GROUNDWATER STUDY AT ARMAND BAYOU NATURE CENTER

A Senior Scholars Thesis

by

DEREK WAYNE MORRISON

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

May 2012

Major: Biological and Agricultural Engineering

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Approved by:

Research Advisor:	Clyde Munster
Associate Director, Honors and Undergraduate Research:	Duncan MacKenzie

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ABSTRACT

Groundwater Study at Armand Bayou Nature Center. (May 2012)

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This paper describes the research done to determine the hydraulic gradient and direction of groundwater flow in two aquifers at the Armand Bayou wetland. One aquifer is an unconfined aquifer at a depth of approximately 15 ft. and the second aquifer is a perched aquifer near the surface. The wetland research site was located in Armand Bayou Nature Center near Houston, Texas. Four well nests were installed at this site. Each well nest consisted of a deep well (13-16 feet deep) installed below the clay lense and a shallow well (1-2 feet deep) installed above the clay lense. The groundwater levels were measured once a week over a two year period at all four well nests. Water levels in Armand Bayou were also measured. The first year the data was recorded was a wet year (17.81 inches of rainfall over collection period) and the second year was an unusually dry year (5.8 inches of rainfall over collection period). The paper presents how the hydraulic gradient and direction of groundwater flow were altered during a drought. The data showed that the typical direction of flow in the aquifers was toward the bayou and that under drought conditions the direction of flow was altered by an average of 10.1˚.

The drought conditions also caused the hydraulic gradient to decrease by an average of 0.00254 ft. / ft.

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CHAPTER I

INTRODUCTION

Armand Bayou Nature Center (ABNC) is a nature center in Houston, Texas and has protected 2,500 acres of land since 1974 with the mission to protect the ecosystem and educate the population about the environment. The center was created when a large number of individuals, corporations, and government agencies, affected by the recent loss of local environmental advocate Armand Yramategui, acquired the 2,500 acres. Armand Yramategui saw that recent land purchases, made from industries such as oil companies and NASA, were encroaching on the local environment and made his objective in life to preserve the wilderness of the area. The nature center has provided and still provides a way for people to experience nature close to their home (ABNC, 2011). The types of land that create Armand Bayou Nature Center include wetlands, bottomland forests, and tall grass prairies.

The purpose of this project was to calculate the hydraulic gradient to determine the direction of flow of groundwater in ABNC. The groundwater at ABNC is held in two aquifers: a perched aquifer and an unconfined aquifer. The perched aquifer is the one located just below ground-level and the water in this aquifer frequently rises above the ground-level in the wetland. Below the perched aquifer is a layer of clay, called the clay lense, which restricts water in the perched aquifer from permeating into the aquifer

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This thesis follows the style of *Transactions of the ASABE*.

beneath the lense. The aquifer beneath the clay lense is an unconfined aquifer since the water level in this aquifer never rises to the level of the clay lense. An unconfined aquifer is defined as an aquifer which may rise and fall without being obstructed by an upper limit. For this article, the perched aquifer will be referred to as the shallow aquifer and the unconfined aquifer will be referred to as the deep aquifer.

Since the passing of the Clean Water Act in 1977, the United States has tried to preserve wetlands to ensure that these natural habitats would not disappear completely. The Clean Water Act states that if groundwater were to flow toward a navigable waterway, such as Clear Lake, ABNC would have an opportunity to become a protected wetland. (EPA, 2011)

The objective of this paper was to determine the hydraulic gradient and direction of flow for both the perched aquifer and unconfined aquifer. This paper considers the impacts of rainfall and changes in the level of the bayou on the hydraulic gradient and direction of flow of the two aquifers. This paper will also consider the differences between direction of the flow and the hydraulic gradient both the perched aquifer and the unconfined aquifer. Four well nests, shown in Figure 1, were used to monitor the fluctuation in both the perched and unconfined aquifer. Three well nests are needed to determine the hydraulic gradient and direction of flow using the United States Geological Survey (USGS) triangular method (Heath, 1987, pp. 10-11). Four well nests were constructed so that two independent triangle configurations could be used to determine the direction of flow and hydraulic gradient for each aquifer. The similarity between the two triangular configurations was also examined.

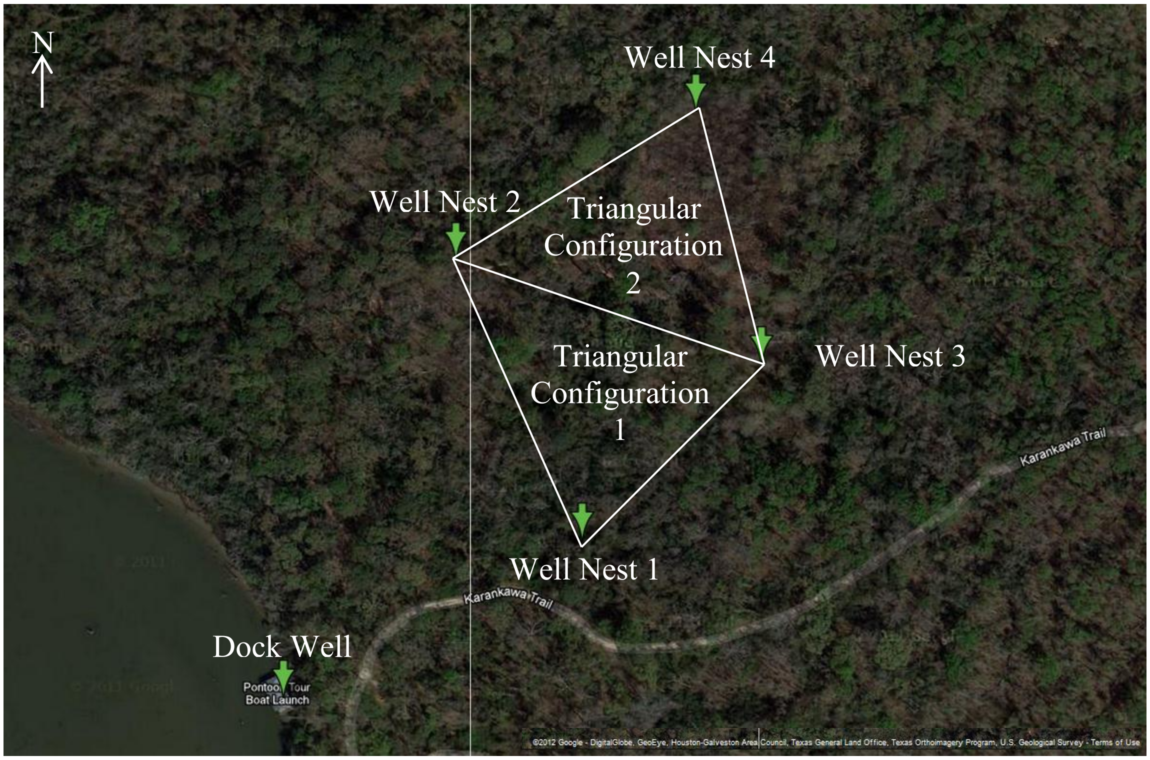


Figure 1. The four well nest locations, the dock well, and the two triangular configurations used to determine the hydraulic gradient and direction of flow at Armand Bayou Nature Center (Google, 2011)

CHAPTER II

METHODS

Construction of the wells

Four well nests were installed at Armand Bayou Nature Center near the bayou. Each nest consisted of two wells, a shallow well and a deep well. A diagram of how the entire well nest was set up is shown in Figure 2. The wells were made of two inch PVC pipes with a six inch well screen attached to the bottom. The purpose of the well screen was to keep silt from obstructing the wells. A cross-section of the well screen can be seen in Figure 3 and Figure 4.

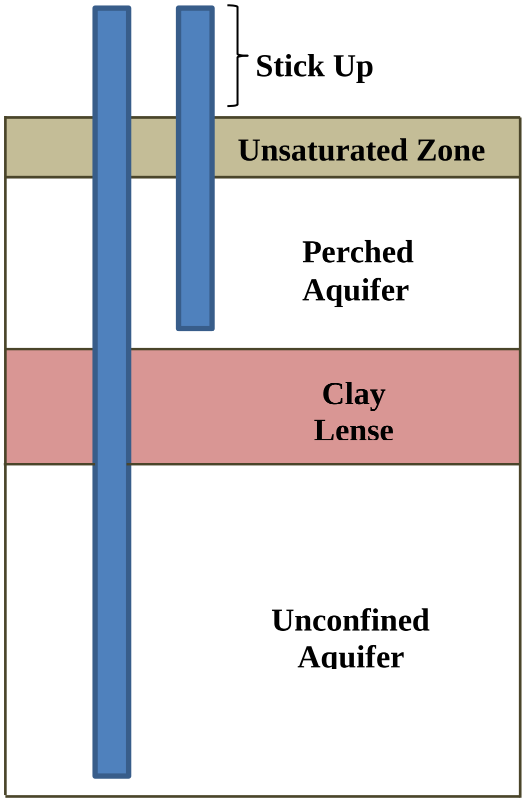


Figure 2. Cross-section of well nest, including well stick up and well screens, and corresponding layers of ground and aquifers used at the Armand Bayou research site

Figure 3. Picture of the well screen attached to the bottom of the well body

Figure 4. Picture of the well being placed into the excavated area

The location, depth, and stick up for each well nest are listed below in Table 1. The stick up refers to the length of pipe above the surface of the soil. The maximum depths given in Table 1 include the stick up distance.

Table 1. Coordinates of each well nest, the dock location, the maximum depths for each well, and the stick up measurements

	Latitude	**Longitude**	**Deep Well Depth (ft.)**	**Shallow Well Depth (ft.)**	**Stick Up (in.)**
Well 1	N 29˚ 35.539’	W 095˚ 04.677’	16.13	4.94	34
Well 2	N 29˚ 35.607’	W 095˚ 04.710’	15.2	3.51	24
Well 3	N 29˚ 35.582’	W 095˚ 04.625’	15.8	5.14	32
Well 4	N 29˚ 35.643’	W 095˚ 04.643’	16.16	3.92	21.6
Dock	N 29˚ 35.507’	W 095˚ 04.758’	8.6	n/a	n/a

The coordinates of each well were found using a Garmin etrex Vista HCx GPS (Garmin, Olathe, KS). A single well was also placed at a nearby dock to monitor the changes in the water level in the bayou. The exact location of this well is shown above in Table 1. At this location, measured from the top of the well, the bayou had a total depth of 9.5 ft. and the well had a maximum depth of 8.6 ft. Each shallow well was used to monitor the fluctuation in the perched aquifer and each deep well was used to monitor the fluctuation in the unconfined aquifer.

Monitoring the wells

The wells were monitored using the electric-tape method using a Sample Pro Water Level Meter (6000YSS, QED, Ann Arbor, MI) as seen in Figure 5.

Figure 5. The Sample Pro Water Level Meter used to monitor the wells at ABNC

The electric-tape method, as described by Heath in Basic Ground-Water Hydrology:

> Involves an ammeter connected across a pair of insulated wires whose exposed ends are separated by an air gap in an electrode and containing, in the circuit, a source of power such as flashlight batteries. When the electrode contacts the water surface… (pg. 72-73)

the device produces both a beeping noise and illuminates a light. Each well nest, along with the well at the dock, was monitored once a week over the collection period. A sample of the form that was used to record data in the field is shown below in Table 2.

Table 2. Example form used in the field to record water level measurements during the collection period

Date	Deep Well Measurement (ft.)	Shallow Well Measurement (ft.)	Ponding? (Y/N)
Well 1			
Well 2			
Well 3			
Well 4			
Dock		n/a	n/a

Calculating the hydraulic gradient and direction of flow

The process described in the following section is acquired from the United States Geological Survey Water-Supply Paper 2220. (Heath, 1987, pp. 10-11) The first step in calculating the hydraulic gradient is to mark the positions of three wells on a scaled down map, as seen in Figure 6.

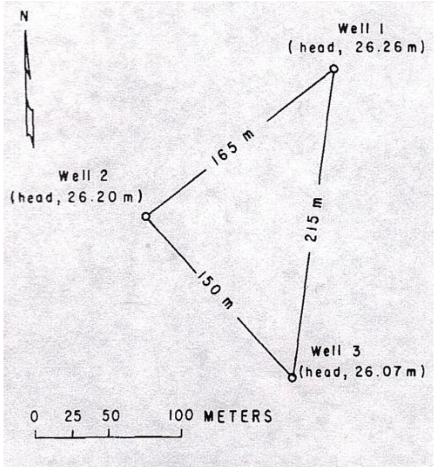


Figure 6. Example of the first step to determine the hydraulic gradient (Heath, 1987, pp. 11)

A line is then drawn between the wells with the highest head and the lowest head. The next step is to calculate the position on this line when the head is equivalent to the intermediate head, as seen in Figure 7.

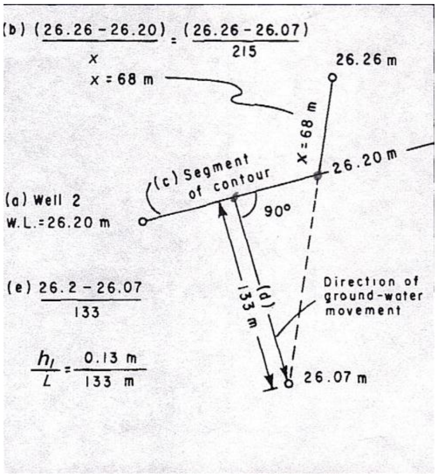


Figure 7. Example calculations to determine the x distance, the hydraulic gradient, and an example of the intermediate head line marking (Heath, 1987, pp. 11)

This distance, x, can be found by using the following equation:

$$\frac{highest\ head - intermediate\ head}{x} = \frac{highest\ head - lowest\ head}{distance\ between\ highest\ and\ lowest\ head\ wells}$$

In the previous equation, x is the distance from the well with the highest head, on the line to the lowest head, where the intermediate head value will occur. A straight line is then drawn between the well with the intermediate head and the point calculated using the previous equation, shown as line (c) in Figure 7. Next, a line is drawn that is perpendicular to the intermediate head line and that intersects the well with the lowest head, shown as line (d) in Figure 7. This line parallels the direction of the flow of the water. The distance of this line is found and used to calculate the hydraulic gradient in the following equation:

$$hydraulic\ gradient = \frac{intermediate\ head - lowest\ head}{distance\ of\ line\ that\ is\ perpendicular\ to\ intermediate\ head\ line}$$

Computer program

After many unsuccessful attempts to find an existing computer program that calculated the hydraulic gradient using GPS coordinates, a computer program was written. The program was created using Microsoft Visual Studio 2010. The program inputs, seen in Figure 8, are the latitude and longitude points for each well location, along with a Microsoft Excel spreadsheet containing the total head of each well.

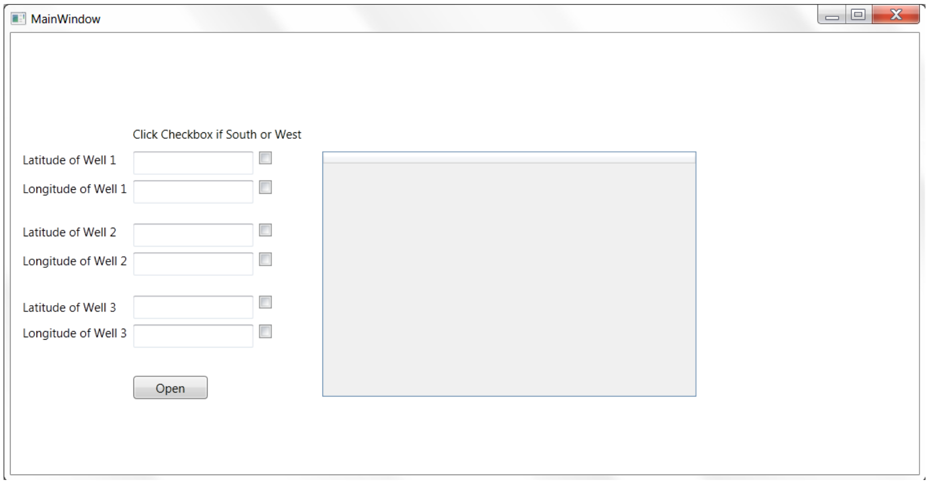


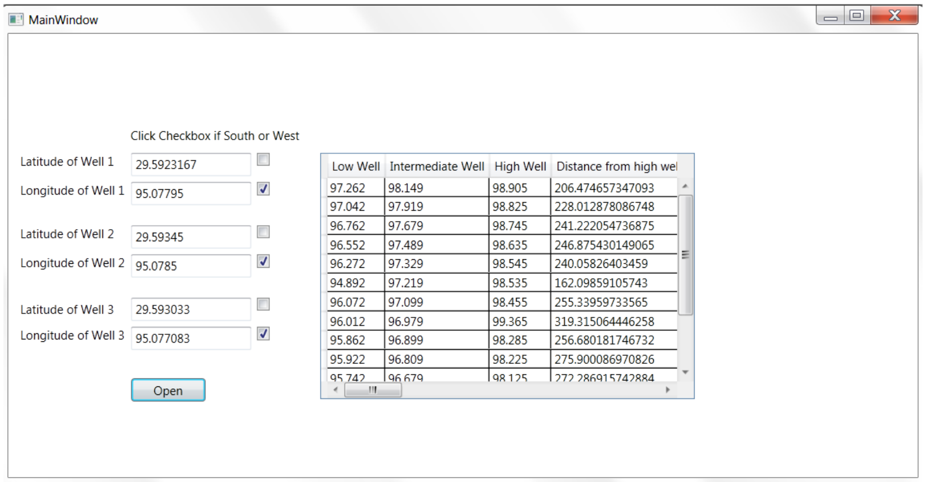
Figure 8. Screen shot of the main window of the program created to automate the process of determining the hydraulic gradient and direction of flow

As shown above in Figure 8, the latitude and longitude of each well are inserted into their respective text boxes. All coordinates must be entered as positive numbers in decimal degree form. The numbers must be positive because the textboxes are not able to read negative numbers. Since the latitude and longitude coordinates are commonly negated to represent South and West, checkboxes were placed next to each textbox. If checked, the coordinate will be negated inside the program to represent South or West. The "Open" button located underneath the coordinate inputs is used to open an Excel spreadsheet. The first column in the spreadsheet is the dates that the wells were measured. The second, third, and fourth columns are the total head of each well. The total head equals the elevation head plus the stick up minus the recorded value. Table 3 shows an example of the necessary spreadsheet.

Table 3. Sample spreadsheet of the well total head inputs that are plugged into the program

Date	**Well 1 Total Head (ft.)**	**Well 2 Total Head (ft.)**	**Well 3 Total Head (ft.)**
5/20/11	105.872	107.145	106.199
7/8/11	105.882	107.045	106.199

The program outputs the three head values in numerical order, the x distance used to draw the intermediate head line, the coordinates of that point, the distance of the line that is perpendicular to the intermediate head line, the coordinates of the point where the perpendicular line intersects the intermediate head line, the hydraulic gradient, and the direction of flow. A sample of the output is shown below in Figure 9.



Click Checkbox if South or West

Latitude of Well 1: 29.5923167 ☐
Longitude of Well 1: 95.07795 ☑

Latitude of Well 2: 29.59345 ☐
Longitude of Well 2: 95.0785 ☑

Latitude of Well 3: 29.593033 ☐
Longitude of Well 3: 95.077083 ☑

Low Well	Intermediate Well	High Well	Distance from high wel
97.262	98.149	98.905	206.474657347093
97.042	97.919	98.825	228.012878086748
96.762	97.679	98.745	241.222054736875
96.552	97.489	98.635	246.875430149065
96.272	97.329	98.545	240.05826403459
94.892	97.219	98.535	162.09859105743
96.072	97.099	98.455	255.33959733565
96.012	96.979	99.365	319.315064446258
95.862	96.899	98.285	256.680181746732
95.922	96.809	98.225	275.900086970826
95.742	96.679	98.125	272.286915742884

Figure 9. Screen shot of the main window of the program displaying a sample of the output

The program works by first sorting the head values to determine which well is the lowest, intermediate, and highest. It then finds the distance and direction between each well. The direction of each line is reported in degree form and is found using a system that makes North equal to 0˚, East equal to 90 ˚, South equal to 180˚, and West equal to 270˚. This information is used to determine the x distance and the coordinates that are x distance from the highest well, as seen above in Figure 7. The distance of the intermediate head line is calculated along with the direction of the line. The distance of the line that is perpendicular to the intermediate head line is found using trigonometry. The triangle that is created by the low well, the x point, and the point where the line is perpendicular to the intermediate head line, as seen in Figure 7, is a right triangle. The angle between the x point and the low well, labeled α, and the angle between the x point and the intermediate head line, labeled β, were found. These two were subtracted from each other to find the measurement of the angle, labeled γ, opposite from the hydraulic gradient distance. This process is shown below in Figure 10.

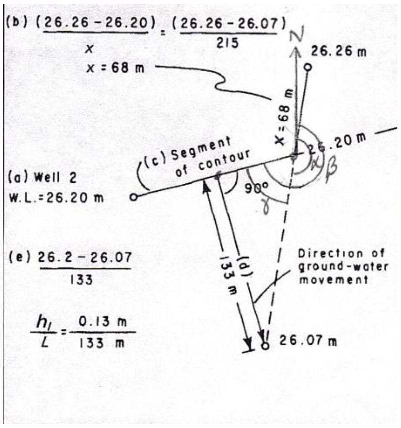


Figure 10. Example diagram of how to determine the inner angle, γ, of the hydraulic gradient triangle (Heath, 1987, pp. 11)

Angle γ was used to determine the hydraulic gradient distance by multiplying the hypotenuse of the right triangle, the distance from the x point to the low well, by the sine of angle γ. That data is used to determine the hydraulic gradient and the direction of flow.

CHAPTER III

RESULTS

The raw data acquired for both the deep and shallow wells during the research process in 2011 and 2010 are shown in Appendix A. The raw data refers to the length from the top of the well casing to the surface of the water in the aquifer. The drought was so severe during the 2011 monitoring period that some weeks the shallow aquifer was completely empty. The calculations of the hydraulic gradient and direction of flow were done on these dates by using the maximum depth of each of the respective wells. The rainwater data was found using the Harris County Flood Watch System.

The total head of each well was then found by using the following equation:

$$Total\ Head = Datum + Elevation\ Difference + Stick\ Up - Raw\ Data$$

The datum chosen for the analysis was 100 ft. The elevation difference, between the well nest location and the dock, and stick up for each well are shown below in Table 4.

Table 4. Elevation differences, measured from the dock location to each well nest, and the stick up measurements for each well nest

	Elevation Difference (ft)	**Stick Up (in)**
Well 1	7.789	34
Well 2	8.475	24
Well 3	8.61	21.6
Well 4	10.601	32

Graphs of the 2011 and 2010 rainfall, bayou depth, and total head for both the deep and shallow wells are shown in Appendix B. These graphs visually symbolize how each well and the bayou react with rainfall events during wet and dry seasons. The 2011 season was a particularly dry season and it was determined that during and after significant rainfall events, the total head for each well continuously decreased while the bayou level stayed relatively constant. During a wet season, such as 2010, the aquifers show a connection between the rainfall event and an increase in the total head of each well. The amount of time taken for the rainfall event to affect the total head of the wells is known as the recharge time. The recharge time for each well, based on 2010 data only, is shown below in Table 5. The lack of rainfall for 2011 prevents any significant findings between rainfall events and recharge times.

Table 5. Recharge time for both the perched aquifer and the unconfined aquifer based on 2010 data

	Recharge Time (Weeks)
Deep Well 1	2
Deep Well 2	2
Deep Well 3	3
Deep Well 4	2
Shallow Well 1	2
Shallow Well 2	2
Shallow Well 3	1
Shallow Well 4	1

The hydraulic gradient was determined using the method described in the Methods section of the paper. The weekly hydraulic gradient and direction of flow for both well nest configurations are shown in Appendix C. Two different hydraulic gradients and directions of flow were found for both the deep and shallow aquifers in order to determine if there was a similar path of flow for the same aquifer using two different well nest configurations. One hydraulic gradient and direction of flow was found using Wells 1, 2, and 3, while the other hydraulic gradient and direction of flow was found using Wells 2, 3, and 4. In general, the two well nest triangular configurations were similar in both the hydraulic gradient and the direction of flow. During 2010 collection period the two configurations had a more similar connection than in 2011. Also, both the deep and shallow aquifers in both years tended to flow in the same direction with an analogous hydraulic gradient. As with the two configurations, the 2010 data showed a more uniform direction of flow and hydraulic gradient between the two aquifers than in 2011.

The average hydraulic gradient and direction of flow for each aquifer were found and are shown below in Table 6. The result of this research was that the water flowed toward the bayou in both aquifers, generally flowing in the south-southeast direction.

Table 6. Average hydraulic gradient and average direction of flow for each year and each aquifer

	Average Hydraulic Gradient (ft./ft.)	**Average Direction of Flow (Degrees from Due North)**
Deep 2011	0.00497112	163.3305411
Shallow 2011	0.004762956	166.0383464
Deep 2010	0.00751086	153.262503
Shallow 2010	0.005227803	177.5854701

The average hydraulic gradient for each week was compared against rainfall events and changes in bayou levels to determine if a correlation existed. These are shown graphically in Appendix D. The data showed that when the ground is constantly saturated, like the conditions during the 2010 monitoring period, the hydraulic gradient for both the deep and shallow aquifers increased after a significant rainfall event. During the 2011 monitoring period a correlation between the hydraulic gradient and a rainfall event could not be proven in either the deep aquifer or the shallow aquifer. The hydraulic gradient and direction of flow for each of the aquifers were also compared to the level of water in the bayou. Both aquifers during 2010 had a positive correlation between the hydraulic gradient and the bayou level, while there was no found correlation between the hydraulic gradient and the bayou level during the 2011 collection period. The direction of flow is another major feature of groundwater flow so it was also compared against rainfall events and changes in bayou levels to determine if a correlation existed. These graphs are shown in Appendix E. During both the 2010 and

2011 periods, no connection between direction of flow and rainfall were established. There was also no connection found, in either year or aquifer, between the direction of flow and the bayou level. Throughout the research period in 2010, the deep well was found to have a positive association between the direction of flow and the hydraulic gradient, while the shallow well had no association between the two. Throughout the 2011 period, both the deep aquifer and the shallow aquifer were found to have negative correlations between the direction of flow and the hydraulic gradient.

Using the averages of each year the effects of a wet season vs. a dry season on the hydraulic gradient and direction of flow can be found. The change in average hydraulic gradient from a wet year to a dry year in the deep well was a decrease of 0.00253974 ft./ft. and the change in average direction of flow from a wet year to a dry year in the deep well was an increase of 10.068˚. The change in average hydraulic gradient from a wet year to a dry year in the shallow well was a decrease of 0.000464847 ft./ft. and the change in average direction of flow from a wet year to a dry year in the deep well was a decrease of 11.5471237˚.

CHAPTER IV

CONCLUSIONS

The major finding of this study was that the water in both aquifers is flowing toward the bayou. This means that Armand Bayou Nature Center has the possibility of becoming a protected wetland. These results will be given to ABNC faculty and staff so that they may pursue this objective. Another finding was that drought conditions altered the flow of the water in the aquifers. The hydraulic gradient for both aquifers was decreased due to the lack of rain. However, the drought conditions did not change the direction of flow of the two aquifers in the same way. The shallow aquifer moved more toward the south while the deep aquifer moved more toward the east. The recharge times are also drastically altered during a drought. This is most likely because the ground needs to be saturated and the vegetation needs to consume the water, leaving very little water to be released in the aquifers. The research done also shows that the calculations for the two triangular configurations of the well nests did not drastically alter the results.

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APPENDIX A

Table A-1. Distance from top of well casing to the surface of the water in the deep wells during summer of 2011

Date	Well 1 Deep (ft)	Well 2 Deep (ft)	Well 3 Deep (ft)	Well 4 Deep (ft)
5/20/2011	13.36	11.57	13.12	12.51
5/27/2011	13.58	11.65	13.36	12.77
6/3/2011	13.86	11.73	13.6	13.08
6/10/2011	14.07	11.84	13.79	13.29
6/17/2011	14.35	11.93	13.95	13.49
6/24/2011	14.73	11.94	14.06	13.61
7/1/2011	14.55	12.02	14.18	13.69
7/9/2011	14.61	11.11	14.3	13.88
7/15/2011	14.76	12.19	14.38	14.01
7/22/2011	14.7	12.25	14.47	14.01
7/29/2011	14.88	12.35	14.6	14.15
8/5/2011	15.04	12.47	14.68	14.3
8/12/2011	15.21	12.58	14.8	14.47
8/19/2011	15.35	12.67	14.86	14.56

Table A-2. Distance from top of well casing to the surface of the water in the shallow wells during summer of 2011

Date	**Well 1 Shallow (ft)**	**Well 2 Shallow (ft)**	**Well 3 Shallow (ft)**	**Well 4 Shallow (ft)**
5/20/2011	n/a	3.33	n/a	3.59
5/27/2011	n/a	3.31	5.06	3.28
6/3/2011	n/a	3.37	n/a	n/a
6/10/2011	n/a	3.44	n/a	n/a
6/17/2011	n/a	3.51	n/a	n/a
6/24/2011	n/a	3.51	5.04	n/a
7/1/2011	n/a	3.52	5.08	3.71
7/9/2011	4.74	3.43	5.08	3.62
7/15/2011	4.73	3.45	5.08	3.61
7/22/2011	4.72	3.48	5.08	3.87
7/29/2011	4.7	3.42	n/a	3.61
8/5/2011	4.73	3.52	5.07	3.61
8/12/2011	4.72	3.51	n/a	3.61
8/19/2011	4.73	3.53	5.08	3.61

Note: There were some weeks that the shallow wells were so low that they did not register. These are marked in Table A-2 by ‘n/a’.

Table A-3. Distance from top of well casing to the surface of the water in the deep wells during summer of 2010

Date	Well 1 Deep (ft)	Well 2 Deep (ft)	Well 3 Deep (ft)	Well 4 Deep (ft)
6/18/2010	11.36	7.26	10.35	-
6/25/2010	n/a	n/a	n/a	-
7/3/2010	11.75	7.86	10.75	-
7/9/2010	11.25	7.3	10.96	9.1
7/16/2010	11.2	7.48	10.71	9.74
7/23/2010	11.31	7.59	10.85	9.85
7/30/2010	11.35	7.74	11.01	10
8/6/2010	11.56	7.92	11.12	10.35
8/13/2010	11.86	8.11	11.32	10.76
8/20/2010	12.15	8.29	11.54	11.14

Table A-4. Distance from top of well casing to the surface of the water in the shallow wells during summer of 2010

Date	Well 1 Shallow (ft)	Well 2 Shallow (ft)	Well 3 Shallow (ft)	Well 4 Shallow (ft)
6/18/2010	4.66	3.16	4.83	-
6/25/2010	n/a	n/a	n/a	-
7/3/2010	4.64	2.4	3.44	-
7/9/2010	4.4	2.02	4.4	1.8
7/16/2010	4.68	2.75	4.6	3.55
7/23/2010	4.69	2.42	4.08	3.4
7/30/2010	4.69	2.62	4.23	3.4
8/6/2010	4.71	3.13	4.66	3.59
8/13/2010	4.71	3.15	4.81	3.58
8/20/2010	4.72	3.2	4.82	3.57

Note: In both Table A-3 and Table A-4 the first three weeks of Well 4 are denoted “-“ because the well nest was not completed until 7/9/2010.

APPENDIX B

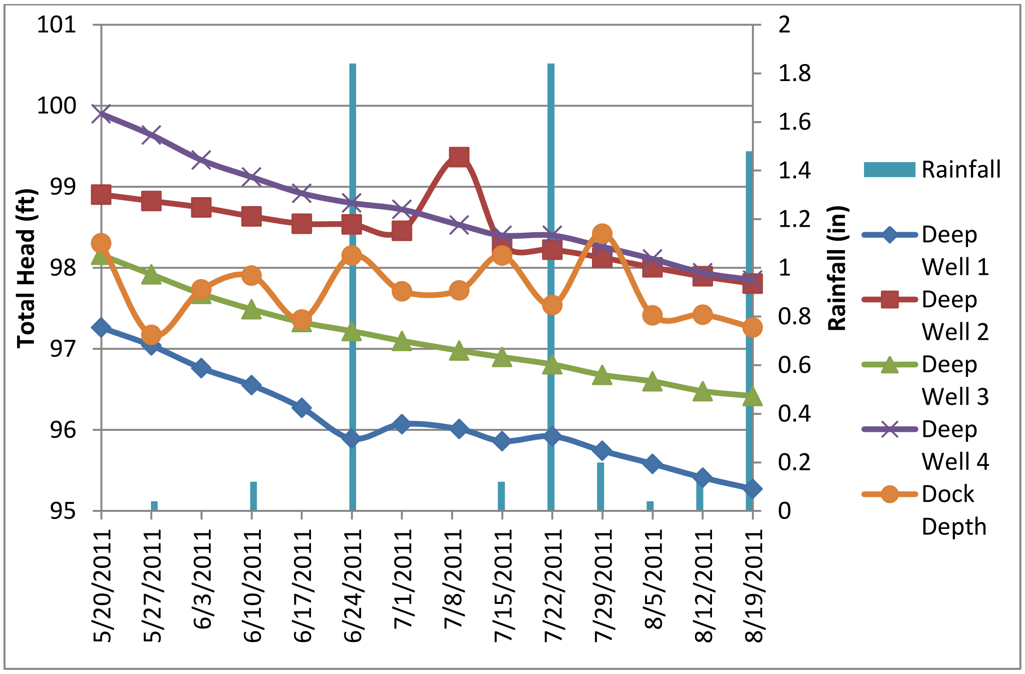

Figure B-1. Graphical representation of weekly rainfall, bayou depth, and total heads of the deep wells in 2011

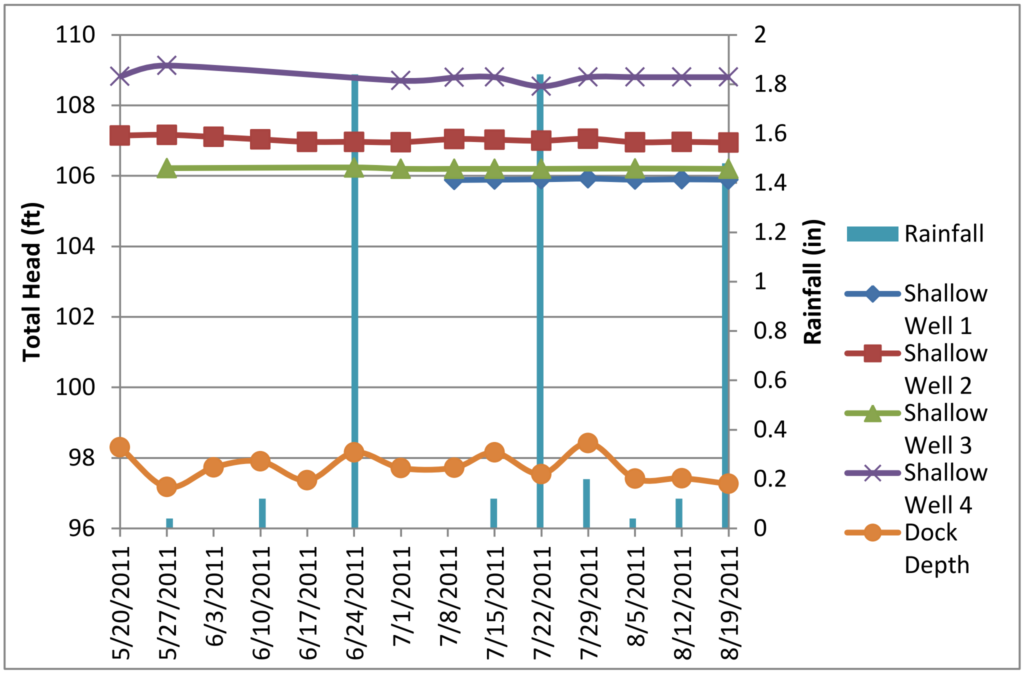

Figure B-2. Graphical representation of weekly rainfall, bayou depth, and total heads of the shallow wells in 2011

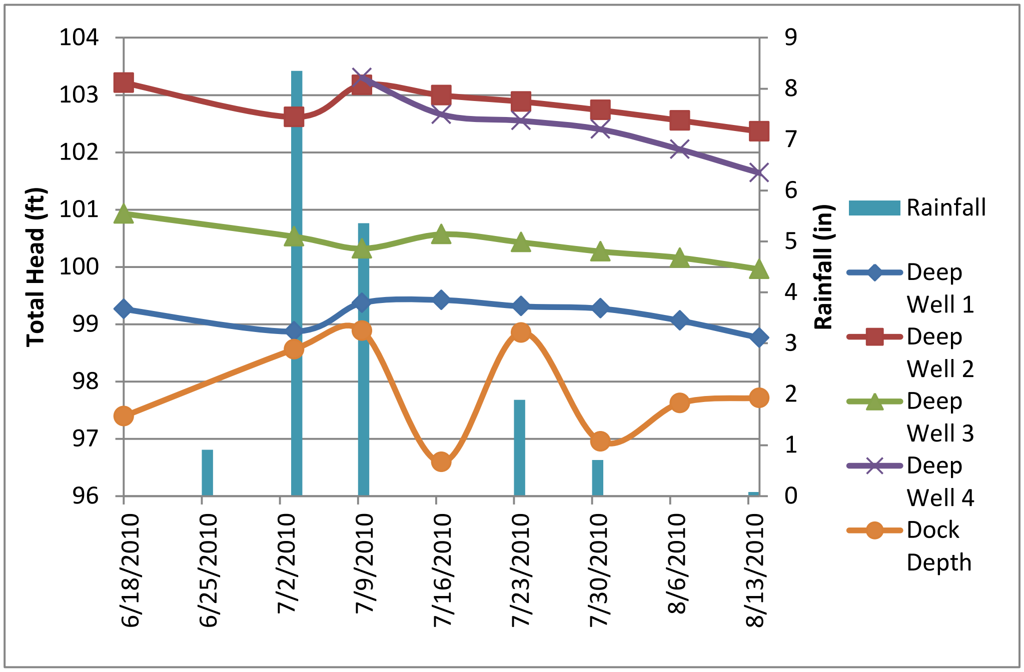

Figure B-3. Graphical representation of weekly rainfall, bayou depth, and total heads of the deep wells in 2010

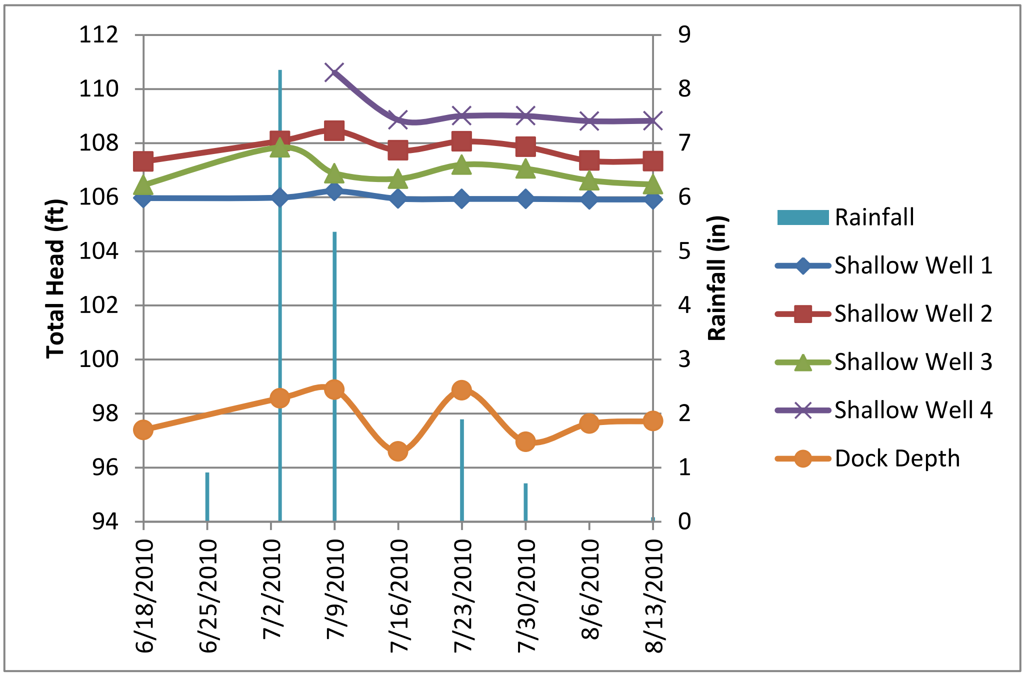

Figure B-4. Graphical representation of weekly rainfall, bayou depth, and total heads of the shallow wells in 2010

APPENDIX C

Table C-1. Weekly hydraulic gradient and direction of flow for both configurations of well nests during 2011 for deep wells

Date	Hydraulic Gradient for Wells 1,2,3 (ft/ft)	Direction for Wells 1,2,3 (Degrees)	Hydraulic Gradient for Wells 2,3,4 (ft/ft)	Direction for Wells 2,3,4 (Degrees)
5/20/11	0.003836133	174.1622988	0.004630943	178.2660228
5/27/11	0.004100863	170.934718	0.004540658	173.5952005
6/3/11	0.004525976	168.9087784	0.004387523	167.7313873
6/10/11	0.004740172	168.0321658	0.004365988	164.9727747
6/17/11	0.005191122	169.0885566	0.004303705	162.0384859
6/24/11	0.008849831	180.4605527	0.004338976	158.877465
7/1/11	0.005401973	166.7100854	0.004453078	158.6884561
7/9/11	0.007515807	156.4758909	0.005519413	133.0681127
7/15/11	0.005489516	166.4996998	0.004217932	154.8081245
7/22/11	0.005183029	163.4577286	0.004429893	156.2783791
7/29/11	0.005368605	164.0329059	0.004431755	155.1919644
8/5/11	0.00548126	165.9171063	0.0042547	154.4977916
8/12/11	0.005627311	166.6222835	0.004161543	152.8350157
8/19/11	0.005768368	168.2407475	0.004075283	152.8624526

Table C-2. Weekly hydraulic gradient and direction of flow for both configurations of well nests during 2011 for shallow wells

Date	Hydraulic Gradient for Wells 1,2,3 (ft/ft)	Direction for Wells 1,2,3 (Degrees)	Hydraulic Gradient for Wells 2,3,4 (ft/ft)	Direction for Wells 2,3,4 (Degrees)
5/20/11	0.002859583	154.1924214	0.007168893	177.8389031
5/27/11	0.00290165	155.0245623	0.00805514	176.0700684
6/3/11	0.002767688	154.7956285	0.006352636	179.1529148
6/10/11	0.002607766	155.9519903	0.006407423	177.656826
6/17/11	0.002449156	157.2570158	0.006467722	176.1903593
6/24/11	0.002450001	159.9060872	0.006381433	175.6264825
7/1/11	0.002426618	157.4571976	0.006970044	174.9888806
7/9/11	0.002609126	155.3289862	0.007163001	176.1507209
7/15/11	0.002542107	155.21244	0.007212068	175.7184621
7/22/11	0.002452227	155.2680094	0.006441193	176.8150354
7/29/11	0.002548473	153.2964882	0.007184689	176.2761273
8/5/11	0.002381985	157.1871585	0.007258783	174.3084856
8/12/11	0.00238377	155.8236225	0.007269724	174.6183284
8/19/11	0.002360037	156.7041522	0.007289828	174.256344

Table C-3. Weekly hydraulic gradient and direction of flow for both configurations of well nests during 2010 for deep wells

Date	Hydraulic Gradient for Wells 1,2,3 (ft/ft)	Direction for Wells 1,2,3 (Degrees)	Hydraulic Gradient for Wells 2,3,4 (ft/ft)	Direction for Wells 2,3,4 (Degrees)
7/3/10	0.008945533	167.5331045	-	-
7/9/10	0.008549723	153.6239354	0.008464456	153.323245
7/16/10	0.008005708	158.83905	0.006365299	145.2781494
7/23/10	0.008005145	158.2311493	0.006451067	145.3626208
7/30/10	0.007762533	156.4398141	0.006479659	145.3902807
8/6/10	0.007825936	158.3350166	0.006002756	141.4470107
8/13/10	0.008075189	159.6495207	0.005713981	136.165297

Table C-4. Weekly hydraulic gradient and direction of flow for both configurations of well nests during 2010 for shallow wells

Date	Hydraulic Gradient for Wells 1,2,3 (ft/ft)	Direction for Wells 1,2,3 (Degrees)	Hydraulic Gradient for Wells 2,3,4 (ft/ft)	Direction for Wells 2,3,4 (Degrees)
7/3/10	0.005816535	193.8342336	-	-
7/9/10	0.005710008	186.4599142	0.007892097	170.828773
7/16/10	0.004029065	165.4655721	0.00579023	183.9515615
7/23/10	0.0050647	177.8504103	0.004809973	183.606701
7/30/10	0.004558312	176.8346433	0.00528352	180.3890971
8/6/10	0.00329727	171.0372595	0.006074061	176.3224783
8/13/10	0.003183743	164.1038777	0.006451924	177.9265893

Note: In both Table C-3 and Table C-4 the first week of Well 4 are denoted “-“ because the well nest was not completed until 7/9/2010.

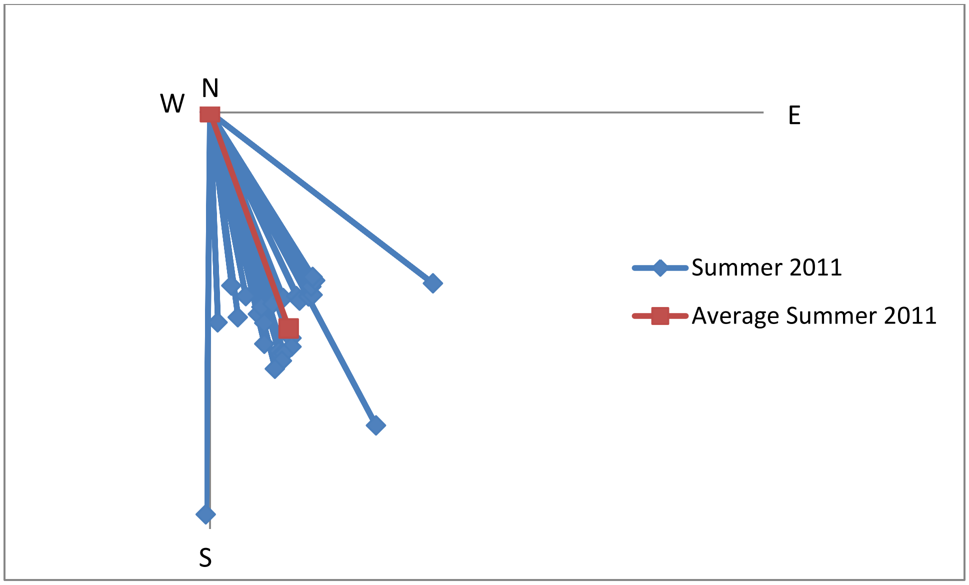

Figure C-1. Visual representation of the hydraulic gradient and direction of flow for the deep well in 2011. The length of the line corresponds to the hydraulic gradient and the direction of flow is represented by the direction of the line.

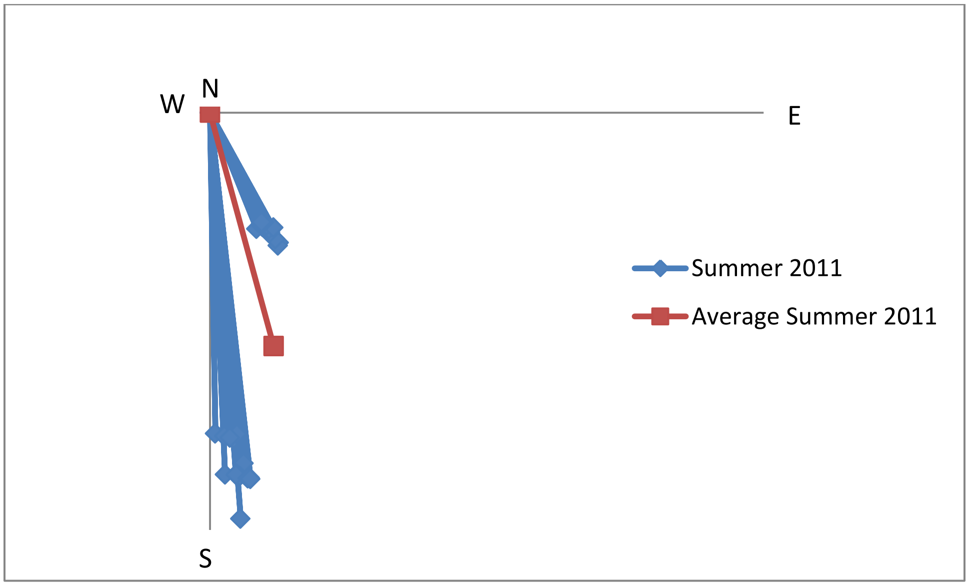

Figure C-2. Visual representation of the hydraulic gradient and direction of flow for the shallow well in 2011. The length of the line corresponds to the hydraulic gradient and the direction of flow is represented by the direction of the line.

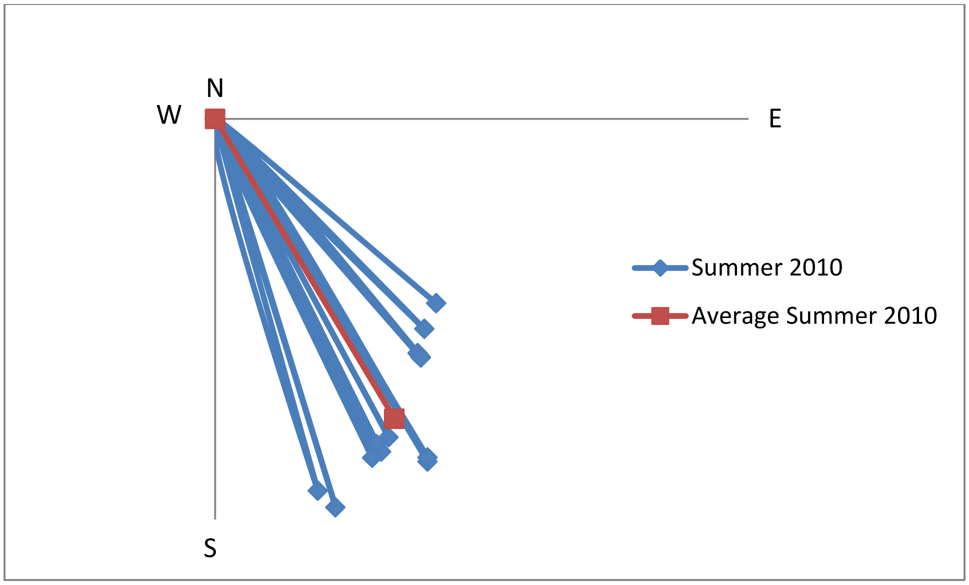

Figure C-3. Visual representation of the hydraulic gradient and direction of flow for the deep well in 2010. The length of the line corresponds to the hydraulic gradient and the direction of flow is represented by the direction of the line.

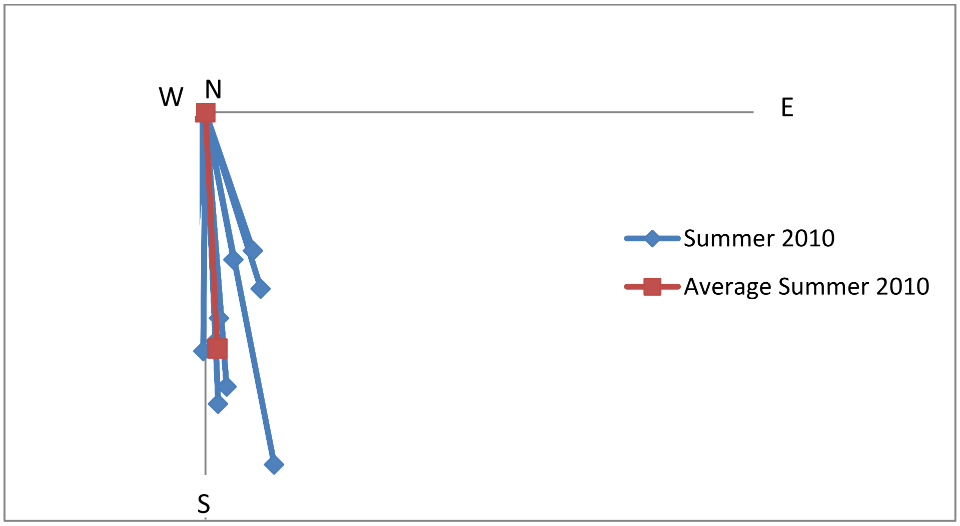

Figure C-4. Visual representation of the hydraulic gradient and direction of flow for the shallow well in 2010. The length of the line corresponds to the hydraulic gradient and the direction of flow is represented by the direction of the line.

APPENDIX D

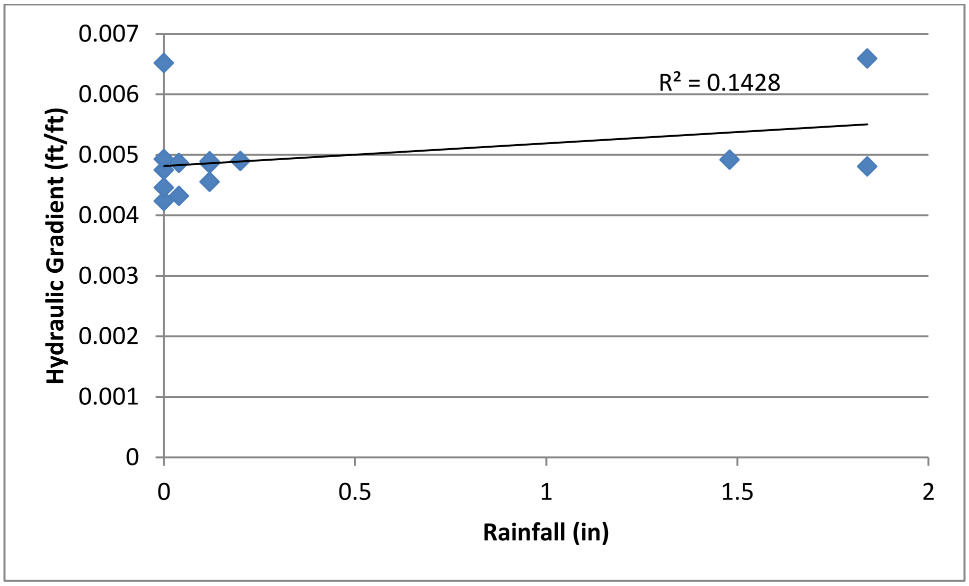

Figure D-1. Comparison of how rainfall events alter the hydraulic gradient in the deep wells during the 2011 collection period

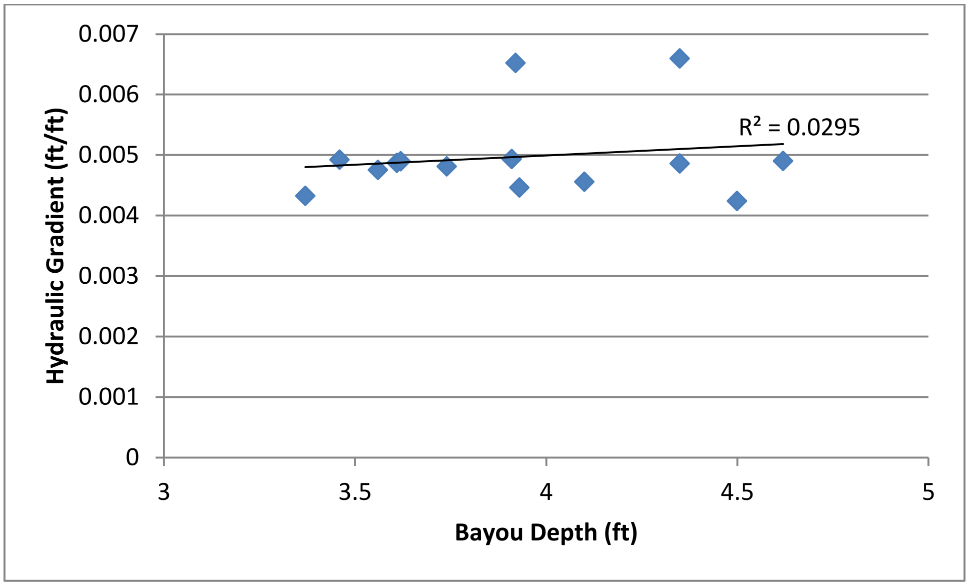

Figure D-2. Comparison of how changes in the bayou depth alter the hydraulic gradient in the deep wells during the 2011 collection period

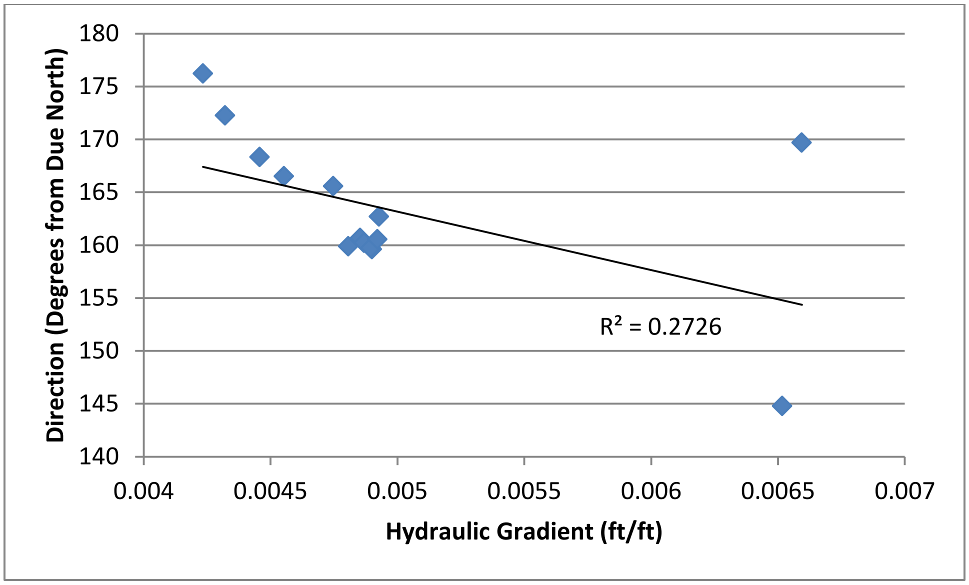

Figure D-3. Comparison of how the direction of flow of the groundwater alter the hydraulic gradient in the deep wells during the 2011 collection period

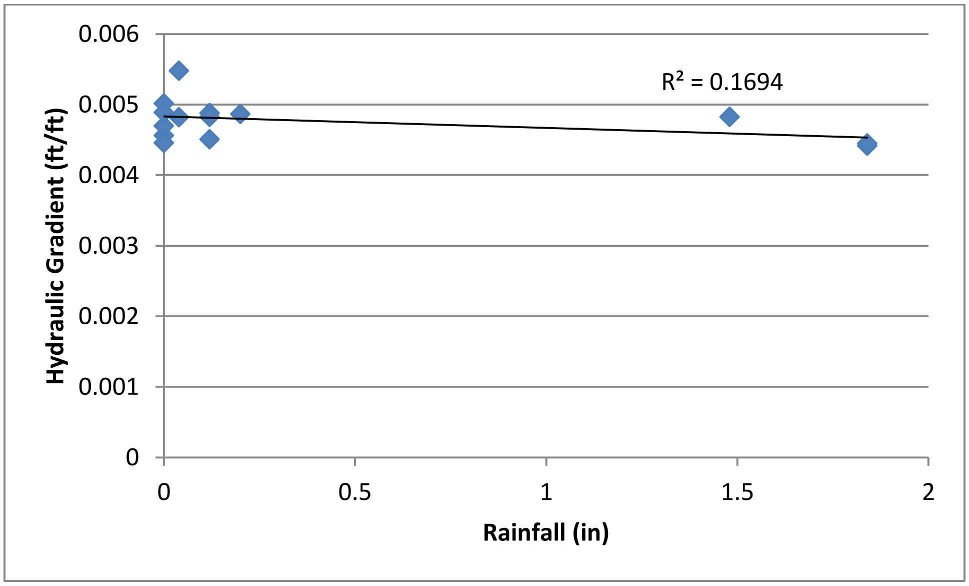

Figure D-4. Comparison of how rainfall events alter the hydraulic gradient in the shallow wells during the 2011 collection period

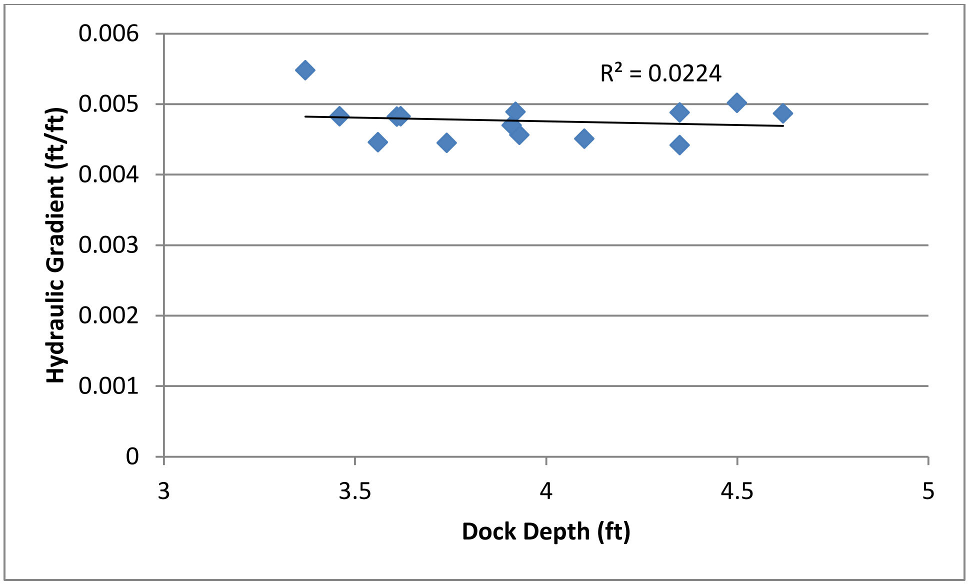

Figure D-5. Comparison of how changes in the bayou depth alter the hydraulic gradient in the shallow wells during the 2011 collection period

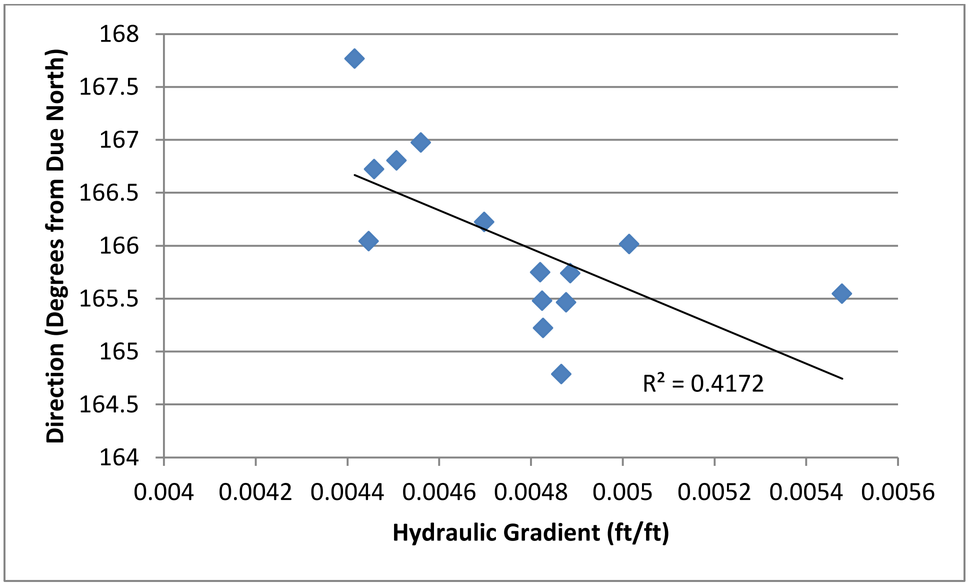

Figure D-6. Comparison of how the direction of flow of the groundwater alter the hydraulic gradient in the shallow wells during the 2011 collection period

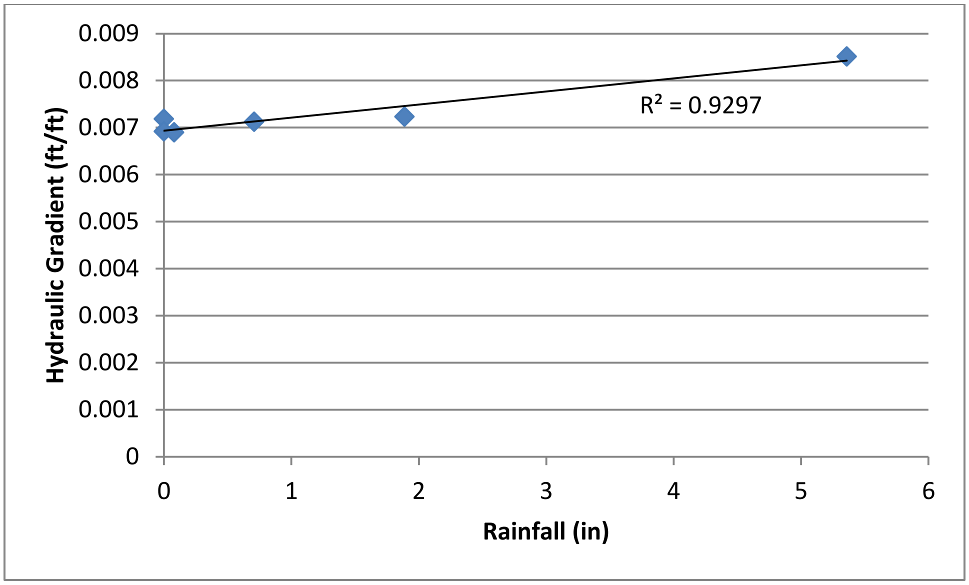

Figure D-7. Comparison of how rainfall events alter the hydraulic gradient in the deep wells during the 2010 collection period

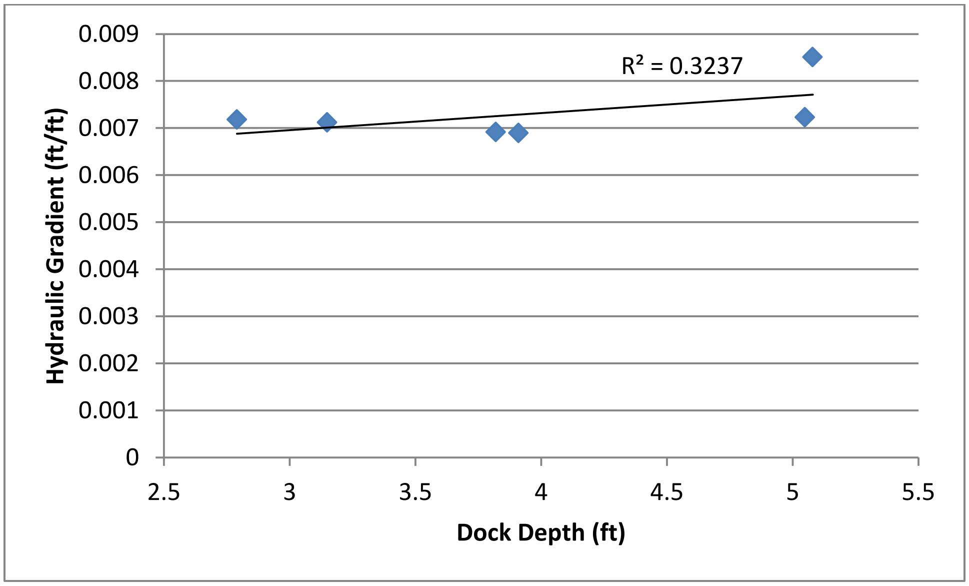

Figure D-8. Comparison of how changes in the bayou depth alter the hydraulic gradient in the deep wells during the 2010 collection period

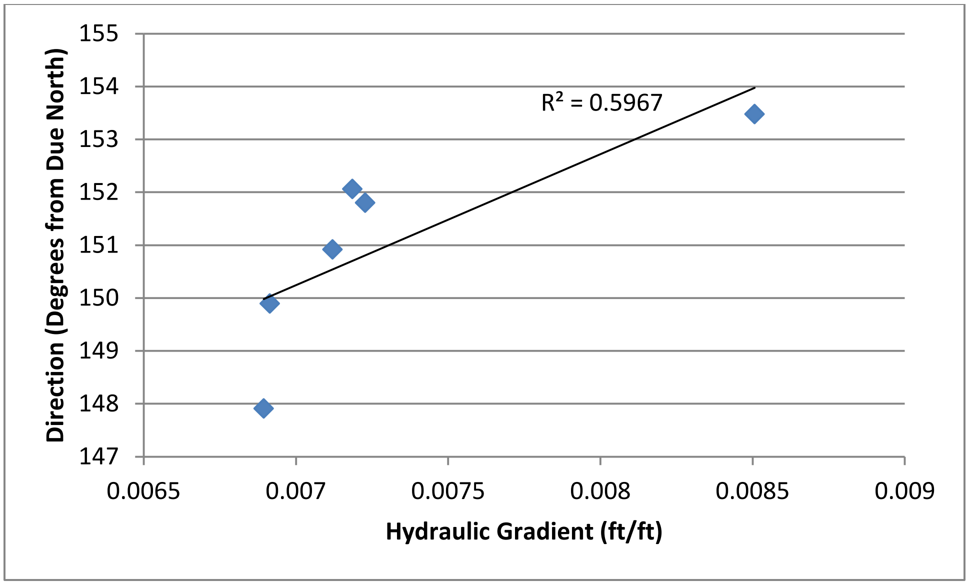

Figure D-9. Comparison of how the direction of flow of the groundwater alter the hydraulic gradient in the deep wells during the 2010 collection period

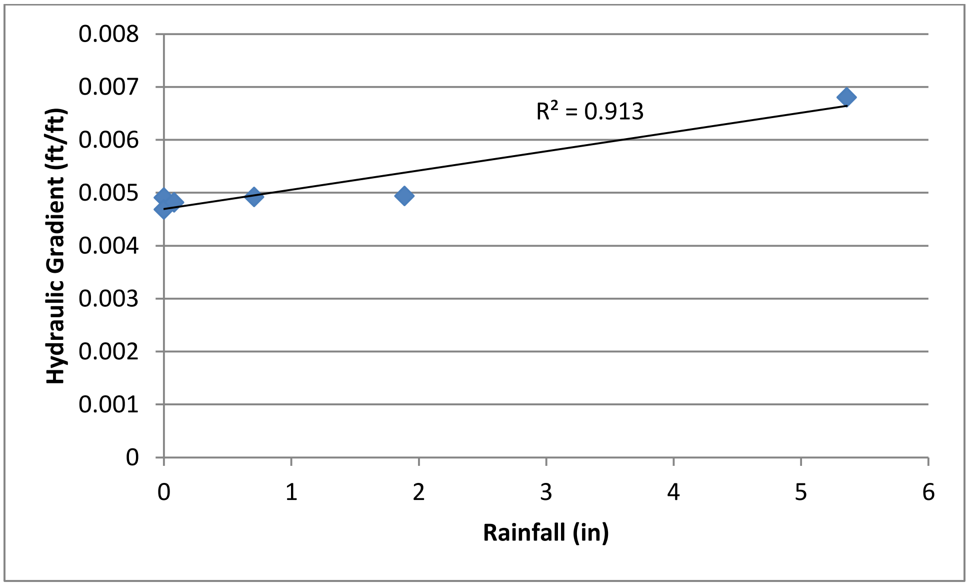

Figure D-10. Comparison of how rainfall events alter the hydraulic gradient in the shallow wells during the 2010 collection period

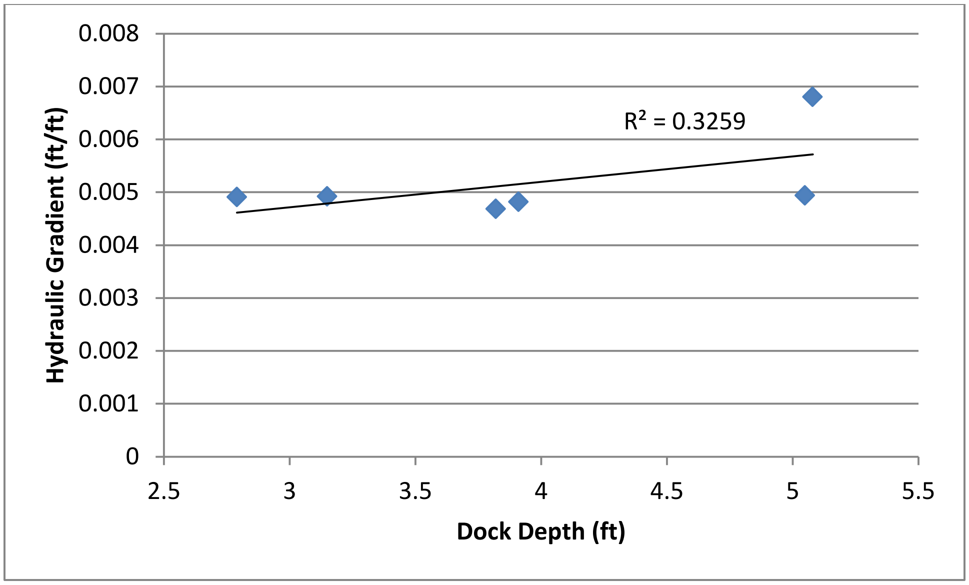

Figure D-11. Comparison of how changes in the bayou depth alter the hydraulic gradient in the shallow wells during the 2010 collection period

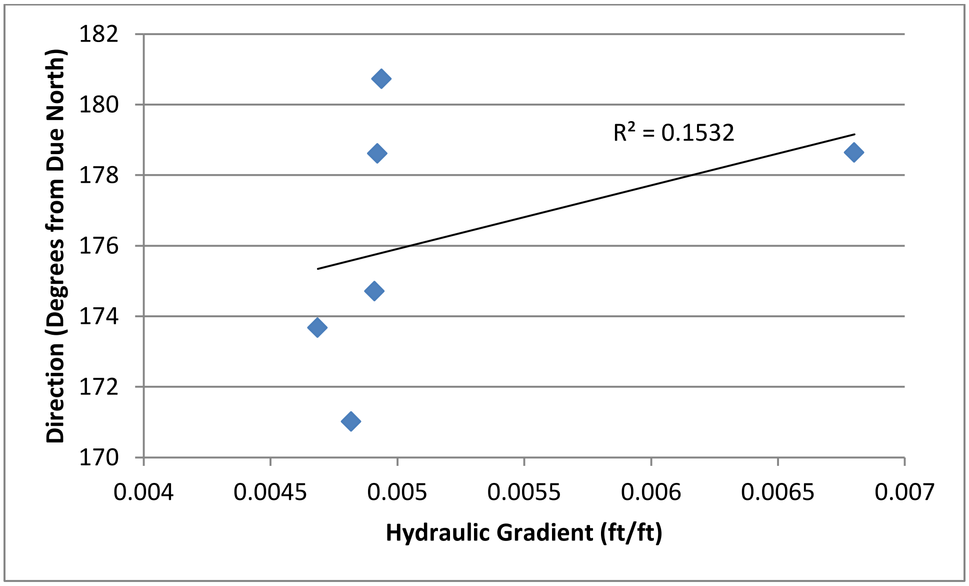

Figure D-6. Comparison of how the direction of flow of the groundwater alter the hydraulic gradient in the shallow wells during the 2010 collection period

APPENDIX E

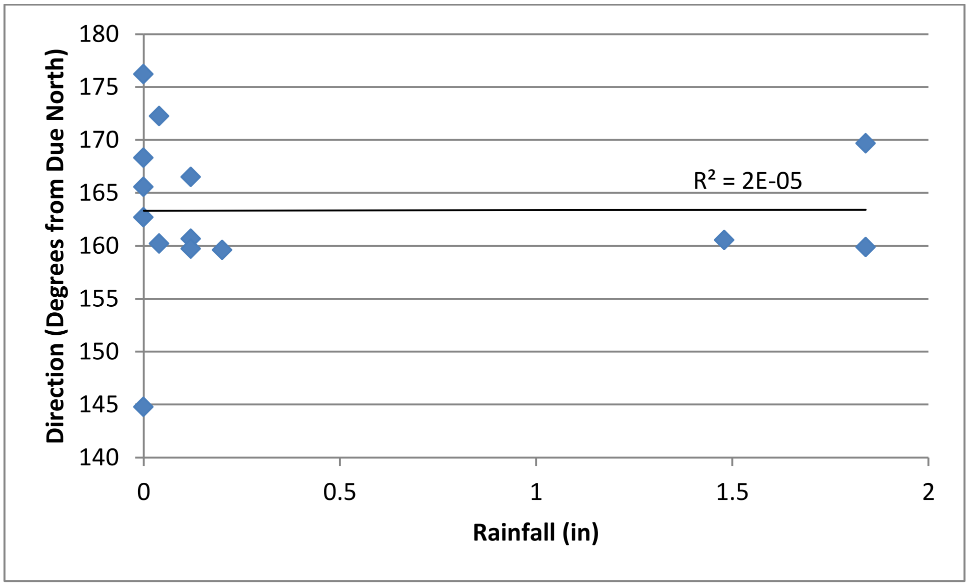

Figure E-1. Comparison of how rainfall events alter the direction of flow in the deep wells during the 2011 collection period

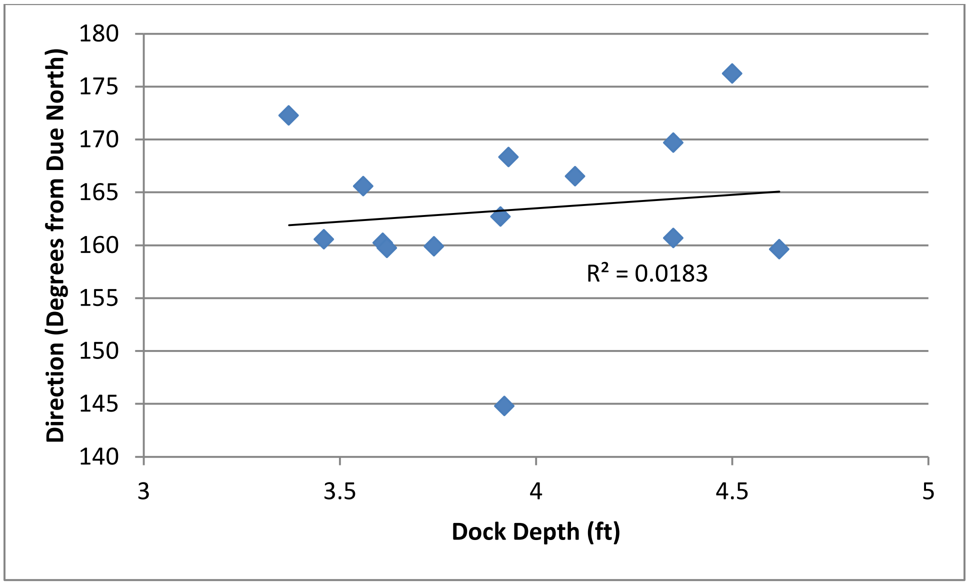

Figure E-2. Comparison of how changes in the bayou depth alter the direction of flow in the deep wells during the 2011 collection period

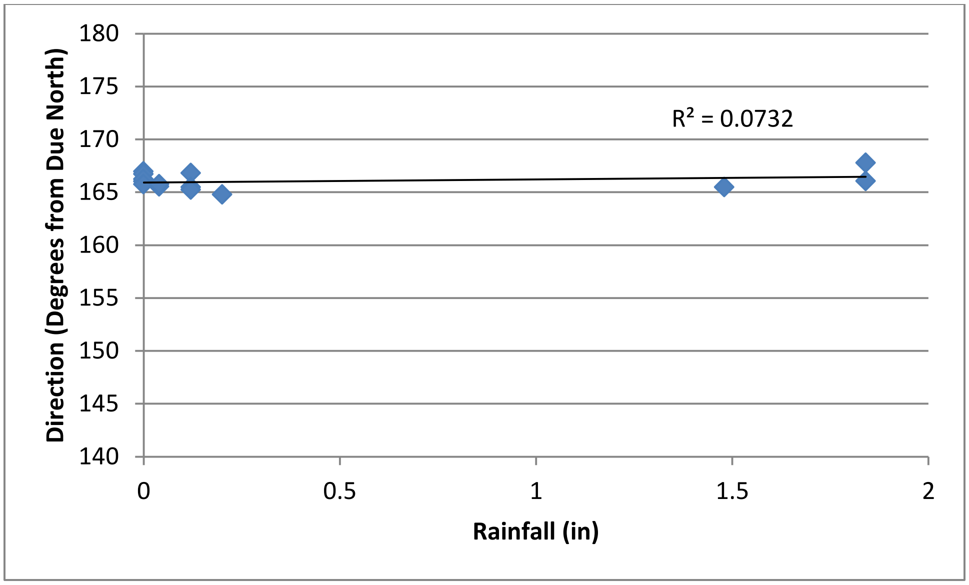

Figure E-3. Comparison of how rainfall events alter the direction of flow in the shallow wells during the 2011 collection period

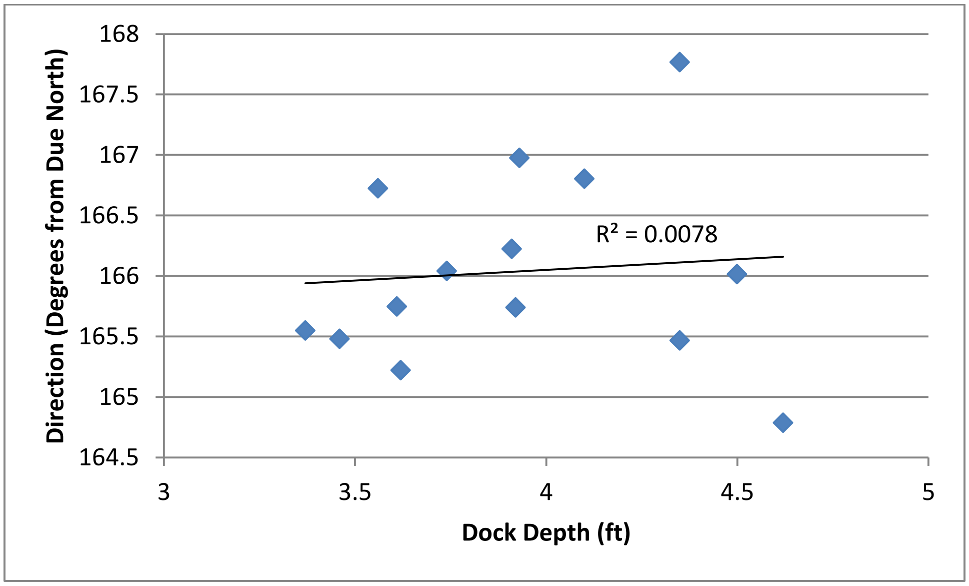

Figure E-4. Comparison of how changes in the bayou depth alter the direction of flow in the shallow wells during the 2011 collection period

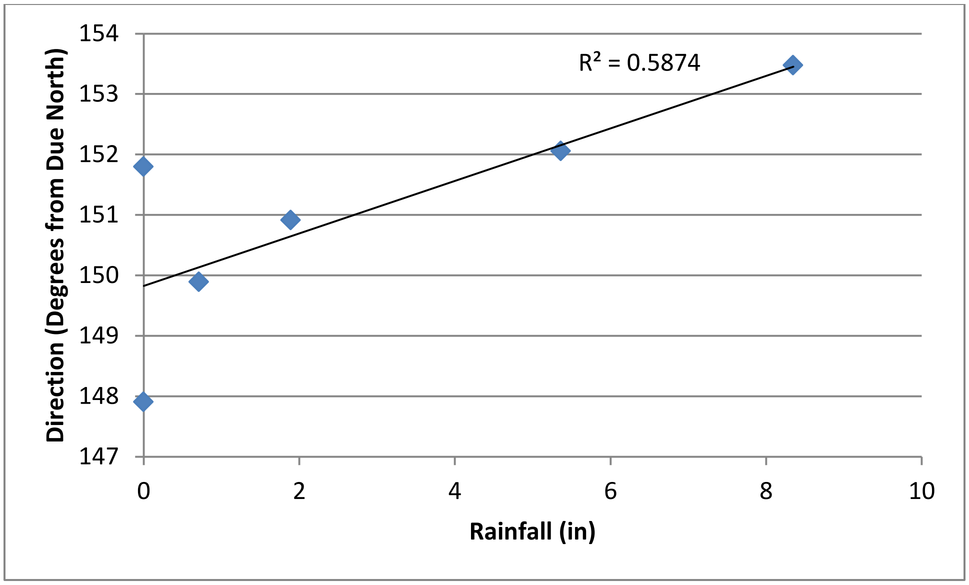

Figure E-5. Comparison of how rainfall events alter the direction of flow in the deep wells during the 2010 collection period

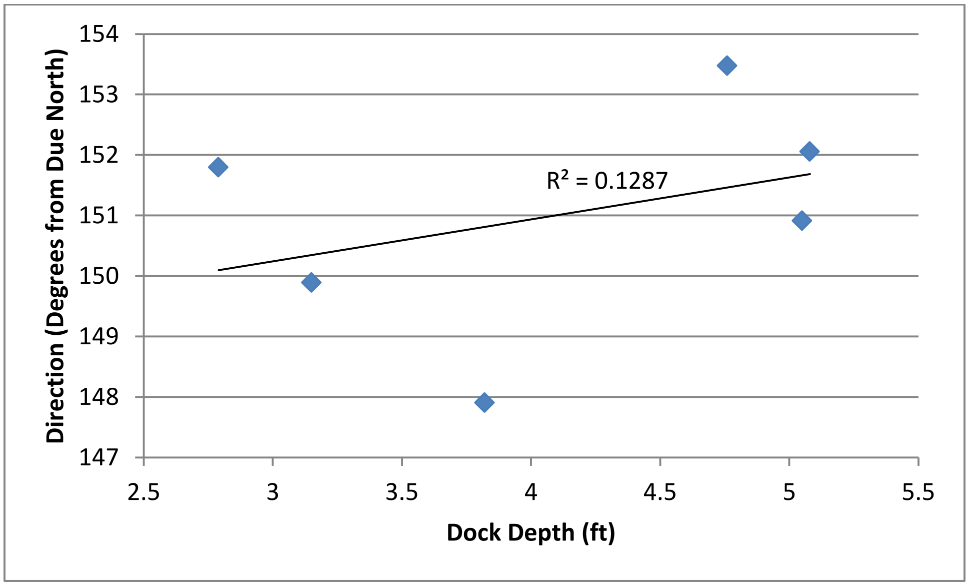

Figure E-6. Comparison of how changes in the bayou depth alter the direction of flow in the deep wells during the 2010 collection period

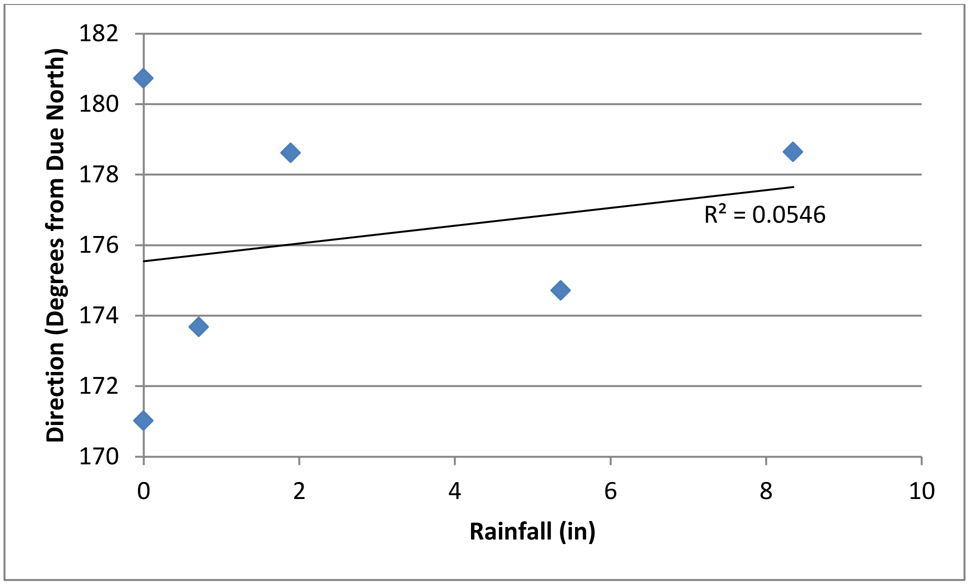

Figure E-7. Comparison of how rainfall events alter the direction of flow in the shallow wells during the 2010 collection period

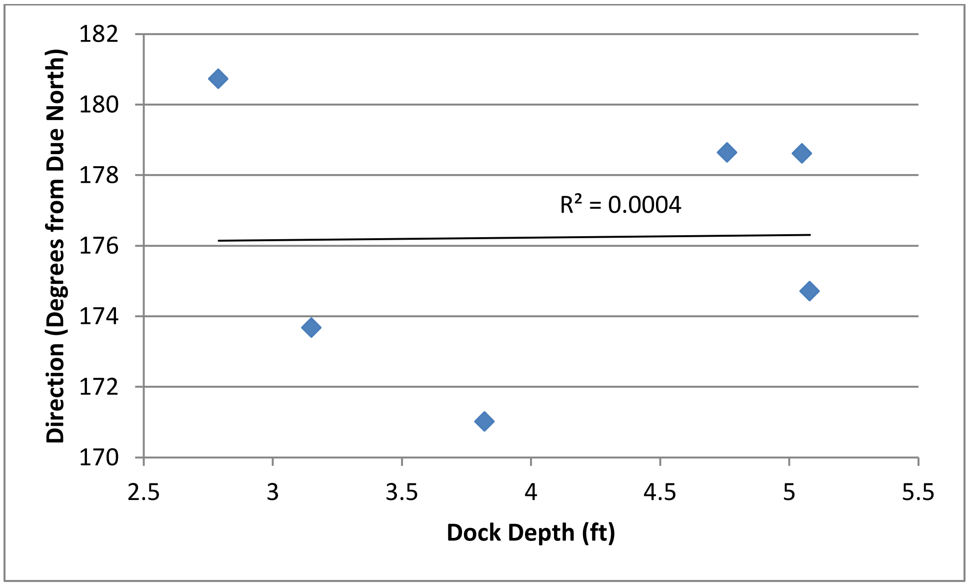

Figure E-8. Comparison of how changes in the bayou depth alter the direction of flow in the shallow wells during the 2010 collection period

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