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Three-Dimensional Underseepage Evaluation for Profit Island Vicinity Levee, North of Baton Rouge, Louisiana

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Three-Dimensional Underseepage Evaluation for Profit Island Vicinity Levee, North of Baton Rouge, Louisiana

Frank T.-C. Tsai, Navid H. Jafari, Ye-Hong Chen, and Jack A. Cadigan

*Department of Civil & Environmental Engineering
Louisiana State University
3255 Patrick F. Taylor Hall
Baton Rouge, LA 70803*

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Vicinity Levee Seepage Evaluation"

Abstract

This project developed a three-dimensional (3D) seepage model to evaluate efficiency of 84 relief wells and factors of safety (FoS) along the Profit Island vicinity levee (PIVL), north of Baton Rouge, Louisiana. The PIVL model was built based on US Geological Survey MODFLOW-USG. Moreover, a 3D seepage model of RocScience RS3 was also built for a specific study of relief well experiments conducted by the US Army Corps of Engineers in the 1930s and 1940s. The PIVL model was calibrated with measured piezometric head data and relief well flow rates in 1997. Six flood scenarios were conducted: the extreme flood (56 feet), design flood (52.4 feet), 1997 flood (50 feet), 2008 flood (49.22 feet), 2017 flood (45.55 feet), and 2018 flood (49.1 feet). The modeling results show that FoS are all above 1.5 given relief wells at the 1997 design condition. FoS calculated by the blanket theory are more conservative than those by the PIVL model because designed discharge rates were not observed in the field. In comparison with measured flow rates in 2008, the PIVL modeling result indicates potential clogging at many relief wells. New piezometric data and well discharge data are recommended to re-evaluate factors of safety.

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Preface

This study was conducted for the US Army Corps of Engineers, New Orleans District, under Contract W912P8-17-P-0054, “Three-Dimensional Simulation for Profit Island Vicinity Levee Seepage Evaluation.” The technical monitor was Mr. Tzenge-Huey Shih.

The work was performed by the Department of Civil and Environmental Engineering, Louisiana State University.

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The Commander of ERDC was COL Teresa A. Schlosser, and the Director was Dr. David W. Pittman.

1 Introduction

Background

The Pointe Coupee to Arbroth Seepage Control Project (USACE 1990) was designed to alleviate seepage pressures underneath the Profit Island Vicinity Levee (PIVL) along the Mississippi River levee, north of Baton Rouge, Louisiana. The extent of the project reach involved installation of 84 relief wells near Profit Island (Figure 1). The relief wells were located adjacent to the landside toe of the levee, and the outflow was channeled into a series of prepared ditches that drain water into Lake Clause and Tiger Bayou.

Relief wells installed adjacent to earthen embankments aim to relieve pore-water pressure at landside toe of the levee and downstream of the reservoir, thus limiting the formation of sand boils. They act like valves to relieve the water pressure and allow excess water to be diverted safely, for example, to a canal. Relief wells can effectively reduce sand boil formation by relieving the water pressure within the foundation alluvial sands. To achieve this functionality, it is necessary to predict the flow rate exiting through relief wells under various hydrologic conditions.

Numerical models are frequently used to evaluate flow patterns in a groundwater system, predict the effects of seepage reduction measures, and ultimately develop a better understanding of the groundwater flow system (Cheng et al. 2014). Both two-dimensional (2D) and three-dimensional (3D) models are useful tools for evaluating groundwater flow, including the 2D SEEP/W (Geo-Slope 2012), the 3D groundwater module of WASH123D¹ (Yeh et al. 2003), and the US Geological Survey (USGS) MODFLOW-related programs. However, there are strengths and limitations to each. For example, modeling complex geology, topology, land use, embankment characteristics, man-made features, etc., is more feasible via a 3D model to estimate groundwater flow beneath the embankment can often be more appropriate compared to a 2D model.

¹ Yeh, G. T., G. B. Huang, H. -P. Cheng, F. Zhang, H. C. Lin, E. Edris, and D. Richards. 2003. Draft. A Numerical Model of Flow, Heat Transfer, and Salinity, Sediment, and Water Quality Transport in Watershed Systems of 1-D Stream-River Network, 2-D Overland Regime, and 3-D Subsurface Media (WASH123D: Version 2.0). Technical Report Draft, Engineer Research and Development Center, U. S. Army Corps of Engineers, Vicksburg, MS, November 2003.

Objective

The objective of this study is to evaluate, in comparison to the blanket theory, how the 3D model performs upon modeling underseepage across PIVL embankments in complex geological environments and how the groundwater flow system responds to the PIVL relief wells (Chen et al. 2021).

Approach

The project utilized a large number of well logs to construct a complex hydrostratigraphy model for the PIVL study area. MODFLOW-USG (Panday et al. 2017) was employed to develop a 3D seepage model based on the hydrostratigraphy model and simulate hydraulic heads and well flows. Six flood scenarios were conducted: the extreme flood (56 ft)^{1,2}, design flood (52.4 ft), 1997 flood (50 ft), 2008 flood (49.22 ft), 2017 flood (45.55 ft), and 2018 flood (49.1 ft). Levee factors of safety were calculated and compared based on the 3D seepage model and the blanket theory.

¹ For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

² For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Figure 1. Map of Pointe Coupee to Arbroth-Alfords relief wells along the levee near Profit Island, Louisiana.



2 Field Reconnaissance of 2017 Flood

The Mississippi River experienced a flood event from May to June 2017. A peak river stage of 45.55 ft occurred near Profit Island on May 29, 2017. The river stage from May 1 to July 6 is shown in Figure 2. Photos of 84 relief wells along the vicinity levee of the Profit Island (Figure 3) were taken during five field trips on 5/27, 6/2, 6/16, 6/23, and 6/30/2017. The corresponding river stages on these dates were 45.44 ft, 45.22 ft, 41.10 ft, 35.79 ft, and 31.23 ft, respectively. The discharge magnitude from the relief wells was qualitatively classified into four categories: high discharge, moderate discharge, low discharge, and no discharge.

Table 1 shows the classifications for each relief well for the 5 days. Photos in Figure 3 provide the qualitative range of discharges for each category. During high river stage (5/27 and 6/2), 59 relief wells yielded high to moderate discharges, 20 relief wells yielded low discharges, and 5 relief wells had zero discharge. The relief wells with high discharges are primarily located at Reaches 24I and 24P at the north end of the levee reach and Reaches 25O, 25P, 25P, 25S, 25T, and 25U towards the south. The relief wells with low or no discharges are primarily located at Reaches 24K, 24M, 24N, 24O, and 24X. During low river stage (6/30), all relief wells had zero discharge, except for one relief well at Reach 24P that showed low discharge.

Figure 2. Mississippi River stage (feet) near the Profit Island from 5/1/2017 to 7/6/2017. Black dots are dates of field trips.

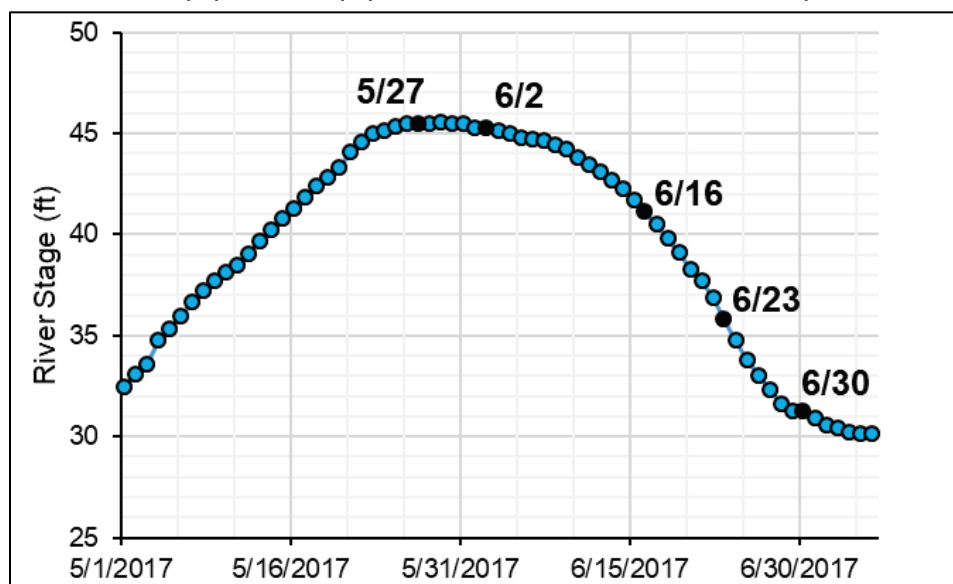


Figure 3. Photographs for classifying the magnitudes of discharge out of relief wells: (a) High flow, (b) Moderate flow, (c) Low flow, and (d) No flow.

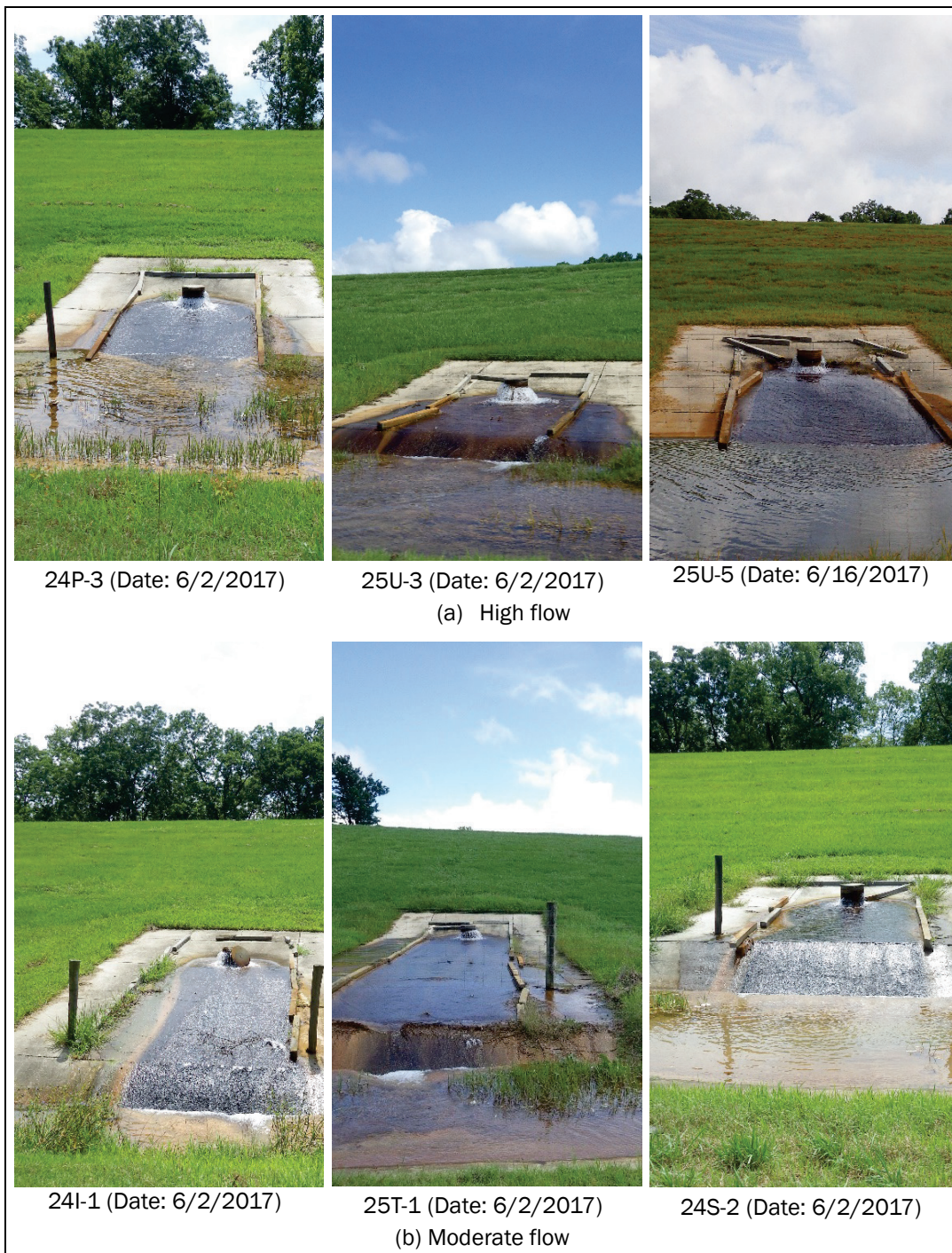


Figure 3. Continued.



24M-3 (Date: 6/2/2017)

240-1 (Date: 6/2/2017)
(c) Low flow

25S-5 (Date: 6/23/2017)

24K-1 (Date: 6/2/2017)
(d) No flow

Table 1. Classification for the magnitudes of discharge out of the relief wells through photographs taken during five field trips on 5/27, 6/2, 6/16, 6/23, and 6/30/2017. H: high flow; M: moderate flow; L: low flow; and N: no flow.

Relief Well	5/27	6/2	6/16	6/23	6/30	Relief Well	5/27	6/2	6/16	6/23	6/30
24I-1	M	M	M	L	N	24X-3	L	L	L	N	N
24I-2	H	H	M	L	N	24X-4	L	L	L	N	N
24K-1	N	N	N	N	N	24X-5	L	L	L	N	N
24K-2	N	N	N	N	N	24X-6	L	L	L	N	N
24M-1	L	L	N	N	N	24X-7	M	M	L	N	N
24M-2	L	L	N	N	N	24X-8	L	L	N	N	N
24M-3	L	L	N	N	N	24Y-1	M	M	M	L	N
24M-4	L	L	N	N	N	24Y-2	M	M	M	L	N
24M-5	L	L	L	N	N	24Y-3	M	M	M	L	N
24M-6	L	L	L	N	N	25A-1	M	M	M	N	N
24M-7	L	L	L	N	N	25A-2	M	M	M	N	N
24M-8	L	L	N	N	N	25B-1	M	M	L	N	N
24M-9	L	L	L	N	N	25B-2	M	M	M	L	N
24M-10	L	L	N	N	N	25C-1	M	M	M	N	N
24N-1	N	N	N	N	N	25C-2	M	M	M	N	N
24N-2	N	N	N	N	N	25C-3	M	M	M	N	N
24N-3	L	L	N	N	N	25G-1	L	L	N	N	N
24O-1	L	L	N	N	N	25G-2	M	M	L	N	N
24O-2	N	N	N	N	N	25G-3	M	M	L	N	N
24P-1	M	M	M	M	L	25G-4	L	L	N	N	N
24P-2	M	M	M	L	N	25K-1	M	M	N	N	N
24P-3	H	H	M	M	N	25M-1	M	M	M	L	N
24P-4	H	H	M	M	N	25M-2	M	M	M	L	N
24Q-1	M	M	M	N	N	25N-1	M	M	M	M	N
24Q-2	M	M	L	N	N	25N-2	M	M	M	M	N
24S-1	M	M	M	N	N	25O-1	M	M	M	L	N
24S-2	M	M	M	N	N	25O-2	H	H	M	M	N
24S-3	M	M	M	N	N	25O-3	M	M	M	M	N
24S-4	M	M	L	N	N	25O-4	M	M	M	M	N
24S-5	M	M	M	N	N	25O-5	M	M	M	L	N
24S-6	M	M	M	N	N	25P-1	H	H	M	L	N
24S-7	M	M	M	N	N	25S-5	H	H	M	L	N
24S-8	M	M	M	N	N	25T-1	M	M	M	N	N
24S-9	M	M	M	N	N	25T-2	M	M	M	N	N
24S-10	M	M	L	N	N	25T-3	M	M	M	N	N
24S-11	M	M	L	N	N	25T-4	H	H	M	N	N
24U-1	M	M	L	L	N	25T-5	M	M	M	N	N
24U-2	M	M	L	N	N	25U-1	H	H	M	M	N
24U-3	M	M	L	L	N	25U-2	H	H	M	M	N
24W-1	M	M	L	N	N	25U-3	H	H	M	M	N
24X-1	M	M	L	N	N	25U-4	H	H	M	M	N
24X-2	L	L	L	N	N	25U-5	H	H	H	M	N

3 Geological and Geotechnical Subsurface Investigations

Geological setting of Profit Island

Profit Island vicinity levee is located along the western bank of the Mississippi River north of Baton Rouge, Louisiana. Lying approximately 253 mi north of Head of Passes in the alluvial valley of the Lower Mississippi River, the study reach is primarily characterized by Holocene point bar, natural levee, abandoned channel, and backswamp deposits (Fisk 1944; Russell 1940;¹). Using estimated ages for river courses that built Profit Island indicates it likely was initially formed approximately 600 yr ago (Poplin and Goodwin 1987) and is present in historical records and maps at least as far back as the Siege of Port Hudson in 1863 (Tucker et al. 2013). The island was created when a permanent secondary river channel, “Profit Island Chute,” severed a bend apart from the main stem of the Mississippi River (Baker et al. 1987; Cobb and Clark 1981;²). During extreme flood events such as 2008 and 2011, the island may become completely submerged¹. The site was one of the meander-cutoff locations proposed to help reinforce the viability of the present channel of the river (Kolb 1980; Martinez 1986) and is the outfall location of the planned Comite River Diversion project¹.

Geotechnical stratigraphy and properties

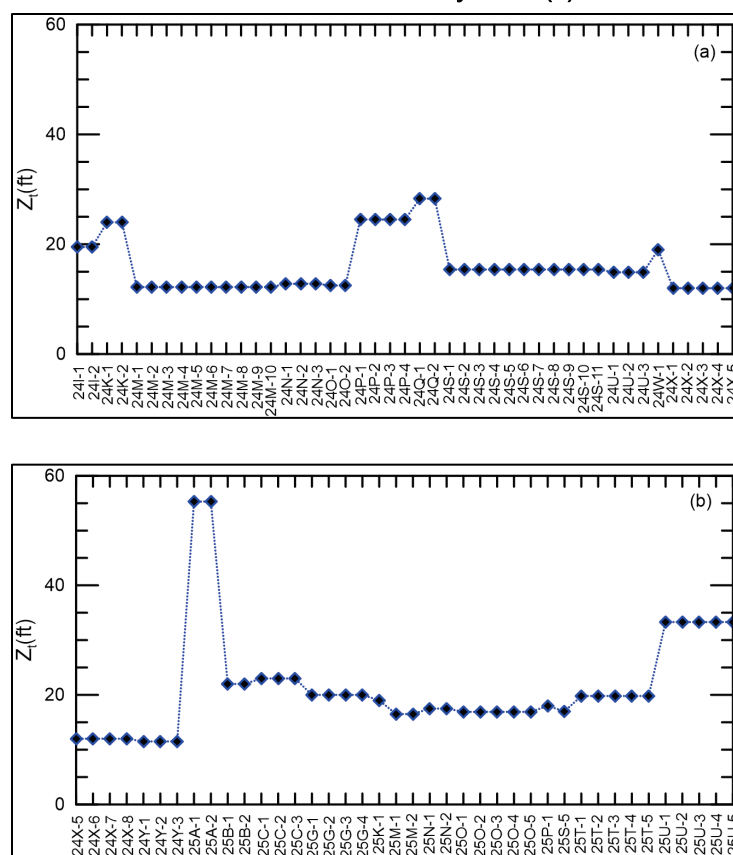
The study area predominantly features an average of 16.5 ft of natural levee deposits overlain on 100 ft of point bar deposits occasionally cut with filled ancient channels bounded underneath by fluvial sands to depths of 180 ft to 330 ft (Saucier 1969). To the west of the artificial levee, the study area is dominantly characterized by backswamp deposits covered by natural levee deposits. Consistent with general trends for the Lower Mississippi River Valley, backswamp deposits in the top stratum form a continuous impervious landside topstratum in conjunction with the natural levee deposits (Fisk 1944). Backswamp deposits began accumulating approximately 12,000 yr ago and continued along the flanks of the river.

¹ USACE. 1983. Unpublished. *Pointe Coupee to Arbroth Seepage Study. Mississippi River Levees*. USACE, New Orleans District, New Orleans, LA.

² USACE. 2012. *Draft Environmental Assessment - Amite River and Tributaries, Louisiana Comite River Basin; Comite River Diversion Supplemental Mitigation Options*. Mississippi Valley Division, Regional Planning and Environmental Division, South New Orleans District, New Orleans, LA.

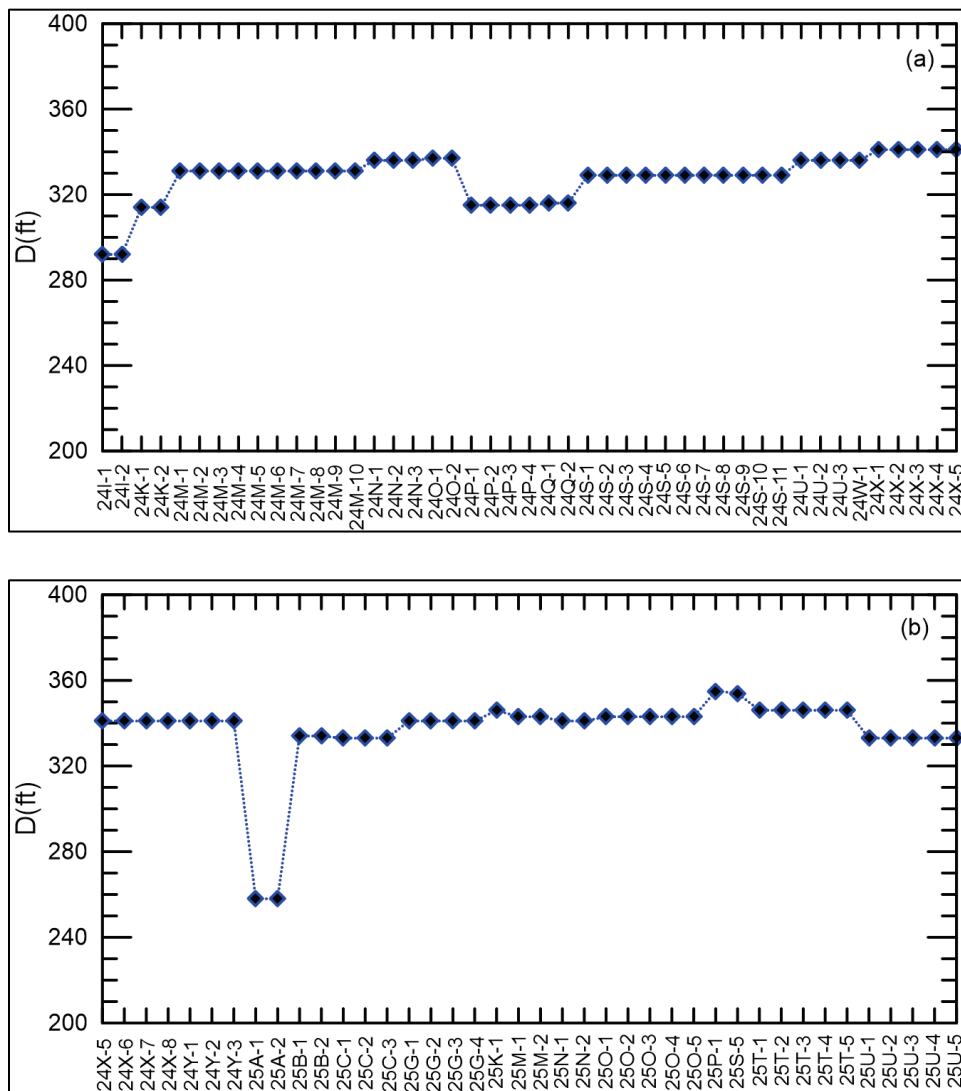
However, as the river meandered, the backswamp deposits may have been eroded and replaced with point-bar deposits in some areas (Saucier 1969). Backswamps comprise low-lying areas generally at lower elevations than the alluvial fans deposited in the natural levee environment (Fisk 1944). As they are located at some distance from the river, they generally received lower energy flood waters that deposited thinly laminated clays and silty clays¹. Typical to regions adjacent to the study area, the natural levees form ridges above the floodplain (Fisk 1944). Thus, the coarsest materials are deposited directly adjacent to the river and fine until they merge with backswamp clay deposits near the locations of the levee toes¹. The impervious blanket varies in thickness across the reach, generally thicker in the southern half of the study reach (from wells 24X-5 to 25U-5). The transformed blanket thicknesses used in seepage analyses follow the same trend and are shown in Figure 4.

Figure 4. Transformed blanket thickness across northern half of study reach (a), and southern half of study reach (b).



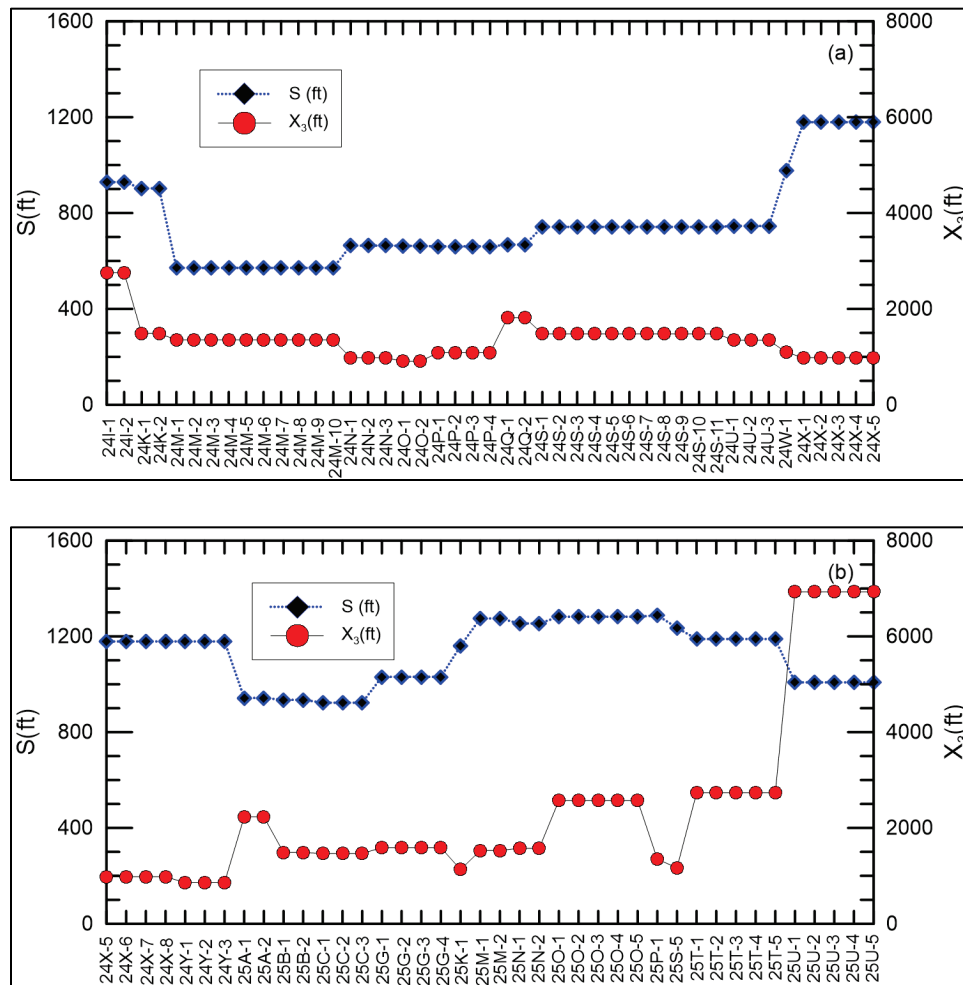
Thick layers of pervious substratum deposits of fluvial sands and gravels were deposited by shallow braided courses of the river as it carried large volumes of coarse glacial debris following the last glacial maximum (Saucier 1969). Autin et al. (1991) classified the meander belt in which the study area currently lies as “Meander Belt 1,” which has been the active channel of the Mississippi River and contains a prehistoric abandoned channel encompassing Lake Clause with its associated point bar deposits immediately to the west of Profit Island (Hinks et al. 1993). In Figure 5, the aquifer thickness is generally greater than 300 ft.

Figure 5. Aquifer thickness along northern half of the study reach (a), and southern half (b).



The study reach generally is characterized by effective seepage entrance (Figure 6) at distances typically between 600 to 1,200 ft from the landside levee toe. Effective seepage exit distances from the levee toes are typically between 1,000 to 3,000 ft, except for at the southernmost relief wells, where the effective seepage exits are approximately 7,000 ft from the toe of the levee.

Figure 6. Effective seepage entrance distance (s) and effective seepage exit distance (X_3) for the northern half of the study reach (a) and the southern half of the study reach (b). The S and X_3 are drawn in Figure 15.



Of the 84 relief wells in the reach, 24I-1, 24I-2, 24P-1, 24Y-1, 24Y-2, 24Y-3, 25C-3, 25M-2, 25O-1, 25O-2, 25P-1, 25S-5, 25T-1, 25T-2, 25T-4, 25U-1, 25U-2, 25U-3, 25U-4, and 25U-5 are recorded to have all or a substantial portion of their screens located in coarse aquifer sands featuring hydraulic conductivities on the magnitude of 300% to 400% of the average aquifer hydraulic conductivity. The remaining 64 wells are screened in finer aquifer layers with hydraulic conductivities equal to or less than the average aquifer hydraulic conductivity and may not flow at design capabilities except during high river stages¹. Most wells are screened in the upper-most portion of the aquifer, at the contact below the point bar deposits².

¹ USACE. 2001. Unpublished. *Operation and Maintenance Manual for Flood Control: Mississippi River Levees Right Descending Bank Atchafalaya Basin Levee District Pointe Coupee to Arborth-Alfords Relief Wells, 252 to 249 River Miles Above Head of Passes, West Baton Rouge Parish, LA*, USACE, New Orleans District, New Orleans, Louisiana.

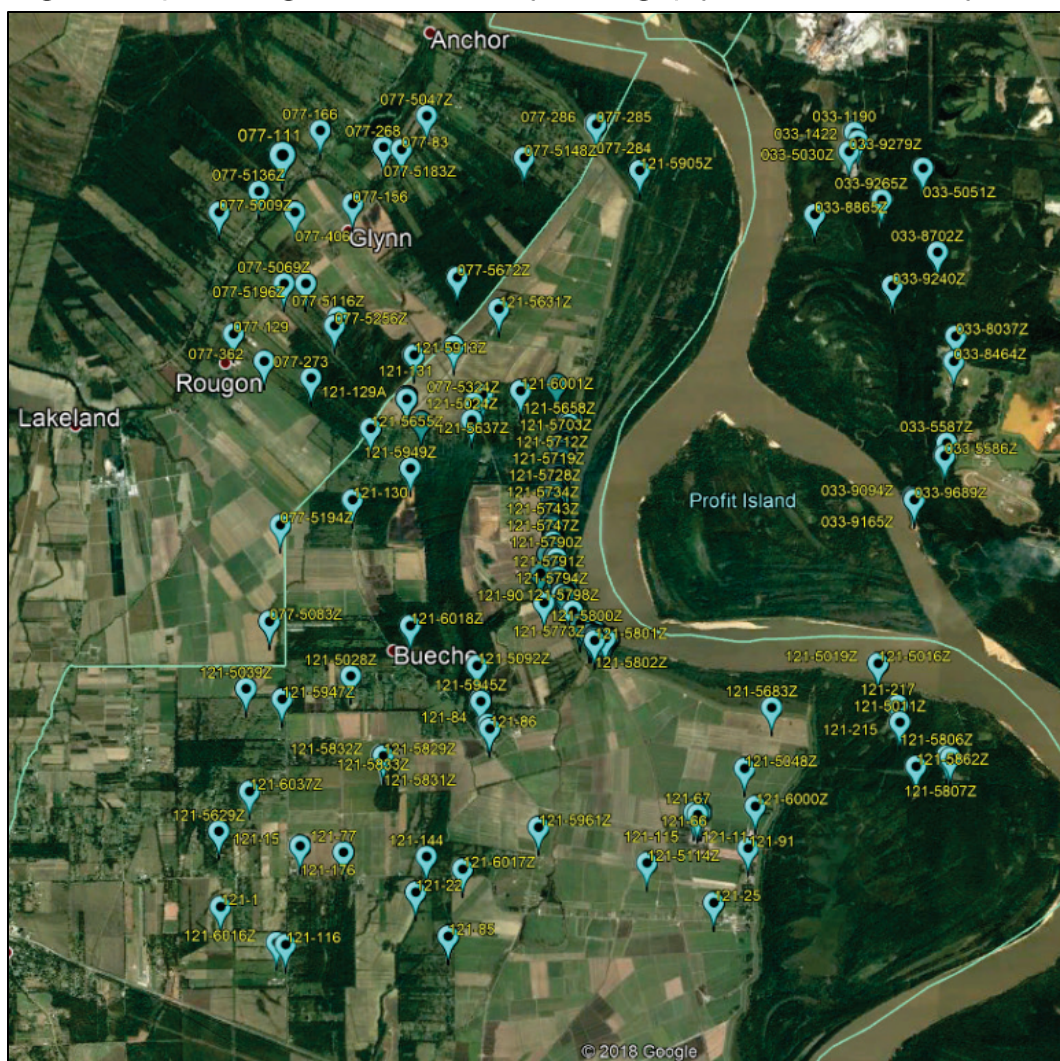
² USACE. 1994. Unpublished. *Pointe Coupee to Arborth Relief Wells Seepage Control and Concrete Slope Pavement, Location & Vicinity Maps and Index to Drawings*. USACE, New Orleans District, New Orleans, LA.

4 Hydrostratigraphy Model Development

Well log data set

A total of 192 well logs was collected from Louisiana Department of Natural Resources and US Army Corps of Engineers (USACE). The well logs include driller logs and electrical logs in East Baton Rouge Parish, West Baton Rouge Parish, and Pointe Coupee Parish. Figure 7 shows the location of the well logs. The lithological type of the well logs was classified into sand facies (aquifer or high-permeability material) and clay facies (aquitard or low-permeability material). Table A-1 in Appendix lists the 192 well logs that were used to construct a hydrostratigraphy model around the Profit Island.

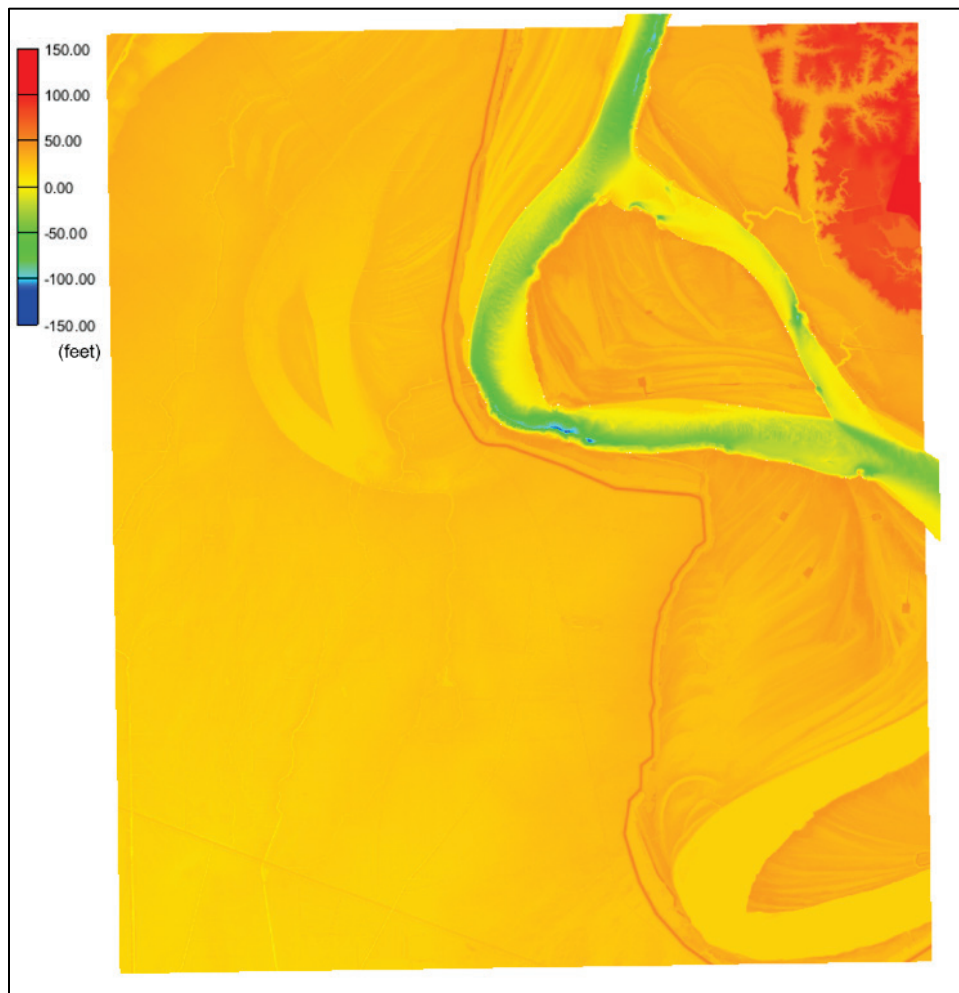
Figure 7. Map of well logs used to construct hydrostratigraphy of sand facies and clay facies.



Mississippi River bathymetry and digital elevation model (DEM)

Bathymetry for the Mississippi River around the Profit Island (River Mile [RM] 245 to 253) was accessed from USACE. The DEM around the Profit Island was downloaded from an open data distribution system, Atlas, hosting publicly available Geographic Information System datasets for the state of Louisiana maintained by the Louisiana State University, Department of Geography and Anthropology. The horizontal resolution of the bathymetry and the DEM is 6.5 ft and 16.5 ft, respectively. The horizontal coordinate reference is NAD 83 and the vertical coordinate reference is NAVD 88. The bathymetry was combined with the DEM through Esri ArcGIS to provide the topography for the hydrostratigraphy model (Figure 8). The riverbed elevation of the Mississippi River around the Profit Island varies from 0 ft to -150 ft. The top elevation of the vicinity levee is approximately 56 ft.

Figure 8. A compiled DEM for the model domain.



Grid generation for hydrostratigraphy model

The model domain included 84 relief wells, the vicinity levee of the Profit Island, and a segment of Mississippi River that connects the Mississippi River Alluvial Aquifer. The dimension of the model domain is approximately 2.9 mi by 3.2 mi (Figure 9). The domain is sufficiently large such that assigned boundary conditions do not influence the seepage flow around the relief wells. A 2D horizontal quadtree grid was developed to contain a coarse background grid with a much finer mesh around the levee reach where the 84 relief wells are located. Figure 10 shows the coarse background grid mesh with a much denser grid mesh around the relief wells. The width of the fine mesh is approximately 330 ft. The refinement was achieved by using the quadtree scheme. The size of the background grid cell is 164 ft by 164 ft. The cell size is gradually reduced to 10.25 ft by 10.25 ft for the area of interest (Figure 11).

Figure 9. A model domain in the orange square.



Figure 10. A 2D horizontal quadtree grid. X-axis is the Universal Transverse Mercator (UTM) Easting in meters. Y-axis is the UTM Northing in meters.

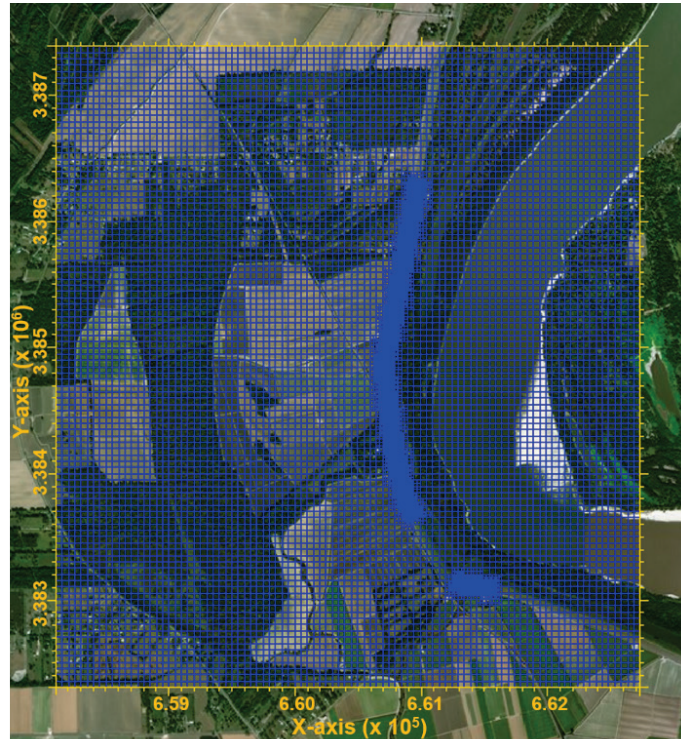
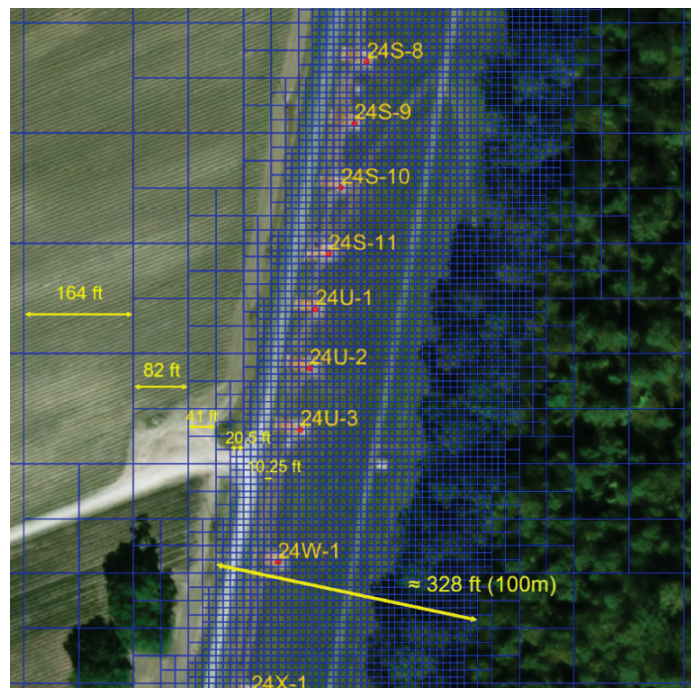


Figure 11. The quadtree grid near the levee. Cell size varies from 164 ft to 10.25 ft. Red dots are labeled by relief well names.



Hydrostratigraphy model

A hydrostratigraphy model around the Profit Island was built based on the well log data (Table A-1) and the compiled DEM (Figure 12) using an indicator kriging method to construct subsurface heterogeneity (Elshall et al. 2013). The well logs provide depth of sand facies and clay facies for the interpolation of subsurface heterogeneity. The DEM provides the topography for the hydrostratigraphy model. The vertical dimension of the hydrostratigraphy model ranges from 60 ft above NGVD 29 to 300 ft below NGVD 29. The constructed hydrostratigraphy model is shown in Figure 12. The hydrostratigraphy model reveals several interesting geological characteristics in the study area. First, the Mississippi River cuts into the foundation alluvial aquifer, creating direct contact at the riverbed (Figure 13). Second, the presence of a non-uniform clay blanket over the land suggests that surficial recharge to the alluvial aquifer is expected to be minimum in the model domain. Third, the alluvial aquifer is not uniformly distributed due to the presence of interbedded clays. Fourth, the relief wells are screened at the alluvial aquifer (Figure 14). Last, the alluvial aquifer and deeper Pleistocene sands (e.g., “400-foot” sand) coalesce in the model domain.

Figure 12. Constructed hydrostratigraphy model. The vertical dimension is exaggerated five times. Light-blue color is sand facies representing the alluvial aquifer. Dark-blue color is clay facies.

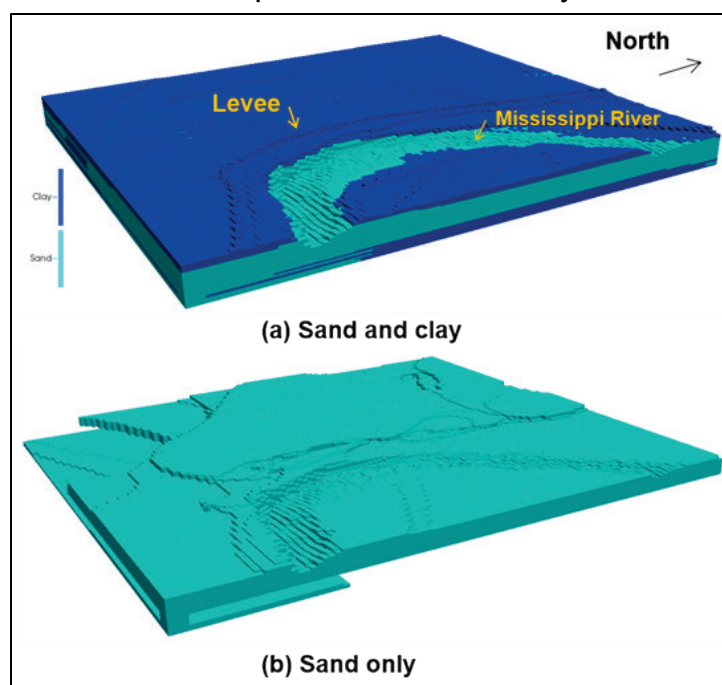


Figure 13. East-west cross section of the hydrostratigraphy model at $y=3,385,110$ ft. X-axis is the UTM Easting in meters. Z-axis is the elevation in feet.

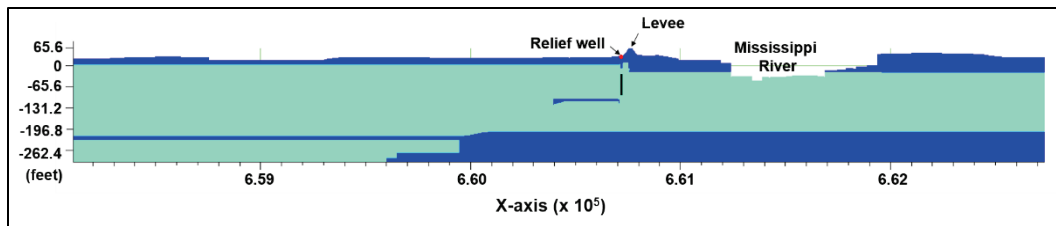
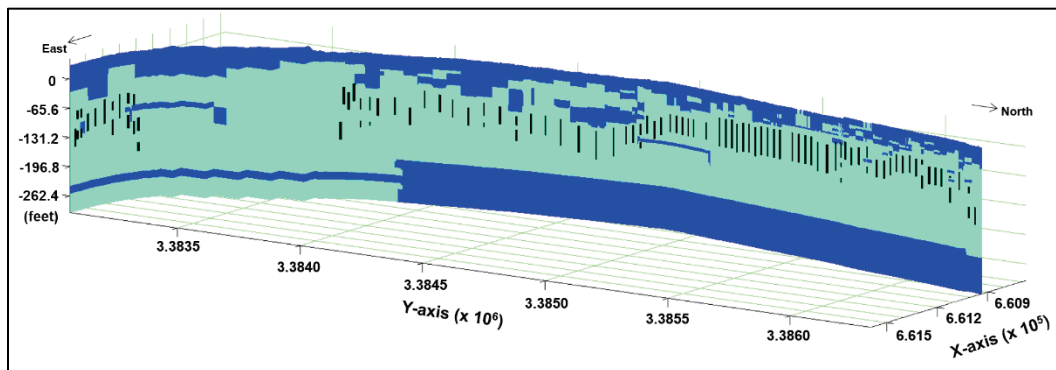


Figure 14. Screens of relief wells (black bars) in a cross section along the vicinity levee of the Profit Island. Light-blue color is sand facies. Dark-blue color is clay facies. X-axis is the UTM Easting in meters. Y-axis is the UTM Northing in meters. Z-axis is the elevation in feet.



5 Review of Relief Well Analysis

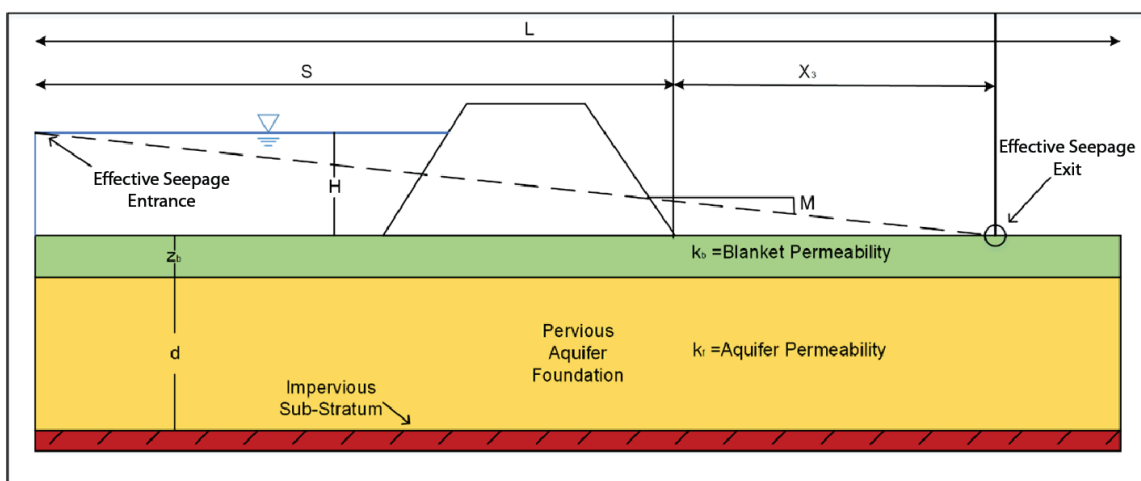
Blanket theory underseepage analysis

Levee underseepage analyses are typically performed for levees using the procedures referred to as the “Blanket Theory,” which originated with Bennet’s (1946) calculations for seepage through top-stratum blankets upstream of dams (Wolff et al. 2002). Current blanket theory calculations are detailed in EM 1110-2-1913, *Design and Construction of Levees*, (USACE 2000) and are summarized herein. There are several assumptions required before making a theoretical seepage analysis using the blanket theory:

1. Seepage may enter the pervious substratum at any point on the riverside, including through riverside borrow pits and through the riverside top stratum.
2. All flow through the top stratum is assumed vertical.
3. All flow through the pervious substratum is horizontal.
4. The levee and top stratum located directly beneath the levee is impervious.
5. All seepage flow is laminar.

A basic diagram of the variables involved in a blanket theory seepage analysis as relevant to relief well design is illustrated in Figure 15.

Figure 15. A schematic of blanket theory and variables (modified from USACE 2000).



where

S = distance from effective seepage entrance to landside levee toe (feet)

L = total length of system (feet)

X_3 = distance from landside levee toe to effective seepage exit (feet)

D = thickness of pervious layer (feet)

z_b = thickness of top stratum blanket (feet)

M = hydraulic grade line (feet/feet)

H = net head of river stage or design grade above top stratum (feet)

k_b = coefficient of permeability of blanket (feet/second)

k_f = coefficient of permeability of pervious substratum (feet/second).

The procedure required to transform a foundation seepage system to satisfy the assumptions of a single pervious substratum and a single top-stratum layer is outlined in Appendix B of EM 1110-2-1913 (USACE 2000).

Relief well system design review

A detailed review of the history of relief well system design is provided by Wolff (2002) and is briefly summarized herein with additional information provided that has become available following the reviews publication. Relief well systems were first designed according to the solutions provided by Muskat (1937) for an infinite line of equally spaced, fully penetrating relief wells. Physical experiments conducted by the USACE Waterways Experiment Station (WES), Vicksburg, Mississippi, were performed in the 1930s and 1940s to account for the effects of well spacing and penetration differences (Turnbull et al. 1949). In 1948, the solution for relief well discharge for an infinite line of fully penetrating wells was modified to account for a leaky top blanket (Barron 1948). The procedures detailed in TM 3-424 (Tyler et al. 1956), which were used during the Profit Island design process¹, were used until EM 1110-2-1914 (USACE 1992). More recently, modifications were proposed to some of the formulas presented in the manual, including for the well factors θ_a and θ_m (Guy et al. 2014).

¹ USACE. 1994. Unpublished. Pointe Coupee to Arbroth Relief Wells Seepage Control and Concrete Slope Pavement, Location & Vicinity Maps and Index to Drawings. USACE, New Orleans District, New Orleans, LA.

The general design procedure involves geological investigations, estimates of geotechnical properties such as hydraulic conductivity and anisotropy of the impervious top stratum, and cost analyses. The study area is divided into levee reaches that contain similar geological and geotechnical properties. An iterative design process changing relief well dimensions and spacing is then performed for each reach to minimize cost while maintaining pressure in the substratum below a pre-determined allowable value. The relief wells at Profit Island were designed assuming that tailwater elevation coincides with the ground surface elevation and that the top stratum extends to great distance without any seepage blockages.

The variables involved in the design and analysis of a relief well system (Figure 16) are the same as those involved in a blanket theory seepage analysis with the additional variables defined as

W = ratio of well screen length to aquifer thickness (feet/feet)

H_w = hydraulic head losses in the well system (feet)

H_{av} = net head in the plane of a well (feet)

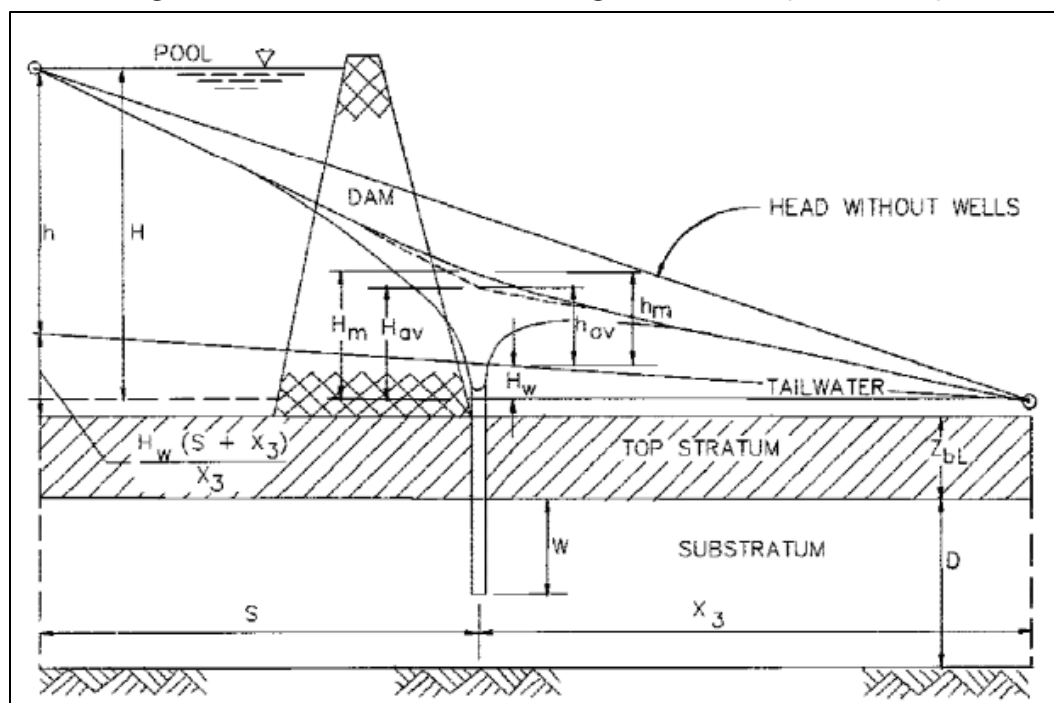
H_m = net head at the midpoint between wells (feet)

h_{av} = head in the plane of a well, without head loss (feet)

h_m = head at the midpoint between wells without head loss (feet).

where W , the well penetration, is the ratio of well screen to the aquifer thickness. In an anisotropic, stratified aquifer, W may be calculated using a transformation method through Equations 4-18 to 4-21 in EM 1110-2-1914 (USACE 1992). A non-fully penetrating well will produce lower flow rates and thus lower pressure reduction than a fully penetrating well under the same pressures (Muskat and Wyckoff 1937; Harr 1962; USACE 1992).

Figure 16 . A schematic of relief well design and variables (USACE 1992).



The relief wells at Profit Island were designed with entrance velocity, turbulence in the gravel filter, friction loss in the screen and riser, and fountain velocity head loss accounted for in the cumulative head loss-term given by Equation 1:

$$H_w = H_e + H_f + H_v \quad (1)$$

where

H_w = hydraulic head losses in the well (feet)

H_e = entrance head losses through screen and filter (feet)

H_f = frictional head losses through screen, riser, connections (feet)

H_v = velocity head loss (feet).

Once a relief well system is in place, head losses can develop from screen, filter, and sands around the wells becoming incrustated. The example calculations indicate that the wells were designed assuming that the screen was already 75% clogged¹. Indicators of incrustation include water at a pH greater than 7, total iron in excess of 2 ppm, total manganese in excess of 1

¹ USACE. 1994. Unpublished. *Pointe Coupee to Arbroth Relief Wells Seepage Control and Concrete Slope Pavement, Location & Vicinity Maps and Index to Drawings*. USACE, New Orleans District, New Orleans, LA.

ppm in conjunction with high pH water and oxygen, and total hardness in excess of 300 ppm (USACE 1992). The relief wells shown in Figure 3(c) illustrate the orange-red staining consistent with iron oxides. As the wells are partially penetrating, significant incrustation occurs at the top-most section of the well (Houben 2006). Corrosion may also occur and deteriorate well performance. The most common causes of well corrosion are low pH water, high dissolved oxygen content, presence of organic acids or iron sulfate, and the presence of hydrogen sulfide or other similar gases (Cedergren 1967). Other factors affecting head losses through the well include water temperature. A 0.6°C change in groundwater temperature may result in a change of flow rate by approximately 1.5% (Cedergren 1967).

The flow rate for a well accounting for head losses is given by

$$Q_w = a\Delta M k_f D \quad (2)$$

$$\Delta M = \frac{H - H_{av}}{S} - \frac{H_{av}}{X_3} \quad (3)$$

where

Q_w = well flow rate (cubic feet/second)

a = relief well spacing (feet)

ΔM = Hydraulic slope (feet/feet).

The main concern and reason for implementing relief well systems are reducing substratum pressure to increase the factor of safety (FoS) at the landside levee toe. The FoS is calculated by dividing the critical gradient “ $i_{critical}$ ” by the ratio “ i ” of the greater of H_{av} or H_m over the blanket thickness. The critical gradient used in the Profit Island design was 0.8. Analysis of safety factors in the 1997 flood event (Figure 17) uses 0.8 as the critical gradient to be consistent with the gradient used in design. In the years following the design process (early 1990s), Wolff et al. (2002) suggest that a critical gradient of 0.65 may be more appropriate for systems in the Lower Mississippi River, a change that significantly lowers the computed safety factors during the flood event.

$$i = \frac{H_{av}}{Z_t} \text{ or } i = \frac{H_m}{Z_t} \quad (4)$$

$$FoS = \frac{0.8}{i} \quad (5)$$

Depending on the relief well design parameters, either H_{av} or H_m will be greater. Fully penetrating wells will have a maximum head located in the midpoint between any two wells in a design reach (USACE 1992). The boring logs, cone penetration tests and previous geological investigations of the Lower Mississippi River indicate that the thickness of the pervious substratum sands along Profit Island make it impractical to install screens that are fully penetrating. Therefore, none of the 84 relief wells in the reach are fully penetrating. Accordingly, the highest pressure head occurs in the plane of the wells instead of at the midpoint between two wells. This is because the uppermost part of the screen receives more inflow than the deeper section of the screens (Houben 2006; Miranda et al. 2014). The relief well calculations for Profit Island correspondingly focus on the values in the plane of wells (i.e., θ_a and H_{avg}).

The head in the plane of a well without head loss h_{av} is calculated using θ_a and θ_m , which are the average and mid-well uplift factors, respectively. Solutions for the uplift factors were first approximated by Bennet and Barron (1957), then refined by Barron¹. In EM 1110-2-1914 (USACE 1992), the procedure for determining the uplift factors calls for utilizing a nomograph based on the work of Bennet and Barron (1957).

Re-arranging the equations presented in EM 1110-2-1914 (USACE 1992) in terms of a partially penetrating relief well that has a maximum substratum pressure in the plane of relief wells, a method to compare inter-year performance of relief wells using only observed well flow rates and observed river stage is presented in Equations 6–8:

$$Q_w = a\Delta M k_f D \quad (6)$$

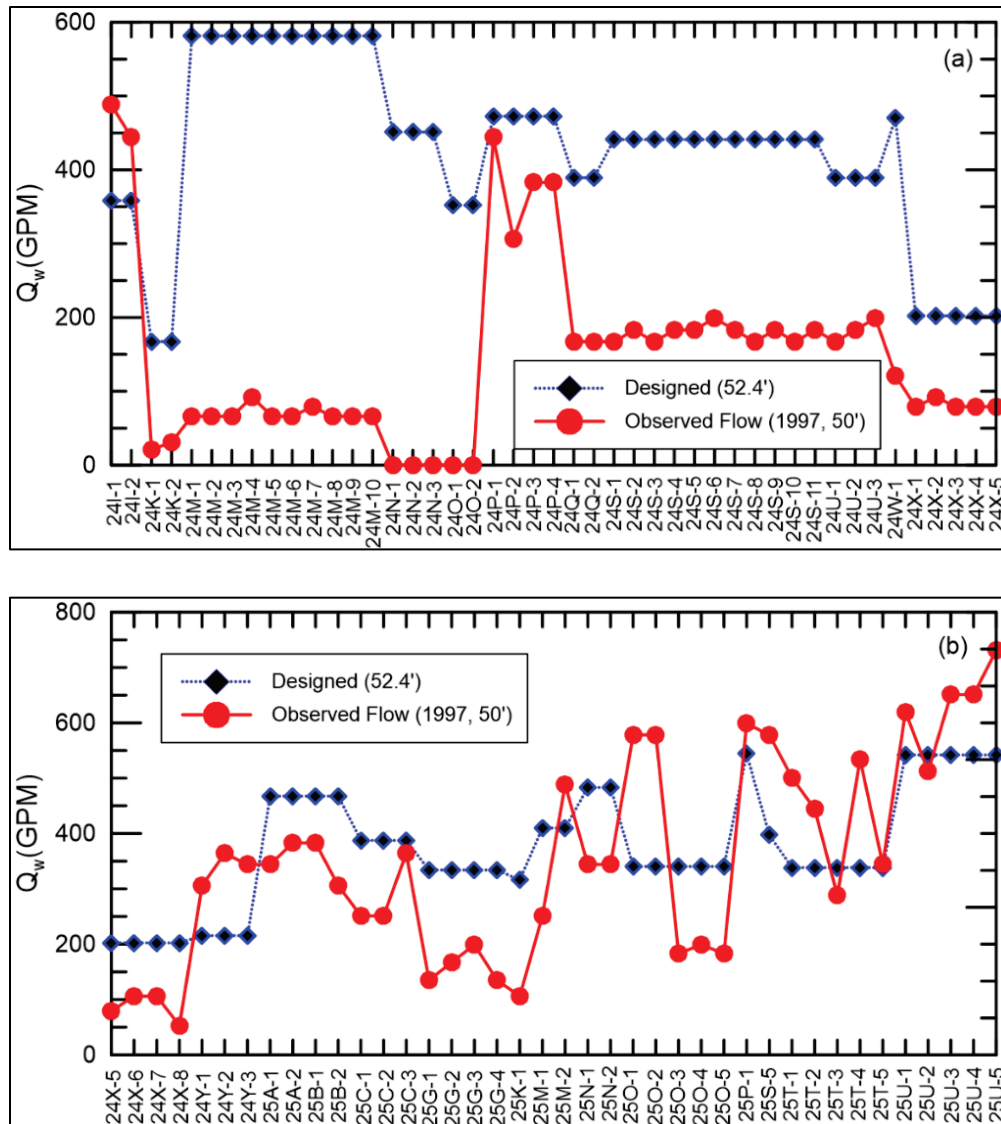
$$\Delta M = \frac{H - H_{av}}{S} - \frac{H_{av}}{X_3} \quad (7)$$

$$H_{av} = \frac{HX_3 - \frac{X_3 SQ_w}{ak_f D}}{S + X_3} \quad (8)$$

¹ Barron, R. 1982. *Mathematical Theory of Partially Penetrating Relief Wells*. Unpublished report prepared for the US Army Engineer Waterways Experiment Station.

In an actual system, the head losses for the well system do not remain constant with time (i.e., screens becoming progressively more clogged), which affect the observed flow rates. While difficult to measure, these head losses are represented analytically in the H_{av} term. As Equation 8 illustrates, H_{av} may be determined using the river stage and observed flowrates, negating the need to measure or determine individual head loss factors to determine safety factors for the study reach. The re-arranged equations require the design blanket theory parameters from the original seepage analysis. Consequently, it is possible to study the FoS provided by a system of relief wells even if the blanket theory parameters change (i.e., the landside effective seepage exit changing due to borrow pits or other developments).

Figure 17. Design vs. observed flow rates for relief wells (a) 24I-1 to 24X-5 and (b) 24X-5 to 25U-5.



In Figure 17a, the designed flow rates for the northern section of the reach were significantly higher than the observed flow rates in 1997. Wells 24N-1 through 24O-2 were not observed flowing. The 24X-5 to 25U-5 wells in the southern section of Profit Island were observed to be flowing more consistently to the design predictions (Figure 17b). Using the transformed equations presented above, the average net head in the plane of the wells was calculated and is shown in Figure 18.

Figure 18. Comparison between design and observed H_{av} for wells (a) 24I-1 to 24X-5 and (b) 24X-5 to 25U-5.

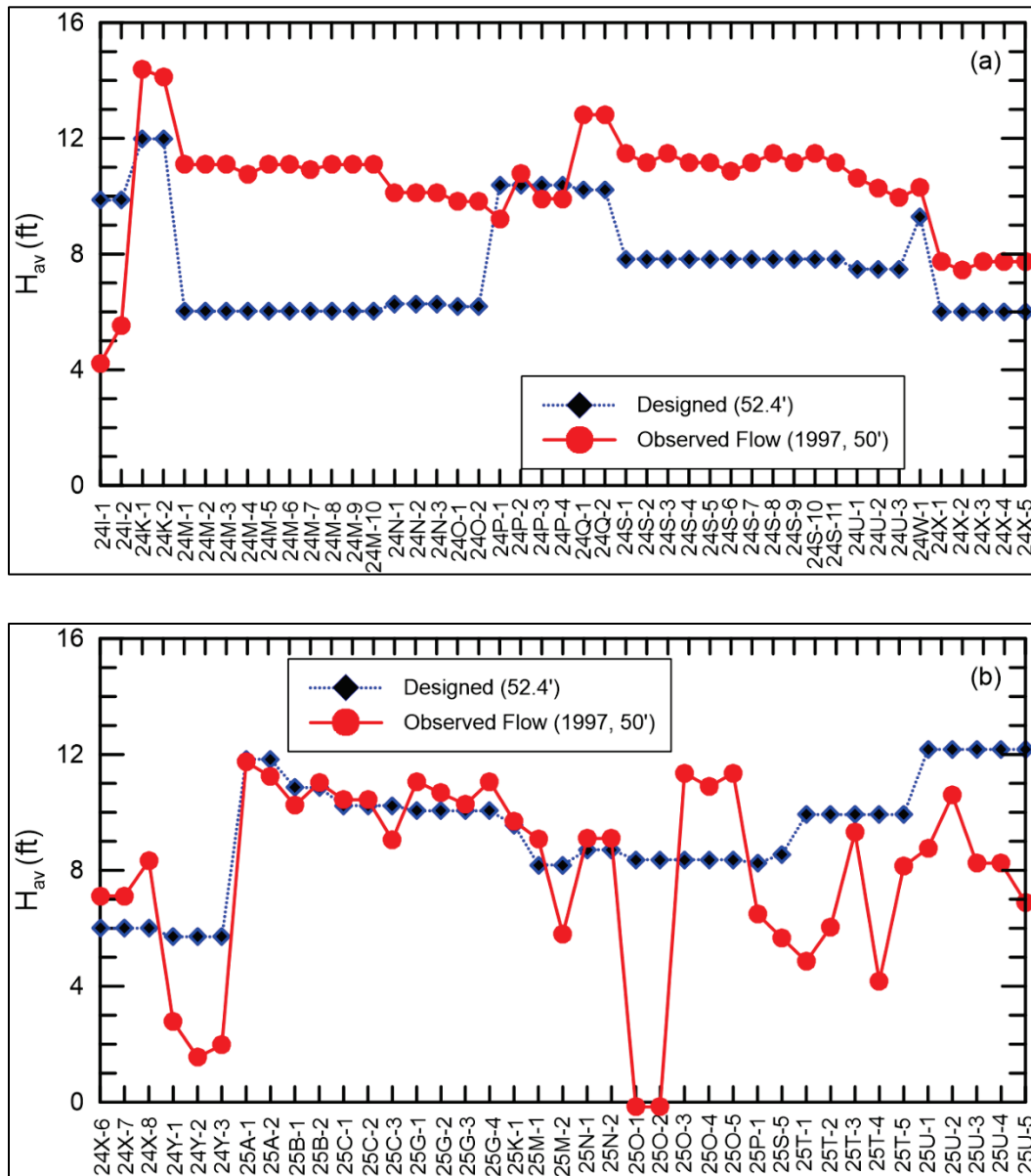
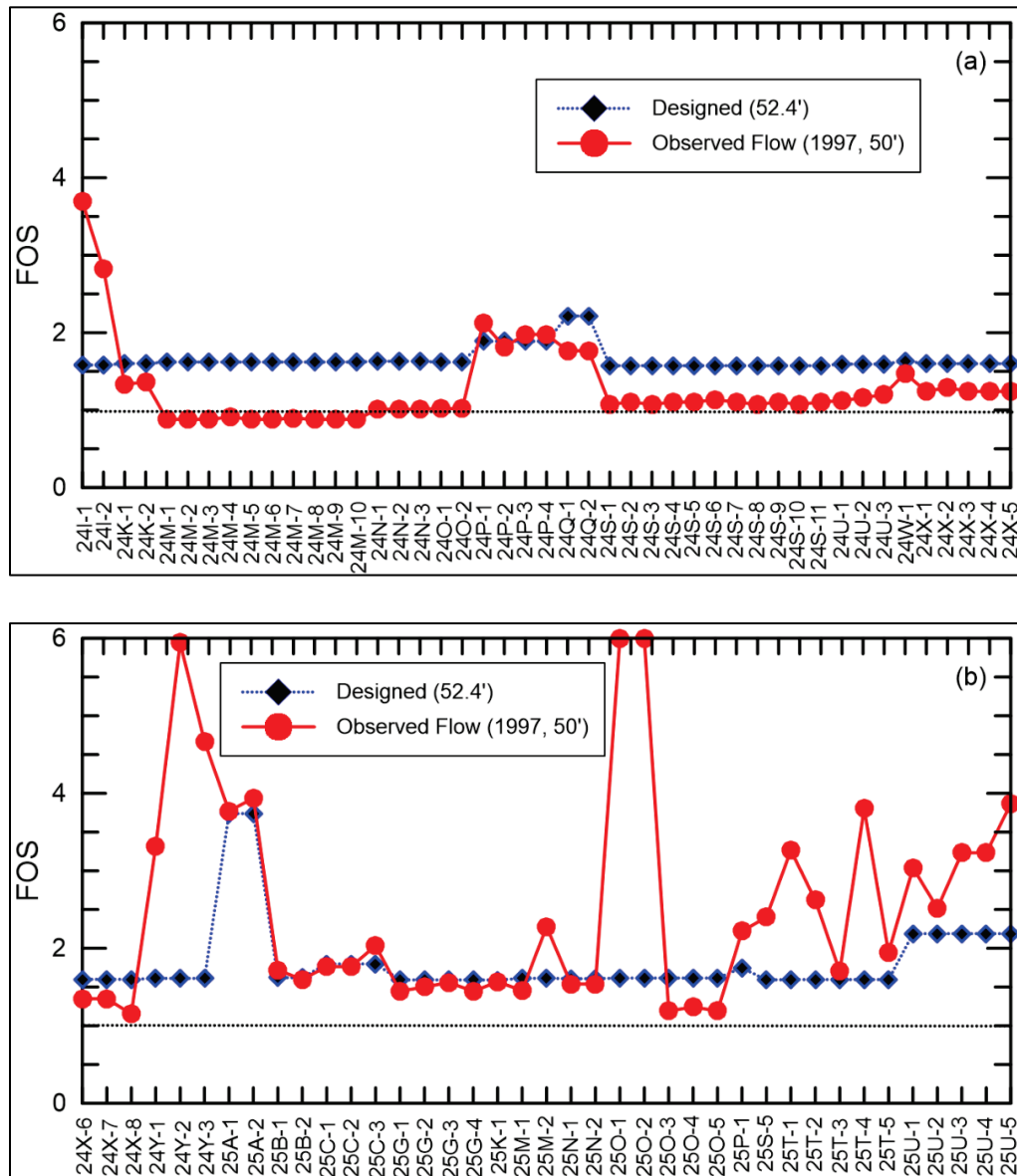


Figure 18 shows the effect that a reduction in flow rates from design has on the net head beneath the top stratum. For the wells in reach 24M, the observed flow rate was significantly lower than design, and accordingly the net head beneath the top stratum is approximately twice as designed. While most wells underperformed, some wells in the southern section outperformed the design rates. Wells 25O-1 and 25O-2 outperformed design to the extent that the average net head was below 0 ft, indicating that the pressure head was below tailwater surface. Using the blanket thickness from the design report, the hydraulic gradient for each well and the corresponding factors of safety were calculated and are shown in Figure 19.

Figure 19. FoS as designed vs. observed for wells (a) 24I-1 to 24X-5 and (b) 24X-6 to 25U-5.

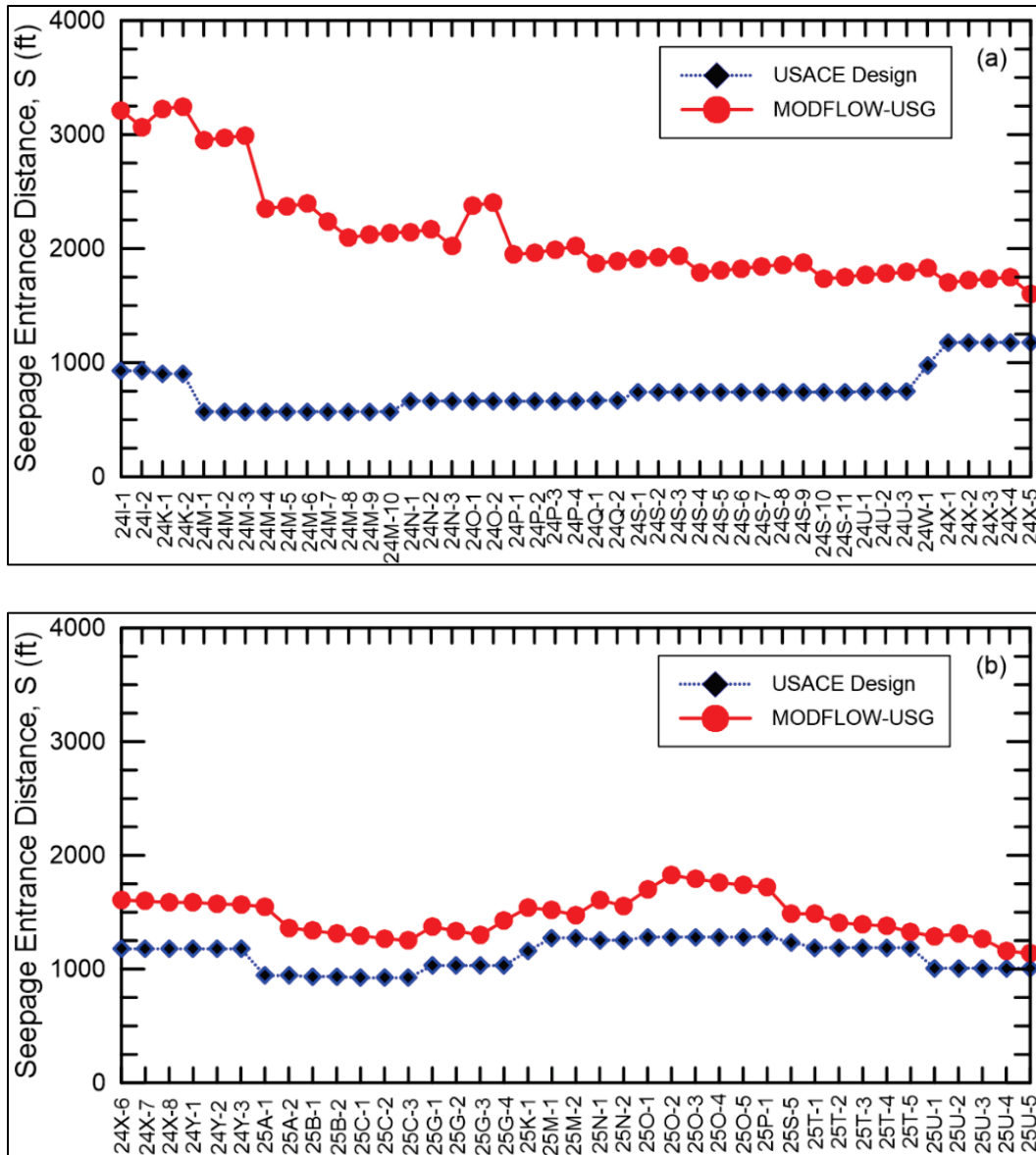


The calculated FoS for the wells in reach 24M are below 1.0, corresponding to the magnitude difference in observed flow rates below design. For the wells overperforming design in the southern section, the FoS of 25O-1 and 25O-2 were greater than 5 and hence were clipped for visibility in Figure 19b.

In the re-arranged equation to calculate the average net head in the plane of wells, the variable S (distance from the seepage source to the relief well location) is subject to variability because it depends on who is designing the system. S is typically estimated using aerial maps (USACE 1992) or piezometer values (Tyler et al. 1956). It has been previously observed for the method using piezometers that an error of 0.05 ft in the reading of the piezometers could result in significant error in the calculation of entrance and exit distances (Wolff et al. 2002). Investigation of the Alton-to-Gale levee system performed in 1976 found that the seepage entrance and exit were usually far shorter than those used in design (USACE 1976). The difference between the seepage entrance distance employed in the MODFLOW-USG model and the effective seepage entrance distance in the USACE design is shown in Figure 20.

One potential source for the large difference between the USACE design and MODFLOW is that the USACE design accounts for riverside depressions or borrow pits while MODFLOW-USG estimates S based on the distance from the river to the relief well. As shown in Figure 20a, the effective seepage entrance distances are far lower in the USACE design than employed in the MODFLOW-USG model for the wells in the northern portion of Profit Island. These wells also feature significantly lower observed flow rates and FoS. A larger effective seepage entrance distance will cause the hydraulic slope ΔM for the equations in the USACE (1992) manual to become more shallow, creating lower hydraulic head beneath the top stratum at the relief well location and thus a lower flow rate as compared to a shorter effective seepage entrance distance such as assumed during the design process.

Figure 20. Effective seepage entrance distance from the 1992 USACE design and seepage entrance distance from the MODFLOW-USG model for wells (a) 24I-1 to 24X-5 and (b) wells 24X-6 to 25U-5.



Three-dimensional (3D) seepage modeling

Finite element methods

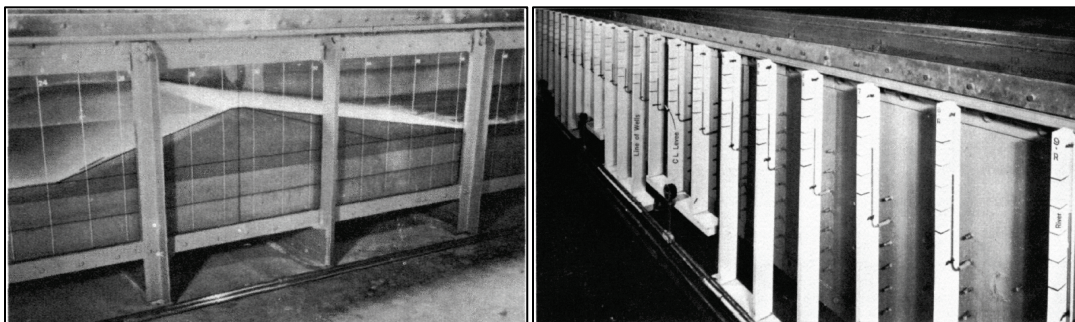
While 2D finite element methods have been applied to relief well design, they are primarily applied to standard 2D underseepage analyses for levees, slopes, dams, and retaining walls. SEEP\W features a plan-view analysis method, which is primarily intended to be used for general well spacing analyses (GeoStudio 2018). Previous 2D finite element models using commercial software for relief wells indicate the necessity of pre-specifying

a pressure head or flow condition. Moreover, 3D finite element models constructed to simulate relief well systems are not available in commercially available software packages typically used in geotechnical design (Cheng 2015; Cheng et al. 2016). Previously developed computer codes for the iterative design process include LEVSEEP (Brizendine et al. 1995; Gabr et al. 1996) and LEVEEMSU (Gabr et al. 1995).

Physical model

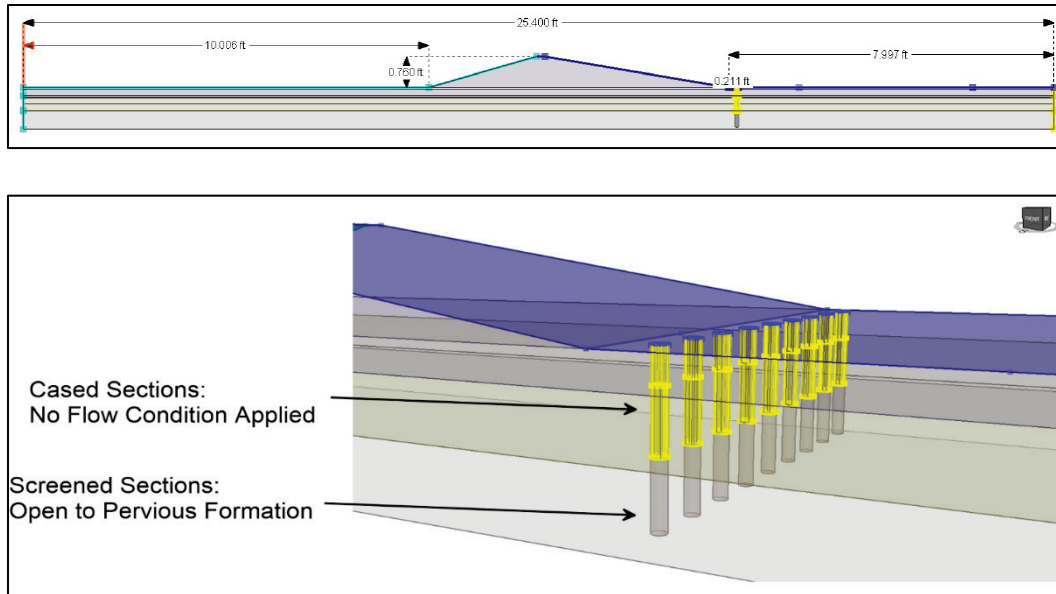
In an attempt to develop a 3D finite element method to model relief wells using commercially available software, a USACE WES physical model was used as verification alongside the RocScience program RS³ (Rocscience 2017). The physical models were used in the late 1930s to early 1940s to conduct extensive laboratory experiments on the effects of borrow pits and relief wells on underseepage and substratum pressures for typical Mississippi River levee cross-sections (Figure 21).

Figure 21. USACE physical relief well models (photos from Turbull et al. 1949).



The model setup and results analogous to the Wolf River and Nonconnah Creek levees of the Memphis Flood Control Project were recreated in the finite element program Rs³ (Rocscience 2017). Two scenarios were modeled: (1) no relief wells and a 100 ft wide borrow pit at the far landside of the model and (2) a line of relief wells that fully penetrated the pervious formation. The model dimensions and boundary conditions for the relief well scenario are shown in Figure 22.

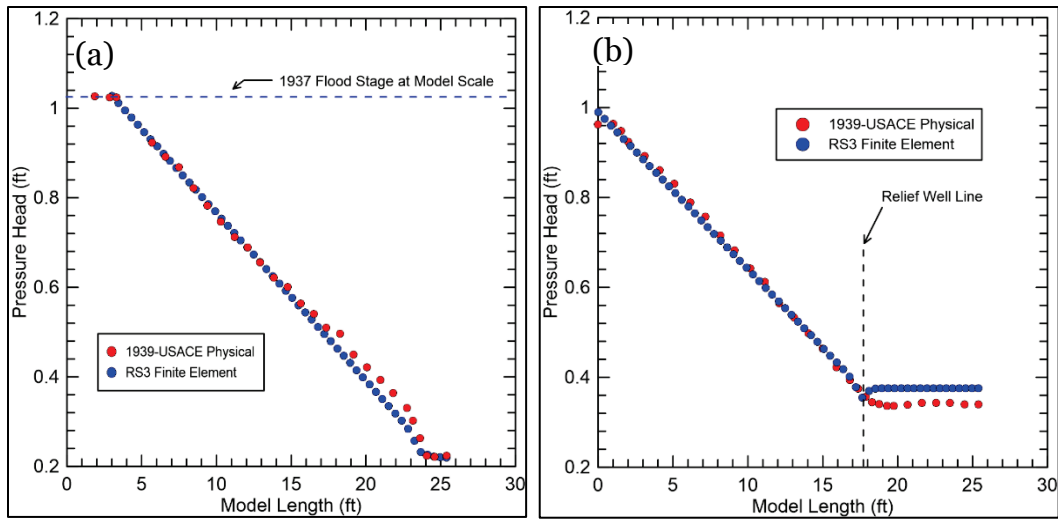
Figure 22. RS³ recreation of 1939 USACE experiment model dimensions and boundary conditions.



A steady-state river stage was applied on riverside of the model. The bottom and side-boundaries were no-flow conditions, and the landside topstratum was modeled as a potential seepage face. The landside vertical boundary was modeled as no-flow, as the physical model contained an impermeable bulkhead. The relief wells were modeled using cylinders placed into the model. The screened sections were open to the pervious formation while the cased sections were modeled with no flow conditions.

The pressure head values for the two scenarios generated by RS³ and the physical model results from 1939 are shown in Figure 23. The borrow pit scenario (Figure 23a) shows a close match between experimental and modeled results. The relief well scenario shows a close match up to the line of relief wells, with a divergence landside of the relief well line. Interestingly, the finite element model illustrates the pressure cone of depression generated by relief wells while the physical model does not. Following the close match of pressure values between the physical and finite element models, the technique was attempted on a full scale well from Profit Island. The technique did not scale, and pressure contours were indistinguishable between the model run without relief wells and with. Further research is needed to refine a technique to easily implement a 3D finite element model of relief well systems. This will be helpful to analyze certain levee reaches without the need of developing a global groundwater analysis.

Figure 23. (a) Pressure head contours for borrow pit scenario and (b) relief well scenario.

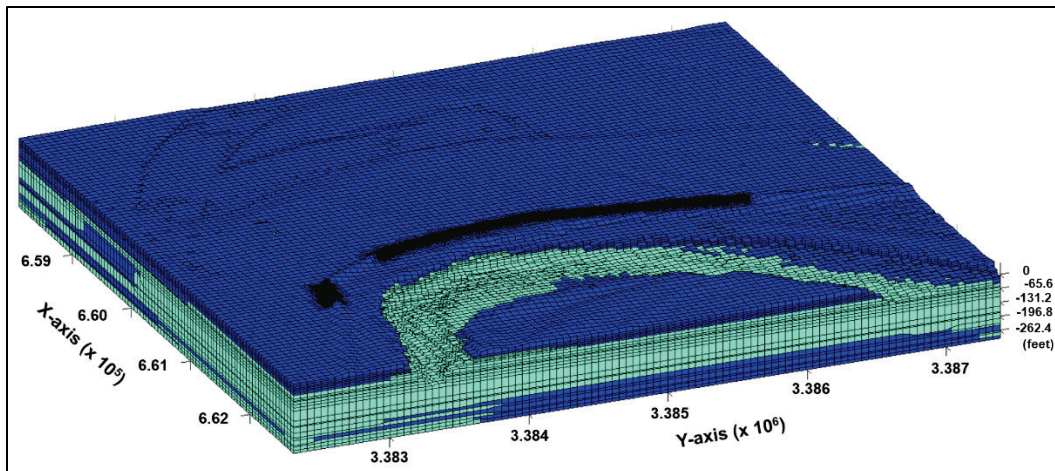


6 PIVL Seepage Model Development

MODFLOW-USG modeling

A Profit Island vicinity levee (PIVL) seepage model (Chen et al. 2021) was created using MODFLOW-USG (Panday et al. 2017). MODFLOW-USG is a modular hydrologic model developed by the USGS in 2013 to support a wide variety of structured and unstructured grid types for simulating groundwater conditions and interaction with surface water. The grid structure of the 3D MODFLOW-USG model was developed based on the hydrostratigraphy model (Figure 12). A grid generation technique was developed to upscale the detailed hydrostratigraphy model into a 24-layer, 1,204,888-cells MODFLOW-USG model. Each layer has the same planar structure as shown in Figure 10. The top elevation, bottom elevation, and soil type for individual cells in each layer are derived from the hydrostratigraphy model. Each cell represents one soil type only, either sand or clay. In Figure 24, dark-blue color represents blankets and clay deposits, and light-blue color represents the Mississippi River Alluvial Aquifer. Groundwater Modeling System (Aquaveo™), a graphical user interface, was used to facilitate input file preparation for building a MODFLOW-USG model.

Figure 24. A computational grid for the 3D MODFLOW-USG model. Light-blue color is sand. Dark-blue color is clay.

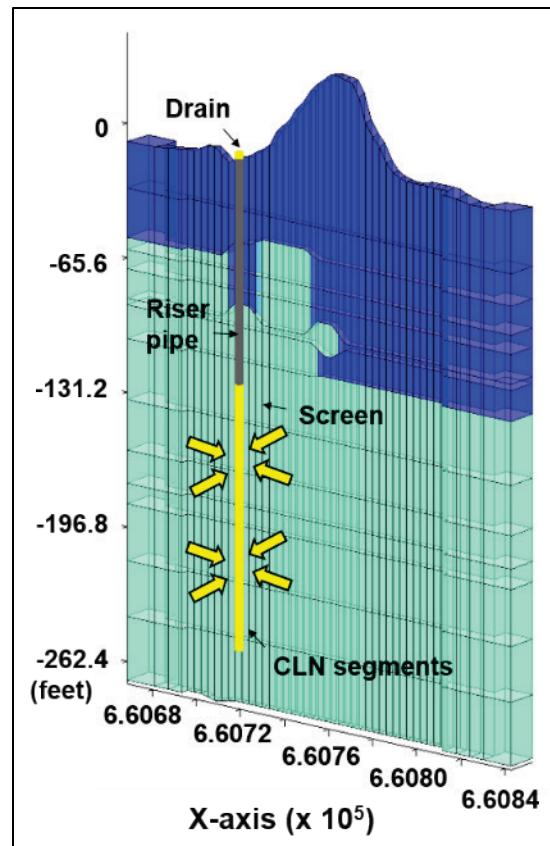


Relief well simulation

A combination of a Connected Linear Network (CLN) Package with a Drain (DRN) Package was developed to simulate a relief well in the MODFLOW-USG model (Figure 25). The CLN is designed to simulate hydraulic head and flow in the screen and in the riser pipe. The DRN Package is designed to remove discharge immediately once flow is produced at the top of the riser pipe. The screen information and top elevation of the rise pipes are shown in Table A-2 in Appendix.

Two primary conduit parameters control flows in the CLN. The conduit conductivity factor (CONDUITK) determines the conductivity of a riser pipe. The conduit conductivity factor of 10^6 is estimated by assuming laminar flow in the conduit (Panday et al. 2017). The skin factor (FSKIN) determines the leakance (conductivity per unit width) of a screen between an aquifer and a riser pipe. High FSKIN value indicates clogging. Low FSKIN value indicates a relief well in a good condition.

Figure 25. A 3D diagram of a relief well in the MODFLOW-USG model. Light-blue color is sand. Dark-blue color is clay. Yellow column is the screen.



Initial condition and boundary conditions

A General-Head Boundary (GHB) Package was developed to assign river stage to computational cells that are in contact with the Mississippi River and to the eastern boundary (Figure 26). The GHB was used to simulate interactions between the Mississippi River and the Mississippi River Alluvial Aquifer. The GHB requires riverbed conductance to represent influence of riverbed materials. The riverbed conductance is derived from Darcy's law:

$$Q = kiA = k \frac{(\Delta H)}{L} A = \Delta H \times A \frac{k}{L} = (\Delta H) \times C \quad (9)$$

where

- Q = flow rate (cubic feet/second)
- K = hydraulic conductivity of riverbed material (feet/second)
- I = hydraulic gradient (feet/feet)
- A = cross-sectional area of flow (square feet)
- ΔH = head loss (feet)
- L = length of flow (feet)
- C = riverbed conductance (square feet/second)
- k/L = riverbed leakance (1/second).

The Mississippi River stage assigned to the GHB Package was linearly interpolated with the river stages measured by gage stations at Baton Rouge and St. Francisville. The linear interpolation is shown in the following:

$$RM250 = RM228.4 + D \times Distance\ Ratio \quad (10)$$

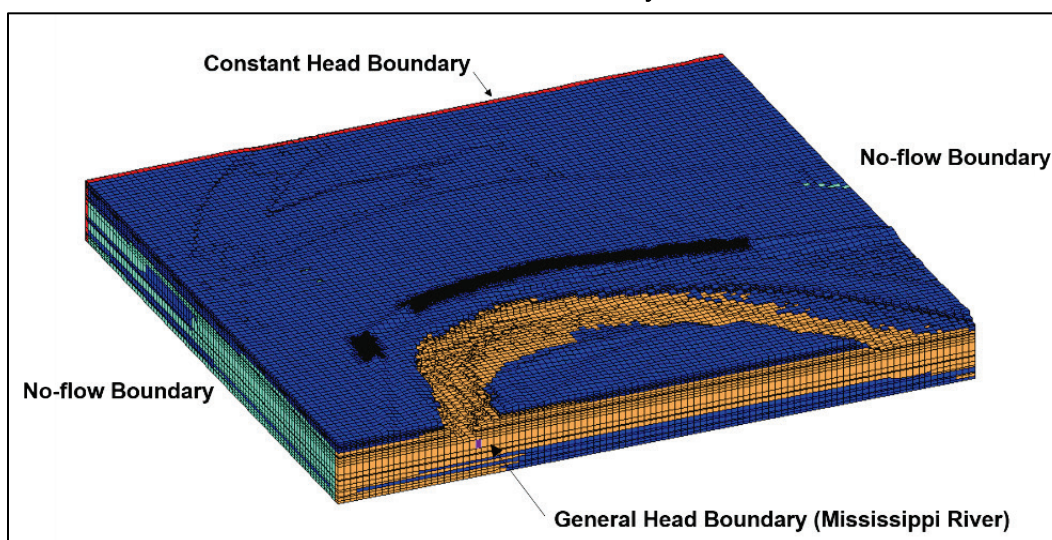
where

- $RM250$ = river stage at RM 250 for the Profit Island
- $RM228.4$ = river stage at RM 228.4 for Baton Rouge - 0.37 ft;
0.37 ft is for the datum correction
- $RM260.3$ = river stage at RM 260.3 for St. Francisville
- D = difference of river stage between Baton Rouge
and St. Francisville
- $Distance\ Ratio = (250-228.4) / (260.3-228.4) = 0.6771$.

The constant head of 20 ft above NGVD 29 was assigned to the western boundary, which was based on the historic groundwater level data. The no-flow boundary condition was assigned to the northern and southern boundaries.

The initial condition for the rest of computational cells were assigned 20 ft above NGVD 29.

Figure 26. Boundary conditions for the MODFLOW-USG model. Light-blue color is sand. Dark-blue color is clay.



Model calibration using 1997 flood event

The MODFLOW-USG model was calibrated with piezometric head data and relief well discharge data during the flood event from March to May 1997 (Figure 27), provided by the USACE. The river stages at RM 250 for the Profit Island in March–May 1997 were also obtained from the interpolation of the river stages at Baton Rouge station and St. Francisville station. The highest river stage during the 1997 event was 50 ft. A sensitivity analysis was developed to quantify the influence of model parameters (aquifer hydraulic conductivity, riverbed leakance, specific yield, and specific storage) on the root-mean-square error (RMSE) for piezometric head and relief well discharge. The RMSE of relief well discharge (Figure 28) and piezometric head (Figure 29) are significantly decreased when aquifer hydraulic conductivity is approximately 0.1 cm/s and riverbed leakance is approximately 1 day⁻¹. The RMSE in relief well discharge is gradually decreased as specific storage approaches 10⁻⁴ m⁻¹ (Figure 30). Specific yield does not influence the modeling results (Figure 31).

Based on the sensitivity of analysis for the input parameters, the model calibration was achieved by mainly tuning river conductance, aquifer hydraulic conductivity, and the FSKIN of relief well screens to minimize prediction errors in piezometric head and relief well discharge. The estimated model parameter values are shown in Table 2. The hydraulic conductivity of the Mississippi River Alluvial Aquifer for the MODFLOW-USG model is assumed homogenous and isotropic. The estimated hydraulic conductivity is approximately 0.14 cm/s, which is within the range of the aquifer hydraulic conductivity reported in the 1990 report (USACE 1990). The clay blanket and clay deposits are assumed low hydraulic conductivity of 10^{-5} cm/s. The estimated riverbed leakance and east boundary leakance are 0.1 day^{-1} and 0.15 day^{-1} , respectively. Then, river conductance was calculated by multiplying river leakance with cross-sectional area (Equation 9). The estimated specific storage and specific yield are close to the values referred by Batu (1998) and Chin (2006). The estimated skin factor of relief well screen for individual wells is shown in Table 3. For the purpose of model calibration, outliers in the measurements were removed while calculating the RMSE. The calibration results show a small RMSE of 18.03 GPM in relief well discharge rate (Figure 32b) and a small RMSE of 0.72 ft in piezometric head (Figure 33b). Figure 32a and Figure 33a show comparisons with all measurements.

Figure 27. Mississippi River stage (feet) near the Profit Island from 3/1/1997 to 5/31/1997. Black dots are 41 days that relief well discharge rate and piezometric head were measured.

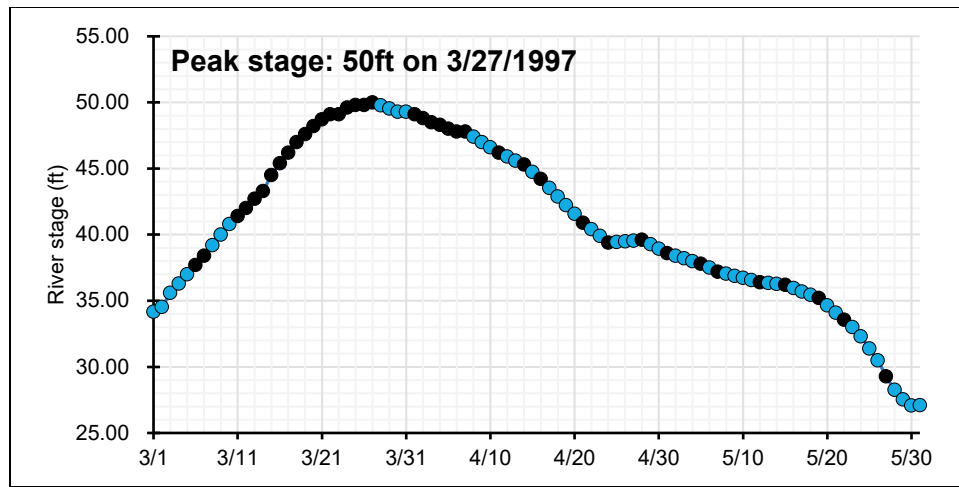


Figure 28. Sensitivity analysis of RMSE in relief well discharge with respect to aquifer hydraulic conductivity and riverbed leakance.

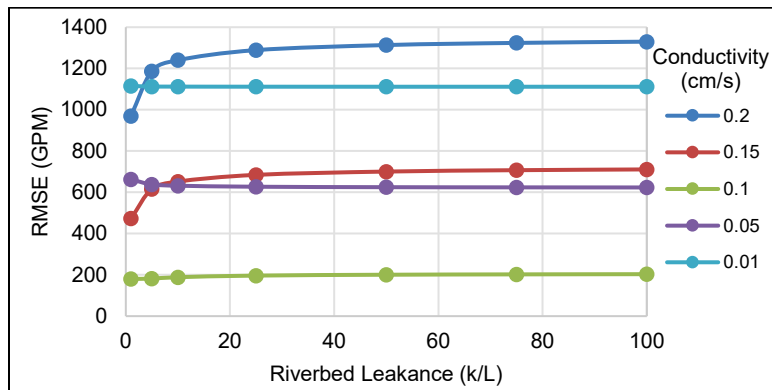


Figure 29. Sensitivity analysis of the RMSE in piezometric head with respect to aquifer hydraulic conductivity and riverbed leakance.

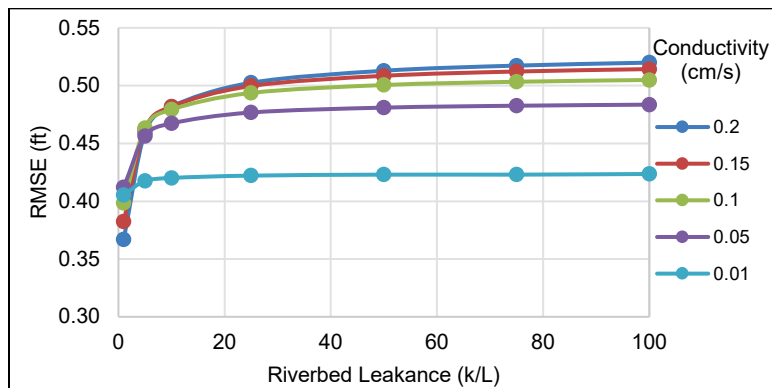


Figure 30. Sensitivity analysis of RMSE in relief well discharge and piezometric head with respect with specific storage.

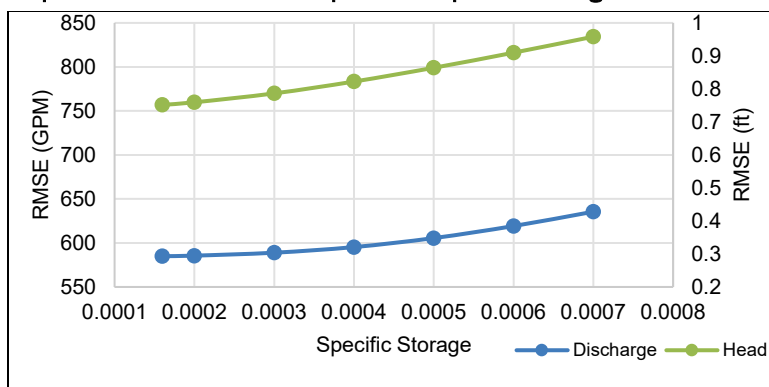


Figure 31. Sensitivity analysis of the RMSE in relief well discharge and piezometric head with respect to specific yield.

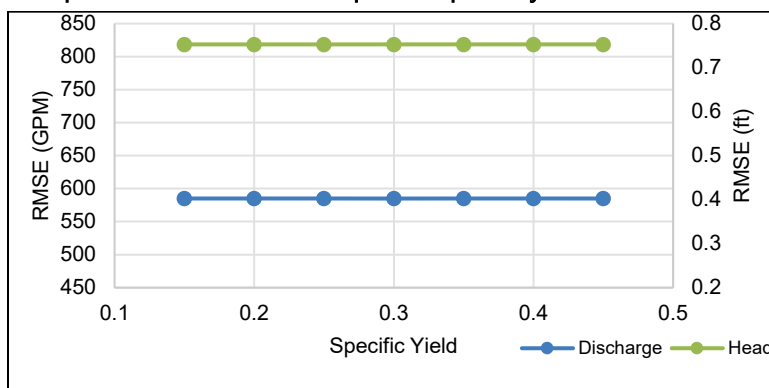


Table 2. Estimated parameters for aquifer and aquitard.

	Hydraulic Conductivity (cm/s)	Specific Yield	Specific Storage (1/m)
Mississippi River Alluvial Aquifer	0.1389	0.3	0.000166
Blanket and clay deposits	0.00001	0.03	0.001919

Table 3. Estimated parameters used in the CLN Package for relief wells.

Relief Well	FSKIN of Screen	Relief Well	FSKIN of Screen	Relief Well	FSKIN of Screen
24I-1	1.2	24S-4	7	25C-2	4
24I-2	2.8	24S-5	7	25C-3	1.4
24K-1	0.01	24S-6	7	25G-1	2.5
24K-2	0.01	24S-7	7	25G-2	2.7
24M-1	5	24S-8	7	25G-3	2
24M-2	5	24S-9	8	25G-4	3.5
24M-3	4	24S-10	9.5	25K-1	4.5
24M-4	3	24S-11	8	25M-1	5.5
24M-5	3.7	24U-1	8	25M-2	1.5
24M-6	3.1	24U-2	9	25N-1	4
24M-7	2.8	24U-3	8.5	25N-2	3.8
24M-8	3.5	24W-1	7	25O-1	1.2
24M-9	3.5	24X-1	9	25O-2	1.3
24M-10	3.5	24X-2	8	25O-3	10
24N-1	0.01	24X-3	8	25O-4	10.5
24N-2	0.01	24X-4	8.5	25O-5	10.5
24N-3	0.01	24X-5	9	25P-1	0.9
24O-1	0.01	24X-6	6	25S-5	2.4
24O-2	0.01	24X-7	5	25T-1	3
24P-1	4.5	24X-8	11	25T-2	4.5
24P-2	6	24Y-1	3.2	25T-3	8
24P-3	4.1	24Y-2	1.6	25T-4	2.7
24P-4	4.2	24Y-3	1.8	25T-5	7
24Q-1	8.5	25A-1	1.3	25U-1	2.3
24Q-2	8.5	25A-2	1.5	25U-2	3.3
24S-1	8.5	25B-1	2	25U-3	2.8
24S-2	7.8	25B-2	4.7	25U-4	2.7
24S-3	7.3	25C-1	4	25U-5	1.6

Figure 32. (a) A scatter plot of simulated vs. all measured relief well discharge rates (gallons/minute) at all relief wells during the March–May 1997 event and (b) a scatter plot excluding outliers.

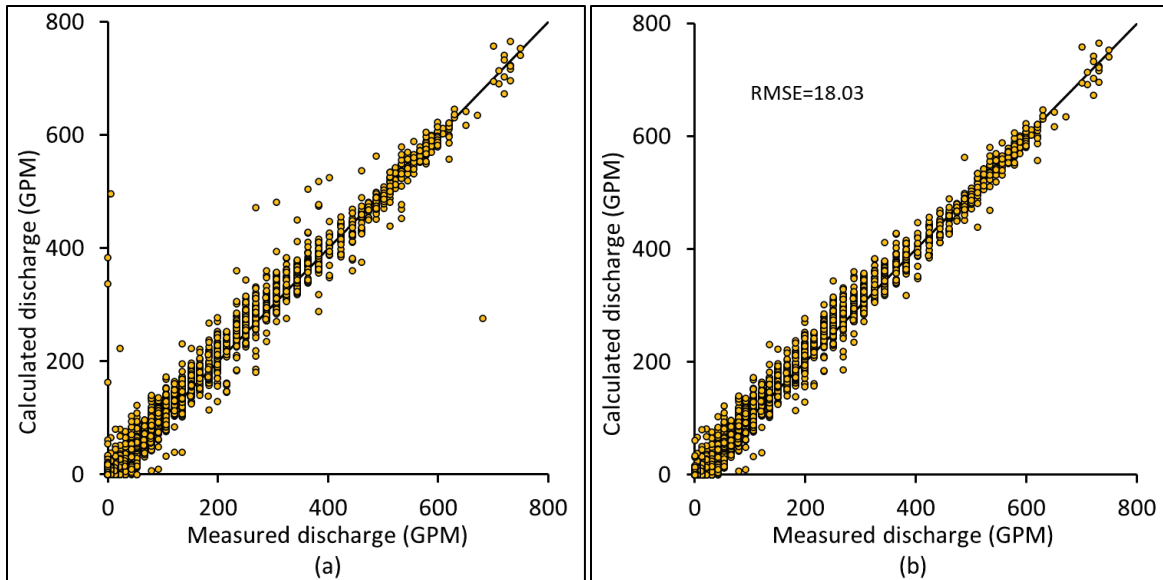
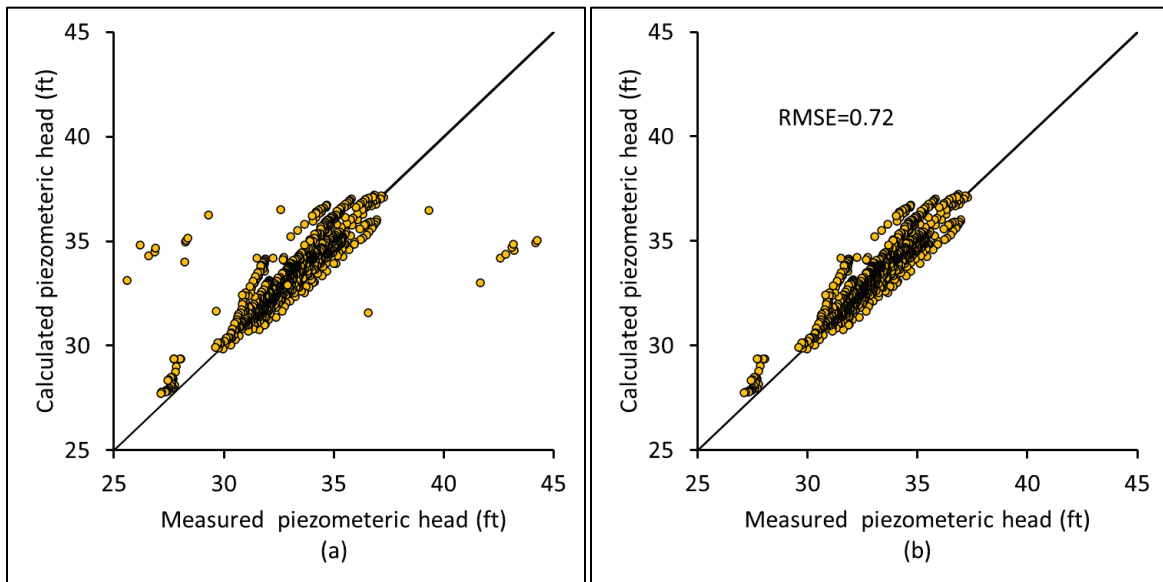


Figure 33. (a) A scatter plot of simulated vs. all measured piezometric heads (feet) at all piezometers during the March–May 1997 event and (b) a scatter plot excluding outliers.



Summary

The MODFLOW-USG model calibrated with measured data in 1997 has acceptable prediction errors in piezometric head and relief well discharge rate. The calibrated parameters for the MODFLOW-USG model are in the range of values in the 1990 Pointe Coupee to Arbroth-Alfords Relief well design study. However, the calibrated MODFLOW-USG model reflects the condition of relief wells in 1997. The present-day condition of the relief wells is unknown, and the capacity may be reduced because of clogging. New measured data are needed for re-validating or re-calibrating the MODFLOW-USG model such that the model produces dependable seepage forecast for the levee for future high river-stage events.

7 Practical Implications

Assumptions

The Profit Island vicinity levee (PIVL) seepage model is assumed to represent the hydrogeological architecture and the conditions of relief well in 1997 (see Chapter 6). Therefore, the PIVL model was adopted to simulate levee underseepage and to predict piezometric head, FoS, and discharge rates of relief wells for desired scenarios.

Hydrography

The scenarios include the extreme flood, design flood, 1997 flood, 2008 flood, 2017 flood, and 2018 flood. For the extreme flood and design flood, the river stages are 56 ft and 52.4 ft above NAVD 88. For the rest of the flood events, the river stages around Profit Island were obtained by interpolating the river stages at Baton Rouge station and St. Francisville station. The results are shown in Figure 34 to Figure 39 for the aforementioned scenarios.

Figure 34. River stage (feet) for the extreme flood, 56 ft.

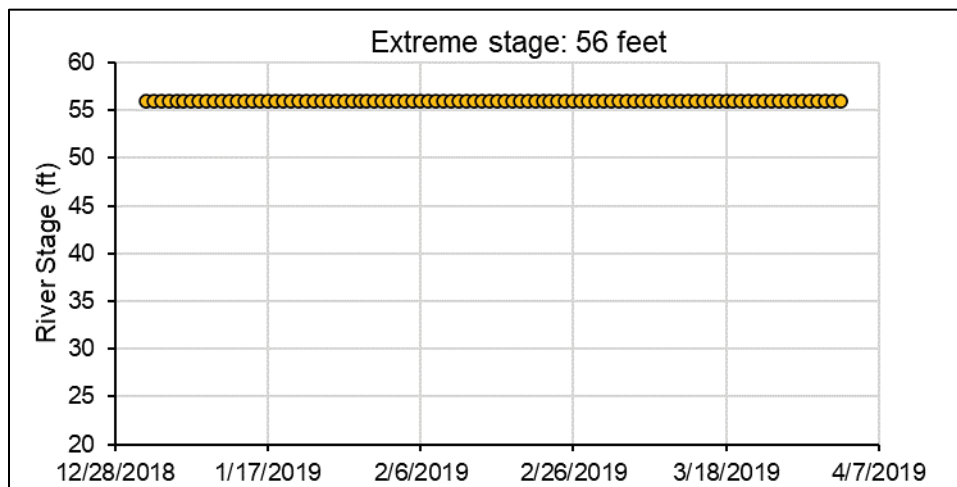


Figure 35. River stage (feet) for the design flood, 52.4 ft.

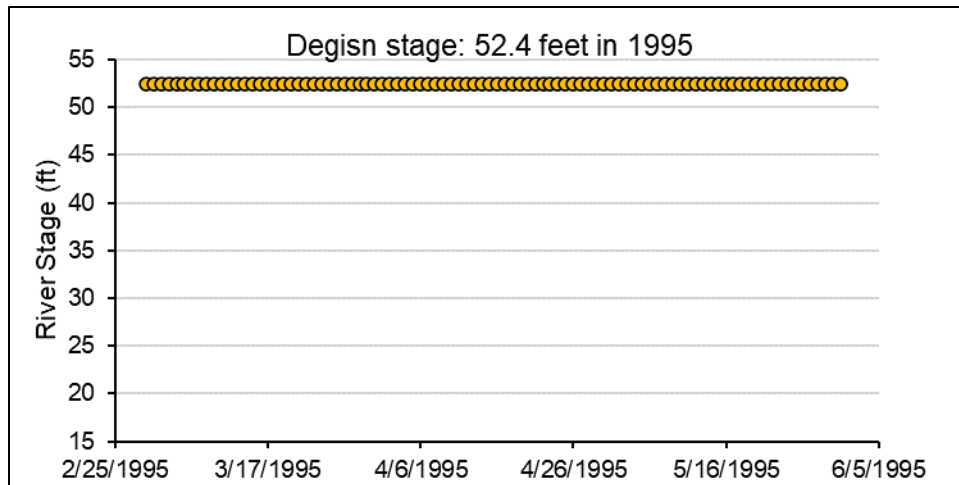


Figure 36. River stage (feet) for the 1997 flood (3/1/97-5/31/97).

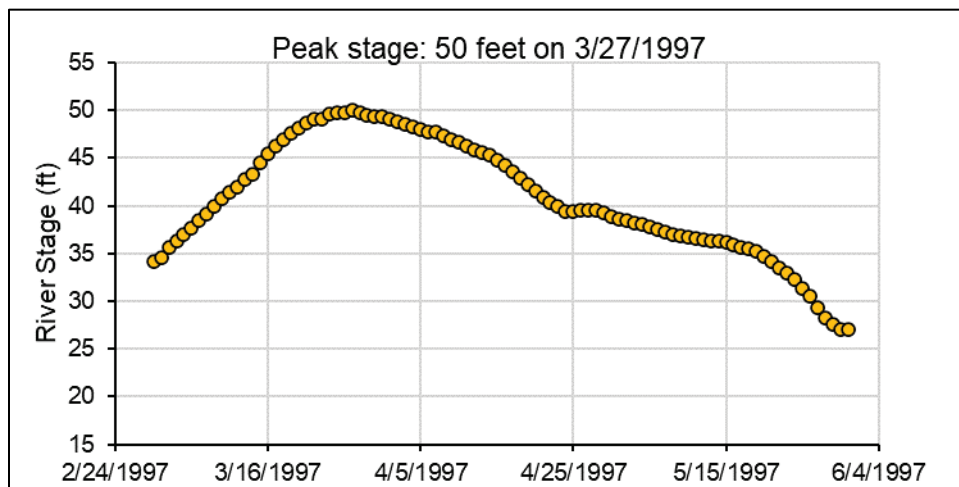


Figure 37. River stage (feet) for the 2008 flood (3/30/08-6/29/08).

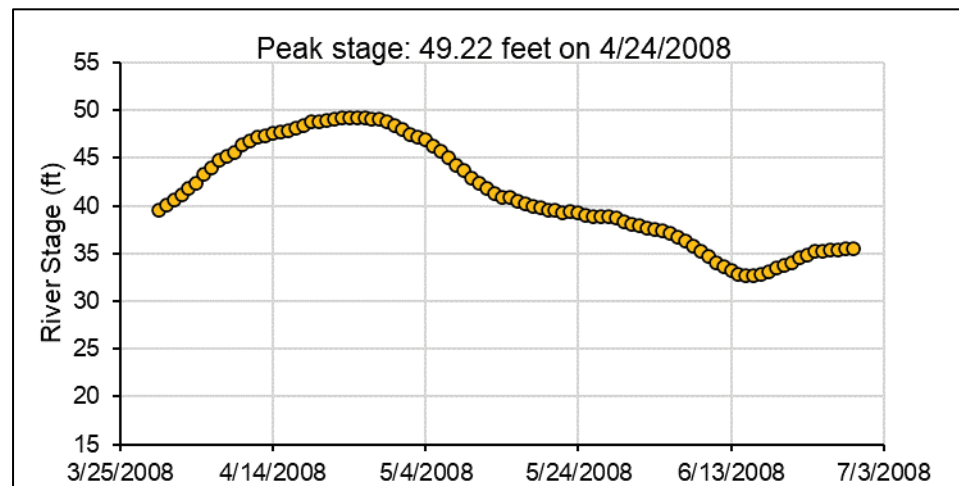


Figure 38. River stage (feet) for the 2017 flood (4/6/17-7/6/17).

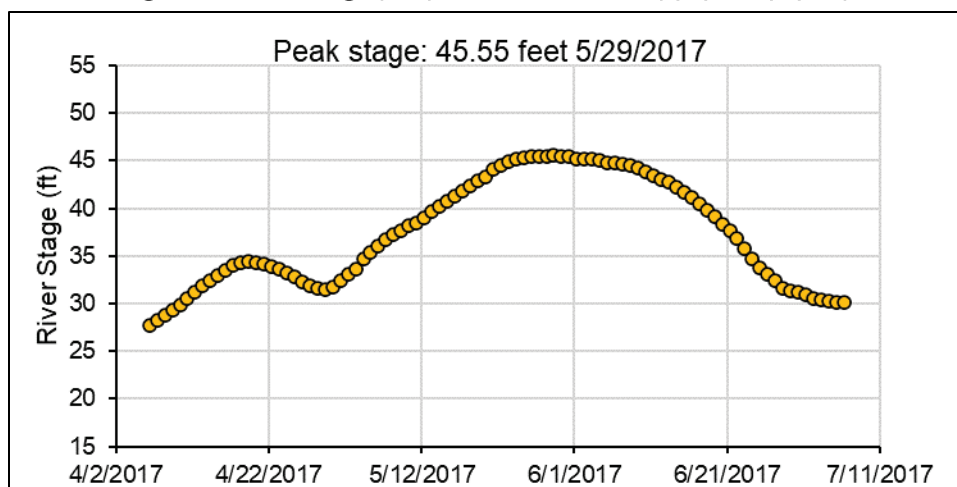
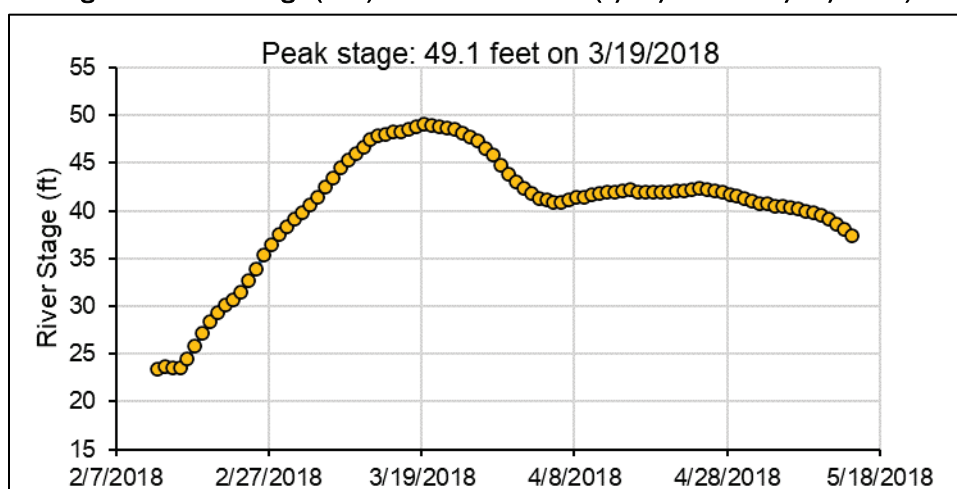


Figure 39. River stage (feet) for the 2018 flood (2/12/2018 to 5/14/2018).



Piezometric head of 27 piezometers

Piezometric head of 27 piezometers at the peak river stage was predicted for the scenarios of the extreme flood, design flood, 1997 flood, 2008 flood, 2017 flood, and 2018 flood (blue lines in Figure 40 to Figure 45). There are two characteristics of piezometric head shown in the prediction results. First, the piezometers towards the south (i.e., Reaches 25Q, 25S, and 25T) indicate higher piezometric head. Second, significant piezometric head decrease (approximately 13 to 15 ft) from peak river stage to the piezometers was documented in the USACE observation data, which indicates limited hydraulic connection between the river and the alluvial aquifer. Nevertheless, piezometric head comparisons for the scenarios run with relief wells and without relief wells are shown in Figure 40 to Figure 45 (see orange lines). For design flood scenario without relief wells, the

piezometric head increases approximately 6 to 9 ft at the piezometers, which indicates that the relief wells operate efficiently to release pore-water pressure underneath the levee. The piezometric head at the south is also higher than the piezometric head at other reaches, showing that more underseepage is occurring at the southern reaches of the levee site.

Figure 40. Piezometric head comparisons with relief wells and without relief wells at extreme flood peak (56 ft).

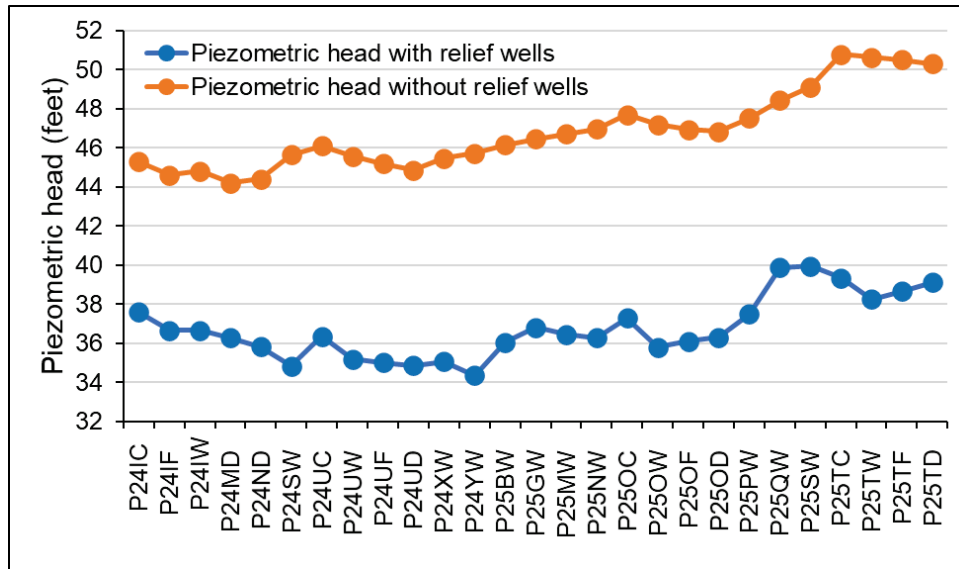


Figure 41. Piezometric head comparisons with relief wells and without relief wells at design flood peak (52.4 ft).

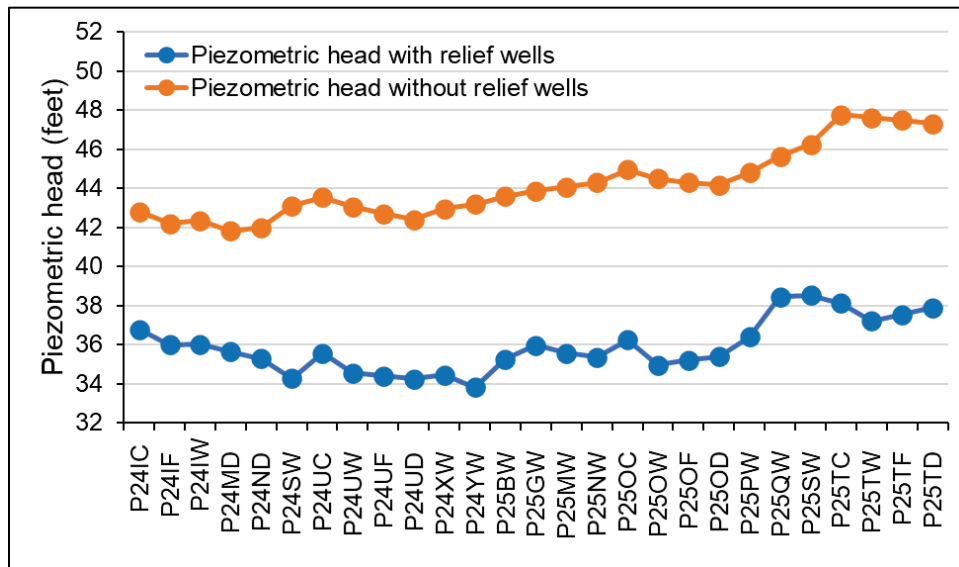


Figure 42. Piezometric head comparisons with relief wells and without relief wells at 1997 flood peak (50 ft).

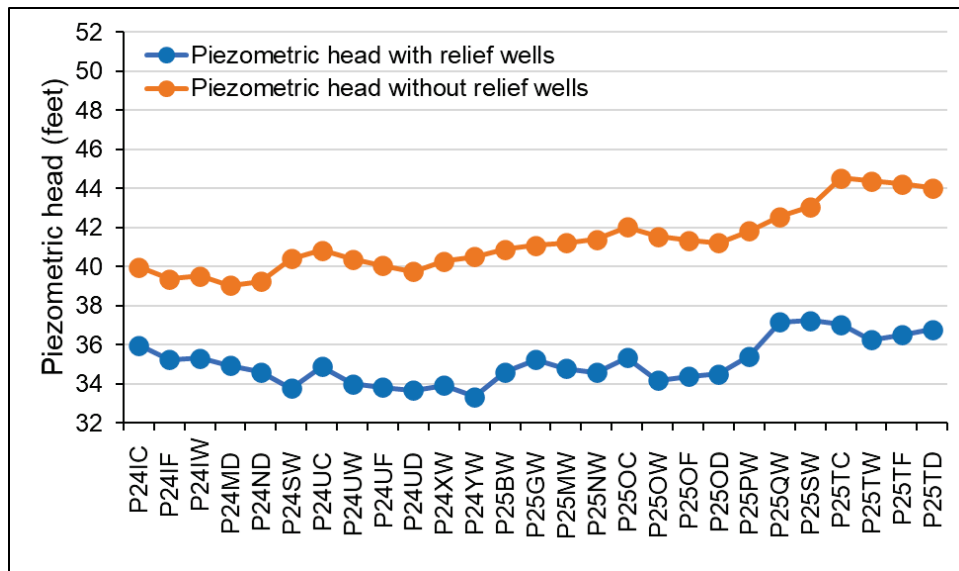


Figure 43. Piezometric head comparisons with relief wells and without relief wells at 2008 flood peak (49.22 ft).

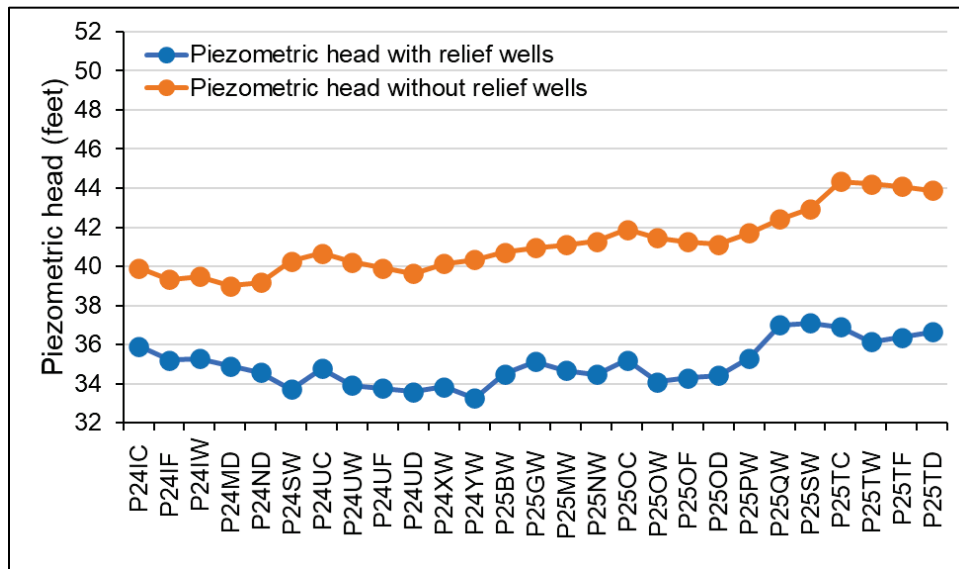


Figure 44. Piezometric head comparisons with relief wells and without relief wells at 2017 flood peak (45.55 ft).

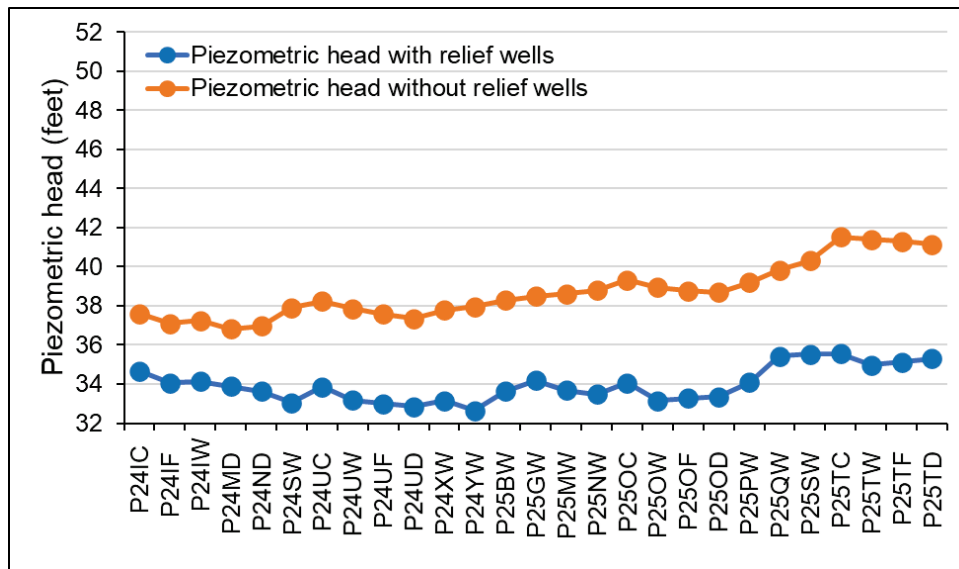
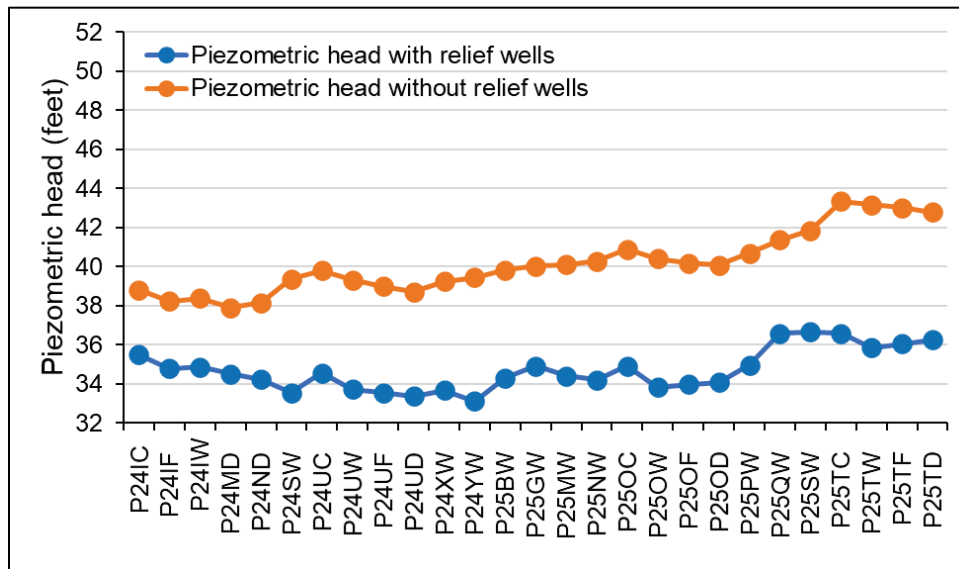


Figure 45. Piezometric head comparisons with relief wells and without relief wells at 2018 flood peak (49.1 ft).



Piezometric head at levee toe

Piezometric heads at the levee toe were compared using the blanket theory in the USACE Pointe Coupee to Albroth (USACE 1990) design report and the 3D MODFLOW-USG model. Six scenarios were compared. The first scenario is a comparison of piezometric heads at each location calculated for an extreme river stage (56 ft) with relief wells. The second scenario includes relief wells at the design river stage (52.4 ft), using the design flow rates as given in the Pointe Coupee to Albroth (USACE 1990) study. The third and fourth scenarios use the observed well flow rates in the blanket theory and simulated flow rates from MODFLOW for the peak 1997 river stage (50 ft) and the peak 2008 river stage (49.22 ft). The fifth and sixth comparisons use the simulated flow rates from the MODFLOW-USG model for the 2008, 2017, and 2018 flood peak to calculate piezometric heads.

Figure 46 illustrates the same calculations performed with the estimated relief well flow rates at the extreme flood stage of 56 ft. The 2D and 3D calculations in Reaches 24K, 24X, 25N, and 25U tend to converge towards similar piezometric head values. From reaches 24M to 24W, the blanket theory overall predicts a higher piezometric head than the MODFLOW solution. The difference of piezometric head is approximately 5 to 10 ft.

Figure 47 displays the same comparison with piezometric heads calculated by the design flow rates. At the design flood stage (52.4 ft), the comparison shows a different trend to the extreme flood. Blanket theory predicts higher piezometric heads in most reaches than the MODFLOW solution, except Reaches 24I, 24X, 24Y, 25M, 25N, and 25O.

Figure 48 and Figure 49 display the same comparisons with piezometric heads calculated for the peak stage of 1997 (50 ft) and 2008 (49.22 ft) using USACE-provided field observed well-flow rates in the blanket theory and simulated flow rates from MODFLOW. The piezometric heads show a similar trend as in Figure 46. Reaches 24M to 24W again show higher piezometric head values calculated using the blanket theory.

Figure 50 and Figure 51 shows piezometric heads for the 2017 (45.55 ft) and 2018 flood crest (49.1 ft) using simulated well flow data, which shows similar trends as in the extreme flood.

Figure 46. Piezometric head comparisons calculated by MODFLOW and blanket theory at extreme flood peak for wells (a) 24I-1 to 24X-2, and (b) wells 24X-3 to 25U-5.

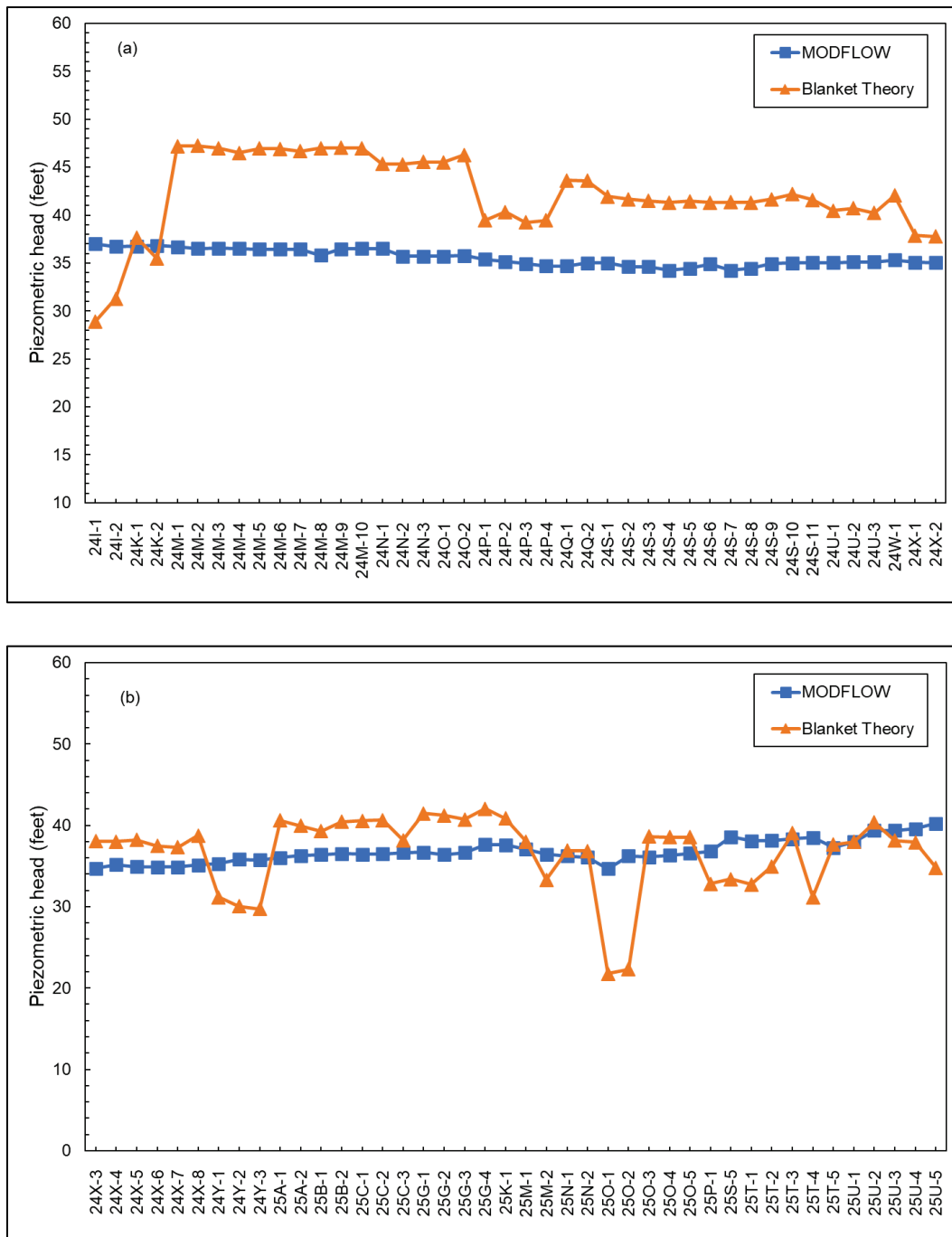


Figure 47. Piezometric head comparisons calculated by MODFLOW and blanket theory at design flood peak for wells (a) 24I-1 to 24X-2, and (b) wells 24X-3 to 25U-5.

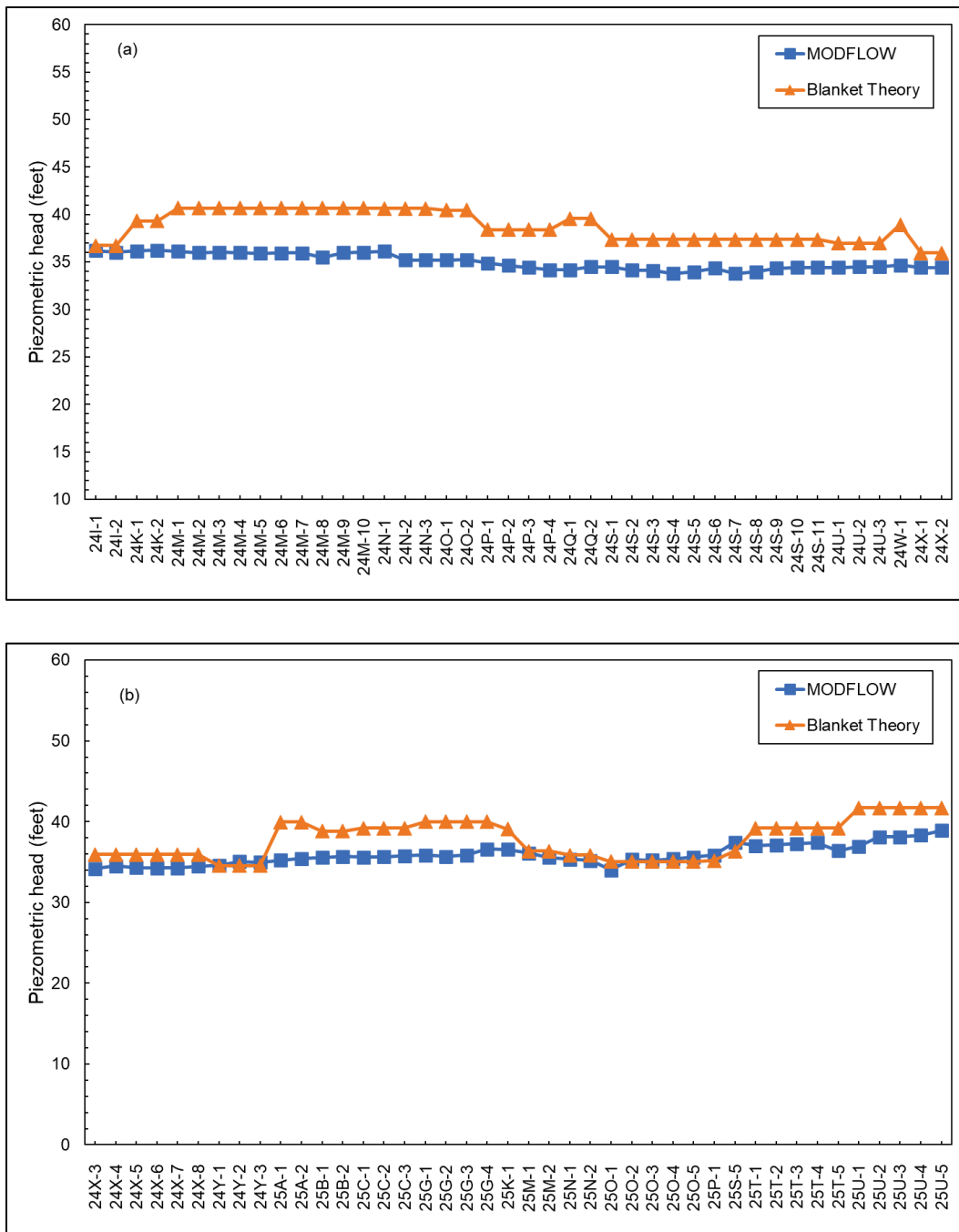


Figure 48. Piezometric head comparisons calculated by MODFLOW and blanket theory at 1997 flood peak for wells (a) 24I-1 to 24X-2, and (b) wells 24X-3 to 25U-5.

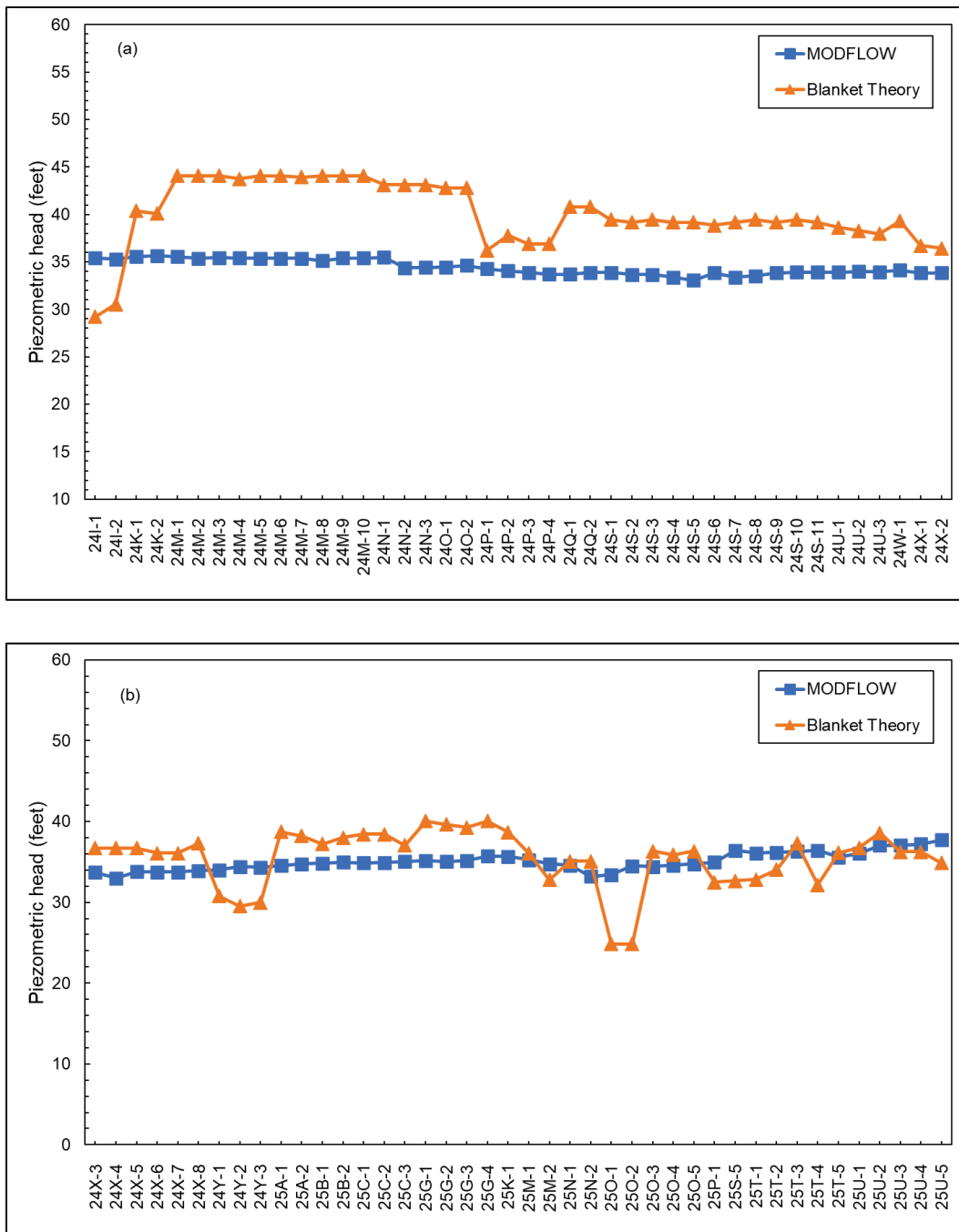


Figure 49. Piezometric head comparisons calculated by MODFLOW and blanket theory at 2008 flood peak for wells (a) 24I-1 to 24X-2, and (b) wells 24X-3 to 25U-5.

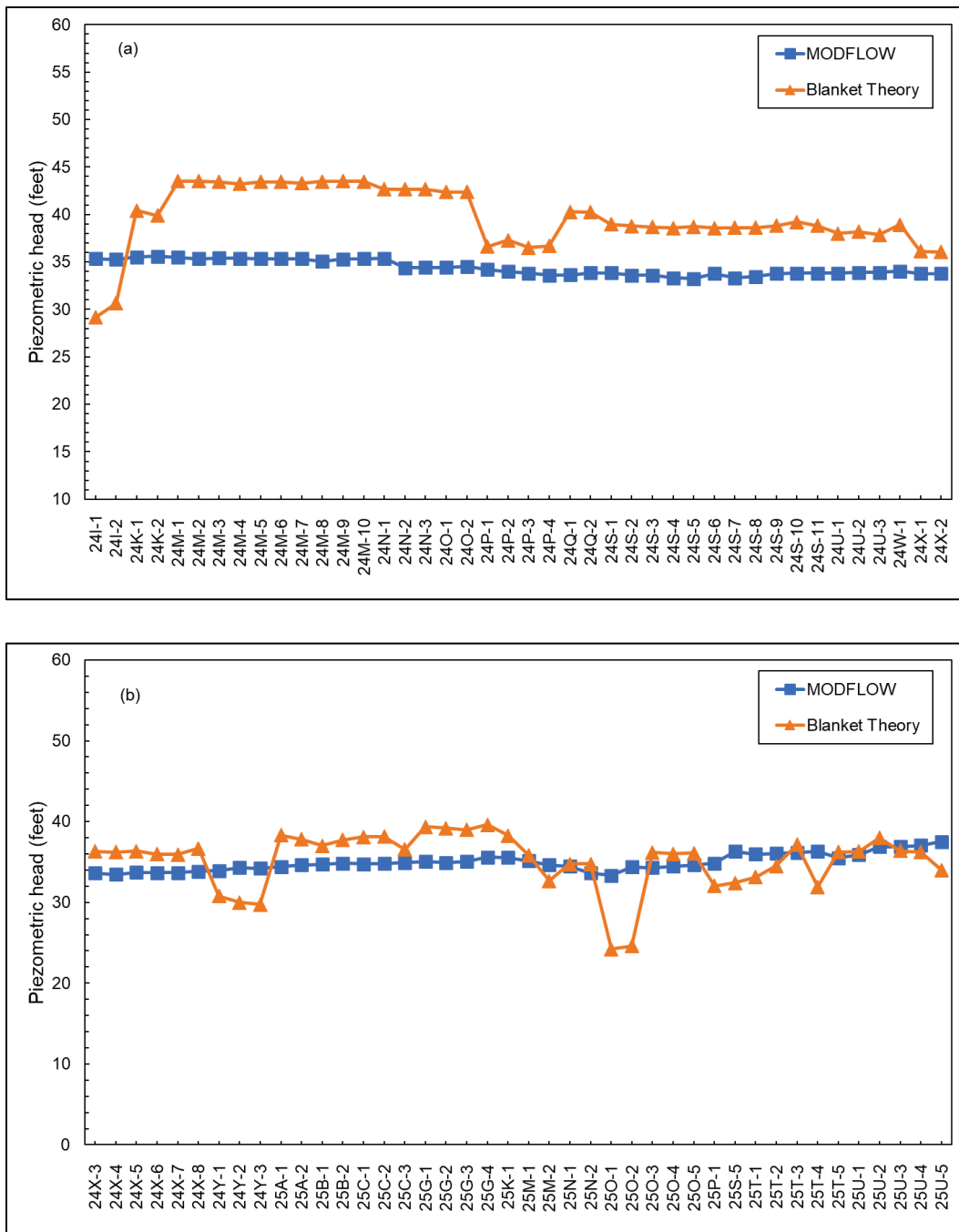


Figure 50. Piezometric head comparisons calculated by MODFLOW and blanket theory at 2017 flood peak for wells (a) 24I-1 to 24X-2, and (b) wells 24X-3 to 25U-5.

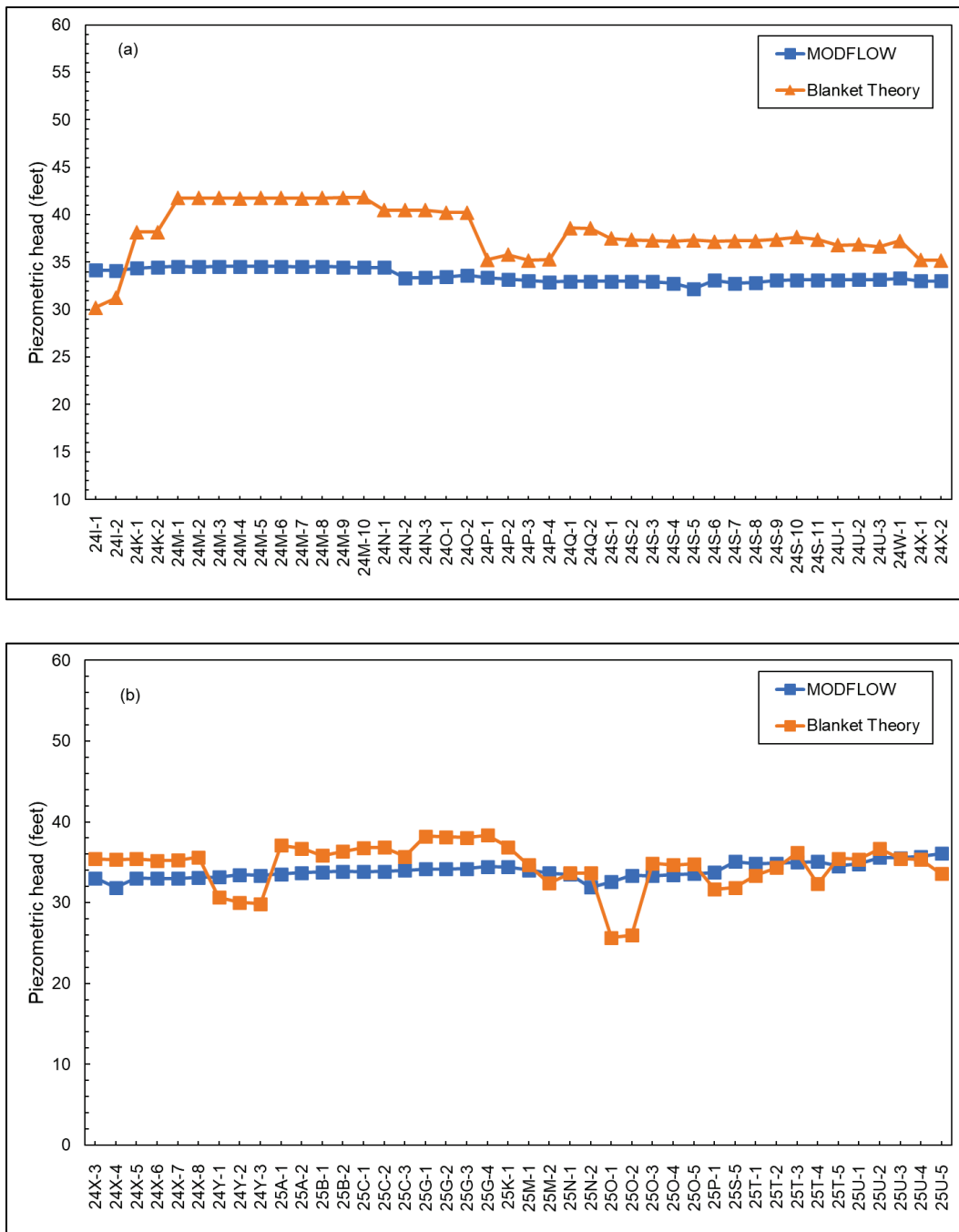
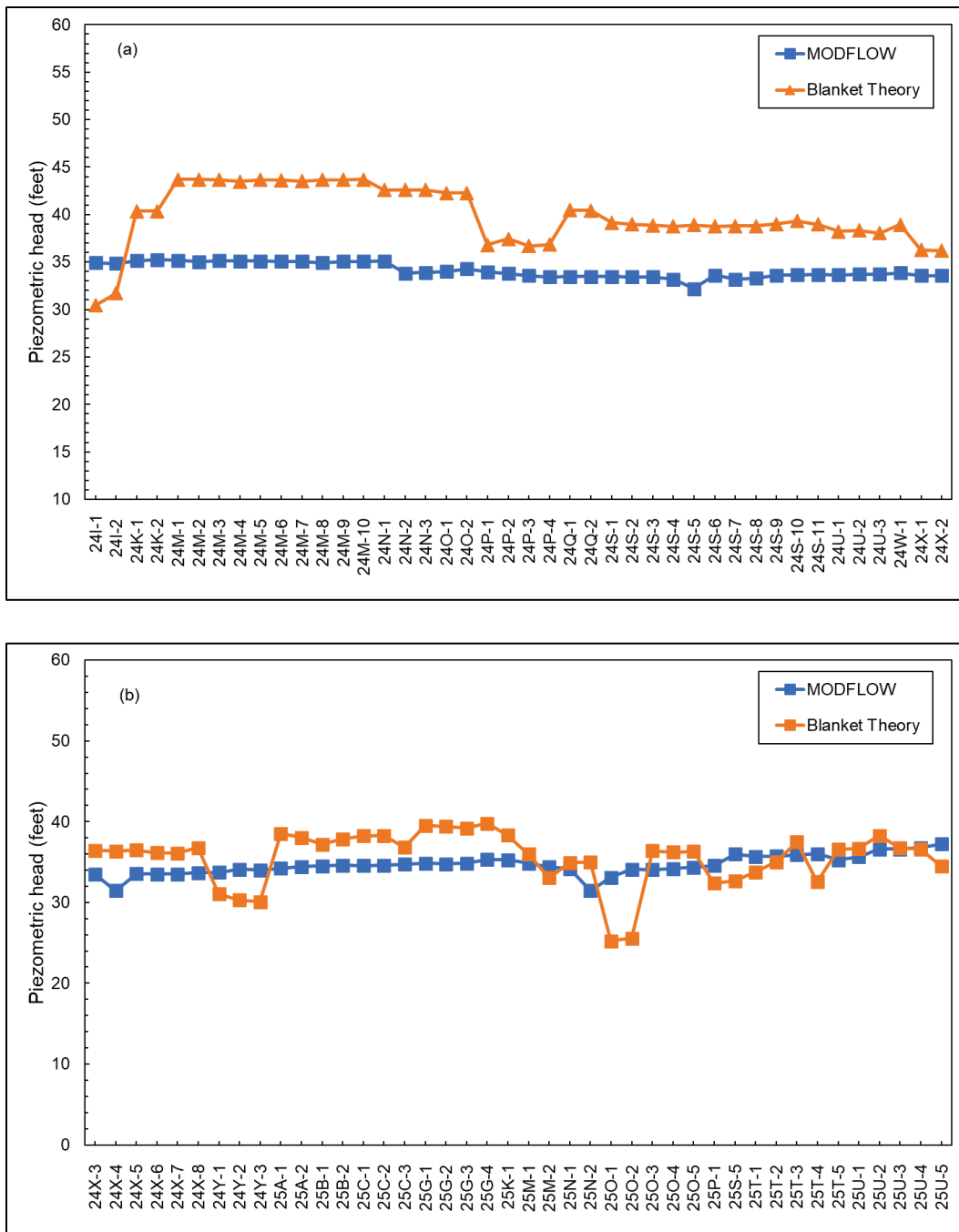


Figure 51. Piezometric head comparisons calculated by MODFLOW and blanket theory at 2018 flood peak for wells (a) 24I-1 to 24X-2, and (b) wells 24X-3 to 25U-5.



Discharge rates

The discharge rate of individual relief wells was predicted for the scenarios of the extreme flood, design flood, 1997 flood, 2008 flood, 2017 flood, and 2018 flood. The simulated discharge rates were categorized into four different groups for each flood event. The groups are based on the following four categories. High discharge rate is above 350 GPM. Medium discharge rate is between 350 GPM and 100 GPM. Low discharge rate is less than 100 GPM but higher than 1 GPM. The discharge rate less than 1 GPM is considered as no discharge. Figure 52 to Figure 57 show the predicted discharge rates of relief wells during a flood for all scenarios.

For the extreme flood, low discharge rates were only predicted at Reaches 24N and 24O for the peak river stage (56 ft). High discharge rates were predicted at Reaches 24I, 24P, 24Y, 25A, 25B, 25C, 25M, 25N, 25O, 25S, 25T, and 25U. For the design flood, low discharge rates were predicted at Reaches 24K and 24X for the peak river stage (52.4 ft). The low discharge rate occurred because of high top elevation of rubber well gaskets. The discharge rates of relief well 24O1 and 24O2 became zero because the piezometric head inside screen of the relief well is lower than the top elevation of rubber well gaskets.

For the 2008 flood, the USACE had an Arbroth river gage reading 49.20 feet and well flow measurements on 04/25/2008. Figure 58 shows a comparison between the modeled discharge rate and the measured discharge rate on 04/25/2008 (the peak-stage day). Figure 58 indicates that in 2008 the condition for many relief wells at Reaches 24I, 24P, 24Y, 25A, 25B, 25M, 25N, 25O, 25P, 25S, 25T, and 25U may have deteriorated due to clogging. These relief wells may have much less FoS than that being predicted by the 3D seepage model. Field measurements of well flow and piezometric head are recommended to assess the current conditions of relief wells and re-validate the PIVL model.

For the 2017 flood, low discharges were predicted at Reaches 24M, 24W, 24X, 25G, and 25K during the peak river stage (45.55 ft). High discharges were predicted for Reaches 25O, 25P, 25S, 25T, and 25U. The predicted discharge rates of relief well are consistent with the observation of relief well discharge during 2017 May–June event (Table 1).

Total predicted discharges at 84 relief wells for the six scenarios are shown in Figure 59 to Figure 64. For the 1997 flood, the 2008 flood, the 2017 flood, and the 2018 flood, the total discharge rate of 84 relief wells reaches a crest at the peak river stage but drops to 2,000 GPM while the river stage is lower than 35 ft (Figure 61 to Figure 64).

Figure 52. Magnitudes of relief well discharge (Q) for the extreme flood.

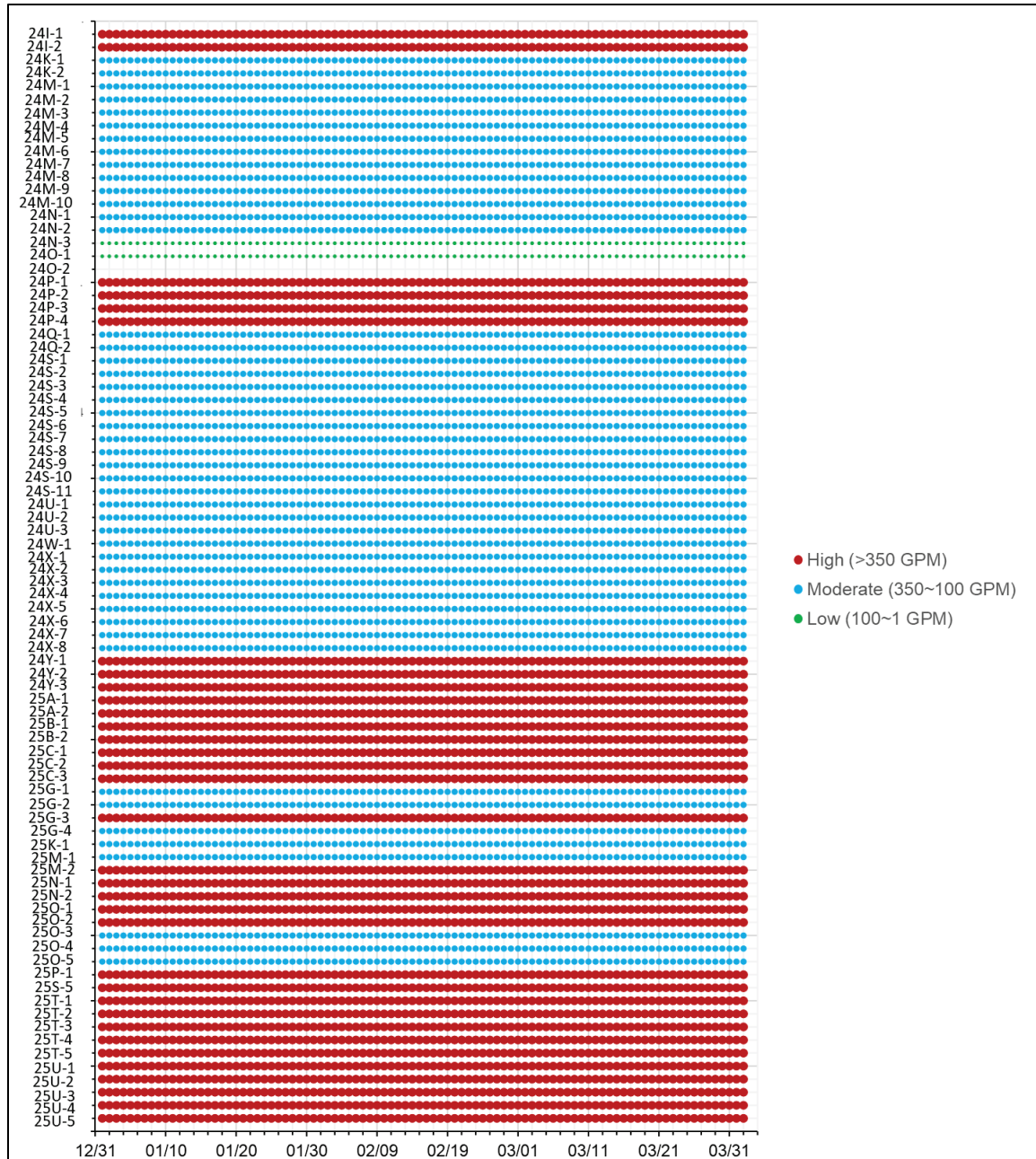


Figure 53. Magnitudes of relief well discharge (Q) for the design flood.

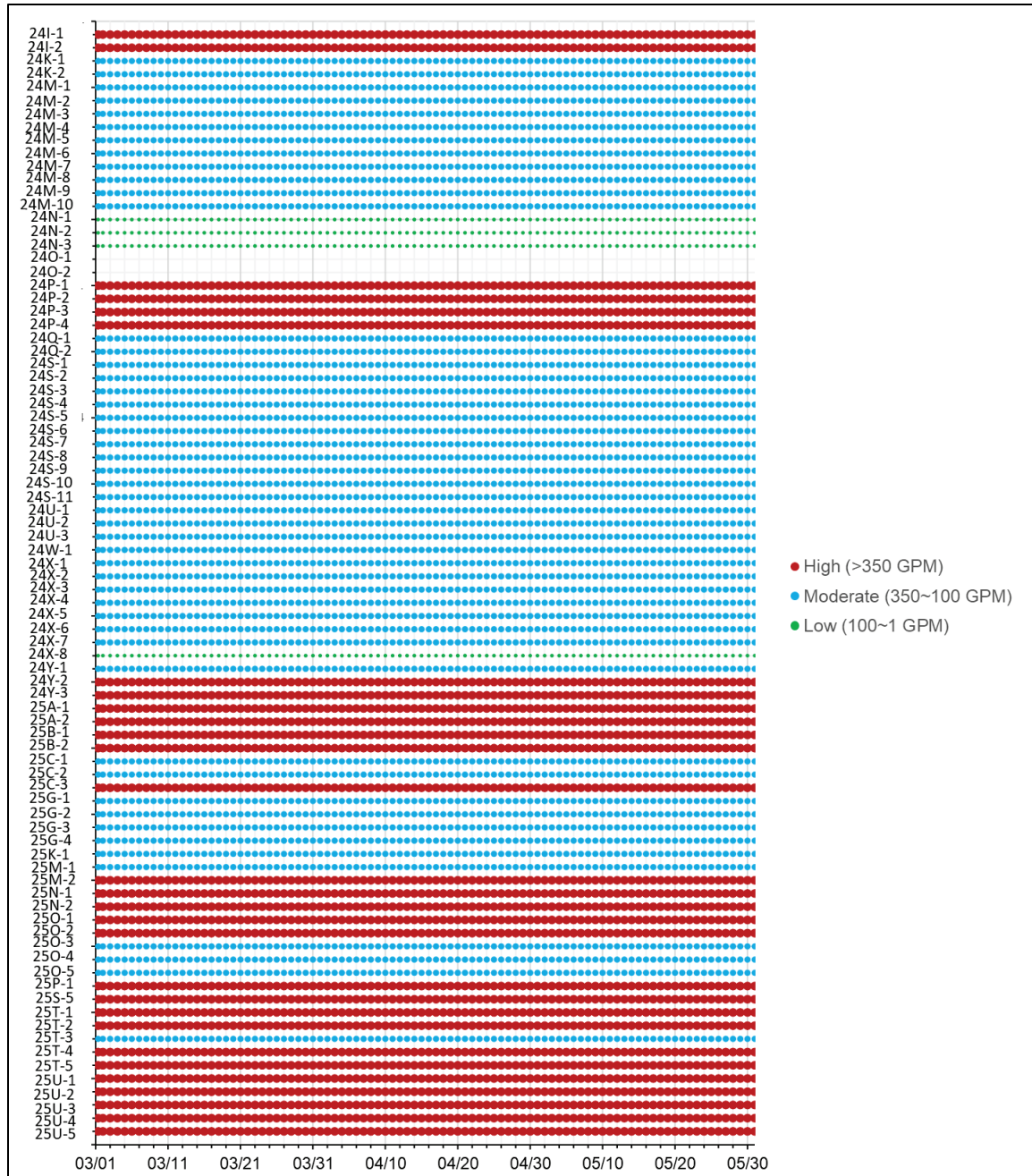


Figure 54. Magnitudes of relief well discharge (Q) for the 1997 flood.

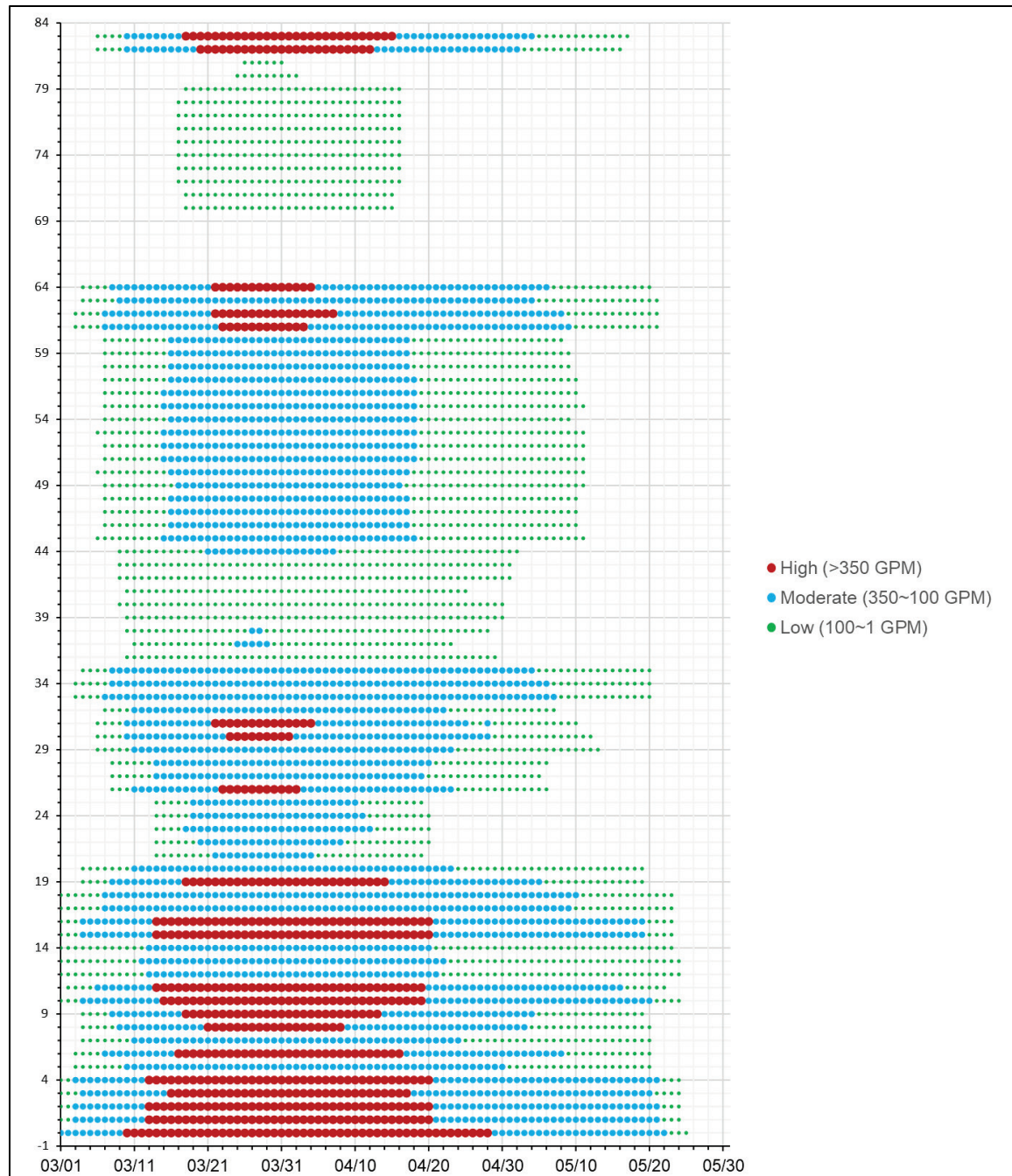


Figure 55. Magnitudes of relief well discharge (Q) for the 2008 flood.

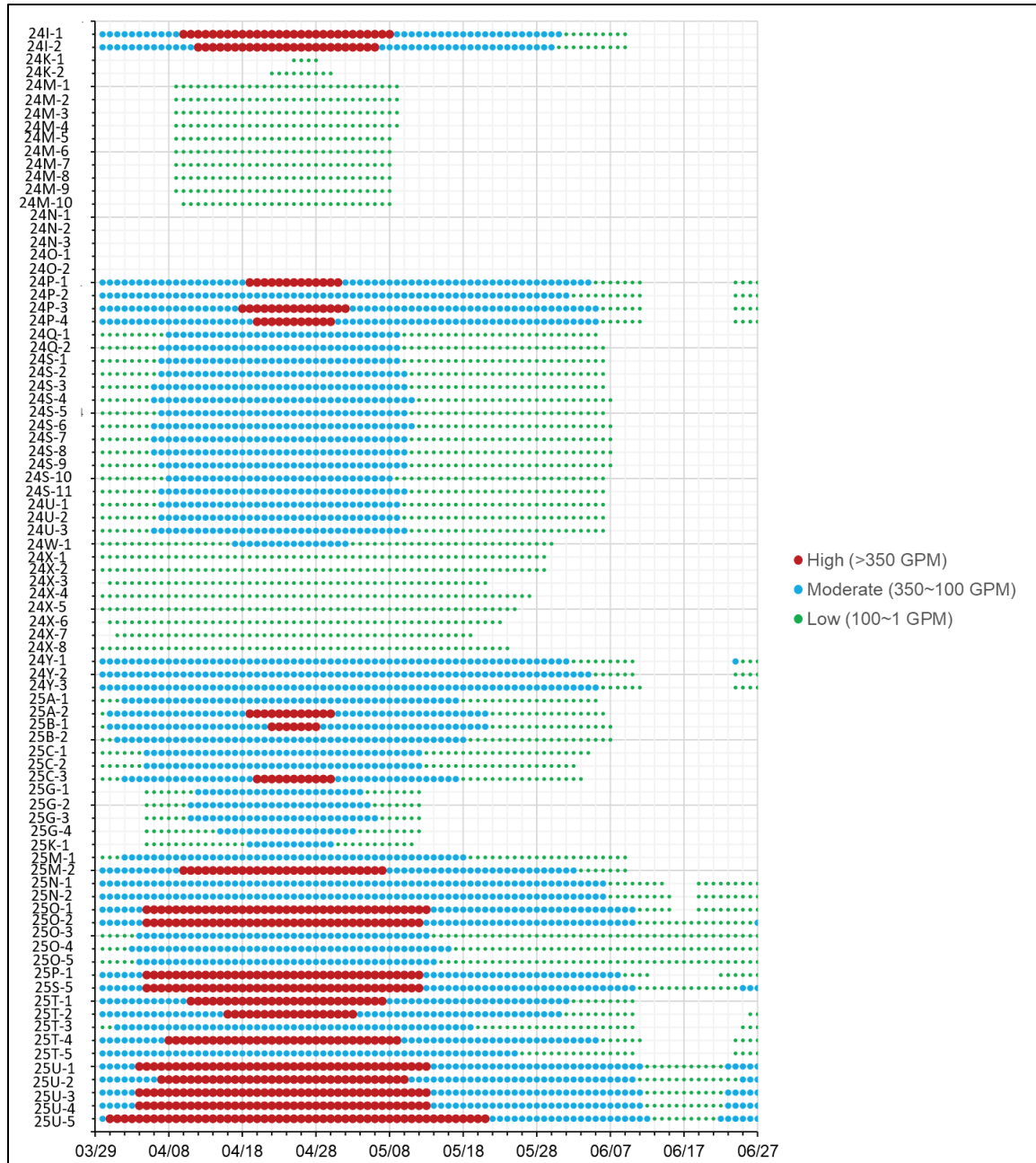


Figure 56. Magnitudes of relief well discharge (Q) for the 2017 flood.

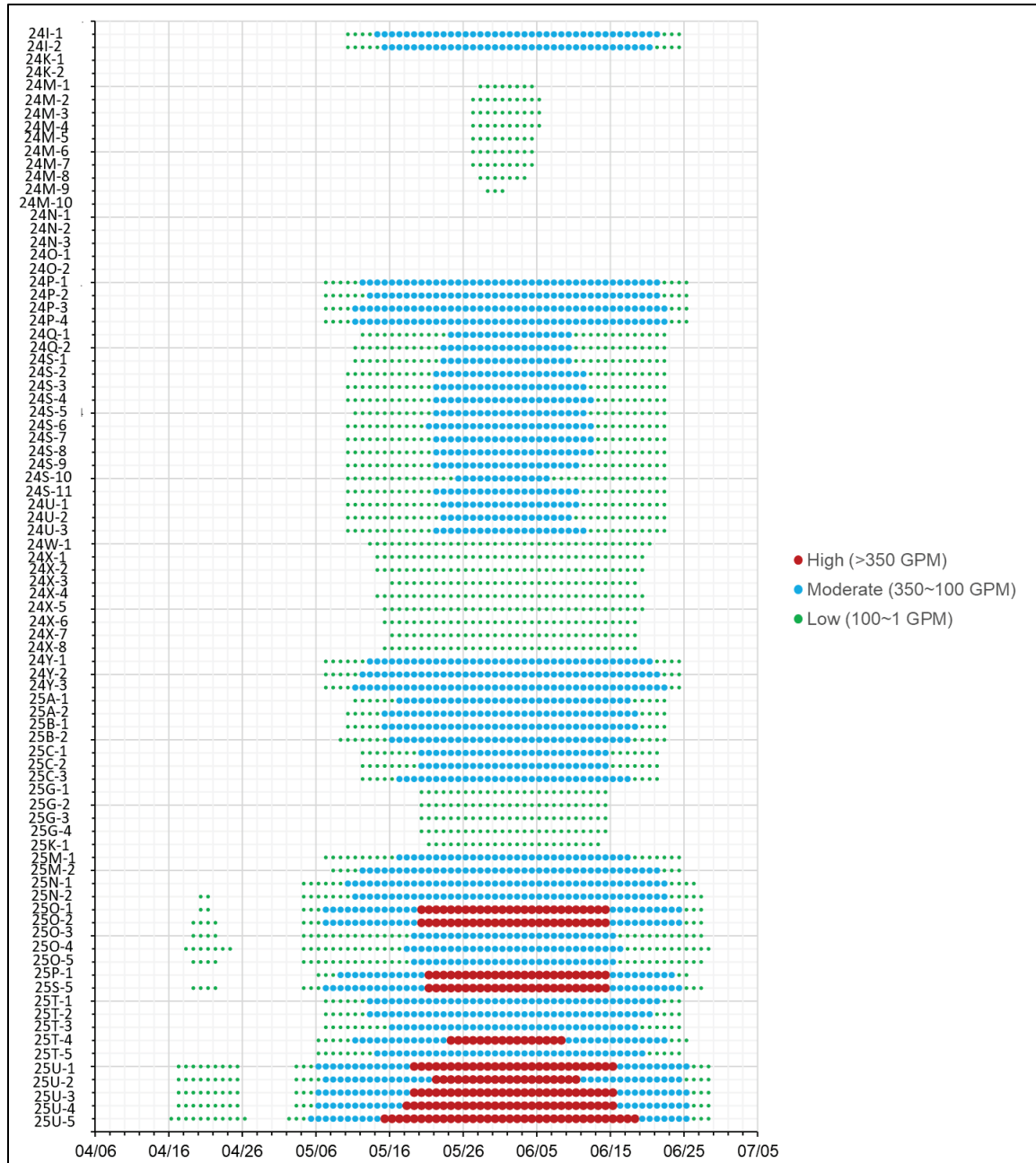


Figure 57. Magnitudes of relief well discharge (Q) for the 2018 flood.

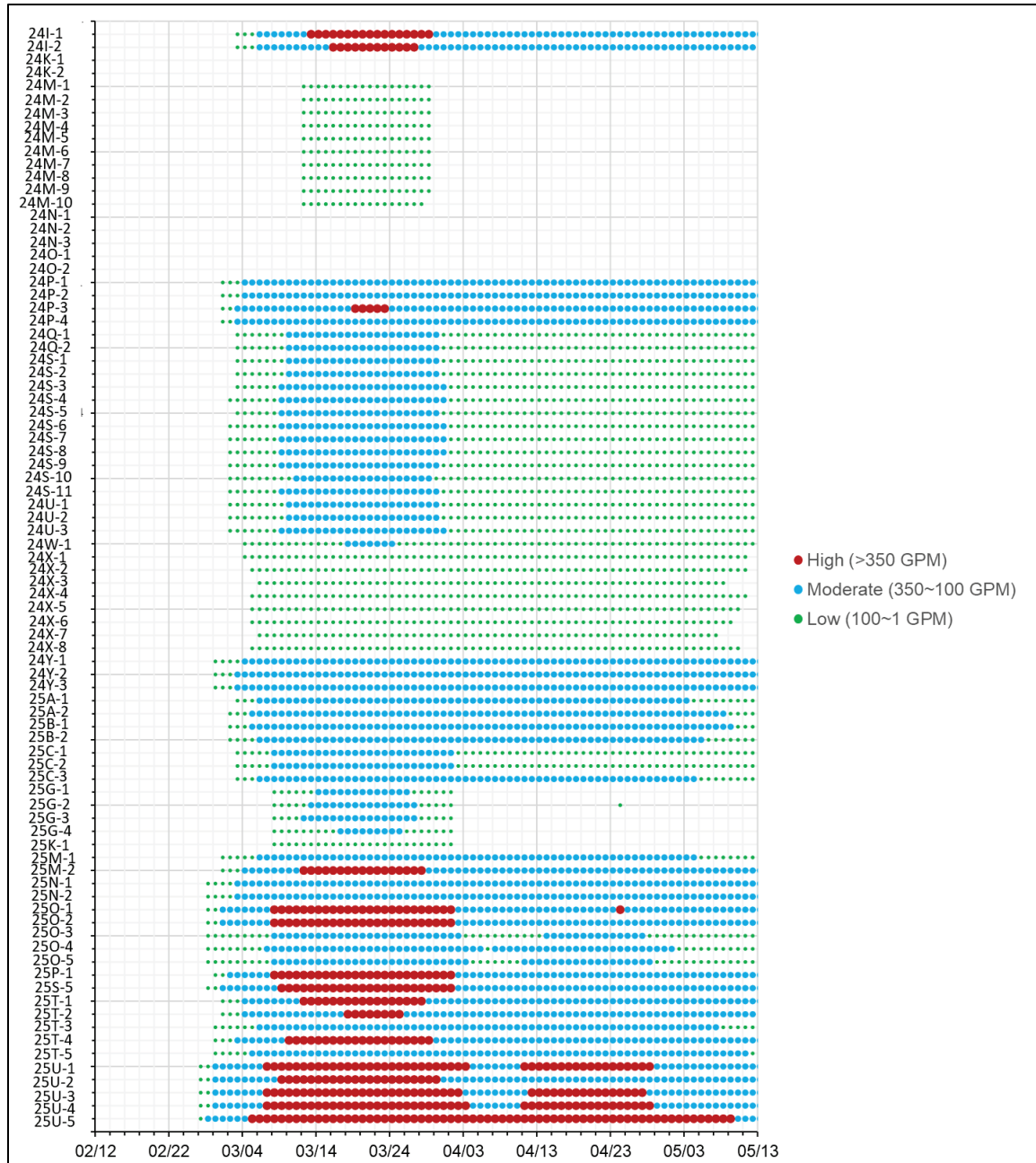


Figure 58. Comparison between the modeled discharge rate and the measured discharge rate on 04/25/2008 (the peak-stage day) for the 2008 flood.

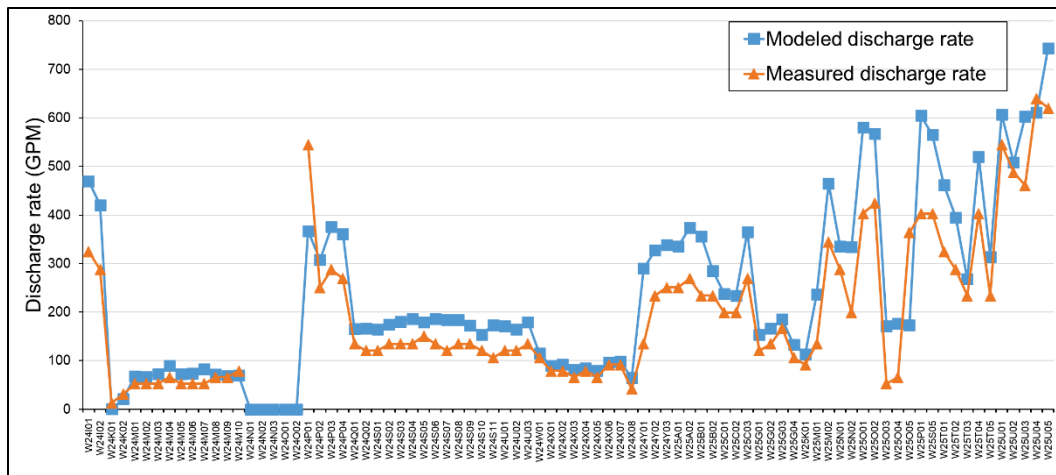


Figure 59. Total predicted discharges at 84 relief wells for the extreme flood.

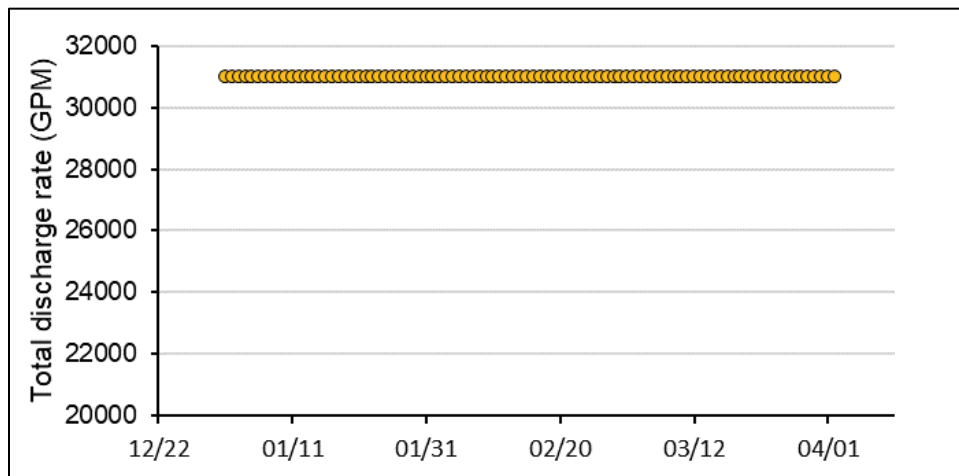


Figure 60. Total predicted discharges at 84 relief wells for the design flood.

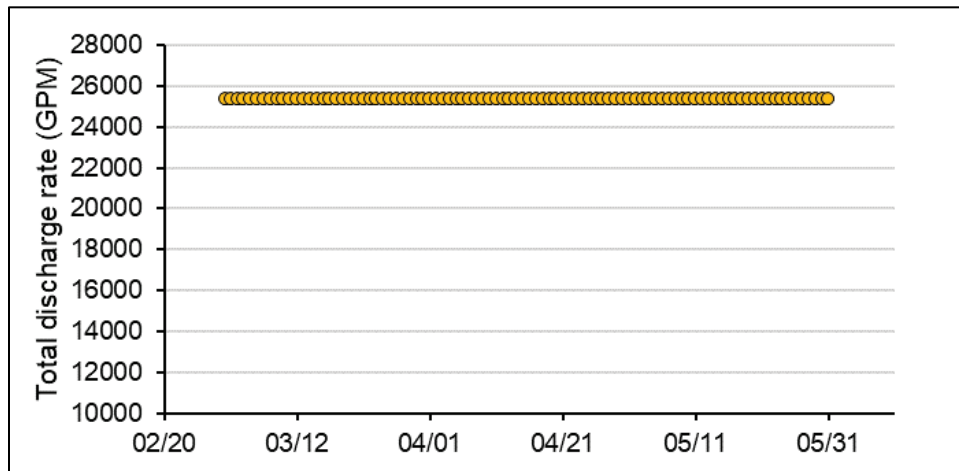


Figure 61. Total predicted discharges at 84 relief wells for the 1997 flood.

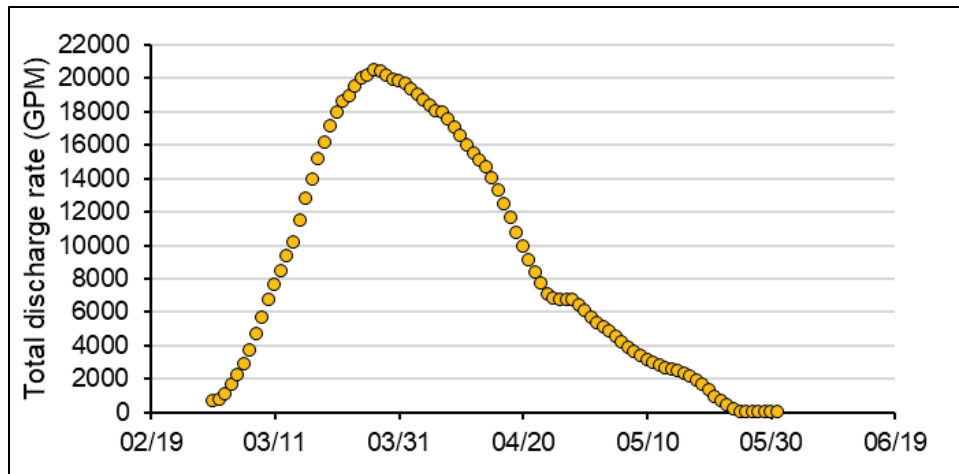


Figure 62. Total predicted discharges at 84 relief wells for the 2008 flood.

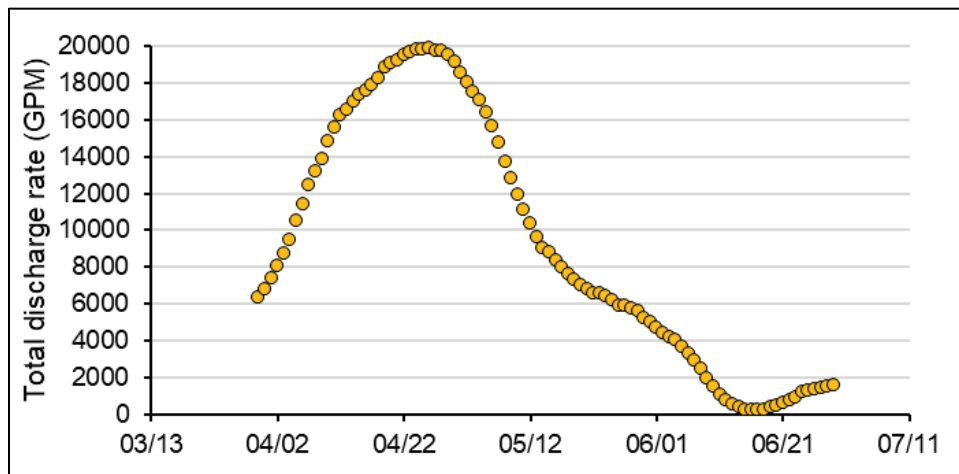


Figure 63. Total predicted discharges at 84 relief wells for the 2017 flood.

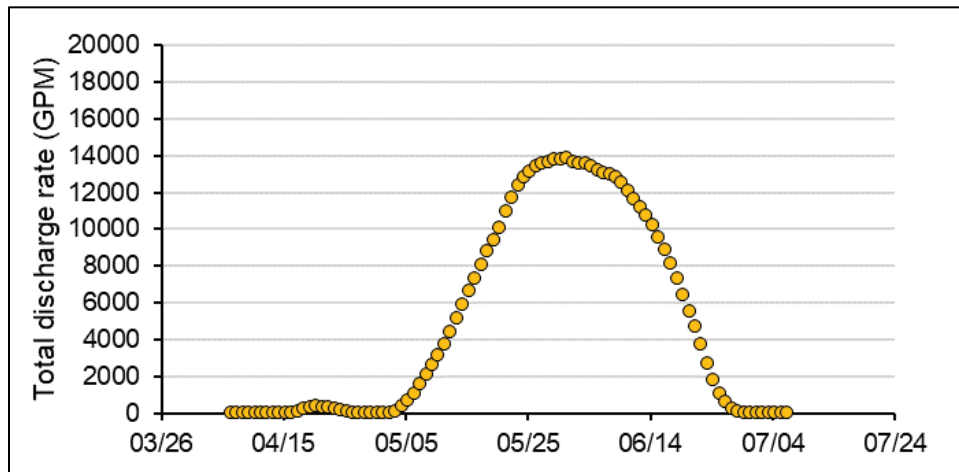
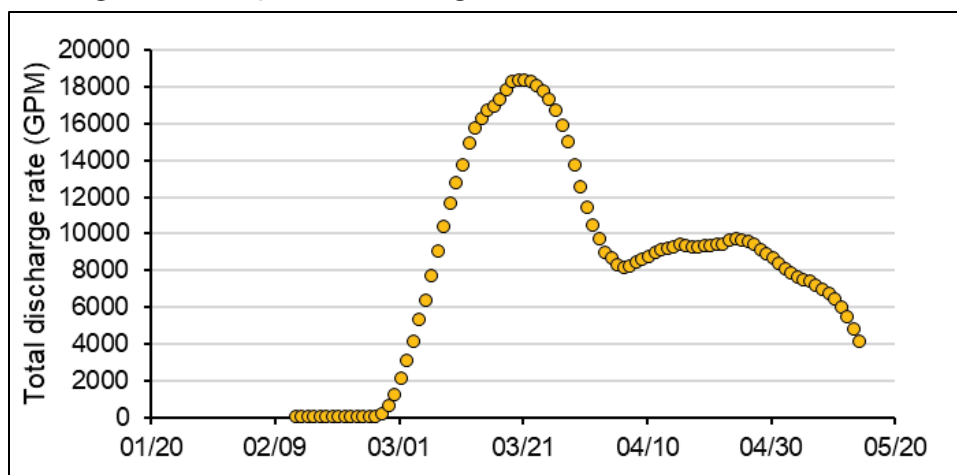


Figure 64. Total predicted discharges at 84 relief wells for the 2018 flood.



Hysteresis

A significant hysteresis relationship was found between the Mississippi River stage and the total predicted discharge of relief wells for the scenarios of the 1997 flood, the 2008 flood and the 2017 flood (Figure 65–Figure 67). At the same river stage (black dots), relief wells discharge more seepages during falling stages than rising stages. The biggest difference of the total discharge between falling stages and rising stages approximately reaches 3,000 GPM.

Figure 65. Hysteresis of total simulated discharge (GPM) from 84 relief wells versus Mississippi River stage (feet) near the Profit Island from 3/1/1997 to 5/31/1997.

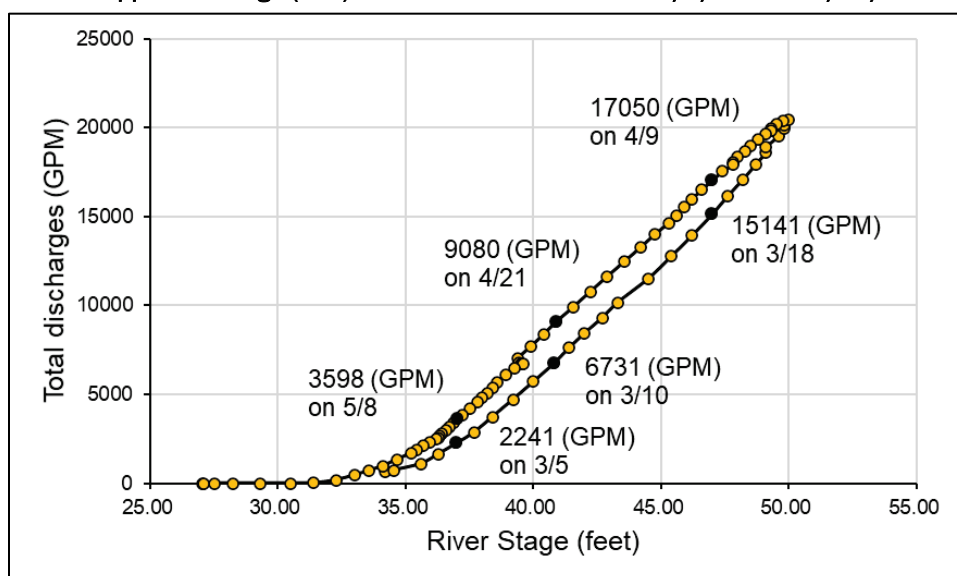


Figure 66. Hysteresis of total simulated discharge (GPM) from 84 relief wells versus Mississippi River stage (feet) near the Profit Island from 3/30/2008 to 6/29/2008.

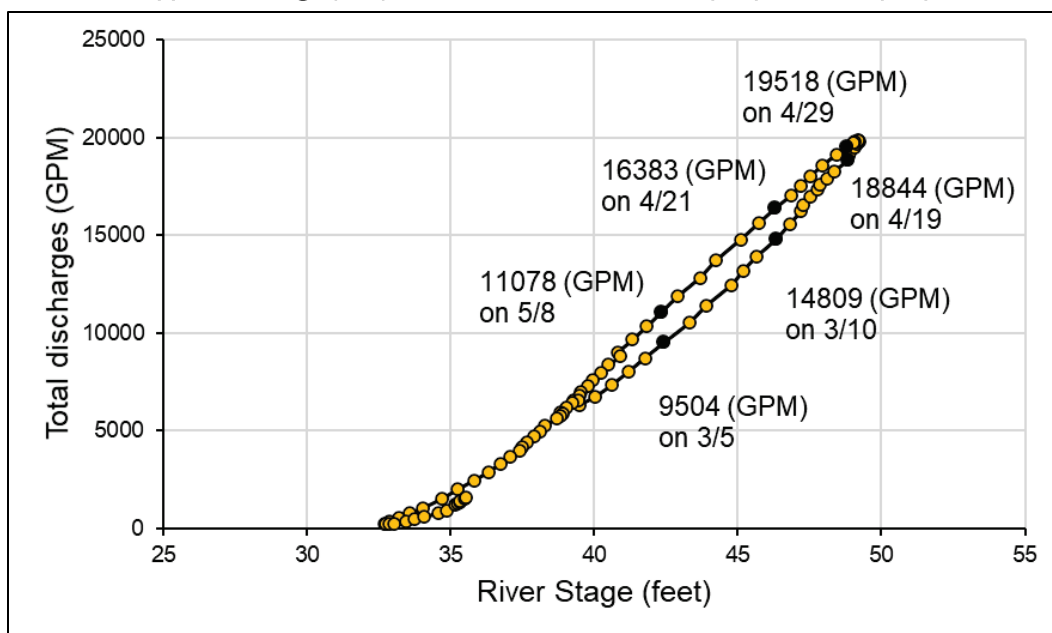
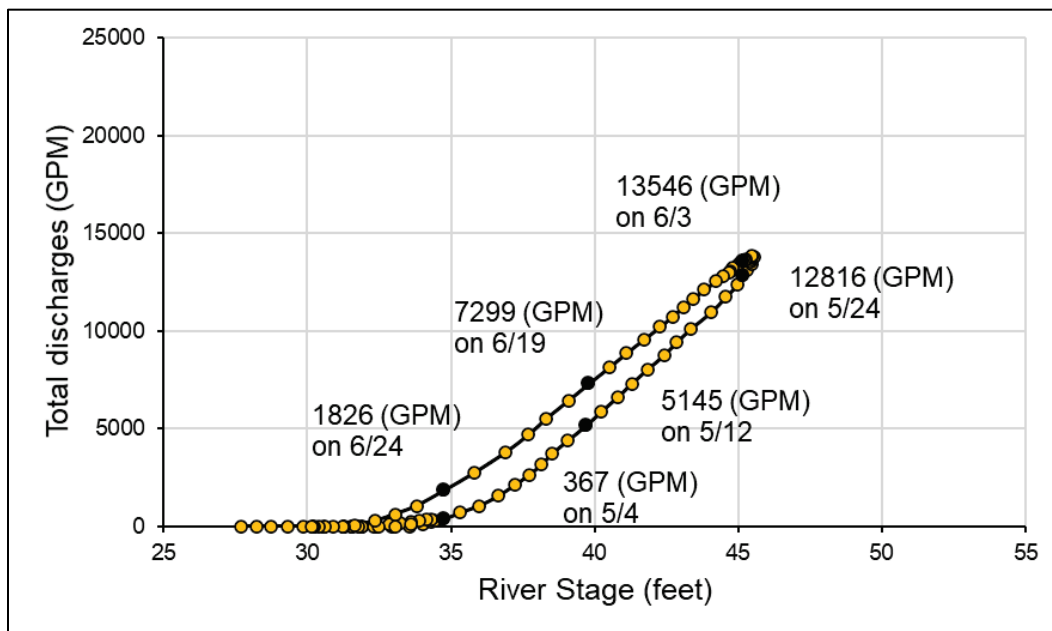


Figure 67. Hysteresis of total simulated discharge (GPM) from 84 relief wells versus Mississippi River stage (feet) near the Profit Island from 5/1/2017 to 7/7/2017.



Factor of Safety (FoS)

FoS at location of individual relief wells was predicted for the scenarios of the extreme flood, design flood, 1997 flood, 2008 flood, 2017 flood, and 2018 flood. Table 4 lists the FoS at peak river stages of these scenarios,

calculated by the PIVL model and blanket theory with and without relief wells. Estimated discharge rates from the PIVL model were applied to the blanket theory to calculate FoS. The calculation of FoS by the PIVL model is as follows:

$$FoS = \frac{0.8}{i}, \quad i = \frac{H_b - L}{Z_t} \quad (11)$$

where

FoS = Factor of Safety (-)

I = hydraulic gradient (feet/feet)

0.8 = critical gradient which is from the Pointe Coupee to Arbroth-Alfords Relief well design study (USACE 1990)

H_b = predicted piezometric head (feet) underneath blanket at peak stage, which is predicted by the PIVL model

Z_t = transformed blanket thickness (feet), which is given by blanket theory

L = land surface (feet).

The FoS value “999” in Table 4 indicates that piezometric head underneath the blanket is lower than ground level. Levee underseepage is not a concern. For the extreme flood (56 ft), the PIVL model shows that Reaches 24K, 24Q, and 25A may have FoS higher than 1.5 even without relief wells. For the design flood (52.4 ft), the PIVL model shows that Reaches 24K, 24P, 24Q, 25A, 25C, 25G, and 25U may have FoS higher than 1.5 even without relief wells. Given relief wells at the design condition (1997 data for model calibration), the PIVL model shows that all reaches have FoS higher than 1.5 for all scenarios. The result demonstrates the importance of having the relief wells for the Profit Island vicinity levee. The blanket theory estimates much lower FoS for all reaches for the design flood scenario as well as other scenarios. Low values of FoS are because the calculated discharge rates by the PIVL model are lower than the design discharge rates. In comparison with the FoS calculated by the 3D model, the values provided by the blanket theory and EM 1110-2-1914 (USACE 1992) are significantly more conservative.

Table 4. Predicted FoS of individual relief wells at the peak stage for the scenarios with and without relief wells. The scenarios include the extreme flood, design flood, the 1997 flood, the 2008 flood, the 2017 flood, and the 2018 flood.

Scenarios	Extreme Flood (56 ft)				Design Flood (52.4 ft)				1997 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W24I01	2.54	3.60	2.60	3.98	1.37	0.76	2.99	1.33	1.82	0.83	3.54	3.41
W24I02	2.64	2.44	2.73	2.47	1.38	0.76	3.10	1.33	1.83	0.83	3.62	2.57
W24K01	15.05	999	15.21	1.64	2.76	1.17	28.64	1.44	4.61	1.29	341.52	1.31
W24K02	16.55	1.72	14.25	2.03	2.74	1.17	25.45	1.44	4.53	1.29	135.17	1.37
W24M01	5.33	2.64	4.42	0.69	1.21	0.72	5.96	1.27	1.85	0.82	9.33	0.89
W24M02	6.82	2.11	4.85	0.69	1.20	0.72	6.59	1.27	1.85	0.82	11.05	0.88
W24M03	6.32	1.87	4.72	0.70	1.21	0.72	6.41	1.27	1.83	0.82	10.25	0.89
W24M04	6.88	3.01	4.87	0.72	1.20	0.72	6.61	1.27	1.82	0.82	10.67	0.91
W24M05	7.44	4.05	5.04	0.70	1.20	0.72	6.84	1.27	1.80	0.82	11.01	0.89
W24M06	7.52	4.31	4.99	0.70	1.19	0.72	6.76	1.27	1.81	0.82	11.00	0.89
W24M07	7.52	3.05	4.97	0.71	1.19	0.72	6.73	1.27	1.81	0.82	11.13	0.90
W24M08	10.35	2.30	7.41	0.70	1.18	0.72	9.94	1.27	1.76	0.82	16.07	0.89
W24M09	8.48	1.29	4.95	0.70	1.18	0.72	6.62	1.27	1.75	0.82	10.96	0.89
W24M10	7.96	0.66	4.83	0.70	1.17	0.72	6.37	1.27	1.74	0.82	10.65	0.89
W24N01	999	0.75	20.08	0.83	1.49	0.89	88.03	1.34	2.45	1.01	999	1.01
W24N02	999	0.75	999	0.83	1.49	0.89	999	1.34	2.69	1.01	999	1.01
W24N03	999	0.75	999	0.82	1.49	0.89	999	1.34	2.65	1.01	999	1.01

Scenarios	Extreme Flood (56 ft)				Design Flood (52.4 ft)				1997 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL model FoS	Blanket Theory FoS	PIVL model FoS	Blanket Theory FoS	PIVL model FoS	Blanket Theory FoS	PIVL model FoS	Blanket Theory FoS	PIVL model FoS	Blanket Theory FoS	PIVL model FoS	Blanket Theory FoS
W24O01	999	0.75	999	0.80	1.45	0.89	999	1.34	2.52	1.02	999	1.02
W24O02	999	0.75	999	0.75	1.44	0.89	999	1.34	2.37	1.02	999	1.02
W24P01	5.01	999	4.00	1.57	1.58	1.24	4.48	1.72	2.02	1.37	5.19	1.96
W24P02	5.27	999	4.20	1.47	1.59	1.24	4.72	1.72	2.03	1.37	5.49	1.83
W24P03	5.52	999	4.42	1.60	1.58	1.24	5.00	1.72	2.02	1.37	5.82	1.98
W24P04	5.89	999	4.67	1.57	1.56	1.24	5.31	1.72	1.99	1.37	6.16	1.95
W24Q01	10.19	999	7.11	1.45	1.96	1.27	8.43	1.96	2.55	1.41	10.28	1.78
W24Q02	8.70	999	6.42	1.45	1.99	1.27	7.54	1.96	2.66	1.41	9.51	1.78
W24S01	4.73	999	3.49	0.88	1.09	0.76	4.10	1.31	1.45	0.84	5.18	1.08
W24S02	5.97	999	3.92	0.90	1.06	0.76	4.67	1.31	1.38	0.84	5.67	1.10
W24S03	6.05	999	3.95	0.91	1.06	0.76	4.71	1.31	1.38	0.84	5.71	1.11
W24S04	6.40	999	4.52	0.92	1.06	0.76	5.39	1.31	1.38	0.84	6.55	1.12
W24S05	6.19	999	4.20	0.92	1.06	0.76	5.02	1.31	1.67	0.84	7.87	1.11
W24S06	5.69	999	3.61	0.93	1.06	0.76	4.32	1.31	1.37	0.84	5.23	1.12
W24S07	6.37	999	4.50	0.92	1.06	0.76	5.40	1.31	1.38	0.84	6.56	1.12
W24S08	6.12	999	4.19	0.92	1.06	0.76	5.03	1.31	1.38	0.84	6.12	1.12
W24S09	5.63	999	3.59	0.90	1.06	0.76	4.31	1.31	1.37	0.84	5.23	1.10
W24S10	5.47	999	3.50	0.87	1.06	0.76	4.21	1.31	1.38	0.84	5.12	1.06
W24S11	5.40	999	3.49	0.91	1.07	0.76	4.20	1.31	1.38	0.84	5.11	1.10

Scenarios	Extreme Flood (56 ft)				Design Flood (52.4 ft)				1997 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W24U01	5.15	999	3.37	0.96	1.03	0.76	4.06	1.33	1.34	0.84	4.95	1.15
W24U02	4.97	999	3.29	0.94	1.03	0.76	3.96	1.33	1.33	0.84	4.82	1.13
W24U03	6.10	999	3.82	0.97	1.08	0.76	4.77	1.33	1.41	0.84	6.06	1.17
W24W01	6.42	1.64	4.55	1.17	1.38	1.23	5.65	1.53	1.81	1.37	7.14	1.47
W24X01	4.00	999	3.13	1.08	0.90	0.90	3.95	1.38	1.20	1.01	5.17	1.30
W24X02	4.00	999	3.14	1.10	0.90	0.90	3.96	1.38	1.20	1.01	5.19	1.31
W24X03	3.99	999	3.53	1.06	0.88	0.90	4.39	1.38	1.16	1.01	5.58	1.27
W24X04	3.58	999	3.05	1.06	0.88	0.90	3.80	1.38	1.79	1.01	9.57	1.28
W24X05	3.53	999	3.30	1.04	0.88	0.90	4.14	1.38	1.16	1.01	5.30	1.26
W24X06	3.22	1.15	3.36	1.13	0.89	0.90	4.23	1.38	1.17	1.01	5.47	1.33
W24X07	3.09	1.19	3.35	1.16	0.88	0.90	4.23	1.38	1.16	1.01	5.48	1.34
W24X08	2.88	1.01	3.07	0.98	0.87	0.90	3.87	1.38	1.14	1.01	4.98	1.20
W24Y01	1.88	2.66	1.92	2.91	0.73	0.89	2.24	1.40	0.93	0.99	2.61	3.12
W24Y02	1.76	3.58	1.73	4.47	0.72	0.89	2.02	1.40	0.90	0.99	2.35	4.32
W24Y03	1.79	3.88	1.75	5.28	0.73	0.89	2.05	1.40	0.92	0.99	2.40	4.87
W25A01	10.24	3.12	9.79	3.25	3.75	2.48	11.90	3.41	4.83	2.74	14.53	3.79
W25A02	9.77	3.27	9.25	3.41	3.70	2.48	11.20	3.41	4.76	2.74	13.61	3.96
W25B01	3.74	1.39	3.58	1.43	1.47	1.13	4.33	1.49	1.89	1.25	5.26	1.70
W25B02	3.61	1.29	3.50	1.31	1.46	1.13	4.22	1.49	1.87	1.25	5.10	1.58

Scenarios	Extreme Flood (56 ft)				Design Flood (52.4 ft)				1997 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W25C01	4.11	1.45	4.15	1.46	1.58	1.23	5.11	1.65	2.06	1.36	6.35	1.76
W25C02	4.12	1.45	4.11	1.46	1.58	1.23	5.05	1.65	2.06	1.36	6.27	1.75
W25C03	3.97	1.79	3.96	1.81	1.58	1.23	4.86	1.65	2.06	1.36	6.02	2.08
W25G01	4.33	1.31	5.04	1.28	1.55	1.13	6.78	1.46	2.10	1.26	9.55	1.50
W25G02	5.50	1.31	5.53	1.31	1.54	1.13	7.39	1.46	2.08	1.26	10.31	1.52
W25G03	4.93	1.38	5.10	1.36	1.53	1.13	6.81	1.46	2.07	1.26	9.55	1.56
W25G04	3.86	1.27	3.86	1.23	1.49	1.13	5.13	1.46	2.03	1.26	7.18	1.46
W25K01	3.64	1.32	3.71	1.28	1.41	1.32	4.96	1.51	1.91	1.47	6.95	1.58
W25M01	2.01	999	2.18	1.20	1.00	0.95	2.59	1.41	1.27	1.05	3.10	1.44
W25M02	2.02	2.75	2.43	2.10	1.00	0.95	2.90	1.41	1.27	1.05	3.50	2.23
W25N01	1.84	1.44	2.24	1.29	0.99	0.95	2.61	1.42	1.23	1.05	3.06	1.54
W25N02	1.81	1.46	2.31	1.29	0.97	0.95	2.70	1.42	1.74	1.05	4.38	1.54
W25001	2.36	999	2.88	999	0.94	0.74	3.37	1.35	1.18	0.81	3.97	999
W25002	1.74	999	2.17	999	0.94	0.74	2.54	1.35	1.17	0.81	3.00	999
W25003	1.76	999	2.21	0.99	0.93	0.74	2.59	1.35	1.17	0.81	3.06	1.17
W25004	1.72	1.13	2.14	1.00	0.93	0.74	2.51	1.35	1.16	0.81	2.96	1.18
W25005	1.69	1.14	2.06	1.00	0.92	0.74	2.41	1.35	1.15	0.81	2.83	1.17
W25P01	1.77	2.58	2.11	2.11	0.98	1.06	2.46	1.56	1.22	1.17	2.90	2.30
W25S05	1.40	2.49	1.79	2.12	0.84	1.10	2.11	1.46	1.05	1.22	2.50	2.40

Scenarios	Extreme Flood (56 ft)				Design Flood (52.4 ft)				1997 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W25T01	1.81	20.15	2.60	3.35	1.04	0.93	3.14	1.41	1.31	1.03	3.85	2.95
W25T02	1.81	4.87	2.57	2.28	1.03	0.93	3.10	1.41	1.30	1.03	3.80	2.32
W25T03	1.79	1.94	2.49	1.44	1.02	0.93	3.00	1.41	1.28	1.03	3.66	1.66
W25T04	1.77	999	2.44	4.97	1.01	0.93	2.93	1.41	1.27	1.03	3.57	3.84
W25T05	2.38	2.22	3.00	1.64	1.00	0.93	3.61	1.41	1.25	1.03	4.38	1.85
W25U01	3.15	3.78	3.82	2.67	1.56	1.25	4.49	1.95	1.92	1.39	5.28	3.06
W25U02	2.46	2.71	3.18	2.16	1.54	1.25	3.74	1.95	1.89	1.39	4.39	2.56
W25U03	2.43	3.62	3.19	2.63	1.53	1.25	3.75	1.95	1.86	1.39	4.39	3.04
W25U04	2.40	3.65	3.11	2.69	1.52	1.25	3.65	1.95	1.85	1.39	4.27	3.09
W25U05	2.36	5.67	2.88	3.92	1.52	1.25	3.38	1.95	1.84	1.39	3.96	4.21

Scenario s	2008 Flood				2017 Flood				2018 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W24I01	1.83	0.86	3.59	3.74	2.74	1.01	4.92	2.99	2.11	0.87	3.97	2.87
W24I02	1.84	0.86	3.67	2.77	2.76	1.01	5.00	2.50	2.12	0.87	4.05	2.32
W24K01	4.67	1.33	1869.58	1.33	14.90	1.58	999	1.58	6.36	1.34	999	1.34
W24K02	4.59	1.33	207.49	1.38	14.25	1.58	999	1.58	6.21	1.34	999	1.34
W24M01	1.87	0.86	9.80	0.93	4.09	1.11	215.39	1.11	2.35	0.86	14.31	0.91
W24M02	1.86	0.86	11.49	0.93	4.10	1.11	1538.74	1.12	2.36	0.86	18.37	0.91
W24M03	1.85	0.86	10.84	0.93	4.02	1.11	173.24	1.12	2.32	0.86	15.61	0.92
W24M04	1.84	0.86	11.30	0.95	3.98	1.11	184.65	1.12	2.30	0.86	16.32	0.93
W24M05	1.83	0.86	11.71	0.93	3.92	1.11	162.30	1.11	2.28	0.86	16.64	0.92
W24M06	1.83	0.86	11.67	0.94	3.92	1.11	202.90	1.11	2.28	0.86	16.90	0.92
W24M07	1.83	0.86	11.70	0.95	3.96	1.11	299.64	1.12	2.30	0.86	17.68	0.93
W24M08	1.79	0.86	17.28	0.93	3.73	1.11	271.83	1.11	2.20	0.86	24.06	0.92
W24M09	1.78	0.86	11.87	0.93	3.71	1.11	999	1.11	2.19	0.86	16.96	0.91
W24M10	1.77	0.86	11.61	0.93	3.67	1.11	999	1.11	2.17	0.86	16.80	0.91
W24N01	2.52	1.06	999	1.06	8.42	1.37	999	1.37	3.33	1.07	999	1.07
W24N02	2.64	1.06	999	1.06	11.90	1.37	999	1.37	4.10	1.07	999	1.07
W24N03	2.62	1.06	999	1.06	11.08	1.37	999	1.37	3.93	1.07	999	1.07

Scenarios	2008 Flood				2017 Flood				2018 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W24001	2.52	1.07	999	1.07	9.84	1.38	999	1.38	3.63	1.08	999	1.08
W24002	2.43	1.07	999	1.07	7.98	1.38	999	1.38	3.20	1.08	999	1.08
W24P01	2.04	1.42	5.30	2.04	2.91	1.70	6.84	2.37	2.27	1.43	5.66	2.00
W24P02	2.05	1.42	5.61	1.90	2.92	1.70	7.26	2.23	2.29	1.43	6.00	1.88
W24P03	2.04	1.42	5.94	2.06	2.91	1.70	7.69	2.39	2.27	1.43	6.35	2.02
W24P04	2.02	1.42	6.30	2.03	2.85	1.70	8.08	2.36	2.23	1.43	6.68	1.99
W24Q01	2.59	1.46	10.62	1.84	3.85	1.76	15.37	2.14	2.91	1.47	11.54	1.82
W24Q02	2.68	1.46	9.68	1.85	4.09	1.76	15.06	2.14	3.11	1.47	11.51	1.82
W24S01	1.46	0.87	5.27	1.12	2.23	1.05	8.23	1.30	1.70	0.88	6.30	1.11
W24S02	1.40	0.87	5.86	1.14	2.08	1.05	8.38	1.32	1.57	0.88	6.34	1.12
W24S03	1.40	0.87	5.90	1.15	2.08	1.05	8.41	1.33	1.56	0.88	6.37	1.13
W24S04	1.40	0.87	6.77	1.16	2.08	1.05	9.66	1.34	1.57	0.88	7.31	1.14
W24S05	1.56	0.87	7.06	1.15	2.70	1.05	17.23	1.32	2.16	0.88	17.77	1.13
W24S06	1.39	0.87	5.42	1.17	2.06	1.05	7.68	1.34	1.55	0.88	5.83	1.15
W24S07	1.40	0.87	6.78	1.16	2.07	1.05	9.68	1.33	1.56	0.88	7.31	1.14
W24S08	1.40	0.87	6.33	1.16	2.08	1.05	9.06	1.33	1.57	0.88	6.83	1.14
W24S09	1.40	0.87	5.42	1.14	2.06	1.05	7.71	1.31	1.55	0.88	5.83	1.12
W24S10	1.40	0.87	5.30	1.10	2.07	1.05	7.57	1.28	1.56	0.88	5.71	1.09
W24S11	1.40	0.87	5.29	1.14	2.08	1.05	7.57	1.31	1.56	0.88	5.70	1.12

Scenarios	2008 Flood				2017 Flood				2018 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W24U01	1.36	0.87	5.12	1.19	2.02	1.06	7.35	1.36	1.52	0.88	5.52	1.17
W24U02	1.36	0.87	4.99	1.17	2.01	1.06	7.13	1.34	1.51	0.88	5.37	1.15
W24U03	1.44	0.87	6.34	1.21	2.20	1.06	10.24	1.38	1.62	0.88	6.97	1.19
W24W01	1.84	1.42	7.45	1.53	2.81	1.74	11.77	1.84	2.07	1.43	8.16	1.53
W24X01	1.22	1.05	5.39	1.34	1.90	1.28	9.31	1.54	1.38	1.05	6.10	1.32
W24X02	1.22	1.05	5.41	1.36	1.90	1.28	9.38	1.55	1.39	1.05	6.14	1.33
W24X03	1.18	1.05	5.83	1.31	1.82	1.28	9.32	1.49	1.33	1.05	6.41	1.29
W24X04	1.49	1.05	6.59	1.33	3.54	1.28	999	1.52	3.05	1.05	999	1.30
W24X05	1.18	1.05	5.54	1.30	1.82	1.28	9.06	1.50	1.33	1.05	6.12	1.28
W24X06	1.19	1.05	5.73	1.38	1.83	1.28	9.61	1.54	1.34	1.05	6.37	1.34
W24X07	1.18	1.05	5.73	1.39	1.82	1.28	9.67	1.54	1.33	1.05	6.38	1.35
W24X08	1.16	1.05	5.21	1.25	1.77	1.28	8.65	1.45	1.30	1.05	5.76	1.23
W24Y01	0.94	1.03	2.68	3.30	1.33	1.24	3.47	3.46	1.04	1.04	2.83	2.99
W24Y02	0.92	1.03	2.42	4.61	1.28	1.24	3.11	4.51	1.00	1.04	2.54	3.98
W24Y03	0.93	1.03	2.47	5.22	1.31	1.24	3.20	4.97	1.02	1.04	2.60	4.41
W25A01	4.91	2.83	15.08	3.91	7.22	3.39	21.70	4.37	5.45	2.85	16.21	3.84
W25A02	4.85	2.83	14.12	4.09	7.09	3.39	20.08	4.56	5.37	2.85	15.12	4.00
W25B01	1.92	1.29	5.45	1.75	2.81	1.54	7.73	1.99	2.13	1.30	5.84	1.72
W25B02	1.90	1.29	5.29	1.64	2.77	1.54	7.42	1.89	2.10	1.30	5.65	1.62

Scenarios	2008 Flood				2017 Flood				2018 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W25C01	2.10	1.41	6.62	1.82	3.14	1.71	9.92	2.09	2.33	1.42	7.16	1.79
W25C02	2.10	1.41	6.53	1.81	3.14	1.71	9.73	2.08	2.34	1.42	7.06	1.79
W25C03	2.10	1.41	6.26	2.15	3.14	1.71	9.27	2.38	2.34	1.42	6.78	2.09
W25G01	2.14	1.30	10.23	1.54	3.53	1.59	24.06	1.73	2.44	1.31	11.79	1.52
W25G02	2.13	1.30	11.01	1.57	3.50	1.59	24.53	1.75	2.42	1.31	12.64	1.54
W25G03	2.12	1.30	10.18	1.60	3.47	1.59	22.88	1.77	2.41	1.31	11.74	1.57
W25G04	2.06	1.30	7.63	1.51	3.36	1.59	16.73	1.71	2.35	1.31	8.83	1.49
W25K01	1.94	1.52	7.41	1.64	3.15	1.86	16.60	1.93	2.21	1.53	8.57	1.63
W25M01	1.29	1.09	3.19	1.49	1.82	1.30	4.32	1.72	1.43	1.10	3.42	1.47
W25M02	1.29	1.09	3.61	2.32	1.83	1.30	4.95	2.44	1.43	1.10	3.88	2.17
W25N01	1.25	1.08	3.13	1.60	1.70	1.29	4.02	1.83	1.37	1.09	3.33	1.56
W25N02	1.49	1.08	3.84	1.59	2.62	1.29	7.27	1.82	2.52	1.09	9.56	1.56
W25O01	1.19	0.84	4.07	999	1.62	0.99	5.26	20.09	1.31	0.84	4.34	59.97
W25O02	1.18	0.84	3.07	999	1.61	0.99	3.98	14.19	1.30	0.84	3.28	23.28
W25O03	1.18	0.84	3.13	1.21	1.60	0.99	4.06	1.37	1.29	0.84	3.34	1.19
W25O04	1.17	0.84	3.03	1.23	1.59	0.99	3.92	1.40	1.29	0.84	3.23	1.20
W25O05	1.17	0.84	2.90	1.22	1.58	0.99	3.76	1.38	1.28	0.84	3.09	1.19
W25P01	1.24	1.21	2.97	2.39	1.68	1.44	3.85	2.55	1.36	1.22	3.17	2.26
W25S05	1.06	1.26	2.56	2.51	1.44	1.51	3.34	2.78	1.16	1.27	2.73	2.39

Scenarios	2008 Flood				2017 Flood				2018 Flood			
	Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells		Without Relief Wells		With Relief Wells	
Relief Wells	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS	PIVL Model FoS	Blanket Theory FoS
W25T01	1.32	1.07	3.97	3.09	1.84	1.29	5.55	2.95	1.45	1.08	4.28	2.74
W25T02	1.32	1.07	3.92	2.43	1.83	1.29	5.47	2.51	1.44	1.08	4.22	2.25
W25T03	1.30	1.07	3.78	1.73	1.80	1.29	5.25	1.94	1.43	1.08	4.06	1.67
W25T04	1.29	1.07	3.68	4.04	1.78	1.29	5.10	3.65	1.41	1.08	3.95	3.47
W25T05	1.27	1.07	4.52	1.93	1.74	1.29	6.25	2.12	1.38	1.08	4.84	1.85
W25U01	1.95	1.44	5.42	3.21	2.60	1.74	7.02	3.60	2.10	1.45	5.72	3.06
W25U02	1.92	1.44	4.51	2.67	2.55	1.74	5.83	3.06	2.06	1.45	4.74	2.59
W25U03	1.90	1.44	4.52	3.18	2.51	1.74	5.84	3.58	2.04	1.45	4.74	3.04
W25U04	1.89	1.44	4.40	3.24	2.50	1.74	5.67	3.63	2.02	1.45	4.61	3.10
W25U05	1.88	1.44	4.07	4.44	2.48	1.74	5.25	4.77	2.01	1.45	4.27	4.12

8 Conclusions and Recommendations

Conclusions

The USGS MODFLOW-USG is a suitable model to simulate 3D seepage flow for levee underseepage investigation. The combination of CLN and DRN Packages formed the approach to simulate a one-dimensional relief well flow. The quadtree grid is sufficient to refine local mesh for levees and around relief wells for better resolution.

Rocscience RS3 is also a potential model to simulate 3D seepage, especially for investigating individual wells or an array of wells within a levee reach. Future work can encompass developing relief well boundary conditions in SEEP/W and RS3 to facilitate relief well design and performance analyses in the geotechnical field.

The PIVL model was calibrated to observed piezometric heads and measured discharge rates during the 1997 flood event. The modeling result is also qualitatively consistent with the observed discharges during the 2017 flood event. The PIVL model indicates that the significant piezometric head decrease (approximately 13 to 15 ft) from peak river stage to the relief wells was due to far seepage entrance at riverbed approximately 1,500 ft away from the relief well. Low discharge observed at Reaches 24K, 24M, and 24X and zero discharge observed at Reaches 24N and 24O are due to high top elevation of relief wells.

The PIVL model shows that without relief wells, at least 75% of relief well locations have FoS lower than 1.5 given the design flood stage 52.4 ft or higher. Given relief wells at the design condition, the PIVL model shows that relief wells may raise FoS above 1.5 for all reaches for the extreme flood scenario.

However, discharge data from the 2008 flood indicate that many relief wells at Reaches 24I, 24P, 24Y, 25A, 25B, 25M, 25N, 25O, 25P, 25S, 25T, and 25U may have deteriorated due to clogging. Field measurements of well flow and piezometric head are recommended to assess the current conditions of relief wells and re-validate the seepage model.

The blanket theory shows a conservative design. The estimated FoS by the blanket theory is much lower than that by the PIVL model. The model technique is applicable to other levees along the Mississippi River and tributaries for the New Orleans District and the Mississippi Valley Division.

Recommendations

The project identifies that many relief wells along Profit Island vicinity levee may have deteriorated due to clogging, specifically based on the 2008 measured data. New piezometric data and well discharge data are recommended to re-validate or re-calibrate the seepage model such that the model produces dependable FoS forecast for the levee for future high river stage events.

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Appendix: Data Sheets

Table A-1. Depth of sand and clay beds of 192 well logs (see Figure 7 for location). Log type: D for drillers' logs and E for electric logs. Log Datum is mainly ground level. Log Start is the starting depth of a well log, beginning with a clay bed. Well log data source: Louisiana Department of Natural Resources (LDNR) and USACE.

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
1	EB-1190		30.63583333	-91.27750000	D	94	0	45	75	140	200							
2	EB-1314		30.59777778	-91.25750000	E	90	115	141	279	645	676							
3	EB-1422		30.63472222	-91.27694444	E	86	60	60	77	123	197	202	281	350	429	444		
4	EB-8037Z		30.60888889	-91.26194444	D	89	0	120	130	150	210	220						
5	EB-8464Z		30.60555556	-91.26222222	D	80	0	12	27	93	101	143	318					
6	EB-8702Z		30.62000000	-91.26472222	D	47	0	120	160									
7	EB-8865Z		30.62500000	-91.28361111	D	40	0	80	180									
8	EB-9094Z		30.58750000	-91.26833333	D	35	0	120	180									
9	EB-9165Z		30.58750000	-91.26833333	D	35	0	160	200	440	460							
10	EB-9240Z		30.61555556	-91.27166667	D	35	0	120	160									
11	EB-9265Z		30.62694444	-91.27333333	D	43	0	140	220									
12	EB-9279Z		30.63333333	-91.27833333	D	86	0	120	200									
13	EB-9689Z		30.58722222	-91.26833333	D	42	0	125	180									
14	PC-83		30.61666667	-91.33861111	D	31	0	25	210	230	318	345	365	505	515	525	533	629
15	PC-111		30.63194444	-91.36555556	D	36	30	120	420	570	690	780	977	1331	1518			
16	PC-146		30.64305556	-91.34000000	E	33	51	51	207	239	285	298	343	423	491	579	713	
17	PC-166		30.63611111	-91.35972222	E	27	59	59	214	230	346	416	424	450	471	594	626	694
18	PC-176		30.64444444	-91.33333333	E	31	44	44	194	207	382	441	522	582	671			
19	PC-268		30.63388889	-91.35000000	D,E	35	2	54	259	268	350	488	550	595	726			

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
20	PC-273		30.60333333	-91.36111111	D	24	0	115	168									
21	PC-284		30.63694444	-91.31722222	D	32	0	25	45	55	280	281						
22	PC-362		30.60555556	-91.36833333	D	30	0	80	160									
23	PC-406		30.62527778	-91.36361111	D	23	0	56	88	105	157							
24	PC-5069Z		30.61583333	-91.36527778	D	33	0	100	170									
25	PC-5083Z		30.57111111	-91.36750000	D	21	0	95	162									
26	PC-5116Z		30.61138889	-91.35694444	D	26	1	80	210									
27	PC-5136Z		30.62805556	-91.36916667	D	30	2	147	195									
28	PC-5148Z		30.63250000	-91.32833333	D	30	0	28	148									
29	PC-5183Z		30.63388889	-91.35000000	D	35	4	60	100									
30	PC-5194Z		30.58388889	-91.36583333	D	20	0	63	132	139	145	148						
31	PC-5196Z		30.61583333	-91.36194444	D	33	0	100	140									
32	PC-5256Z		30.61027778	-91.35750000	D	26	0	80	180									
33	PC-5324Z		30.63361111	-91.34722222	D	25	3	44	53	148	200							
34	PC-5672Z		30.60000000	-91.33611111	D	30	0	120	148									
35	WBR-1		30.53333333	-91.37500000	D	18	10	90	180									
36	WBR-22		30.53527778	-91.34500000	D	15	0	20	286	296	351	391	414	445	550	782		
37	WBR-25		30.53388889	-91.29916667	D	28	0	112	298	341	448	490	512	617				
38	WBR-64		30.57750000	-91.32583333	D	29	21	21	300	343	353	410	422	555	585	623		
39	WBR-77		30.54055556	-91.35611111	D	20	0	75	251	732								
40	WBR-84		30.55750000	-91.33388889	D	24	76	76	254	299	340	410	560	846				
41	WBR-85		30.52944444	-91.34000000	D	20	0	105	275	760								

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
42	WBR-86		30.55694444	-91.33361111	E	25	0	80	188	210	260	267	276	309	350	407	438	487	549	594
43	WBR-90		30.57361111	-91.32527778	D	28	12	12	194	211	268	285	352	392	422	499	509	532	587	751
44	WBR-94		30.58000000	-91.32472222	D	30	0	30	235	535	550	630								
45	WBR-115		30.54583333	-91.30138889	D	27	44	44	238	250										
46	WBR-129B		30.60055556	-91.34638889	D,E	29	0	70	100	140	248	258	438	561	574	585	649	678		
47	WBR-133B		30.60083333	-91.34638889	E	29	0	98	106	142	252	258	446	564	584	592	659	700		
48	WBR-165		30.56111111	-91.33500000	D	23	0	80	110	210	241									
49	WBR-176		30.54138889	-91.36277778	E	20	0	100	105	116	242	274	324							
50	WBR-215		30.56000000	-91.27083333	D	35	0	60	160											
51	WBR-217		30.56000000	-91.27083333	D	30	0	12	190	192										
52	WBR-5016Z		30.56555556	-91.27388889	D	35	1	25	165	170	225	226								
53	WBR-5019Z		30.56555556	-91.27388889	D	36	1	25	180	205	450	480	490							
54	WBR-5023Z		30.59750000	-91.34416667	D	26	0	20	140	150	200									
55	WBR-5024Z		30.59777778	-91.33638889	D	25	0	20	160											
56	WBR-5028Z		30.56388889	-91.35500000	D	22	0	100	180											
57	WBR-5039Z		30.56222222	-91.37111111	D	18	1	80	167											
58	WBR-5048Z		30.55166667	-91.29444444	D	29	0	80	160											
59	WBR-5581Z	24I-1	30.59845000	-91.32135000	D	31	0	41	180											
60	WBR-5631Z		30.61250000	-91.33222222	D	29	10	110	250											
61	WBR-5637Z		30.60111111	-91.33472222	D	25	12	12	200											
62	WBR-5655Z		30.59666667	-91.35194444	D	31	0	50	55	85	150									

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
63	WBR-5656Z	24I-2	30.59817778	-91.32141389	D	31	0	31	41	46	81	86	167					
64	WBR-5657Z	24K-1	30.59783611	-91.32140278	D	35.5	0	41	46	61	111							
65	WBR-5658Z	24K-2	30.59746111	-91.32148056	D	35.5	0	30	70	75	90	95	148					
66	WBR-5659Z	24M-1	30.59708611	-91.32158611	D	34.5	0	38	116									
67	WBR-5660Z	24M-2	30.59681111	-91.32165556	D	34.5	0	30	35	40	115							
68	WBR-5661Z	24M-3	30.59654722	-91.32171944	D	34.5	0	15	20	35	115							
69	WBR-5662Z	24M-4	30.59627778	-91.32177222	D	34.5	0	30	35	45	130							
70	WBR-5683Z		30.55972222	-91.29027778	D	27	0	10	20	120	200							
71	WBR-5685Z		30.60250000	-91.32333333	D	30	10	10	210									
72	WBR-5701Z	24M-5	30.59601111	-91.32184722	D	34.5	0	20	105									
73	WBR-5702Z	24M-6	30.59574167	-91.32191389	D	34.5	0	15	30	45	105							
74	WBR-5703Z	24M-7	30.59546667	-91.32194722	D	34.5	0	35	40	45	105							
75	WBR-5704Z	24M-8	30.59519444	-91.32201944	D	34.5	0	30	35	50	105							
76	WBR-5705Z	24M-9	30.59493056	-91.32209722	D	34.5	0	30	35	40	55	60	115					
77	WBR-5706Z	24M-10	30.59465833	-91.32215833	D	34.5	0	45	60	65	124							
78	WBR-5707Z	24N-1	30.59438333	-91.32218333	D	36	0	31	36	46	126							
79	WBR-5708Z	24N-2	30.59398333	-91.32226389	D	36	0	5	20	41	86	91	116					
80	WBR-5709Z	24N-3	30.59363056	-91.32233333	D	36	0	15	20	25	36	46	101					
81	WBR-5710Z	24O-1	30.59330833	-91.32242778	D	36	0	15	25	41	106							
82	WBR-5711Z	24O-2	30.59304722	-91.32250556	D	36	0	36	41	46	96							
83	WBR-5712Z	24P-1	30.59282778	-91.32262500	D	30.5	0	10	46	51	151							
84	WBR-5713Z	24P-2	30.59260000	-91.32268611	D	30.5	0	17	25	30	36	41	46	51	124			

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
85	WBR-5714Z	24P-3	30.59222500	-91.32276944	D	30.5	0	19	36	41	134							
86	WBR-5715Z	24P-4	30.59183889	-91.32286944	D	30.5	0	36	134									
87	WBR-5716Z	24Q-1	30.59157222	-91.32291944	D	31.5	0	42	125									
88	WBR-5717Z	24Q-2	30.59130278	-91.32298889	D	31.5	0	0	2	10	37	42	125					
89	WBR-5718Z	24S-1	30.59103333	-91.32304722	D	31.5	0	5	37	42	125							
90	WBR-5719Z	24S-2	30.59077778	-91.32310000	D	31.5	0	42	125									
91	WBR-5720Z	24S-3	30.59051944	-91.32315278	D	31.5	0	42	125									
92	WBR-5721Z	24S-4	30.59026111	-91.32320278	D	31.5	0	20	30	47	125							
93	WBR-5722Z	24S-5	30.59000556	-91.32325833	D	31.5	0	42	125									
94	WBR-5723Z	24S-6	30.58974722	-91.32332222	D	31.5	0	37	42	47	125							
95	WBR-5724Z	24S-7	30.58948889	-91.32338333	D	31.5	0	47	125									
96	WBR-5725Z	24S-8	30.58923333	-91.32343889	D	31.5	0	51	126									
97	WBR-5701Z	24M-5	30.59601111	-91.32184722	D	34.5	0	20	105									
98	WBR-5702Z	24M-6	30.59574167	-91.32191389	D	34.5	0	15	30	45	105							
99	WBR-5728Z	24S-11	30.58845833	-91.32363056	D	31.5	0	20	32	36	130							
100	WBR-5729Z	24U-1	30.58822778	-91.32369167	D	31.5	0	37	45	50	125							
101	WBR-5730Z	24U-2	30.58798333	-91.32372500	D	31.5	0	20	125									
102	WBR-5731Z	24U-3	30.58773611	-91.32377500	D	32	0	38	125									
103	WBR-5732Z	24W-1	30.58719444	-91.32388611	D	32	0	51	115									
104	WBR-5733Z	24X-1	30.58665278	-91.32402222	D	32	0	23	34	51	115							
105	WBR-5734Z	24X-2	30.58641667	-91.32408056	D	32	0	22	35	57	115							
106	WBR-5735Z	24X-3	30.58617222	-91.32413611	D	32	0	48	52	60	115							
107	WBR-5736Z	24X-4	30.58592500	-91.32417778	D	32	0	33	115									

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
108	WBR-5737Z	24X-5	30.58568333	-91.32423333	D	32	0	52	115									
109	WBR-5738Z	24X-6	30.58533889	-91.32425556	D	32	0	30	125									
110	WBR-5739Z	24X-7	30.58509722	-91.32423333	D	32	0	57	135									
111	WBR-5740Z	24X-8	30.58484722	-91.32420000	D	32	0	23	35	39	126							
112	WBR-5741Z	24Y-1	30.58460000	-91.32420833	D	30.5	0	17	53	70	80	90	125	140	159			
113	WBR-5742Z	24Y-2	30.58435833	-91.32417222	D	30.5	0	47	65	100	149							
114	WBR-5743Z	24Y-3	30.58411111	-91.32415556	D	30.5	0	29	35	48	75	105	154					
115	WBR-5744Z	25A-1	30.58368889	-91.32410000	D	31.5	0	37	70	106	185							
116	WBR-5745Z	25A-2	30.58308611	-91.32403889	D	31.5	0	23	77	121	199							
117	WBR-5746Z	25B-1	30.58248333	-91.32396667	D	31.5	0	34	80	112	185							
118	WBR-5747Z	25B-2	30.58187778	-91.32389722	D	31.5	0	25	68	85	180							
119	WBR-5748Z	25C-1	30.58134722	-91.32385278	D	32	0	35	42	46	155							
120	WBR-5749Z	25C-2	30.58085556	-91.32377778	D	32	0	33	49	87	155							
121	WBR-5750Z	25C-3	30.58036389	-91.32373333	D	32	0	37	56	107	175							
122	WBR-5751Z	25G-1	30.57983333	-91.32360278	D	33.5	0	56	149									
123	WBR-5752Z	25G-2	30.57931944	-91.32350000	D	33.5	0	80	152									
124	WBR-5753Z	25G-3	30.57880556	-91.32339722	D	33.5	0	82	152									
125	WBR-5754Z	25G-4	30.57829722	-91.32328611	D	33.5	0	28	35	60	149							
126	WBR-5755Z	25K-1	30.57790000	-91.32314444	D	33.5	0	28	38	40	49	69	149					
127	WBR-5756Z	25M-1	30.57740556	-91.32307778	D	31	0	38	45	60	119							
128	WBR-5757Z	25M-2	30.57692222	-91.32295000	D	31	0	45	159									
129	WBR-5758Z	25N-1	30.57643611	-91.32286389	D	30	0	35	138									

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
130	WBR-5759Z	25N-2	30.57590000	-91.32271111	D	30	0	28	40	49	143							
131	WBR-5760Z	250-1	30.57565556	-91.32265556	D	30	0	80	168									
132	WBR-5761Z	250-2	30.57534722	-91.32253889	D	30	0	27	49	70	175							
133	WBR-5762Z	250-3	30.57517500	-91.32243056	D	30	0	33	113									
134	WBR-5763Z	250-4	30.57503611	-91.32234444	D	30	0	28	133									
135	WBR-5764Z	250-5	30.57491389	-91.32226389	D	30	0	23	123									
136	WBR-5765Z	25P-1	30.57482222	-91.32220000	D	31	0	35	197									
137	WBR-5766Z	25S-5	30.56968611	-91.31833333	D	31	0	60	120	133	229							
138	WBR-5767Z	25T-1	30.56962500	-91.31816111	D	32	0	29	122	135	185							
139	WBR-5768Z	25T-2	30.56953889	-91.31795278	D	32	0	31	47	70	125	135	177					
140	WBR-5769Z	25T-3	30.56942500	-91.31759444	D	32	0	30	127	150								
141	WBR-5770Z	25T-4	30.56935000	-91.31727778	D	32	0	43	185									
142	WBR-5771Z	25T-5	30.56929444	-91.31685000	D	32	0	90	155									
143	WBR-5772Z	25U-1	30.56922222	-91.31641944	D	31	0	90	157									
144	WBR-5773Z	25U-2	30.56918333	-91.31598889	D	31	0	60	162									
145	WBR-5774Z	25U-3	30.56916944	-91.31559444	D	31	0	60	134	139	177							
146	WBR-5775Z	25U-4	30.56916111	-91.31540278	D	31	0	60	174									
147	WBR-5776Z	25U-5	30.56915556	-91.31525000	D	31	0	60	188									
148	WBR-5777Z	P24IC	30.59800500	-91.32093900	D	30	0	50	121									
149	WBR-5778Z	P24IF	30.59806600	-91.32145900	D	38	0	35	95									
150	WBR-5779Z	P24IW	30.59809700	-91.32173000	D	49	0	35	117									

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
151	WBR-5780Z	P24MD	30.59700700	-91.32262500	D	34	0	35	87									
152	WBR-5781Z	P24ND	30.59464100	-91.32314500	D	33	0	35	94									
153	WBR-5782Z	P24SW	30.58911200	-91.32347400	D	48	0	35	95									
154	WBR-5783Z	P24UC	30.58757100	-91.32335000	D	31	0	50	121									
155	WBR-5784Z	P24UD	30.58777500	-91.32446300	D	40	0	35	92									
156	WBR-5785Z	P24UF	30.58771600	-91.32415100	D	40	0	35	91									
157	WBR-5786Z	P24UW	30.58767600	-91.32383900	D	52	0	35	92									
158	WBR-5787Z	P24XW	30.58604800	-91.32416900	D	34	0	35	96									
159	WBR-5788Z	P24YW	30.58456800	-91.32418400	D	45	0	38	111									
160	WBR-5789Z	P25BW	30.58206600	-91.32396700	D	49	0	40	143									
161	WBR-5790Z	P25GW	30.57958000	-91.32357100	D	49	0	37	126									
162	WBR-5791Z	P25MW	30.57713900	-91.32313400	D	49	0	37	136									
163	WBR-5792Z	P25NW	30.57616000	-91.32278600	D	49	0	37	123									
164	WBR-5793Z	P25OC	30.57536500	-91.32198600	D	32	0	52	114									
165	WBR-5794Z	P25OD	30.57499600	-91.32279500	D	32	0	35	81									
166	WBR-5795Z	P25OF	30.57507500	-91.32262700	D	32	0	39	82									
167	WBR-5796Z	P25OW	30.57514500	-91.32243800	D	36	0	35	96									
168	WBR-5797Z	P25PW	30.57460800	-91.32206200	D	35	0	34	98									
169	WBR-5798Z	P25QW	30.57250000	-91.32083300	D	31	0	40	92									
170	WBR-5799Z	P25SW	30.57088800	-91.31971700	D	53	0	37	97									
171	WBR-5800Z	P25TC	30.56976600	-91.31737000	D	55	0	51	147									
172	WBR-5801Z	P25TD	30.56885800	-91.31762500	D	27	0	34	118									

No.	Well Name (LDNR)	Well Name (USACE)	Latitude (deg.)	Longitude (deg.)	Log Type	Log Datum (ft)	Log Start (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)	Clay (ft)	Sand (ft)
173	WBR-5802Z	P25TF	30.56913600	-91.31755800	D	29	0	39	120	173								
174	WBR-5803Z	P25TW	30.56938800	-91.31748100	D	33	0	35	124									
175	WBR-5805Z		30.55333333	-91.26277778	D	37	0	12	51	70	150							
176	WBR-5806Z		30.55333333	-91.26333333	D	36	0	12	51	70	100							
177	WBR-5807Z		30.55305556	-91.26277778	D	37	0	12	51	70	100							
178	WBR-5827Z		30.55333333	-91.35000000	D	22	0	10	14									
179	WBR-5828Z		30.55333333	-91.35000000	D	22	0	10	14									
180	WBR-5829Z		30.55333333	-91.35000000	D	22	0	10										
181	WBR-5830Z		30.55333333	-91.35000000	D	22	0	10										
182	WBR-5831Z		30.55333333	-91.35000000	D	22	0	10										
183	WBR-5832Z		30.55333333	-91.35000000	D	22	0	14										
184	WBR-5833Z		30.55333333	-91.35000000	D	22	0	14										
185	WBR-5862Z		30.55194444	-91.26805556	D	45	0	47	187									
186	WBR-5905Z		30.63083333	-91.31055556	D	40	0	230	340	480	510	520						
187	WBR-5913Z		30.60638889	-91.34527778	D	30	0	60	180									
188	WBR-5947Z		30.56083333	-91.36555556	D	24	10	110	140									
189	WBR-5949Z		30.59138889	-91.34583333	D	25	0	20	140									
190	WBR-6016Z		30.52861111	-91.36638889	D	16	2	30	120									
191	WBR-6017Z		30.53833333	-91.33777778	D	19	0	80	150									
192	WBR-6018Z		30.57055556	-91.34583333	D	16	0	105	150									

Table A-2. Top elevation of rubber well gasket on the riser pipe and screens of relief wells.

Relief well	Top of Rubber Well Gasket (ft)	Top of screen (ft)	Bottom of screen (ft)	Relief well	Top of Rubber Well Gasket (ft)	Top of screen (ft)	Bottom of screen (ft)
24I-1	31.01	-107.4	-147.4	24X-5	32.01	-39.9	-79.9
24I-2	31.04	-64.7	-79.7	24X-6	32.05	-50.2	-90.2
24I-2	31.04	-109.7	-134.7	24X-7	32.15	-60.2	-100.2
24K-1	35.53	-34.7	-74.7	24X-8	32.01	-49.9	-89.9
24K-1	35.53	-109.7	-134.7	24Y-1	30.53	-70.1	-95.1
24K-2	35.53	-47.5	-52.5	24Y-1	30.53	-110.1	-125.1
24K-2	35.53	-72.5	-107.5	24Y-2	30.53	-75.1	-115.1
24M-1	34.50	-35.3	-75.3	24Y-3	30.53	-80	-120
24M-2	34.48	-35.5	-75.5	25A-1	31.57	-85.2	-150.2
24M-3	34.50	-36.6	-76.6	25A-2	31.55	-97	-162
24M-4	34.51	-24.9	-34.9	25B-1	31.52	-90.6	-150.6
24M-4	34.51	-59.9	-89.9	25B-2	31.51	-79.7	-139.7
24M-5	34.54	-25.2	-65.2	25C-1	31.95	-75.2	-120.2
24M-6	34.53	-20.1	-60.1	25C-2	32.03	-75	-120
24M-7	34.51	-24.1	-64.1	25C-3	32.00	-84.8	-104.8
24M-8	34.51	-23.8	-63.8	25C-3	32.00	-114.8	-139.8
24M-9	34.50	-34.9	-74.9	25G-1	33.50	-65.7	-105.7
24M-10	34.51	-44.5	-84.5	25G-2	32.00	-84.8	-104.8
24N-1	36.02	-45	-85	25G-2	32.00	-114.8	-139.8
24N-2	36.06	-20	-45	25G-3	33.54	-75.1	-115.1
24N-2	36.06	-65	-80	25G-4	33.50	-60.1	-100.1
24N-3	36.00	-24.8	-64.8	25K-1	33.51	-50.2	-90.2
24O-1	36.00	-29.8	-69.8	25M-1	30.99	-45	-85
24O-2	35.99	-20	-60	25M-2	30.96	-85.3	-125.3
24P-1	30.52	-24.4	-59.4	25N-1	30.02	-65.6	-105.6
24P-1	30.52	-69.4	-79.4	25N-2	30.02	-70.4	-110.4
24P-1	30.52	-104.4	-114.4	25O-1	30.03	-69.3	-99.3
24P-2	30.50	-25	-90	25O-1	30.03	-124.3	-134.3
24P-3	30.47	-35.2	-100.2	25O-2	30.00	-73.8	-98.8
24P-4	30.49	-34.6	-99.6	25O-2	30.00	-123.8	-138.8

Relief well	Top of Rubber Well Gasket (ft)	Top of screen (ft)	Bottom of screen (ft)	Relief well	Top of Rubber Well Gasket (ft)	Top of screen (ft)	Bottom of screen (ft)
24Q-1	31.51	-24.8	-89.8	250-3	30.02	-40.5	-80.5
24Q-2	31.51	-25.1	-90.1	250-4	29.74	-60.2	-100.2
24S-1	31.51	-24.9	-89.9	250-5	29.99	-48.3	-88.3
24S-2	31.51	-24.8	-89.8	25P-1	30.52	-127.1	-167.1
24S-3	31.53	-24.6	-89.6	25S-5	30.94	-118.7	-148.7
24S-4	31.50	-24.8	-89.8	25S-5	30.94	-173.7	-193.7
24S-5	31.57	-24.8	-89.8	25T-1	31.97	-64.3	-89.3
24S-6	31.50	-24.6	-89.6	25T-1	31.97	-124.3	-154.3
24S-7	31.51	-24.8	-89.8	25T-2	31.96	-59.8	-84.8
24S-8	31.51	-30	-95	25T-2	31.96	-109.8	-139.8
24S-9	31.51	-25	-90	25T-3	31.96	-59.9	-114.9
24S-10	31.52	-25.7	-90.7	25T-4	31.93	-74.1	-94.1
24S-11	31.53	-30.2	-95.2	25T-4	31.93	-114.1	-149.1
24U-1	31.53	-24.5	-89.5	25T-5	31.98	-65	-120
24U-2	31.52	-24.8	-89.8	25U-1	30.95	-80.8	-120.8
24U-3	31.50	-25.2	-90.2	25U-2	30.95	-87.9	-127.9
24W-1	32.00	-41.1	-81.1	25U-3	30.95	-73.2	-93.2
24X-1	32.01	-40.7	-80.7	25U-3	30.95	-118.2	-138.2
24X-2	32.01	-41.2	-81.2	25U-4	30.96	-74.6	-94.6
24X-3	32.17	-41.4	-81.4	25U-4	30.96	-119.6	-139.6
24X-4	32.01	-39.9	-79.9	25U-5	30.94	-114.6	-154.6

Acronyms and Abbreviations

2D	two-dimensional
3D	three-dimensional
CLN	Connected Linear Network
DEM	Digital elevation model
DRN	Drain
FoS	factor of safety
FSKIN	skin factor
GHB	General-Head Boundary
LDNR	Louisiana Department of Natural Resources
NGVD 29	National Geodetic Vertical Datum of 1929
PIVL	Profit Island Vicinity Levee
RM	River Mile
RMSE	root-mean-square error
USACE	US Army Corps of Engineers
USGS	US Geological Survey
UTM	Universal Transverse Mercator
WES	Waterways Experiment Station

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