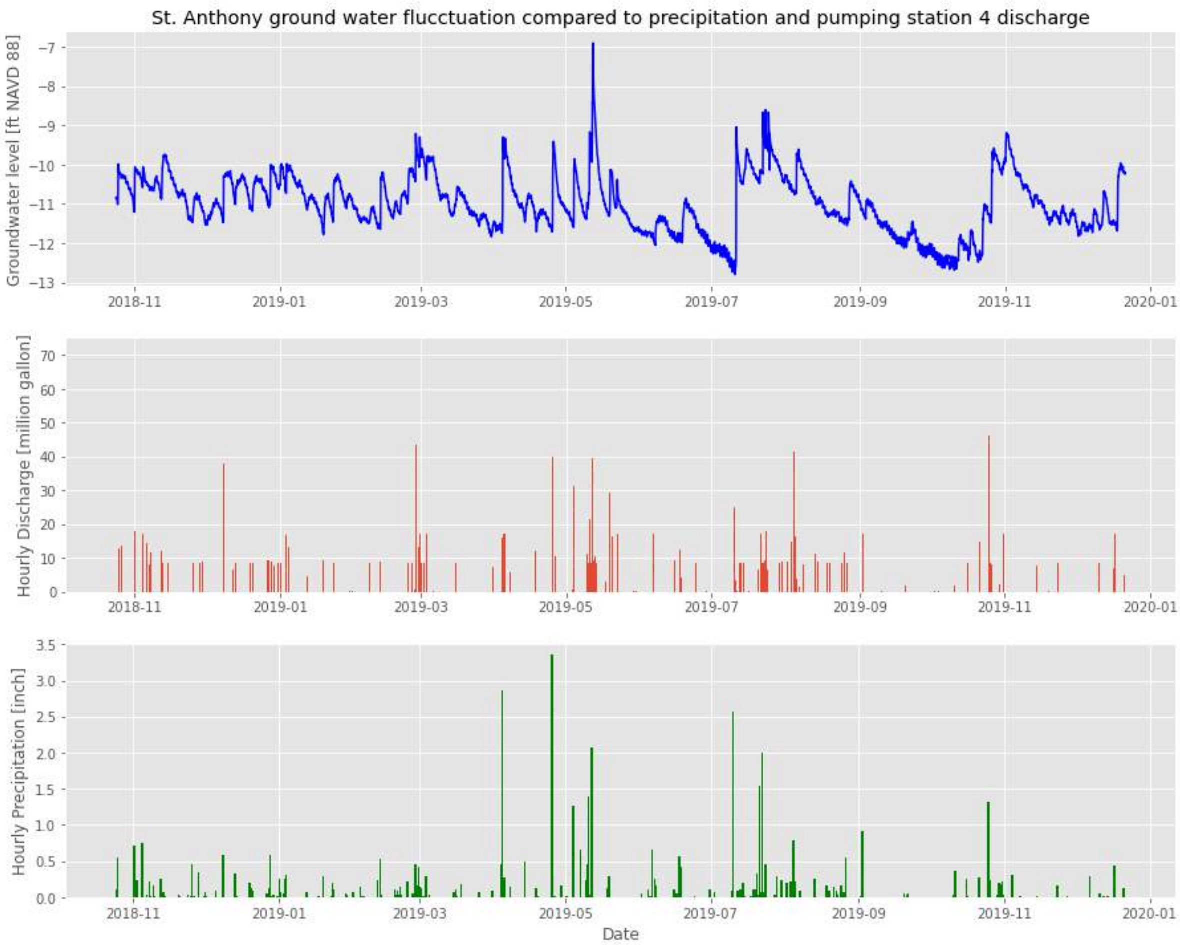

Figure 5.6: St. Anthony groundwater fluctuation compared to the daily DPS 4 discharge

In the hydrographs below, a closer look is taken at individual precipitation events. Here, the hourly storm water pump discharge is plotted (red line) along with the hourly rain intensity (blue bars) for individual, independent rain events. The events chosen for the hydrographs are all events following dry periods, ensuring that the storm system was empty beforehand.

The first thing that stands out when looking at Figures 5.7 till 5.18 is the pumping station efficiencies. All precipitation events are pumped out of the system within at most ten hours. Further, for DPS 1, almost all chosen peak events show low lag times; the timing of the peak precipitation intensity coincides with that of the peak discharge value. For peak events 3 and 4 for DPS 1, there is a slight delay of 3 hours and 1 hour respectively. The low lag times can also be seen in DPS 4's hydrographs. Only Figures 5.14 and 5.17 have a slight lag. The small time lags suggest there is a fast response between precipitation and pumping station discharge.

Assuming a linear relationship between precipitation and run-off and assuming constant precipitation events, the pumping station catchments can be represented by a reservoir model in which [Savenije, 2009]:

$$Q = I\left(1 - e^{-t/K}\right) \tag{5.4}$$

Where Q is the storm water run-off, I is the precipitation, and K the storage coefficient, a coefficient representing the residence time of a linear reservoir model. Finding the residence time gives a numerical definition to the response time between precipitation and run-off. By plotting the hydrographs on a logarithmic based y-axis, the coefficient can be found with [Savenije, 2009]:

$$\text{Slope} = -\frac{1}{K} \tag{5.5}$$

For each of the twelve hydrographs shown below, the storage coefficients were found. The average storage coefficient for DPS 1 was 1.08 hours and 2.39 hours for DPS 4. This suggests that there is a faster run-off response in DPS 1's catchment, which coincides with the percentage of paved area in each catchment. DPS 1's catchment is 70% paved, while that of DPS 4 is only 61% paved. The larger the paved area, the faster the run-off response.

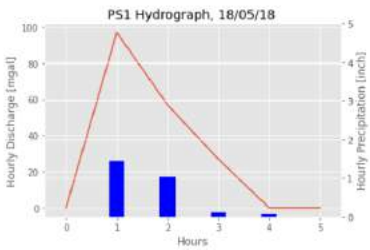

Figure 5.7: Hydrograph for peak 1 for DPS 1

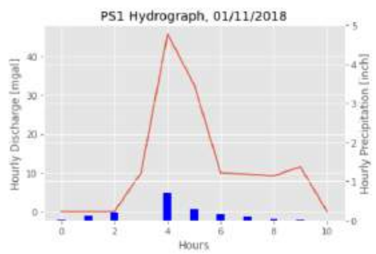

Figure 5.8: Hydrograph for peak 2 for DPS 1

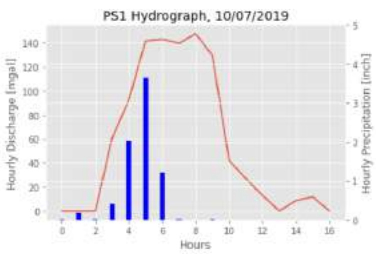

Figure 5.9: Hydrograph for peak 3 for DPS 1

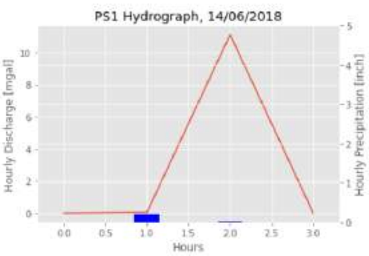

Figure 5.10: Hydrograph for peak 4 for DPS 1

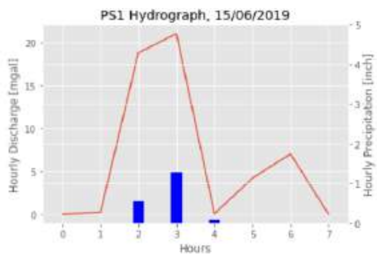

Figure 5.11: Hydrograph for peak 5 for DPS 1

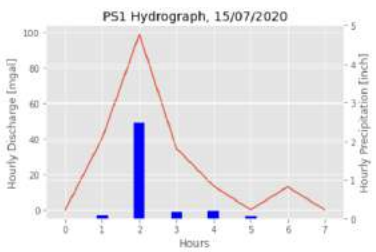

Figure 5.12: Hydrograph for peak 6 for DPS 1

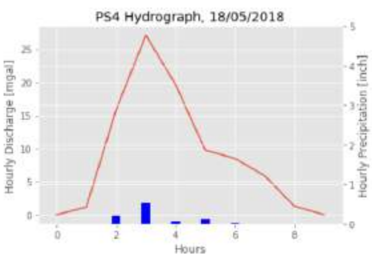

Figure 5.13: Hydrograph for peak 1 for DPS 4

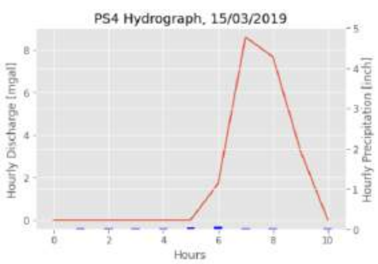

Figure 5.14: Hydrograph for peak 2 for DPS 4

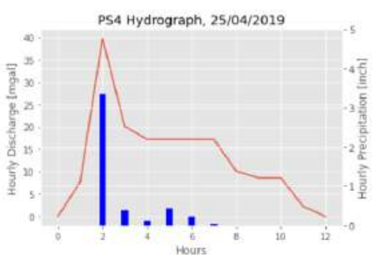

Figure 5.15: Hydrograph for peak 3 for DPS 4

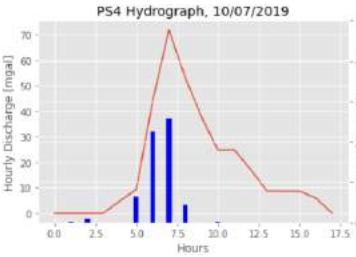

Figure 5.16: Hydrograph for peak 4 for DPS 4

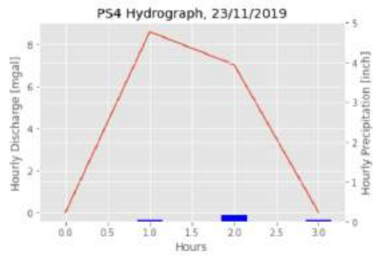

Figure 5.17: Hydrograph for peak 5 for DPS 4

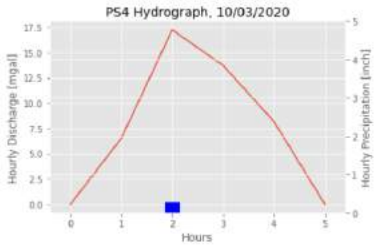

Figure 5.18: Hydrograph for peak 6 for DPS 4

When quantitatively looking at a larger scale, i.e. not only visually (Figure 5.6) and not at individual precipitation events (hydrographs), only a modest system response between precipitation and storm water pump discharge was found. When plotting the impulse-response relationship between the two factors on an hourly basis, the modelled discharge was able to explain 50% of the precipitation. In Figure 5.19, the hourly measured discharge data points (blue line) between May 2018 and June 2019 can be seen along with the modelled points (red line) based on the impulse-response relationship. The timing of many of the peaks are well modelled, but the intensities vary slightly from reality. The variance can be seen in Figure 5.20. What this suggests is that there are other processes, like groundwater drainage or high irrigation run-offs, which occur that cloud the precipitation-discharge relationship. At the beginning of 2019, a large variance can be seen between the expected discharge and the real discharge. As mentioned at the beginning of Section 5.2, during this period the storm water pumps of DPS 1 had to compensate for the disabled constant duty pumps, meaning that not only storm water was being pumped.

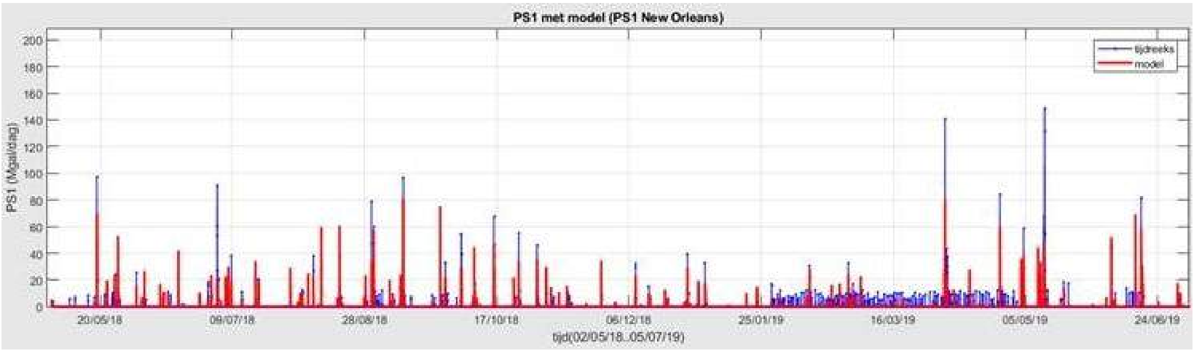

Figure 5.19: DPS 1 impulse-response relationship between precipitation and discharge [Baggelaar, 2021]

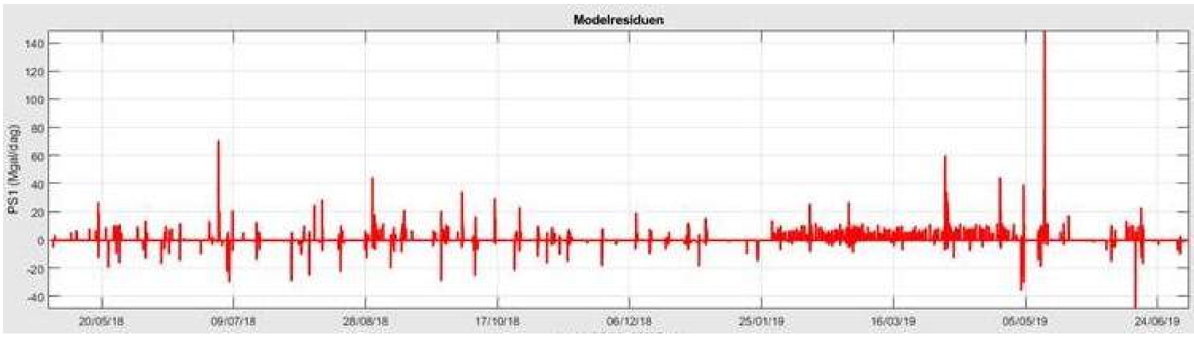

Figure 5.20: DPS 1 impulse-response relationship: variance between measured data and modelled data [Baggelaar, 2021]

5.2.2. Groundwater component of storm water pump discharges

As explained in Section 5.1, the actual storm water drainage would be compared to the ideal storm water drainage. The discharge-precipitation plots for DPS 1 and 4 can be seen below in Figures 5.21 and 5.22 respectively. The black line in the figures represents the ideal discharge - precipitation relationship and the blue points represent the measured rainfall and storm water pump discharges between the 1st of May 2018 and the 23rd of September 2020. All the points above the black line reveal groundwater drainage into the storm drainage system. Points below the black line can be explained by pumping station discharges on very dry days, where storm water leaks into the soil.

When comparing Figure 5.21 to Figure 5.22, it stands out that DPS 4 has a larger groundwater component than DPS 1, as more data points are located above the black line. This was to be expected as DPS 4 is located by a major drainage canal, the London Avenue Canal, and by the Lake Pontchartrain coastline, which causes increased groundwater flows during high water periods [Stuurman et al., 2013] and thus a larger groundwater infiltration into the drainage system. By DPS 1, it is more likely that storm water in the drainage system will leak into the drier ground, explaining the data points under the black line.

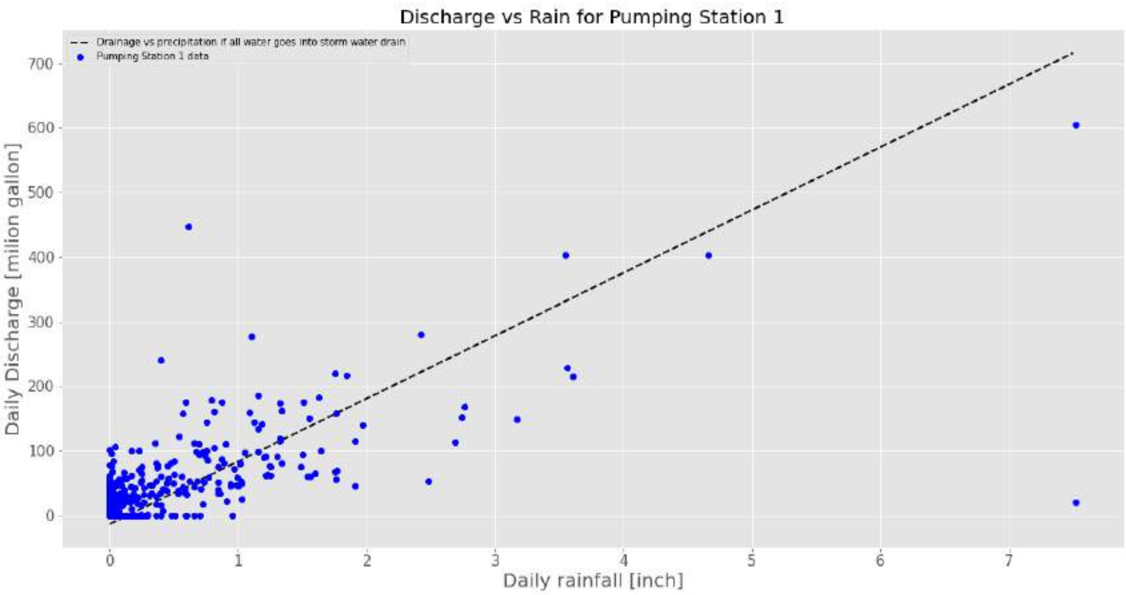

Figure 5.21: Daily discharge vs rain for DPS 1

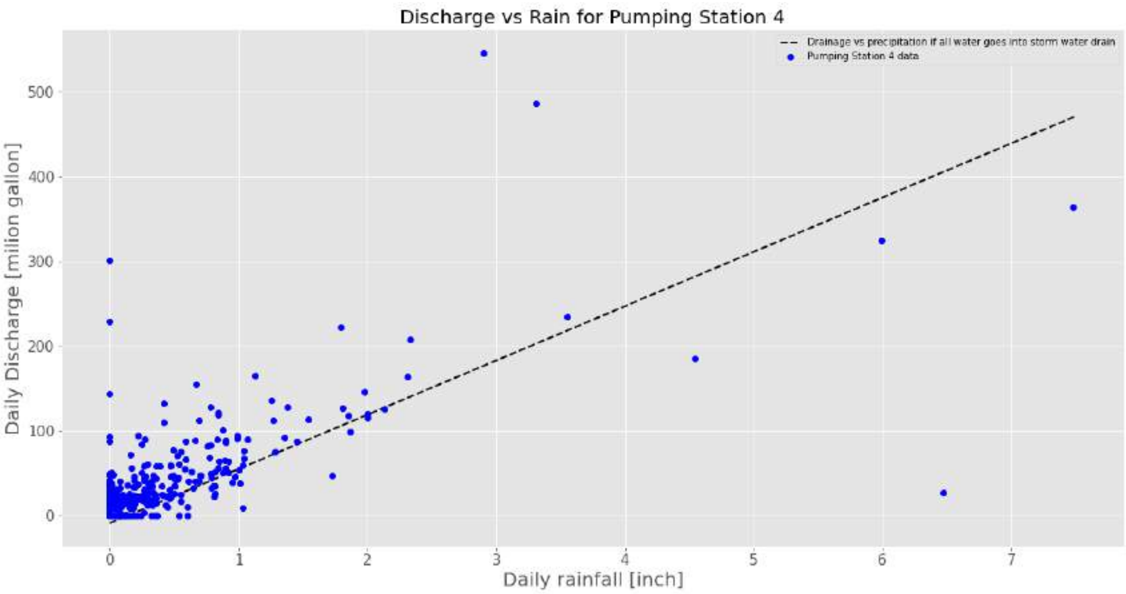

Figure 5.22: Daily discharge vs rain for DPS 4

In order to find a yearly average for the amount of groundwater seeping into the storm water drainage pipes, the differences between the measured discharges and the ideal discharges for all data points above the black line were found. Over the 876 days, the groundwater drainage for DPS 1 was 4.40 billion gallons and 4.70 billion gallons for DPS 4, or 1.83 and 1.96 billion gallons per year (6.92 and 7.42 million m^3 per year).

This method was applied to all pumping stations within the study area in order to find the total groundwater drained through the storm water pumps. The final distribution per region can be found in Figure 5.23 and the values per pumping station can be seen in Table 5.1.

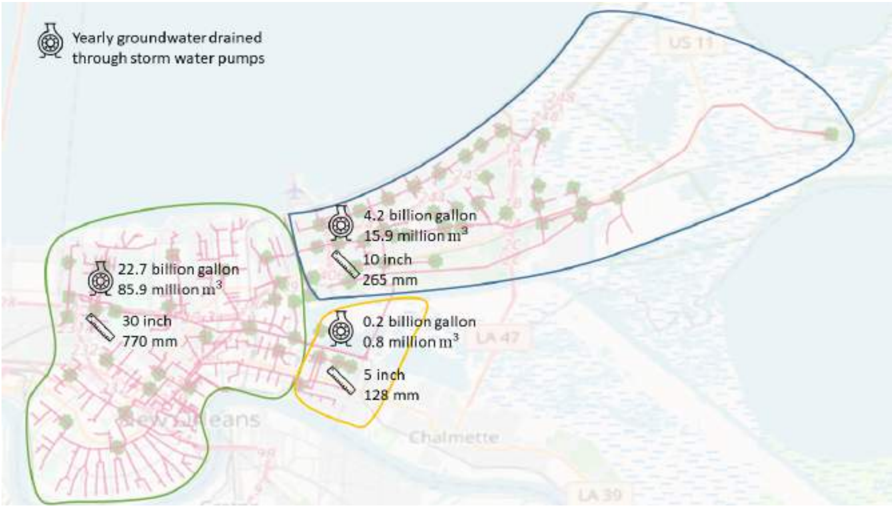

Figure 5.23: Yearly groundwater flow through storm water pumps

When looking at Table 5.1, it can be said that for all the pumping stations, the groundwater drainage can be explained by either the size of the pumping station catchment or by the proximity to a drainage canal or the lake. Further, it is assumed that DPS 17 does not drain any ground water. Many of the CD pumps in the Orleans Metro system send water to DPS 17, after which the DPS 17 pump forwards the dry weather flow to the river [SWBNO, 2021a]. So, DPS 17 does not drain any water from the surrounding area.

Catchment	Pumping station	Paved area [acre]	Groundwater drained over 2 years [mgal]	Yearly groundwater drainage [bgal per year]
Orleans Metro	DPS 1	3.581,80	4.392,00	1,83
	DPS 2	1.529,90	480,00	0,20
	DPS 3	1.871,20	8.064,00	3,36
	DPS 4	2.357,30	4.776,00	1,99
	DPS 6	1.966,30	24.168,00	10,07
	DPS 7	1.597,90	5.160,00	2,15
	DPS 12	1.451,20	5.448,00	2,27
	DPS 17	440,60	-	-
	DPS 19	2.053,30	1.968,00	0,82
	DPS Pritchard	782,10	17,23	0,01
Orleans East	DPS 10	1.687,70	96,00	0,04
	DPS 14	1.406,30	3.912,00	1,63
	DPS 16	1.219,10	2.640,00	1,10
	DPS 18 (Maxtent Canal)	546,30	1.224,00	0,51
	DPS 20	280,50	528,00	0,22
	DPS Elaine	484,20	336,00	0,14
	DPS Dwyer	491,40	2,40	0,001
	DPS Grant	628,40	1.320,00	0,55
Lower Ninth Ward	DPS 5	873,20	480,00	0,20

Table 5.1: Groundwater component of storm water pump discharges per pumping station

5.2.3. Groundwater component of constant duty pump discharges

When looking at Figure 5.4 and Figure 5.5, it can be seen that the constant duty pumps are working during both wet and dry days, confirming the influence of the external factors listed at the beginning of the chapter. As mentioned before as well, the constant duty pumps in DPS 1 were under maintenance between February 2019 till May 2019 justifying why they were not used during this period. For the constant duty pumps of DPS 4 however, it is not known why the pumps are only turned on under fifty times over the two year time span.

As explained in the Methods section, an indication of the groundwater component for the different constant duty pumps would be given by summing up all the dry weather discharges. This total adds up to 37,215.33 million gallons over the two years of data which is equal to 15.47 billion gallons per year (58.56 million m^3 per year). The distribution per constant duty pump can be seen below in Table 5.2.

Catchment	CD pumping station	Groundwater drained over 2 years [mgal]	Yearly groundwater drainage [bgal per year]
Orleans Metro	DPS 1	3856,41	1,60
	DPS 2	3394,33	1,41
	DPS 3	0,10	0,00
	DPS 4	85,41	0,04
	DPS 6	7889,71	3,28
	DPS 7	20463,69	8,51
	DPS I10	108,51	0,05
	DPS Pritchard	0,00	0,00
Lower Ninth Ward	DPS 5	1417,16	0,59

Table 5.2: Groundwater component of constant duty pump discharges per pumping station

Looking at this table a few characteristics stand out. The constant duty pumps for both DPS 3 and DPS Pritchard are seldom turned on, while, in contrary, the constant duty pumps of DPS 7 pump out more than the storm water pumps do, see Table 5.1. Having a better understanding of the run times of the constant duty systems would help in estimating the amount of groundwater drained through these systems. This could be achieved by examining the logs for manually operated pumps, showing when, why and for how long the constant duty pumps were turned on for.

The groundwater drainage due to the constant duty pumps per catchment can be seen in Figure 5.24. As there are no constant duty pumps in Orleans East, this catchment is not shown in the figure.

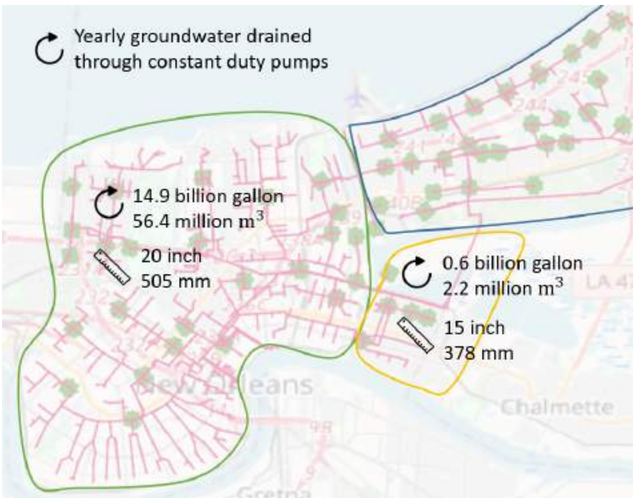

Figure 5.24: Yearly groundwater flow through constant duty pumps

5.3. Conclusion

The total groundwater drained through the storm water drainage system can be seen in Table 5.3. This includes both the groundwater pumped through the storm water pumps, as well as the groundwater pumped through the constant duty pumps.

Region	Yearly groundwater drained through storm water pumps				Yearly groundwater drained through constant duty pumps				Total yearly groundwater drained through storm water drainage system			
	[billion gallon]	[million m3]	[inch]	[mm]	[billion gallon]	[million m3]	[inch]	[mm]	[billion gallon]	[million m3]	[inch]	[mm]
Orleans Metro	22,70	85,93	30	770	14,89	56,36	20	505	37,59	142,29	50	1275
Orleans East	4,19	15,86	10	265	-	-	-	-	4,19	15,86	10	265
Lower Ninth Ward	0,20	0,78	5	128	0,59	2,23	15	378	0,79	3,01	20	506
Total study region	27,09	102,57	23	578	15,48	58,59	13	330	42,57	161,16	36	908

Table 5.3: Overview of groundwater drained through storm water drainage system per catchment

From the impulse-response model, it was found that only 50% of the storm water pump discharge of DPS 1 could be explained by the measured precipitation, revealing the presence of other processes, such as groundwater drainage. The amount of groundwater drained differs per pumping station catchment area and depends on the size of the catchment area, and location of the catchment compared to drainage canals and Lake Pontchartrain.

The groundwater flow through the constant duty pump systems is hard to quantify with the available data. The total discharge measured on dry days include both groundwater drainage and other water sources like irrigation run-off. For the manually operated constant duty pumping stations, a log showing when and why the pumps were turned on would help in understanding the constant duty pumping station behaviors.

6
Drinking water system

The current drinking water infrastructure stretching across the Greater New Orleans region has segments which are over 100 years old [SWBNO, 2021b], see Figure 6.1. Due to the age of the network, damage caused during natural disasters, like Hurricane Katrina, the ground movement sensitivity of the region and the existing land subsidence, the drinking water system loses a significant amount of water during transport.

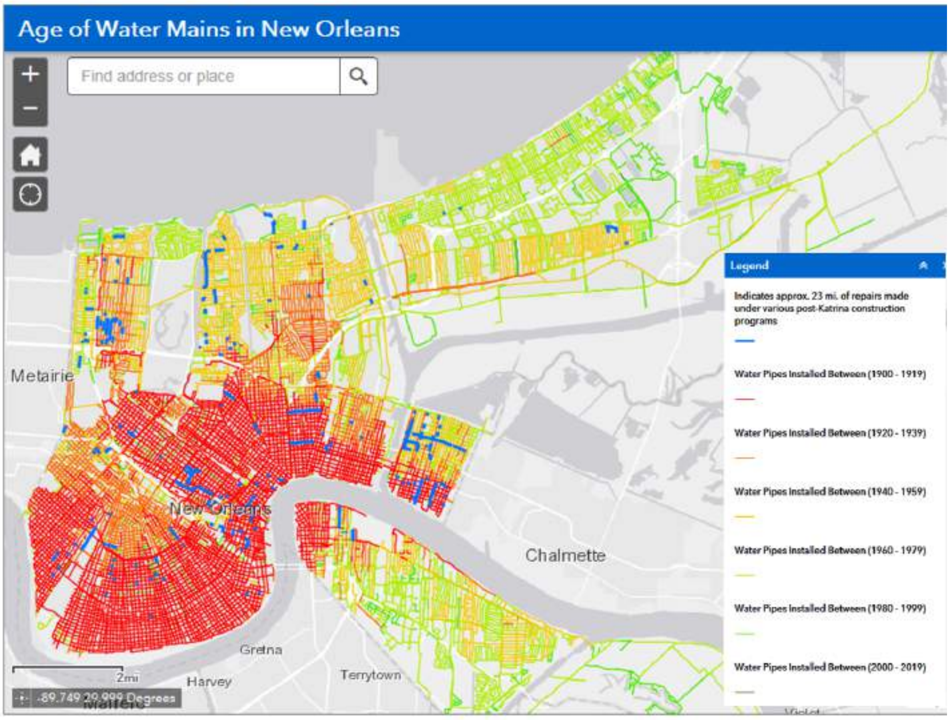

Figure 6.1: Age of drinking water mains [SWBNO, 2021b]

In this chapter, the drinking water losses across Orleans Metro, Orleans East and the Lower Ninth Ward will be quantified.

6.1. Method

In order to quantify the drinking water losses, the Water Audit written up by Freeman LLC will be used [Freeman, 2019]. In the Audit, the total water losses are made up of two components: the apparent losses and the real losses. The apparent losses include customer metering inaccuracies, water theft, illegal connections, data handling issues, and errors in the billing system. The real losses consist of transmission and distribution main leakages, and service connection leakages [Freeman, 2019]. As we want to know how much drinking water seeps into the ground, only the real losses will be looked at.

The Water Audit summarizes the drinking water components between 2008 and 2017. For this research, the newest data points will be used, namely those of 2017.

6.2. Results

In 2017, the total real losses came out to be 30,171 million gallons (114.21 million m^3). About 54 billion gallons (204.41 million m^3) of drinking water was produced, meaning that 55% of the total produced drinking water was lost during distribution.

This 30 billion gallons of water loss represents the drinking water loss across Orleans Metro, Orleans East, the Lower Ninth Ward, and the Algiers area on the West Bank. As mentioned in Chapter 2, in this study, only the East Bank is analysed. The total drinking water loss was therefore, proportionally split across the East Bank areas according to the lengths of the drinking pipe mains per catchment. On the East Bank, a total loss of 26.60 billion gallons per year was then found (100.69 million m^3). The drinking water loss distribution per region can be seen below in Figure 6.2.

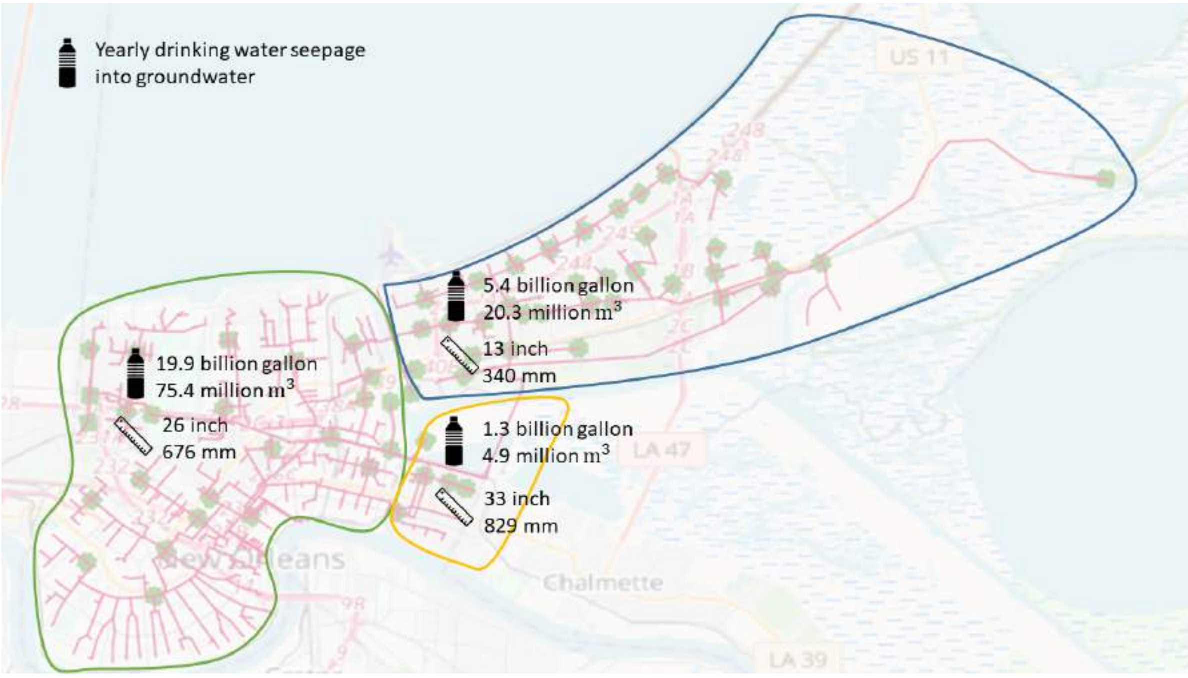

Figure 6.2: Drinking water loss distributions across the East Bank

To put the total drinking water loss into perspective: 26.60 billion gallons per year of drinking water leaking across the 43 thousand acres (174km^2) of the East Bank study region, is equal to a yearly loss of 22.35 inches (567.59 mm) over the whole territory.

6.3. Conclusion

In 2017, 55% of the produced drinking water was lost into the ground through leakages in the drinking water mains and at service connections. This is an enormous proportion of water lost resulting in inefficiencies and financial losses.

In this study, the drinking water leakage was spread evenly across the East Bank, however, when looking at Figure 6.1, it can be seen that there is a higher concentration of old mains in the south western part of the region, meaning there are probably higher leakage rates there compared to the other areas.

7 Conclusions and recommendations

In this final chapter a groundwater balance will be made using the groundwater flows found in the previous chapters. This will be followed by a conclusion of what these groundwater losses and increases represent for the studied region of New Orleans. Finally a brief recommendation will be given regarding future studies related to understanding and quantifying the groundwater system of New Orleans.

7.1. Groundwater balance

A groundwater balance has been made, looking at all the shallow groundwater fluxes. These shallow groundwater fluxes do not include groundwater pumped up for industries or power plants, as this water is pumped up from below a deep impermeable clay layer [Stuurman et al., 2013], separating the deep groundwater from the shallow groundwater balance.

The fluxes that replenish groundwater are: 1) precipitation surplus, 2) drinking water leakages and 3) seepage from Lake Pontchartrain, the Mississippi River, and the outfall canals. The groundwater depleting fluxes are: 1) the sewer system drainage and 2) storm water system drainage.

All these fluxes have been found in this study, except for the water seeping into the ground from the lake and outfall canals. Assuming there is no relative change in groundwater storage across the year, the replenishing fluxes should be equal to the depleting fluxes, giving the following balance:

Precipitation surplus + Drinking water leakages + Seepage = Sewer system drainage + Storm water drainage system

or

Seepage = Sewer system drainage + Storm water system drainage - Precipitation surplus - Drinking water leakages

$$\text{Seepage} = 31.2 + 42.6 - 23.1 - 26.6 \tag{7.1}$$

$$\text{Seepage} = 24.1 \text{ billion gallon / year or } 91.2 \text{ million m}^3 \text{ / year} \tag{7.2}$$

The groundwater balance can be seen in Figures 7.1 and 7.2 and the groundwater flux ratios in Figure 7.3. The largest draining flux comes from the storm water drainage system and it is closely followed by the sewer water drainage system. These fluxes give a first indication about the sizes of different groundwater drainage components, but a deeper analysis should be done to increase the quantitative certainty of some of the fluxes, as will be described in Chapter 7.3.

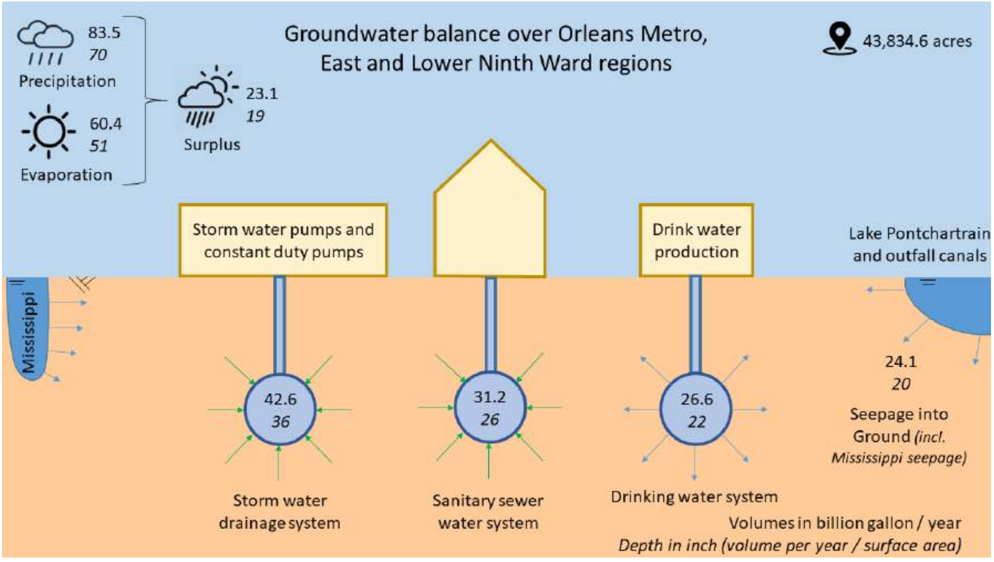

Figure 7.1: Groundwater balance for study region, imperial units

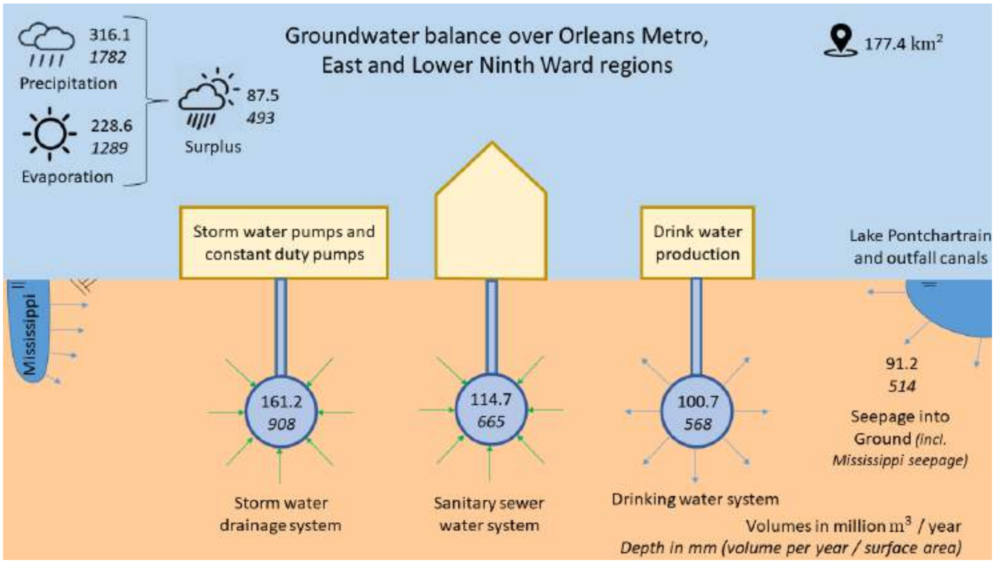

Figure 7.2: Groundwater balance for study region, metric units

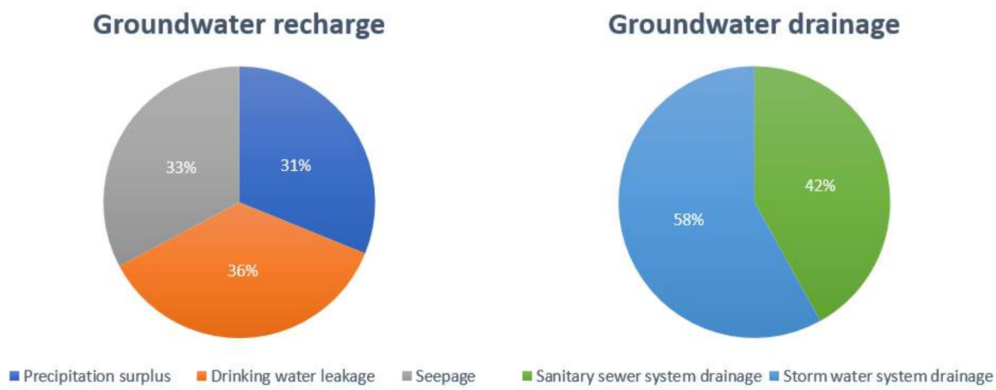

Figure 7.3: Groundwater flux ratios

7.2. Conclusions

When looking at the water balance and the conclusions made in the previous chapters, the following findings can be concluded. The first is the influence of the drainage infrastructure on the groundwater level. In Chapter 3, it was found that the depth of the groundwater drainage level depends not only on the depth of the closest drainage system, but by all the drainage pipes located near by.

The second is the amount of groundwater that is currently being treated in the WWTP. More than 50% of the water treated is relatively clean groundwater. This adds a huge, unnecessary stress onto the water treatment system.

The third regards the groundwater drained through the storm water drainage system. The storm water drainage system is the largest groundwater drainage component contributing to 58% of the total drainage. This includes both the groundwater drained through the storm water pumps and the groundwater drained through the constant duty pumps.

The final aspect is the amount of drinking water lost during distribution. As seen in Chapter 6, 55% of the produced drinking water is lost, producing 22 inches (570mm) of groundwater recharge. This is slightly more than 30% of the annual rainfall and makes the drinking water losses a larger groundwater recharge than the annual precipitation surplus.

Within this study, certain uncertainties and assumptions must be noted. Firstly, due to lack of data, the potential evaporation was used instead of the actual evaporation. Secondly, much of the data collected and analysed covered different time periods, meaning there could be discrepancies between dry and wet years. For example the sewer system data used spanned across 2016 till 2018 while the storm water drainage data spanned across 2018 till 2020. Further, it was assumed that the fluctuation in sewer flow was fully caused by extra groundwater drainage. Lastly, it was also assumed that the water pumped out by the constant duty pumps on dry days was all drained groundwater, instead of making a distinction between drained groundwater and run-off.

7.3. Recommendations

The following recommendations are given for future studies in order to better understand and quantify the groundwater system of New Orleans:

- Monitor the water quality of both the WWTP influent and the storm water pumping station discharges to get a better understanding of the water origin. Detecting chlorine would suggest water originating from the drinking water network. Finding water with a low conductivity would suggest rain water, while finding water with a high conductivity would suggest water originating from the lake. Adding and following natural tracers like deuterium or tritium would also make it possible to derive the origin of the discharged water.

- Measure the amount of water seeping into the ground by Lake Pontchartrain, the Mississippi river, the outfall canals, and Bayou St. John. In this study, the seepage flux was found by balancing out the groundwater balance, however, it is important to see if this value matches reality. An estimation of the seepage can be found by installing temporary sheet piles and monitoring their subsidence over time. Another method could be by installing mini-filters in the ground by near to the banks and following and measuring naturally occurring tracers and the temperature of the water.

- Get a better understanding of the influences of the different groundwater fluxes. What would happen to the groundwater level if the drinking water system was repaired and the groundwater recharge decreased by approximately 30%?

- Get a better understanding of the (constant duty) pumping station operations. This would help in understanding why for example, the constant duty pump discharge at DPS 7 is so large and why certain constant duty pumps were hardly used between May 2018 and September 2020. Having a better understanding of the pump management, would allow for a better indication of how much groundwater actual drains through this system.

- Measure and collect radiation data to get a better approximation of the yearly actual evaporation. This can be done by designing and installing an evapotranspiration monitoring network throughout New Orleans made up of a combination of small lysimeters and open water evaporation pans.
- Install a network of groundwater monitors across the city and gather clusters of data points from both the water levels inside the sewer and storm water pipes and the groundwater levels next to the pipes. This would allow for a better insight into the groundwater drainage behaviour.
- Investigate the actual drinking water leakage distribution across the study region depending on the age of the water mains.

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A
Sub-catchment data

Catchment	Sub-catchment	Area			
		Total [acre]	Total [hectare]	Unpaved [acre]	Unpaved [hectare]
Jefferson Basin	Canal Street PS	348,90	141,20	239,70	97,01
	Bonnabel	3.157,00	1.277,62	2.199,90	890,29
	Suburban	3.459,90	1.400,20	2.329,90	942,90
	Elmwood	4.407,70	1.783,77	2.690,80	1.088,95
	Duncan	5.195,10	2.102,43	3.099,70	1.254,43
	Parish Line PS	1.434,00	580,33	738,50	298,87
	Harahan (UC)	1.998,90	808,94	1.294,90	524,04
	Jefferson gravity north	5.367,50	2.172,20	3.396,70	1.374,63
	Jefferson gravity south	3.003,70	1.215,58	1.900,80	769,24
	Total basin	28.372,70	11.482,02	17.890,90	7.240,35
Orleans Metro	PS 1	5.099,50	2.063,69	3.581,80	1.449,53
	PS 2	1.838,10	743,85	1.529,90	619,14
	PS 3 north	1.062,50	429,98	714,50	289,15
	PS 3 south	1.806,90	731,23	1.156,70	468,11
	PS 4	3.857,50	1.561,07	2.357,30	953,99
	PS 6 north	470,50	190,40	308,70	124,93
	PS 6 south	2.669,80	1.080,43	1.657,60	670,82
	PS 7 north	1.336,50	540,86	973,20	393,85
	PS 7 south	940,50	380,61	624,70	252,81
	PS 12	2.184,60	884,08	1.451,20	587,29
	PS 17	626,50	253,54	440,60	178,31
	PS 19 *	3.079,20	1.246,11	2.053,30	830,96
	Monticello	934,70	378,26	635,20	257,06
	Pritchard Place	1.160,50	469,64	782,10	316,51
	PS 17th street canal *	172,80	69,93	58,40	23,63
	PS Orleans ave. canal *	173,80	70,33	97,80	39,58
	PS London ave. canal *	177,80	71,95	55,30	22,38
	*Total basin (outfall pumps *)*	27.591,70	11.165,96	18.478,30	7.478,07
Orleans East	PS 10	2.854,90	1.155,34	1.697,70	687,05
	PS 14	3.230,90	1.307,50	1.406,30	569,12
	PS 15	1.767,20	715,16	1.358,30	549,70
	PS 16	2.060,50	833,85	1.219,10	493,36
	PS 18	1.215,80	492,02	546,30	221,08
	PS 20	427,50	173,00	280,50	113,52
	Grant st.	1.427,40	577,65	628,40	254,31
	Elaine st.	1.146,80	464,09	484,20	195,95
	Dwyer rd.	650,50	263,25	491,40	198,87
	Total basin	14.781,50	5.981,86	8.112,20	3.282,96
St. Bernard	PS 5	1.461,40	591,41	873,20	353,38
	Fortification 1	2.698,50	1.092,04	1.020,90	413,15
	Guichard 2	949,20	384,13	572,70	231,77
	Bayou Villiere 3	2.155,30	872,22	1.201,80	486,36
	Meraux	1.494,70	604,88	367,30	148,64
	E.J. Gore 5	4.646,00	1.880,17	476,00	192,63
	Bayou Ducros 7	1.765,80	714,59	427,70	173,09
	St. Mary 8	4.715,50	1.908,30	631,90	255,73
	Total basin	19.886,40	8.047,74	5.571,50	2.254,76
	Total Greater New Orleans	90.632,30	36.677,59	50.052,90	20.256,13

Table A.1: Sub-catchment areas [Dolman, 2013]

B
Storm drainage pump yearly plots

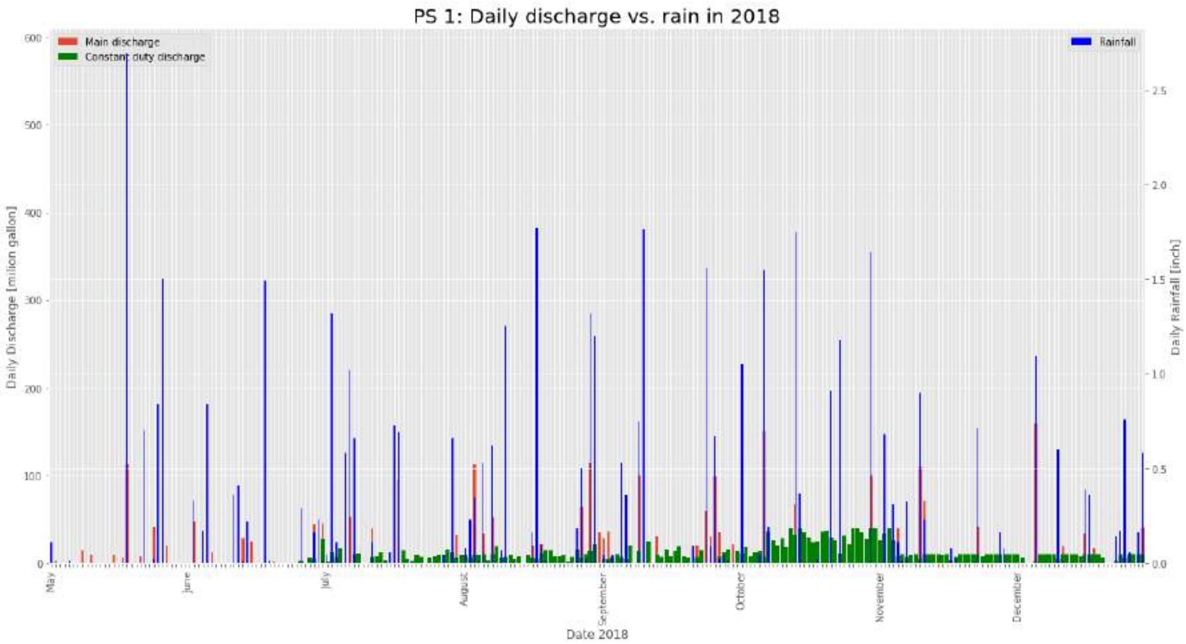

Figure B.1: DPS 1 pump discharge, rainfall time series for 2018

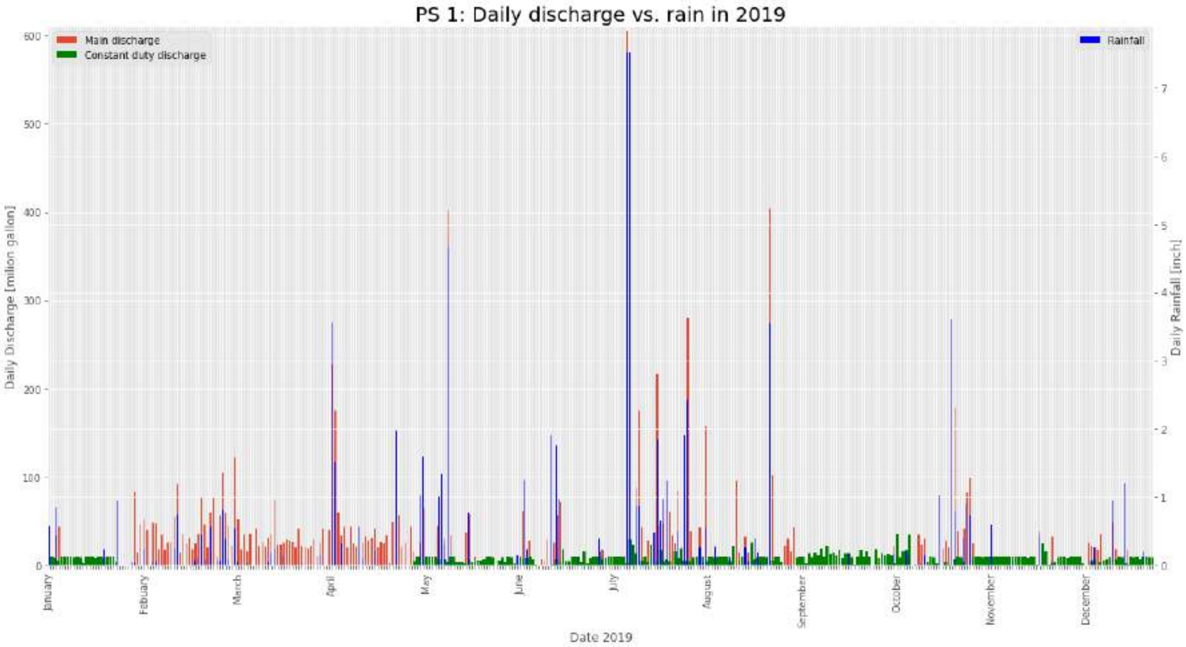

Figure B.2: DPS 1 pump discharge, rainfall time series for 2019

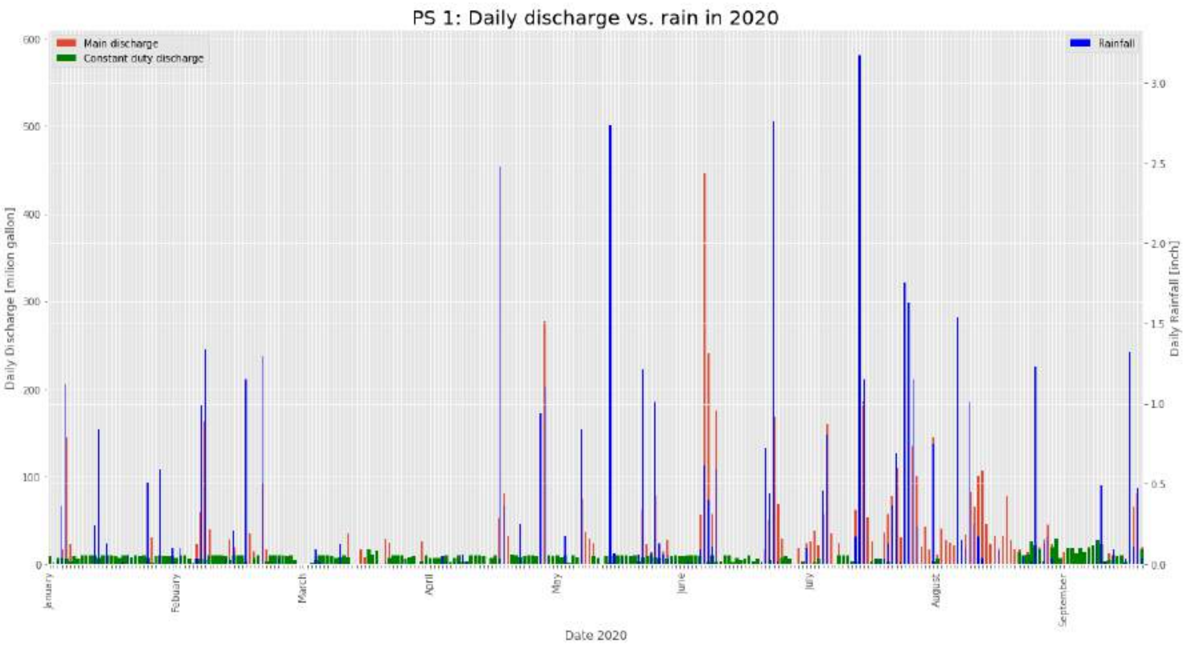

Figure B.3: DPS 1 pump discharge, rainfall time series for 2020

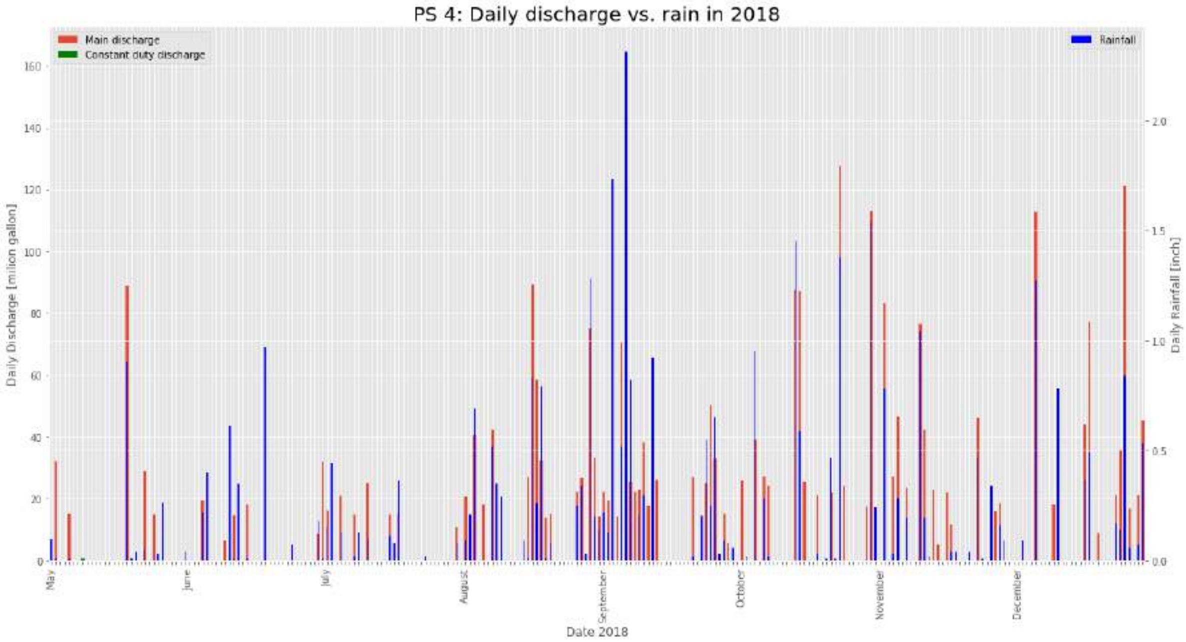

Figure B.4: DPS 4 pump discharge, rainfall time series for 2018

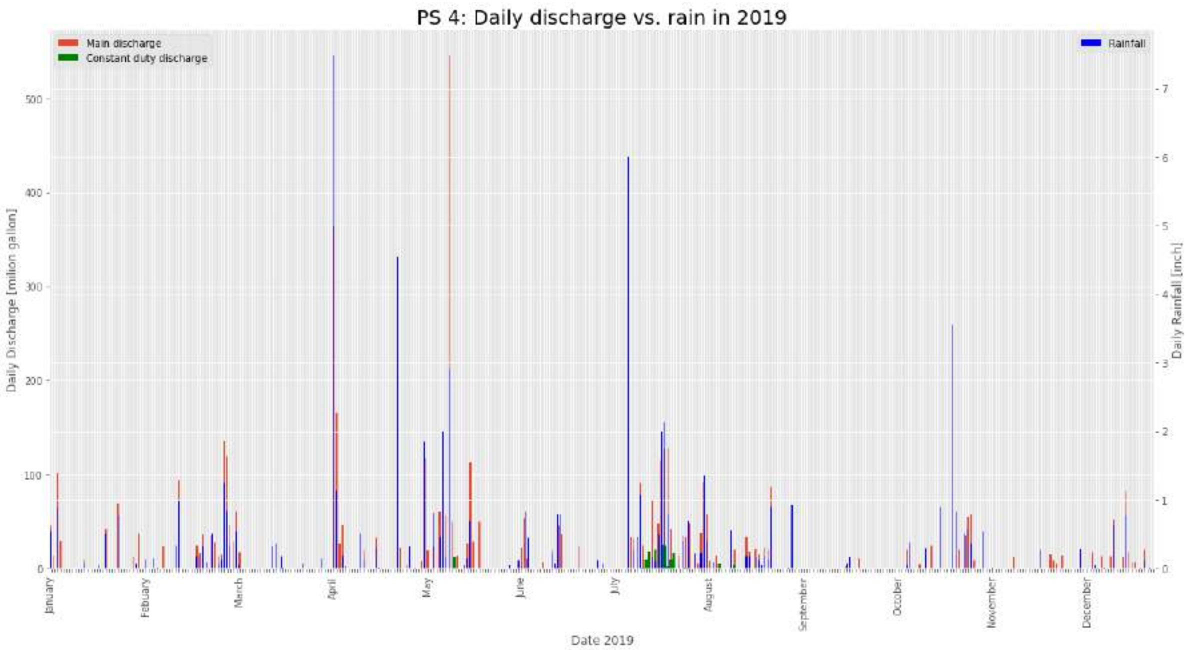

Figure B.5: DPS 4 pump discharge, rainfall time series for 2019

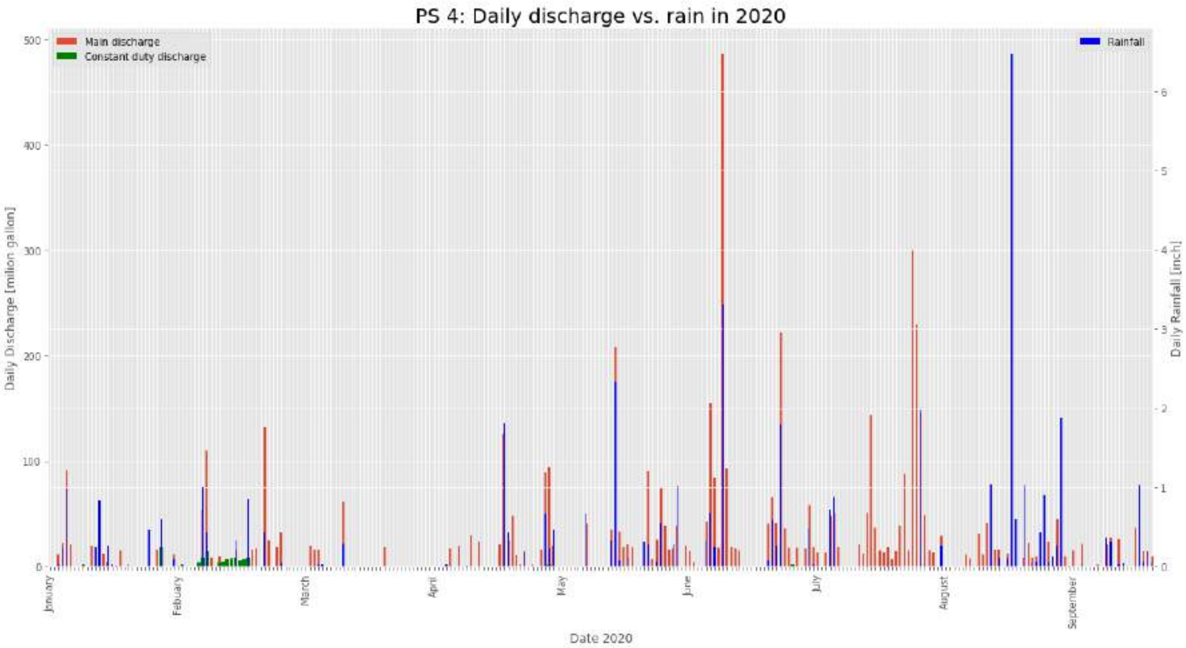

Figure B.6: DPS 4 pump discharge, rainfall time series for 2020

C
Constant duty pump yearly plots

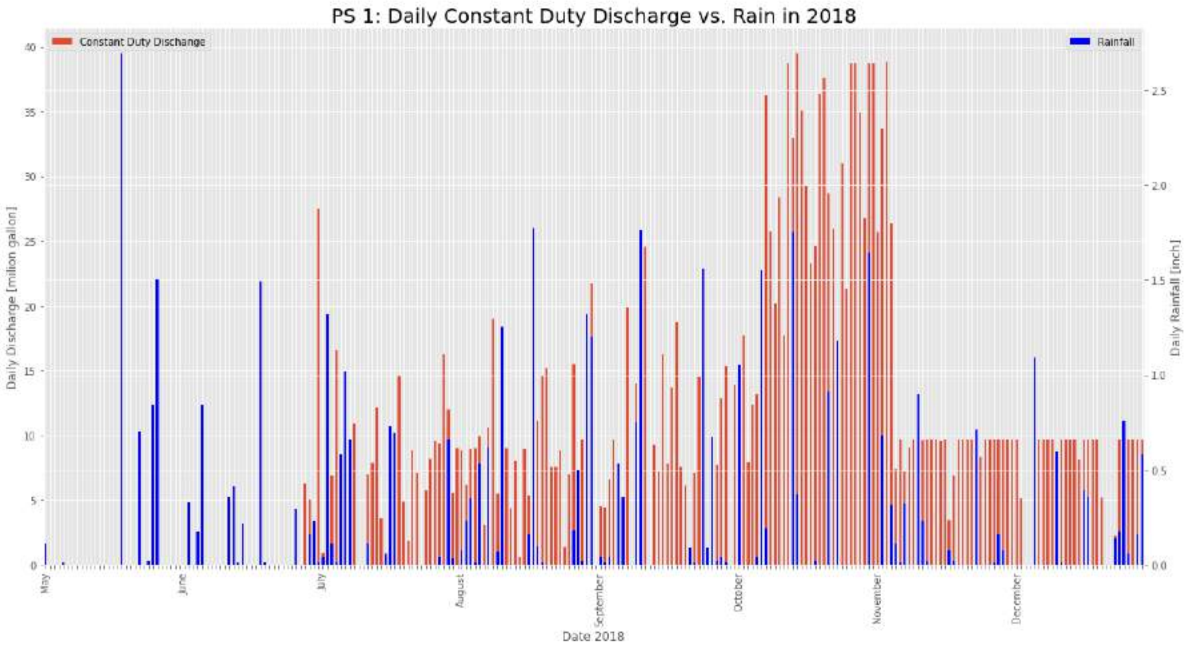

Figure C.1: DPS 1 constant duty pump discharge, rainfall time series for 2018

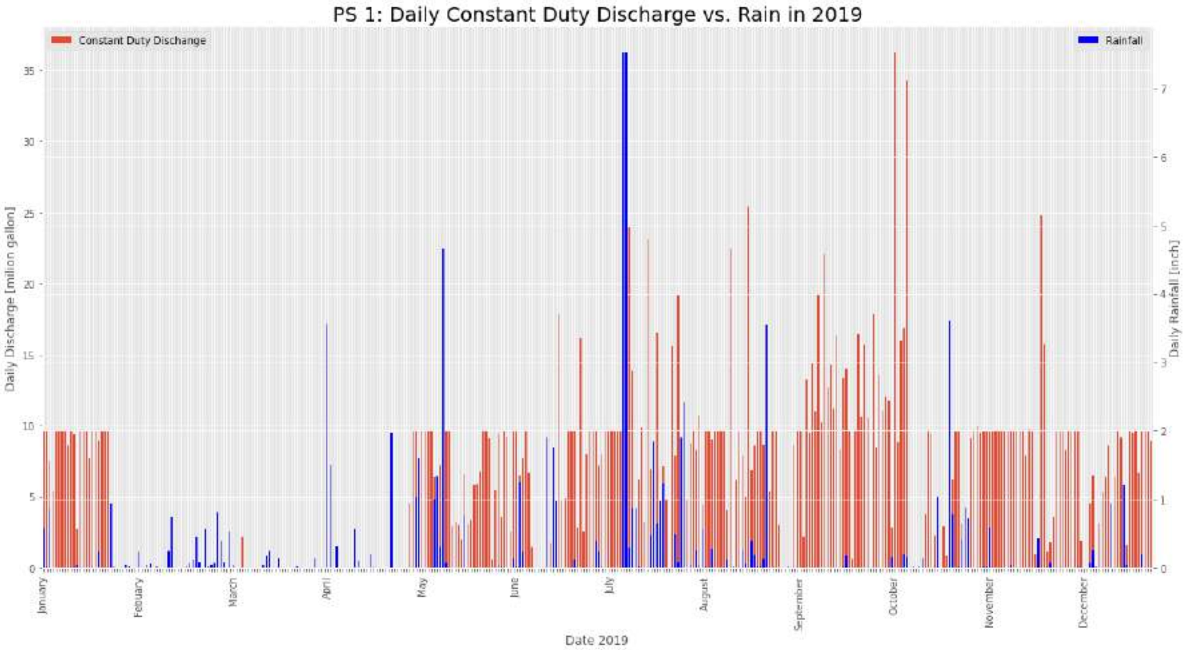

Figure C.2: DPS 1 constant duty pump discharge, rainfall time series for 2019

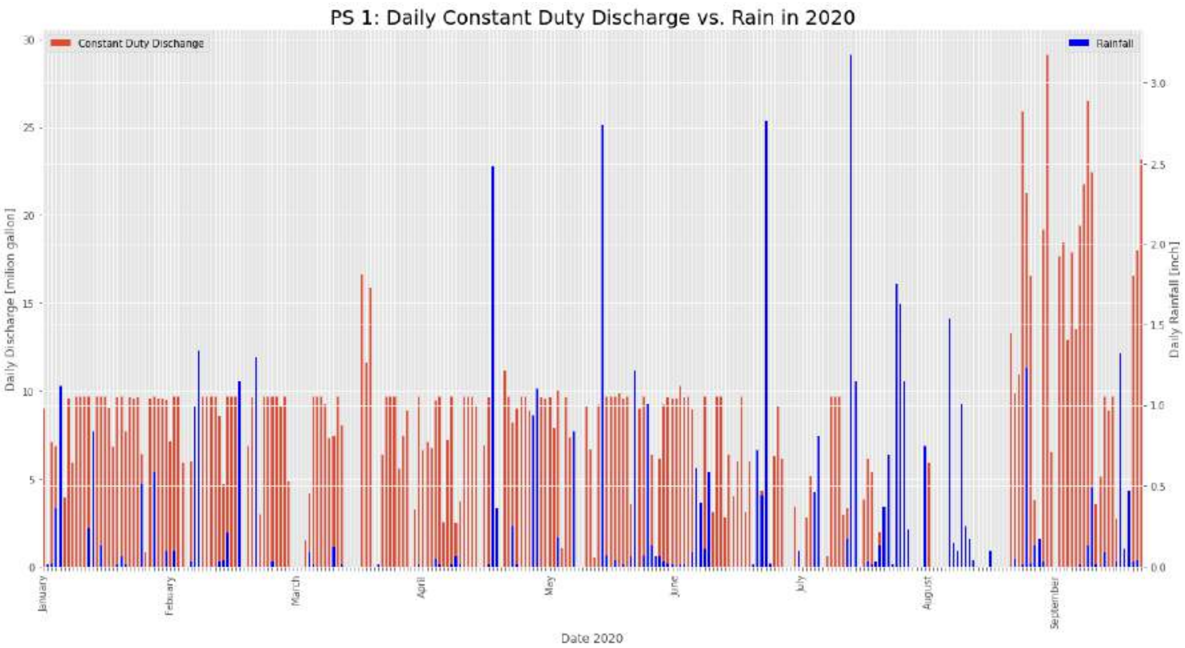

Figure C.3: DPS 1 constant duty pump discharge, rainfall time series for 2020

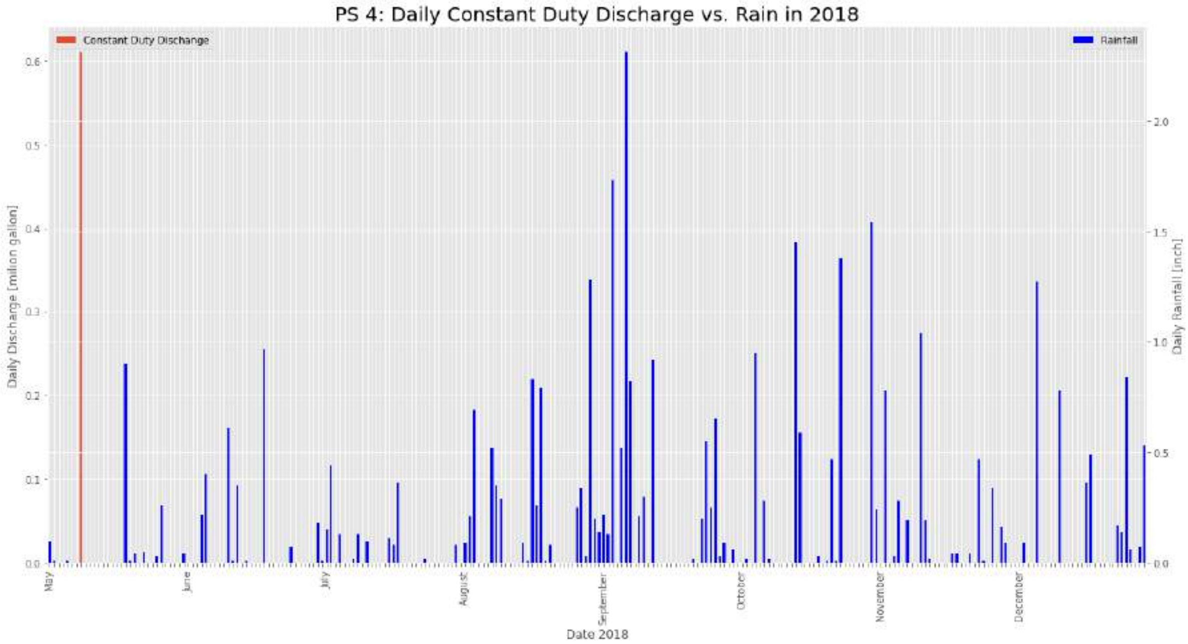

Figure C.4: DPS 4 constant duty pump discharge, rainfall time series for 2018

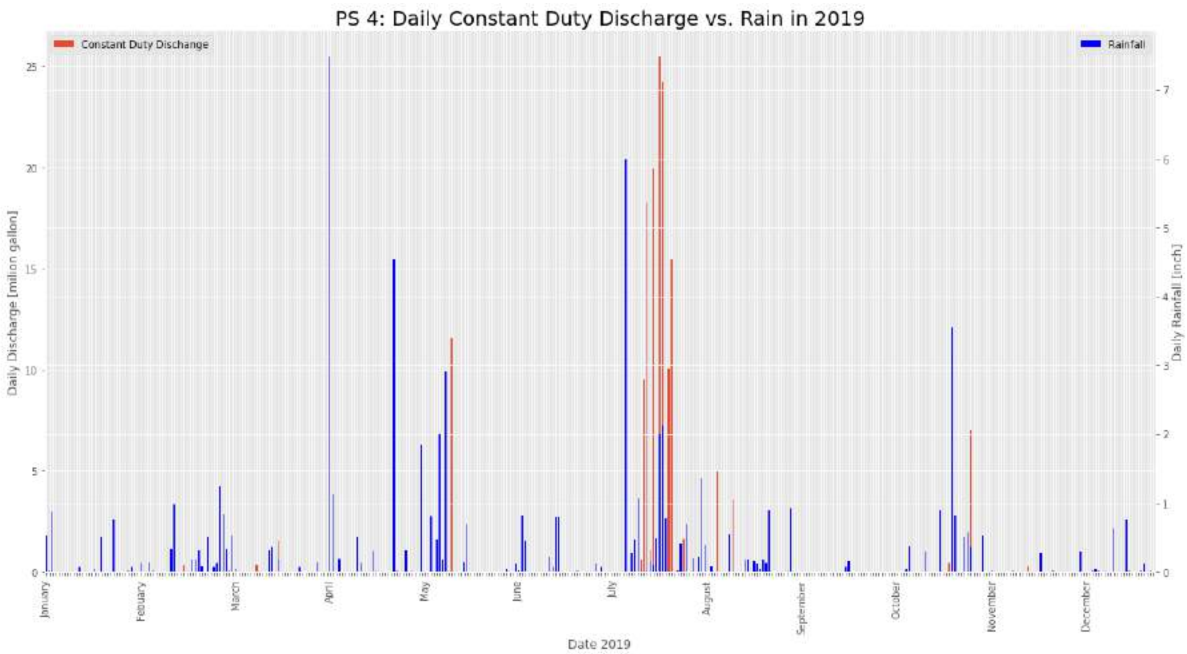

Figure C.5: DPS 4 constant duty pump discharge, rainfall time series for 2019

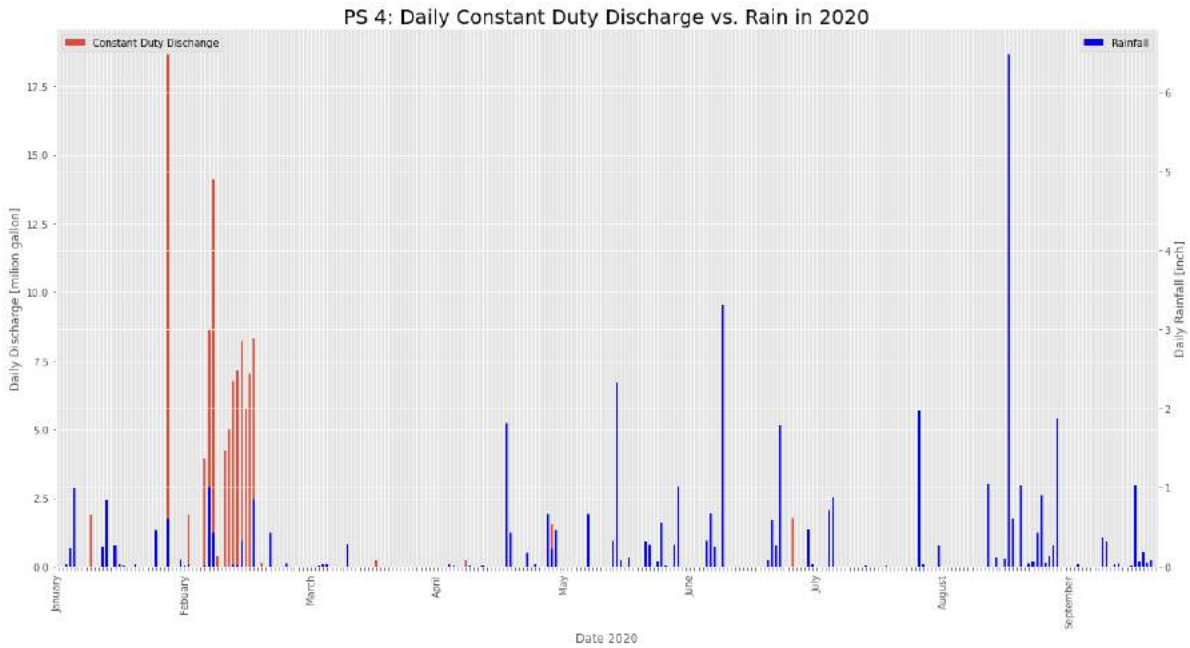

Figure C.6: DPS 4 constant duty pump discharge, rainfall time series for 2020