SPATIAL AND TEMPORAL ANALYSIS OF WATER FLOW IN BIG WOODS, BARATARIA PRESERVE, LOUISIANA, USA

A THESIS

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ACKNOWLEDGEMENTS

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1. INTRODUCTION

Built by the seventh largest delta on Earth, coastal Louisiana contains roughly 37 percent of the estuarine herbaceous marshes in the continuous United States (Couvillion et. al, 2011). Louisiana's wetlands are among the most biologically productive ecosystems in North America and sustain the largest commercial fishery in the lower 48 States (LCMP, 2017). A wetland is an area with a water table at, near or above the land surface either seasonally or continuously throughout the year (Salimi et al., 2021). Over the previous century, humans have changed this landscape to best fit their needs and, in the process, altered the natural flow and distribution of water. Climate change also plays a large role in altering wetlands both by direct and indirect effects of variations in rainfall intensity and frequency, increasing temperature, and extreme events such as hurricanes (Salimi et al., 2021). Studies have found that water modifications such as levees and dams have permanently impounded water in some areas, which has limited the regeneration of swamps, and causes the death of mature trees (Salinas et al. 1986; Chambers et al. 2005; Amos 2006). Additionally, they claim that this harms the productivity of swamps.

Located 15 miles south of New Orleans, Louisiana, the Barataria Preserve protects more than 26,000 acres of coastal wetlands in the Mississippi River delta. Jean Laffite National Historical Park and Preserve (JLNHP&P) consists of six historical locations spread through southern Louisiana; Barataria Preserve, French Quarter Visitor Center, Prairie Acadian Cultural Center, Acadian Cultural Center, Wetland Acadian Cultural Center, and Chalmette Battlefield and Cemetery, this study takes place in Barataria Preserve. Large portions of the Park's infrastructure (roads, parking areas, trails, buildings) lie on relatively higher ground, yet even these areas are experiencing increases in flooding frequency, duration, and depth. In order to plan and inform management of the JLNHP&P, we seek site-specific understanding of the hydro-climatological regime across the Preserve landscape at the key infrastructure “Big Woods” section within Barataria Preserve (figure 1).

JLNHP&P’s resource management team has established an Elevation & Hydrology Monitoring Array project that consists of monitoring stations throughout the Preserve. Water level monitoring wells were sited adjacent to facilities (buildings, parking areas, and trail heads) and at intervals along transects extending across different locations in Barataria Preserve, with elevation markers and atmospheric measuring devices in key locations. The Big Woods portions of the Elevation & Hydrology Monitoring Array design aimed to position wells across the eastern natural levee ridge of Bayou des Familles, the primary Mississippi River distributary that shaped this part of the Barataria Basin. Wells are positioned at similar elevations on both the western channel side and the impounded natural levee back slope to the east spanning its full topographic range and its matrix of interconnected ecosystems.

The work in this study supports analysis and interpretation of the hydrology data observed across this Elevation & Hydrology Monitoring Array. It is important to note, there have been no other studies on this scale of resolution within the defined area. This project directly informs the following high priority planning needs: a vegetation management plan for the Preserve, large-scale landscape restoration projects, and park-wide plans for adapting to increasing coastal flooding and vulnerability to strong tropical storms.

To achieve this goal, these questions will be explored. 1) How does the surface water drainage rate differ between seasons? 2) Is there a difference in well drainage times based on topography? 3) What areas are most frequently flooded?

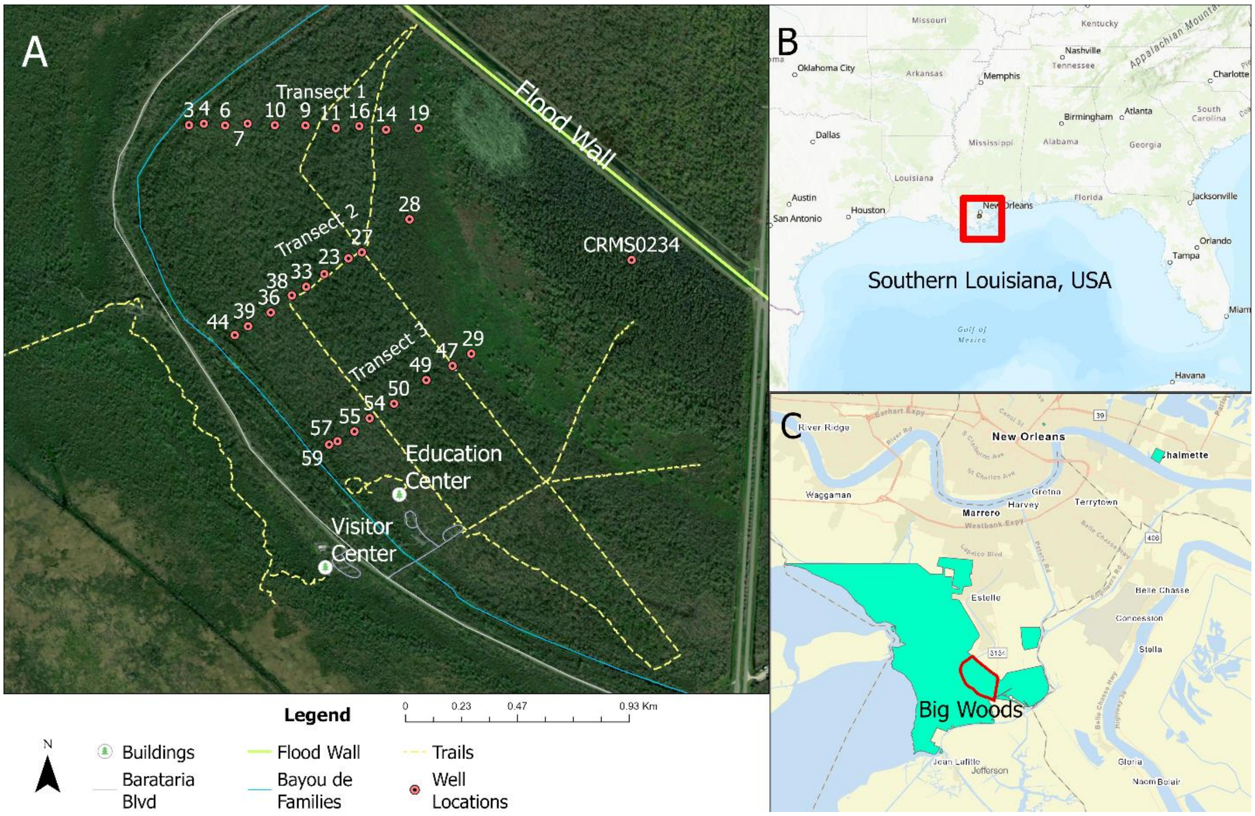


Figure 1: A) Shows location of wells on their respective transect along with trails/road/key locations within the park. B) A zoomed-out extent noting location of C. C) Defining the "Big Woods" area within JLNHP&P (shaded area).

2. GEOLOGIC SETTING

Formation of the Barataria Preserve occurred over two major episodes of the Mississippi River delta formation: the St. Bernard (4500 – 2000 BP) and Plaquemine - Modern (1000 – present) (Byrnes et al, 2019). Periods of lobe building occurred within each of these episodes (Holmes, 1986; Day Jr et al, 2007). Most Mississippi River flow in the area that is now Barataria Preserve was channeled through the distributary known as Bayou de Familles. Eventually this area was completely cut off from the Mississippi River as delta formation occurred elsewhere.

Natural levees are embankments along river banks, formed when sediment transported during times of flood is directed toward the bordering floodplain, where it settles out in low velocity areas. Levees normally show a relatively steep slope in the direction of the main channel and fall off steadily toward the floodplain. Highest elevations of the floodplain are typically found at the river's edge (Branß et.al, 2016). The natural levee ridges deposited by Bayou de Familles are the highest terrain in Barataria Preserve. This narrow "upland" zone lies less than 2 meters above sea level. Soil on the levee is relatively dry and composed of clays and fine sands. On either side of the levee, standing water is encountered more frequently and the landscape turns into a swamp-like environment.

Vegetation composition is closely aligned with elevation. Species such as live oak (*Quercus virginiana*) are found in the higher elevations on the natural levee. At lower in elevation, red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), green ash (*Fraxinus pennsylvanica*), hackberry (*Celtis occidentalis*), and American elm (*Ulmus americana*) dominate. Bald cypress (*Taxodium distichum*), tupelo gum (*Nyssa sylvatica*) and pumpkin ash (*Fraxinus profunda*) tress make up the majority in the flooded back swamp with dwarf palmetto (*Sabal minor*) dominating the understory (Denslow & Battaglia, 2002).

Driven by the natural compaction of river-deposited sediment, this part of the delta is subsiding rapidly. Rates of subsidence have been observed throughout the area ranging from 2 to 7 mm per year (Byrnes et al, 2019). This leads to an exceptionally high rate of relative sea level rise of up-to 12 mm $\pm$ 8 mm per year locally (Jankowski et al, 2017).

The study area is comprised of a three kilometer by two kilometer, meander bend of Bayou Des Familles (Swanson 1991). Situated on the outside of “New Orleans Hurricane and Storm Damage Risk Reduction System” (HSDRRS) flood walls surrounding greater New Orleans, Barataria Preserve is continually impacted by not only natural ecological systems but human interference as well. The system totals approximately 93 miles of levees and 22 miles of floodwalls. The United States Army Corp of Engineers (USACE) began to construct the original levee system in 1927, while the HSDRRS levees began construction anywhere from 1960’s to the 1980’s. The new HSDRRS levees were completed to 100-year risk reduction in 2011 (USACE, 2011). Flood walls and levees are constructed to protect human infrastructure from storm surge events. Flood walls are made of manmade materials such as concrete and sheet pilings while levees are compacted and built up soils. The flood wall situated along the northeastern perimeter of Big Woods is constructed from concrete, sheet pilings and compacted soil. The Army Corp of Engineers has a typical design for flood wall construction that can be altered to be site specific. While specific design plans for the flood wall near Big Woods have not been obtained, the typical design states for sheet pilings to a depth of 20-25 ft. below surface with “T” shaped concrete foundations, and a 1V:3H ratio of slope (vertical to horizontal) for the surrounding soil.

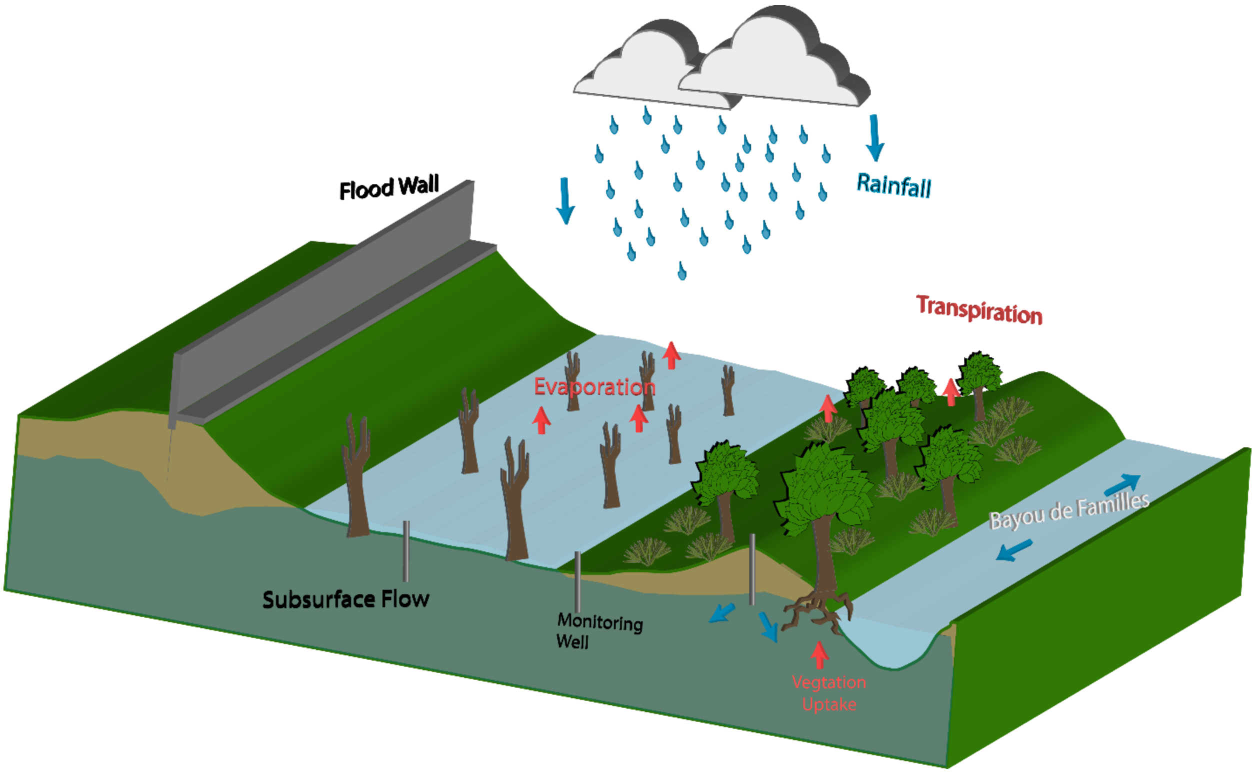


Figure 2: Section of Big Woods showing the hydrologic cycle. Note not all hydrologic flows are displayed.

Little is known about the hydrologic cycle in the study area. Planning and managing water resources and the environment effectively requires an understanding of water budgets and underlying hydrologic processes (Healy et al. 2007). Figure 2 illustrates the flows that we know are impacting the water cycle in Big Woods, although the magnitude of any all of these fluxes, barring rainfall, is unknown. The main inflows to Big Woods are rainfall and surface and subsurface flow from outside of the study area. Outflows are evaporation, transpiration, surface runoff, and subsurface flows. We do not know if there is subsurface flow below the flood wall and, if there is, the directionality of this flow. Further, whether there is surface water flow out of the impounded area near the floodwall is not known. Although measurements of surface and subsurface drainage will be made in this study, we do not make estimates of any individual flows or subsurface drainage directions.

3. METHODS

3.1 Well Installation

To understand the movement of water in Big Woods, 27 shallow monitoring wells were installed along three transects between 2014 and 2017. Each transect includes 8 – 10 wells and spans an elevation gradient of approximately 0 to 2 meters above local sea level. Transects were chosen to capture the full topographic range of Big Woods and cross all of its interconnected ecosystems, spanning from the west side of the natural levee close to Bayou de Familles into the eastern back slope area impounded by the man-made levee on the park's boundaries. An additional well that is part of the Coastwide Reference Monitoring System (CRMS), Well CRMS0234, is also referenced in this study and will be noted when its data is used. See figure 1 for CRMS0234's location.

Shallow monitoring wells allow flow of water through perforations along most of the length of the pipe below ground. The water level in a monitoring well returns the water pressure integrated over the long, perforated portion of the pipe. This water level is equivalent to the local water table. The wells are two inch diameter slotted at 0.010 inch and 10 feet long PVC well pipe, fitted with a conical tip on their bottom end and topped with a securable screw cap. The installation of the wells was done by hand with a 2 ¼ inch diameter hand auger to a depth of 6 feet below surface. The well pipe is designed to have 4 feet of pipe left exposed above the ground surface to capture flooding events. Any gaps in the ground left during the installation

Well_ID	Latitude	Longitude	Elevation
03T1EL2W	29.8004	-90.12055	0.196808
04T1EL3W	29.8005	-90.11999	0.686735
06T1EL4W	29.8004	-90.1192	0.806435
07T1EL4W	29.8005	-90.11836	0.854224
09T1EL5T	29.8004	-90.1162	1.129131
10T1EL5T	29.8004	-90.11734	1.162642
11T1EL4E	29.8003	-90.11507	0.796115
14T1EL2E	29.8002	-90.1132	0.540991
16T1EL3E	29.8004	-90.1142	0.626006
19T1EL2E	29.8003	-90.11199	0.55163
23T2EL4E	29.7954	-90.1146	0.819853
27T2EL3E	29.7957	-90.1141	0.746259
28T2EL3E	29.7969	-90.11232	0.707236
29T3EL2E	29.7919	-90.11002	0.372609
33T2EL5T	29.7944	-90.11618	1.00024
34T2EL5T	29.7948	-90.1155	1.039825
36T2EL4W	29.7934	-90.1175	0.788385
38T2EL4W	29.794	-90.11671	0.807028
39T2EL3W	29.7929	-90.11834	0.59857
44T2EL2W	29.7926	-90.11884	0.161247
47T3EL3E	29.7914	-90.11072	0.449671
49T3EL4E	29.7909	-90.1117	0.854524
50T3EL5T	29.79	-90.1129	1.008525
54T3EL4W	29.7895	-90.11381	0.892348
55T3EL4W	29.789	-90.11438	0.849417
57T3EL3W	29.7886	-90.11501	0.567386
59T3EL2W	29.7885	-90.11532	0.3576
CRMS0234	29.7954	-90.10404	-0.03861

Table 1: A list of all wells in the study area Big Woods with spatial locations and elevations in meters referenced to NAVD88.

process were filled with silica sand. A list of all 27 well is provided in table 1 along with their spatial locations and elevation in meters related to the North American Vertical Datum of 1988 (NAVD88). The naming convention for the wells is a combination of the well number (first two numbers in the Well ID), the transect it is located in (T1, T2, or T3), the wells elevation rounded to the nearest foot (EL#), and its location in relation to the natural levee ridge (E for east, W west, or T for top). For example, 03T1EL2W would read as; 03 (Well 03), T1 (Transect 1), EL2 (Elevation of 2 feet), W (West of the levee ridge).

3.2 Levelogger and Other Data Collection

Inside each well is a Levelogger manufactured by Solinst positioned near the bottom of the well, which records pressure and temperature every hour. Barometric pressure is collected from a similar Solinst logger suspended near the top (instead of near the bottom) of a single well that is identical to those deployed in the array of transects. With sensors at the tip, the Levelogger records pressure exerted by the columns of water and air above. Data is corrected to remove atmospheric pressure collected from the barometer to isolate water pressure and give a vertical height of water above the logger. This height is then referenced and corrected to NAVD88 to give an absolute water elevation. This method was done to give a standardization of height of the water table for all loggers to the reference datum of NAVD88.

From here a water level relative to the surface of each well is calculated and unless otherwise stated, all figures will show water levels in reference to the local land surface at the well, which is shown as '0 m' on figures. In other words, positive values indicate the surface is flooded, and negative values indicate the water table is below the surface. Water level data is downloaded via Bluetooth into software from Solinst, converted into csv files, and appended to a master dataset.

Precipitation and air temperature data are collected hourly at the visitor center in the park via tipping-bucket rain gauge integrated in a Campbell Scientific RAWSP microprocessor-automated weather station. This data along with data sourced from National Atmospheric and Oceanic Administration (NOAA) are used in this paper.

3.3 Data Selection and Cleaning

The original data was provided by Jean Lafitte National and Historic Preserve for this analysis. The team at the Preserve has detailed steps on how data is appended to master files and stored within their servers. The steps taken here are done after the data was appended and delivered. The original files are organized by transect and individual well, resulting in 27 files, each with their own unique values. To begin, each file is manually checked for consistent naming conventions, and a search for NaN (not a number) or missing values is performed. The data is plotted over the entire timescale to look for outliers and large gaps (greater than two months) in the timeline. Table 2 below lists the wells with noticeable outliers and large gaps:

OUTLIERS	**DATA GAPS**
03T1EL2W	04T1EL3W
39T2EL3W	19T1EL2E
47T3EL3E	27T2EL3E
	49T3EL4E
	29T3EL2E

Table 2: Wells with outliers and data gaps found in the dataset.

Outliers were manually checked and removed if thought to be due to recording or device issues. An example of this is with well 03T1EL2W where readings of more than 15,000 m were recorded. These outliers were removed and will not be used in the analysis. Wells with data gaps will still be used but if data is not present for the time of analysis, they will not be included.

The original datasets include 18 columns of data (from left to right):

Well #, Well ID, Well Serial, Date, Time, non-daylight savings Time standardized, Non daylight savings Date standardized, NDST time and date combined, Temperature (°C), Water Level (Raw) (m), Water Level (BC) (m), Well Surface Elevation (m), Well Height (cm), Cable Length (cm), Cable Slack/Mud Accumulation (cm), Absolute Elevation of Logger (relative to NAVD-88) (m), Absolute Elevation of Water Table (relative to NAVD-88).

Only a few columns will be used for this analysis: Well ID; Date and Time Combined; and a new column called Water Level. This new column is calculated by taking the *Absolute Elevation of Water Table* and subtracting the *Well Surface Elevation*, which provides a water level relative to the ground level for each well.

3.4 Data Analysis

3.4.1 Code to prepare data

To easily navigate the large datasets, Python code was utilized in order to group and sort the data. Multiple scripts were created depending on what variable was going to be manipulated. In general, the script will pull the file, group the desired variables, and then allow for different statistical analysis on the data, such as sum, minimum, maximum, standard deviation, and moving average. The data is kept in hourly format. This allows for flexibility of timeframes. From here the data can also be grouped by frequency of events.

3.4.2 Drainage Rates

To find drainage rates for each well, local minimum and maximum water level and the time in-between measurements were needed. When looking manually at a chart this can be easy to identify, but hand measurements for all the data would be too time consuming. A code was created to collect these data. The code works by grouping data into 12 hour windows and looks for a local minimum or maximum. If found, it will assign that value and search the 12 hour window to determine if the water level continues to decrease from a local maximum or increase from a local minimum. If the pattern continues through the original 12 hour window, the code will shift to the next 12 hour window and look for a change in trend to assign the overall minimum or maximum of an event. The time in between these values is stored as a count of hours and then divided by 24 to get a drainage rate of meters per day.

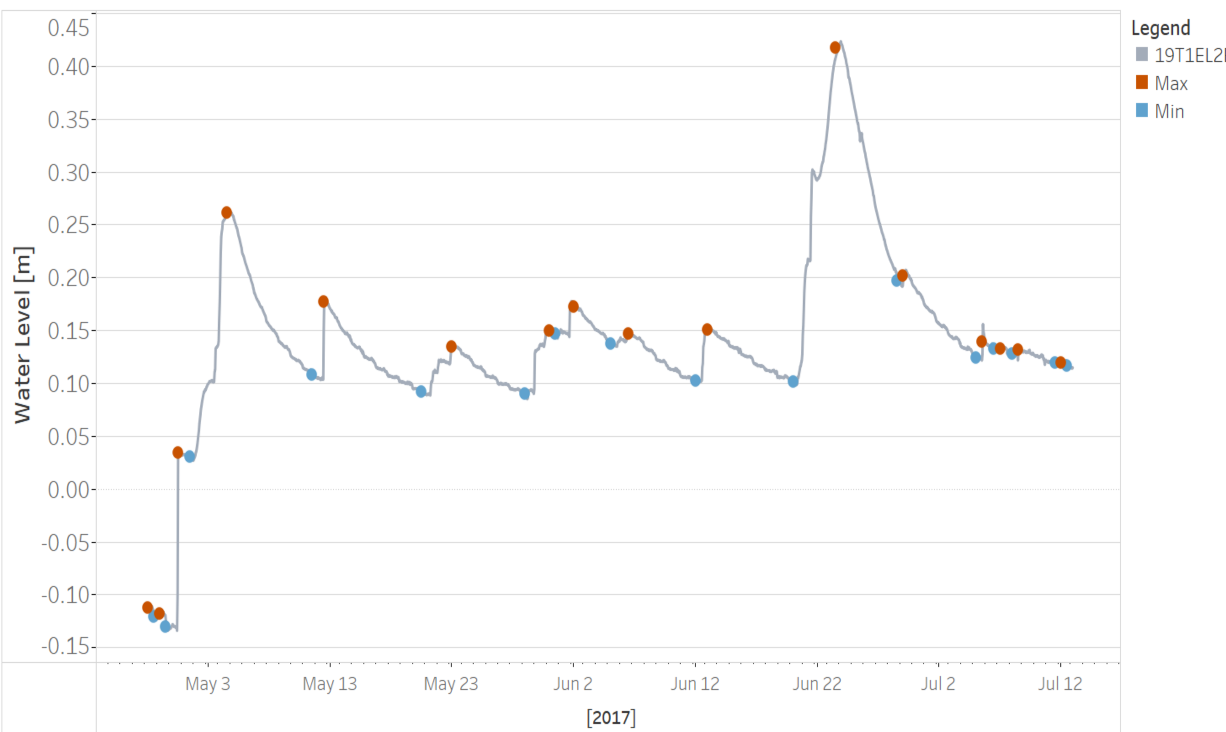


Figure 3: Shows the plotted points chosen by python function to locate local Min and Max points to create drainage rates.

Multiple timeframe variations of this code were run, and the grouping of 12 hours for the timeframe for searching for local minimum and maximum proved to be the most accurate when compared to a manual selection of local minimum and maximums. The goal is to compare the drainage rates between seasons and elevation of the wells (figure 3).

3.4.3 Count of Days Inundated

A day spent inundated counts as 24 hourly water depths showing greater than 0.0 m. A separate code was used to calculate the number of days within each month that a well spent inundated. In other words, a day spent inundated is not necessarily from 12 am day 1 to 12 am day 2. There is also the concern of the wells not having a full amount of records (365 days per year). In order to remove bias from more or less data recorded for a particular year, the counts of days inundated are normalized to the counts of records for the year.

3.5 Well Selection

This study focuses on the behavior of a subset of wells. Many of the wells behave similarly, and wells were chosen to represent the different behavior of the water table across the study area Wells were chosen to span the following variables: location, elevation, days spent inundated, similar behavior as neighboring wells, and representation of areas with less well density. The wells below were selected, and the reason for their inclusion is given.

- Transect 1: 3, 7, 16 and 19
    - T1 has the most complete dataset and the most variation in well behavior, and will have the most wells for analysis.
    - Well 3 is closest to Bayou de Familles and has a high count of days spent inundated.
    - Well 7 is mid-way up the natural levee and has variation in inundation.

- Well 16 shows increasing number of inundated days and on the back slope of the natural levee.
- Well 19 is in the impounded low-lying area.

- Transect 2: 44, 33, and 28
  - Well 44 is closest to Bayou de Familles.
  - Well 38 is on the natural levee but might be in an historic run-off channel as it has more days inundated compared to surrounding wells.
  - Well 28 is in the impounded low-lying area.

- Transect 3: 57, 50, and 29
  - Well 57 was chosen over Well 59 (59 is closer to Bayou de Familles) as Well 57 has a longer data record and both share similar inundation counts.
  - Well 50 is consistent with its levels and inundation counts and is on the natural levee.
  - Well 29 is in the impounded low-lying area.

4. RESULTS

4.1 Rainfall Totals

The yearly rainfall and average temperatures are shown in table 3. The sources for this data are the National Oceanic and Atmospheric Administration (NOAA) website using the Louis Armstrong New Orleans International Airport (MSY) and the weather station located within JLNHP&P boundaries. The data record for JLNHP&P begins in September of 2015, so annual data begins in 2016. There is an average of 46.2 centimeter difference between the yearly rainfall totals at the two locations. The two stations are approximately 26 kilometers apart, and this may play a role in the different values, along with how the stations are constructed and other varying factors that can add to error in measurements. Additionally staff from the park have recently (late 2022) adjusted the location of the rain gauge as it was believed to be in a rain shadow and this can account for the large differences seen in the two records. The stations do record most of the same rainfall events and that is important when looking for well response and drainage rates. Yearly average temperature values have an average difference of 2.3 degrees Fahrenheit between the two stations. This study will generally use JLNHP&P

Annual Rainfall and Temperatures

Year of Record	MSY Airport: Rainfall [cm]	JLNHP&P: Rainfall [cm]	MSY Airport: Temp Average [F]	JLNHP&P: Temp Average [F]
2014	139.0		68.9	
2015	181.2		71.9	
2016	179.7	114.9	73.0	70.8
2017	183.9	124.5	71.4	70.4
2018	156.4	127.3	71.7	69.6
2019	158.8	126.0	72.3	69.4
2020	182.2	112.4	73.0	70.4
2021	218.6	190.0	71.7	69.5

Table 3: The total annual rainfall and average annual air temperatures from MSY Airport and JLNHP&P.

temperature data for all analyses. However, like the rainfall data, temperature data before 2016 was not available at JLNHP&P, and the MSY Airport records will be used for that time period.

4.2 Drainage Rates and Water Levels

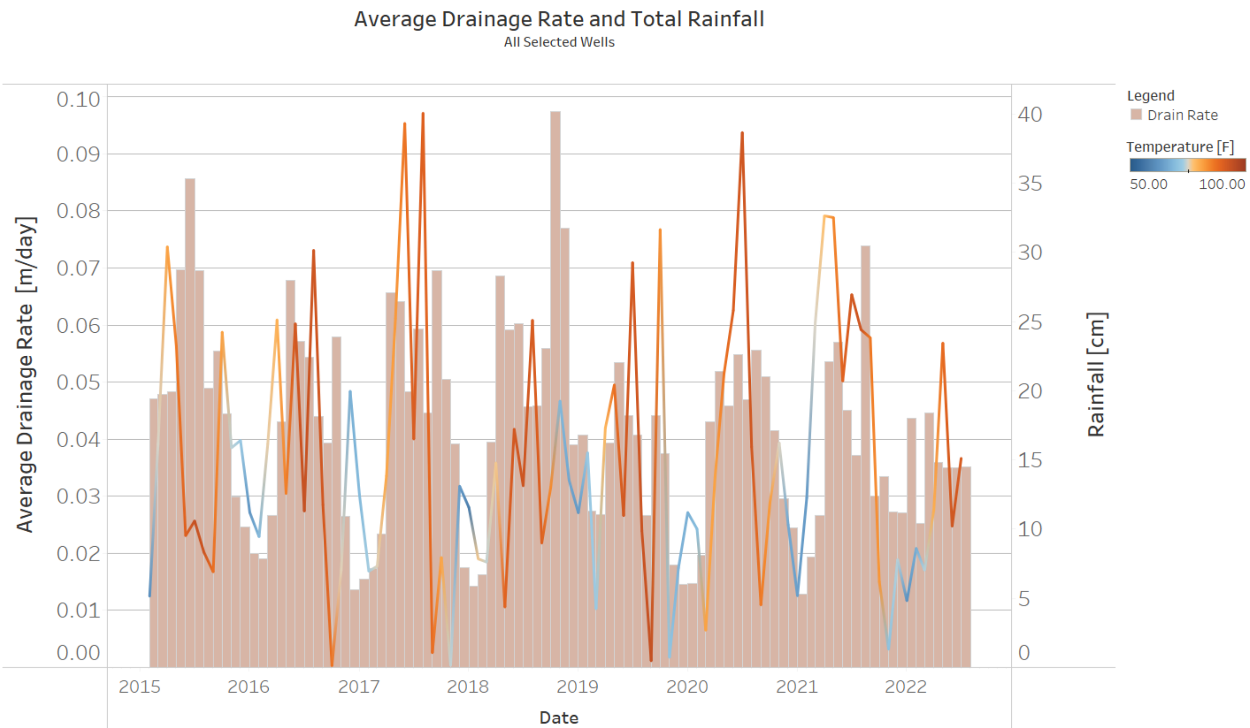


Figure 4: Time series of average monthly drainage rate (bars, left axis), averaged overall all selected wells, and monthly total rainfall (line, right axis) colored by monthly average temperature.

Figure 4 shows the average monthly drainage rate in meters per day averaged over all selected wells in the study area. Also shown in Figure 4 is the monthly total rainfall colored by average monthly air temperature. The color gradient used to show average monthly temperature has a median point of 75 degrees Fahrenheit. To compare drainage rates among seasons, three-month sections were chosen and averages of the drainage rates were created. The “summer” months consist of July – September, while the “winter” months are January – March of the following year. Table 4 breaks down the percentage difference between seasons.

Average Drainage Rates per Season (m/d)				
Year	**Summer**	**Winter**	**Percent Difference**	**Range**
2016	**0.06**	**0.02**	**165%**	**0.05**
2017	**0.05**	**0.02**	**145%**	**0.04**
2018	**0.06**	**0.02**	**148%**	**0.06**
2019	**0.05**	**0.03**	**55%**	**0.03**
2020	**0.04**	**0.03**	**44%**	**0.03**
2021	**0.05**	**0.02**	**161%**	**0.04**
2022	**0.05**	**0.04**	**24%**	**0.05**

Table 4: Averages of drainage rate for all selected wells in the study area shown at a rate of meters per day as defined by season for each year. Percent difference is the absolute difference between the values divided by the smaller value. Range is the largest value subtracted from the lowest value. Rates were rounded to the nearest hundredth.

The average percent difference in drainage rate between seasons is 106%. The maximum drainage rate for all date ranges was recorded in October 2018 (0.097 m/d) and the minimum in January 2021 (0.013 m/d).

The drainage rate measurements include evapotranspiration, along with the flow of surface and subsurface water. In other words, anything that decreases local water levels is included as drainage. Thus, temperature should be a control on drainage rate. To investigate this, we plot drainage rate as a function of temperature at each of the selected wells (Figs. 5 - 14). Relatively higher drainage rates for each well only occur during periods of higher temperatures. Well location also plays a role in these measurements as wells that are consistently inundated aren’t as affected by the changing of temperatures. Note that not every drainage event signal is found for the same temperatures across the wells. The algorithm works on 12 hours windows that may vary from well to well and will have variations in temperature at the time of record. Also, some wells don't record drainage when other wells do. Note that only non-zero values are shown in Figs. 5-14, but small values are not well resolved on the plots.

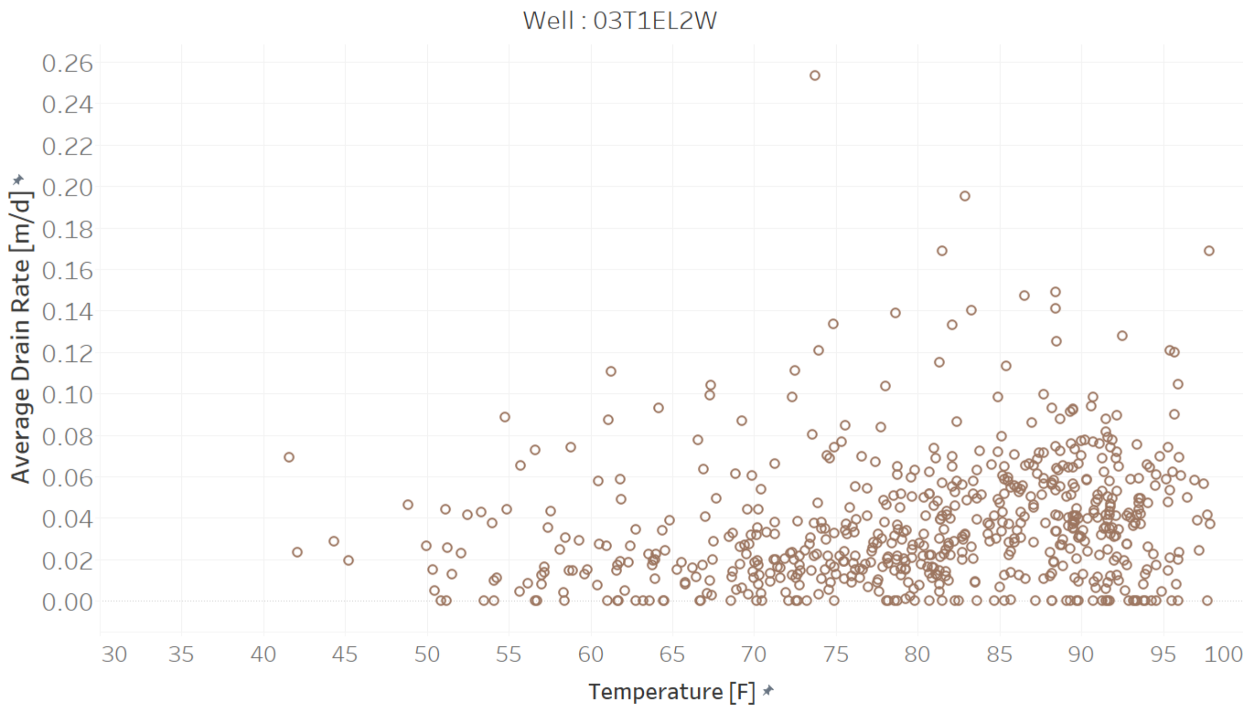


Figure 5: Plot showing the relationship between drainage rates and air temperature for Well 03T1EL2W

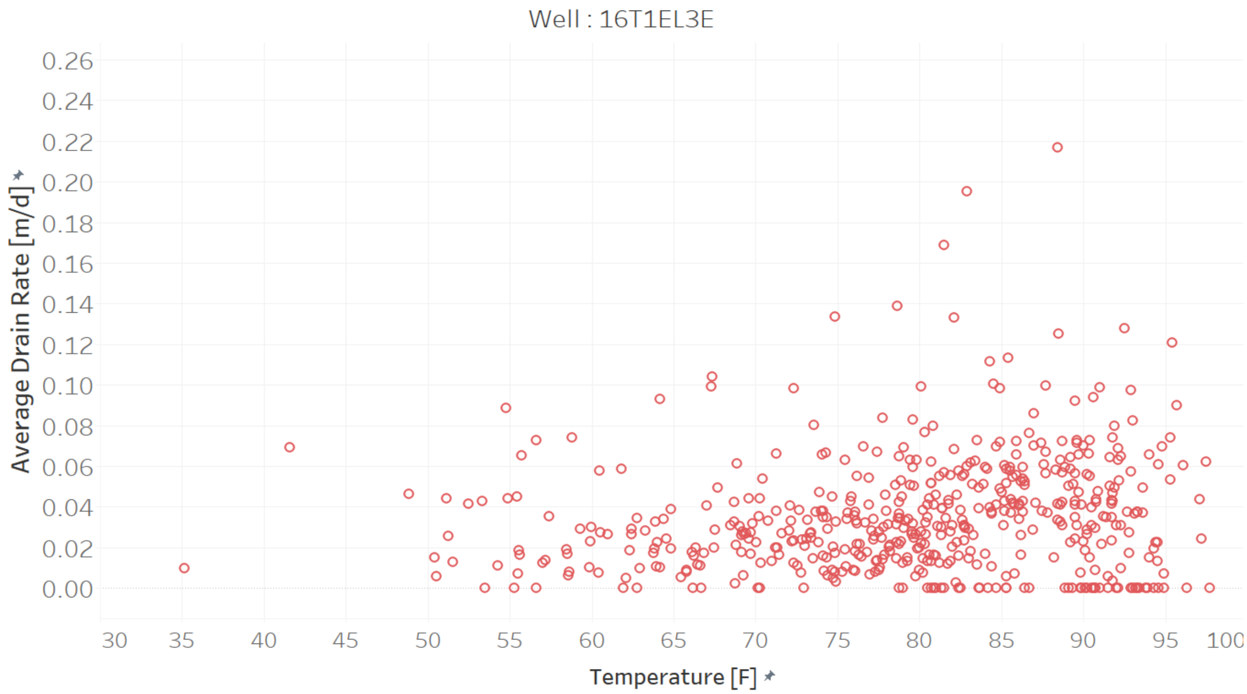


Figure 6: Plot showing the relationship between drainage rates and air temperature for Well 16T1EL3E

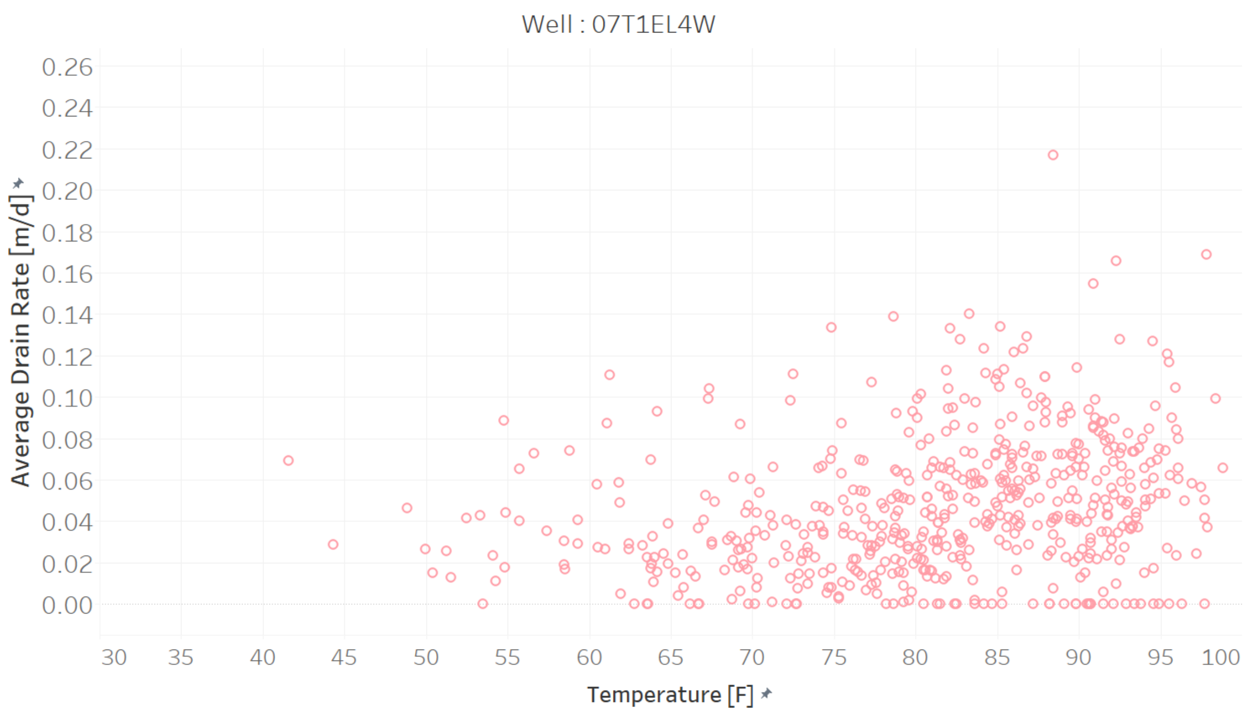


Figure 7: Plot showing the relationship between drainage rates and air temperature for Well 07T1EL4W

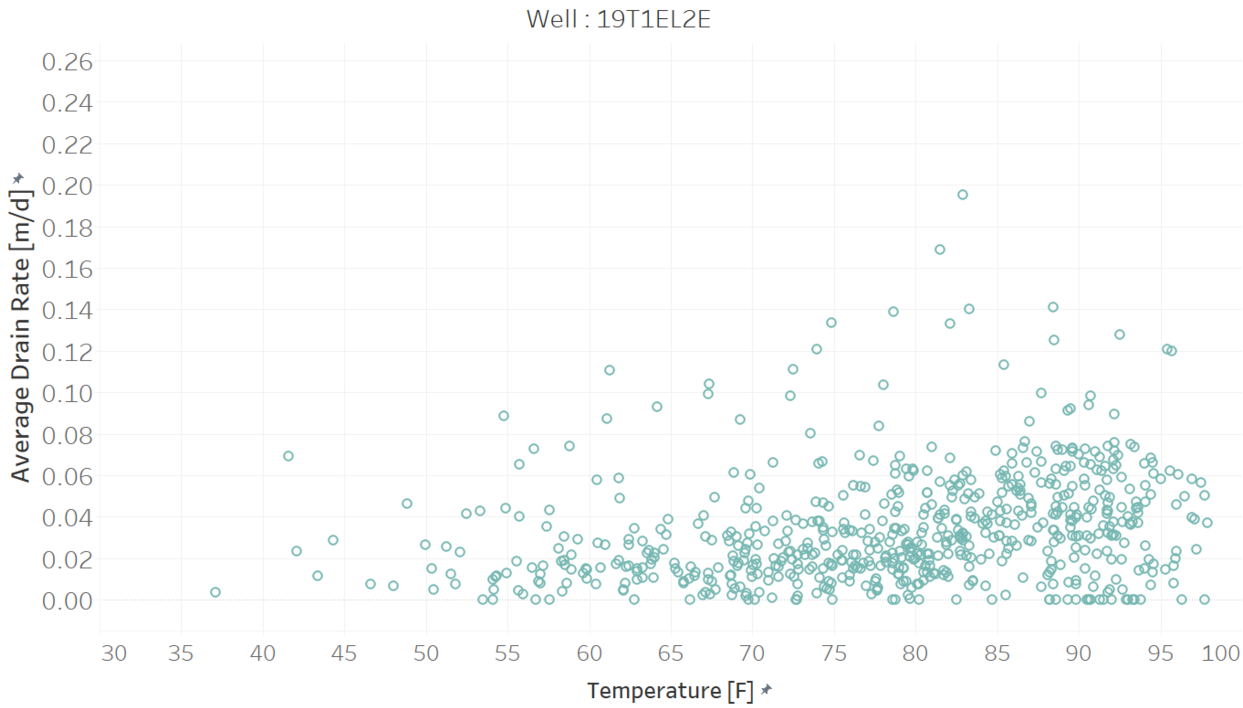


Figure 8: Plot showing the relationship between drainage rates and air temperature for Well 19T1EL2E

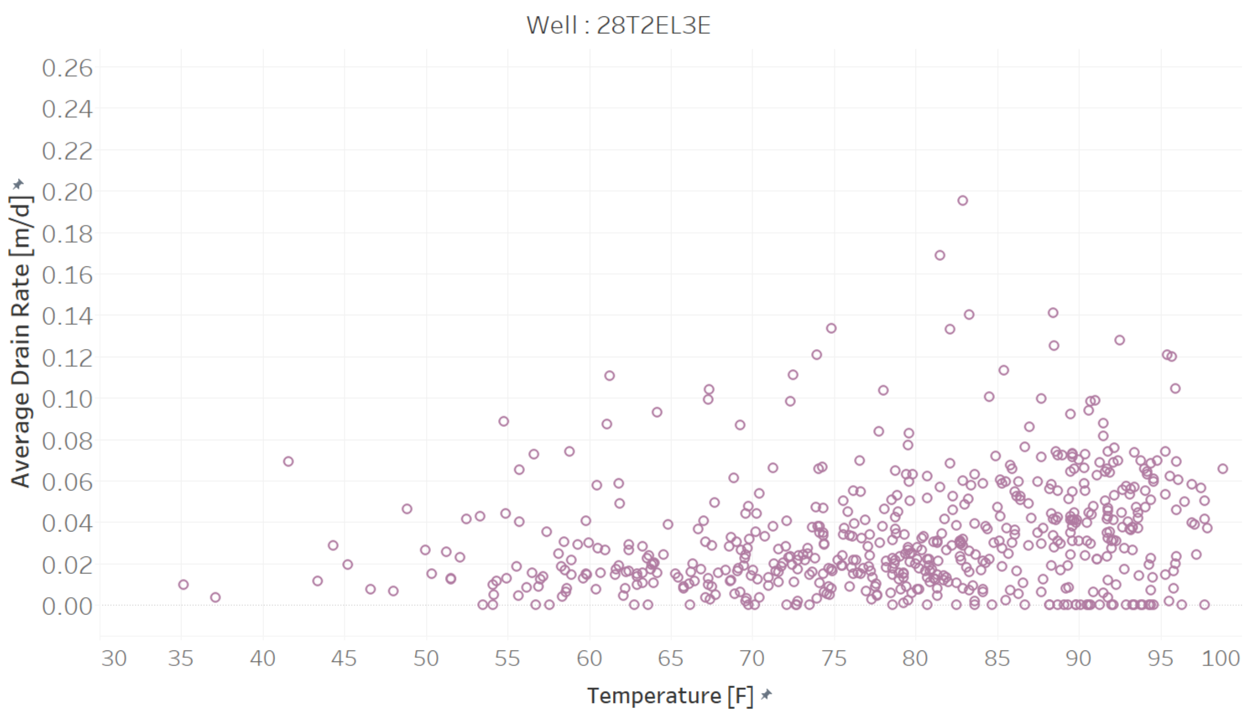


Figure 9: Plot showing the relationship between drainage rates and air temperature for Well 28T2EL3E

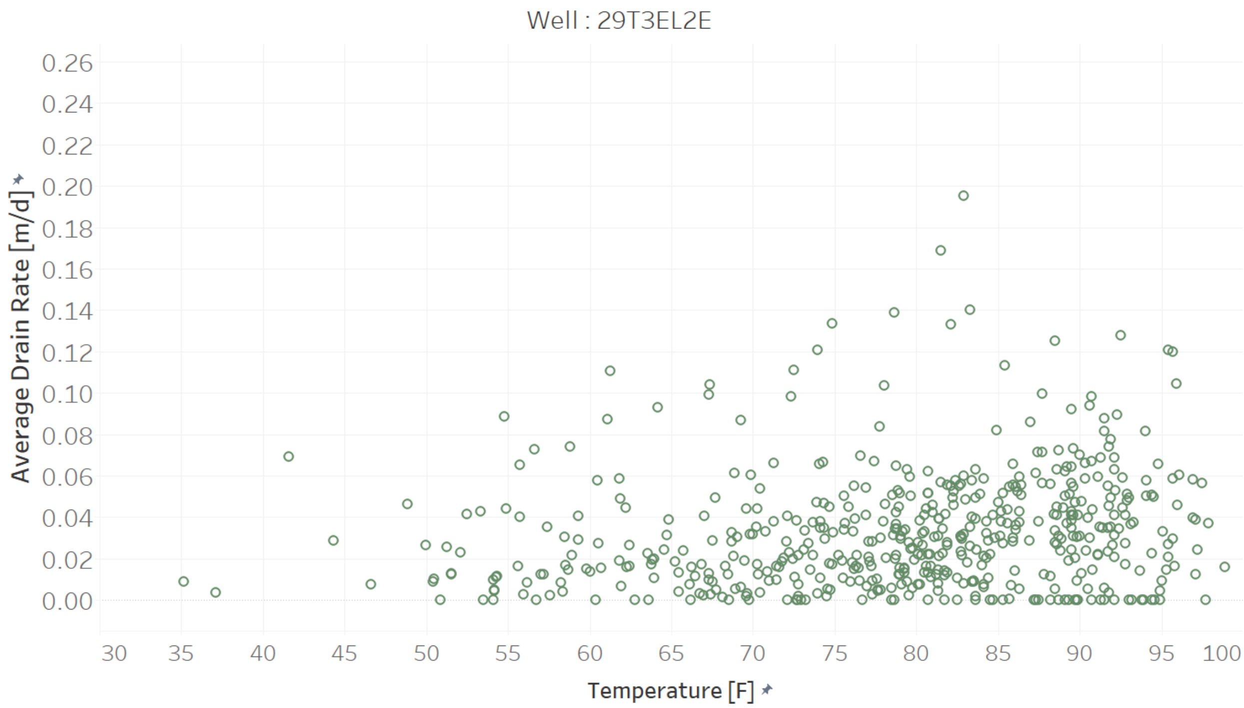


Figure 10: Plot showing the relationship between drainage rates and air temperature for Well 29T3EL2E

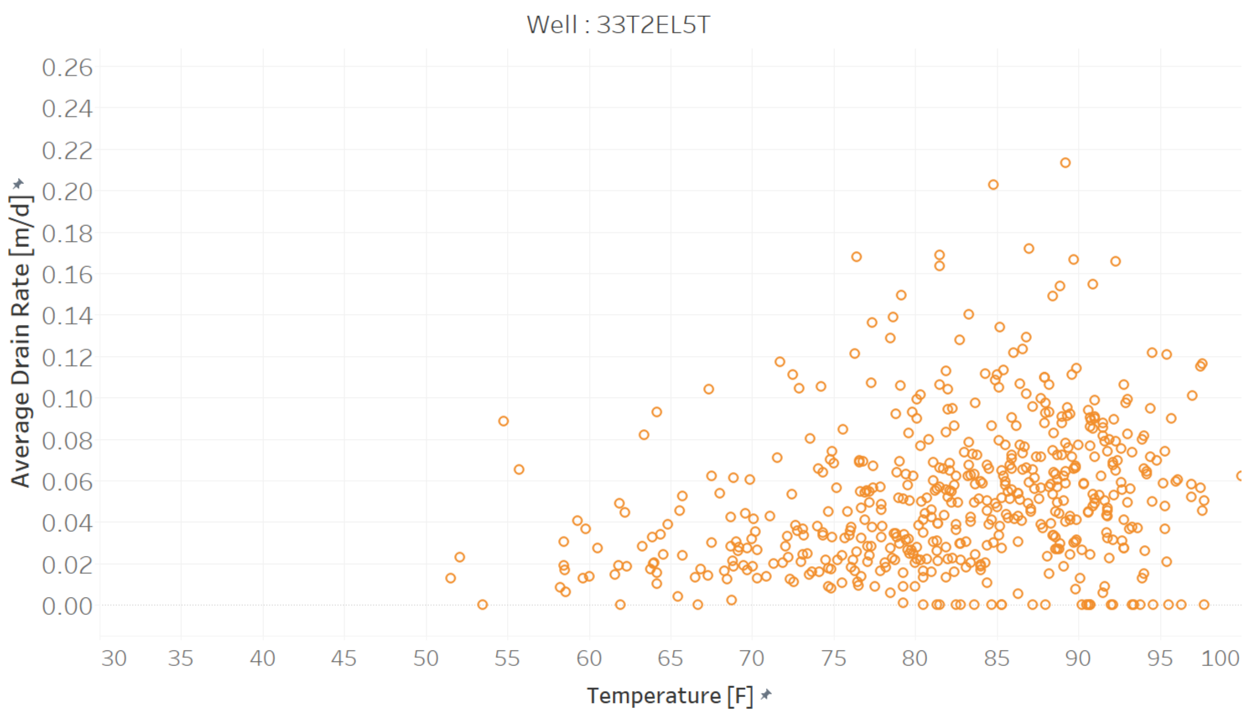


Figure 11: Plot showing the relationship between drainage rates and air temperature for Well 33T2EL6T

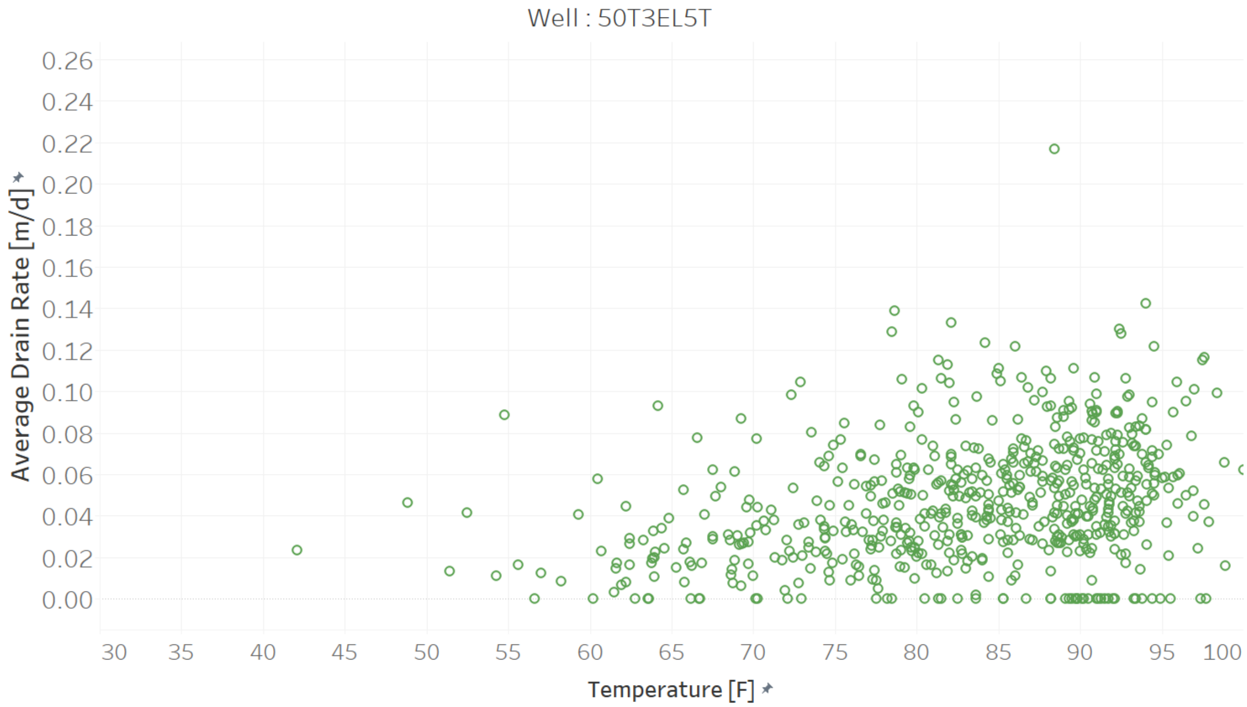


Figure 12: Plot showing the relationship between drainage rates and air temperature for Well 50T3EL5T

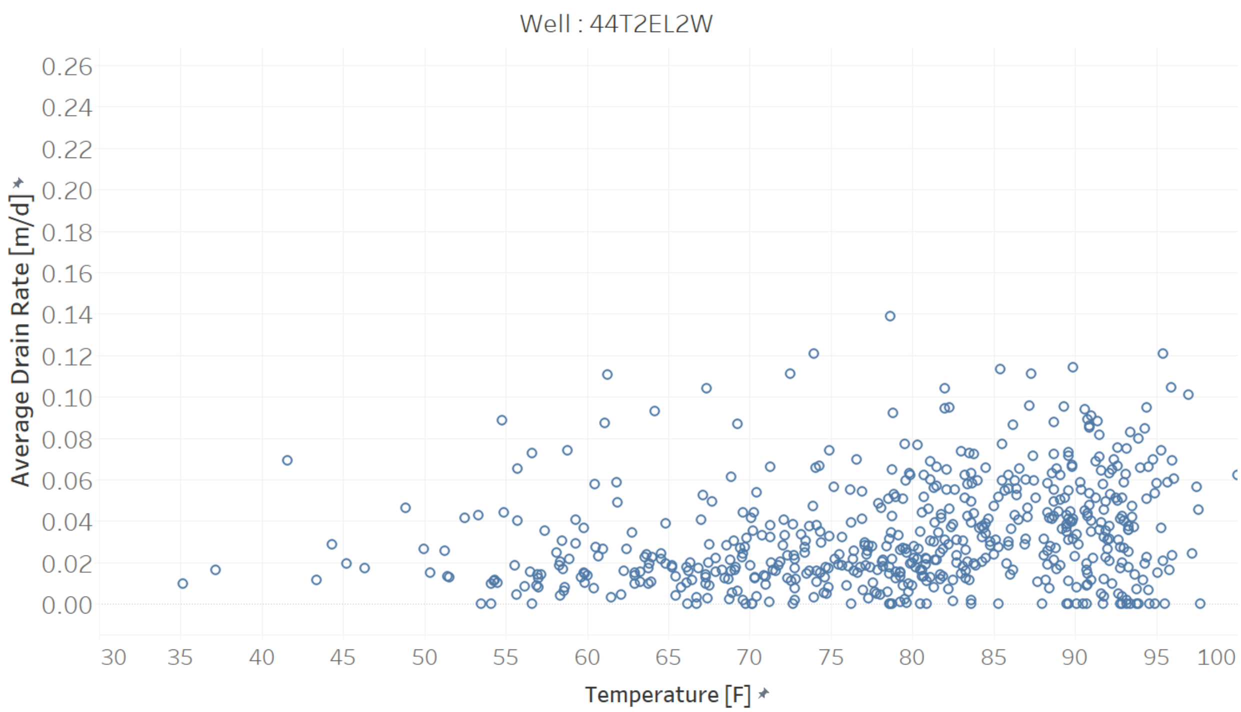


Figure 13: Plot showing the relationship between drainage rates and air temperature for Well 44T2EL2W

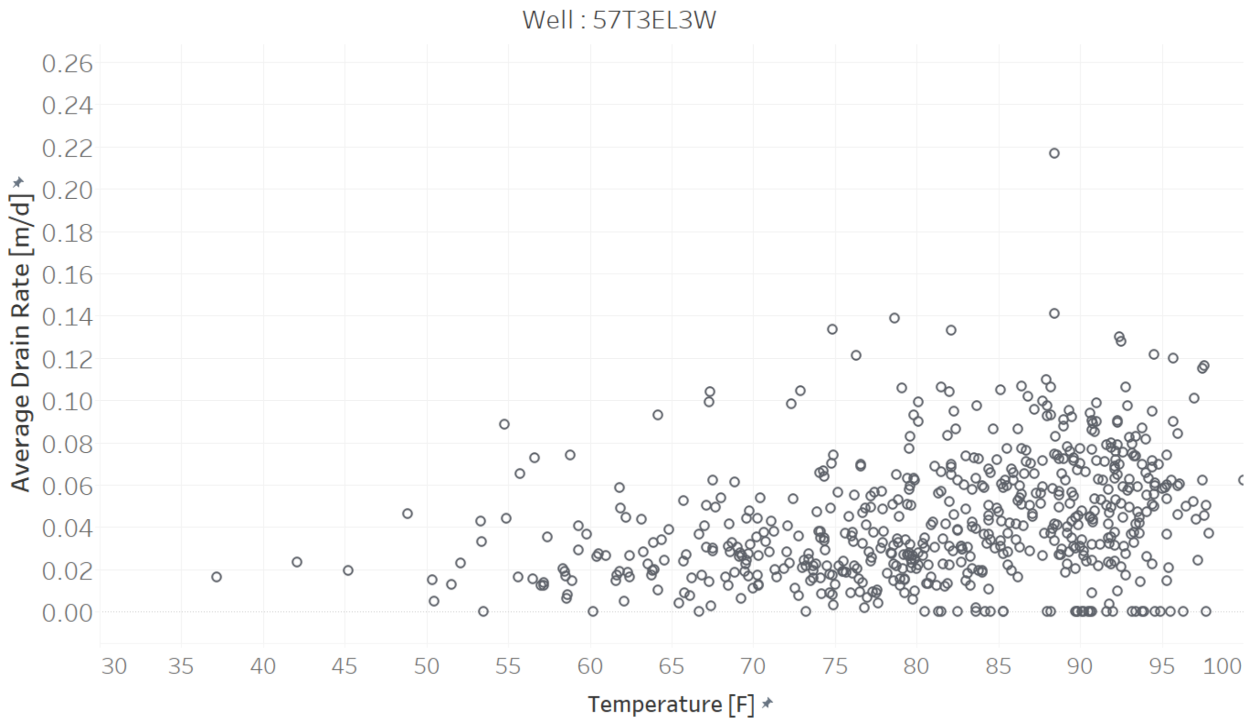


Figure 14: Plot showing the relationship between drainage rates and air temperature for Well 57T3EL3W

Well Statistics			
Well ID	Correlation	R^2	P-Value
03T1EL2W	0.05	0.003	0.321
07T1EL4W	**0.47**	**0.224**	**< 0.0001**
16T1EL3E	**0.29**	**0.087**	**< 0.0001**
19T1EL2E	0.03	0.001	0.574
28T2EL3E	0.20	0.041	0.001
29T3EL2E	0.10	0.010	0.080
33T2EL5T	**0.40**	**0.158**	**< 0.0001**
44T2EL2W	**0.24**	**0.057**	**< 0.0001**
50T3EL5T	**0.57**	**0.328**	**< 0.0001**
57T3EL3W	**0.41**	**0.164**	**< 0.0001**

Table 5: Correlation values of temperature and drainage rate for the selected wells.

Correlations were derived from linear regression on the data at each well and are displayed in table 5. Wells highlighted yellow show mild significance between temperature and drainage rate.

The correlations are difficult to interpret as there are more variables controlling the drainage rate beyond temperature. To better understand the data, hourly data is plotted at shorter timescales for each of the selected wells over a short time period (Figures 15 and 16). These data illustrate that following the same rainfall event, drainage rate can greatly vary among the different wells. Beyond temperature, location on the landscape is a primary control on drainage rate. The wells in figures 15 and 16 that have less relative change in water level over time are generally the wells that remain inundated over time, either near Bayou des Familles or in the area near the flood protection wall.

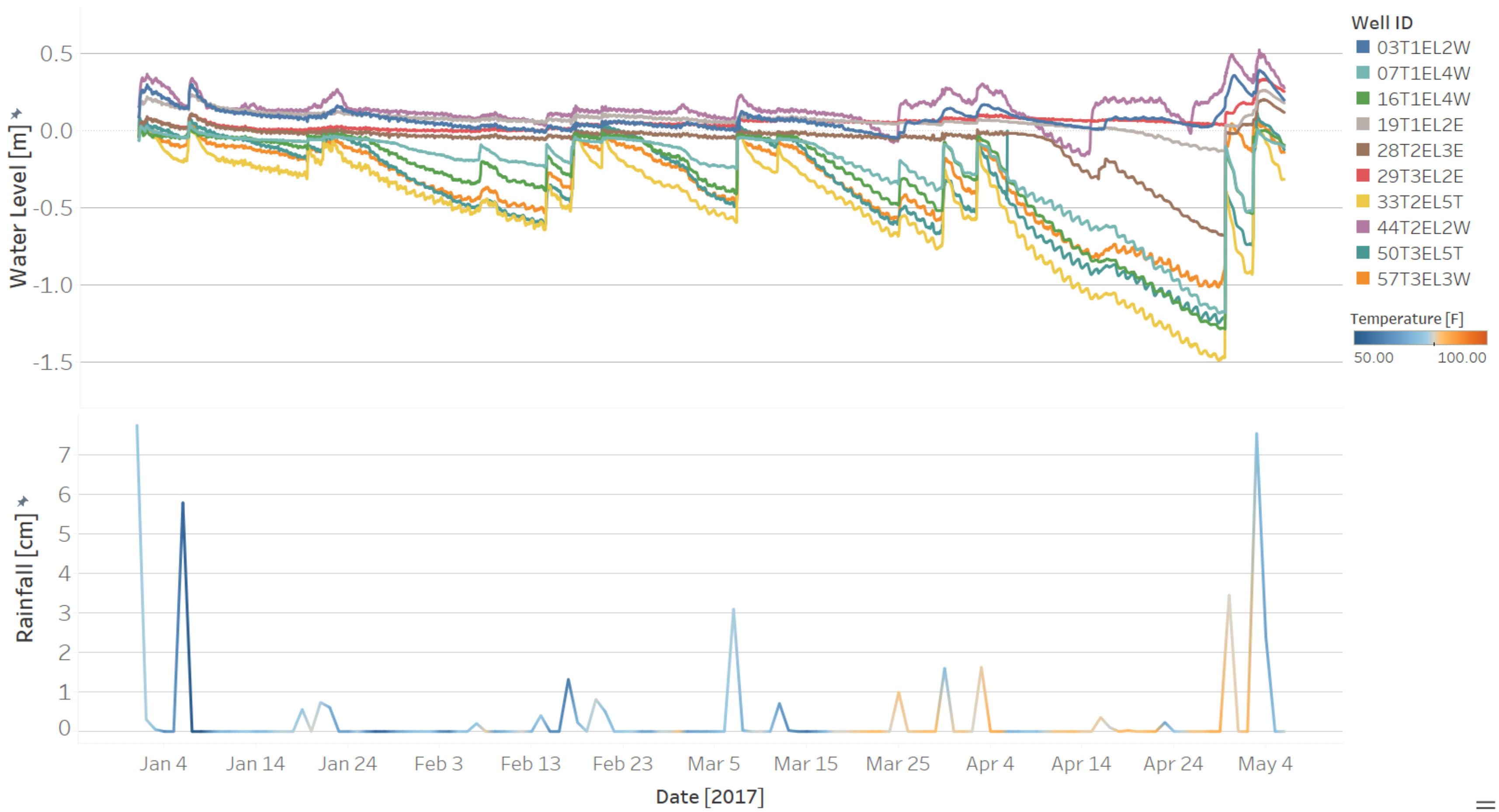


Figure 15: Time series from January to April 2017 with water level (m) in top plot and rainfall (cm) colored by average daily temperature on bottom plot.

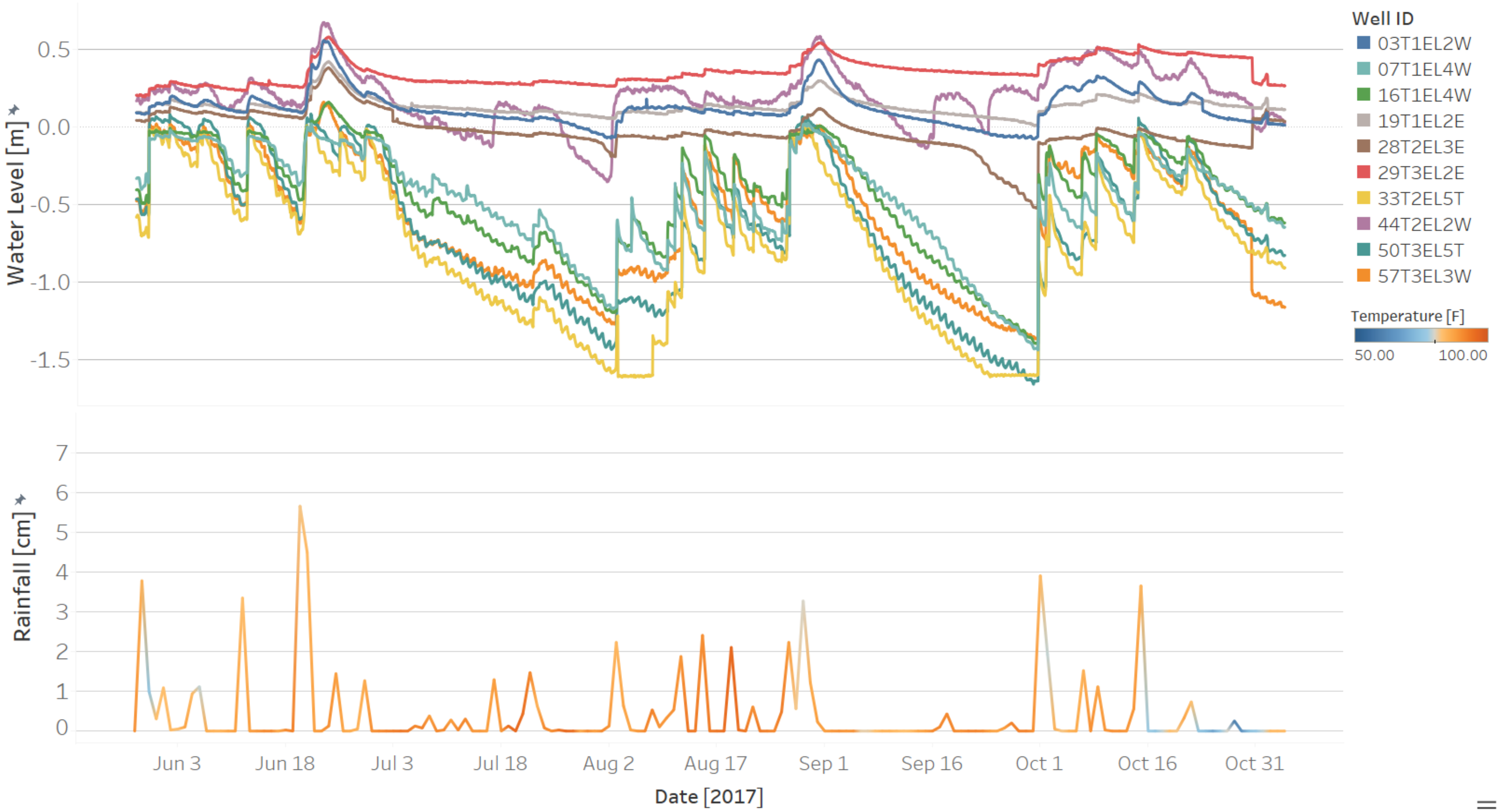


Figure 16: Time series from June to October 2017 with water level (m) in top plot and rainfall (cm) colored by average daily temperature on bottom plot.

Temperature [F]			
Month in 2017	Min	Max	Average
January	39	80	60.1
February	59	81	64.4
March	57	83	67.3
April	69	86	71.3
May	68	90	73.9
June	79	92	80.1
July	85	96	83.2
August	80	96	83.1
September	81	92	80.1
October	60	90	72.9
November	62	84	64.9
December	43	85	55.5

Table 6: Minimum, Maximum, and Average temperature reading for each month in the year 2017 at Big Woods.

Table 6 shows the minimum, maximum, and average temperatures through 2017 for Big Woods. The total rainfall depth from January to April, 2017 is 31.5 cm, with an average temperature of 67 F. In contrast, from June to October, 2017 the total rainfall depth is 59.4 cm with an average temperature of 80 F. Both rainfall rate and temperature control drainage rate in the wells. When the rainfall rate outpaces the drainage rate, the area around a well can remain inundated.

4.3 Days Spent Inundated

Figure 17 shows the percentage of days spent inundated per year including all 27 wells. A day spent inundated is counted as 24 hours, continuity does not apply, with a well water height greater than 0.0 m. These calculations were done by month to find the number of inundated days per month at each well and then presented in a total percent per year. However, not all wells have continuous records (365 days per year, 366 days in 2020 for the leap year), making it difficult to interpret the data in Figure 17. To remove any bias from missing data, days inundated were normalized by the number of days of available data in that year (Figure 18).

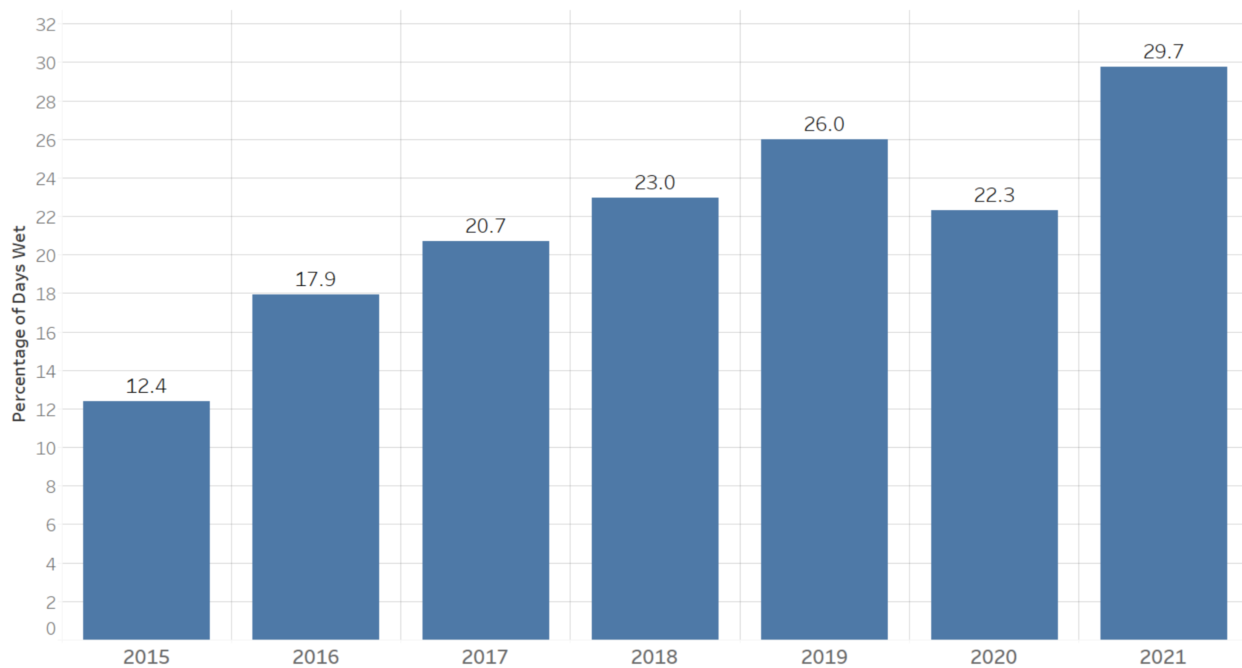


Figure 17: Percentage of time spent wet for all 27 wells in study area, not only selected.

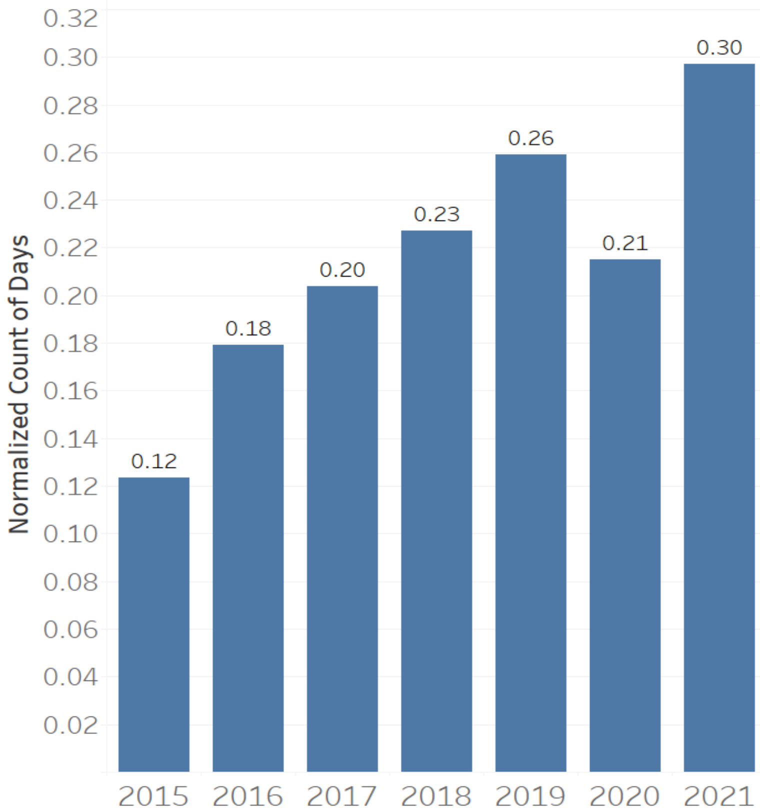


Figure 18: Count of days spent inundated after normalizing by total number of days recorded in that year.

Water Level Rate of Change per Year							
Transect 1			Transect 2			Transect 3	
Well ID	mm/yr		Well ID	mm/yr		Well ID	mm/yr
03T1EL2W	0.00		23T2EL4E	0.08		29T3EL2E	0.07
04T1EL3W	-0.01		27T2EL2E	0.11		47T3EL3E	0.07
06T1EL4W	0.01		28T2EL3E	0.30		49T3EL4E	0.10
07T1EL4W	0.06		33T2EL5T	0.13		50T3EL5T	0.07
09T1EL5T	-0.01		34T2EL5T	0.07		54T3EL4W	0.14
10T1EL5T	0.04		36T2EL4W	0.19		55T3EL4W	0.09
11T1EL4E	0.06		38T2EL4W	0.07		57T3EL3W	0.17
14T1EL2E	0.03		39T2EL3W	0.26		59T3EL2W	0.02
16T1EL3E	0.07		44T2EL2W	-0.02			
19T1EL2E	0.02					CRMS0234	0.02

Table 7: Rate of change in average water level for each well. Red- Negative or no change. Light green- Positive rate. Dark green- Greater than or equal to +0.10mm/yr.

Using linear regression, the water level rate of change for each well was found and is shown in table 7. Data was plotted for daily averages over the entire date record available for each well. Then a 30-day moving average was calculated and the trend was found. The moving average was done to help eliminate bias at the start and end points of the dataset. Note some wells do have longer records than others.

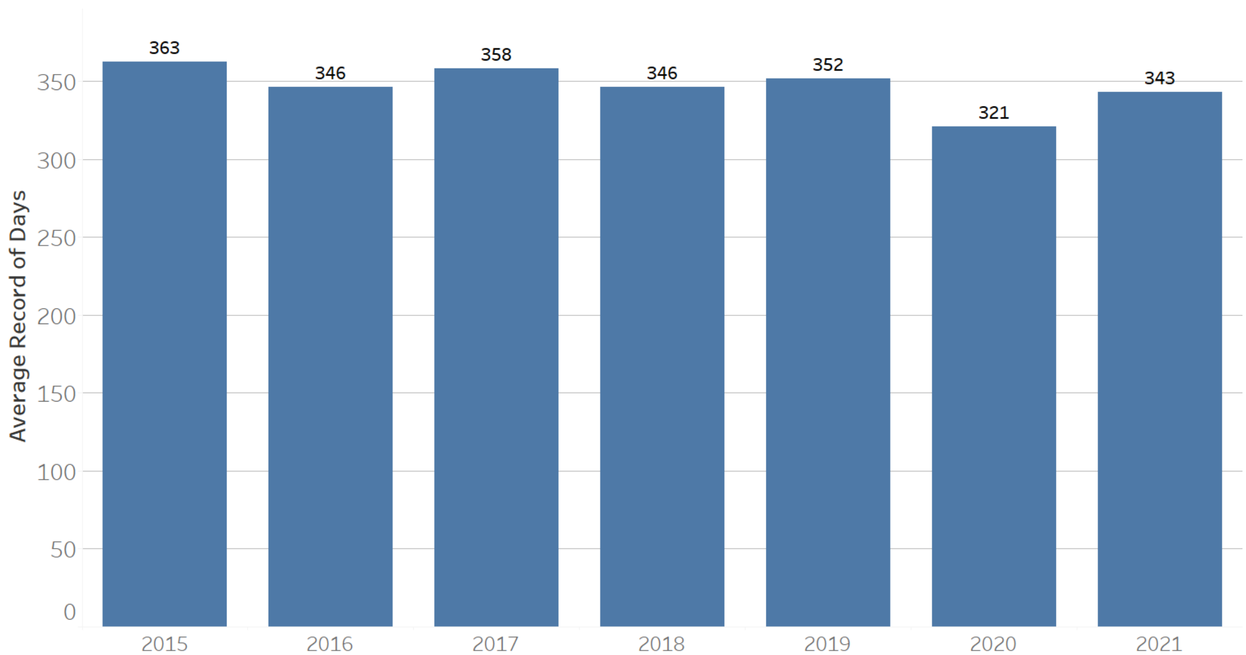


Figure 19: Plot showing the average number of days of record for all wells in all transects

Figure 19 shows the average number of days recorded per year for all wells. All years have an average over 300 days. This implies there is ample data in all years to make comparisons among the years.

4.4 Location and Elevation

Well behavior is partially controlled by the location on the landscape and the surface elevation where the wall is installed. Figure 20 shows the location of the selected wells in relation to the land surface topography.

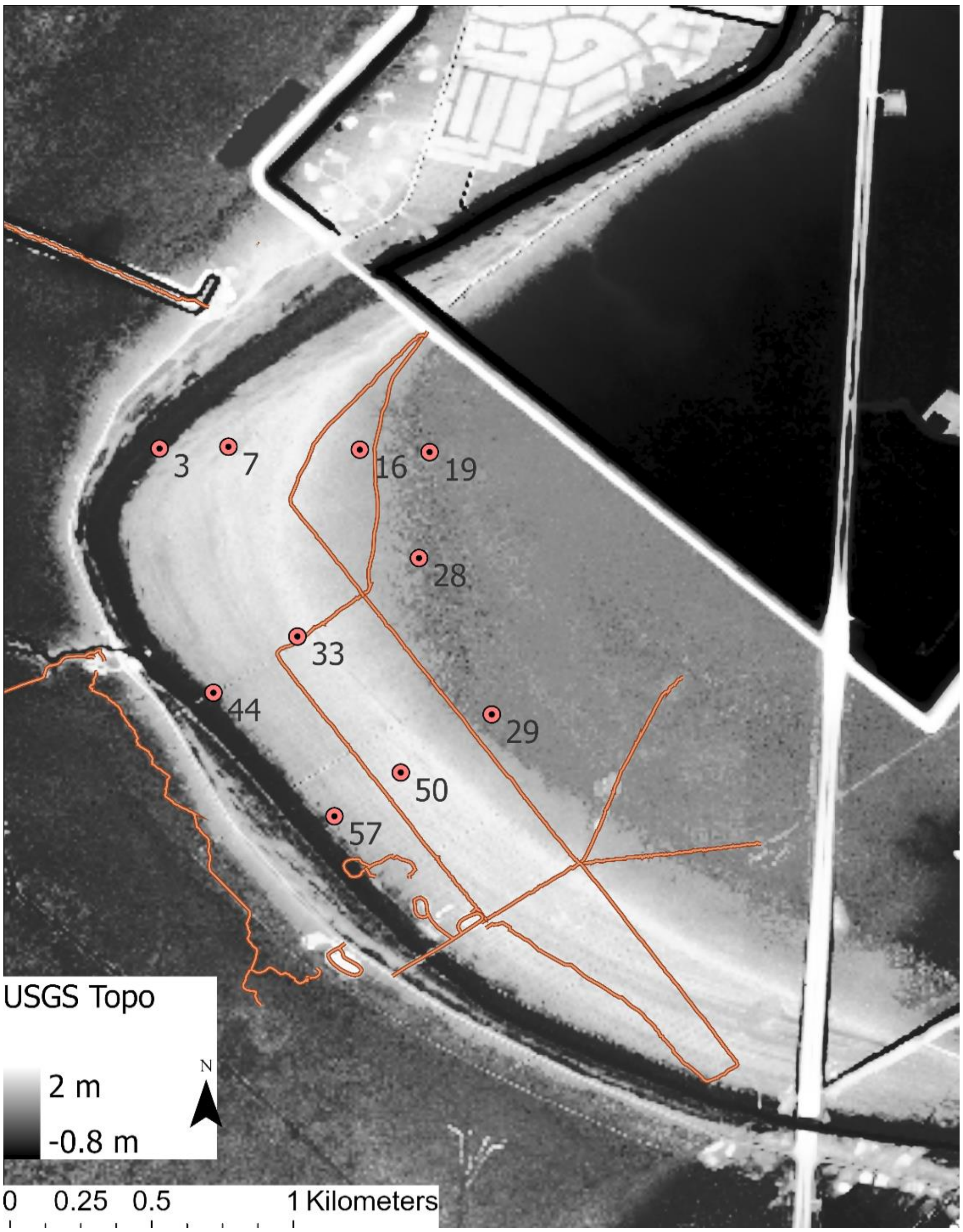


Figure 20: Topographic map showing the selected wells and trails through the study area.

The average drainage rate over five years (2017 - 2022) for each selected well is plotted against the land surface elevation where each well is installed (figure 21). Drainage rate generally increases with land surface elevation. Something to note is the three wells that are on the highest parts of the topography (07, 33, and 50) also all have the highest drainage rates. Also interesting is that well 28 is in a higher location than well 3 but has a lower drainage rate.

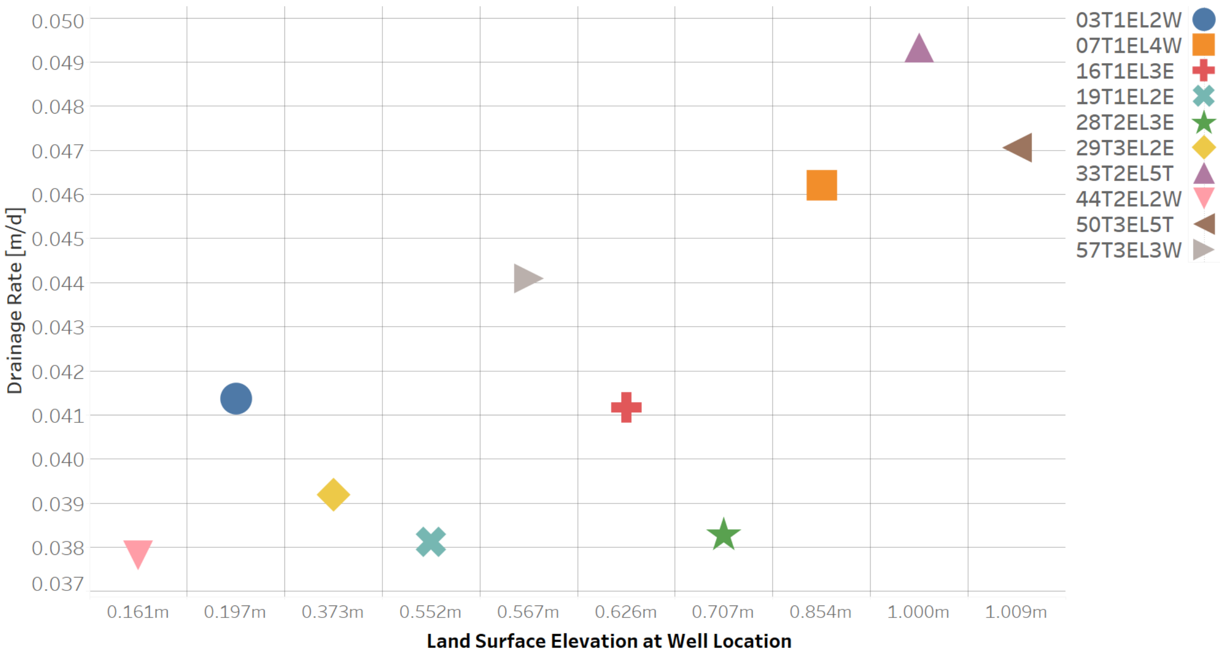


Figure 21: The relationship between average drainage rates over the period 2017 - 2022 with land surface elevation at the well location.

The relationship between elevation, water level and drainage rates will be further explored in the discussion section. These relationships are useful for determining what zones within the study area can be labeled as higher risk for flooding.

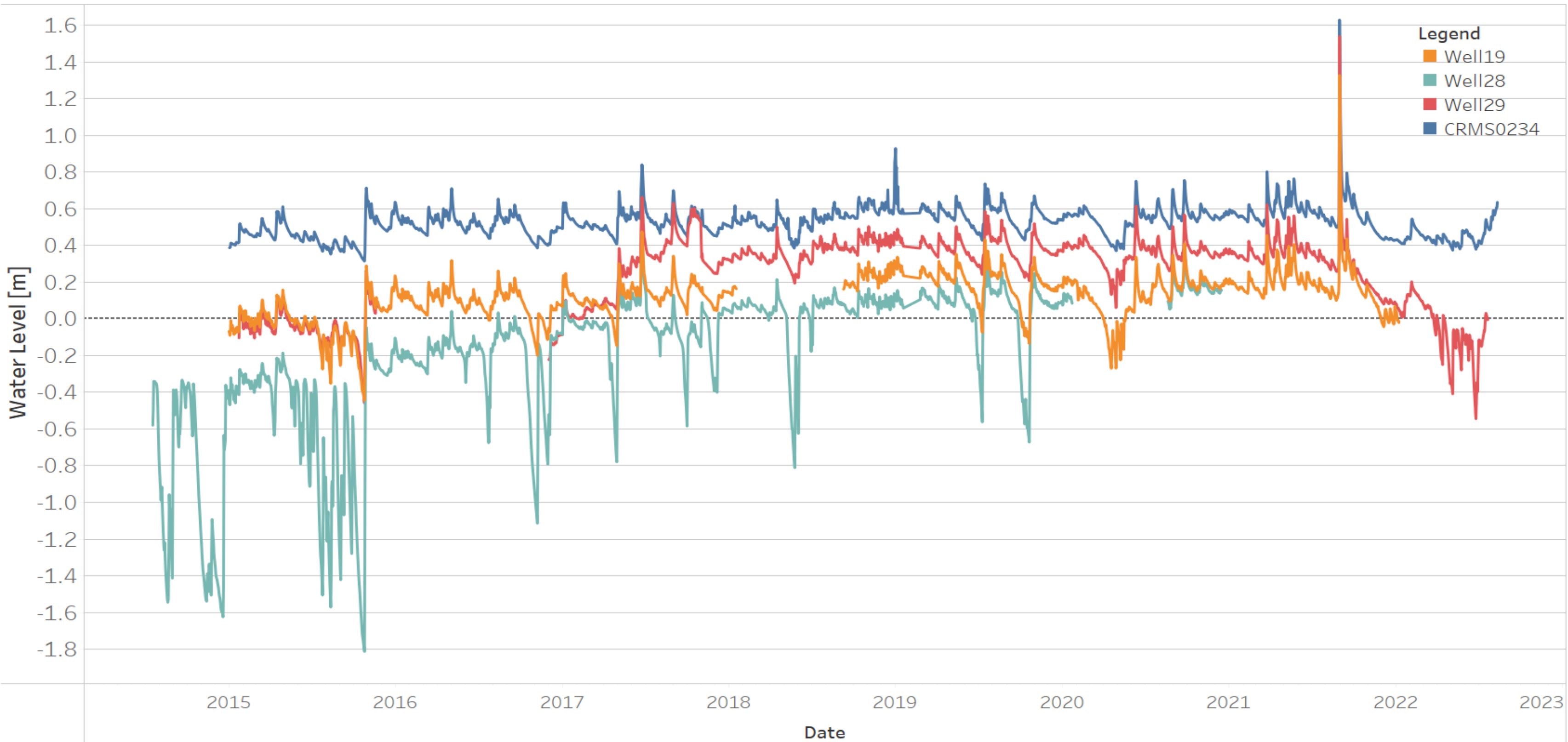


Figure 22: Time series of impounded area wells along with CRMS0234.

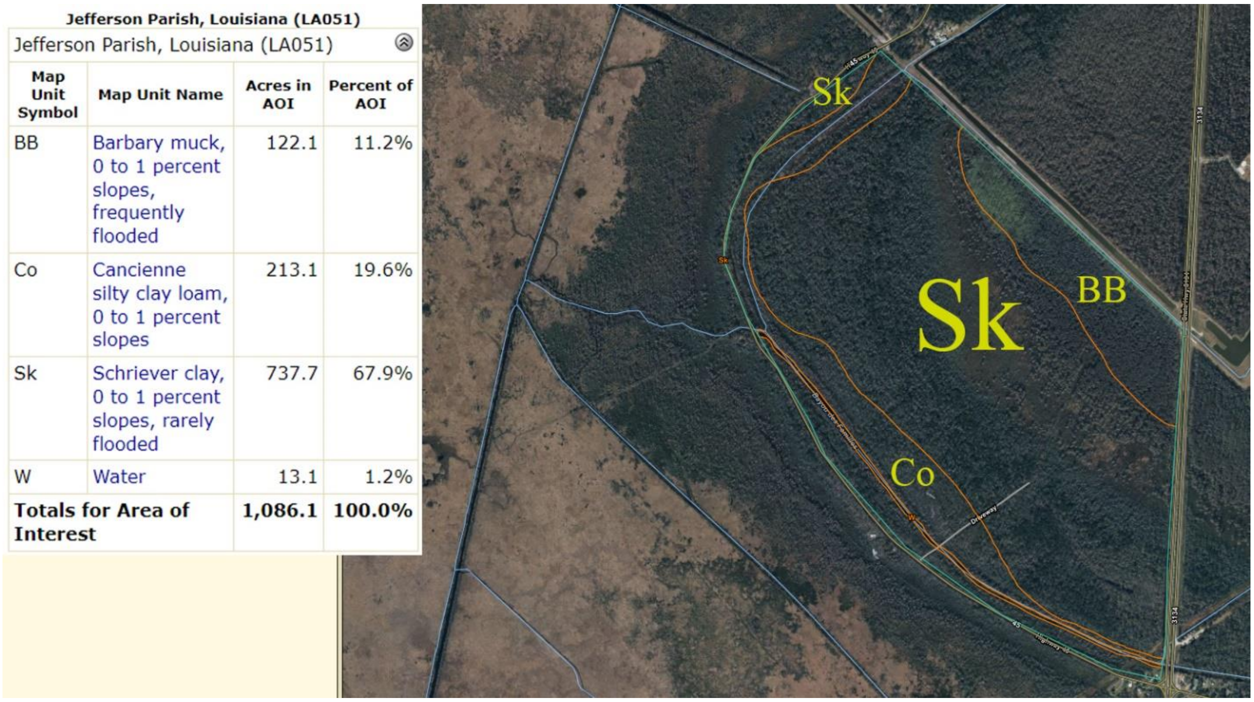
Figure 22 shows the three wells farthest into the impounded area (19T1EL2E, 28T2EL3E, and 29T3EL2E) along with CRMS0234. CRMS0234 shows constant inundation for the entirety of the data record. We find it important to add this comparison to understand what the conditions are where we otherwise have no data. This group of wells respond similarly to each other and that relationship can be useful for interpolating water levels into areas we lack data. From this graph we also see that water levels from CRMS0234 remain relatively steady with a slight positive trend, found to be +0.02mm/year.

5. DISCUSSION

5.1 Controls on drainage rate

Drainage rates are affected by numerous factors, not all of which are explored in this study. One of these factors is soil type. The field area consists of mainly clay and fine sands. The National Resource Conservation Service (NRCS) website provides a soil survey map with recorded drainage rates (figure 23). Schriever clay (Sk) makes up 67.9% of the area, Cancienne silty clay loam (Co) 19.6%, and Barbary muck (BB) 11.2%. The reported drainage rates are, 0.0

to 0.04 m/d (Sk), 0.12 – 0.37 m/d (Co), and 0.0 – 0.04 m/d (BB) (Soil Survey Staff, 2022). The drainage rates shown fall within the range of rates found using water level in wells.


Jefferson Parish, Louisiana (LA051)

Jefferson Parish, Louisiana (LA051)

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
BB	Barbary muck, 0 to 1 percent slopes, frequently flooded	122.1	11.2%
Co	Cancienne silty clay loam, 0 to 1 percent slopes	213.1	19.6%
Sk	Schriever clay, 0 to 1 percent slopes, rarely flooded	737.7	67.9%
W	Water	13.1	1.2%
Totals for Area of Interest		**1,086.1**	**100.0%**

Figure 23: Screenshot from https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. Showing the study area and the soil types with percentage of coverage.

It is reaffirming that our measured values agree with those based on soil type. However, this study focuses on changes in drainage rates with elevation and seasonality. Soil and vegetation types directly impact drainage but these variables were not explicitly considered in our study, although we discuss the potential impact of these variables below. The main controls on well drainage rates were found to be elevation, or whether located in the impounded area or close to the channel, and seasonality.

5.1.1 Elevation and Location

The range in topography of the study area is approximately 2 meters. The highest areas are on the natural levee, and the lowest areas are along the channel and impounded area. The wells with the highest elevations have the highest drainage rates (figure 21). Wells positioned on the natural levee generally draw down between rainfall events, whereas there may be no change in water level between rainfall events in the lower elevation wells (Figure 15). We hypothesize that there is subsurface water flow from the higher elevation locations to the lower elevation locations, leading to the drain out after storms in high elevation wells. However, the inundated lower elevation areas are not well drained, and these areas remain inundated.

There is a noticeable difference in vegetation cover across the study. Higher elevation areas have more dense vegetation, including trees, and higher drainage rates regardless of season. However the lower elevation impounded area that remains inundated for long periods has few living trees, leading to what is described as a “Ghost Forest” (figure 24).

Figure 24: Showing ghost forest with dead trees and old stumps alongside the more densely vegetated area.

Studies on ghost forests tend to focus mainly on sea-level rise and the resulting increase in salinity in a previously freshwater ecosystem (Kirwan et al. 2019, Smart et al. 2020, Ury et al. 2021). While this study does not look at water quality, it is important to note that salinity can play a role in the creation of the ghost forest. Events such as hurricanes can cause extreme flood events that may introduce saline water into the system. While the water will eventually drain in hours to days, salinity effects can remain for years to decades in the groundwater (Kirwan et al. 2019).

Studies done on similar ecosystems have found that bald cypress (*Taxodium distichum*) show a decrease in growth rate and increase in mortality following times of prolonged freshwater inundation (Mitsch et al. 1979; Mitsch and Ewel 1979; Megonigal et al. 1997). While more water-resistant vegetation dominates the lower elevations in Big Woods, increasing frequency and duration of inundation is likely affecting the vegetation density. Areas with lower vegetation density remove less water through transpiration. This leads to a positive feedback loop - as more water remains on the landscape, more vegetation dies off, and transpiration is reduced.

The signature of evapotranspiration (ET), or the lack of transpiration in the wetter areas, is illustrated in Figure 25. The sawtooth pattern in the higher elevation wells (07, 16, and 33) in figure 25 illustrates the daily uptake and release of water by vegetation during the hottest parts of the day. In contrast, the water level in well 29, in the impounded area with less vegetation, does not have this same daily periodicity.

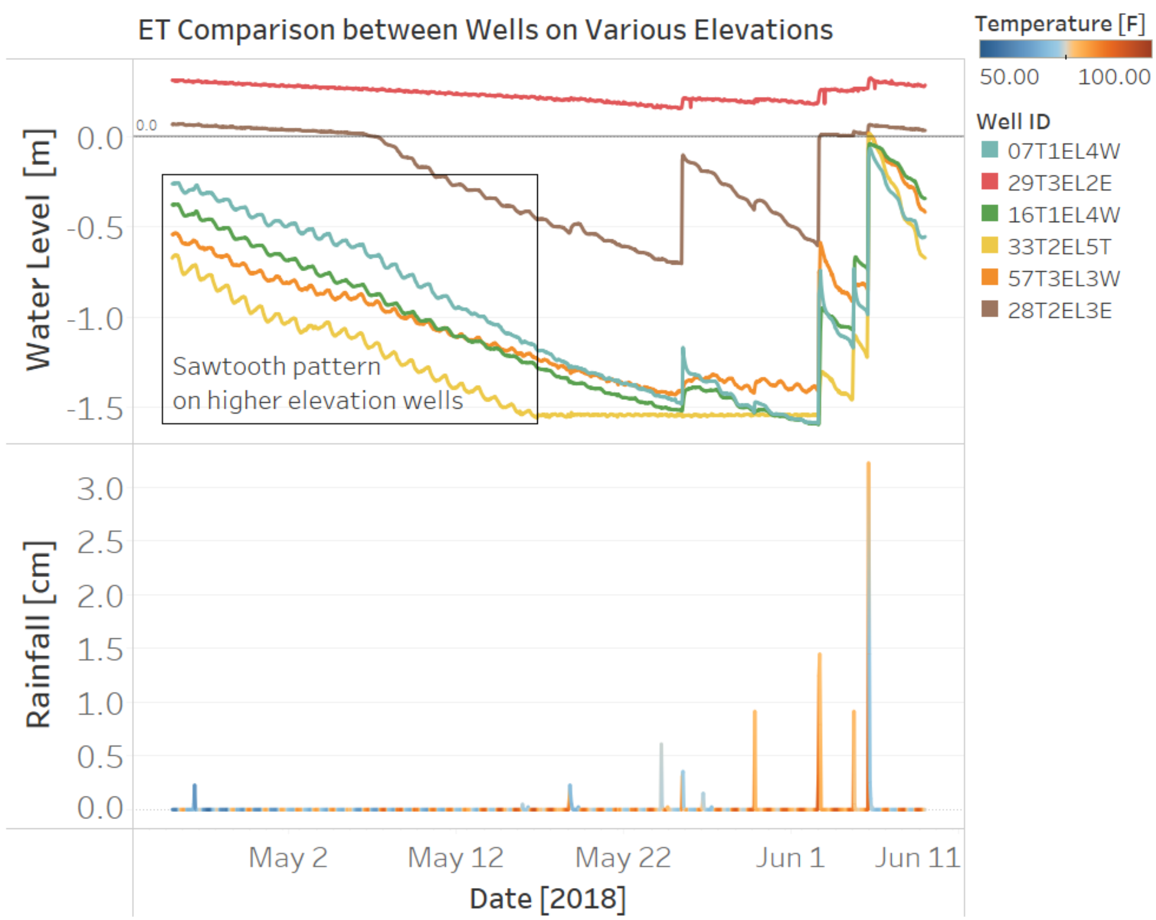


Figure 25: Showing evapotranspiration in different wells in May 2018. Hourly data.

ET is largest during sunlit parts of the day, leading to a decline in water level during the day from about 9 am to 7 pm. From 7 pm to 7 am, water level rises again (Figure 26). However, the gain does not offset the losses from the previous day, thus the water level declines overall. A study by Gonthier & Kleiss (1996) speaks on diurnal fluctuations of water level. The cause is two opposing influences on groundwater surrounding the wells. First the uptake of groundwater by evapotranspiration in the upper part of the alluvial aquifer during the day. Second is the flow from the lower part of the alluvial aquifer to the upper part increases the water level at night. The smallest ET rate is just prior to dawn when the vapor pressure deficit is at its daily minimum (Gribovszki et al. 2008). Wells 07, 16, and 33 have daily fluctuations with a peak between 6 - 9am and a local minimum between 5 - 7 pm.

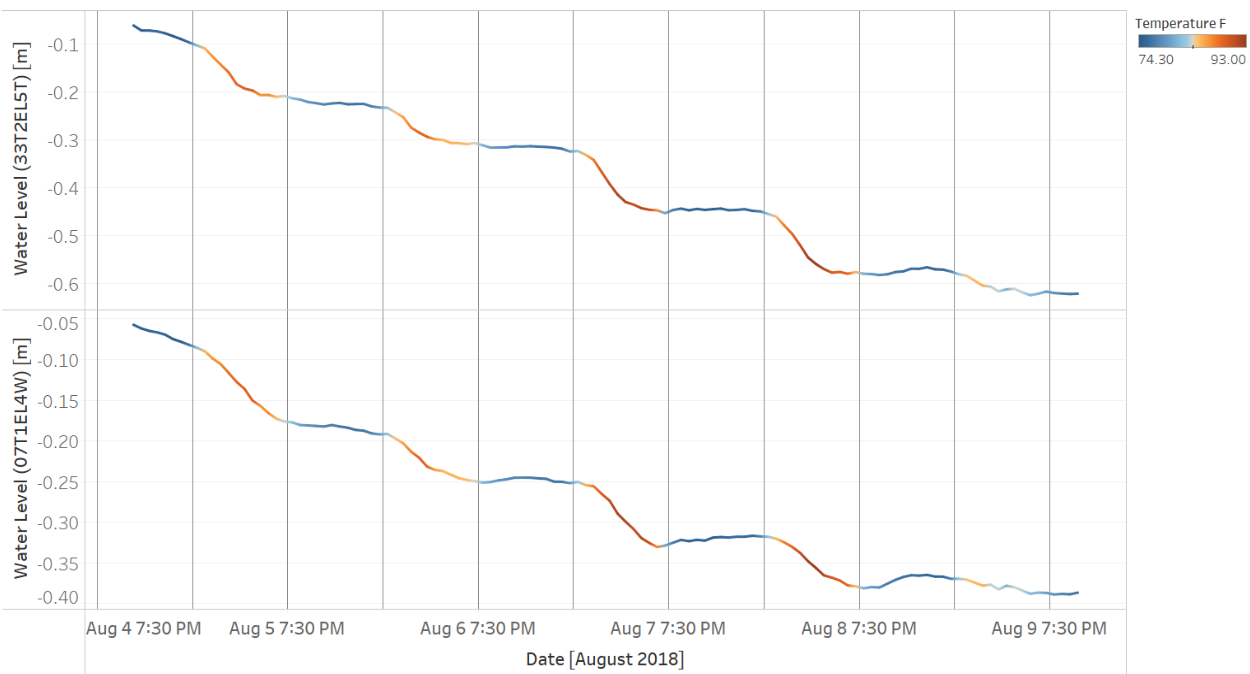


Figure 26: Zoom in showing daily water level fluctuations seen in well 07T1EL4W and 33T2EL5T over a five day period.

Tidal influence was also considered due to the proximity of the study area to the coast. Figure 27 shows the hourly water level data of Well 07T1EL4W with the air temperature as the color gradient and the tide gauge from Grand Isle. The well water level consistently follows the diurnal cycle of the most rapid fall in well level during the warmest time of day. The tide records will move in and out of phase with the water levels leading to the conclusion that there is no influence from tides on the levels within the study area. Additionally, studies done by White, 1932 and Gerla, 1992 have successfully calculated ET rates based on diurnal fluctuations.

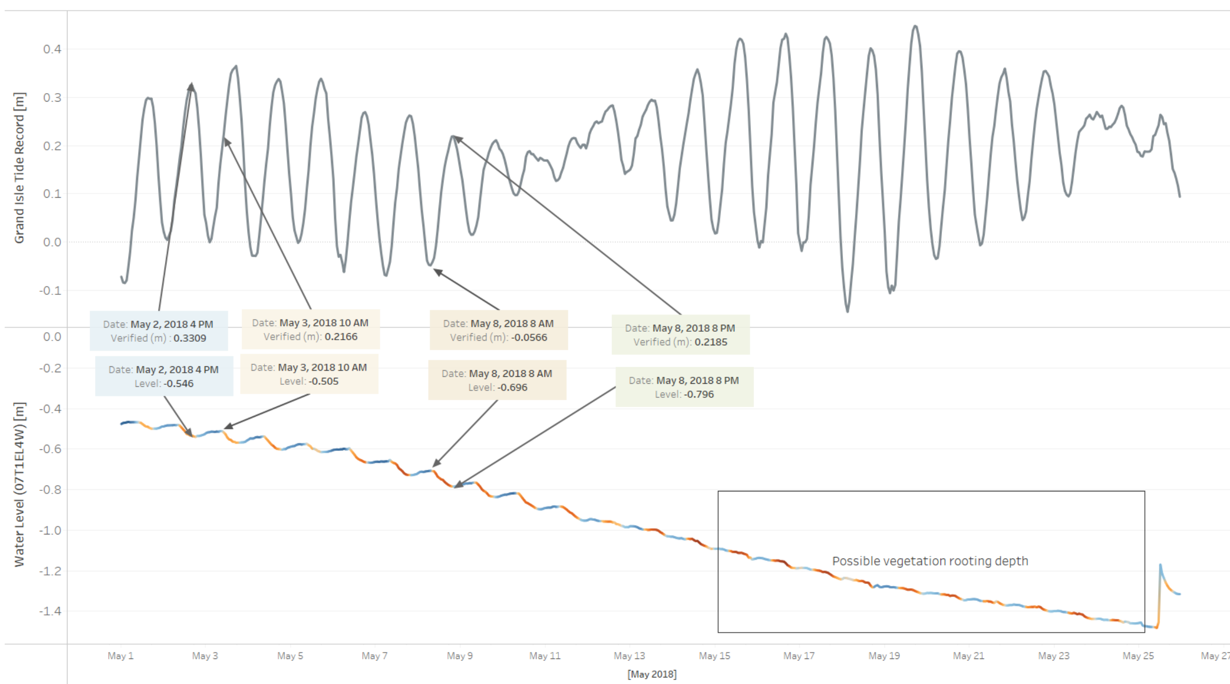


Figure 27: Tide gauge and water level records shown through May 2018. Annotations denote specific times and compare the two time series. Black box indicates zone of possible vegetation rooting depth where ET signal is lost.

5.1.2 Seasonality and temperature

Seasonal changes are observed in drainage rates. This is due in part to the changes in air temperature and frequency and duration of rainfall events. Temperature ranges from the low 30s to upper 70s in the cooler months (November – March) and from the 70s to upper 90s in the warmer months (April – October). These temperature changes directly influence evapotranspiration (ET) rate. There is, on average, a 106% difference in total average drainage rates when comparing between seasons. This is when considering the study area as a whole. Well response varies, but the underlying pattern of higher drainage rate during the warmer months always holds true. Higher elevation wells with denser vegetation have higher drainage rates than those at lower elevations with less vegetation coverage. It is expected that during the cooler months, vegetation will experience a loss in leaf coverage, reducing losses from transpiration.

Changes in ET with setting, season, and temperature have been observed in other studies. Allen et al., (2016) conducted a study in backwoods swamp forests of southern Louisiana that focused on evaporation rates for vegetated versus open water areas. Average evaporation rates were 1.35± 0.10 mm day^{-1} and 1.36± 0.06 mm day^{-1}, respectively. Their study was done over a period of 5 months and found that evaporation was higher in open water during summer in comparison with evaporation measured in the vegetated areas. However, during the fall this relationship switched and vegetated areas had higher evaporation rates. While our study does not have any open water, we feel this can still be used as an example for the areas with less vegetation. Those areas will experience the increase in evaporation during warmer months and less during the cooler months. We see this when looking at the well responses in varying seasons. Wells in the impounded area that are consistently inundated show more fluctuations in water level in higher temperatures, whereas in cooler temperatures the water levels will remain more consistent (figures 15 and 16).

Zhang et al., (2005) explored the effects of land cover on water table, ET, and ground water recharge in Jasper County Iowa. They had two wells located in similar conditions on opposing sides of a creek except that one was installed into a grass covered field and the other with bare land. Their results showed the grass covered side lowered the water table and reduced groundwater recharge. The bare land had higher water levels and a significantly slower subsurface drainage in comparison with the grass covered location. These results are comparable to those from Big Woods. The wells in the lower elevation areas with significantly less vegetation coverage often spend more time inundated and are slower to drain when compared to their higher elevation counterparts. Once an area becomes inundated the ability of vegetation to absorb water diminishes. Inundated land leads to less available oxygen for vegetation to transpire (Banach, et al 2009). This is why we do not see the diurnal signals in times of inundation.

5.2 Flooding Frequency

Over the time of observations, the amount of time that the Big Woods are inundated is increasing (Figure 17 and 18). The results generally show increases in the percentage of days inundated from year to year for the duration of our study. The year 2020 breaks with the general trend. This may be because that was the year with the least recorded rain at JLNHP&P.

It may also be due to missing data during wet times of the year. In general, these results illustrate that some areas are spending more days wet than dry, making these at-risk areas for the park. The impounded area is one of these at-risk areas, and the wells just on the border of the impounded area show signs that they may be at risk in the future. Wells 14T1EL2E, 28T2EL3E, 16T1EL3E and 47T3EL3E are situated on the back slope on the natural levee to the impounded area. All of these wells are showing a positive trend of time spent inundated over the span of seven years, although the increase at well 16 is less pronounced. Note that 2021 is not shown for well 28T2EL3E because it is missing too much data in that year (Figure 28).

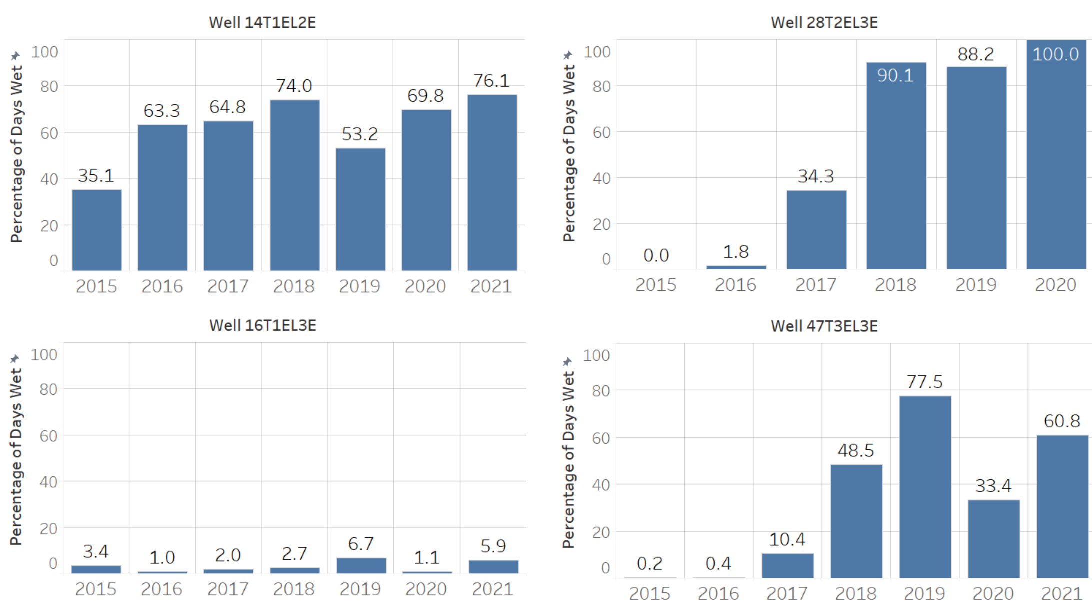


Figure 28: Wells 14T1EL2E, 28T2EL3E, 16T1EL3E and 47T3EL3E showing their percentage of days spent inundated for each year.

These wells illustrate the ongoing consequences of the flood protection wall and the resulting lack of drainage in this part of the Big Woods. These wells can be seen as the proverbial canary in a coal mine, illustrating a trend that will likely continue if nothing is done to move water out of the impounded area of the Big Woods. Forecasted changes in climate may exacerbate flooding. A comparison of studies done by Easterling et al. (2017) found a consensus in the prediction for increases in heavy precipitation events and extremes in precipitation events.

As discussed above, the increase of inundation has impacted vegetation cover and will cause the death of trees that are less flooding resistant. This has already happened in the wells at lower elevation on the backslope. As the number of days spent inundated increases in locations that used to be relatively dry, even just a few years ago, it is likely that the ghost forest will spread. This will likely cause a positive feedback loop, in which the area with lower drainage rates continues to increase, the days spent inundated increases, and so on.

From a land management point of view, the trends should be considered as a warning bell. While there are currently no public trails in the deeper sections of the impounded area where wells 19T1EL2E, 28T2EL2E, and 29T3EL2E are located, other areas with public walking trails are becoming wetter and wetter. The land around well 47T3EL3E is flooded for the majority of the year, and this well is located directly on a public trail (Figure 29). A majority of the trails in the study area are not boardwalks and can become difficult to navigate after rainfall events. To keep these trails operational, many will require elevated boardwalks in the near future, unless drainage is added to the impounded area. Alternatively, new trail designs can be implemented to only allow travel along the higher elevations on the top of the natural levee ridge. Figure 29 shows three areas with different flood risk, as defined by past water levels and the duration of flooding events over the past five years.

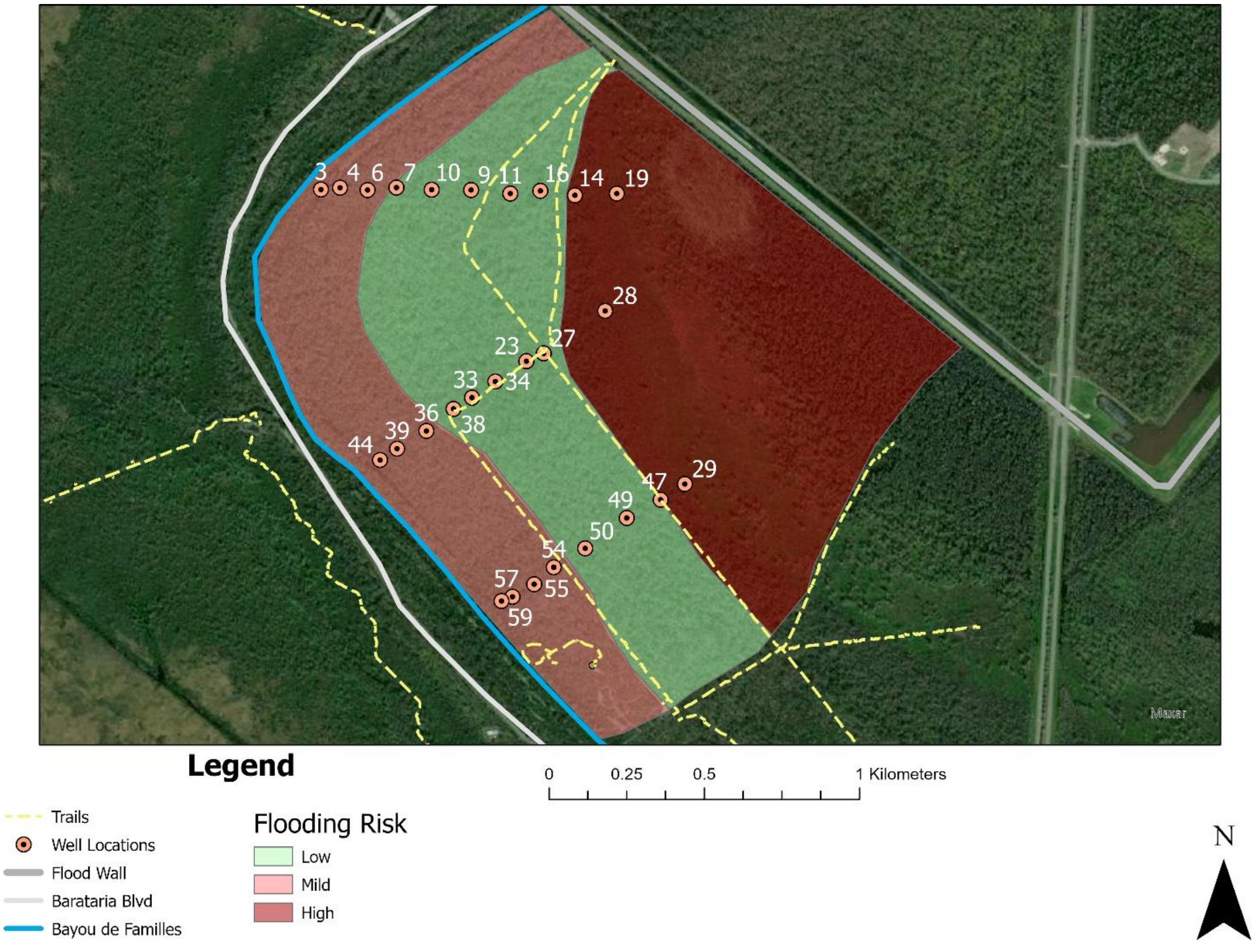


Figure 29: Areas split into zones of varying risk for flooding.

These areas of risk are based on previous water levels and time spent inundated. High risk applies to the impounded area but this is also where the least amount of data is available. All three wells that represent the impounded area spend a majority if not the entire year flooded. The data also shows this area of high risk is increasing as wells that border the impounded area are increasing in both duration and frequency of flooded events. The natural levee represents the low risk area where there have been records of flooding but only for extreme events or short periods of time. The remaining area represents the mild risk as it has the added capability of draining into Bayou de Familles to remove water. However, during extreme events proximity to Bayou de Familles can add to the flood risk.

5.3 Addition/Removal of Wells

There are currently 27 water level monitoring wells spread between three transects within the Big Woods area. This does not include any wells positioned at the Education Center or Visitor Center, nor does it include wells installed westward of Bayou de Familles that into the Preserve's march landscape and the Barataria Basin's estuarine lakes. A goal of this study was to also give recommendations to park management on the density and placement of monitoring wells within the study area. The leveloggers are set to record a data point every hour and this timeframe is a good choice in order to give a high temporal resolution of the data. This frequency of data does lead to larger data files, but the data files are small enough that this is not a concern. Two different recommendations for addition/removal of wells are made. First is a preferred scenario that maximizes data collection and spatial coverage. Second is a minimum number of required wells to continue with analysis of the area without a substantial loss in data coverage.

5.3.1 Preferred Recommendation

Transect 1 currently has ten wells and based on water levels wells 04, 06, 07, 09, 10, and 11 all follow very similar water level patterns. These similarities can been seen in figure 30.

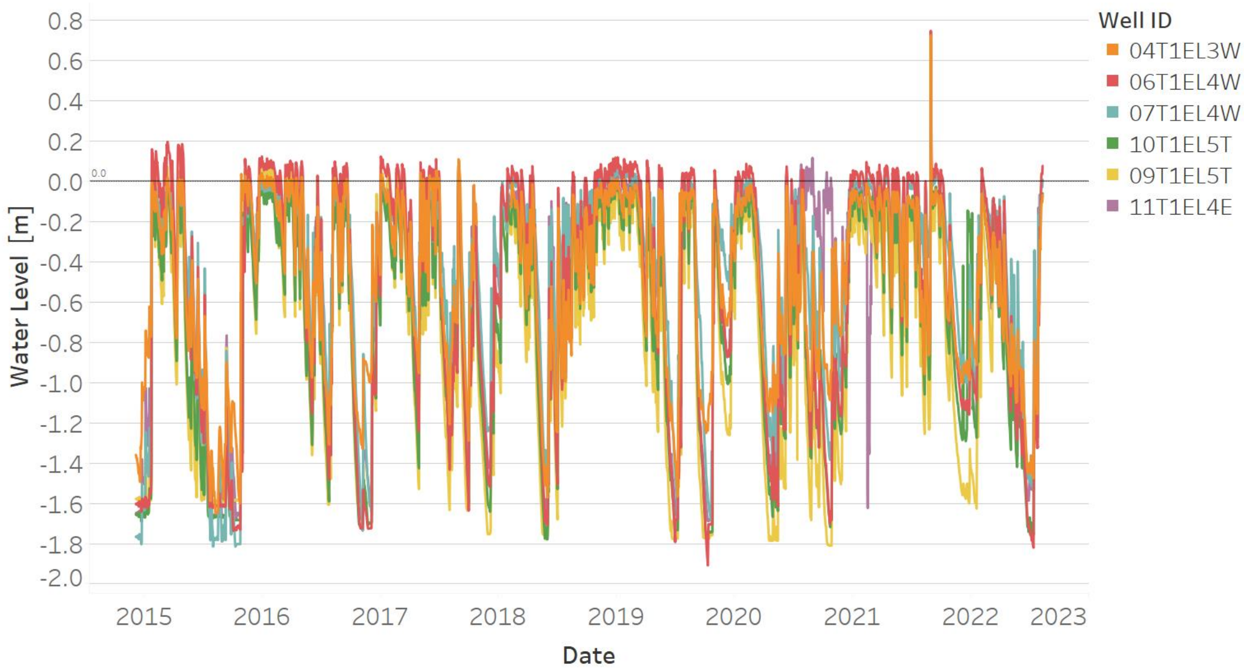


Figure 30: Daily water levels for wells in transect 1 that show redundancy

The recommendations for Transect 1 would be the removal of three wells total, with the suggested wells being Wells 04T1EL3W, 06T1EL4W, and 09T1EL5T. These wells are suggested for removal because the other remaining wells would adequately capture the elevation range on this transect and the observed water fluctuations.

This same process was applied to the remaining two transects leading to the following suggestion of wells for removal:

Transect 1 - Wells 04T1EL3W, 06T1EL4W, and 09T1EL5T

Transect 2 – Wells 23T2EL4E, 34T2EL5T, and 39T2EL3W

Transect 3 – Wells 59T3EL2W and 55T3EL4W

This scenario leaves 19 wells on the landscape.

5.3.2 Less Preferred Recommendation

If maintaining 19 wells is too much given park resources, more wells could be removed, leaving 16 wells. In this less preferred scenario, the following wells would be removed:

Transect 1 - Wells 04T1EL3W, 06T1EL4W, 09T1EL5T, and 16T1EL3E

Transect 2 – Wells 23T2EL4E, 34T2EL5T, 38T2EL4W, and 39T2EL3W

Transect 3 – Wells 59T3EL2W, 50T3EL5T and 55T3EL4W

These recommendations are based on the same considerations from the preferred scenario but also take into consideration wells in other transects that can be used to represent the area lost from the removal of a well in one transect. For example, well 50T3EL5T on top of the natural levee could be removed because there is some redundancy with well 33T2EL5T that is also on top of the natural levee.

Loss of more wells means less accuracy when predicting the degree of flooding in the future. The data set that the park has collected is extremely unique, given the duration, frequency, and spatial resolution. As noted, hydrologic studies in southern Louisiana have relied on fewer data points over a shorter period of time. These wells provide an invaluable insight into the movement of water across this area with relatively dense trails. Given climate change predictions and continual subsidence, this area is vulnerable to future change. The insight provided by this well network will greatly aid the park in making future science-based land management decisions.

5.3.3 Addition of Wells

The addition of other wells would benefit future hydrologic studies in the park. Three additional wells into the impounded area would help to more completely understand the flows of water within the study area. The locations chosen would represent both the low lying impounded area where vegetation is most at risk as well as the natural flow of surface water out of this impounded area to the southeast (Figure 31). These locations are also near current trails, and would help with monitoring and maintaining the trails. These suggestions did not consider any limiting conditions such as accessibility for installation and monitoring. In the future, remote connection to the levelogger would reduce the effort required for data collection.

5.4 Additional Land Management Recommendations

This study suggests that increased flooding may be leading to the death of vegetation, which could then increase flooding. This positive feedback loop is a negative for land management and park use. The high risk flood area is encroaching on current trails (Figure 29). Reducing flooding in the impounded area of Big Woods would lead to a more sustainable future for the park and its visitors.

Revegetation may help to reduce flooding in the impounded area and stop or slow the spread of the inundated area. This natural solution to remove water from the landscape also has benefits for carbon drawdown. How revegetation could be successfully done was beyond the scope of this study. However, if it is possible, it would likely be less expensive than big engineering projects to increase the flow of water out of the study area.

With a better understand of surface and subsurface flow directions, it is possible that some engineering efforts could help to remove water from the impounded area. As the study area is completely surrounded by man-made infrastructure there should also be further study done on whether water flows through drainage culverts past Leo Kerner Parkway (Highway 3134), and how those can be improved or maintained.

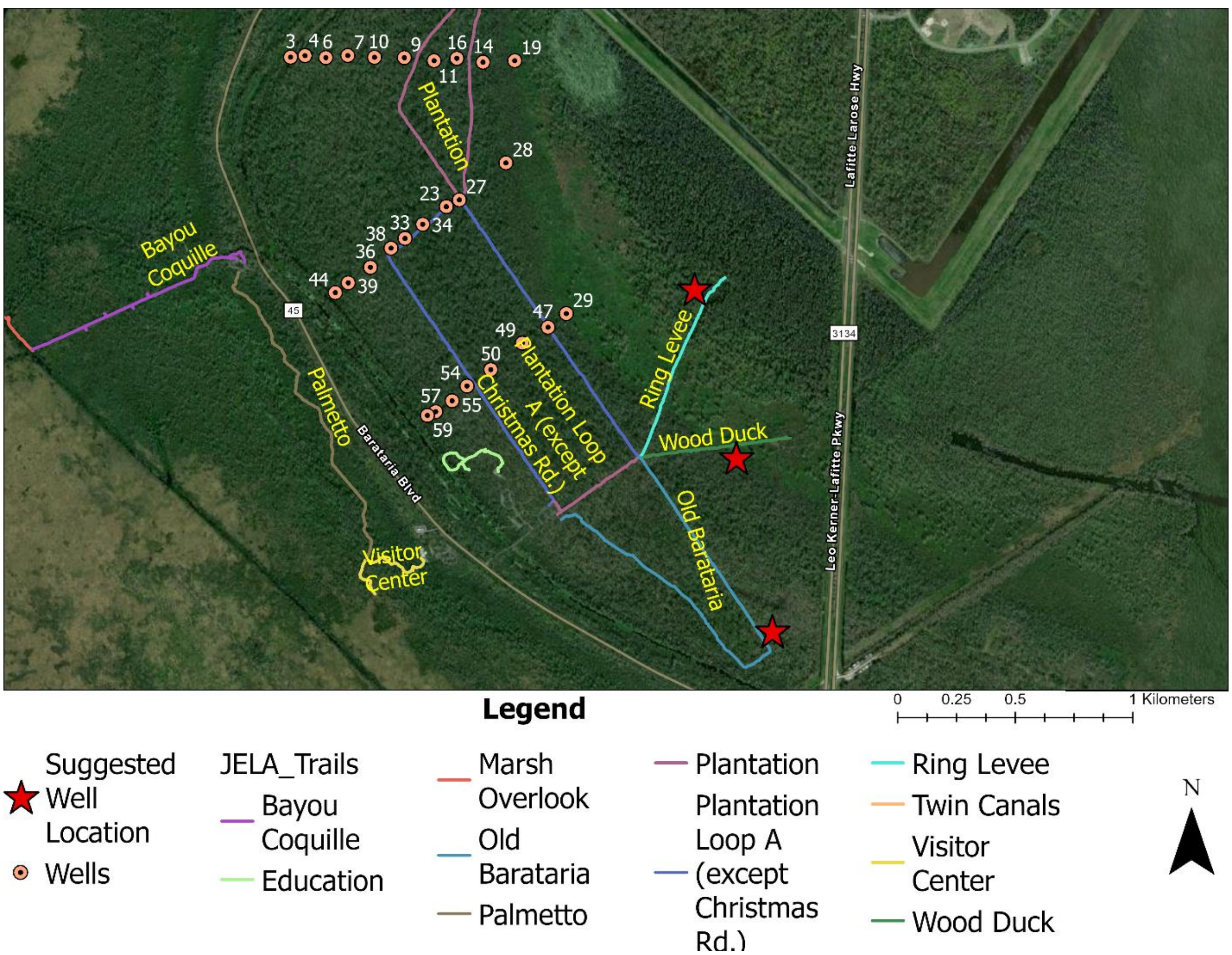


Figure 31: Map of suggested wells to be added into the Big Woods study area.

6. FUTURE WORK

A number of directions could be taken to build on this work and further test hypotheses.

- A deeper investigation into the transpiration signal should be done. Estimates of potential transpiration rates could be calculated using the Penman-Monteith equation.
- Given the location of the study area, further study should explore whether tides are influencing well levels. Spectral analysis could be used to determine the periodicity seen in the data, and this periodicity could be compared to the tidal frequency.
- This area may be a relatively isolated from inputs from the Gulf of Mexico. More exploration into the whether a tidal signal can be detected would help to understand hydrologic connectivity. Further, salinity levels in water throughout the study area would also be useful for understanding this connectivity. If revegetation projects are carried out, knowing the salinity of the water will be vital.
- The Coastwide Reference Monitoring System (CRMS0234) gauge has data on local percentage of land and water in the area. This data could be explored to test whether our findings of increased flooding agree with the data.
- Future work should consider the impact of subsidence on the results. This analyses assumed a fixed surface level for all of the analyses. However, if the areas where wells are installed are actively subsiding, the results presented here could be an underestimation of the number of days flooded. Park staff are currently collecting subsidence data that could be incorporated into future analyses.
- Develop a historical timeline of stressors on the system. These stressors include building of levees and flood walls, major storms, and land use changes in the area. Linking the

timing of these events to historic changes in vegetation and flooding could help to pull apart the impact of natural and human stressors on this study area.

- A better understanding of subsurface flow directions could be developed from these data. This study only considered local water levels at each well, and it did not use the data to quantify subsurface flow rates and directions. Modeling of subsurface flow using the well data would improve our understanding of the local water cycle. Further, quantifying the depth of piling used for the hurricane flood wall and whether this has changed over time would help to clarify whether the flood wall is impeding connectivity and exacerbating flooding.
- Finally, a better understanding of the predictions for local climate change would improve scientific land management decision making. For example, if the timing of rainfall or the intensity of rainfall events changes, this could impact days flooded estimates. Similarly, increased temperatures could lead to greater evapotranspiration and drying of the area.

7. CONCLUSION

The array of wells in the Big Woods area of Jean Lafitte National Historic Park & Preserve offers a unique opportunity to study the water cycle in a swampy area that is experiencing subsidence and vegetation and climatic change, along with past and present land use change and changes in drainage patterns. In this study we used the spatially dense array, which records shallow subsurface and surface water depths hourly, to explore how seasonality and topography impact both drying following storms and amount of time that areas remain wet throughout the year. Our study has three main scientific findings.

1. Temperature plays a key role in how water is moved in the area. Seasonal variations in temperature control evapotranspiration rates which influence drainage rates across the landscape. Low drainage rates are measured at all temperatures, but the highest drainage rates are only measured when the temperature is relatively high.
2. Location and elevation impact drainage rates and time spent inundated. The relatively high elevation of the natural levee shows faster response times and less time spent inundated compared to areas near Bayou des Familles or within the impounded area next to the flood wall. Wells near the flood wall remain flooded for longer than wells near Bayou des Familles.
3. Vegetation enables local removal of water and increases drainage rates. Dense areas on higher elevation parts of the landscape that are well vegetated show a transpiration signal in the well response. In contrast, in the impounded area, where vegetation is dead or dying, no transpiration signal is detected in the well response. With no or minimal transpiration to enable soil drying, the impounded area stays wet longer, drowning out remaining vegetation, creating a positive feedback loop. This feedback loop may cause the ghost forest area to grow in area. Future work could use other variables collected by the park meteorological station, such as solar radiation and relative humidity to estimate transpiration rates and better quantify the impact of vegetation on the local water balance.

We make the following observations and recommendations to JLNP land managers based on our study.

1. In the flooded areas of Big Woods, the number of days inundated increased over the duration of this study. The area prone to flooding may be increasing, rendering some trails unusable for longer and longer periods each year. However, these observations are with the caveat that the duration of time studied was very short. At least 30 years of data are required to perform a statistically robust analysis of whether there is a trend.
2. Improved drainage from the backslope area of Bayou des Familles may enable vegetation growth or revegetation efforts. The close link among vegetation, evapotranspiration, and drainage suggest that the presence of vegetation enables drying. However, continual inundation kills vegetation, producing a positive feedback loop that enables further flooding. This study did not explore surface or subsurface water flow directions. However, a better understanding of surface and subsurface water flow into and out of the area near the flood wall could inform management options for improved drainage and revegetation.

The data provided by this well array is unique and important for future scientifically driven land management decision making. Currently the dataset is too short for long term significant statistical analysis. Keeping some, or ideally most, of the wells in place will lead to a better understanding of whether the observed short-term trends are representative of future long-term trends. With ongoing subsidence and forecasted increased hurricane intensity, future flooding could make some current trails unusable given current maintenance procedures, for example keeping a dirt path, rather than a boardwalk. The well array, along with subsidence patterns and vegetation change, can lead to more robust, scientifically-based, revegetation and improved drainage plans, if such management options are explored.

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