Appendix E

Analyses of Flow Directions, Horizontal Gradients, and Vertical Hydraulic Gradients

Introduction

Plots of groundwater flow directions and horizontal hydraulic gradients inferred from triangulated wells and vertical gradients calculated within well nests from wells that are equipped with water level data loggers as of 2012 are presented in this appendix. With the exceptions noted below, the data presented below were collected through the second quarter of 2012. Wells in which data loggers have been deployed to record water levels are listed in Table H-1. Figure H-1 shows the locations of wells with data loggers as of the 2nd Quarter of 2012. Flow directions and horizontal hydraulic gradients are estimated using groups of three wells completed at similar depths in the suprapermafrost aquifer. Figure H-2 shows the groups of wells used for the flow direction and horizontal hydraulic gradient estimates.

Several of the NPR monitoring wells have experienced frost-jacking to the extent that the well casings protruded above the protective covers. During October 2011, the tops of some well casings had to be cut so they would fit in their monuments and all of the wells in which water levels are measured were resurveyed to determine the degree to which frostjacking had changed the elevations of these measuring points. The casings for wells MW-157A and MW-158A were cut down in 2010. None of the other wells in which data loggers were deployed in 2011 had to be cut down. Methods for handling these datum changes are presented in the following subsection. Similar adjustments to the tops of well casings and resurveying are occurring in September 2012 and do not affect the data presented in this appendix.

Handling of the Well Resurvey due to Frost Jacking

Evaluation of the influence of frost jacking and evaluation of data collected since October 2011 are described in this subsection. The frost jacking likely consisted of the well casings being lifted by accumulating frost in the winter, followed by some subsidence as the seasonal frost melts in the spring/summer. The net effect is a lifting of the well casing to the extent that the casing has to be cut down to allow the protective cover to be placed over it. Rather than attempt to recreate the history of the datum changes in the wells, some of which span multiple years, the decision was made to apply the surveyed changes in tops of the casings simultaneously. The correction was applied to data from October 6, 2011 onward.

In the future, well casing surveys will be updated annually, at a time when the seasonal frost has dissipated. Corrections to the groundwater elevation calculations from the wells will be applied following the day on which the majority of the resurveys are made.

The frost jacking reduces the accuracy of the water level estimates for the manual measurements and data logger readings by as much as approximately 0.86 feet in extreme cases. Offsets in the hydrographs for the data loggers at the time of the 2011 resurvey ranged from -0.43 feet to 0.86 feet (see Table H-2).

Note that the offsets for wells MW-162B and MW-186A have changed since the data reported in the March 2012 version of the *Revised Site Characterization Report* (RSCR) (Barr, 2012).

Inaccuracies in the water level estimates may, in turn, reduce the accuracy of the flow direction, horizontal hydraulic gradient, and vertical hydraulic gradient estimates described below. The degree to which flow direction, horizontal hydraulic gradient, and vertical hydraulic gradient estimates are affected depends on the relative changes of the measurement points of the wells involved in each calculation and the distance between measurement points (horizontal distance between wells for flow direction and vertical distance between well screens for vertical gradients), so quantitative statements about measurement accuracy cannot readily be made. In general, flow direction estimates for groups of wells that are located closer together will be more greatly influenced by changes in the elevation of the measurement points. Examples of the influence of the well casing elevation corrections on flow direction and hydraulic gradient estimates are described in the following subsections.

Discussion of Water Level, Flow Direction, and Horizontal Hydraulic Gradient Data

The direction of groundwater flow indicated between triangulated groups of wells with water levels monitored using data loggers was calculated and plotted (for example, see Figure H-3). The upper plot shows the variation of flow direction throughout the period of record. The data are plotted in degrees counterclockwise from due east. The lower plot shows the water elevations in each of the wells used in the calculation. As with the USGS wells southeast of the NRP, and with the exception of Group 1, the flow direction in the suprapermafrost aquifer is typically most easterly in the summer when the Tanana River stage is higher and more westerly in the other seasons when Tanana River stage is lower (see Appendix W of the RSCR [Barr, 2012] for more detail). Group 1 is influenced by gradients induced by the groundwater extraction system and the resurvey due to the relatively small distance between the wells.

The flow direction data are also summarized in rose diagrams (for example, see Figure H-4a). Some outliers in the flow directions likely exist within the data sets. For example, the water level recorded in Well MW-156A dropped abruptly in April 2011 and returned to similar levels prior to this event over approximately four days (see Figure H-18). This caused a large swing in the calculated flow direction that likely did not occur. Well MW-156A is also included in five other flow direction calculations (see Figures H-21, H-24, H-27, H-30, and H-39). No other examples were noted. Excluding the likely outliers and the results for Group 1, the calculated flow directions show similar ranges in individual well groups to those from the USGS wells southeast of the refinery, in which an 18.9 degree variation has been observed (see Appendix W of the RSCR [Barr, 2012]).

Data logger malfunctions occurred in wells MW-150A, MW-151A, and MW-156A during 2011. These data loggers were out of service prior to the resurvey and not replaced until the 2nd quarter of 2012. As a result, the influence of the well casing elevation corrections due to frost jacking prior to the 2011 resurvey can be evaluated in one group of wells: MW-111, MW-113, and MW-186A. Figure H-3 shows the apparent offset that occurred due to the resurvey. Top of casing changes were applied on October 6, 2011 and resulted in an apparent change in flow direction of approximately 16 degrees. Figure H-4a shows the variability of flow directions calculated between these wells prior to the resurvey. Figure H-4b shows the variability of flow directions calculated between these wells after the resurvey.

Horizontal hydraulic gradients were also calculated between the groups of wells (for example, see Figure H-5). The gradients tend to be greatest in the summer when the Tanana River stage is highest and recharge from the river to the alluvial aquifer is greatest. The horizontal hydraulic gradient ranges from 0.00058 to 0.0028.

Flow directions and horizontal hydraulic gradients estimates from the data logger program are presented in Figures H-3 to H-42.

Discussion of Vertical Hydraulic Gradient Data

This section discusses vertical hydraulic gradients observed within the suprapermafrost aquifer. Vertical hydraulic gradients as measured within well nests wells monitored with data loggers in 2012 are presented in this appendix. All combinations of nested wells were considered. The vertical hydraulic gradients were calculated as the water elevation measured in the well with the shallower screen minus the water elevation measured in the well with the deeper screen divided by the vertical separation between the screen midpoints. Based on this definition, negative vertical hydraulic gradients indicate an increasing hydraulic head with depth in the aquifer and suggest movement of water from deeper in the formation toward the shallower portion of the formation (upward gradient). Conversely, positive vertical hydraulic gradients indicate a decreasing hydraulic head with depth in the aquifer and suggest movement of water from shallower in the formation toward the deeper portion of the formation (downward gradient)

Plots of vertical hydraulic gradients within well nests are shown in Figures H-43 through H-50. Data logger malfunctions in wells MW-150A and MW-151A prevented water level data from being collected in these wells after the resurvey in October 2011. The data logger in MW-150A was removed from the monitoring program due to the proximity of well nest MW-150 to well nest MW-151 and the desire to place transducers over a larger area. The data logger in MW-151A was returned to service in April 2012.

Figure H-43 shows estimated vertical gradients for the MW-151 well nest. The estimated vertical gradient between wells A and B in this nest fluctuated between downward and upward prior to the 2011 resurvey and has been upward since the data loggers were placed back in service in 2012. Estimated gradients between wells A and C and B and C in the MW-151 well nest have been almost entirely upward.

The estimated vertical gradient between wells A and B in the MW-162 well nest was downward prior to the 2011 resurvey but changed to upward due to the resurvey (Figure H-44). The well screen midpoints are separated by over 50 feet and the adjustments due to the survey were relatively small (-0.04 and 0.06 feet), but because the sense of change was opposite and the head difference between the wells was small (absolute value of approximately 0.05 feet), the estimated gradient reversed. Following the resurvey, the estimated vertical gradient has changed from upward to downward in the following months.

The estimated vertical gradients between wells A and C in the MW-164 and MW-169 well nests and wells A, B, and C in the MW-181 nest are consistently upward (see Figures H-45, H-46, and H-49).

The estimated vertical gradients in the MW-170 and MW-186 well nests are primarily upward (Figures H-47 and H-50). The estimated vertical gradient in the MW-172 nest changed from downward to upward from May to June 2012 (see Figure H-48).

Figure H-51 shows all of the vertical hydraulic gradient estimates based on data logger measurements combined in one plot as a function of the day of the year. The majority of the estimates (3505 out of 4366) are upward, 46 are neutral, and 815 (19 percent) are downward.

Conclusions

Frost jacking of the observation wells used for estimating flow direction, horizontal and vertical hydraulic gradients adds to the measurement error of these estimates beyond those associated with the water level measurement themselves. Periodic resurveying of the wells resets the elevations of the measurement points and keeps the errors from accumulating.

The differences between the rose diagrams shown on Figures H-4a and H-4b suggest that frost jacking of well casings and periodic changes to the well casing elevations may require that the flow variation data be considered only in groups between surveys. Handling the data in this way will still provide an estimate of the variability in flow direction, although some uncertainty may exist as to the actual direction of flow. This group of wells (Group 1) is closer together than any other group, so is most susceptible to changes in the measurement elevations of the wells.

Although the majority of estimates of vertical gradient indicate an upward component of vertical flow, 19 percent of the estimates from data logger measurements indicate a downward component of vertical flow (downward gradient).

References

Barr, 2012. Revised Site Characterization Report, North Pole Refinery, North Pole, Alaska. DEC File Number: 100.38.090. Prepared for Flint Hills Resources Alaska, LLC. March 2012.

Table H-1
Summary of Water Level Data Logger Deployment

Data Loggers Deployed in 2010 to 2011	Data Loggers Deployed in 2012
	MW-109
MW-111	MW-111
MW-113	MW-113
MW-150A	
MW-150B	
MW-151A	MW-151A
MW-151B	MW-151B
MW-151C	MW-151C
MW-156A	MW-156A
MW-157A	MW-157A
MW-158A	MW-158A
MW-161A	MW-161A
MW-162A	MW-162A
MW-162B	MW-162B
	MW-164A
	MW-164C
	MW-169A
	MW-169C
MW-170A	MW-170A
MW-170C	MW-170C
	MW-172A
	MW-172B
	MW-175
	MW-181A
	MW-181B
	MW-181C
MW-186A	MW-186A
MW-186B	MW-186B
MW-186C	MW-186C
	MW-304-125
	MW-304-150
	MW-306-150
	O-12
	S-43

Table H-2

Summary of Changes in Estimated Water Level for Wells with Data Loggers after the Resurvey in October 2011

Well	Change in Water Level on 10/6/2011
MW-111	-0.12
MW-113	-0.29
MW-150A	-0.01, Data logger not in service after 10/14/11
MW-150B	-0.01, Data logger not in service after 10/14/11
MW-151A	Data logger not in service
MW-151B	0.11
MW-151C	0.20
MW-156A	Data logger not in service
MW-157A	0.86
MW-158A	0.29
MW-161A	-0.43
MW-162A	-0.04
MW-162B	0.06
MW-170A	0.12
MW-170C	0.06
MW-186A	0.18
MW-186B	-0.09
MW-186C	-0.03

Figure H-1
LOCATIONS OF WELLS WITH DATA LOGGERS
AS OF 2ND QUARTER 2012
North Pole Refinery
Flint Hills Resources Alaska, LLC

Bar Footer: ArcGIS 10.0, 2012-09-27 17:45 File: I:\Client\FlintHills\Alaska\ReportMaps\NPR\Site_Characterization_Report_Addendum\Figure 2 Groups of Wells with Data Loggers Q2 2012.mxd User: arm2

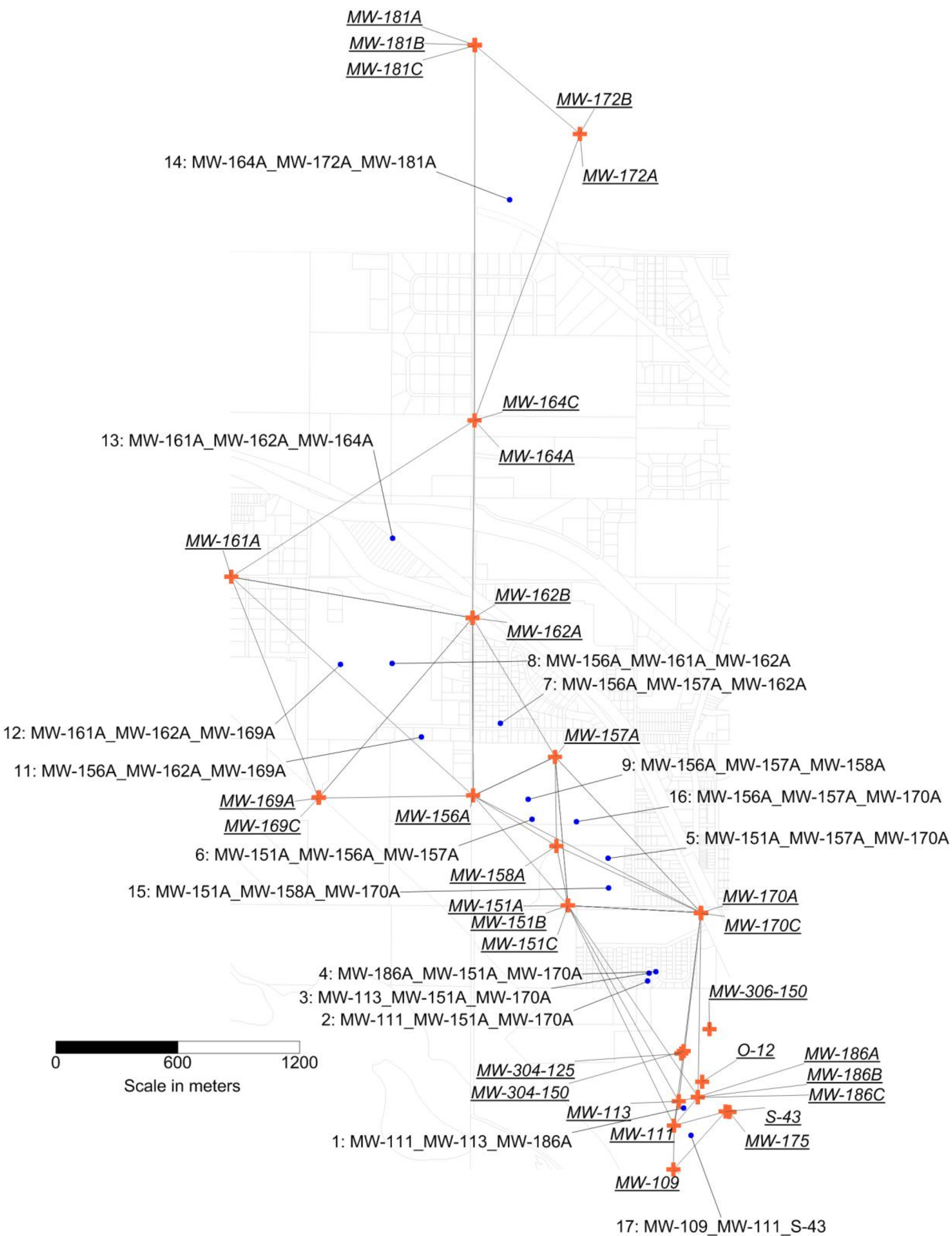


Figure H-2

Groups of Wells with Data Loggers used in Flow Direction Estimates as of 2nd Quarter 2012

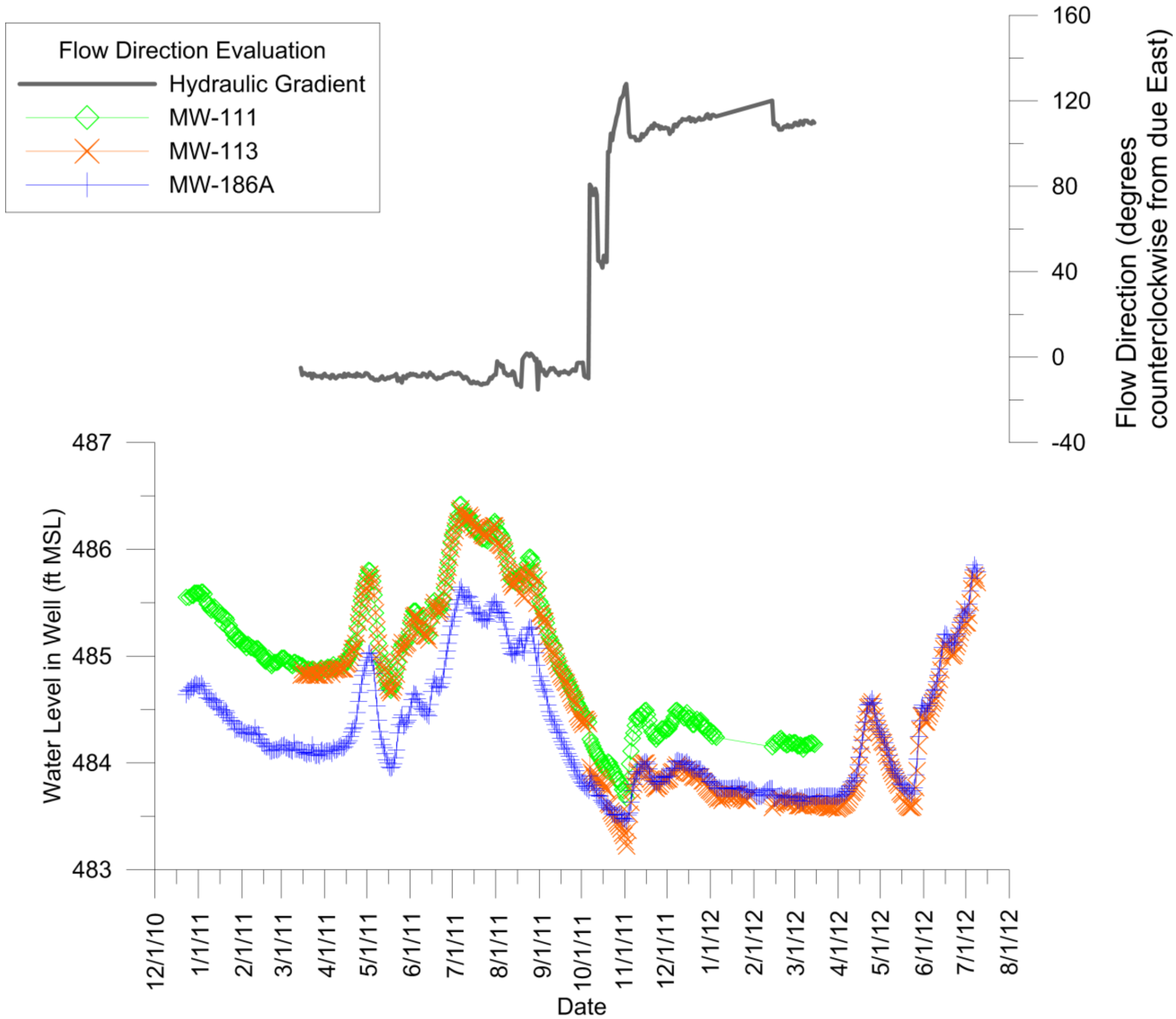


Figure H-3

Plots of the Flow Direction between Wells MW-111, MW-113, and MW-186A (upper plot) and Water Levels (lower plot) (Group 1)

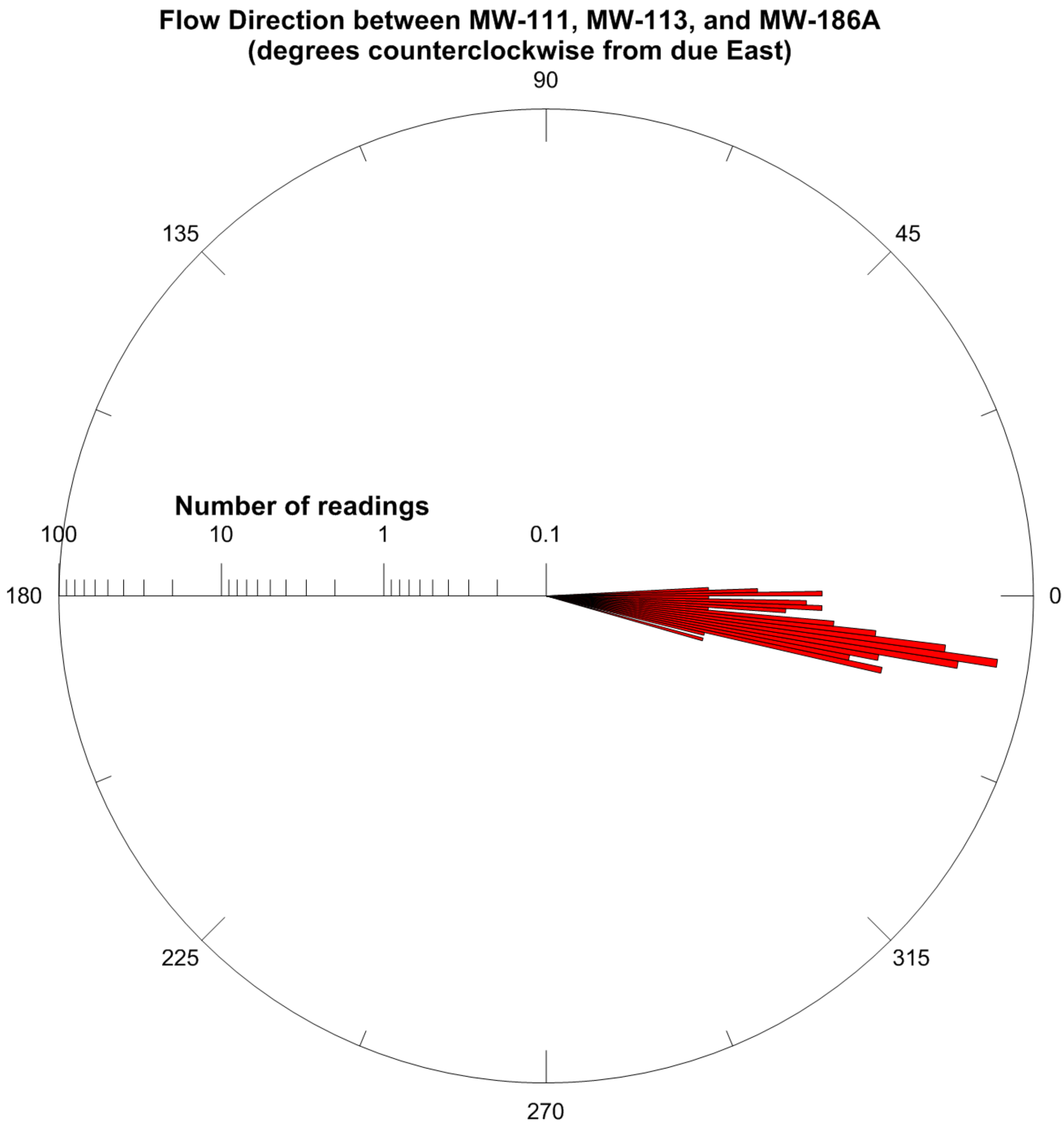


Figure H-4a

Rose Diagram of Flow Direction between Wells MW-111, MW-113, and MW-186A for Data Prior to the Resurvey (Group 1)

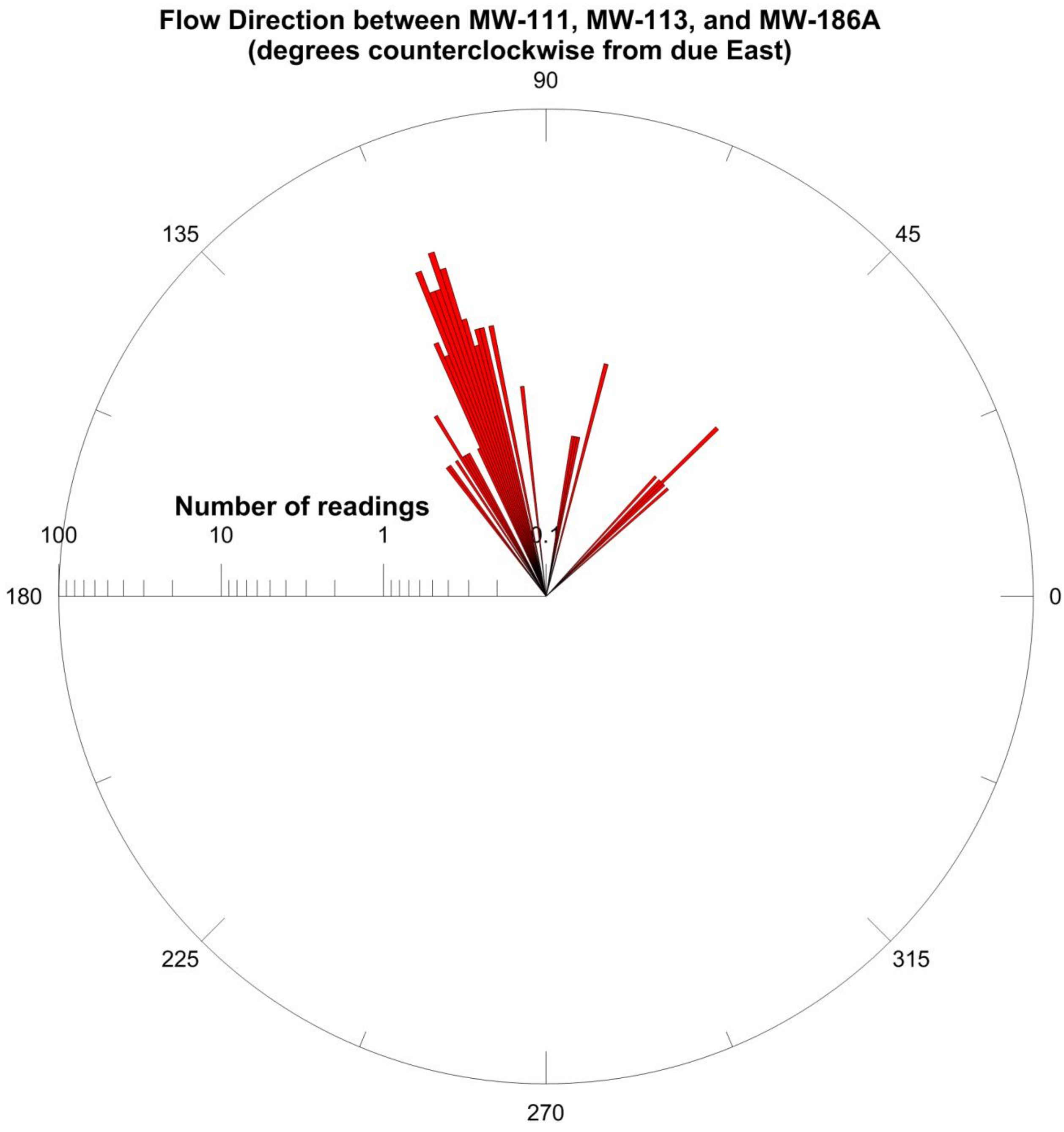


Figure H-4b

Rose Diagram of Flow Direction between Wells MW-111, MW-113, and MW-186A for Data After the Resurvey (Group 1)

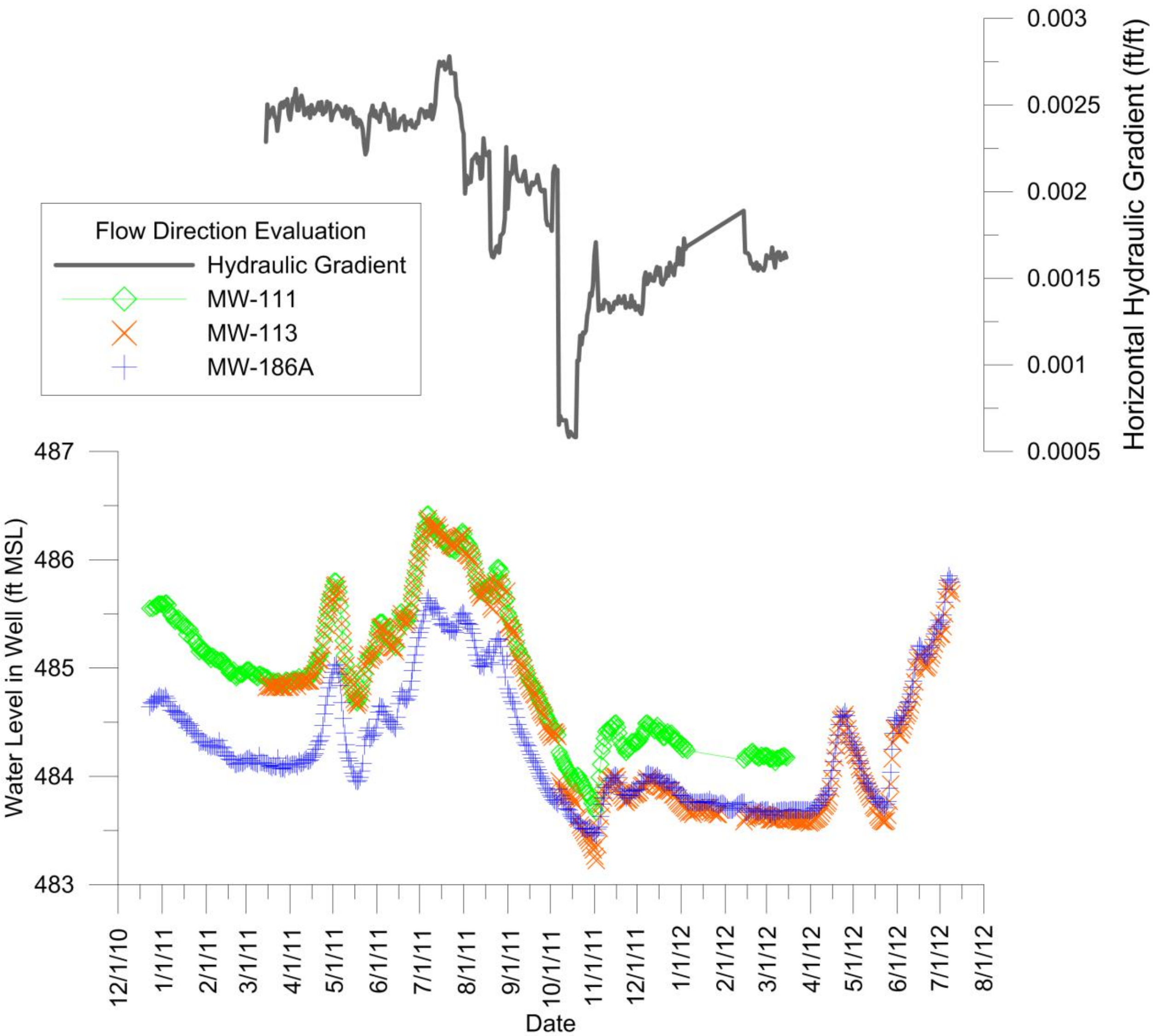


Figure H-5

Plots of the Horizontal Hydraulic Gradient between Wells MW-111, MW-113, and MW-186A (upper plot) and Water Levels (lower plot) (Group 1)

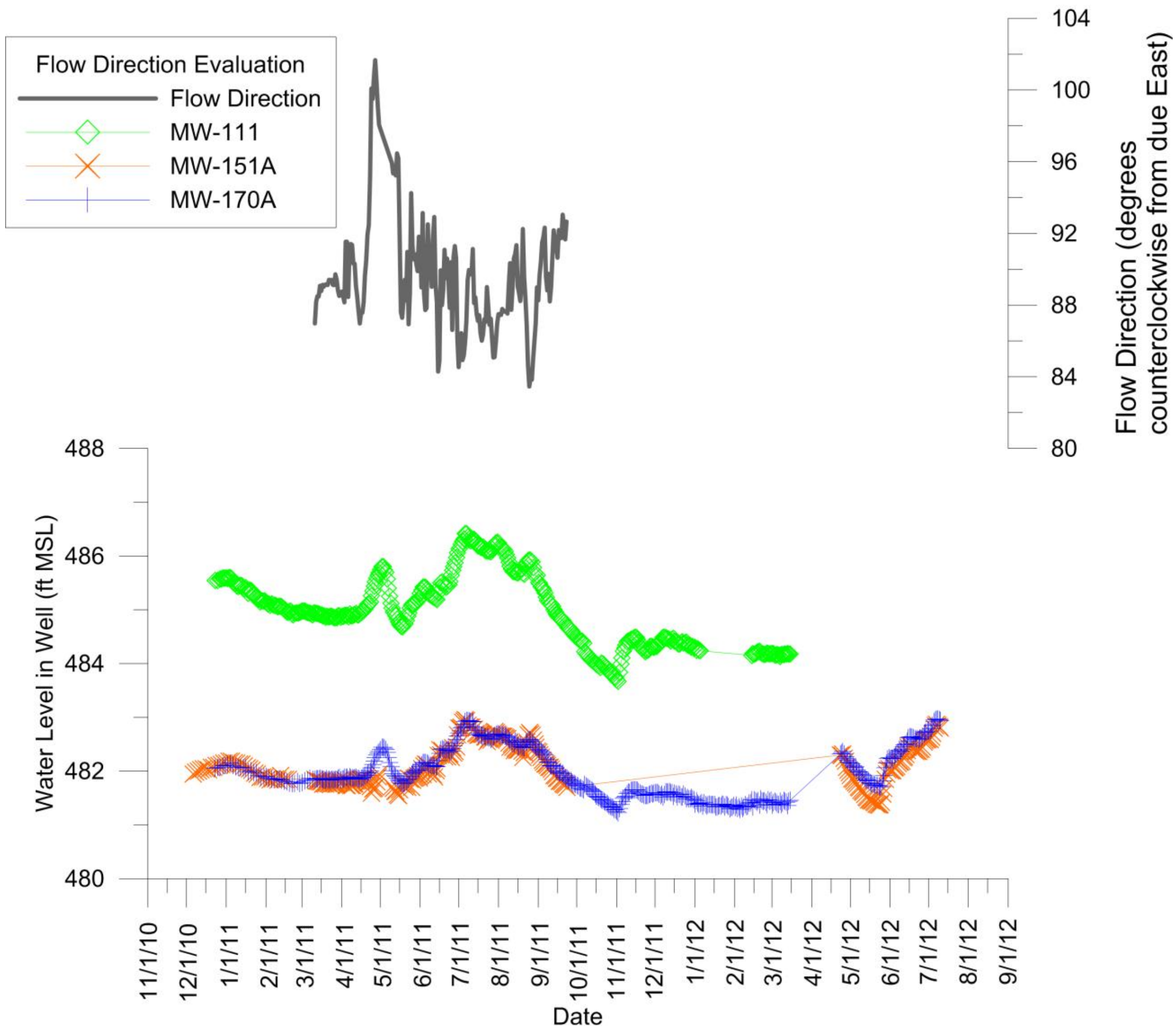


Figure H-6

Plots of the Flow Direction between Wells MW-111, MW-151A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 2)

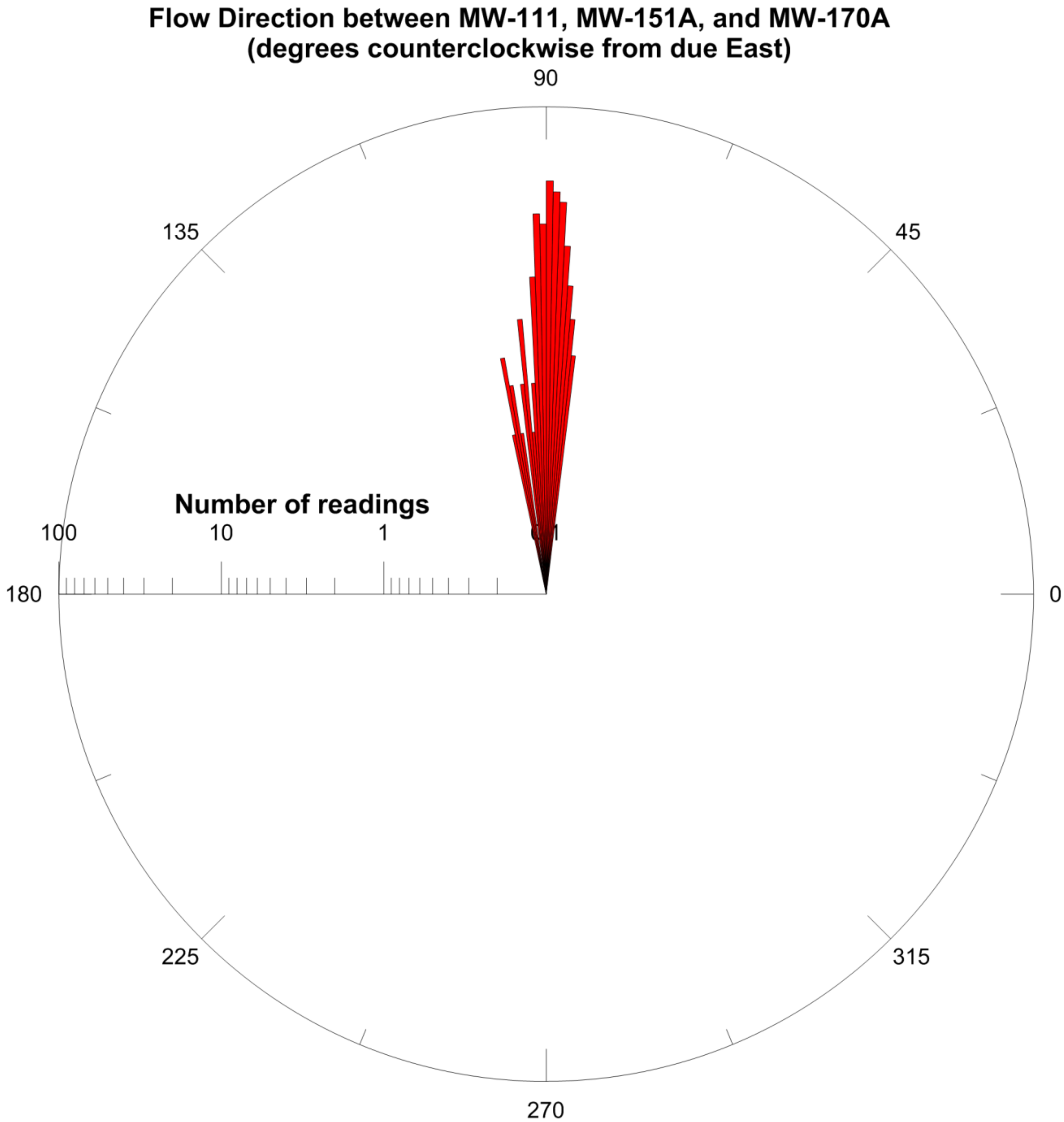


Figure H-7

Rose Diagram of Flow Direction between Wells MW-111, MW-151A, and MW-170A (Group 2)

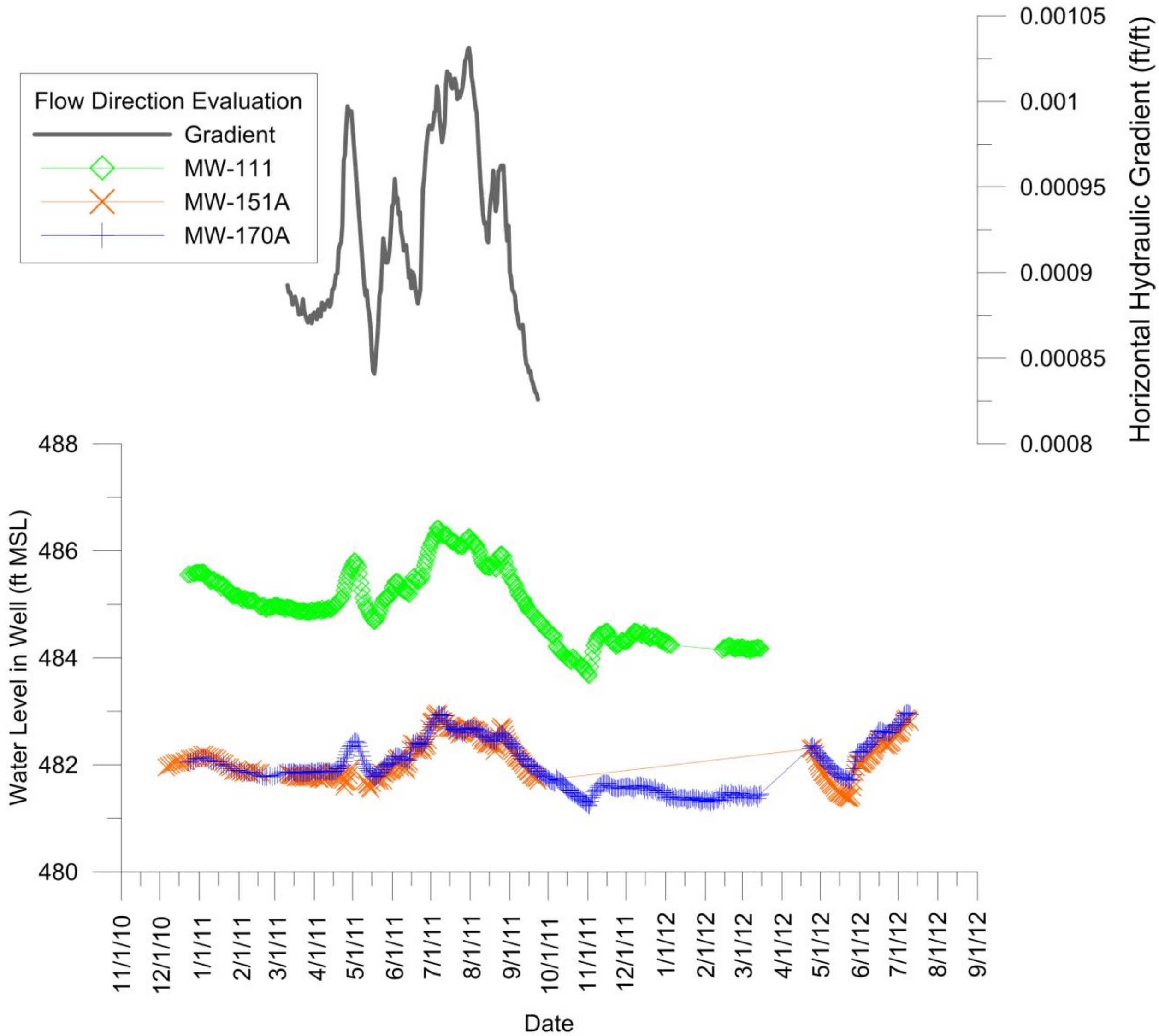


Figure H-8

Plots of the Horizontal Hydraulic Gradient between Wells MW-111, MW-151A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 2)

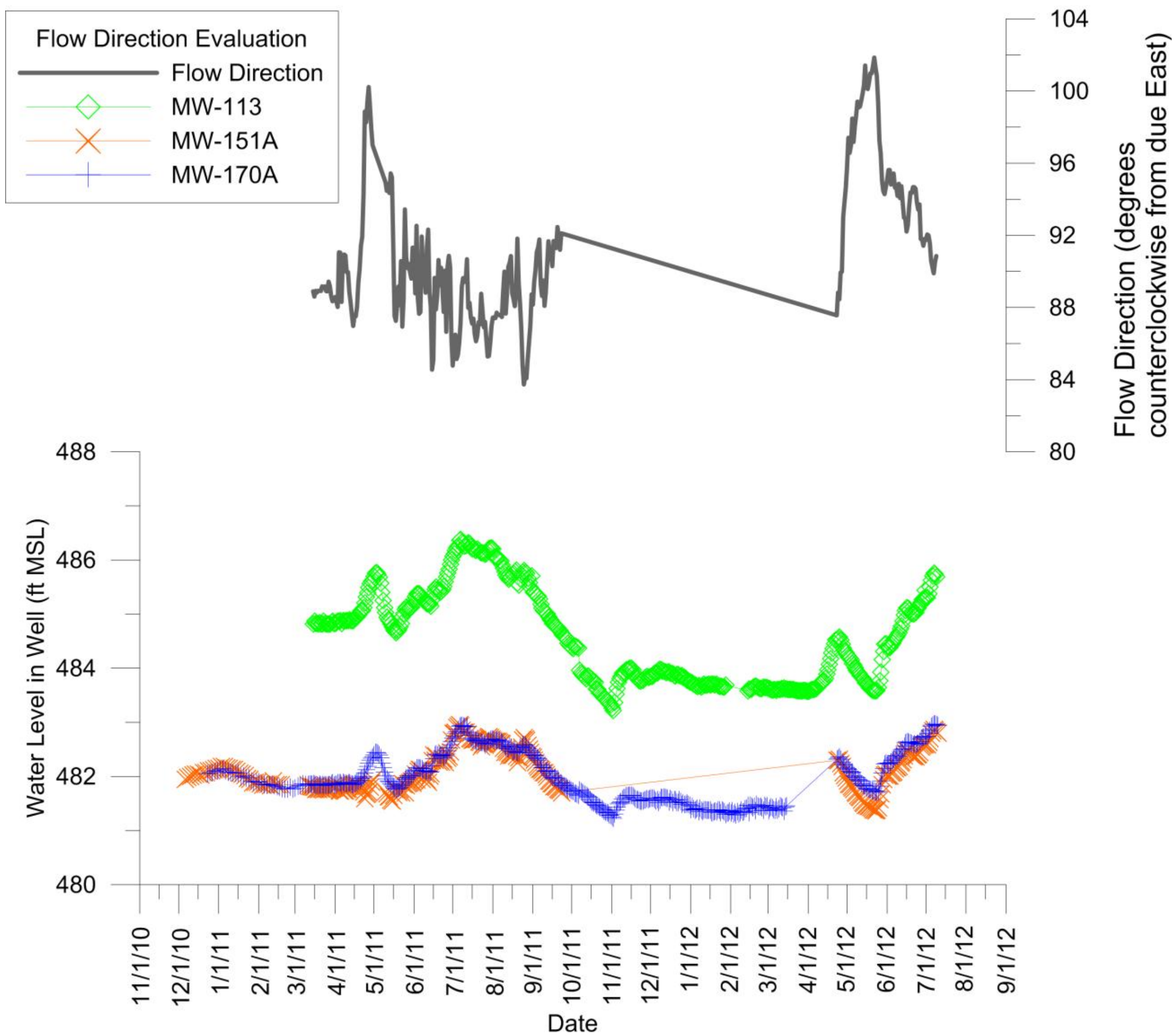


Figure H-9Plots of the Flow Direction between Wells MW-113, MW-151A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 3)

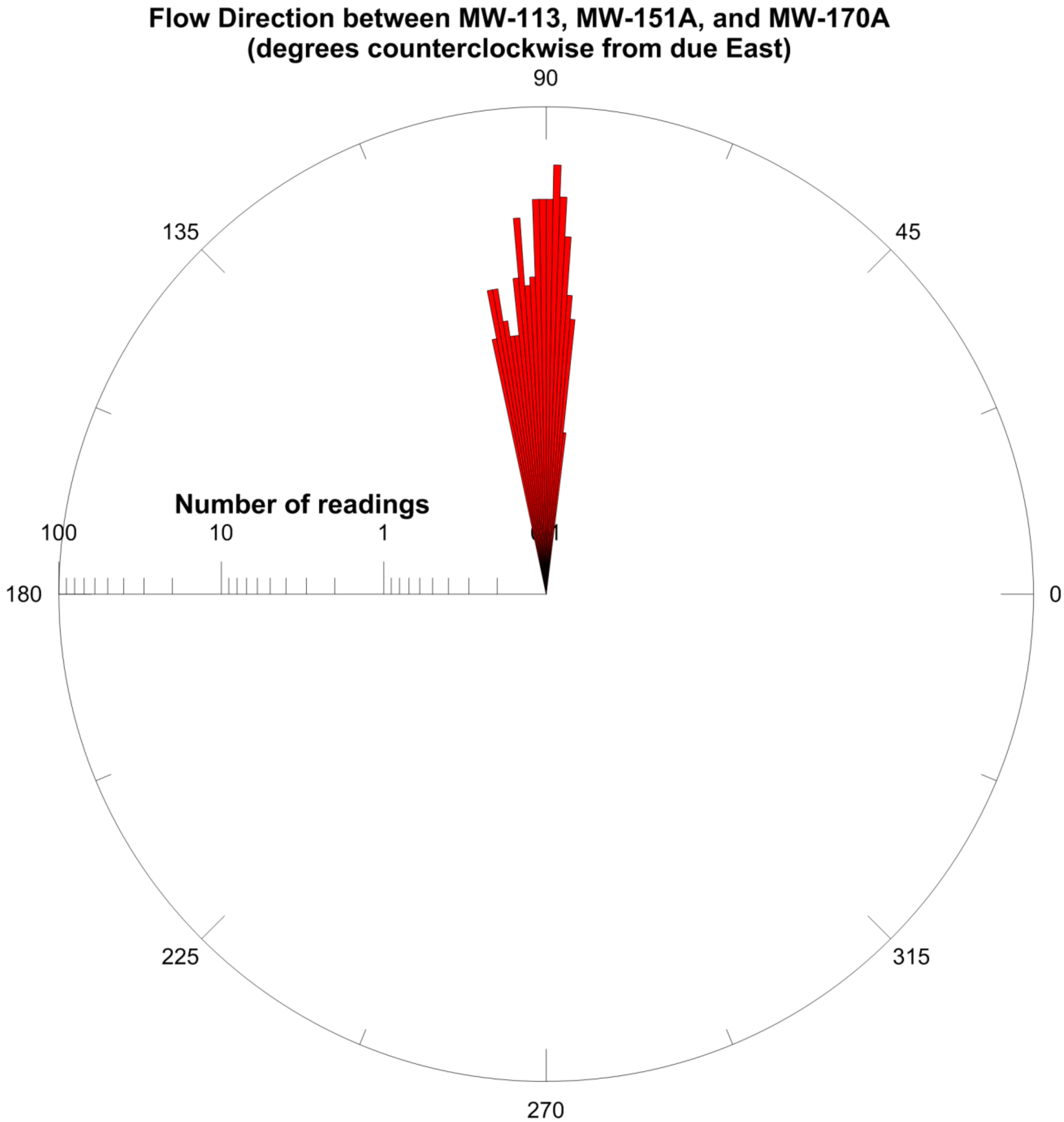


Figure H-10

Rose Diagram of Flow Direction between Wells MW-113, MW-151A, and MW-170A (Group 3)

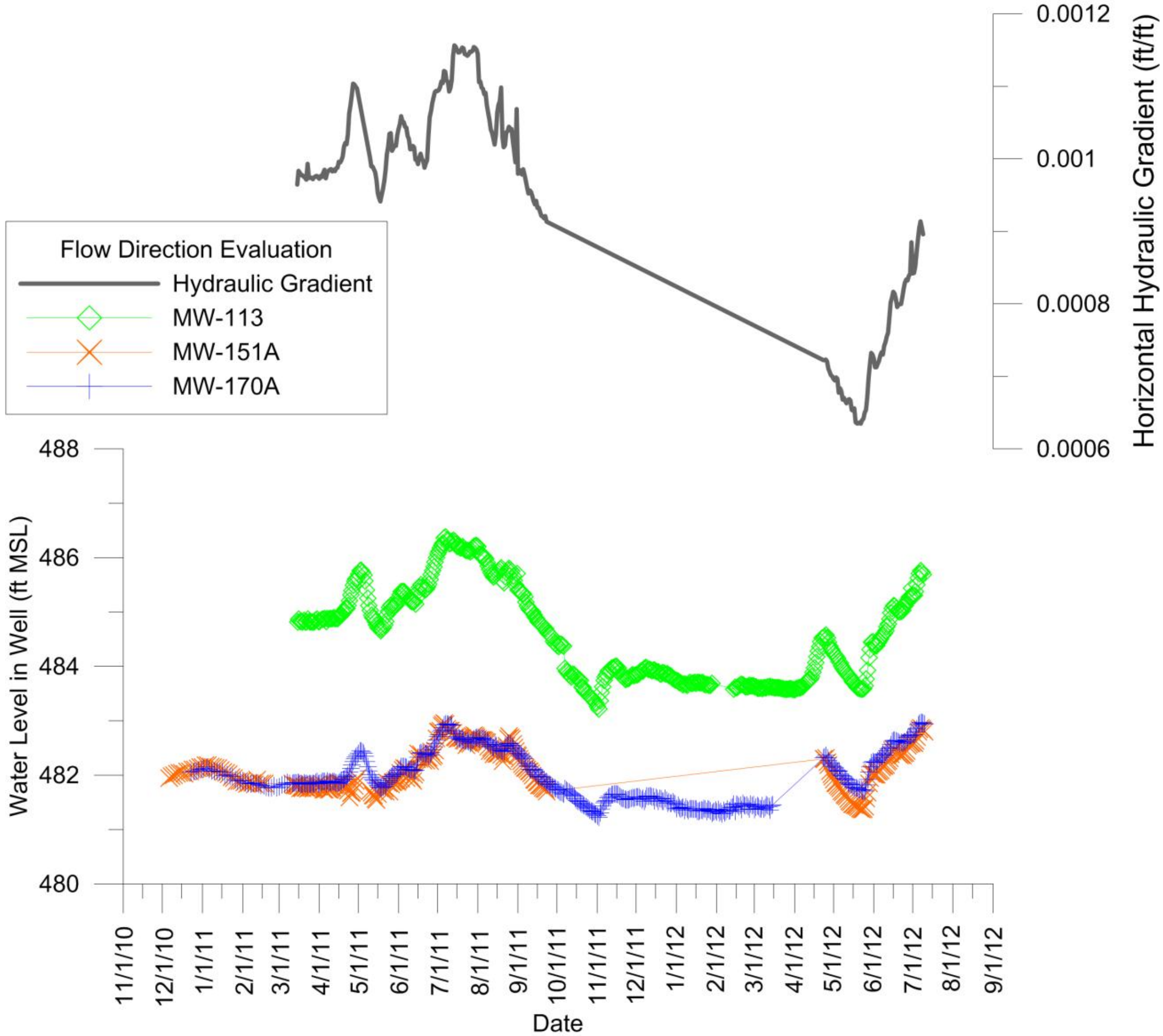


Figure H-11

Plots of the Horizontal Hydraulic Gradient between Wells MW-113, MW-151A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 3)

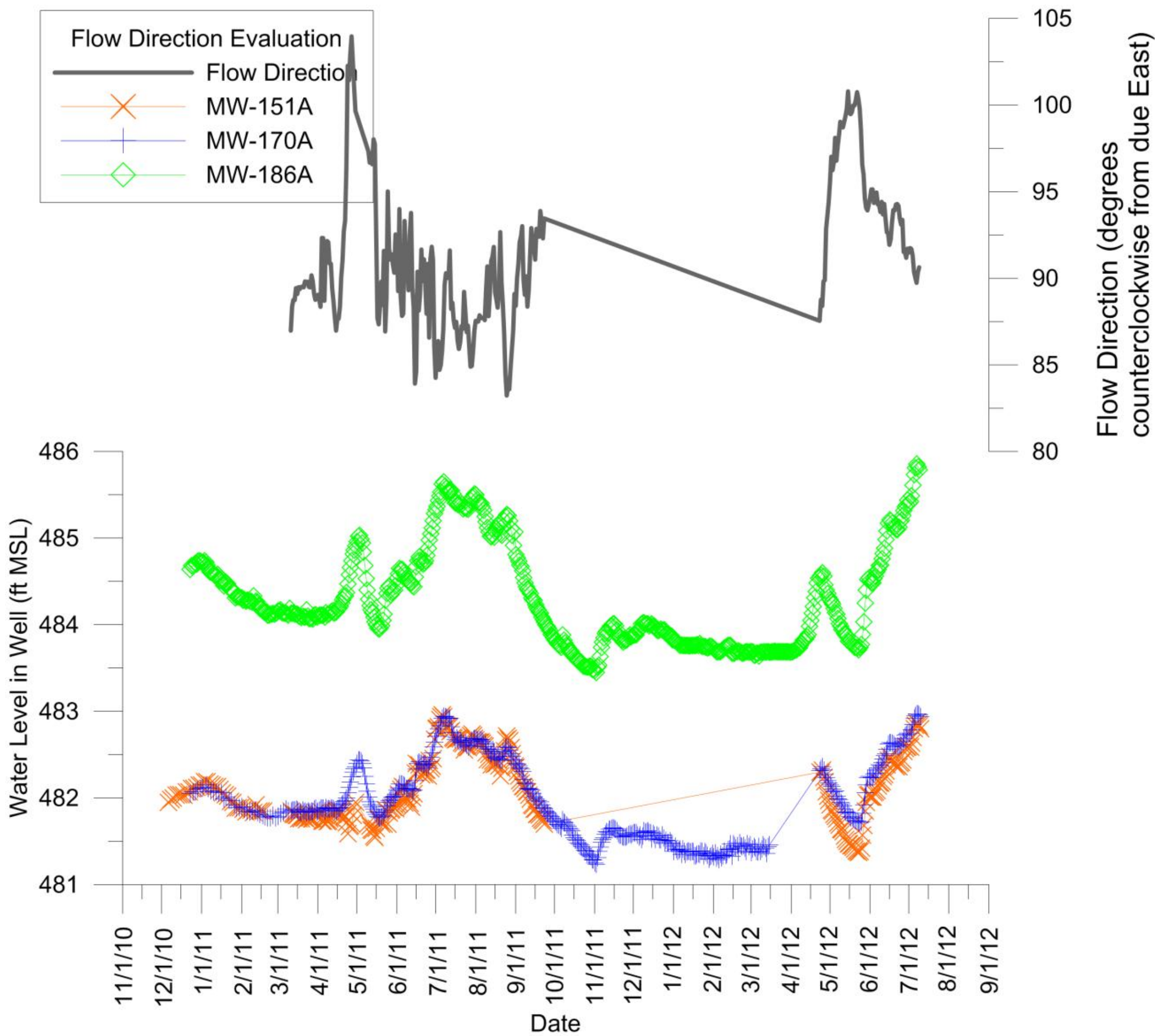


Figure H-12

Plots of the Flow Direction between Wells MW-186A, MW-151A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 4)

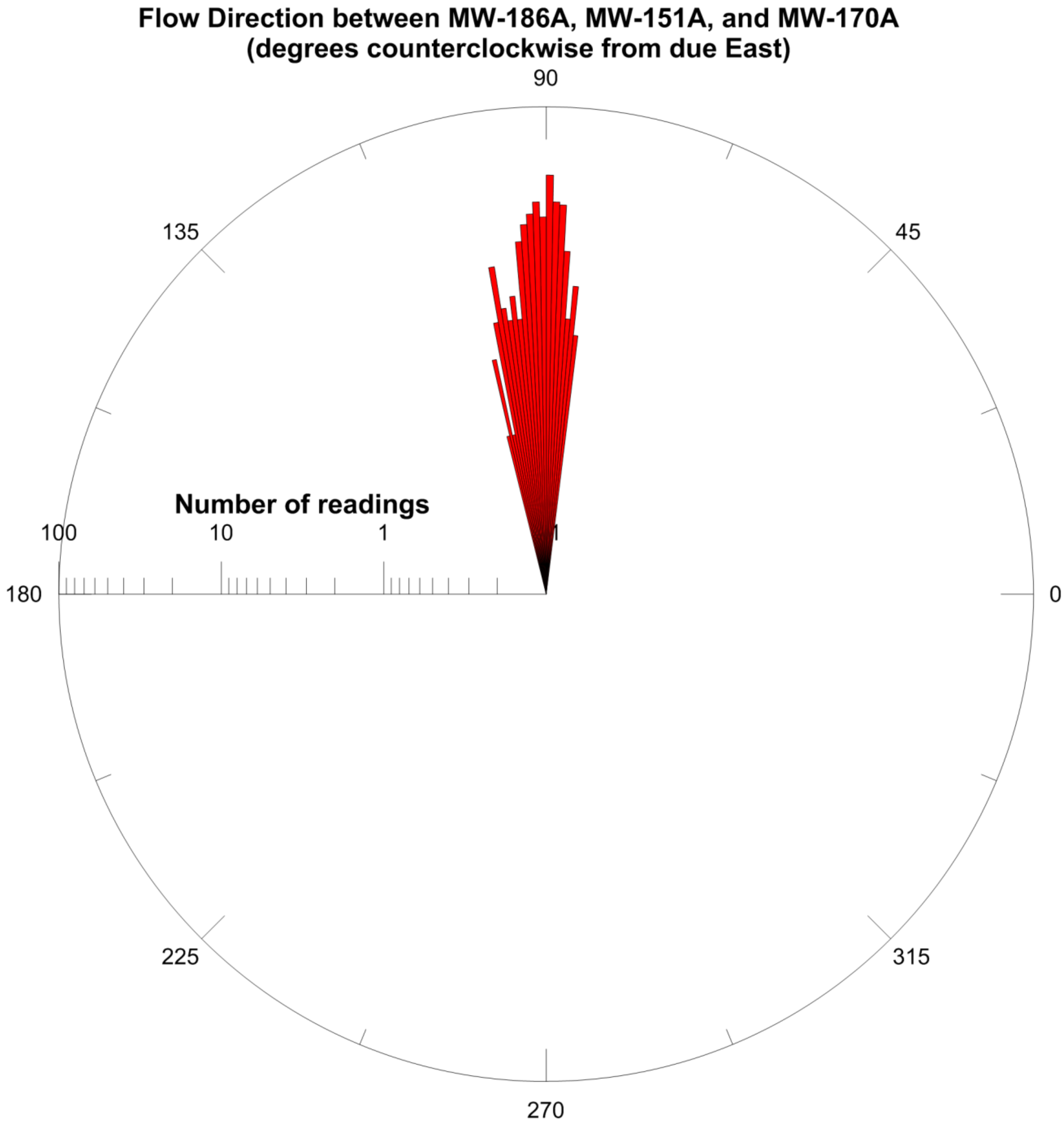


Figure H-13

Rose Diagram of Flow Direction between Wells MW-186A, MW-151A, and MW-170A (Group 4)

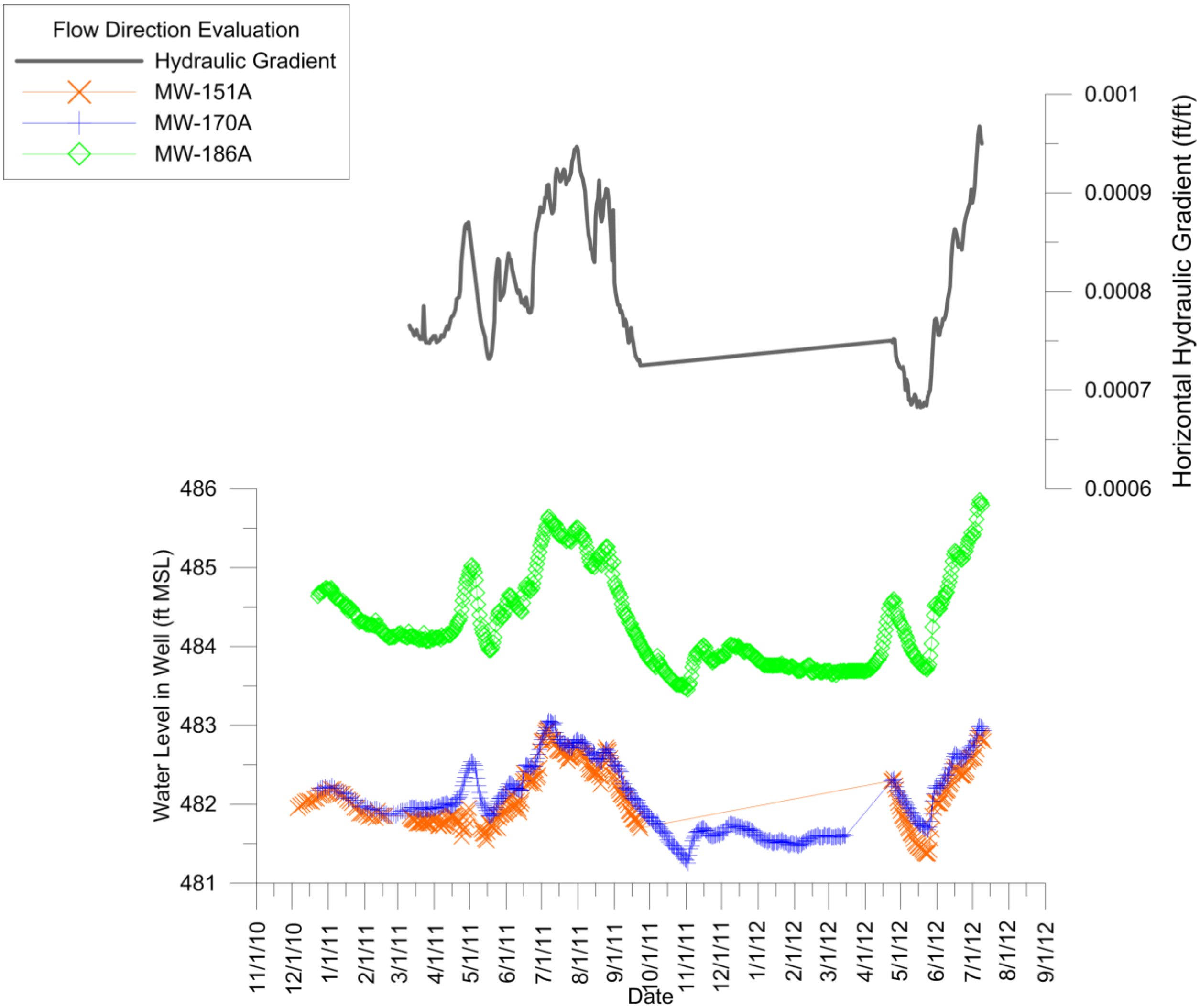


Figure H-14

Plots of the Horizontal Hydraulic Gradient between Wells MW-186A, MW-151A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 4)

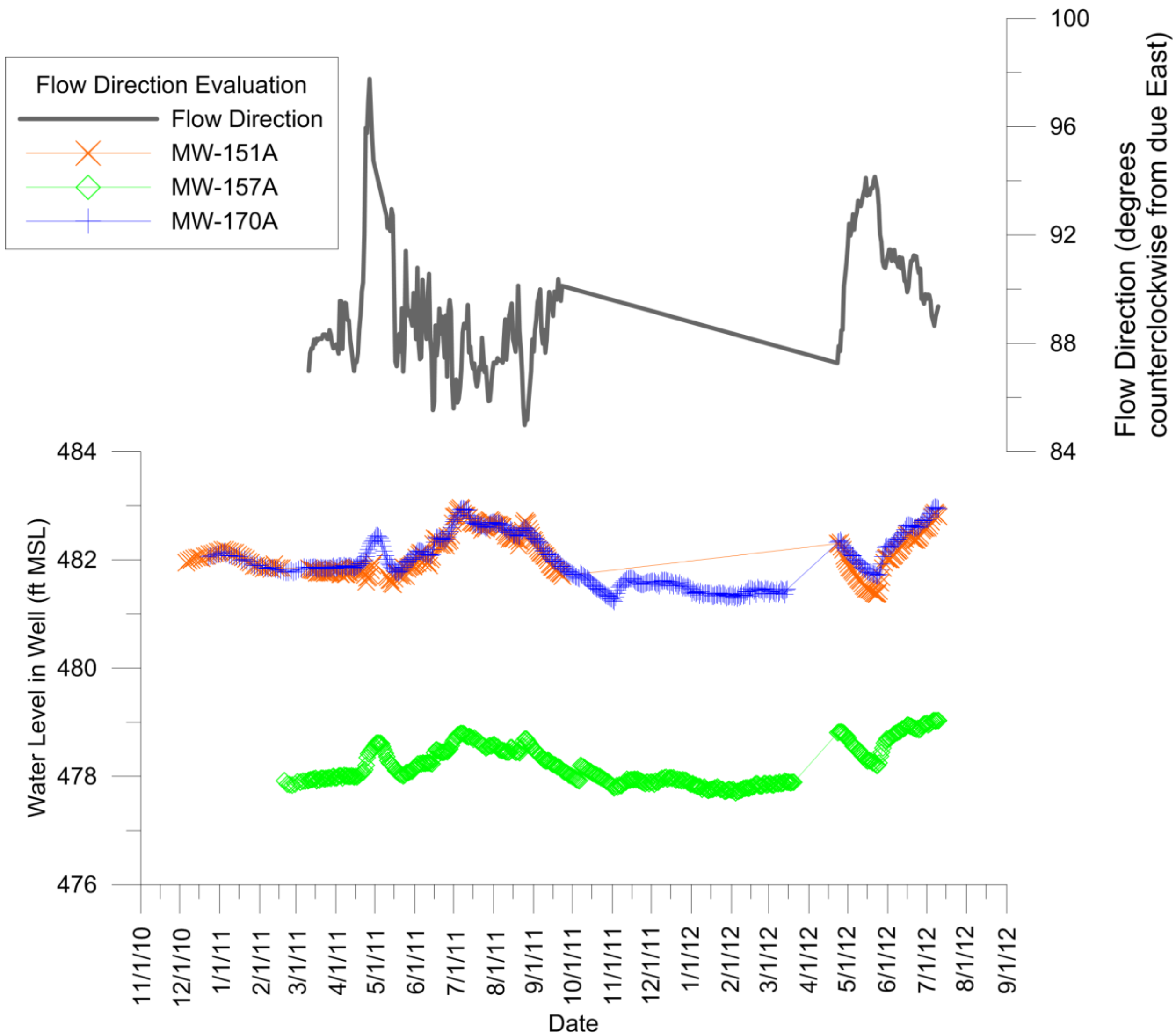


Figure H-15

Plots of the Flow Direction between Wells MW-151A, MW-157, and MW-170 (upper plot) and Water Levels (lower plot) (Group 5)

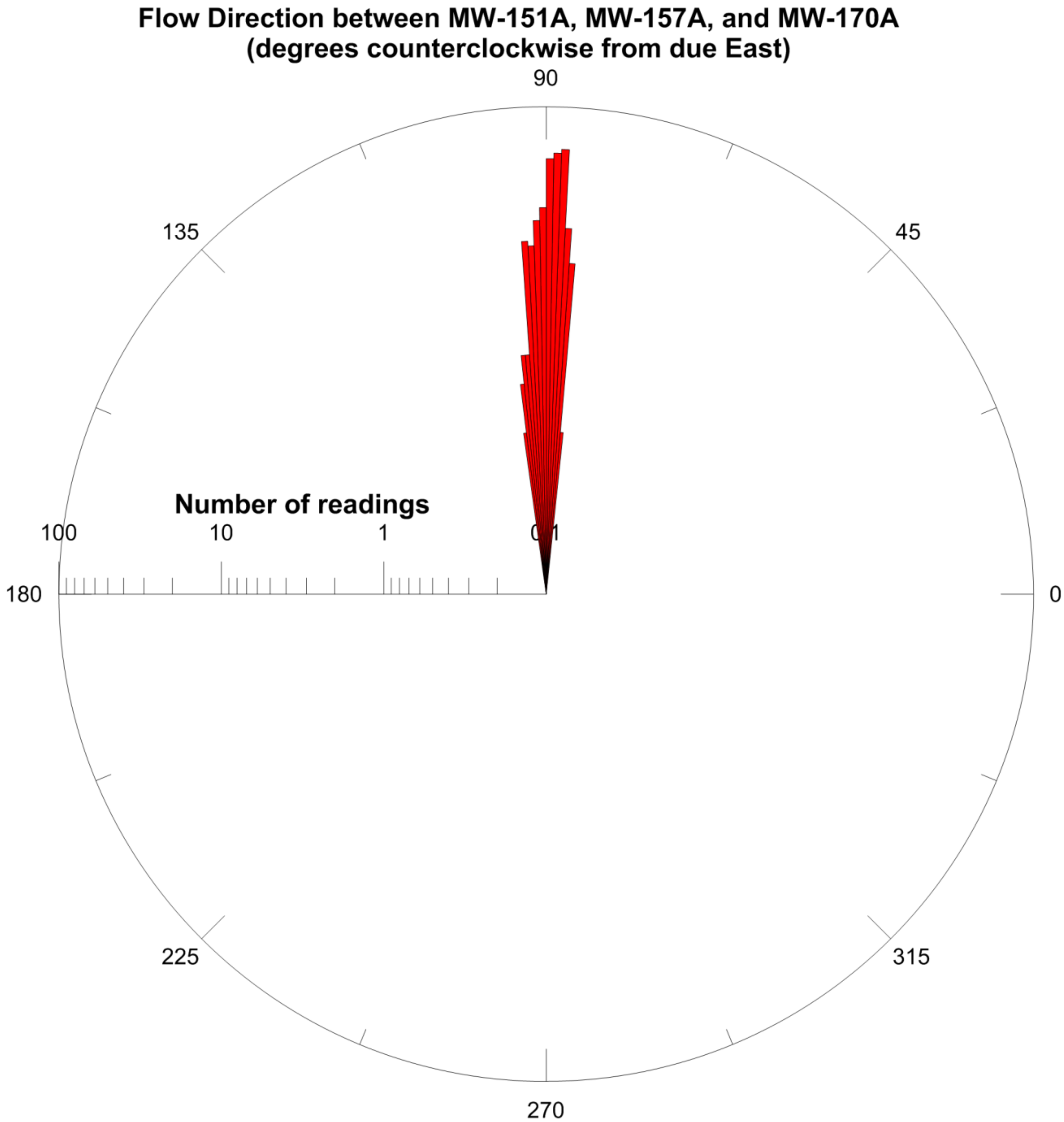


Figure H-16

Rose Diagram of Flow Direction between Wells MW-151A, MW-157, and MW-170 (Group 5)

Figure H-17

Plots of the Horizontal Hydraulic Gradient between Wells MW-151A, MW-157, and MW-170 (upper plot) and Water Levels (lower plot) (Group 5)

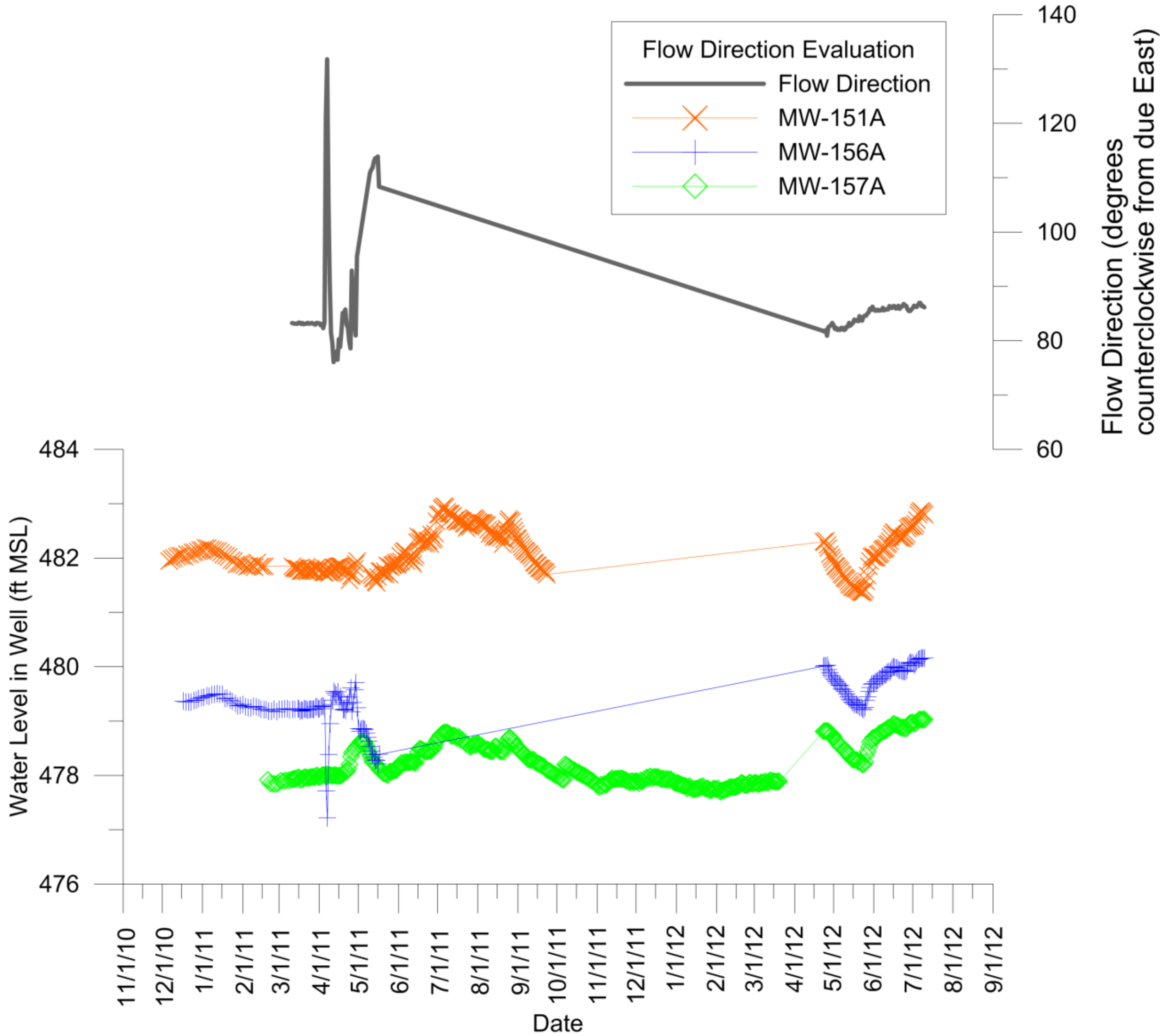


Figure H-18

Plots of the Flow Direction between Wells MW-151A, MW-156A, and MW-157A (upper plot) and Water Levels (lower plot) (Group 6)

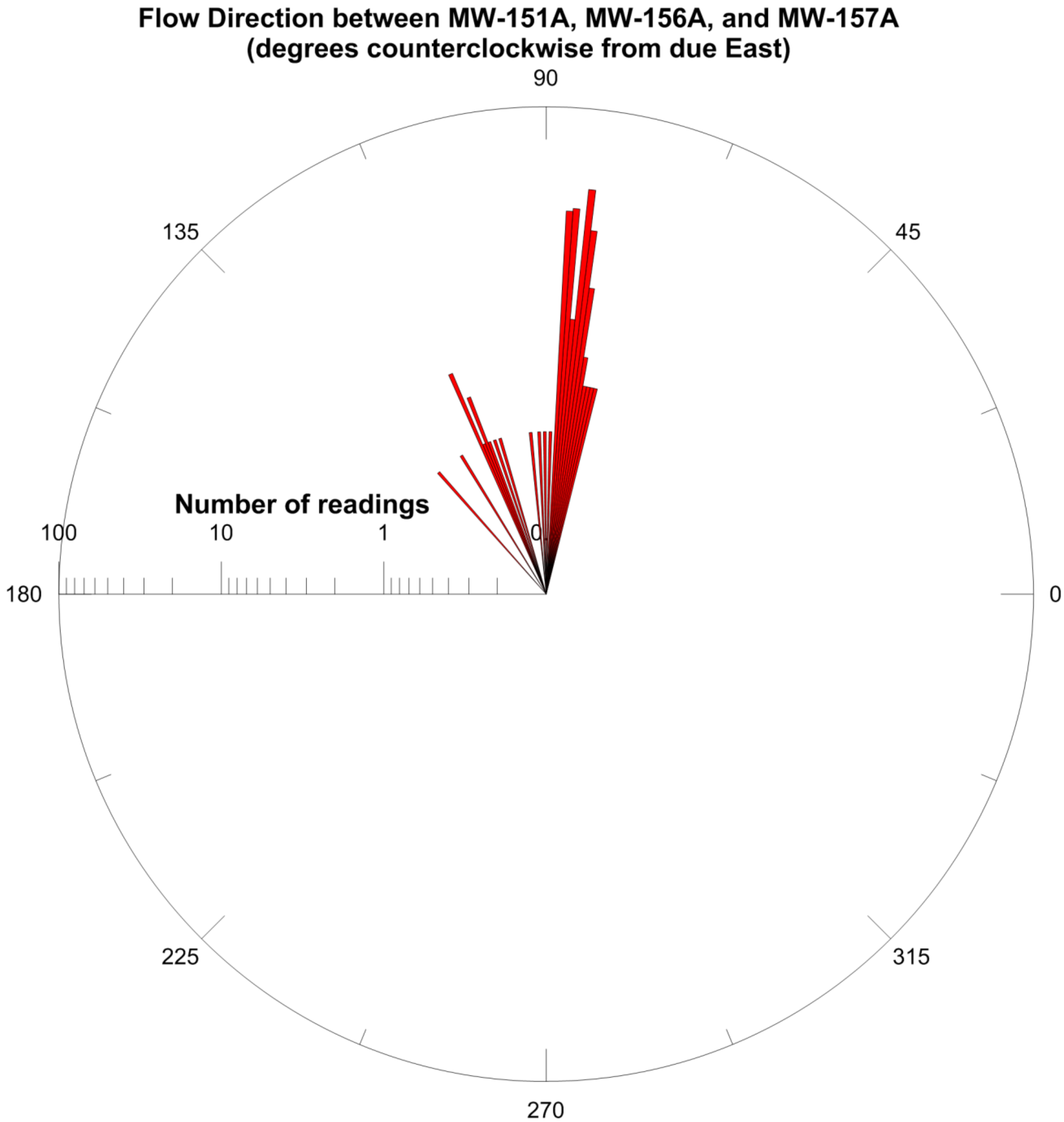


Figure H-19

Rose Diagram of Flow Direction between Wells MW-151A, MW-156A, and MW-157A (Group 6)

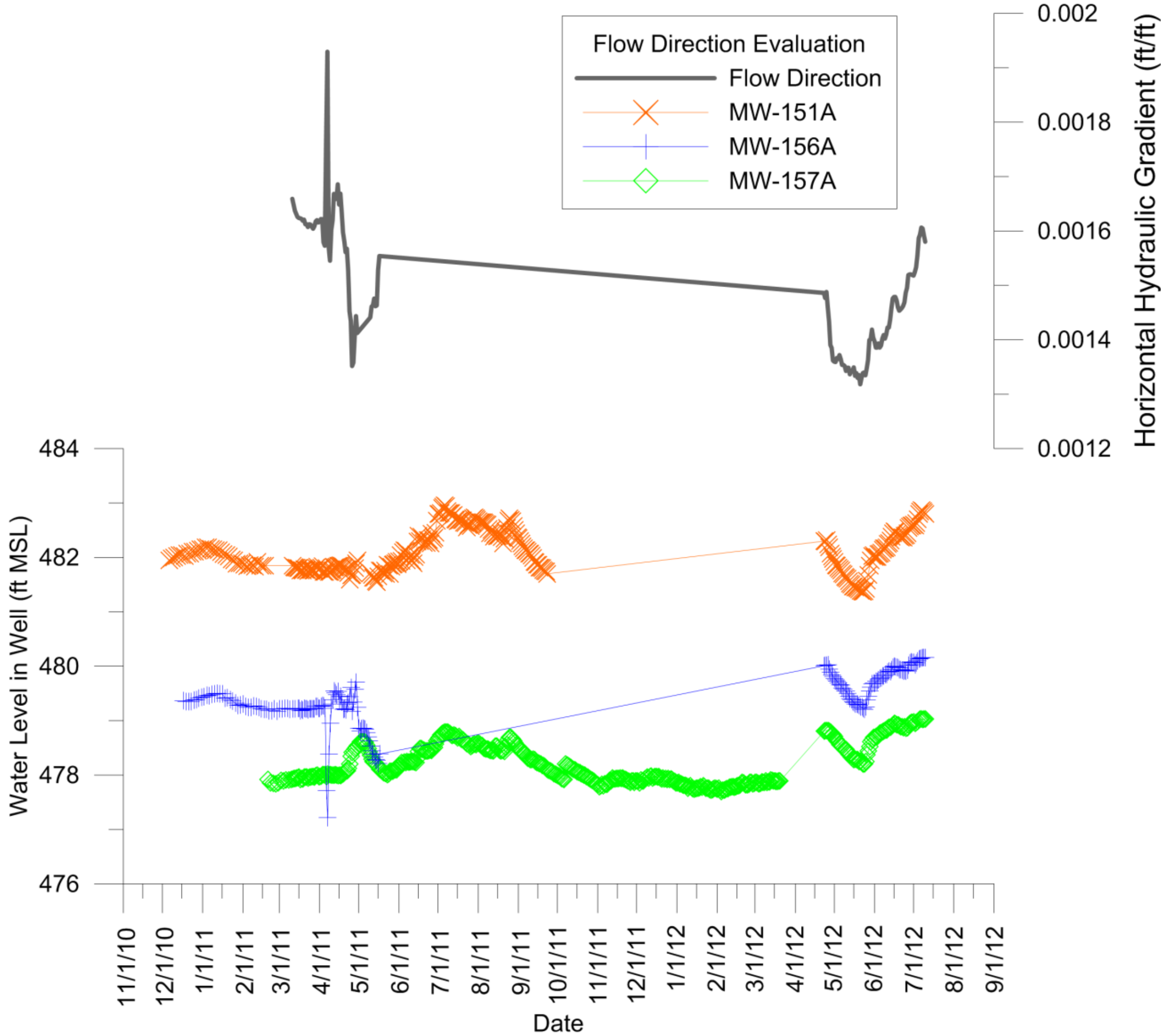


Figure H-20

Plots of the Horizontal Hydraulic Gradient between Wells MW-151A, MW-156A, and MW-157A (upper plot) and Water Levels (lower plot) (Group 6)

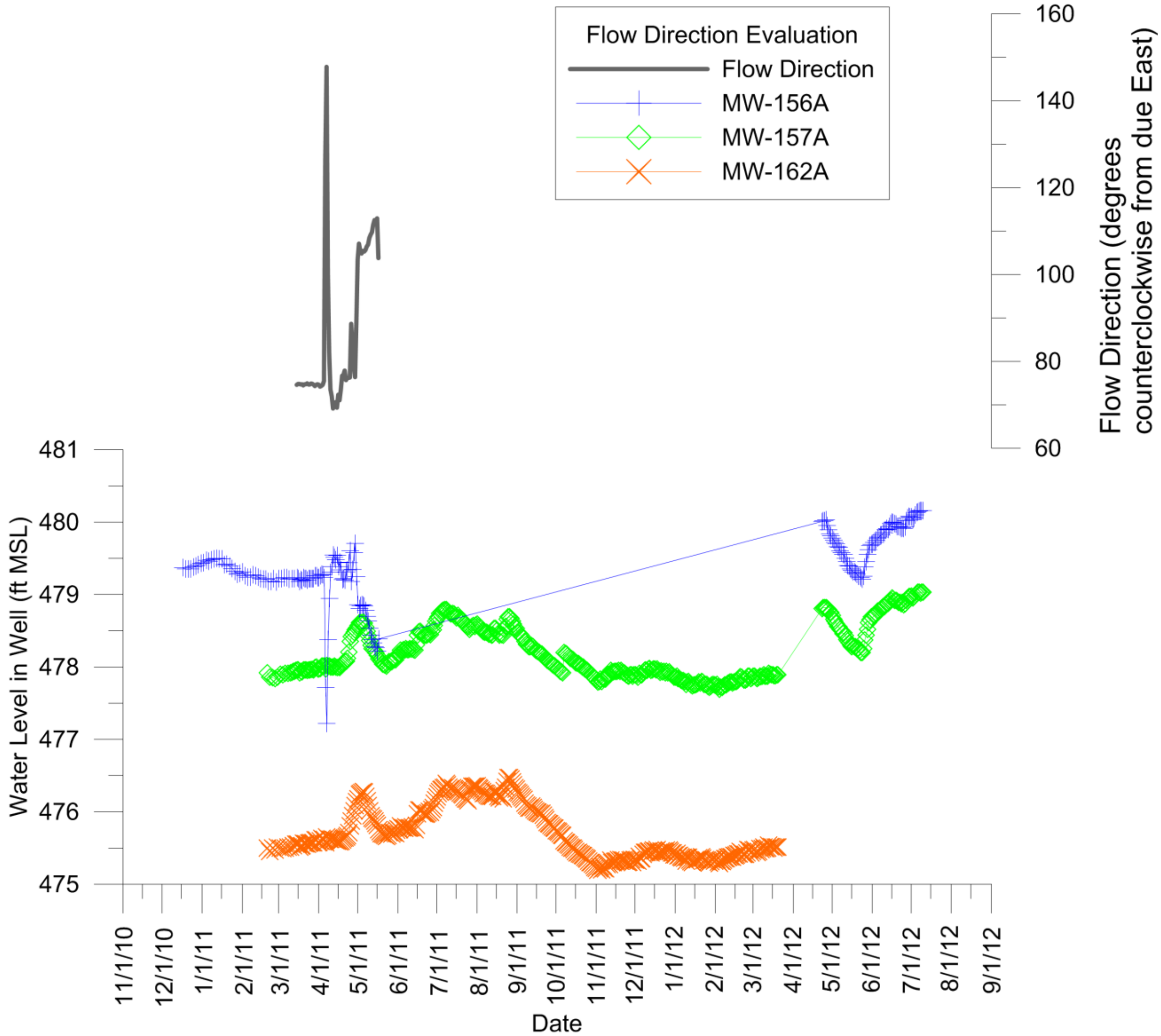


Figure H-21

Plots of the Flow Direction between Wells MW-156A, MW-157, and MW-162 (upper plot) and Water Levels (lower plot) (Group 7)

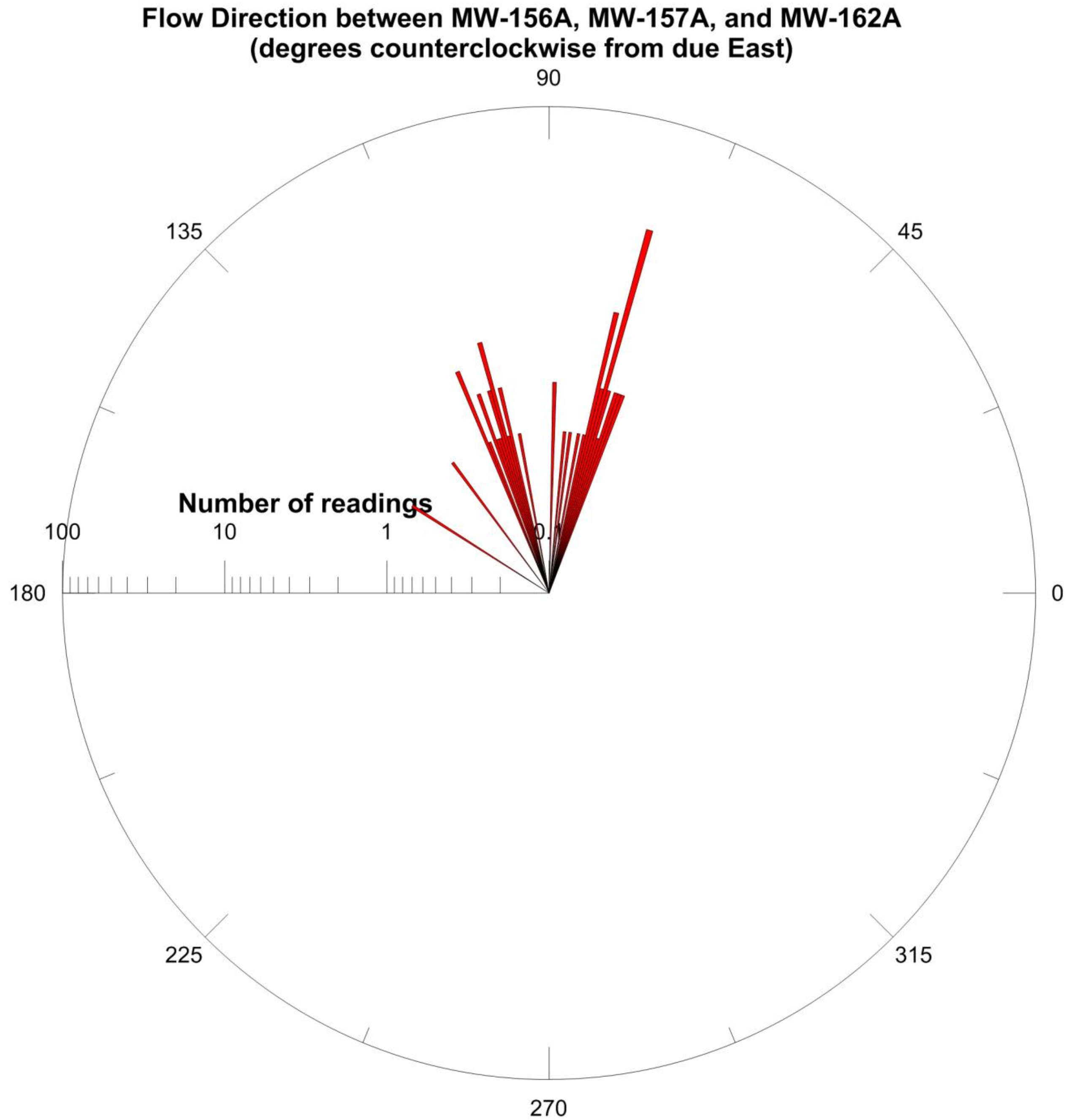


Figure H-22

Rose Diagram of Flow Direction between Wells MW-156A, MW-157, and MW-162 (Group 7)

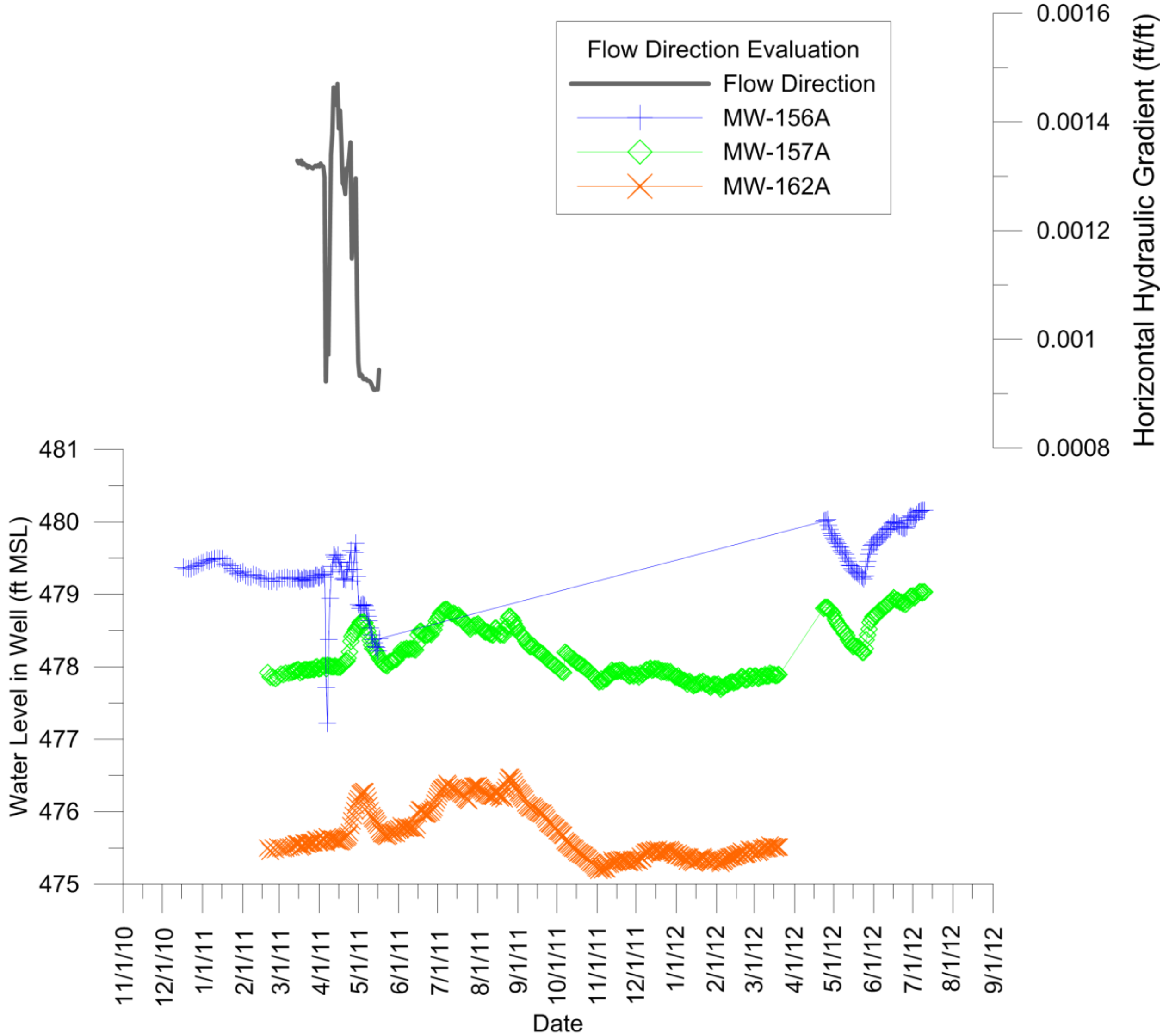


Figure H-23

Plots of the Horizontal Hydraulic Gradient between Wells MW-156A, MW-157, and MW-162 (upper plot) and Water Levels (lower plot) (Group 7)

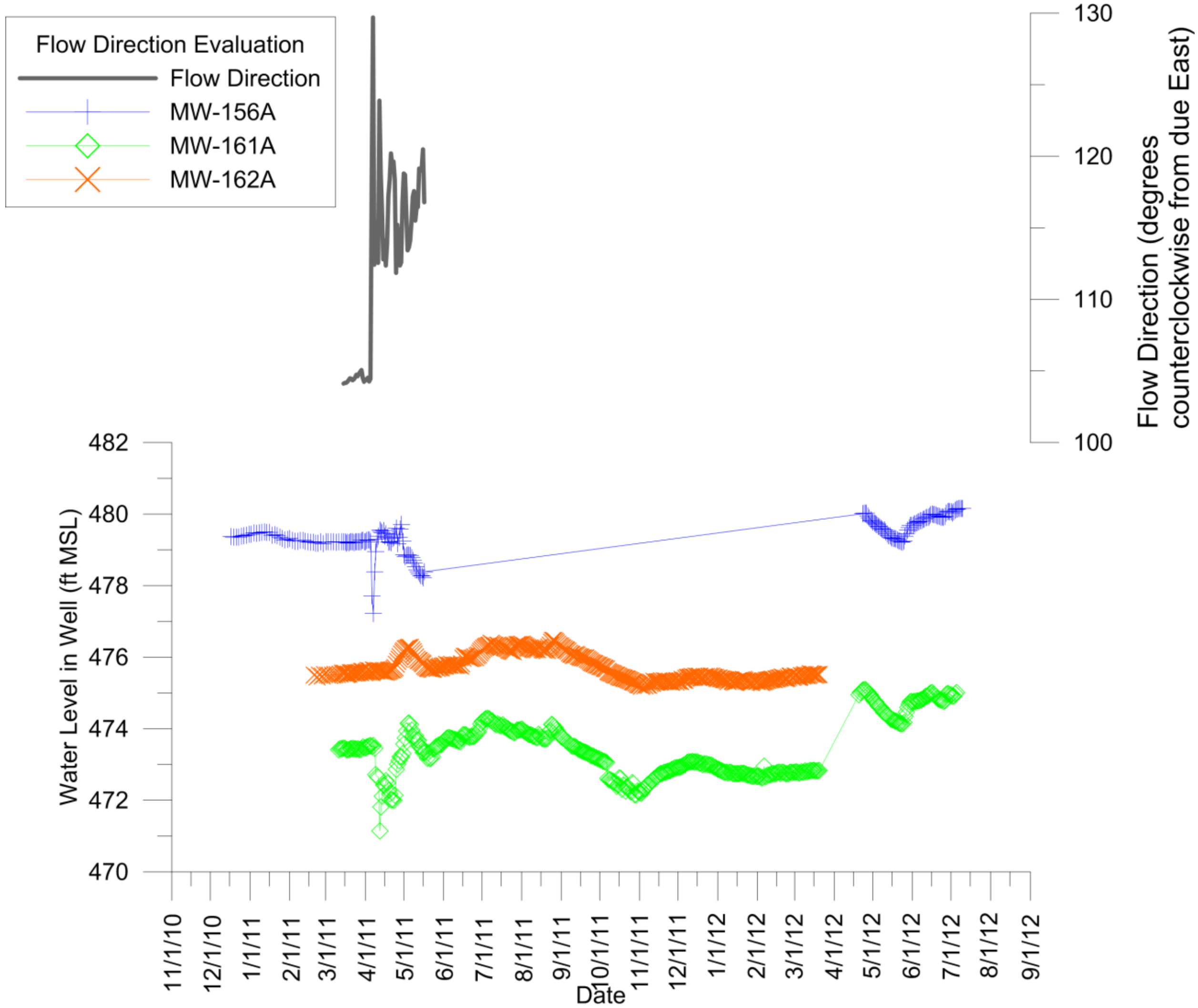


Figure H-24

Plots of the Flow Direction between Wells MW-156A, MW-161, and MW-162 (upper plot) and Water Levels (lower plot) (Group 8)

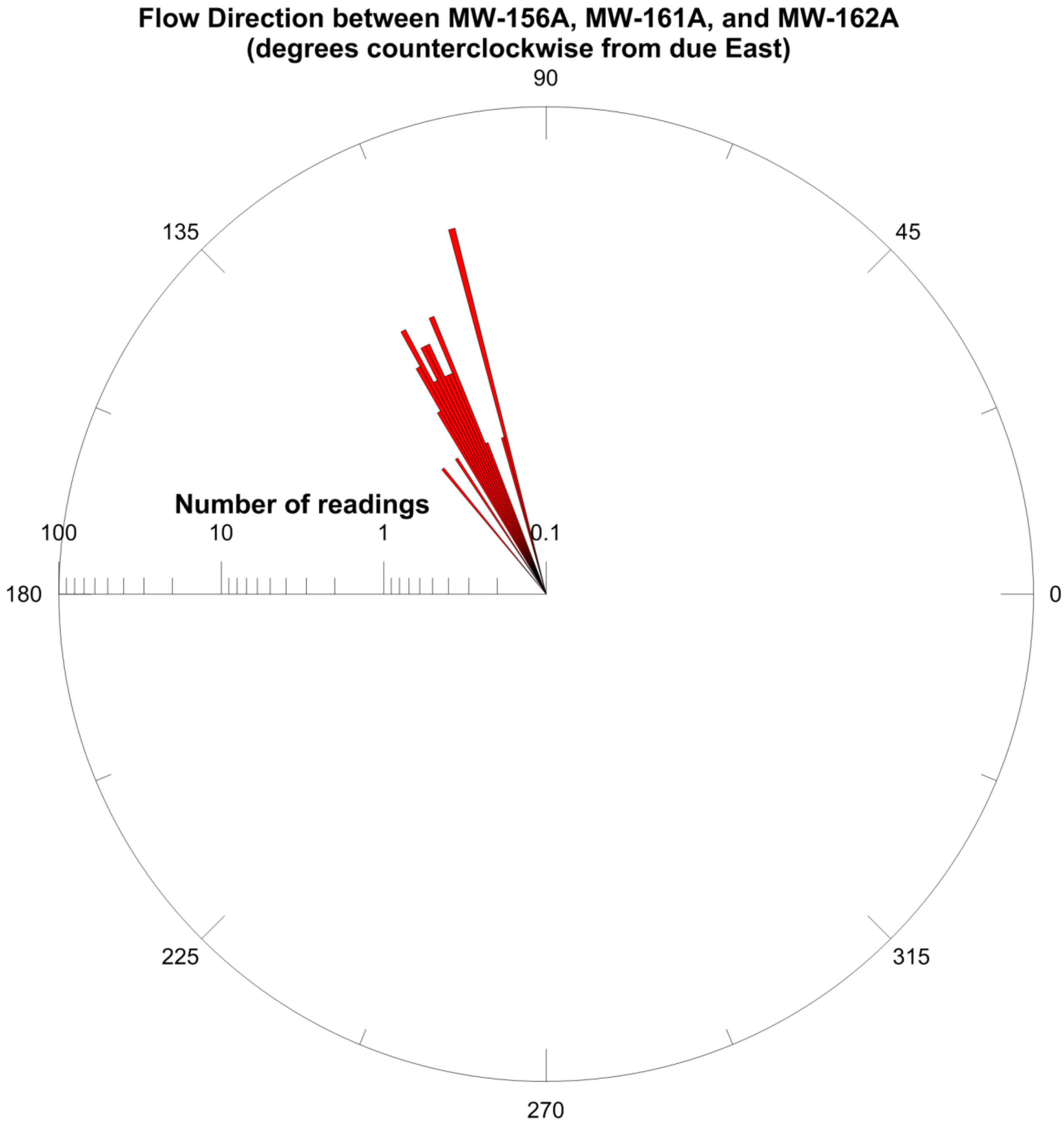


Figure H-25

Rose Diagram of Flow Direction between Wells MW-156A, MW-161, and MW-162 (Group 8)

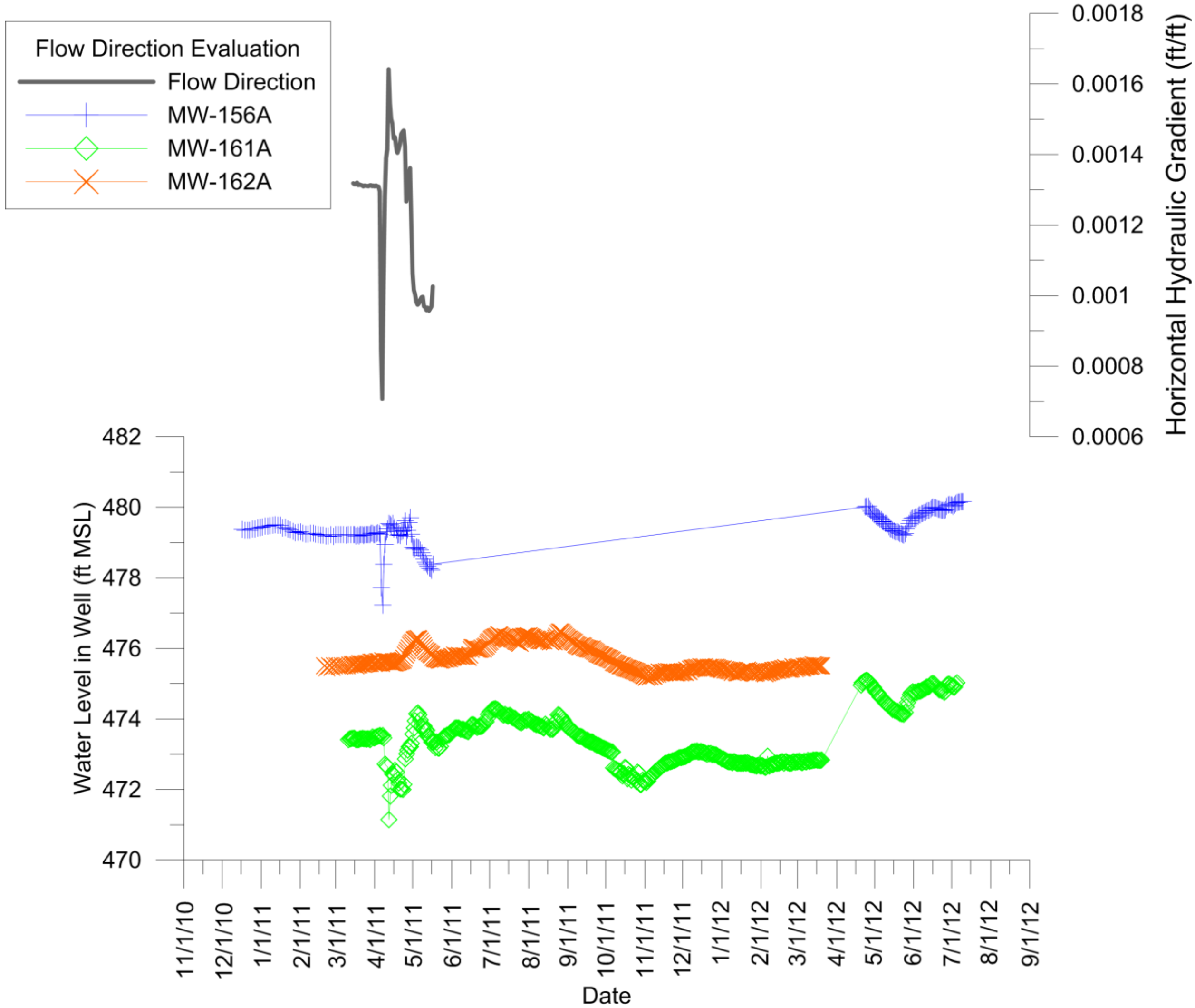


Figure H-26

Plots of the Horizontal Hydraulic Gradient between Wells MW-156A, MW-161, and MW-162 (upper plot) and Water Levels (lower plot) (Group 8)

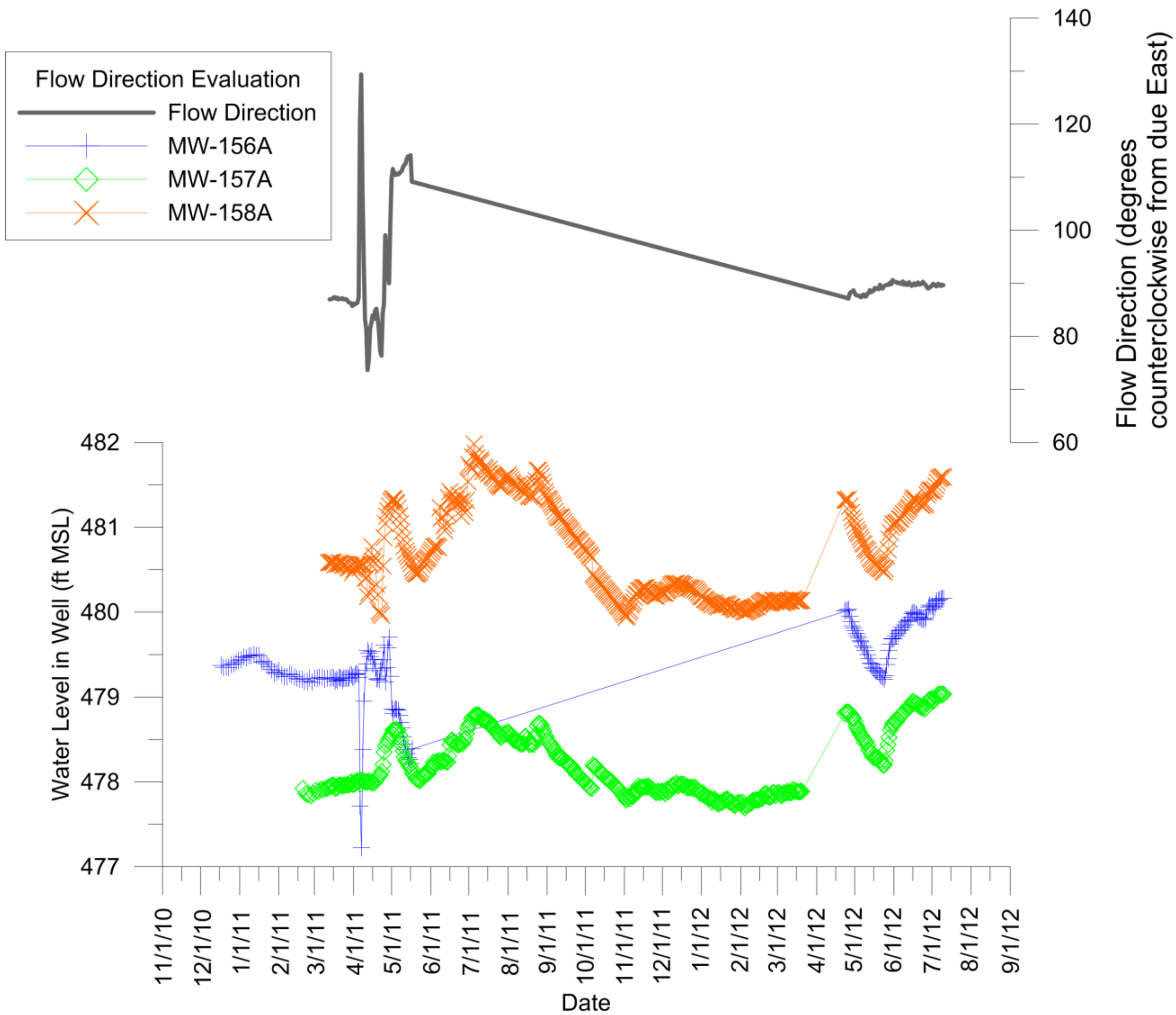


Figure H-27

Plots of the Flow Direction between Wells MW-156A, MW-157, and MW-158 (upper plot) and Water Levels (lower plot) (Group 9)

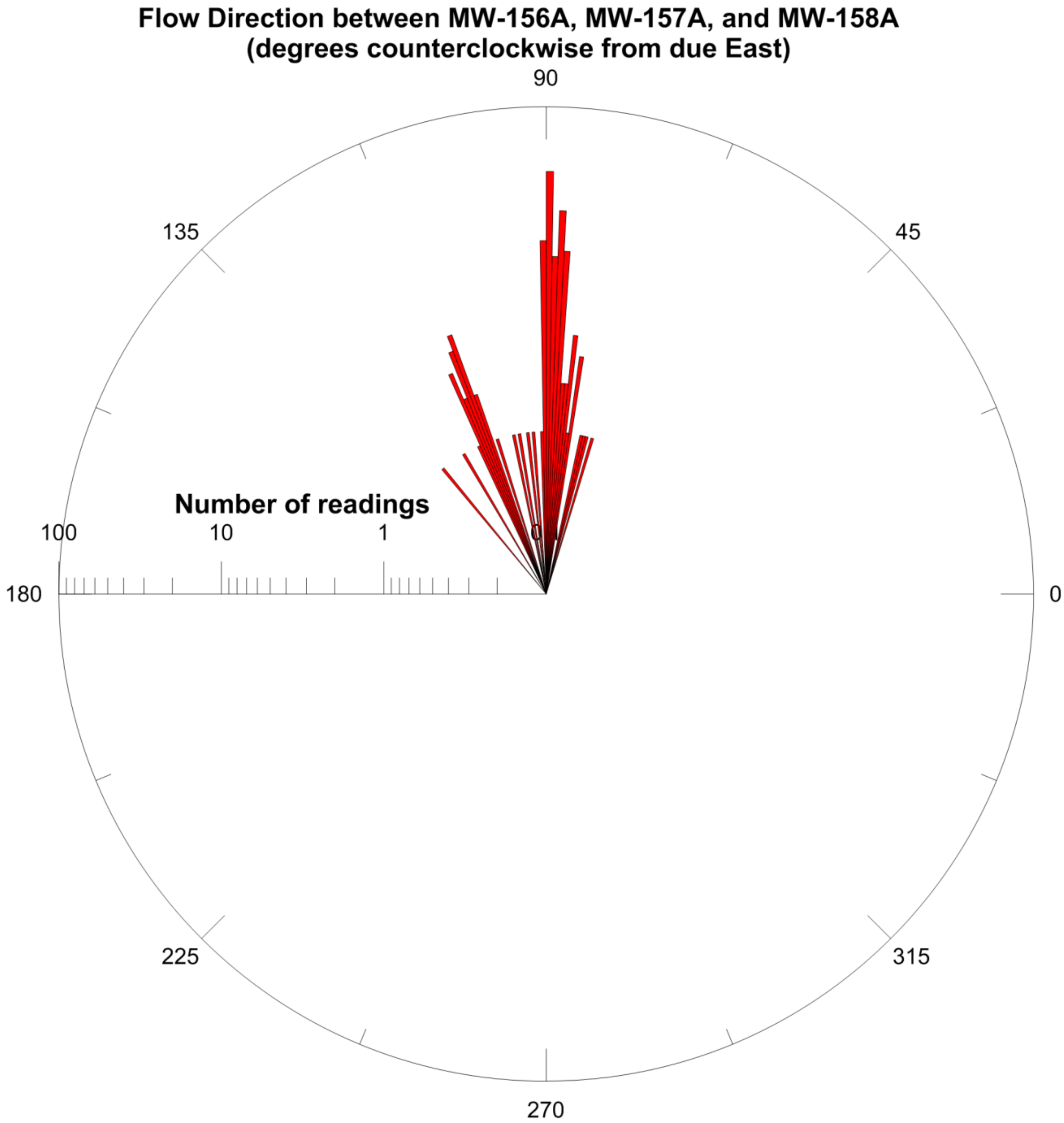


Figure H-28

Rose Diagram of Flow Direction between Wells MW-156A, MW-157, and MW-158 (Group 9)

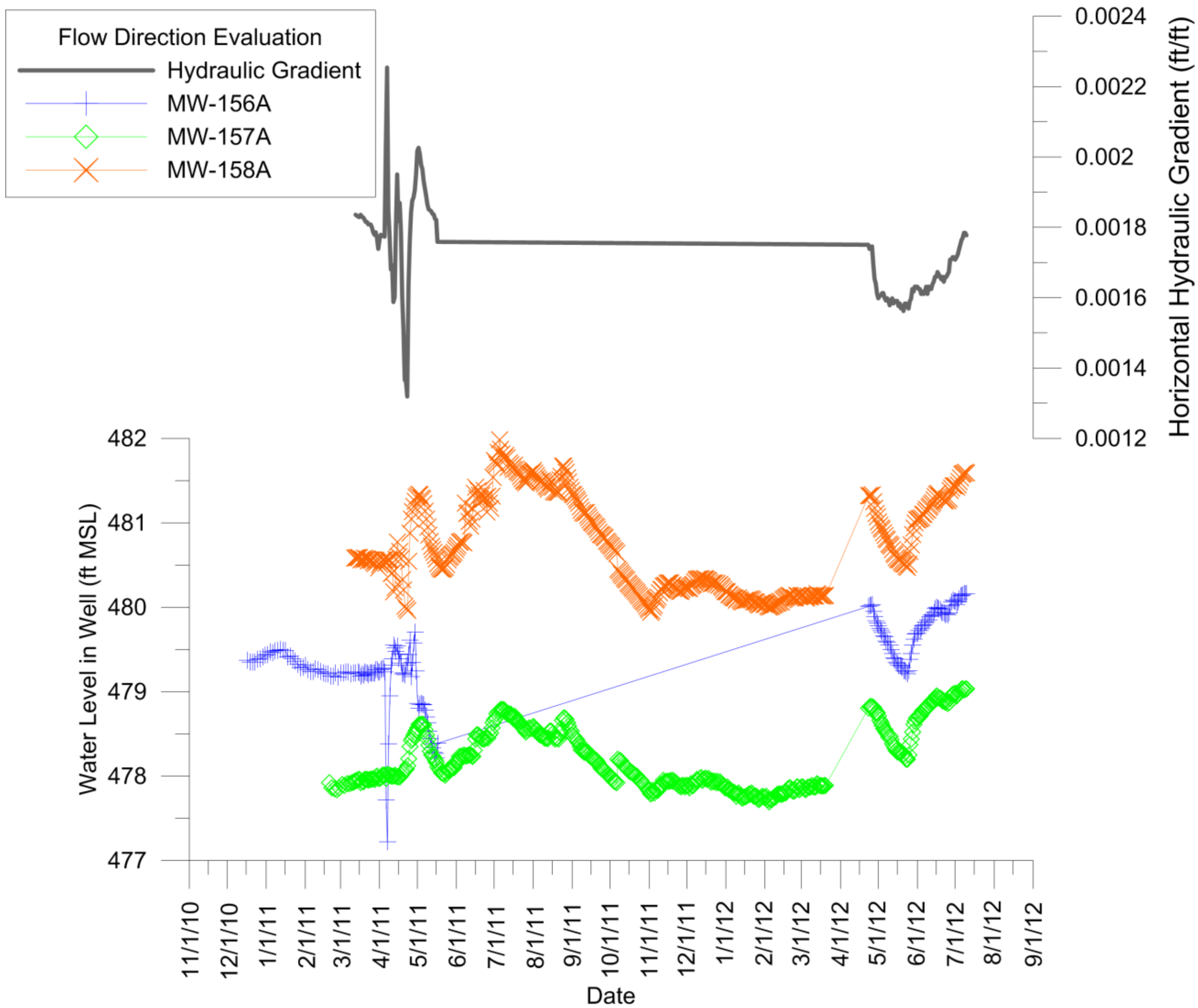
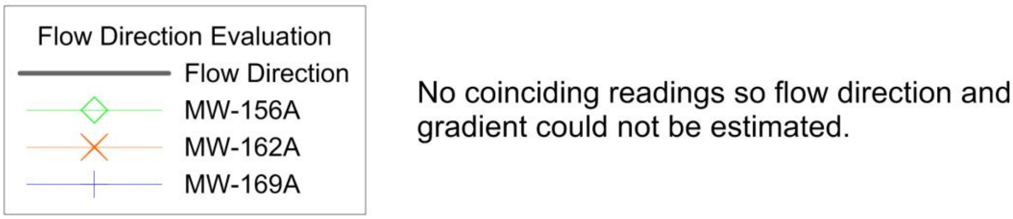


Figure H-29

Plots of the Horizontal Hydraulic Gradient between Wells MW-156A, MW-157, and MW-158 (upper plot) and Water Levels (lower plot) (Group 9)



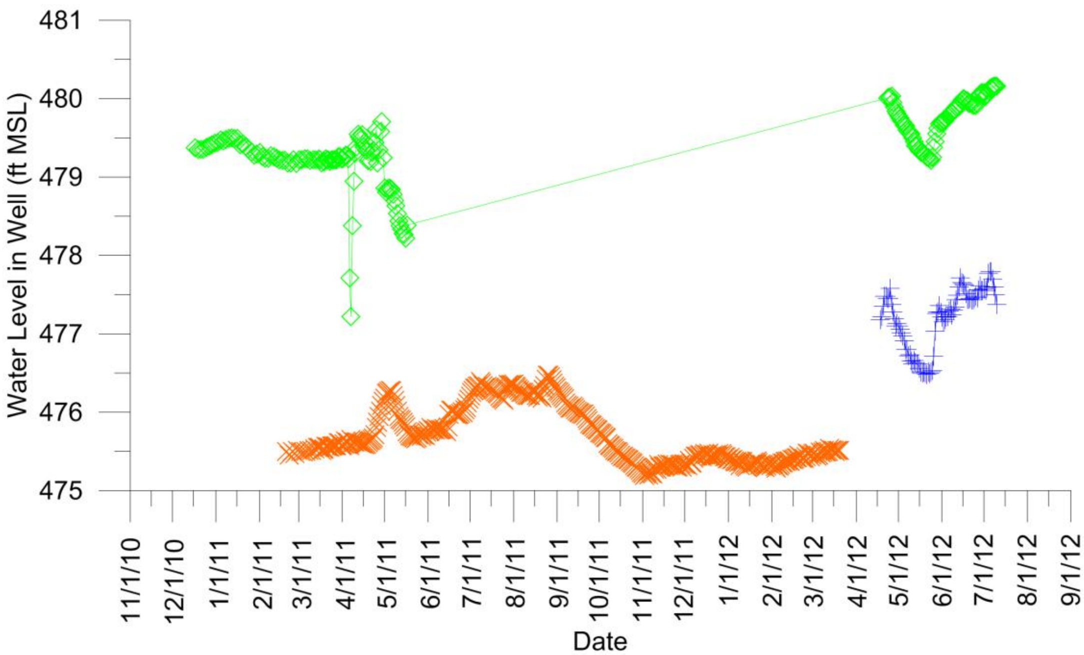
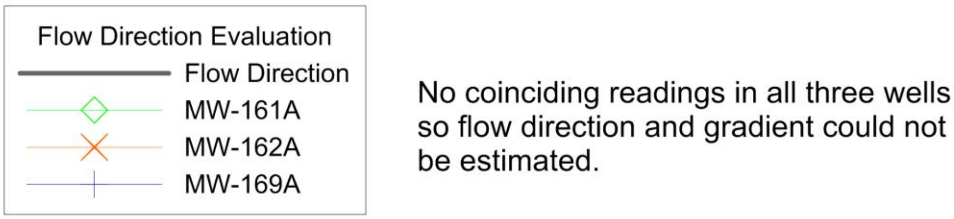


Figure H-30

Plots of the Flow Direction between Wells MW-156A, MW-162A, and MW-169A (upper plot) and Water Levels (lower plot) (Group 11)



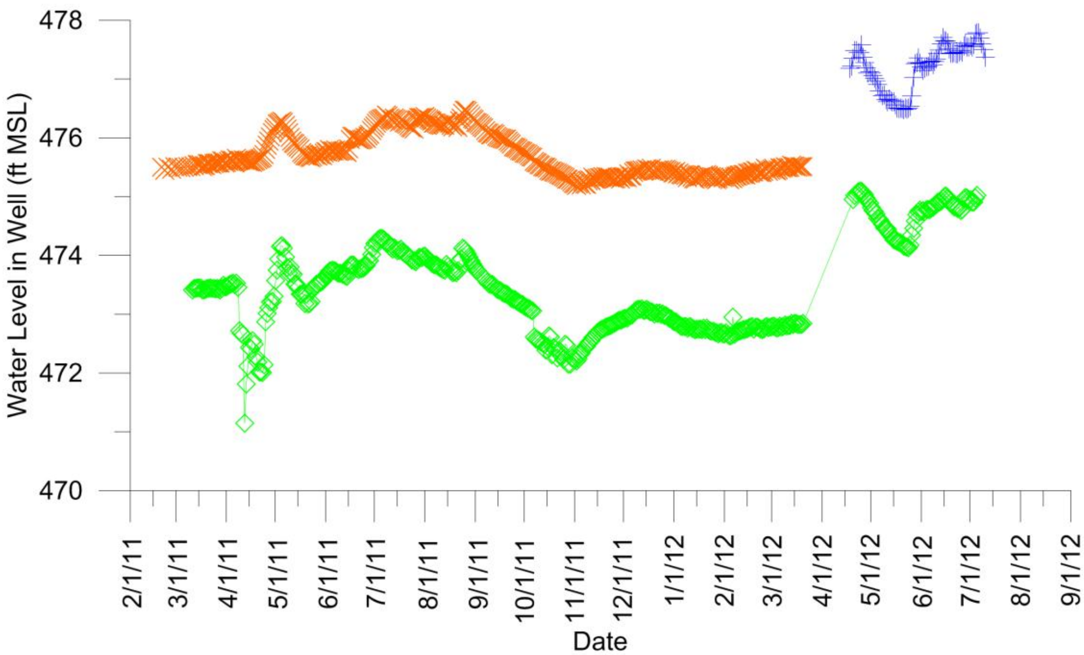


Figure H-31

Plots of the Flow Direction between Wells MW-161A, MW-162A, and MW-169A (upper plot) and Water Levels (lower plot) (Group 12)

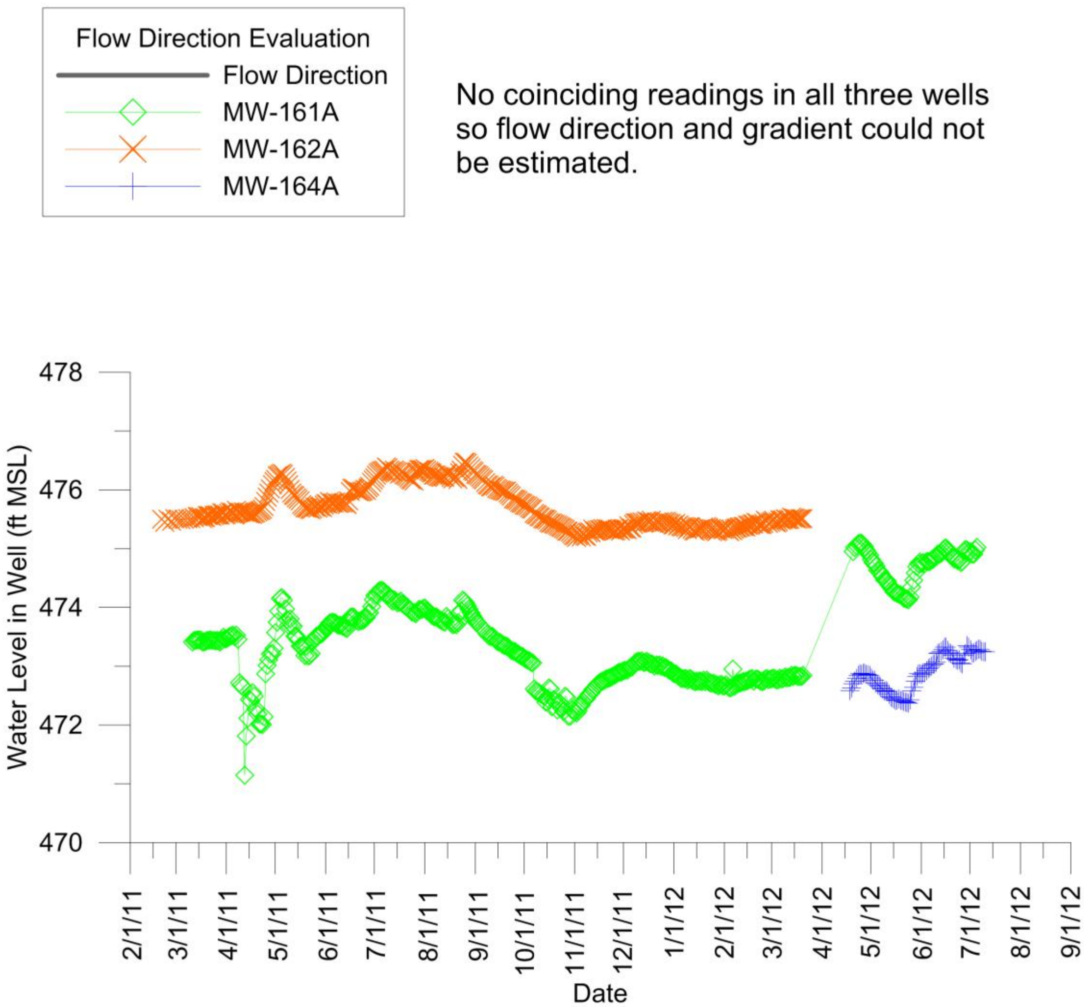


Figure H-32

Plots of the Flow Direction between Wells MW-161A, MW-162A, and MW-164A (upper plot) and Water Levels (lower plot) (Group 13)

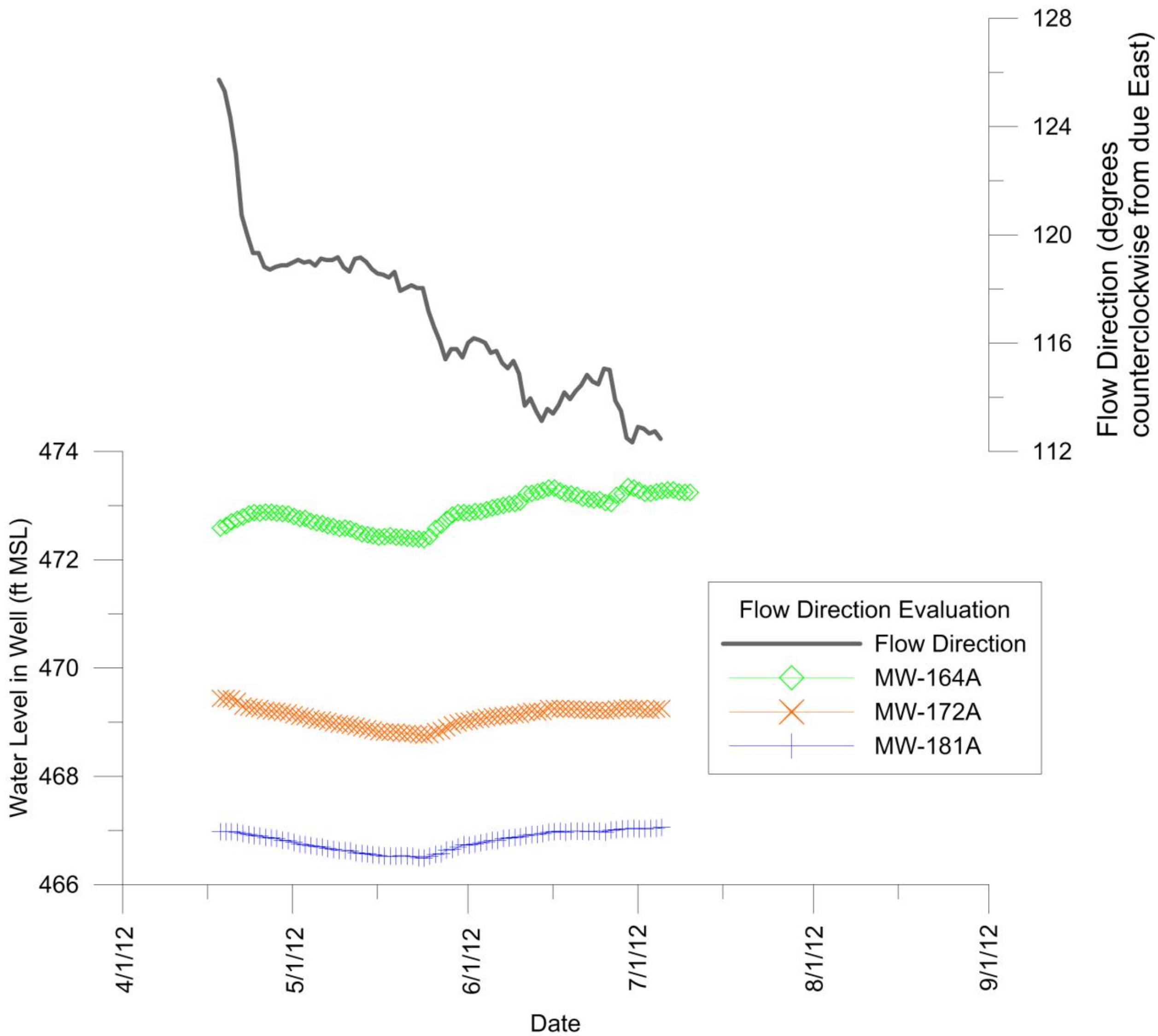


Figure H-33

Plots of the Flow Direction between Wells MW-164A, MW-172A, and MW-181A (upper plot) and Water Levels (lower plot) (Group 14)

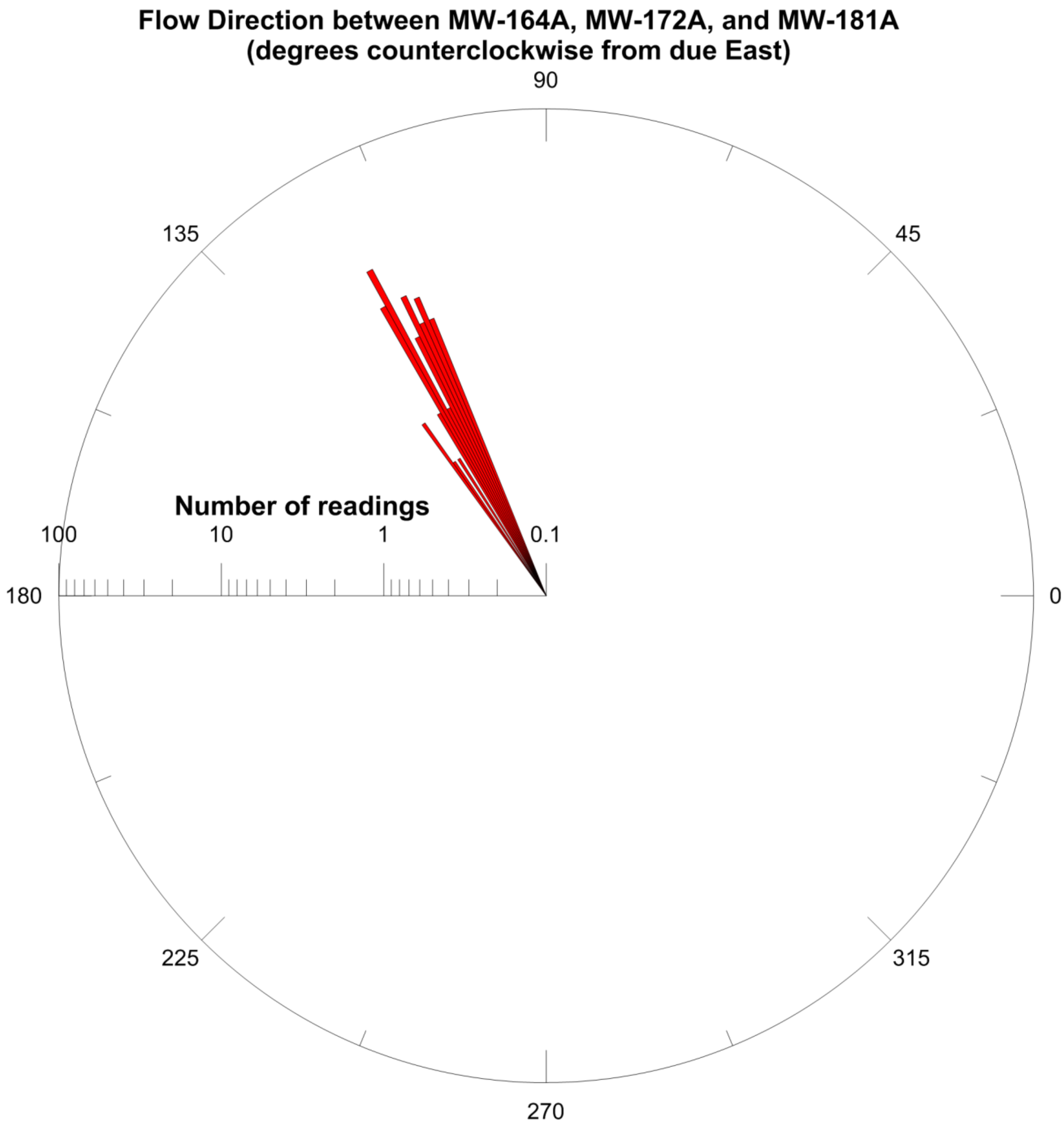


Figure H-34

Rose Diagram of Flow Direction between Wells MW-164A, MW-172A, and MW-181A (Group 14)

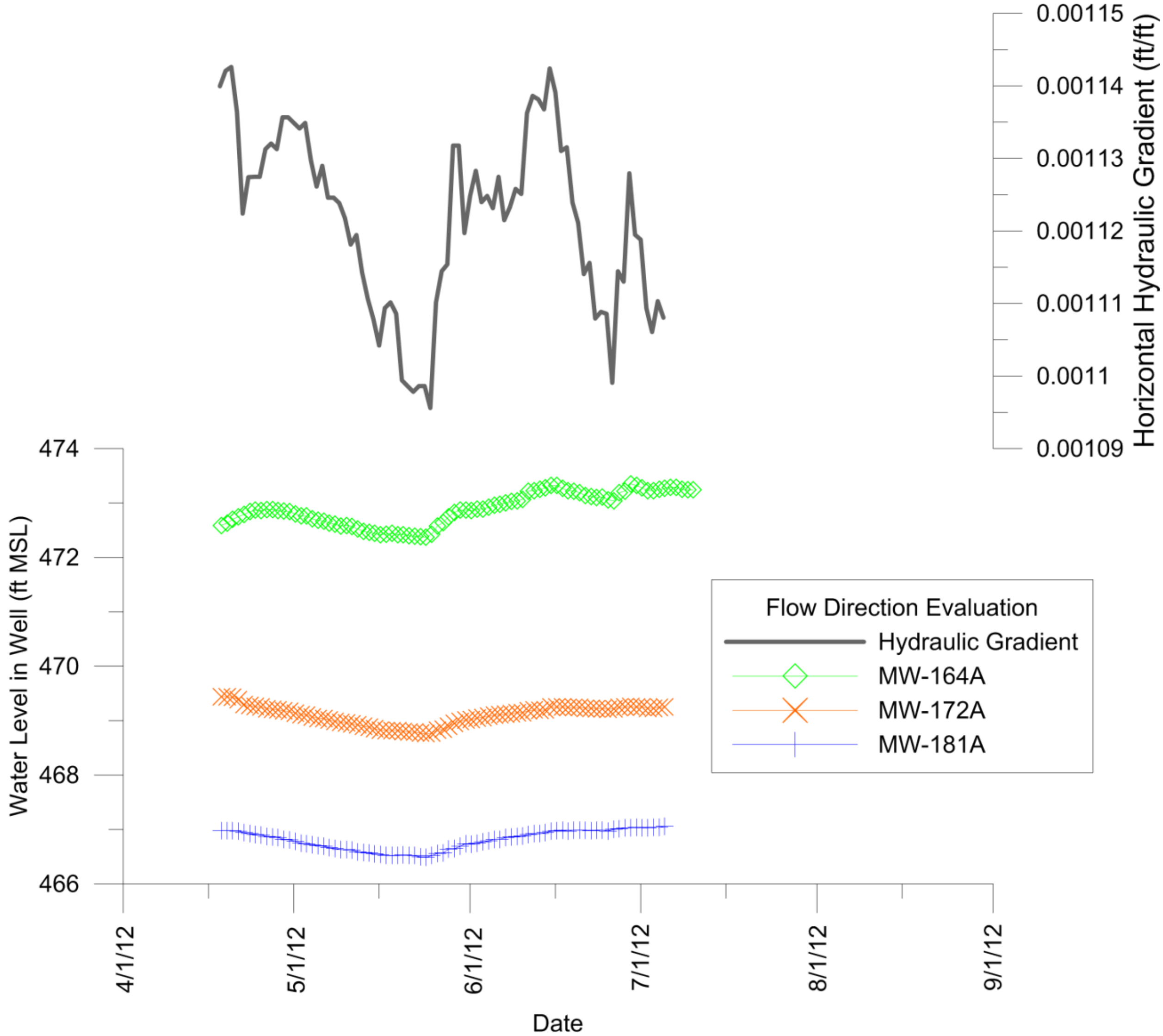


Figure H-35

Plots of the Horizontal Hydraulic Gradient between Wells MW-164A, MW-172A, and MW-181A (upper plot) and Water Levels (lower plot) (Group 14)

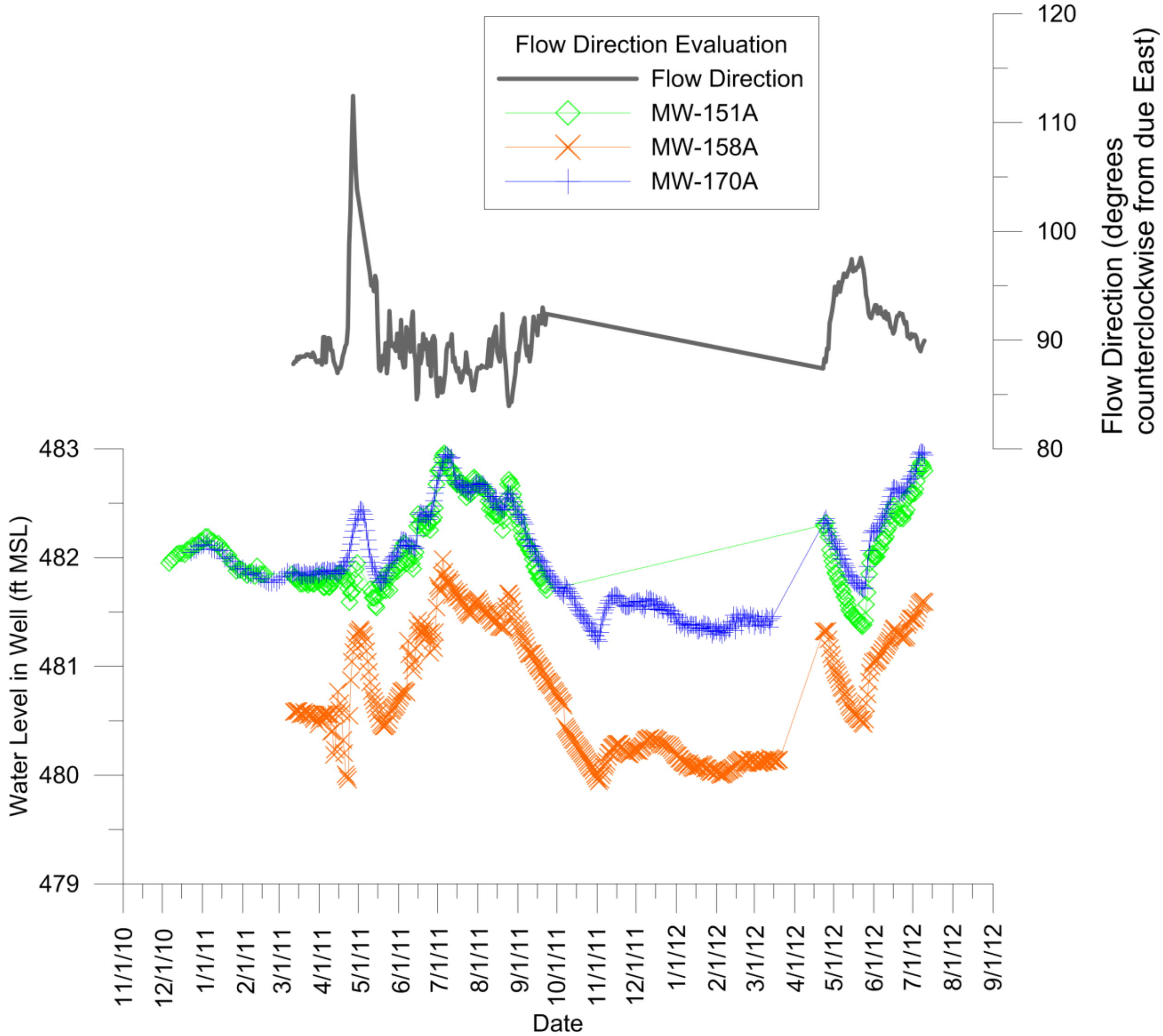


Figure H-36

Plots of the Flow Direction between Wells MW-151A, MW-158A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 15)

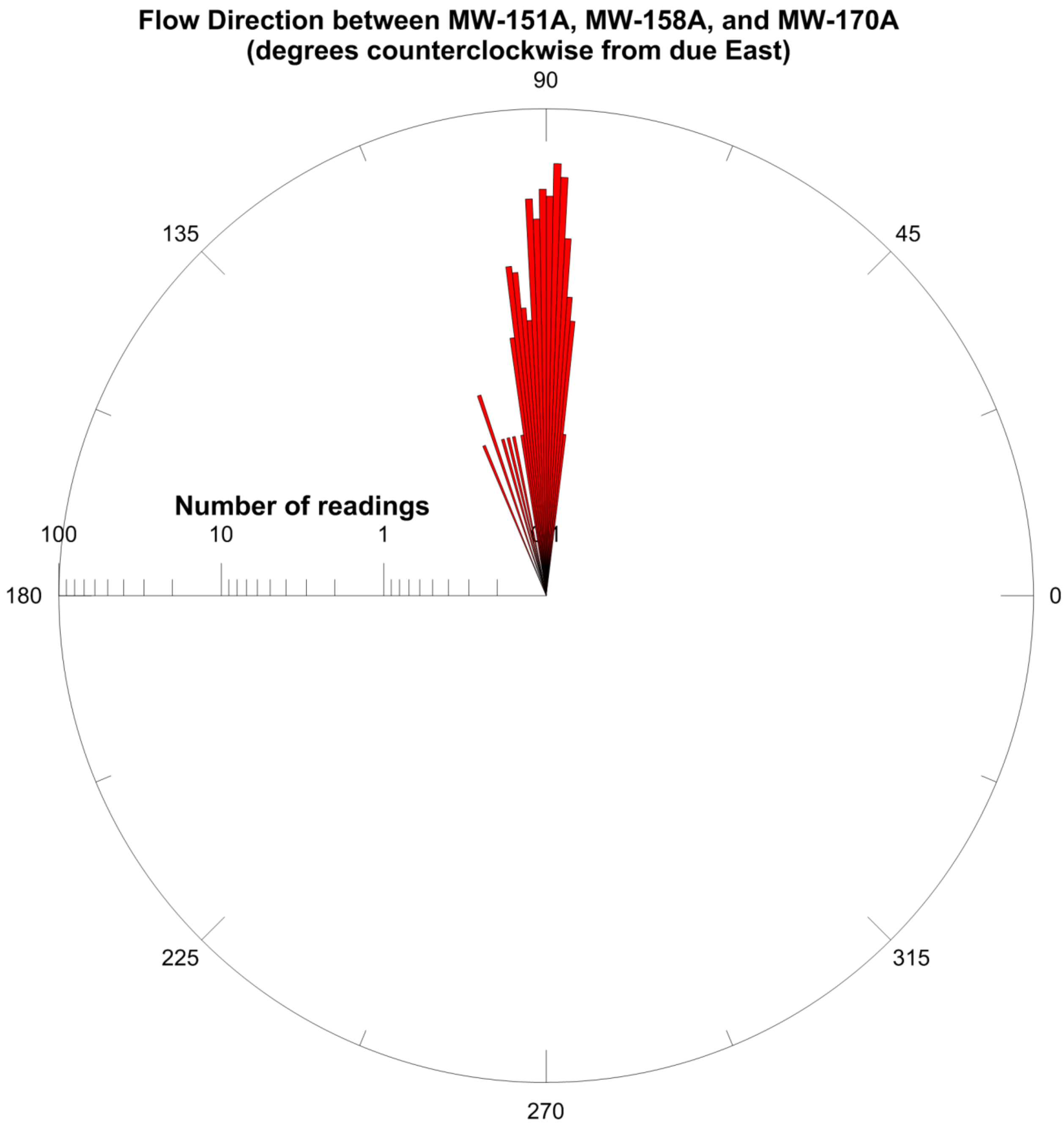


Figure H-37

Rose Diagram of Flow Direction between Wells MW-151A, MW-158A, and MW-170A (Group 15)

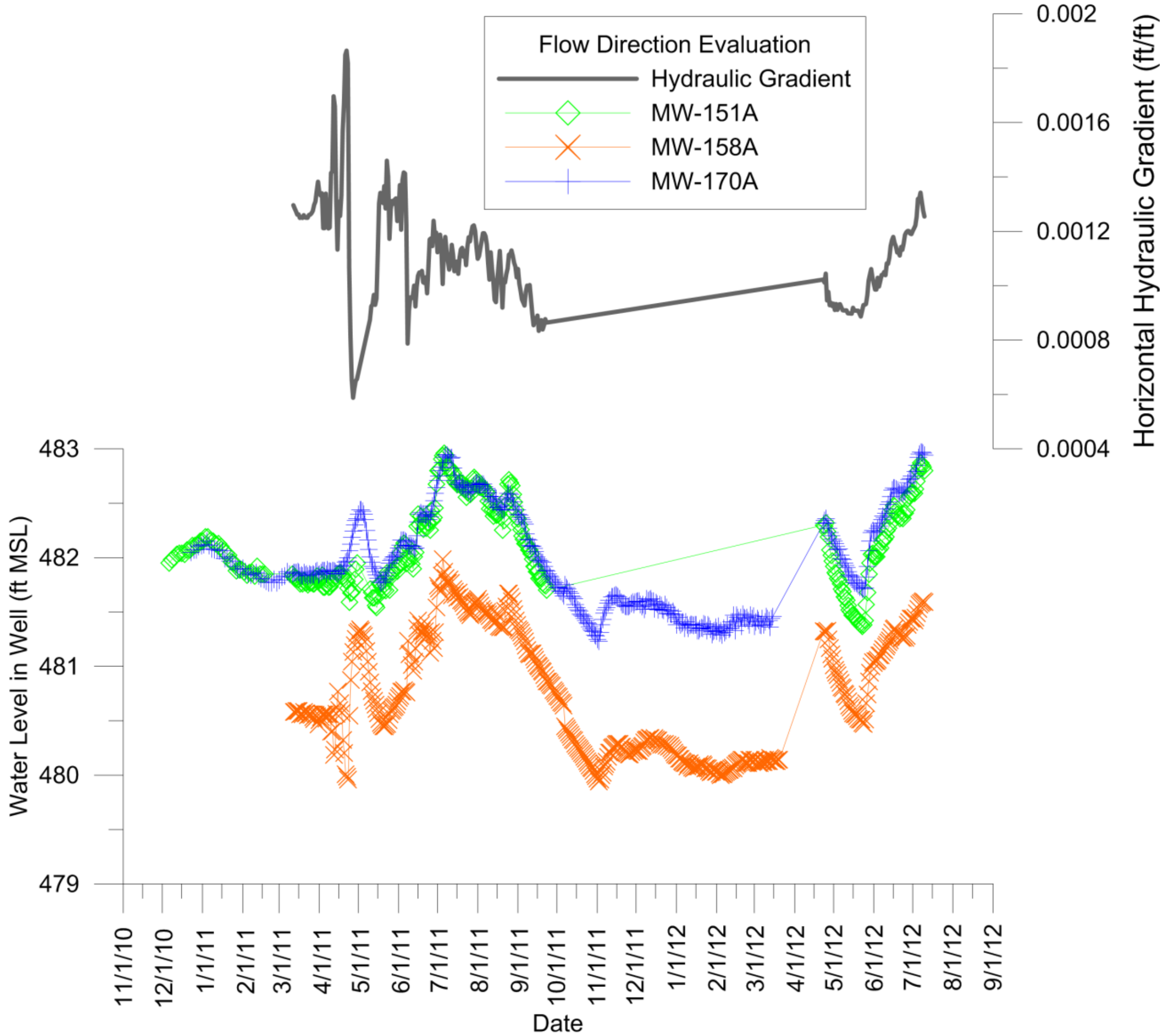


Figure H-38

Plots of the Horizontal Hydraulic Gradient between Wells MW-151A, MW-158A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 15)

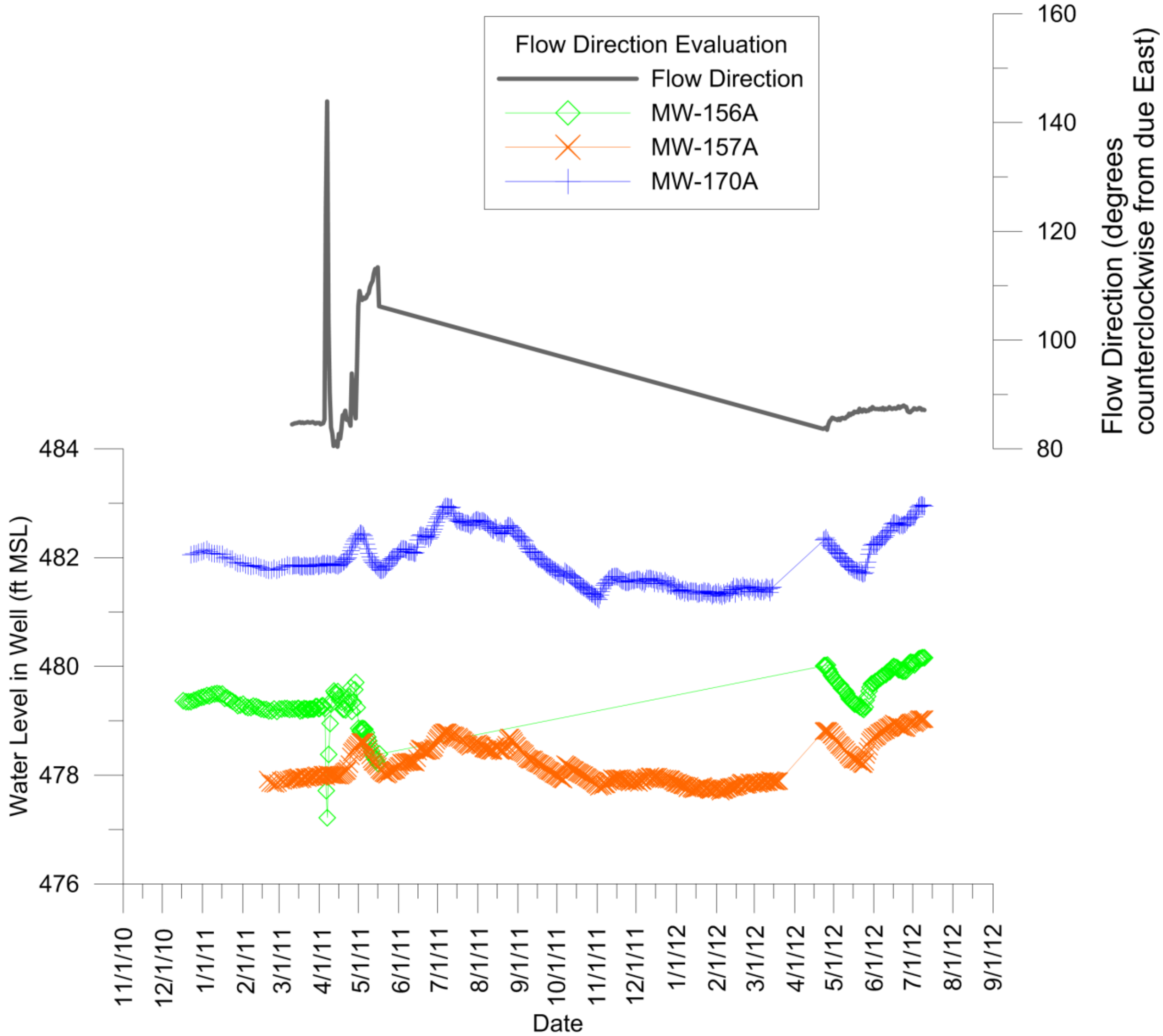


Figure H-39

Plots of the Flow Direction between Wells MW-156A, MW-157A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 16)

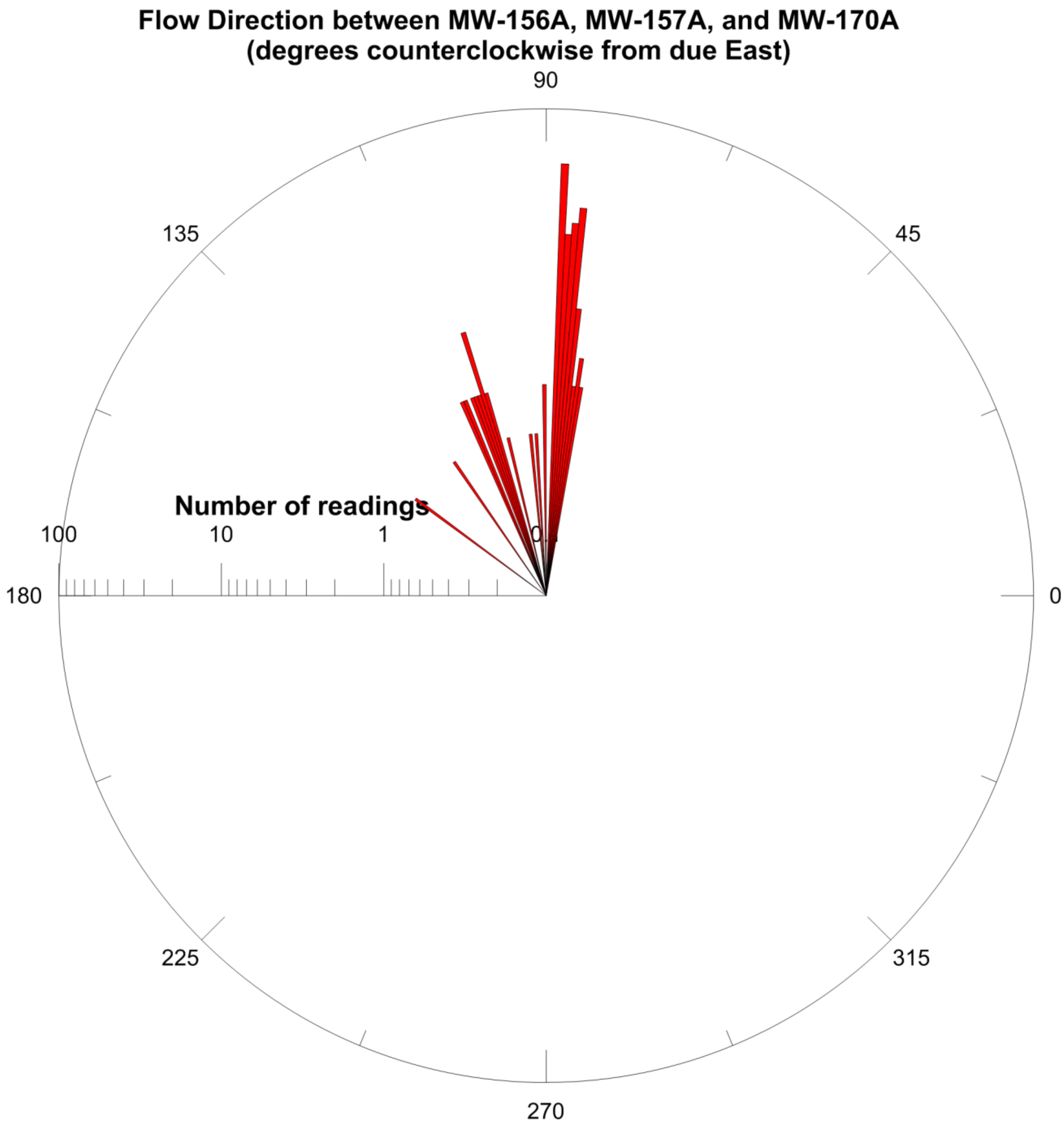


Figure H-40

Rose Diagram of Flow Direction between Wells MW-156A, MW-157A, and MW-170A (Group 16)

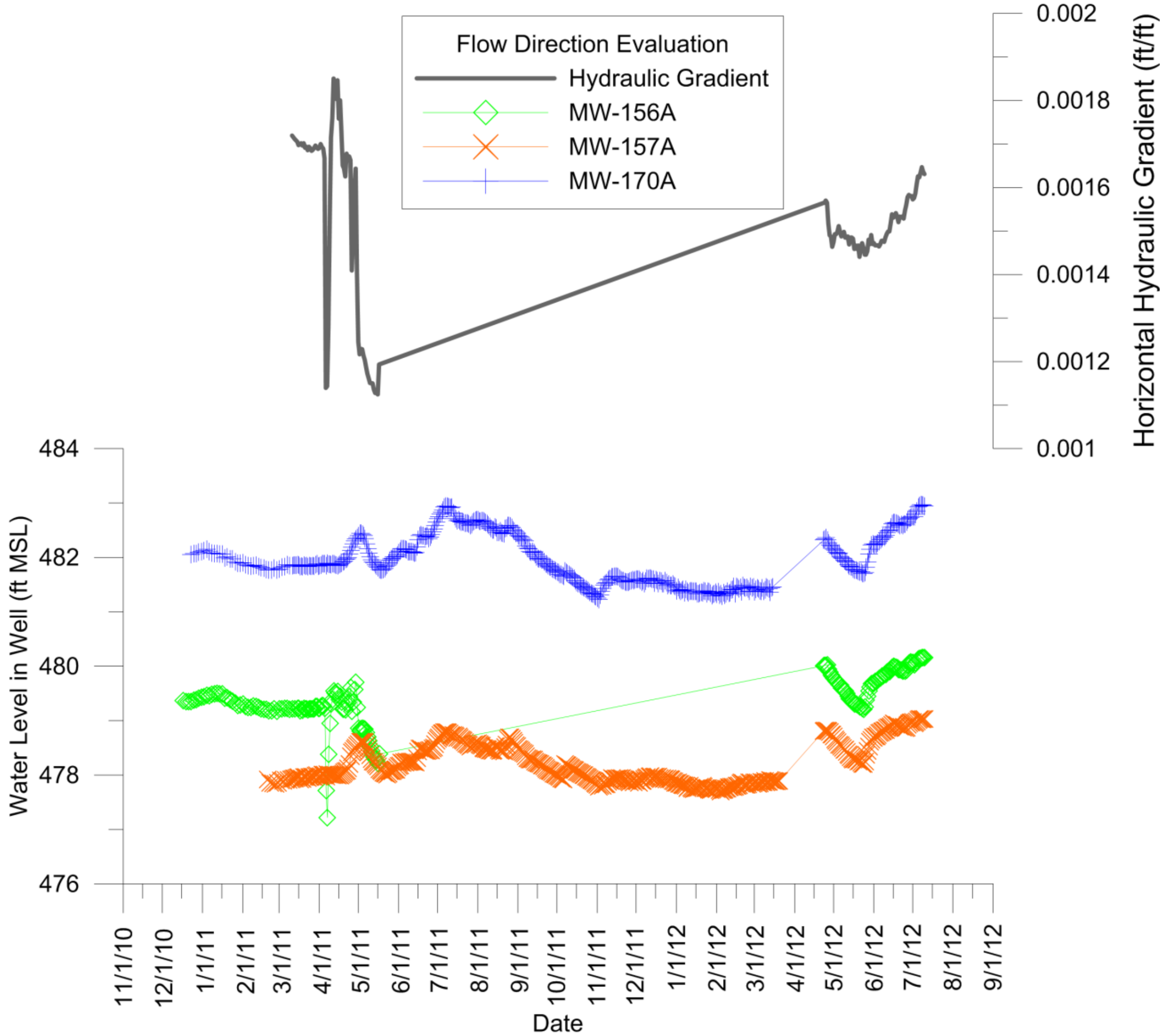


Figure H-41

Plots of the Horizontal Hydraulic Gradient between Wells MW-156A, MW-157A, and MW-170A (upper plot) and Water Levels (lower plot) (Group 16)

No coinciding readings in all three wells so flow direction and gradient could not be estimated.

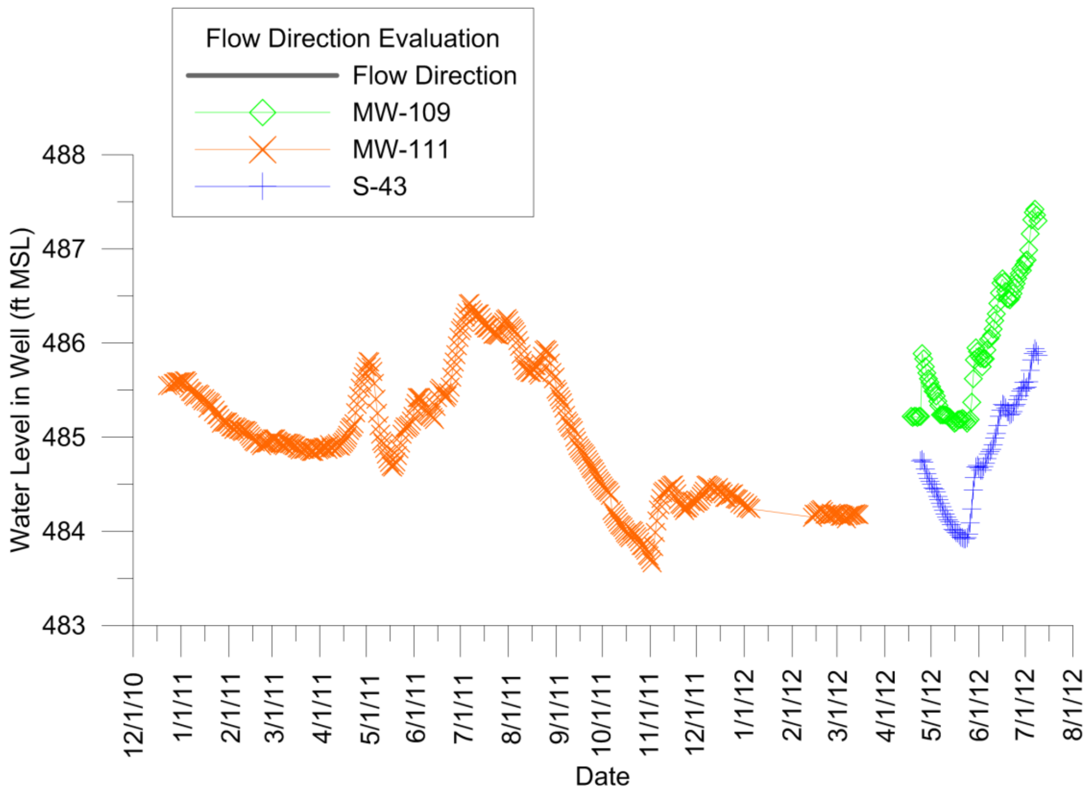


Figure H-42

Plots of the Flow Direction between Wells MW-109, MW-111, and S-43 (upper plot) and Water Levels (lower plot) (Group 17)

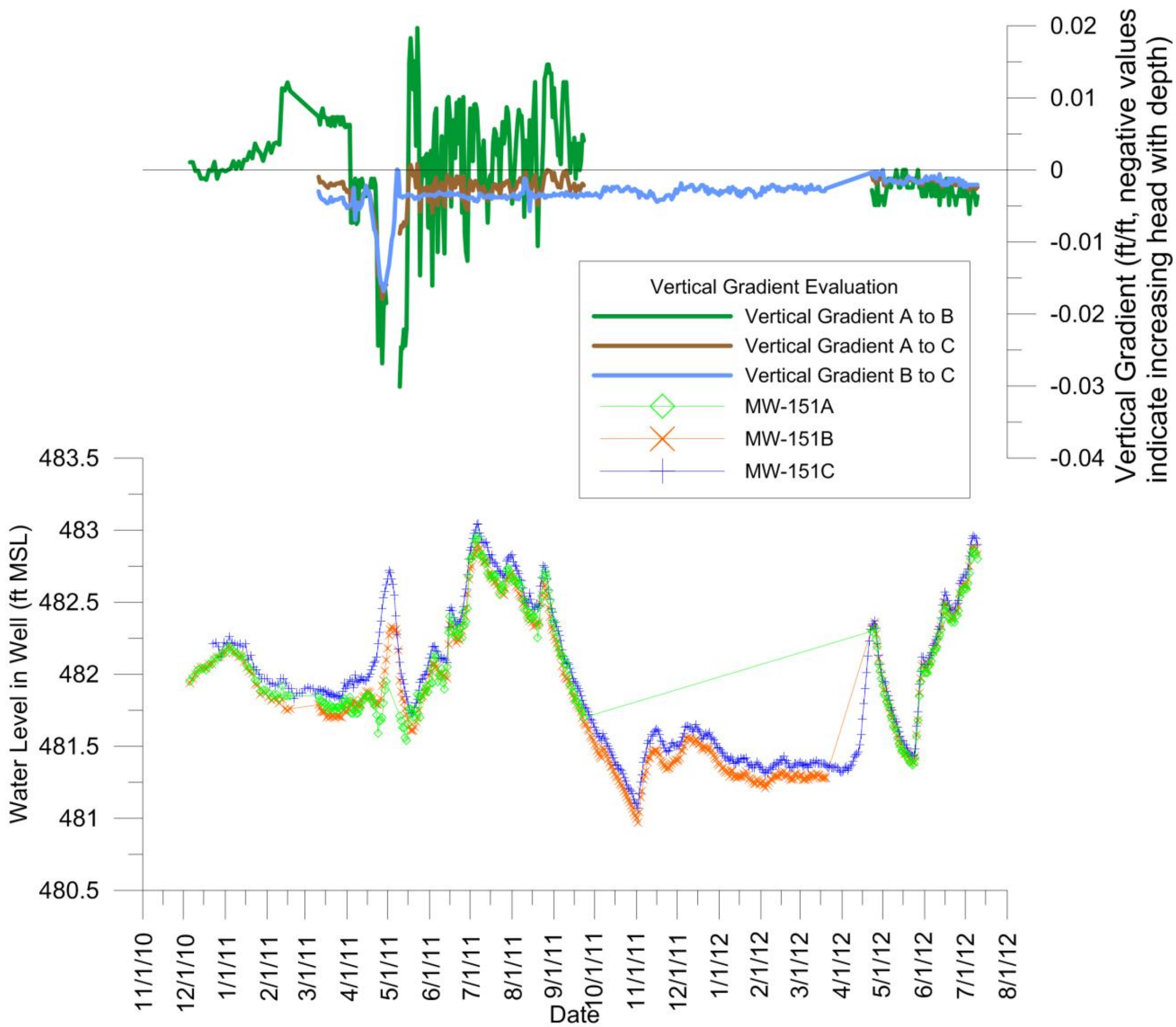


Figure H-43

Plots of the Vertical Hydraulic Gradient in the MW-151 Well Nest (upper plot) and Water Levels in the Nested Wells (lower plot)

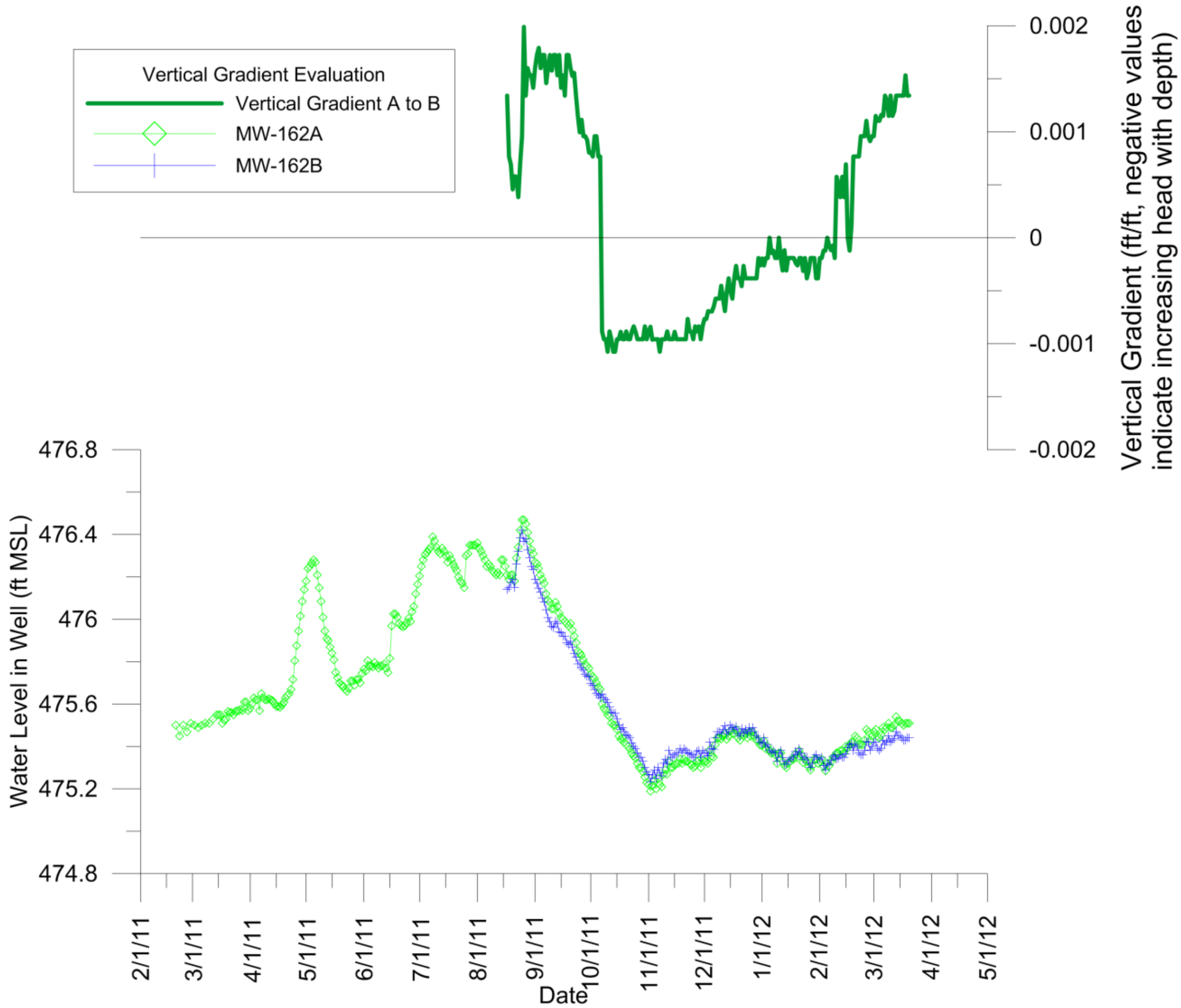


Figure H-44

Plots of the Vertical Hydraulic Gradient in the MW-162 Well Nest (upper plot) and Water Levels in the Nested Wells (lower plot)

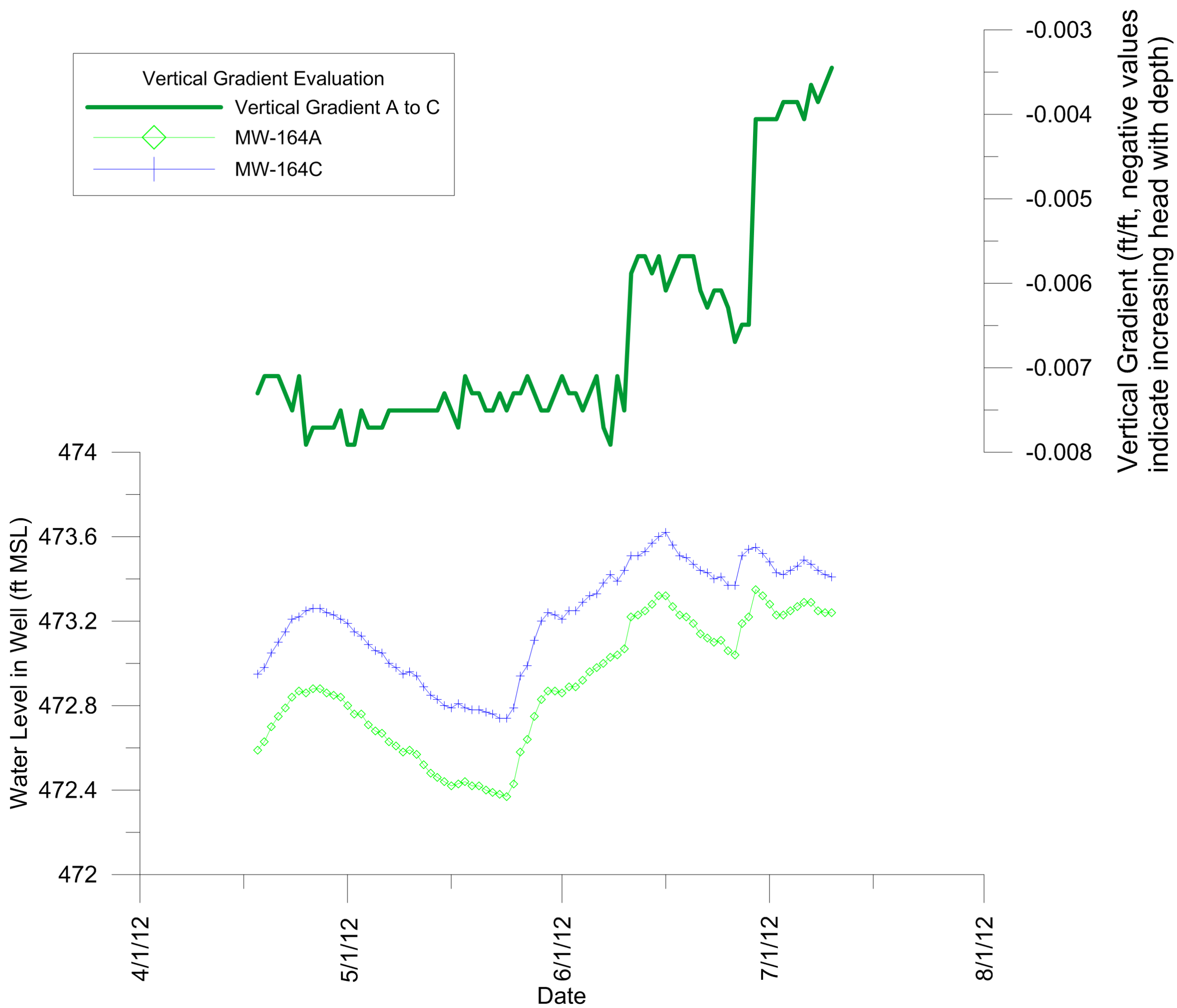


Figure H-45

Plots of the Vertical Hydraulic Gradient in the MW-164 Well Nest (upper plot) and Water Levels in the Nested Wells (lower plot)

Figure H-46

Plots of the Vertical Hydraulic Gradient in the MW-169 Well Nest (upper plot) and Water Levels in the Nested Wells (lower plot)

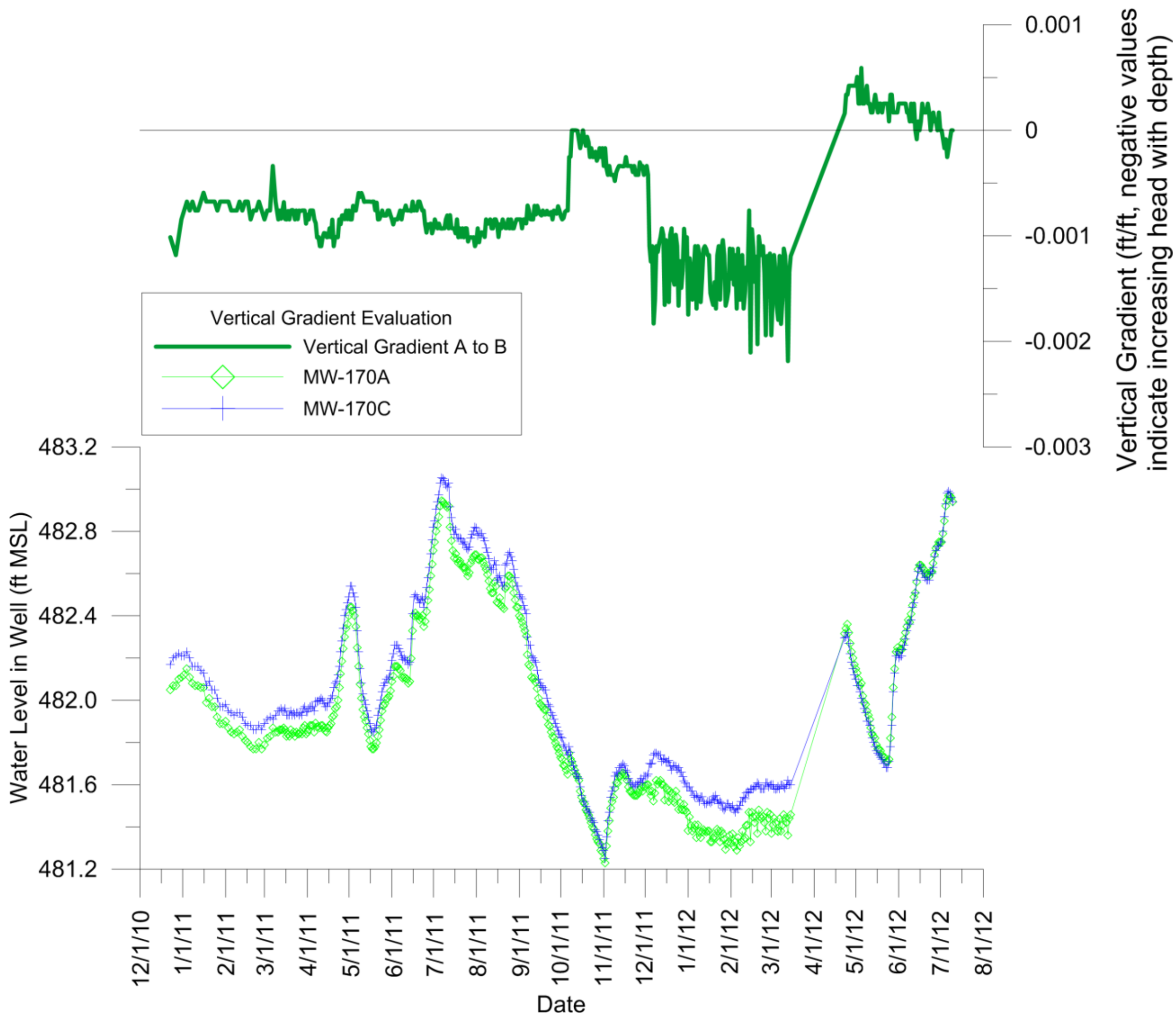


Figure H-47

Plots of the Vertical Hydraulic Gradient in the MW-170 Well Nest (upper plot) and Water Levels in the Nested Wells (lower plot)

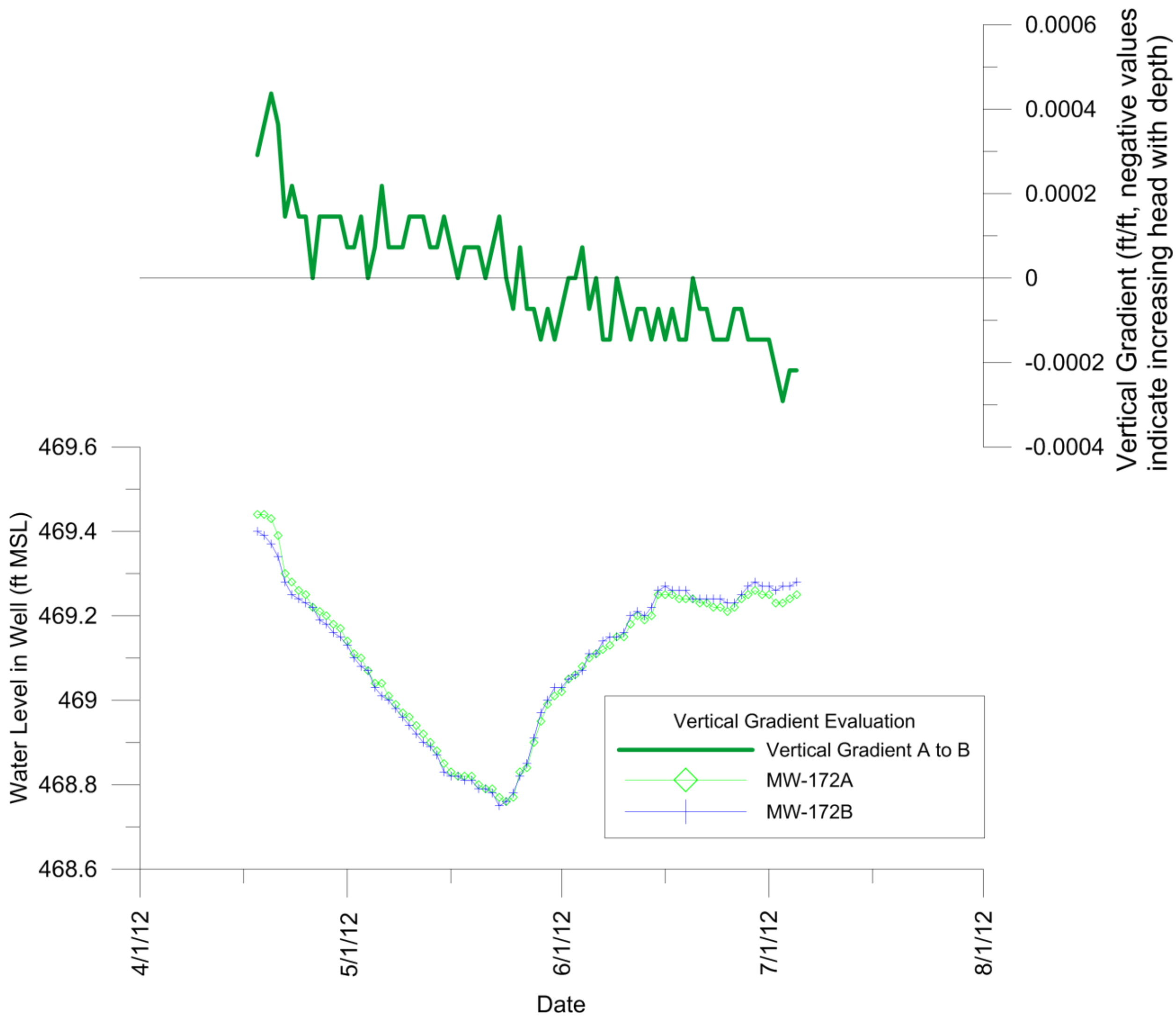


Figure H-48

Plots of the Vertical Hydraulic Gradient in the MW-172 Well Nest (upper plot) and Water Levels in the Nested Wells (lower plot)

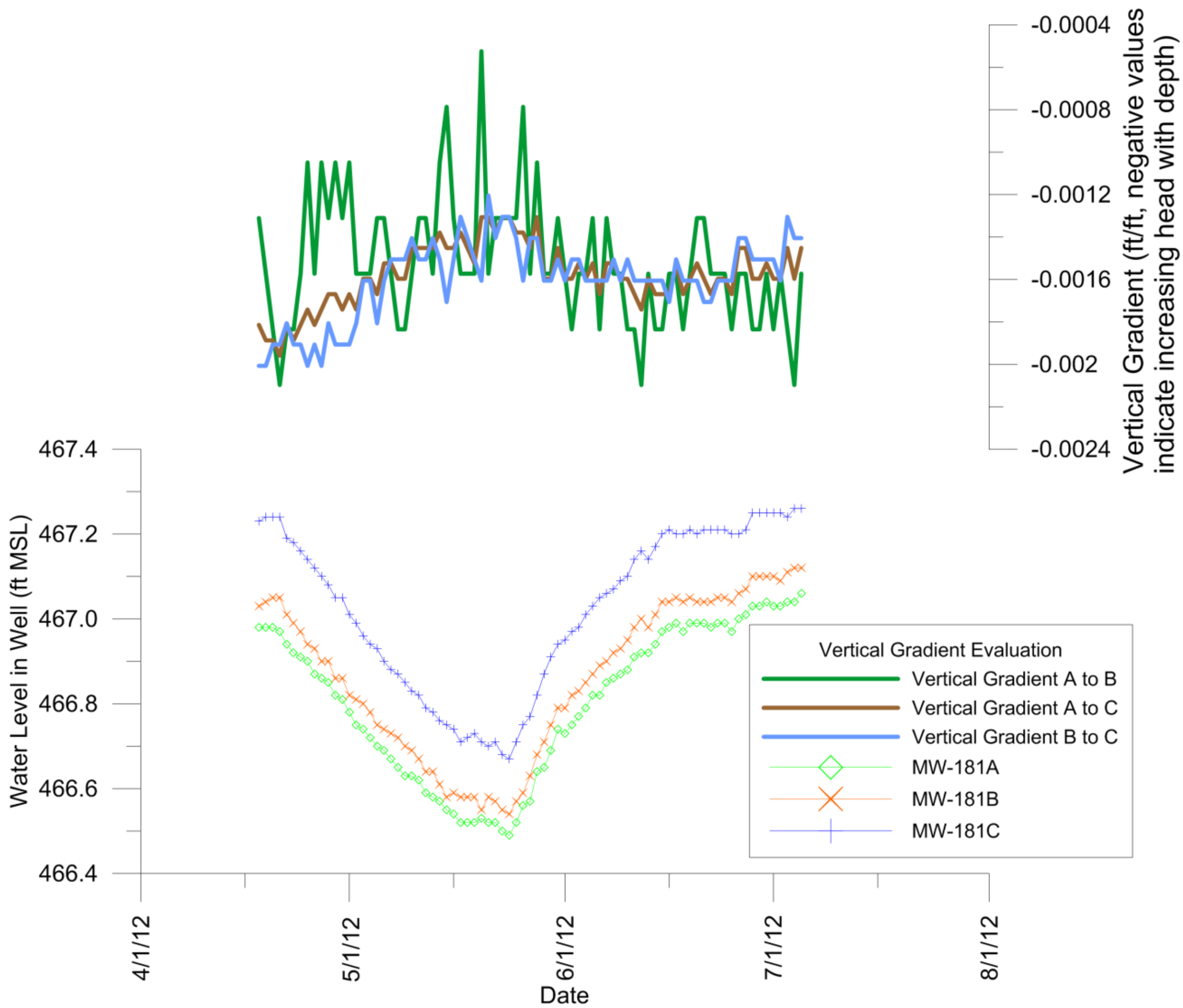


Figure H-49

Plots of the Vertical Hydraulic Gradient in the MW-181 Well Nest (upper plot) and Water Levels in the Nested Wells (lower plot)

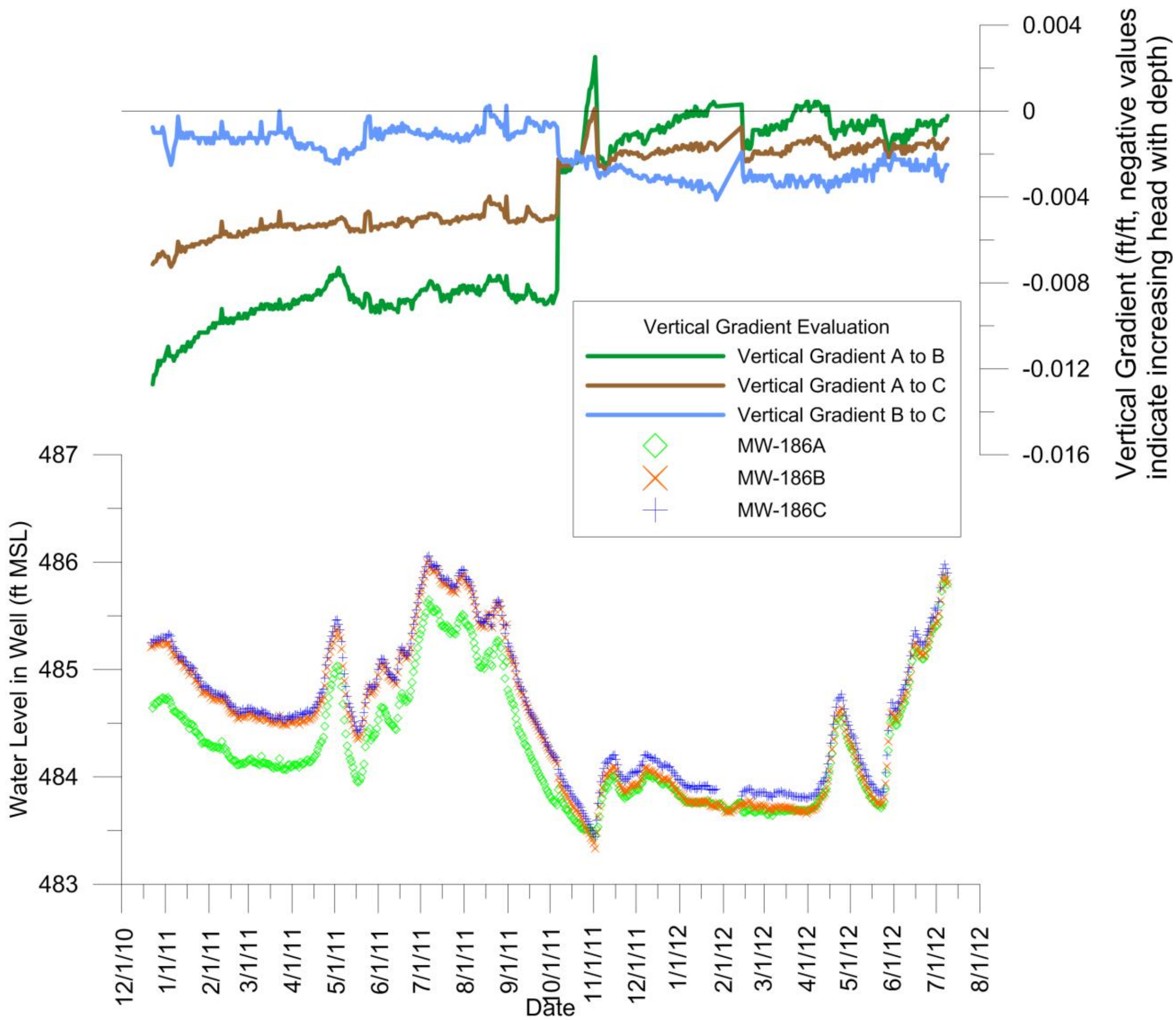


Figure H-50

Plots of the Vertical Hydraulic Gradient in the MW-186 Well Nest (upper plot) and Water Levels in the Nested Wells (lower plot)

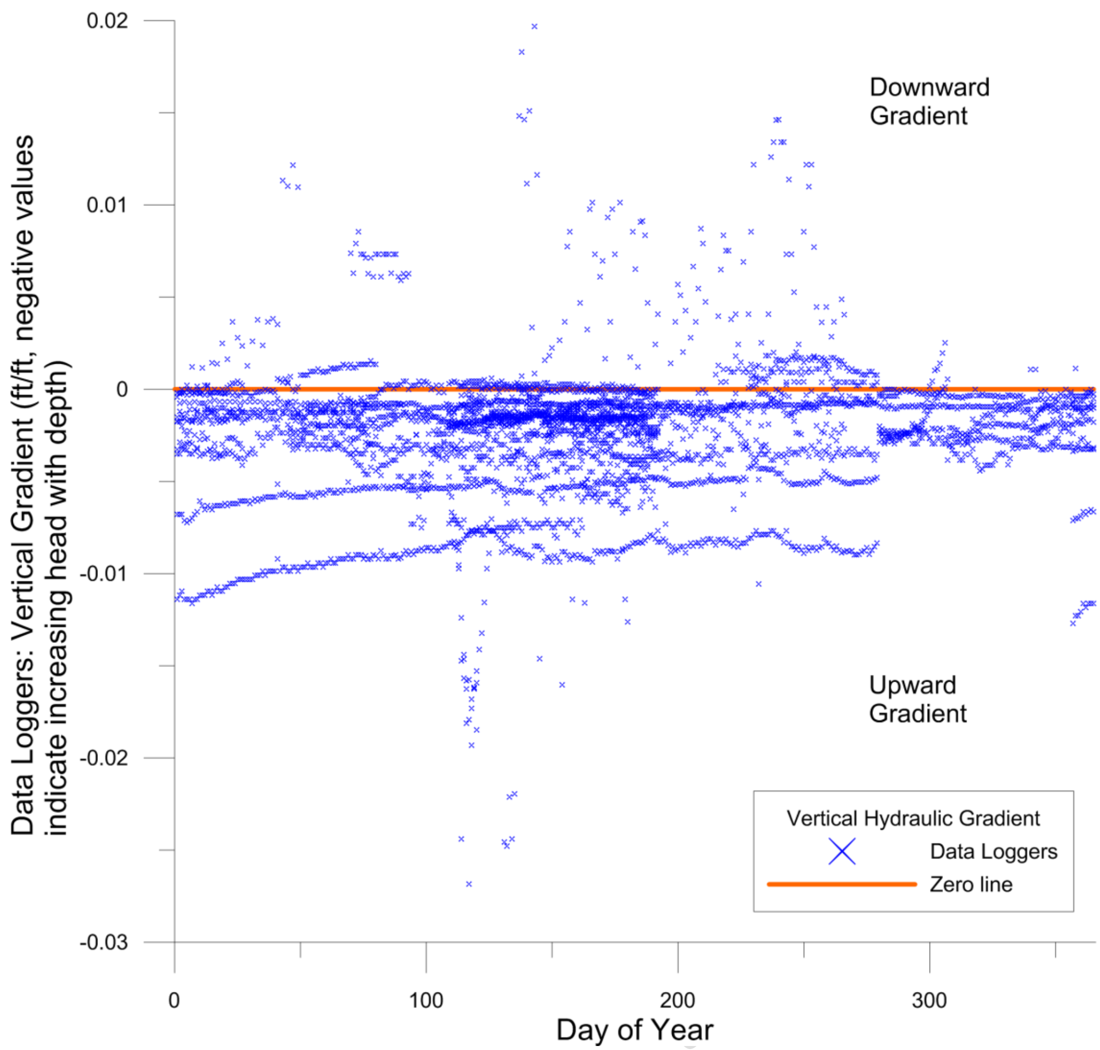


Figure H-51

Plots of all of the Vertical Hydraulic Gradient Data from Wells with Data Loggers versus the Day of the Year