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The Investigation Of Okhissa Dam Using A Real-Time Monitoring System

Corey Alexander Hamil
University of Mississippi

THE INVESTIGATION OF OKHISSA DAM USING A REAL-TIME MONITORING SYSTEM

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Corey A. Hamil

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ABSTRACT

According to the National Inventory of Dams (NID), the United States has approximately 87,000 dams. Many of these dams are more than 50 years old and need to be investigated to ensure their safety to the public. A real time monitoring system can obtain a more reliable evaluation of the dam's performance as well as serve as an early warning system to inform officials of a dam's condition.

Okhissa Dam was selected for investigation using a real-time monitoring system. Okhissa Dam is located in a region that contains both a phreatic aquifer and a confined aquifer. Prior to this investigation of Okhissa Dam artesian conditions were present. The Artesian conditions were alleviated by placing additional fill material on the downstream side. It is presumed these high piezometric water levels resulted from pressure in the aquifer due to communication from Okhissa Lake. The goal of this investigation is to determine if the reservoir is influencing the piezometric water levels and how these water levels can be used to evaluate slope stability and provide a real time warning.

The comparison of water levels recorded by the shallow and deep piezometers to reservoir water levels show the reservoir has no influence on the shallow phreatic aquifer. However, the reservoir water levels are potentially affecting the deeper confined aquifer water levels. The largest fluctuation in the groundwater levels occurred with the intentional reduction of two feet in the reservoir level on December 16, 2014. This would have been the best predictor of variation in groundwater elevations at the dam, but the reservoir data was not collected due to sensor damage.

Using the software GeoStudio Slope/W® Student Version, the dam is analyzed for slope stability. Okhissa Dam was analyzed for slope stability under conditions of steady state seepage and rapid drawdown. The results of steady state seepage analysis exceed the minimum design factor of safety of 1.5. The analysis for rapid drawdown is approximated due to insufficient knowledge of the behavior between the piezometric line and the upstream slope soils. The real time factor of safety readings show Okhissa Dam is stable.

DEDICATION

This thesis is dedicated to my beloved Pa-paw who will always be with me in my heart and continue to look after me and my family from the heavens. I want to thank my family, who without their support system, I could not have done this. I doubted myself many days if this could be accomplished and if I could really do this, but not one single day did they doubt me. I just want to thank them from the bottom of my heart for the support and guidance they have always given me. Without their support I would not have this opportunity. I want to thank God for this moment, and providing me the strength and determination to complete this endeavor.

LIST OF ABBREVIATIONS AND SYMBOLS

NID	National Inventory of Dams
MARIS	Mississippi Automated Resource Information System
MDEQ	Mississippi Department of Environmental Quality
USDA	United States Department of Agriculture
NRCS	Natural Resource Conservation Service
FS	Factor of safety
USACE	United States Army Corp of Engineers
ASCE	American Society of Civil Engineers
ASDSO	Association of State Dam Safety Officials
FERC	Federal Energy Regulatory Commission
ADAS	Automated Data Acquisition System
EMS	Engineered Monitoring Solutions
USSD	United States Society on Dams
USBR	United States Department of Interior, Bureau of Reclamation
PZ	Piezometer (confined aquifer)
GOW	Groundwater Observation Well (phreatic aquifer)
PWP	Pore Water Pressure
P	Pressure
G	Linear gage factor
R_1	Field reading

R_0	Initial factory reading
K	Thermal factor
T_1	Field temperature reading
T_0	Initial factory temperature reading
γ_d	Dry unit weight of soil material
ϕ	Angle of friction for total stress
c	Cohesion for total stress
ϕ'	Angle of friction for effective stress
c'	Cohesion for effective stress
CL	Center line of dam
USCS	Unified Soil Classification System
CU	Consolidated undrained
UU	Unconsolidated undrained
CU'	Consolidated undrained with effective stresses
k	Permeability of soil
Δh	Change in water head
V	Voltage
I	Current
USGS	United States Geological Survey
NCPA	National Center for Physical Acoustics
z	Thickness of overburden
γ_b	Buoyant unit weight of overburden
H	Excess water head above ground surface or free water surface

RH	Relative Humidity
BP	Barometric Pressure
BCD	Burns Cooley Dennis, Inc.
NIST	National Institute of Standards and Technology
TVA	Tennessee Valley Authority
WSDE	Washington State Department of Ecology
SPT	Standard Penetration Test

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I want to thank the United States Department of Agriculture (USDA) for the funding of this project.

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1. INTRODUCTION

1.1 Introduction to dams

A dam is a water retaining structure designed to restrict flow of water into a specific region. Our nation's dams provide essential benefits such as drinking water, irrigation, hydropower, flood control, and recreation. The safe operation and proper maintenance of these dams is critical to sustaining their provided benefits while preventing the possibility of a dam failure. The widespread purposes dams shown in Figure 1.1 displays how vital dams are to the national infrastructure of the United States.

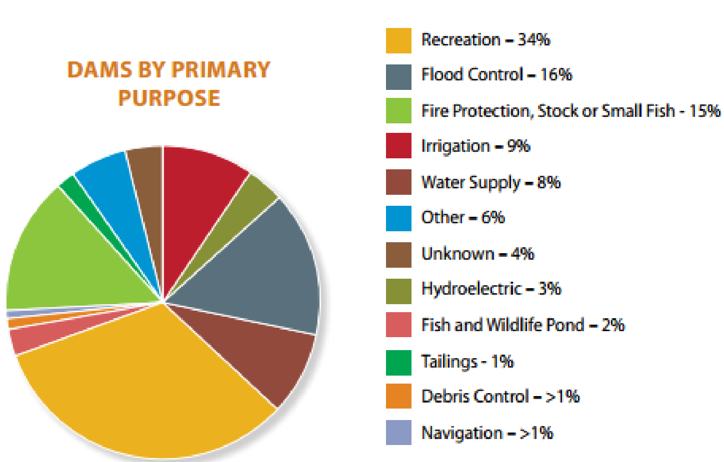

Figure 1.1: Primary purpose of the nations' dams (Dam Safety, 2012)

The National Inventory of Dams (NID) is a database managed by the Army Corps of Engineers (USACE) which contains information about dams all across the United States. According to the NID (2013) database, there are currently over 87,000 dams in the United States.

According to the American Society of Civil Engineers (ASCE), the average age of America's dams is 52 years, which surpasses the design life. It is stated, by 2020 nearly 70 percent of the dams in the United States will be 50 years or older (ASCE, 2013). There are approximately 4,000 deficient dams in the United States, 2,000 of which are high-hazard dams (ASCE, 2013).

The American Society of Dam Safety Officials (ASDSO) estimates an investment of $21 billion will be necessary to restore this critical component of the United States' aging infrastructure (ASDSO, 2014). The distribution of Mississippi's 3,630 dams can be seen in Figure 1.2 (NID, 2013). The NID database shows that 422 dams within the state of Mississippi were completed in the early 1960s and before. This makes 422 dams 50 years or older, thus reaching the lifespan of the original design of these structures (NID, 2013). This concern of aging dams requires more investigation and monitoring in order to maintain and / or institute necessary remediation techniques to restore dams to a level of high efficiency (NID, 2013).

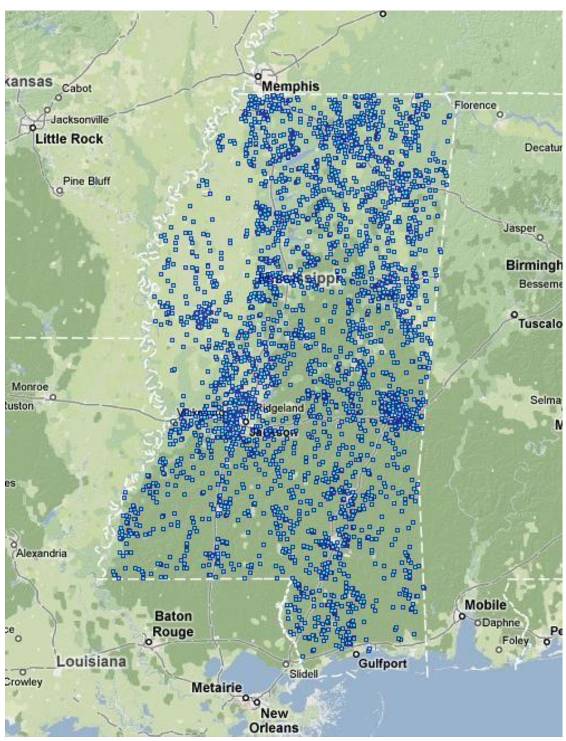

Figure 1.2: Distribution of dams in Mississippi (NID, 2013)

The 2013 infrastructure report card created by the ASCE gave America's dams a "D" grade, which is considered poor condition (ASCE, 2013). Many of these dams were built in low hazard areas with small populations and limited urban development with the primary purpose to protect underdeveloped agricultural land. However, limited population and minimal urban growth are no longer the case. The overall number of high-hazard dams continues to increase and was estimated to be 14,000 in 2012.

Dams are assigned to one of three classes: low, significant or high hazard. Dam classification is determined by the amount of damage that would occur downstream in the event of a dam breach (MDEQ, 2001). Dam classification criteria also includes: the effect of the public's confidence due to a failure, stability of materials, size of population and urbanization downstream, and potential future developments as shown in Table 1.1.

Table 1.1: Classes of dams (NRCS, 2005)

Dam Classification	
Classification	**Attributes**
Low Hazard Class	Dams located in rural or agricultural areas where failure may damage farm buildings, agricultural land, or township and country roads.
Significant Hazard Class	Dams located in predominantly rural or agriculture areas where failure may damage isolated homes, main highways or minor railroads, or cause interruption of use or service of relatively important public utilities.
High Hazard Class	Dams located where failure may cause loss of life, serious damage to homes, industrial and commercial buildings, important public utilities, main highways, or railroads.

Concrete and earthen embankments are the two most common types of dams in the United States (NID, 2013). Nearly 86% of the nation's dams are earthen embankments (NID, 2013). Figure 1.3 shows the national distribution of types of dams. The population of dams within Mississippi consists of nearly 100% earthen embankment dams.

Mississippi's dams received a grade of "D" from the ASCE. Mississippi does not have a substantial number of high hazard dams due to the low population densities. There is concern that dams and levees in the state are not being sufficiently monitored as Mississippi ranks as one of the lowest states in funding and staffing per dam (ASCE, 2013).

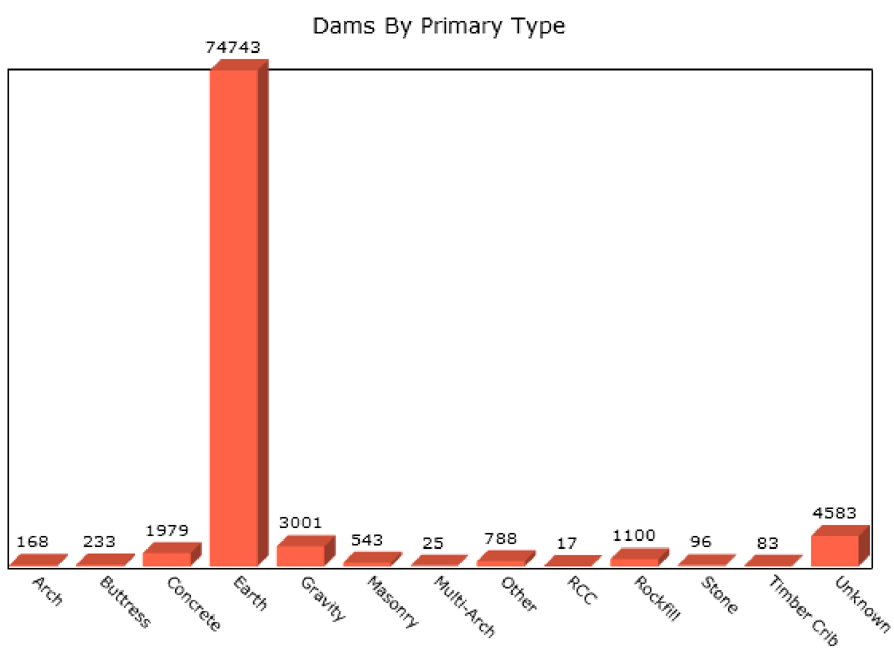

Figure 1.3: National dam distribution by type (NID, 2013)

Various entities hold the right to dam ownership, including: federal, state, local, and private ownership. The NID shows that 65% of the United States' dams are privately owned, and 78% of Mississippi's dams are privately owned (NID, 2013).

According to the ASCE, the federal government owns 3,225 dams, or approximately 4%. Surprisingly, the USACE only owns 694 dams; state agencies regulate more than 80% of the nation's dams. A breakdown of national dam ownership entities is displayed in Figure 1.4 (NID, 2013). Privately owned dams are maintained by the individual owner(s). The maintenance includes inspections and continuous monitoring to identify existing cracks and erosion processes (Pagano, Fontanella, Sica & Desideri, 2010).

The general upkeep of these dams, whether they are privately owned or maintained by federal, state, or local authorities, is critical to the welfare of the public as well as to economic and environmental prosperity (NRCS, 2005).

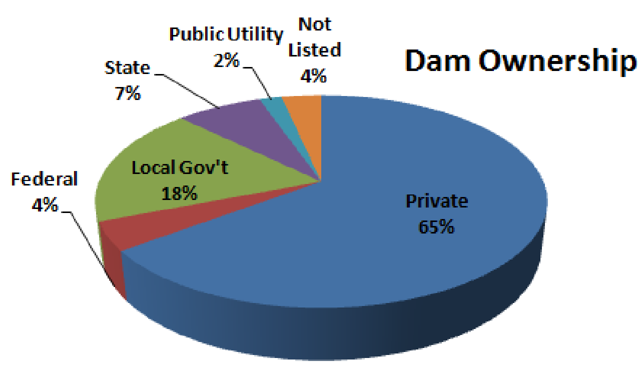

Figure 1.4: Dam ownership across the United States (ASDSO, 2013)

1.2 Failure of dams

The Washington State Department of Ecology (WSDE) investigated the national dam failure types, then categorized the failures into four key failure types: overtopping, foundation defects, piping and seepage, and conduits and valves. The chart in Figure 1.5 indicates the percentage of each failure type.

The major causes of earthen embankment failure are overtopping, foundation and structural defects, and piping, as well as additional failure causes may exist for individual structures (Wu, 2011).

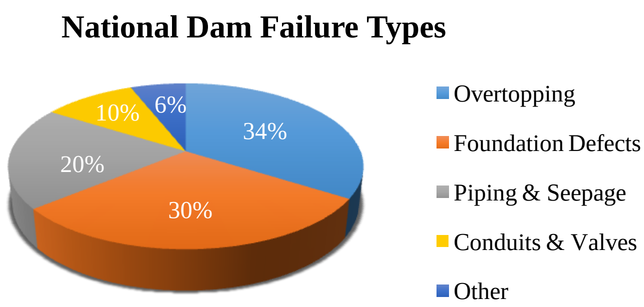

Figure 1.5: Dam failure types (WSDE, 2013)

The leading cause of failure, overtopping, causes 34% of national dam failures. Overtopping can be the result of an inadequate spillway design, a blocked spillway, or the settlement of the dam crest (Case, 2012). The second most common type of failure is foundation defects, the cause of 30% of dam failures across the United States. This type of failure can be the result of slope instability, high uplift pressures, or foundation seepage. The third most common type of dam failure is piping and seepage, which leads to 20% of dam failures in the United States (WSDE, 2013). The effects of piping and seepage lead to erosion of the dam's core material and cracks in the dam, both of which weaken the structural integrity of the dam. The fourth type of dam failure results from conduit and valve deterioration of the dam, and accounts for 10% of dam failures across the United States. These failures are caused by material being washed into the conduit through the joints and / or cracks. The remaining 6% of dam failures across the United States is currently undetermined (Case, 2012).

The failure of embankment dams poses a threat to the surrounding economy, environment, and public. As the dams age, and as the population of a particular area continues to increase, the danger of a catastrophic failure continues to grow. The ASDSO reported 173 dam failures and 587 incidents compromising the integrity or safety of dams across the United States (ASDSO, 2013).

Figure 1.6 is a map that includes all ASDSO reported dam failures prior to 1900 through 2014. The figure displays the approximate location of these failures, the range of years in which they occurred (circle color), and the related fatalities (circle size). The large red dot is New Orleans, Louisiana, and represents the levee failures of 2005 due to Hurricane Katrina (ASDSO, 2014).

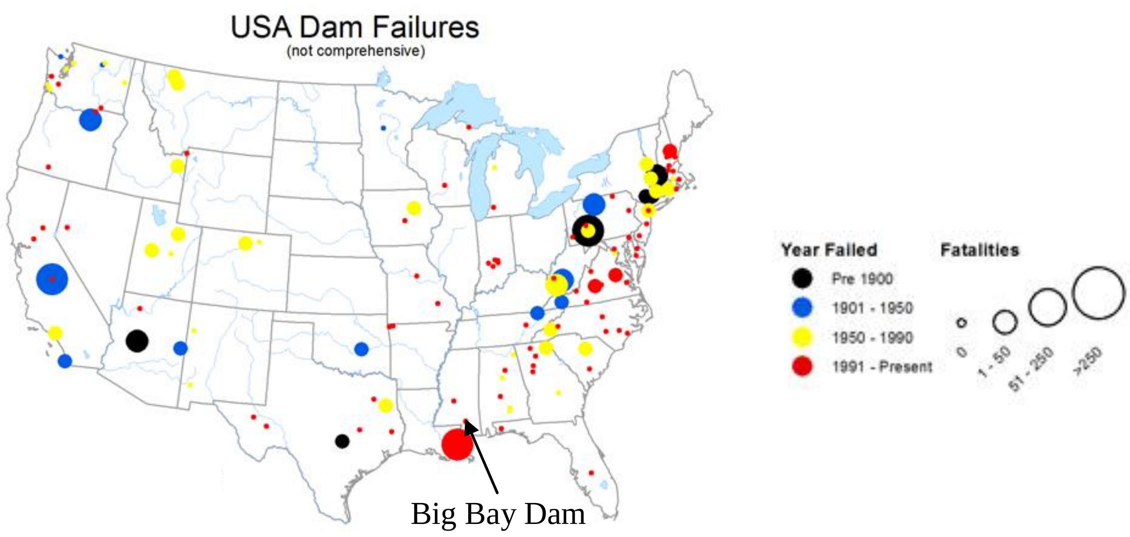

Figure 1.6: Locations of dam failures from pre-1900 to present (ASDSO, 2014)

The labeled red dot in the lower Mississippi area in Figure 1.6 indicates the failure of the Big Bay Dam in Lamar County, MS. The Dam embankment failed on March 12, 2004, releasing 17,500,000 cubic meters (14,200 acre-feet) of water.

The Dam failed due to a breach in the vicinity of the principal spillway. The total account of damage from the dam breach included 104 structures with no injuries or fatalities (Yochum, Goertz, & Jones, 2008).

The poor condition of our nation’s dam infrastructure is a result of the lack of funding and resources needed to oversee the extensive dam network. The Federal Energy Regulatory Commission (FERC) controls only 2,600 dams across the United States, and the remaining dams rely on individual state dam safety programs for inspection. State dam safety programs retain the responsibility of permitting, inspecting, and enforcing authority for 80% of the United States’ dams (NRCS, 2005). Therefore, state dam safety programs have the responsibility for public safety, but unfortunately, many state programs lack sufficient resources and are managed with ineffective regulatory authority. For example, Mississippi’s dam safety program has on average four full-time employees that each oversee approximately 855 state regulated dams (ASCE, 2013). Mississippi provides $433,862 for dam safety, ranking as one of the lowest states in dam safety funding and staffing per dam (ASCE, 2013). Many state dam safety programs are operating with limited resources, which restrict the critical inspections needed and regulatory actions necessary to properly maintain the nation’s dam infrastructure. The number of dams needing repair continues to grow, while the funding required increases.

1.3 Previous work with monitoring systems

The use of instrumentation to monitor the performance of dams is becoming a primary component of a successful dam safety program. A monitoring system provides continuous data needed for an effective dam analyses and provides an early warning of critical conditions affecting the dam (Dunnicliff, 1993).

A monitoring system is implemented to characterize site conditions, monitor construction activities, and aspects of the dam's performance (e.g.: pore pressure, settlement, deformation, and seepage). However, an implemented monitoring system is not a substitute for regular visual inspections of a dam, which are an essential part of a dam safety program (Carter, Hosko & Rubertis, 2000).

The complexity of dam monitoring systems can range from a simplified system that measures one characteristic to a highly elaborate system (Mullaney, 2009). Researchers at Rensselaer Polytechnic Institute (RPI) are developing a comprehensive system for monitoring and assessing the condition of dams and levees in the United States. This project is funded by the United States National Institute of Standards and Technology (NIST). The project includes three integrated systems to form a "smart network" that provides a long-term continuous assessment of dams from both underground and aerial perspective. The goal is to collect data and pair it with computational simulation methods to build accurate and predictive models of how different dams should react to different environmental conditions. Figure 1.7 demonstrates the field setup for the continuous monitoring system developed by Rensselaer Polytechnic Institute (Mullaney, 2009).

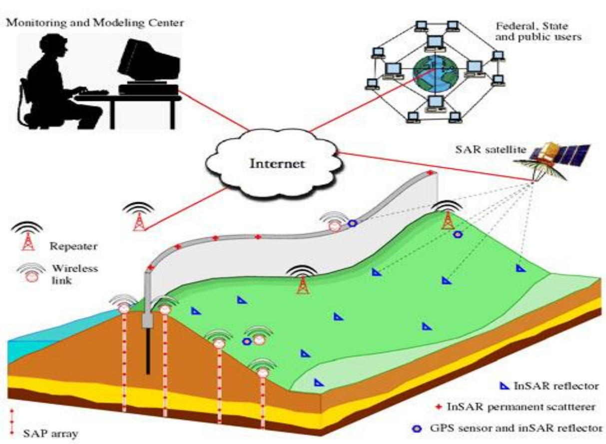

Figure 1.7: Continuous monitoring system proposed by RPI (Mullaney, 2009)

Fern Ridge Dam in Eugene, Oregon is owned and operated by the USACE. This Dam is used for flood control and irrigation to surrounding agriculture. A real time monitoring system was installed once depressions were noticed along the dam's surface. Turbid water was seen flowing from the internal drainage system, leading to the assumption that internal erosion (piping) was occurring. The monitoring plan included retrofitting the existing standpipe piezometers with 59 automated vibrating wire piezometers to allow continuous monitoring of the piezometric water elevations. The monitoring system is equipped to measure and log pore water levels, reservoir levels, seepage flow, turbidity, barometric changes, and rainfall. The system uses spread spectrum radios, CR1000 data logger and a cellular modem for data transmission, communication and collection. The goal of the Fern Ridge Dam monitoring system is to collect piezometric elevation data to establish warning level criteria and establish a dataset that is collected by an automated system (Myers & Scofield, 2008).

Diamond Valley Lake is located 75 miles north of San Diego is instrumented with a real time monitoring system that includes vibrating wire piezometers. The existing Casagrande piezometers were retrofitted with vibrating wire piezometers and automated data collection. The vibrating wire piezometers record the development of pore water pressures in the dam's core during construction and its response to the initial reservoir fill. (Smith, Jernigan, & Arita, 2000).

Recorded piezometer and reservoir water level data can be used to conduct a correlation analysis. The correlation plot includes the piezometer water level plotted against reservoir water level. A linear trend indicates a correlation between the piezometer water level and reservoir water level and the slope of the linear trend indicates how much influence the reservoir water level has on the piezometer water level.

The scatter along the line of regression forms an elliptical hysteresis and the amount of scatter indicates the lag in the piezometer water level response, relationship strength, and indicates if other influences are affecting the relationship (Gall, 2007).

1.4 Motivation for research

The health and state of the aging and overburdened civil infrastructure in the United States has been subjected to renewed scrutiny over the last few years. The American Society of Civil Engineers reports that this current state of the dams threatens the economy and quality of life in every state, city and town in the nation (Abdoun, Bennett & Simm, 2013). This should instill a mindset that is more concerned and attentive to this key piece of our nation's critical infrastructure. The geotechnical problems an earth dam could experience during their operational stages are primarily related to slope instability and internal erosion (Pagano, Fontanella, Sica & Desideri, 2010). A dam's structural integrity, performance, and safety to the downstream population depends on timely visual inspections and the efficiency of monitoring systems. Visual inspections are limited to identifying surface irregularities of the dam and will not detect internal deficiencies until the dam is compromised, bringing a monitoring system to the forefront of dam safety (Carter, Hosko, & Rubertis, 2000). The use of a monitoring system leads to a quicker and more efficient detection of dam deficiencies (Pabst, 2014).

A real-time monitoring system and its collected data supports visual inspections by providing an accurate data set. Okhissa Dam in Franklin County, Mississippi, was selected for research using a real-time monitoring system, because this dam was not instrumented for the means of automated data collection. Instead, 21 Casagrande standpipe piezometers are read manually once a month using a Solonist water level meter to determine changes in aquifer levels.

The data gained from ten instrumented wells is used to determine reservoir communication to the downstream aquifers and establish a warning system based on the water level threshold criteria.

The objective of this research project is to establish a wireless and portable remote monitoring system. Next, use the data from the deployed monitoring system to determine if there is communication between the reservoir and the groundwater aquifers on site. A correlation analysis is conducted using Microsoft Excel® to show that changes in the aquifer water level are directly or indirectly related to the changes in the reservoir water level. Critical piezometric water level thresholds are established as they relate to specific factors of safety against uplift. The water level thresholds serve as the warning element of the monitoring system, alerting dam officials when the piezometric water levels approach each set threshold level as they relate to a factor of safety of 1.5, 1.4, and 1.0. Finally, Okhissa Dam is analyzed for slope stability using GeoStudio 2012® and the structural material properties of the dam obtained from NRCS soil analysis reports.

2. PHYSICAL SITE DESCRIPTION AND SITE INVESTIGATION

2.1 Introduction

In November of 2013 a meeting between the National Center for Physical Acoustics (NCPA) Porous Media research group, USDA Forestry Service, USDA Natural Resource Conservation Service was held to select a research site. The plan for instrumentation and potential needs, such as power, security and installation requirements were explained to the officials of the USDA. After much deliberation, Okhissa Dam was selected as the site of interest and study. The need for increased monitoring of Okhissa Dam stems from higher than expected pore water pressure measurements of the confined aquifer; and the evaluation of communication between the reservoir and groundwater aquifers. The potential failure modes for Okhissa Dam are uplift pressures leading to foundation defects.

The Okhissa Dam site provided a stable work environment with security granted access only. As for the instrumentation installation, the USDA agreed to allow the use of existing Casagrande standpipe piezometers and monitoring wells as well as installation of instrumentation to record the reservoir water level on the concrete riser of the principle spillway.

2.2 Physical Location of Okhissa Lake

Okhissa Lake is located in Franklin County, Mississippi within the Homochitto National Forest, four miles south of Meadville, MS (population: 437) and two miles south from Bude, MS (population: 1,040). Okhissa Lake is located on Porter Creek and part of the Porter Creek watershed. The site is one mile upstream of the confluence of Porter Creek and the Homochitto River. A view of the location of Okhissa Lake is shown in Figure 2.1.

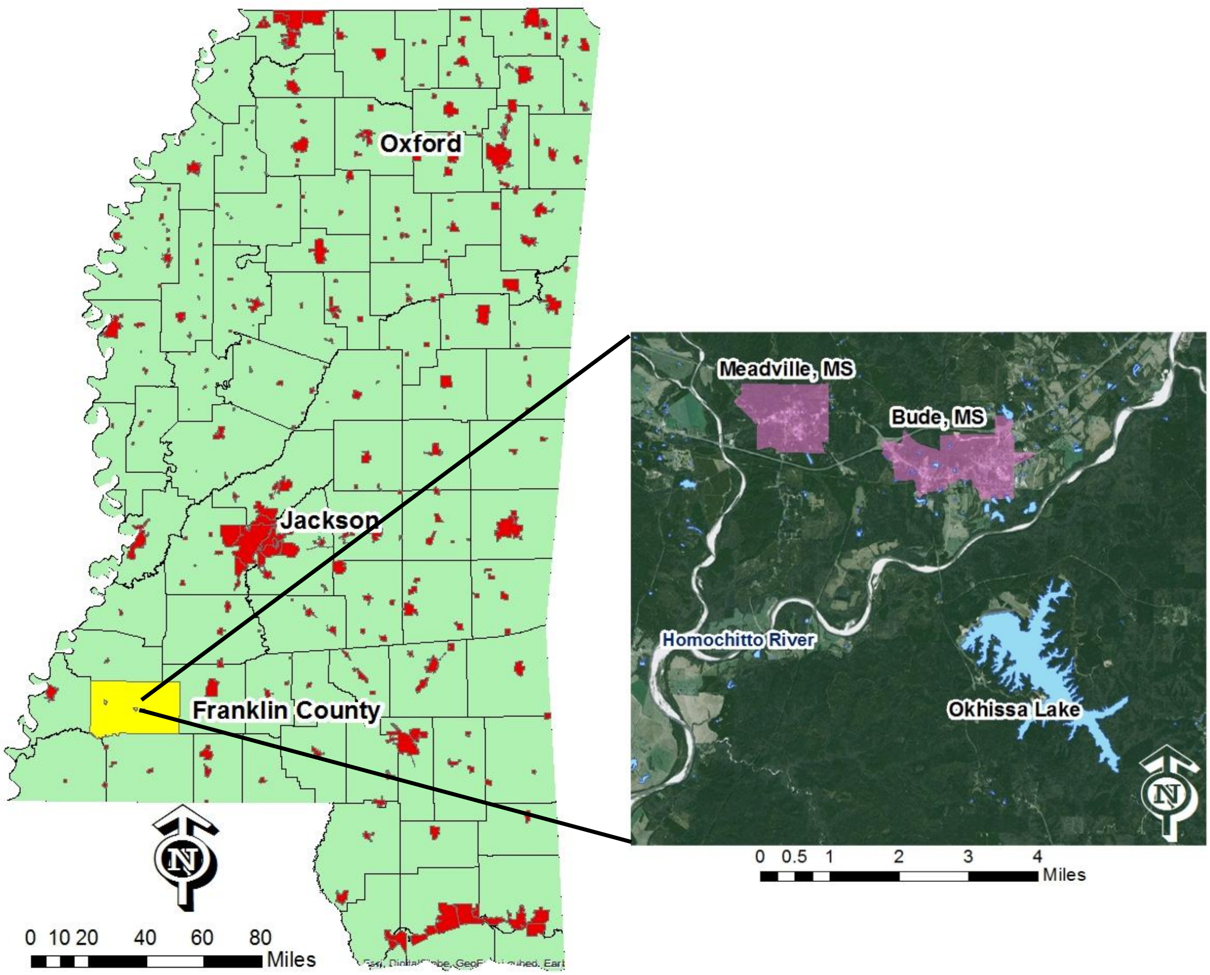

Figure 2.1: Site location (ArcMap 10.2.2 ®).

2.3 Land Use

The land immediately surrounding Okhissa Lake is densely forested. Urban development is within the downstream flood area of Okhissa Lake, deeming Okhissa Dam a high hazard dam. Okhissa Lake was established to encourage economic growth, and rural development in this region of southwest Mississippi. This recreational lake opened to the public in 2007 with a vision to become one of Mississippi's premier largemouth fisheries and a renowned fishing destination within Mississippi (Mississippi Wildlife and Fisheries, 2007). A detailed image of the land use surrounding the Okhissa Lake site is shown in Figure 2.2.

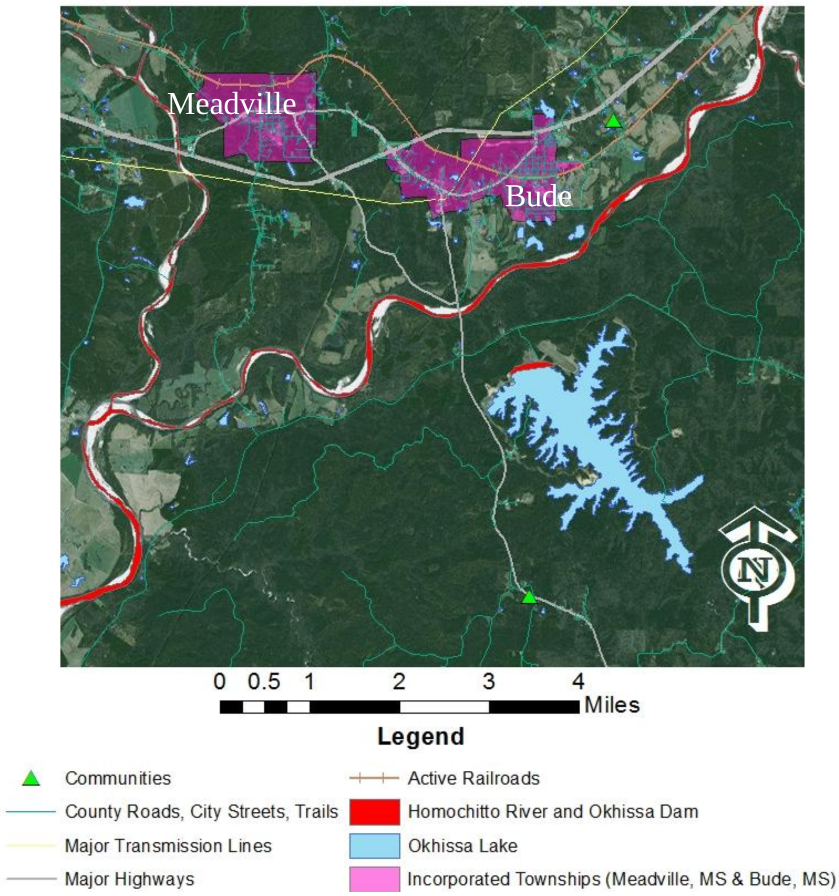

Figure 2.2: Surrounding site land use (ArcMap 10.2.2®)

2.4 Site Geology

A full geologic site investigation of the proposed Okhissa Lake site was conducted by the NRCS in 1996 for preliminary design requirements. The purpose of this investigation was to study the erosion characteristics of the Porter Creek watershed, the proposed sediment basin and the expected material removal quantity from the Porter Creek watershed. The geologic investigation focused on the surface geology, proposed centerline of the dam, foundation drain and upstream toe, auxiliary spillway, principle spillway, and borrow material. This section includes the investigative results on general and surface geology, centerline of the dam, foundation drain and upstream toe and principle spillway (NRCS, 1996).

2.4.1 General and Surface Geology

The Okhissa Dam site is located within the Gulf Coastal Plain Province and situated within a subdivision of the Mississippi known as Southern Pine Hills. The overall topography of the Okhissa site is very hilly with moderate to steep abutments and narrow alluvial valleys. The elevation of the Okhissa Lake site ranges from 210 feet in the creek bottom to nearly 400 feet mean sea level (MSL) atop the ridges surrounding the site. The dam foundation materials of Okhissa Lake consist of Miocene clays and sands belonging to the Pascagoula/Hattiesburg formation. The "bedrock" material was located in deeper borings along the centerline of the dam and on the abutment ends. This "bedrock" material is composed of interbedded stiff clays and dense, silty, fine to very fine sands (NRCS, 1996). The ridges surrounding the site are made up of Pleistocene sands and gravels of the Citronelle formation. The floodplain of Okhissa is composed of a heterogeneous mix of unconsolidated fine grained soils, sands and gravel eroded from the surrounding hills. The surface geology of the Okhissa Lake site is shown in Figure 2.3 (NRCS, 1996).

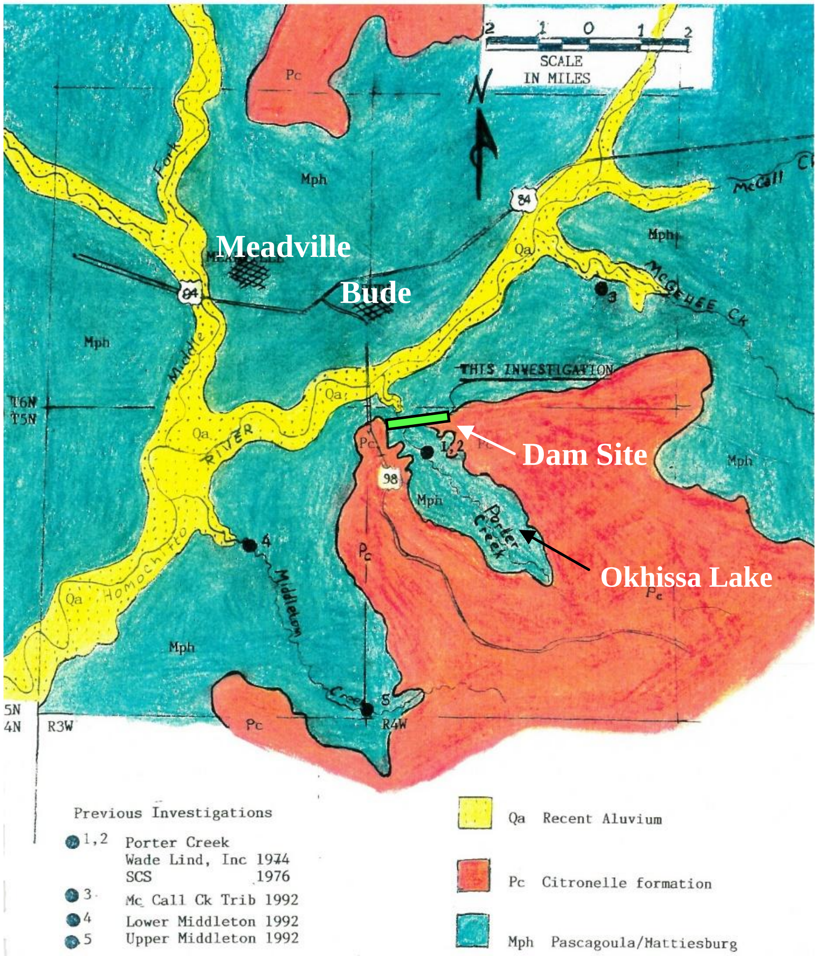

Figure 2.3: Surface geology of Okhissa Lake (NRCS, 1996).

2.4.2 Geology of Okhissa dam Centerline

The plan called for a 96 foot dam height with a crest length of 2,800 feet requiring approximately 1.8 million cubic yards of compacted fill. The dam's centerline geology and makeup was determined by 26 bore holes. The 26 holes were bored using a flight auger, hollow stem auger, wash bit, or standard penetration test (STP), or a combination of these methods. Disturbed samples were collected from the auger cutting, additionally undisturbed samples were collected using the hollow stem auger. The collected samples were used to obtain soil characteristics and determine strata features.

Figure 2.4 shows the vertical cross section of the centerline borings with approximate depth as well as the labeled geology for the dam's centerline (NRCS, 1996).

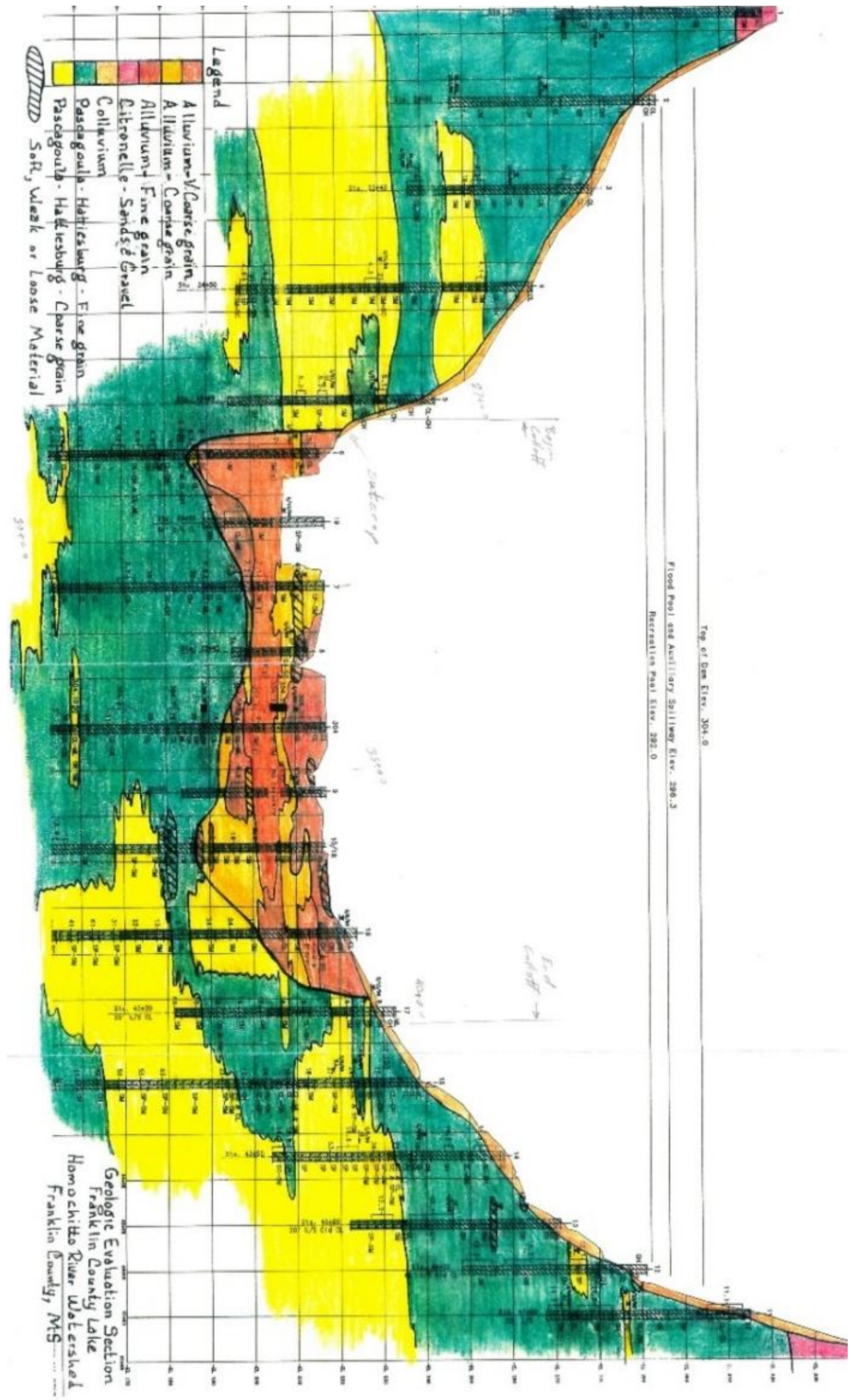

Figure 2.4: Geology of Okhissa Lake dam's abutments and foundation (NRCS, 1996).

2.4.3 Geology of Principle Spillway

The principle spillway crosses the dam's centerline at station 34+09. The soil and geology investigation of the principle spillway location included eight bores and a total of 45 samples (nine undisturbed and 36 disturbed). The borings of the foundation revealed an area of non-uniform soils consisting of soils classified as silty and sandy clays (CL, CL-ML, CH) located at an elevation of 205 feet. The residual soils of the Pascagoula-Hattiesburg formation are located below an elevation of 185 feet. Two more exploratory boreholes were bored on either side of the principle spillway's slough downstream of the dam's foundation. The exploratory location to the left of principle spillway revealed a zone of weak sandy clay (CL), dense sands, and high plastic clays. The exploratory borehole on the right bank of the principle spillway shows results of a sandy to course layer underlain by very soft clays (NRCS, 1996).

2.4.4 Geology of Borrow Area

The borrow area for the construction of Okhissa Lake dam was composed of several different areas. The excavation of the auxiliary spillway yielded an estimated 1.3 million cubic yards of the required 1.8 million cubic yards of material. The auxiliary spillway is located near the north abutment of the dam. All borrow material obtained from this area was colluvium and residuum, derived from the Citronelle and Pascagoula-Hattiesburg formation and used for the construction of the Okhissa Lake dam. The borrow area was investigated with 13 geotechnical exploratory borings, ranging in depth from 18 to 104 feet in depth. The results yielded clayey and gravelly sands (SC, GC) atop the ridges. The next layer revealed a thick sequence of clean, fine to gravelly sand (SM) from 10 to 40 feet thick followed by moderate to high plastic white and grey clays (CH).

Downslope of the ridge material was classified as a sequence of clays and clayey silts (ML, ML – CL) and clayey and silty sands (SC, CL). Below this silty zone a layer 6 to 15 feet thick of medium to very stiff, moderate plasticity, blue green and tan clay (CL-CH, CH) was encountered (NRCS, 1996).

2.5 Precipitation

Precipitation data is collected at the Okhissa Dam site by the monitoring system and the data is compared to the readings recorded by the National Oceanic and Atmospheric Administration (NOAA) station 1.53 miles from the site. Precipitation is a critical parameter to measure and record as rainfall fills the reservoir and recharges the aquifer at varying rates (Parks, 2012). Table 2.1 displays the yearly rainfall totals for years 2012 to 2015. The years of 2012 and 2013 would have higher reservoir and groundwater levels than 2014 due to higher precipitation levels.

Table 2.1: Table of recent yearly precipitation totals (NOAA).

Year	Rainfall Total (inches)
2012	69.08
2013	67.33
2014	51.33
January-May (2015)	13.55 (so far)

2.6 Construction of Okhissa Lake dam

In 1999, Franklin County was promised the construction of a 1,051 acre lake with a marina, fishing, boating, cabins, a lodge, and a conference center, making this area a potential vacation destination. The project was commissioned and designed by the NRCS, who also oversaw the dam's construction.

This project did not come without its complications. Construction of Okhissa Dam began in 2000 and concerns related to the design of the principle spillway inlet conduit were revealed, leading to the removal of initial contractors, and a halt in the project (Mississippi Business Journal, 2004).

The Okhissa Dam project sat unattended, empty and overgrown with weeds for nearly five years until the project was rebid with the intent to complete. Inspections were performed before construction resumed on the Okhissa Project. The inspections detected joint separation within the inlet box and based on the dams' review, the stability of the dam was in question. The recommendations to rectify the inlet box included additional soil borings to check the stability of the foundation and embankment and develop a suitable monitoring plan to include instrumentation. (Millete, 2003). The NRCS conducted an extensive evaluation and inspection, revealing hairline cracks and differential displacement between the joints as shown in Figure 2.5. Upon inspection it was determined the box sections were structurally designed to carry all applied soil and water loads, and there was no concern for structural failure.

Figure 2.5: Box conduit inspection (Bingham, 2014).

The completed principle spillway inlet conduit is show in Figure 2.6. Okhissa Dam's cost for the Okhissa Lake recreation project was estimated to be $34 million. Okhissa Lake opened to the public on November 7, 2007 and was deemed a Bill Dance Signature Lake (Picayune Item, 2007). Unfortunately, the promise of cabins and a resort has not come to fruition for Okhissa Lake. The fishing for Okhissa Lake has continued to be promising, but the hope for this location to be a vacation destination to aid economic growth in this area has not occurred. A timeline of significant occurrences is provided in Figure 2.7.

Figure 2.6: Final concrete box conduit (Bingham, 2014).

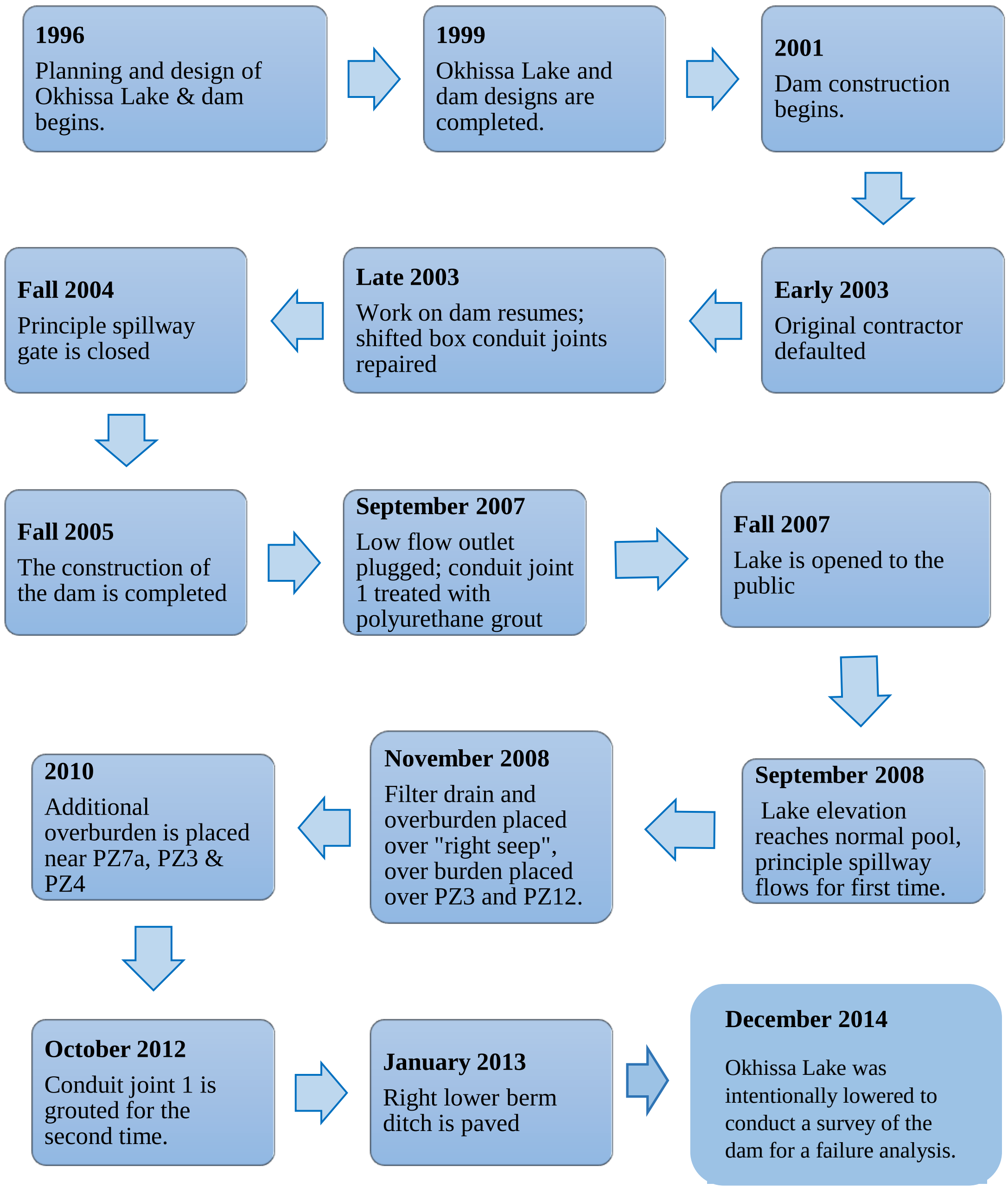

Figure 2.7: Okhissa timeline of major events (Bingham, 2014).

Okhissa Dam is owned and operated by the USDA Forestry Service. Okhissa Dam is designated as a class “b” and is designed to meet Mississippi’s freeboard criteria for a “high hazard” dam (Millete, 2003). This classification means the dam is located in an area where failure could cause a loss of life, as well as, significant damage to homes, industrial and commercial buildings, utilities, highways and railroads (MDEQ, 2001). The design for Okhissa Dam was extensively researched and prepared in order to achieve a high level of confidence in the effective performance of the dam. The flood map of Okhissa Lake and the impacted areas is shown in Figure 2.8.

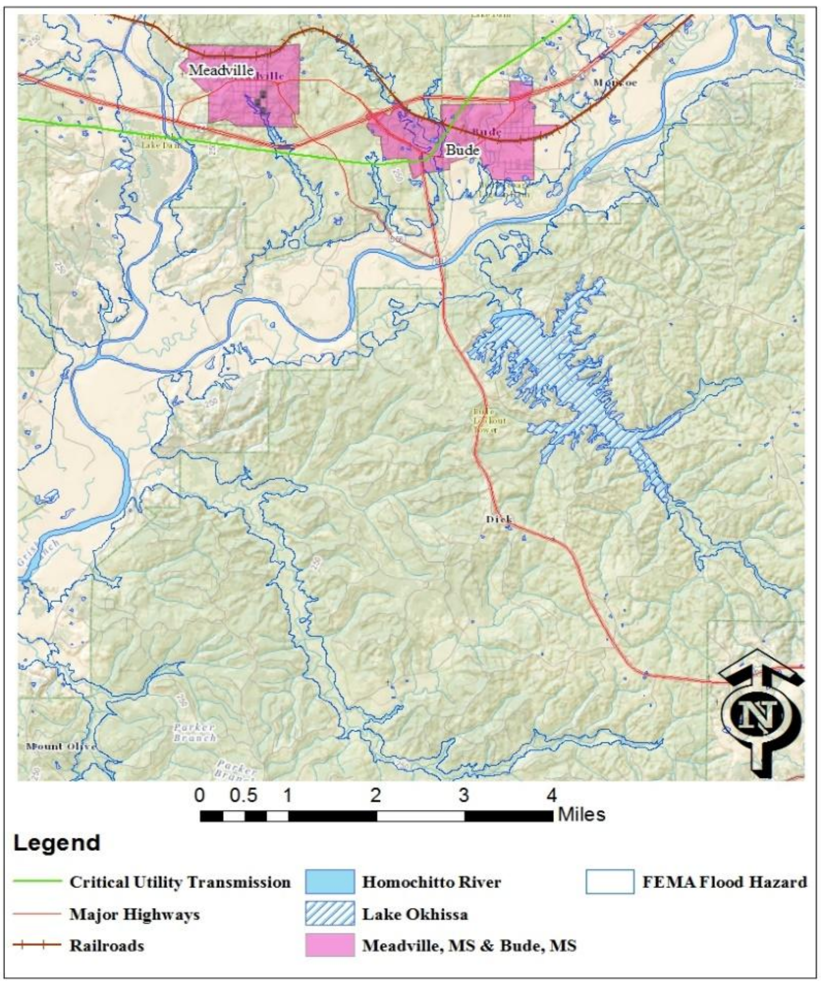

Figure 2.8: Flood hazard map (MARIS, 2014), ArcMap 10.2.2®

Okhissa Lake is a single purpose lake, designed for recreational use only. The dam's crest elevation is 303.6 feet above MSL, making the total dam height 97.1 feet. Okhissa Dam is the second tallest dam in Mississippi, behind Sardis (117 feet), but largest in the U.S. Forest Service system. The dams' crest is designed to meet the high hazard freeboard criteria of 30.7 inches of rainfall and a 24-hr storm duration (Millette, 2003). The NRCS has minimum top width criteria based on the dam's height, requiring a minimum crest width of 26 feet for a dam of multipurpose use, Okhissa Lake dam is 30 feet in width at the crest and nearly 700 feet wide at the base (NRCS, 2005). The crest length of Okhissa dam is approximately 2,500 feet. The total storage capacity of Okhissa Lake is 44,065 acre feet. The auxiliary spillway for Okhissa Dam is located on the north end of the dam and is 1,155 acres.

The internal properties of the Okhissa Dam consists of a clay core and a chimney drain designed to release all water that may seep through the clay core. The dam is equipped with a principle and auxiliary spillway. The auxiliary spillway was formed by clearing and excavating the borrow site on the north end of the dam and removing 1.3 million cubic yards of material. The principle spillway crosses the centerline of the dam at station 34+09. This structure consists of a 90 foot tall riser with a concrete reinforced box conduit measuring 6 feet by 6 feet with a maximum discharge of 423 cubic feet per second (NRCS, 1996). The primary features of Okhissa Lake dam are shown in Figure 2.9.

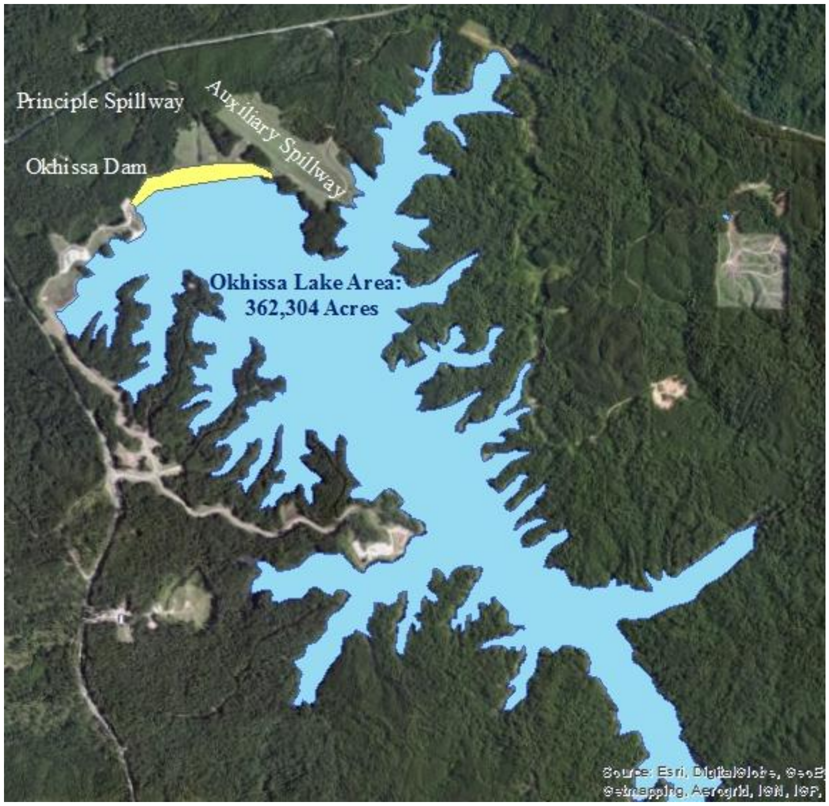

Figure 2.9: Features of Okhissa Lake (ArcMap 10.2.2®).

2.7 Current Okhissa Monitoring and Site Investigation

Okhissa Dam is primarily instrumented with manual monitoring technology, Casagrande style piezometers, and a reservoir level staff gage. This site includes two groundwater aquifers of monitoring interest. The deeper groundwater aquifer of Miocene sands is confined by an impermeable clay layer ranging from two to ten feet thick, separating it from the shallow gravel zone and phreatic aquifer. The NRCS installed four piezometers (GOW) in 2004 to monitor groundwater levels at 10 to 20 foot depths in the shallow phreatic alluvial sands and gravels. Three additional piezometers: PZ 3, PZ 4, and PZ 5 were installed by Burns Cooley Dennis, Incorporated in December of 2004, to monitor groundwater levels from the deeper Miocene sands of the confined aquifer.

The average depths of these piezometers are 25 to 50 feet. In 2005, NRCS personnel installed an additional five piezometers along the left abutment of the dam, and Burns Cooley Dennis, Incorporated placed an additional four piezometers to monitor the Miocene sands of the downstream flood plain. The piezometer levels are measured manually and read using a water level meter and visually read off the staff gage; precipitation data is obtained from a local NOAA station. The measurements for the reservoir elevation and piezometers were taken every 7 days until readings reached a stable, consistent level; presently, readings are taken once a month using a Solonist water level meter (Adams, 2006).

The trends exhibited by the shallower GOW piezometers reveal slight seasonal groundwater change. Some of the changes seen in these piezometers include an increase of nearly four feet in the shallow aquifer from 2004 to 2006. The confined aquifer exhibited a water level increase of approximately six feet in PZ3 and PZ4 from 2004 to 2006. There was growing concern of uplift occurring in the surrounding area of PZ3 and PZ4, as these wells were experiencing artesian conditions. To remedy this concern an additional four feet of fill was added to this area to increase the overburden, alleviating the artesian conditions. PZ 5 established a groundwater elevation of 227 feet at the time of installation in January 2004, and increased to a piezometric elevation of 242 feet by March of 2004. PZ 5 is currently reading an elevation of 254 to 255 feet. There are a total of 11 standpipe piezometers (PZ) monitoring the confined aquifer and 10 standpipe piezometers (GOW) monitoring the phreatic aquifer. The reservoir water level increased from an elevation of 220 feet in November of 2004, when the principle spillway gate was closed, to 262 feet in March of 2005 (Adams, 2006). The current reservoir water level is 291 to 292 feet.

3. OKHISSA LAKE MONITORING SYSTEM

3.1 Introduction

The use of instrumentation to monitor the performance and efficiency of dams is essential for a successful dam safety program (USACE, 1995). Instrumentation provides data for monitoring the safe performance during the various phases of a dam's life including design; construction; first filling of the reservoir; evaluation of long term, in service performance; and to manage or predict unsatisfactory performance (Hamby, Choquet & Long, 2013). The need for monitoring systems is increasing as the personnel resources available for dam safety monitoring remains limited. A properly designed and installed monitoring system will save labor, improve the quality of collected data and ameliorate the dam owner's ability to detect a developing safety condition (Myers, 2013). Instrumentation may not directly benefit the dam, but expands general knowledge in order to benefit future dam design efforts (Myers & Stateler, 2008).

In this study, Okhissa Dam was selected to install a monitoring system. The Lake site is instrumented with 21 Casagrande style standpipe piezometers, with 11 monitoring the confined aquifer (PZ) and 10 monitoring the phreatic aquifer (GOW). The primary monitoring parameter is piezometer and reservoir water levels. The analysis of real time data of piezometer and reservoir water levels will determine if the reservoir is affecting the water levels of the confined aquifer. It will also provide confidence that the slurry trench is serving as an effective cutoff wall between the reservoir and phreatic aquifer.

The method of implementing a continuous monitoring system that collects piezometer water level data aides in evaluating reservoir and groundwater aquifer communication.

3.2 Vibrating Wire Piezometers

Vibrating wire piezometers were selected as the primary sensor type for the Okhissa Dam monitoring system due to their high degree of accuracy and ability to be incorporated into a wireless automated system (Bartholomew, Murray & Goins, 1987). The sensor utilizes a sensitive stainless steel diaphragm connected to a vibrating wire. Pressure changes on the diaphragm causes the tension of the wire to change and deflect, resulting in a frequency (Hz) output. The measured frequency is directly proportional to the change in pressure applied to the diaphragm (USACE, 1995). The components and elements of a vibrating wire piezometer are displayed in Figure 3.1.

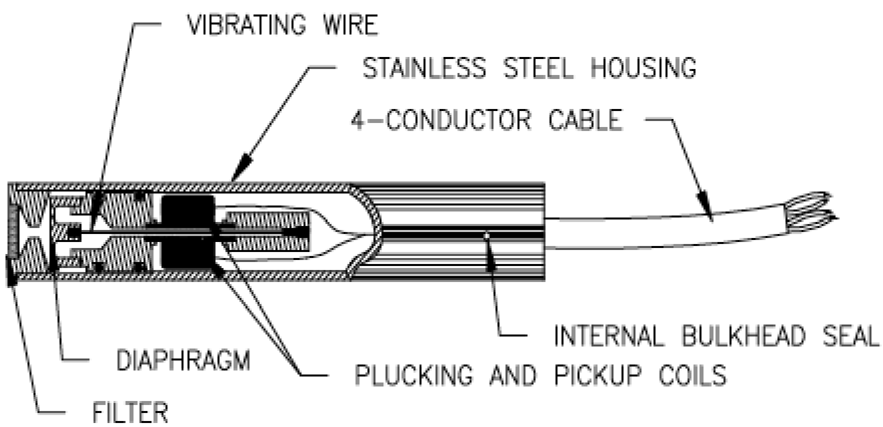

Figure 3.1: Vibrating wire piezometer (Geokon, 2011)

Two types of vibrating wire piezometers are installed at Okhissa Lake. The sensors monitoring the groundwater levels are vented vibrating wire piezometers with a calibrated pressure range of -14.50 to 50.76 psi (-100 to 350 kPa). The water level sensor monitoring Okhissa Lake is a 10.15 psi (70 kPa) vented vibrating wire piezometer.

Both vibrating wire piezometer types are manufactured by Geokon, Incorporated. A vented vibrating wire piezometer is chosen to eliminate the applied correction factor for barometric pressure. A vent tube extending from the atmosphere to the sensor element applies barometric pressure back to the vibrating wire piezometer sensor. This transfer of barometric pressure to the sensor creates a gauge pressure rather than an absolute pressure measurement (Geokon, 2011).

3.2.1 Installation

The vented vibrating wire piezometers are installed in the existing two inch Casagrande standpipe piezometers at Okhissa Dam. The vibrating wire piezometers are not grouted or sealed within the standpipe piezometers, as they are property of the NRCS. Sealing the vibrating wire piezometers would make the Okhissa Dam monitoring system a permanent installation, and the goal of the project is to establish a wireless portable system. The vibrating wire piezometer porous filter tip is removed and filled with water to saturate the instrument prior to placing the sensor down the standpipe well. The "used" sensor cable is measured in order to subtract that length from the standpipe riser elevation to obtain a piezometric water elevation with respect to MSL. Before the sensors are lowered, a zero reading is first established by calibrating the sensor at zero pressure to obtain an initial digits and temperature reading. The vented vibrating wire piezometers include a desiccant chamber that has a screw type seal that is removed before the sensor is put into service (Geokon, 2011). The sensors are lowered to an elevation approximately two feet above the screen of the standpipe piezometer to prevent any influence of organics and soil that may affect the accuracy of sensor measurements. The remaining cable that connects to the data acquisition box at each well is run through PVC conduit to protect the sensor signal cable. Figure 3.2 shows a cross-section of the vibrating wire piezometer standpipe installation. A photograph of an instrumented well at the Okhissa Lake site is seen in Figure 3.3.

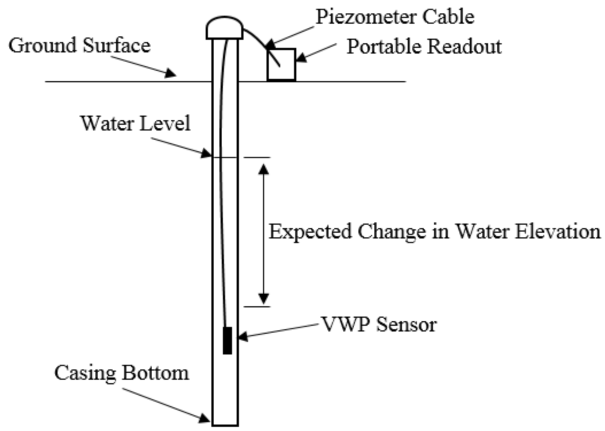

Figure 3.2: Typical installation in standpipes.

Figure 3.3: Well instrumentation at Okhissa Lake.

The installed vibrating wire piezometer sensor used to monitor the water level of Okhissa Lake is installed on the principle spillway concrete riser. The reservoir sensor is housed within a two inch PVC section secured to the riser access ladder, stabilizing the reservoir sensor and minimize the effect of drift.

The vibrating wire piezometers' filter tip is removed and filled with water, and the "used" sensor cable is measured to obtain a water level value as it relates to MSL. A zero reading is established for the reservoir vibrating wire piezometer and it was lowered down the PVC casing. Next, the installed vibrating wire piezometers are connected to the spectrum analyzers to be read on programmed intervals, continuously monitoring piezometer levels. Figure 3.4 shows an image of the sensor locations at Okhissa Lake.

Figure 3.4: Sensor node locations at Okhissa Lake (Google Earth, 2012®)

3.2.2 Calibration and Calculations

Each vibrating wire piezometer is calibrated at a specific temperature and over a range of pressures. A unique calibration sheet is provided with each vibrating wire piezometer sensor. The vibrating wire piezometer is a temperature sensitive instrument and includes a thermistor which allows for a temperature measurement and a temperature correction to be applied to the vibrating wire piezometer.

The sensor output is a frequency, measured in Hertz, (Hz). This frequency output is converted to units called digits. The equation to convert the vibrating wire piezometer output from Hz to a unit of digits is:

$$\text{Digits}=\left(\frac{1}{\text{Period}}\right)^2 * 10^{-3} \text{ or } \text{Digits}=\frac{\text{Hz}^2}{1000} \tag{3.1}$$

The vibrating wire piezometer records temperature for the temperature correction by using a thermistor. The thermistor measures resistance with temperature change, this output is in Ohms. The following equation converts the output of the thermistor from ohms to a temperature, T (°C):

$$T=\frac{1}{A+B(\ln(R))+C(\ln(R))^3}-273.2 \tag{3.2}$$

where A, B and C are unique calculated coefficients and ln(R) is the natural log of the thermistor resistance.

The units of digits is converted to engineering units of pressure in kilopascals (kPa) or pounds per square inch (psi) using the specific calibrated values provided on the sensor calibration sheet.

The equation to convert digits to a pressure, P, for the sensors used at the site is:

$$P=G(R_1-R_0)+K(T_1-T_0)-(S_1-S_0) \tag{3.3}$$

where, G is the linear gage factor and K is the thermal factor and both values are provided by Geokon on each vibrating wire piezometer's calibration sheet. The values of R_0 and R_1 represent the zero pressure digits reading. The value for R_0 is obtained by conducting a field calibration at zero pressure. R_1 is each subsequent field reading. The value for T_0 is obtained conducting a field calibration with the sensor at zero pressure. T_1 is the field measured temperature reading. The values for S_1 and S_0 can be disregarded as the vibrating wire piezometers at Okhissa Lake are vented piezometers, and a correction for barometric pressure is neglected.

The pressure value obtained from Equation 3.3 is converted to a measurement of pressure head and added to the elevation of the piezometers tip to obtain a total head value, H.

$$H=P*2.3108 \tag{3.4}$$

P is the pressure obtained from Equation 3.3, the value of 2.3108 is a conversion factor from psi to feet of water (Geokon, 2011).

3.3 Real-Time Monitoring System

The advantage of using instruments such as vibrating wire piezometers is their ability to be incorporated into a wireless, real-time monitoring system (Dunnicliff, 1993). The monitoring system at Okhissa Dam includes automated instrumentation of piezometers located at the dam's toe, abutment and the downstream flood plain. An automatic rain gage, temperature and relative humidity probe, and barometric sensor (Campbell Sci., 2012) are integrated into the Okhissa Dam monitoring system.

3.3.1 Data Collection, Communication, and Storage

Data collection and communication is accomplished using three components: AVW206 vibrating wire spectrum analyzer, RF401 spread spectrum radio and a CR1000 data logger all from Campbell Scientific, Incorporated. The link for remote communication with the real-time monitoring system is established with the use of a GX400 Airlink Cellular Modem.

This data is communicated to an off-site server at the NCPA, where the data is stored, processed and made available for a numerical and graphical presentation via a webpage.

Weather proof boxes at each instrumented well houses the AVW206 spectral analyzer. The Campbell Scientific® AVW206 allows for the measurement of the installed VWPs. The AVW206 supplies the sweeping frequency, or "pluck", to the VWP to record a frequency response. The AVW206 is equipped with a 900 megahertz (MHz) radio link which enables communication with a corresponding spread spectrum radio connected to a data logger (Campbell Sci., 2015). The instrumented well stations use a 900 MHz Yagi antennae to wirelessly transmit the recorded frequency response to the data logger. The AVW206 is a two channel spectrum analyzer, capable of connecting two vibrating wire piezometers to the module. The AVW206 is powered by a 12 Volt sealed battery that is charged by a 20 Watt solar panel. The load, AVW206, solar panel, and battery are connected to a charge controller, supplied by Morningstar®, to ensure the battery does not become overcharged. The selected charging method is slow switching; the default mode is pulse width modulation (PWM). The PWM mode creates interference in the radio link and the wireless data communication. To resolve this issue, the regulation wire loop is cut to allow for slow switch charging. Precautions are taken to guard the electronics at each well from lightening damage by grounding each antennae and AVW206. The well monitoring equipment is mounted on a removable pole, to maintain the goal of system portability. A picture of the well instrumentation is displayed in Figure 3.5.

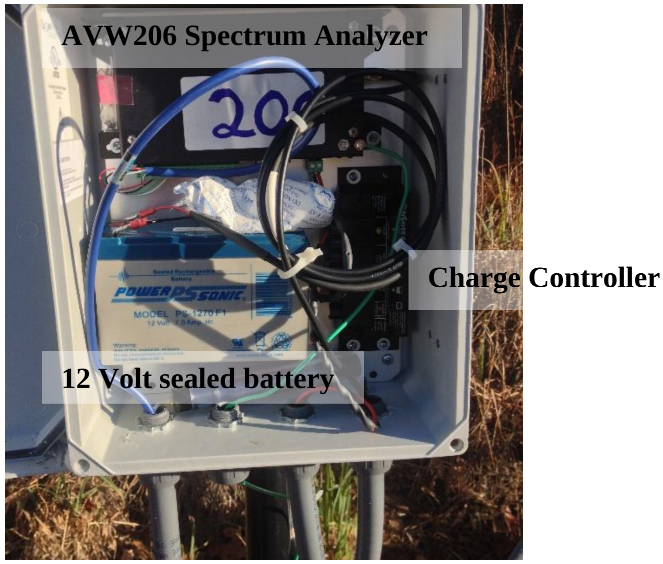

Figure 3.5: PZ and GOW instrumentation.

3.3.2 CR1000 Data Logger

All Okhissa Dam instrumentation and sensors are connected to the CR1000 data logger through the RF401 spread spectrum radio, both Campbell Scientific, Incorporated products (Campbell Sci., 2012). The spread spectrum radio is equipped with a 900 MHz antennae that receives the signal from each instrumented well on its scheduled data collection intervals. The RF401 is connected to the CR1000 data logger through the RS232 serial port. The frequency data received from the instrumented wells is transmitted to the CR1000, which converts the collected frequencies to temperatures, pore water pressure, and water head by the previously listed equations within the software program stored in the CR1000.

Instrumentation scans are set to meet site specific site conditions or specified instrumentation criteria. The Okhissa Dam monitoring system is programmed to record all data every five minutes. This particular scan rate is not of set criteria or condition, but an arbitrary scan rate to provide a real-time recording element to the Okhissa Dam system.

The continuous monitoring system contains an electronic rain gage, temperature and relative humidity probe, and barometric sensor, all wired to the analog inputs on the CR1000 data logger. The recorded data is stored momentarily on the data logger and transmitted via a cellular phone modem, which is wired to the analog inputs of the CR1000. The monitoring system is remotely accessed through the cellular modem and transmits the data to the NCPA where the data is processed and made available on the NCPA Dam Monitoring webpage. The electronics of the data collection system are powered by a deep cycle 24 Volt AGM battery charged by a 40 Watt solar panel which are wire to a Morningstar® Sunsaver10 charge controller set to the slow switching charging method (regulation wire loop is cut). The data collection setup at Okhissa Dam is shown in Figure 3.6.

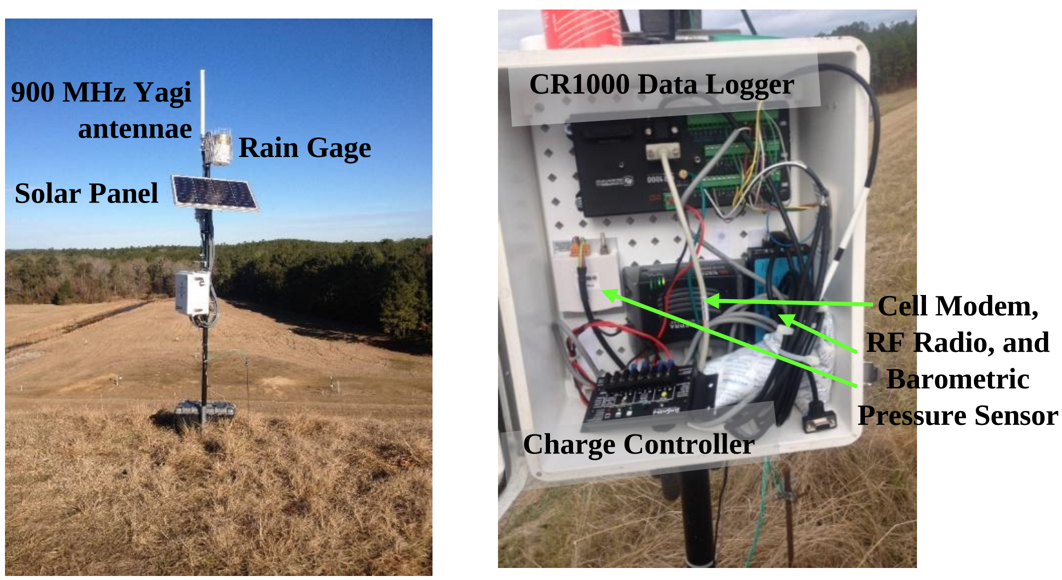

Figure 3.6: Data collection station for Okhissa Lake investigation.

3.3.3 LoggerNet® Monitoring Software

The LoggerNet® monitoring software can relay raw or processed data using the written monitoring program stored on the CR1000 data logger (Campbell Sci., 2014). The LoggerNet® software is used to configure hardware communication and calibrate the sensors used for the Okhissa Dam monitoring system. The specific monitoring program stored on the CR1000 data is written using LoggerNet®. The data collection schedules, processing formulas, and deployed sensor calibration factors are written in the monitoring program to read and process collected data. This software system allows data to be communicated from the Okhissa Dam site via cell phone to files on the NCPA server where the information is stored, processed and made available to the user to view in real-time. The incoming processed data is available to users through the NCPA website, under the Porous Media research group project in Dam Monitoring.

The collected monitoring data from Okhissa Dam is immediately available on its designated webpage, http://ncpa.olemiss.edu/okhissa-lake-dam-monitoring-system/. The data files containing the raw and processed data are made available to the USDA officials at their request. The data files are stored in a .csv format to create time history and correlation plots using Microsoft Excel®. A summary of the data and communication flow from the Okhissa Dam site to the webpage is provided in Figure 3.7.

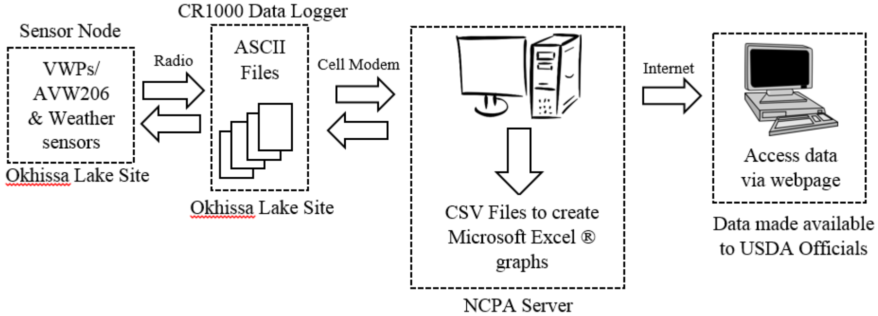

Figure 3.7: Communication and the flow of data collection.

4. DATA AND ANALYSIS

4.1 Data Presentation

The monitoring system at Okhissa Lake began collecting data on October 26, 2013. The system required troubleshooting over the coming months as a result of programming errors, communication failures, and sensor calibration issues. These issues were addressed and properly resolved and the collected data was accepted on July 1, 2014. This chapter displays the data collected from July 1, 2014 through April 15, 2015.

4.1.1 Display of Recorded Water Levels with Precipitation

The data presentation displays responses of the GOW and PZ wells and the concurrent rainfall. These figures include reservoir levels, water elevations in the wells, and precipitation data taken from two sources. The first source of precipitation data is collected from the Okhissa monitoring system. The collected data contains error due to clogging of the sensor during certain time periods. The second source of precipitation data is from a National Oceanic and Atmospheric Administration (NOAA) weather station located at 31.41°N, 90.85°W, approximately 1.56 miles from the monitoring system's rain gage. The NOAA weather station did not collect data from December 12, 2014 through January 12, 2014, for reasons that are not known. It is postulated that the water levels in the shallow GOW wells should be correlated to the rainfall, but the PZ water elevations should not be impacted by rainfall. Additional figures will include the reservoir water level plotted with the GOW and PZ water levels.

These time history plots show trends in the collected data, and enable the reader to discern if the piezometer readings are impacted by the reservoir and precipitation. The gates of the principle spillway were opened on December 16, 2014 to reduce the reservoir water level by two feet to conduct a survey of the dam for a full failure analysis on Okhissa Lake dam. A timeframe from December 10, 2014 to March 25, 2015 will focus on the intentional two foot reduction of Okhissa Lake water level and the responses in the PZ and GOW elevations.

The data presentation and further data analysis will not include piezometers PZ5, PZ14 or GOW6. The response of piezometer PZ5 contains excessive noise in the data, causing the dataset to be unreliable. Part of the piezometer PZ14 is being removed from data analysis as it experienced a drift in data. This was credited to a calibration issue as evident when the well was manually measured on February 18, 2015 and the result of that measurement was three feet less than the logged value. The sensor was recalibrated on February 18, 2015 and has returned to an expected value of water elevation. As a result of this calibration issue, and not knowing exactly when the sensor became problematic, the logged data contains a large span of incorrect data. GOW6 contains a very noisy frequency response resulting in a dataset that has larger than expected fluctuations.

A visual inspection of Okhissa Lake water levels and daily precipitation totals provide insight to how rainfall affects the logged water elevations of Okhissa Lake. Figure 1.4 displays the reservoir elevations (red) plotted from July 1, 2014 through April 15, 2015, collected rainfall data (magenta), and sourced NOAA rainfall data (blue). The significant decrease in reservoir level occurring before January 1, 2015, specifically begins on December 16, 2014, is an intentional reduction in the reservoir water level.

The principle spillway gate was opened to reduce the reservoir water level by two feet to conduct a survey of the dam surface to aid in a failure analysis conducted by the USDA. The gap in the data from December 22, 2014 to February 18, 2014 is due to the sensor cable being severed. The sensor was pulled into the gate opening and the sensor cable was cut when the principle spillway gate was closed on December 22, 2014. A new sensor was installed on February 18, 2015.

The points labeled 1, 2, and 3 in Figure 1.4 show a significant rainfall event with the corresponding reservoir increase in water level. Point 4 of Figure 4.1 displays a more gradual elevation increase of the reservoir during a period of time of multiple rain events as the Okhissa Lake elevation returns to normal pool after the intentional two foot reduction in water level.

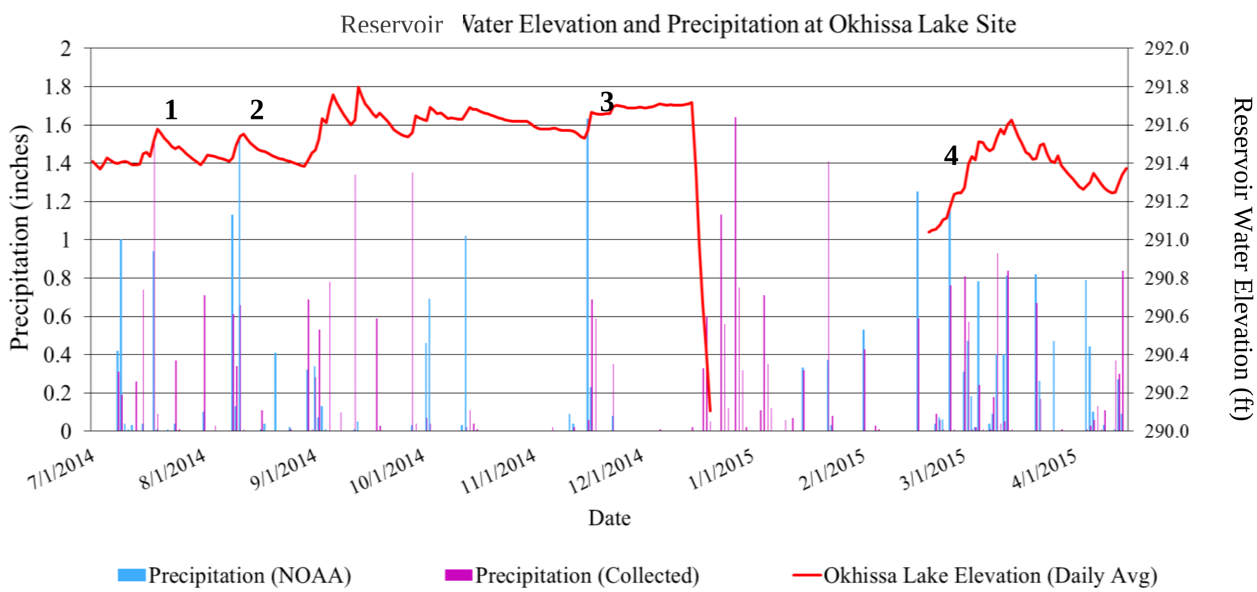

Figure 4.1: Daily precipitation and reservoir water levels.

A comparison of GOW4 water level and precipitation data suggests rainfall has an impact on the logged water elevations of GOW4. Figure 4.2 displays the water elevations recorded by GOW4 (green), the system's collected rainfall data (magenta), and the NOAA sourced data (blue). GOW4 is located at the toe of the dam, 287 feet downstream of the dam's center line.

The gap in the collected GOW4 water level data is due to the loss of communication for this sensor node. The loss of communication is attributed to a failed charge controller, meaning the sensor node was unable to be properly recharged by the solar panel. The battery voltage was reduced to less than 12 V, disabling the sensor and all data transmitting functions. The charge controller was replaced on December 6, 2014, restoring power, charging and communication capabilities. The well elevation exhibits responses to precipitation as shown by increases at points 1, 2, and 3 label on Figure 4.2. The decreasing trend in the data from July 1, 2014 through November 18, 2014 is due to the summer months of July, August, and September being a more arid time period. The magnitude of the responses in the GOW4 water level data at points 1, 2, and 3 associated with rainfall events are dependent upon the amount of infiltration versus runoff and absorption by vegetation and the soil. The data labeled by points 4 and 5 in Figure 4.2 shows a gradual increase in the water level of GOW4 due to a period of smaller but more frequent rainfall events.

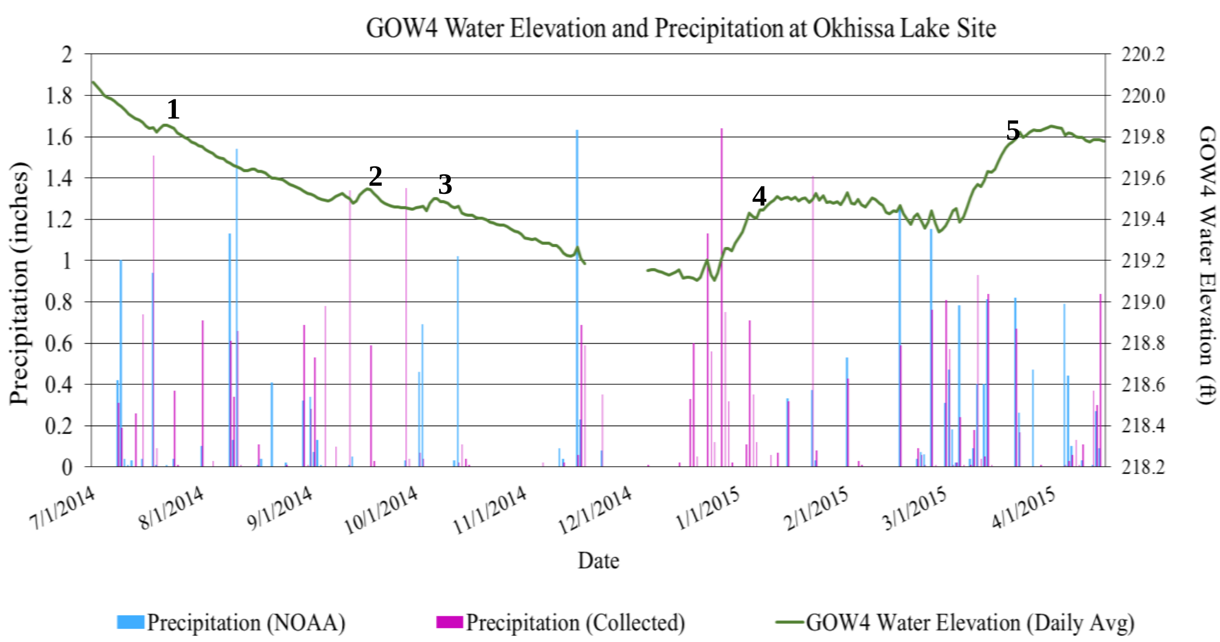

Figure 4.2: Daily precipitation and piezometer (GOW4) water levels.

A visual inspection of recorded GOW14 water levels and precipitation suggests rainfall is also impacting GOW14 water levels. Figure 4.3 displays the GOW14 daily average water elevations (orange) plotted along with the system collected rainfall (magenta) and NOAA precipitation data (blue). GOW14 is located 530 feet downstream of the dam's centerline and in a lower lying area of thick, tall grass. Figure 4.3 displays water level responses in GOW14 associated with rainfall events as annotated by 1, 2, 3, and 4. The responses of GOW14 displays a larger magnitude than that of GOW4. One contributing factor is GOW14 is at a lower ground elevation of 220 feet and all the surface water flow is directed toward the point of GOW14. During site visits this area was continually saturated along the surface, whereas the other well locations were not. The slope of the land towards GOW14 increases the amount of surface water and thereby causes increased fluctuations as seen in Figure 4.3.

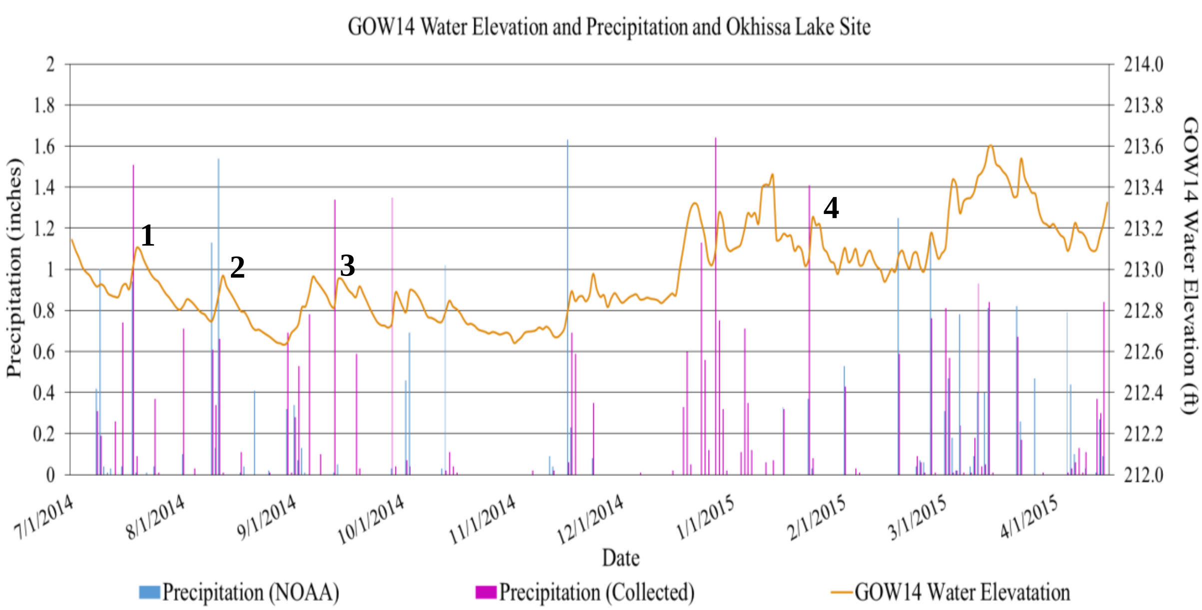

Figure 4.3: Daily precipitation and piezometer (GOW14) water levels.

The rainfall is expected to contribute to the elevations of the phreatic aquifer monitored by GOW4 and GOW14; infiltration of rainfall is the primary recharge component. The distance between GOW4 and GOW14 well locations is 243 feet, and an elevation difference of 8.1 feet. The surface gradient between these two well locations is 0.033. The groundwater flow is towards GOW14 and its logged water elevation is approximately 6 feet lower than the logged water elevation data of GOW4. The groundwater gradient is approximately 0.025 with the flow direction from GOW4 to GOW14.

The following figures display daily precipitation and PZ water elevations. The water elevations of the PZ wells are not expected to fluctuate due to rainfall events, considering the aquifer is confined by a strata of clay that ranges from 10 to 15 feet in thickness.

A visual display of collected water elevation data for PZ3 as a daily average (magenta) along with the system collected precipitation (orange) and NOAA precipitation data (blue) is provided in Figure 4.4. Visual inspection of Figure 4.4 shows influence of precipitation on the water levels of PZ3, but these fluctuations are possibly due to changes in reservoir water elevations associated with the precipitation. PZ3 is located 311 feet downstream of Okhissa Dam's center line along the downstream toe. The logged water elevation data for PZ3 shows a consistent trend during the summer and fall months, drier time period with less rainfall and consistent reservoir water levels. Peaks at labels 1, 2, and 3 appear to show a response to precipitation, but these peaks in the logged PZ3 water elevation data could be associated with the changes in reservoir levels associated with rainfall. The average water level recorded by PZ3 is 228.5 feet, and the water level is approximately 9 and 15 fifteen feet higher than GOW4 and GOW14 respectively.

The higher water level seen in PZ3 in comparison to GOW4 and GOW14 is due to the fact that the PZ wells are monitoring a confined aquifer, which exhibits higher pressure in comparison to phreatic aquifer conditions.

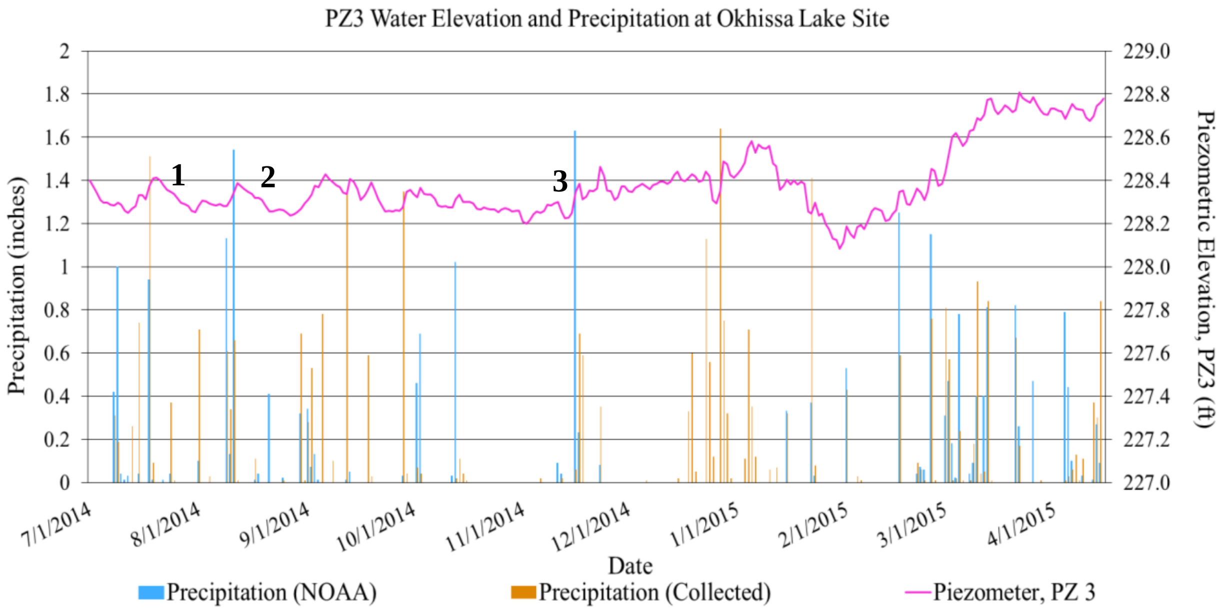

Figure 4.4: Daily precipitation and piezometer (PZ3) water levels.

A visual inspection of the daily water level averages for PZ4 (green), as well as two precipitation datasets, the system's collected daily rainfall values (orange), and NOAA's daily rainfall values (blue), shown in Figure 4.5, provides insight to the impact rainfall has on PZ4. The water level data of PZ4 is missing from November 18, 2014 through December 6, 2014, due to the charge controller as discussed for GOW4. Both sensors (PZ4 and GOW4) are wired to the same vibrating wire analyzer and sensor node. Figure 4.5 shows the well is influenced by precipitation events, as shown by water level increases of PZ4 during precipitation events at points 1, 2, 3 and 4. A decrease in the water elevation of PZ4 occurs from January 1, 2015 through February 1, 2015, includes sparse rainfall events and likely response to the intentional Okhissa Lake water level decrease.

The points, 1, 2 and 3 may be associated with rainfall events, but in connection to the water level increases in Okhissa Lake, and not strictly precipitation events.

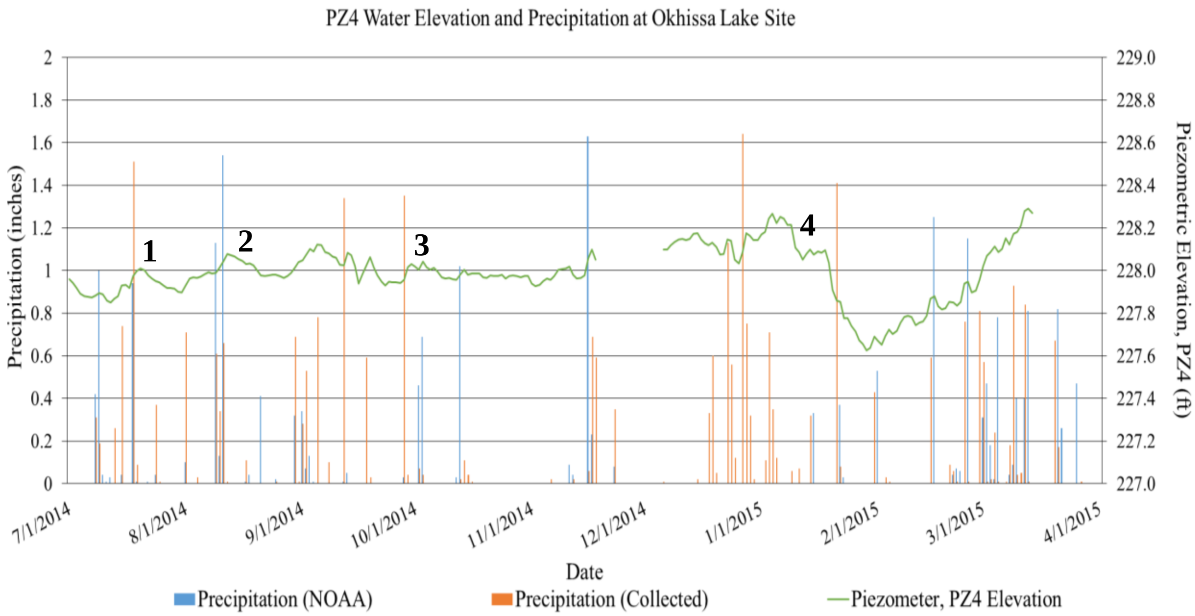

Figure 4.5: Daily precipitation and piezometer (PZ4) water levels.

A visual inspection of the graphed daily average water levels of PZ12 and precipitation shown in Figure 4.6 indicates PZ12 is impacted by rainfall. Figure 4.6 shows the piezometric elevations of PZ12 (purple), plotted with the daily rainfall data collected (orange) and NOAA daily rainfall totals (blue). The water level data for PZ12 shows a consistent elevation level between 227.4 feet and 227.6 feet where a decrease occurs soon after January 1, 2015. The rainfall events at points 1, 2, 3, and 4 show potential well elevation responses to rainfall events. The increases in PZ12 water level at points 1, 2, 3 and 4 are attributed to water elevation increases of Okhissa Lake during rainfall events. A decrease in PZ12 water level is seen shortly after January 1, 2015, and matches with the previously plotted piezometers, PZ3 and PZ4.

Further analysis will be conducted to determine the association with this decrease in water elevation of PZ4 and if it is in connection to the intentional Okhissa Lake water level reduction, which occurred on December 16, 2014.

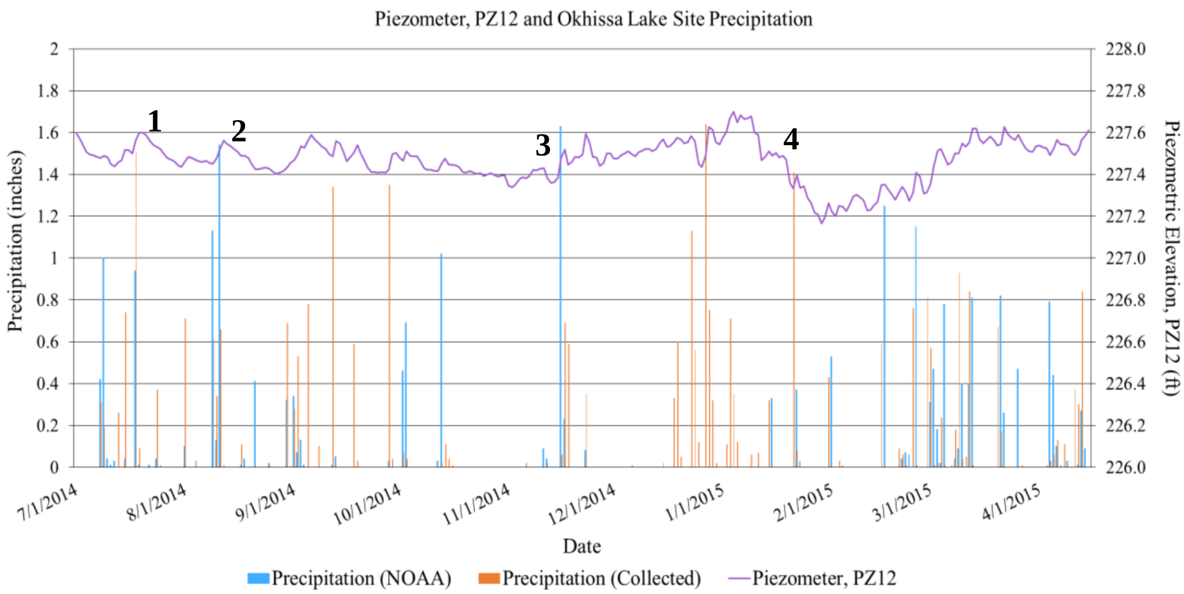

Figure 4.6: Daily precipitation and piezometer (PZ12) water levels.

A visual display of daily average PZ13 water elevations and daily precipitation magnitudes is provided in Figure 4.7. This figure displays the piezometric elevations of PZ13 (dark blue) plotted with the daily system collected precipitation (orange) and NOAA daily precipitation (blue). PZ13 is located 302 feet from the Okhissa Dam's centerline with a ground surface elevation of 225 feet. The points, 1, 2, 3 and 4 show a potential response to rainfall events in PZ13 water level data and are not strictly attributed to precipitation, but the increase of Okhissa Lake water level due to rainfall. The plotted data of PZ13 from July 1, 2014 through December 1, 2014 indicates a slight decreasing trend, attributed to drier summer months. The water level decrease of PZ13 from January 1, 2015 to February 1, 2015 is PZ13's response to the intentional Okhissa Lake elevation decrease on December 16, 2014.

PZ13's return to normal pool elevation, in response to the reservoir water level reduction from February to March, reveals an increase that is less dramatic as the returns shown in PZ3, PZ4, and PZ12.

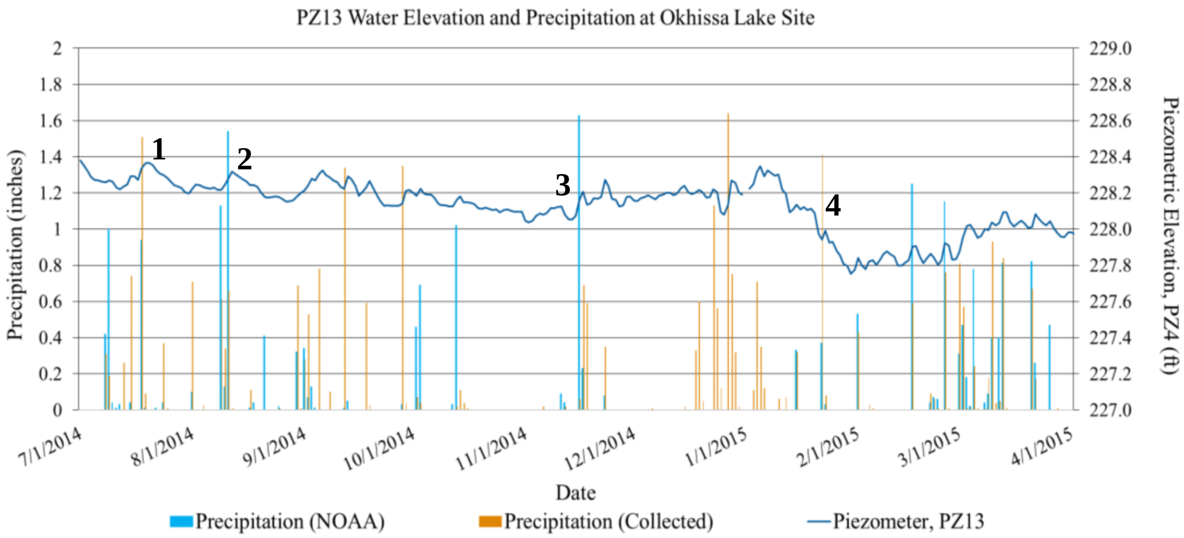

Figure 4.7: Daily precipitation and piezometer (PZ13) water levels.

The water level data of each PZ well displays similar responses to each measurable rainfall event. The PZ wells show a water elevation decrease from January 2015 through February 2015, indicating the well responses to the drawdown of Okhissa Lake that occurred from December 16, 2014 through December 22, 2014. The recharge from the decrease in the PZ water elevations occurs from February to March, as the wells return to normal pool from the reservoir water level reduction. The following figures show a relationship between the GOW and PZ water levels, precipitation and the reservoir water level. These figures are beneficial in qualitatively determining the factor that is influencing the PZ and GOW water levels. The gap in Okhissa Lake water level data is the result of the sensor cable being severed by the principle spillway gate when it was closed on December 22, 2014.

4.1.2 Display of Piezometer and Reservoir Water Levels with Precipitation

A qualitative representation of the water level data of GOW4 (green), plotted with Okhissa Lake water levels (red) along with the daily collected precipitation (blue) and NOAA precipitation (orange) is provided in Figure 4.8. The plotted water elevation of GOW4 is offset by 219 feet, therefore, 219 feet must be added to the plotted value to obtain the true piezometric water level of GOW4. The Okhissa Lake water level data is offset by 290 feet. The actual water level of Okhissa Lake is obtained by adding 290 feet to the plotted data. Figure 4.8 represents different trends in the plotted piezometric water level for GOW4 and Okhissa Lake. Based on visual inspection Okhissa Lake does not appear to have an effect on the piezometric water level of GOW4. The piezometric water level of GOW4 is continuing to decrease as the Okhissa Lake water elevation increases and more shows more constant water levels. Figure 4.8 reveals slight GOW4 responses to rainfall, but lacks a distinct relationship between the reservoir water level and GOW4 water level.

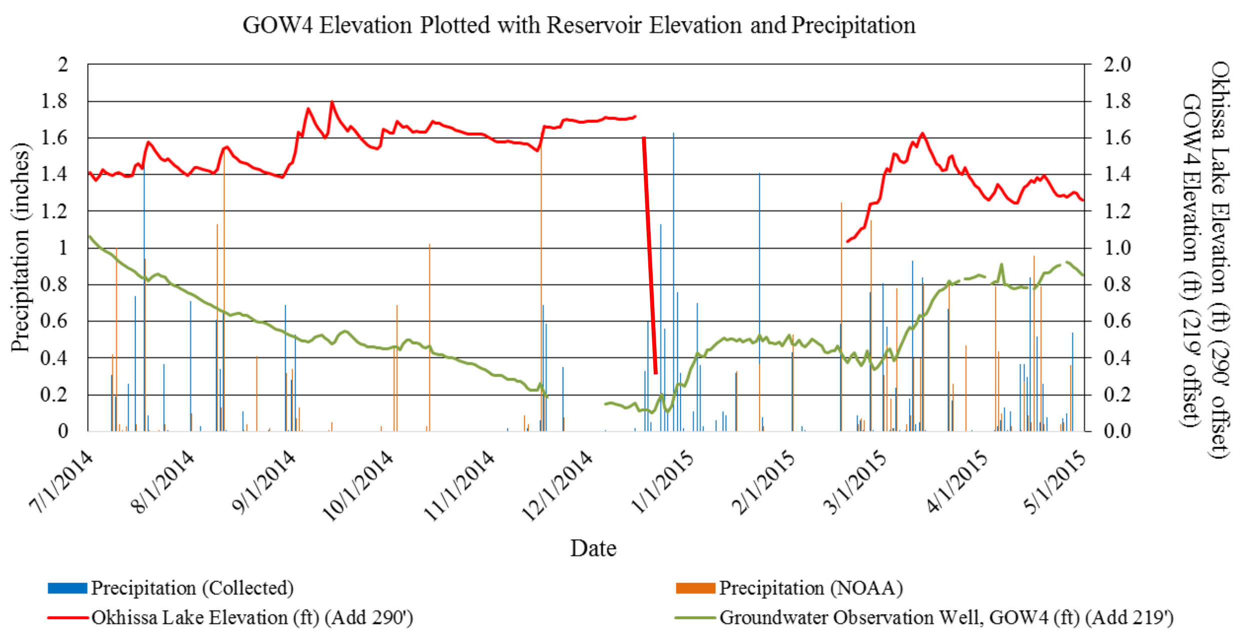

Figure 4.8: Reservoir and piezometer (GOW4) water levels with daily precipitation.

The qualitative presentation of water elevation data of GOW14 (purple) with the Okhissa Lake water level (red), collected precipitation (blue) and NOAA precipitation (orange) is shown in Figure 4.9. The plotted Okhissa Lake water level is offset by 290 feet. The piezometric water level of GOW14 is offset by 217 feet. The water level changes in Okhissa Lake are attributed to precipitation, as rainfall in the Porter Creek watershed is the only contributor to the lake water level. GOW14 shows responses in water level changes related to the reservoir water level changes, and with similar magnitudes. The increased piezometric water level changes seen in GOW14 in comparison to GOW4 is attributed to the lower elevation in ground surface. The surface water flows toward GOW14, resulting in more infiltration than seen at the location of GOW4. It is expected the rainfall events at the Okhissa Lake site contribute to the recharge of the water level recorded by GOW14. Visual inspection of Figure 4.9 also reveals a potential contribution from Okhissa Lake.

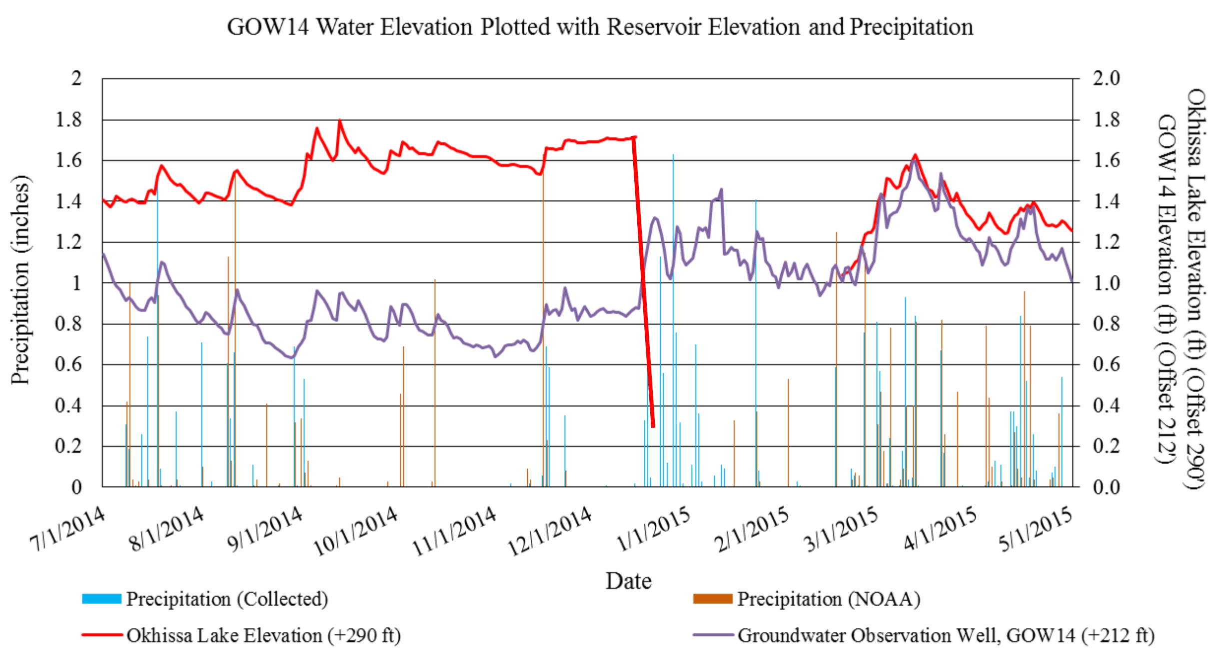

Figure 4.9: Reservoir and piezometer (GOW14) water levels with daily precipitation.

Okhissa Lake water level (red) is plotted with collected precipitation (blue) and NOAA precipitation (orange) as they relate to each PZ water level. The water level of Okhissa Lake is offset by 290 feet and the PZ water level is offset by 227 feet. Figure 4.10 provides insight to how the rainfall events affect water elevations of Okhissa Lake and in turn affects the water elevation of the PZ wells. Visual inspection of Figure 4.10 shows a possible connection between Okhissa Lake water level changes and the water level changes seen in the PZ wells due to precipitation events.

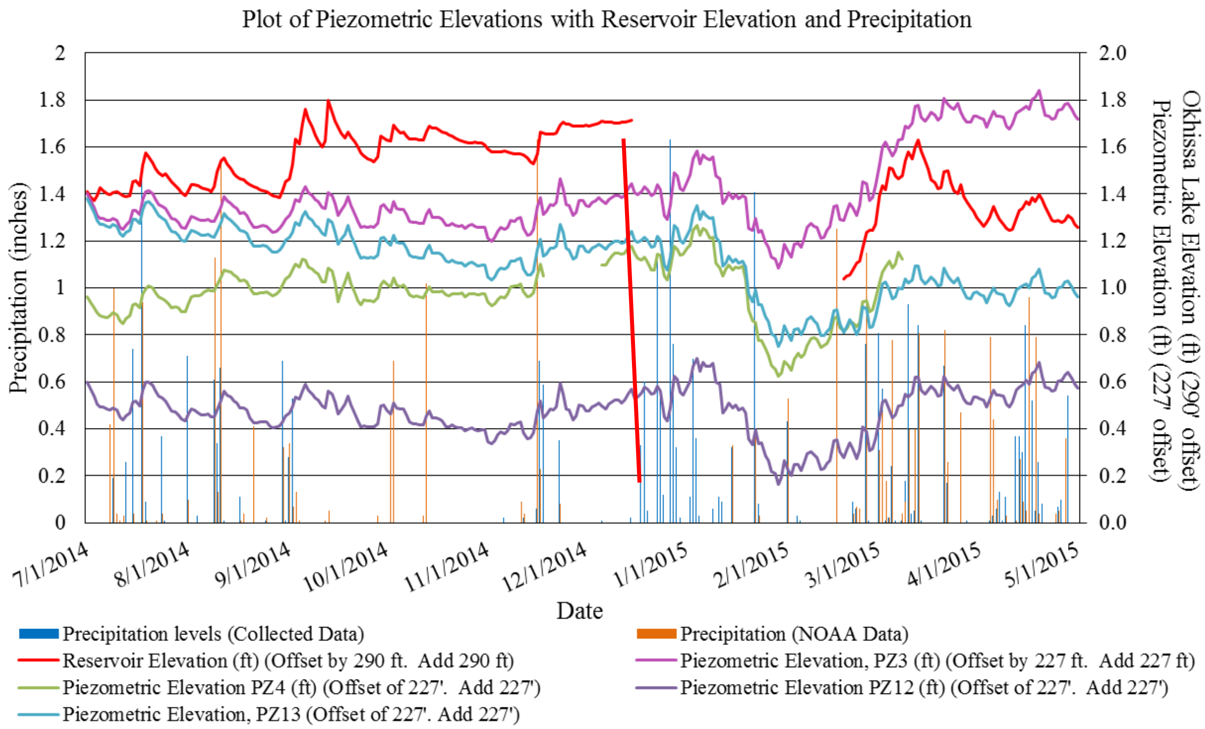

Figure 4.10: Reservoir and piezometer (PZ) water levels with daily precipitation.

4.1.3 Piezometer Response to Reservoir Drawdown

Okhissa Lake water level was intentionally reduced by two feet over the course of six days beginning December 16, 2014. Based on the data obtained prior to December 16, 2014, a decrease in water level of the PZ wells is expected, in response to the reservoir water level reduction. The largest decrease in logged water levels for the PZ wells is 6 inches occurring over the course of a month beginning January 1, 2015.

The following will focus on the time the reservoir water level was intentionally reduced beginning on December 16, 2014 and ending on December 22, 2014, when the principle spillway gate was closed and subsequent refilling of the reservoir occurred. The data is plotted from December 10, 2014 through March 25, 2015, displaying the response in the instrumented PZ and GOW wells. A response to the intentional reduction of Okhissa Lake water elevation in the GOW wells indicates potential communication between Okhissa Lake and the phreatic aquifer, which would call into question the effectiveness of the installed slurry trench.

The typical plot for collected data from a real time monitoring system is a time history plot (Bartholomew, Murray & Goins, 1987). Okhissa Lake water elevation (red) from December 10, 2014 to December 22, 2014 is plotted in Figure 4.11 and Figure 4.12. These same figures also display the piezometric water elevation for GOW4 during this same timeframe. Figure 4.11 provides a visual representation of the logged five minute data, and Figure 4.12 provides the daily averages of Okhissa Lake and GOW4 water levels. The data for the Okhissa Lake sensor ends on December 22, 2014 due to the sensor cable being severed during the closure of the principle spillway gate. The VW piezometer that measures the reservoir water level is assumed to have moved as soon as the gate was opened.

The reservoir was at a constant elevation of 291.7 feet, leading up to the opening of the principle spillway gate on December 16, 2014. The water level of GOW4 was also constant at an elevation of 219.15 feet. The principle spillway gates were opened on December 16, 2014 and remained open for six days to lower the water level two feet. The response of GOW4 to the two foot water level reduction of Okhissa Lake is not revealed. The water levels of GOW4 are increasing during the intentional water level reduction of Okhissa Lake, providing evidence a connection between Okhissa Lake and GOW4 does not exist and the slurry trench is operating effectively.

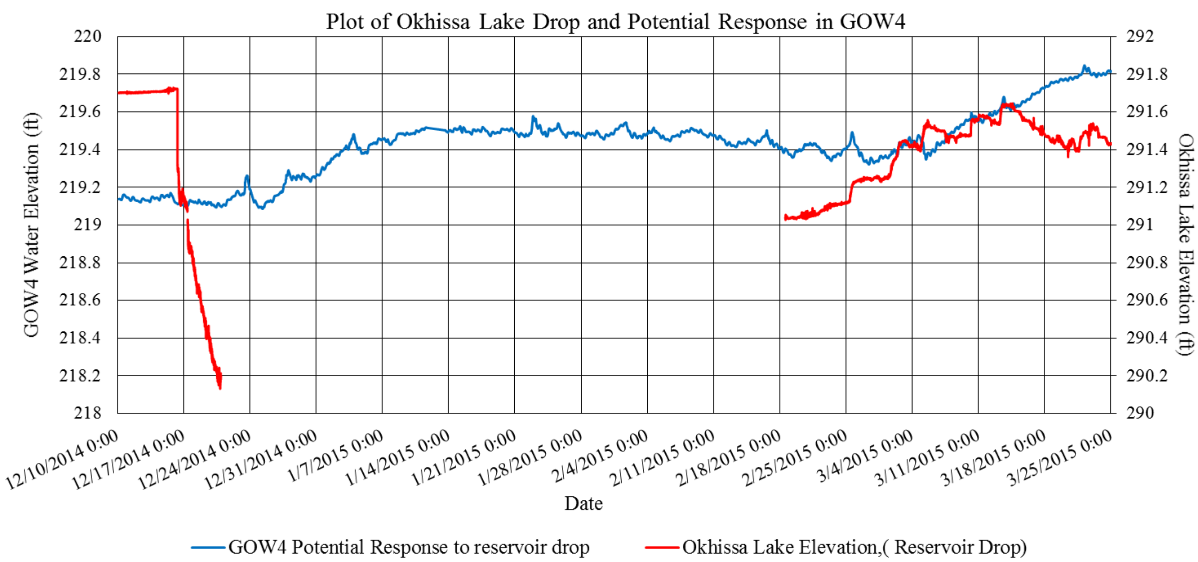

Figure 4.11: Intentional drawdown and potential piezometer (GOW4) response (5 minute data).

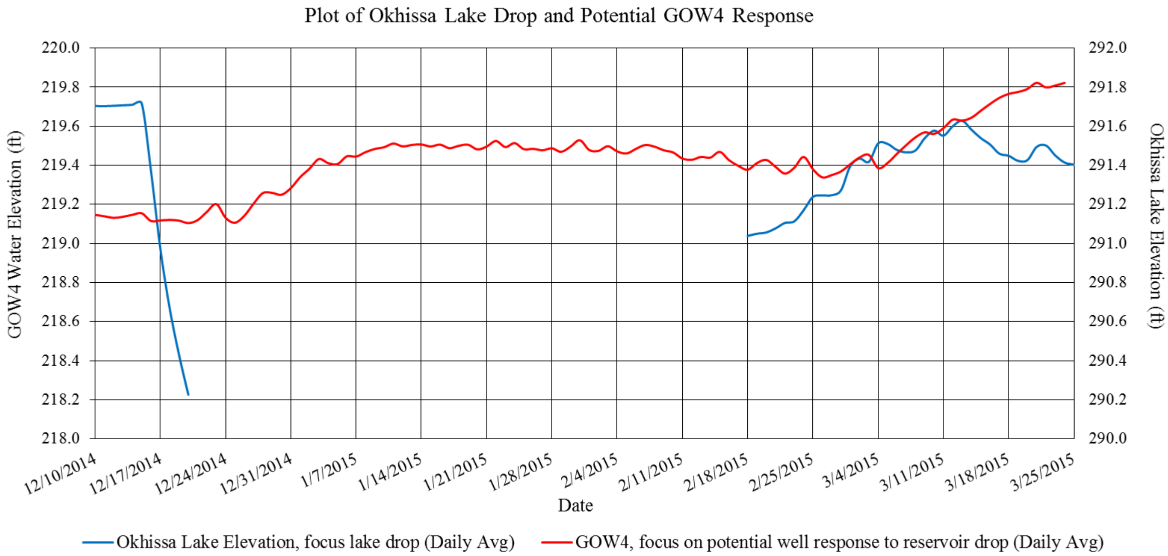

Figure 4.12: Intentional drawdown and potential piezometer (GOW4) response (daily average).

The piezometric water level data for piezometer (GOW14 (blue)) is plotted from December 10, 2014 through March 25, 2014, to observe any potential response in piezometer (GOW14) to the reservoir water level reduction. The water level response of piezometer (GOW14) is indicated by points 1, 2 and 3 in Figure 4.13 and Figure 4.14. Figure 4.13 displays the logged five minute water levels and Figure 4.14 displays the daily average water levels. Label 1 reveals a potential response in piezometer (GOW14) to the Okhissa Lake water level reduction, as piezometer (GOW14) water level begins to decrease. The water level of piezometer (GOW14) at Label 1 is 213.4 when the water level begins to decrease, resulting in a time lag of 22 days. The final minimum elevation in the potential response is 213.0 feet indicated by label 2. Label 3 indicates the piezometer (GOW14) water level's postulated return to normal pool on March 11, 2015 at an elevation at 213.5 feet in magnitude. Piezometer (GOW4) and piezometer (GOW14) have two different responses during the time, subsequent to when Okhissa Lake was lowered.

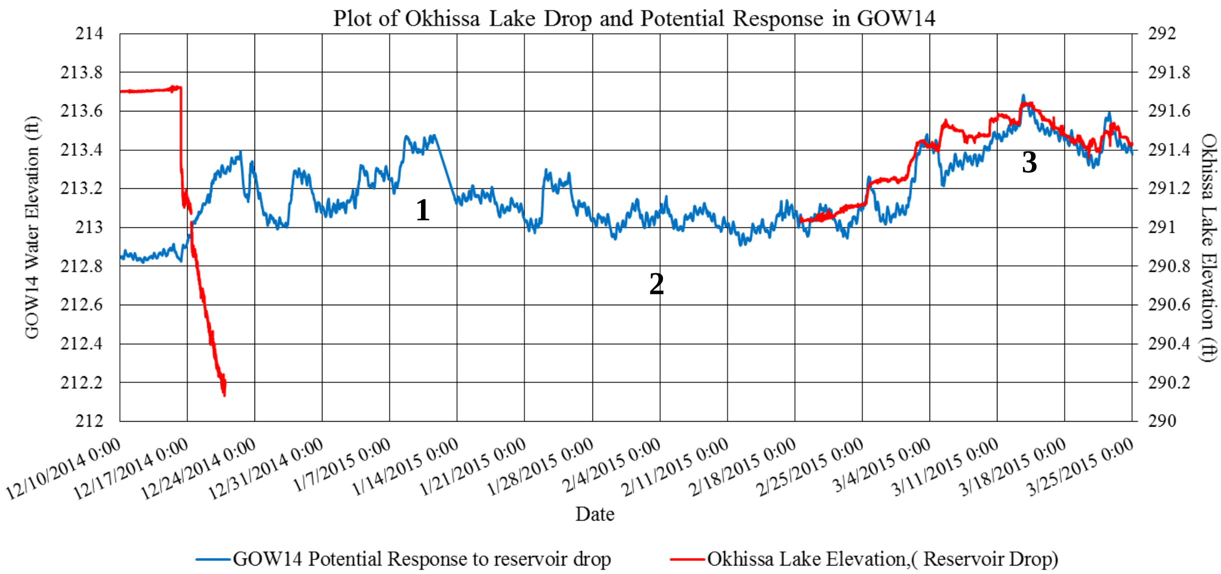

Figure 4.13: Intentional drawdown and potential piezometer (GOW14) response (5 min. data).

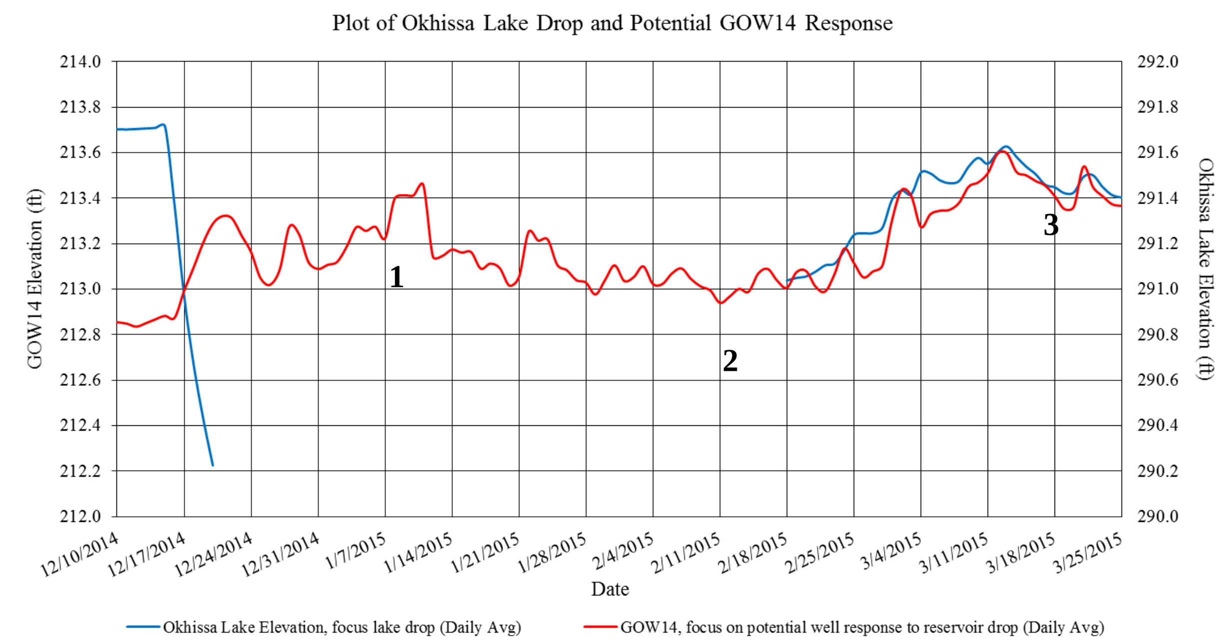

Figure 4.14: Intentional drawdown and possible piezometer (GOW14) response (daily average).

The comparison of piezometric and reservoir water levels is a necessary comparison to determine if there is influence between the confined aquifer and reservoir. Reservoir water level (red) from December 10, 2014 to March 25, 2014 and piezometric water levels of the PZ wells are plotted in Figure 4.14 and 4.15. Figure 4.14 is the collected five minute data for Okhissa Lake water elevations and PZ piezometric water levels. Figure 4.15 is a plot of the daily average water elevations of Okhissa Lake and PZ wells. The data for the confined aquifer is consistent. The trends of each PZ sensor are very similar in their responses to the intentional reservoir water level reduction.

PZ3 indicates an initial response on January 7, 2015 to the intentional reservoir water level reduction indicated by label 1 in Figure 4.14 and 4.15. A time lag of 22 days is observed in piezometer (PZ3) response. Label 2 indicates the lowest water level on January 28, 2015. The water level of PZ3 at label 2 is 228.1 feet, resulting in a decrease of 6 inches over 21 days. PZ3 returns to normal pool on March 11, 2015 at a water level of 228.8 feet indicated label 3. PZ3 returned to normal pool in 63 days from the time of the initial response on January 7, 2015. The new sensor for Okhissa Lake was installed on February 18, 2015 with an elevation of 291.0 feet. The reservoir appears to return to normal pool on March 11, 2015 indicated by label 3.

The time response of piezometer (PZ4) to the intentional Okhissa Lake water level reduction is similar to piezometer (PZ3). The water level of PZ4 is 228.2 feet at normal pool. The minimum water level is 227.6 feet on January 28, 2014, which is a water level decrease of 0.6 feet or 7.2 inches over 21 days. PZ4 shows a slightly larger decrease in water level in comparison to PZ3. A return to normal pool for PZ4 occurs on March 11, 2015 at an elevation of 228.2 feet.

The normal pool water level of PZ12 is 227.7 feet. A decrease in water level of PZ12 occurs over the course of 21 days to a minimum water elevation of 227.2 feet on January 28, 2015, and returns to normal pool on March 11, 2015 to an elevation of 227.6.

The normal pool water level of PZ13 is 228.3 feet. The minimum water level for piezometer (PZ13) is 227.8 feet and ascends to normal pool of 228.0 feet. The response of PZ13 displays a slight difference in comparison to the other PZ water level responses. Figure 4.14 and 4.15 depicts a slightly lower water level for PZ13 and a new normal pool water elevation of 228.0 feet.

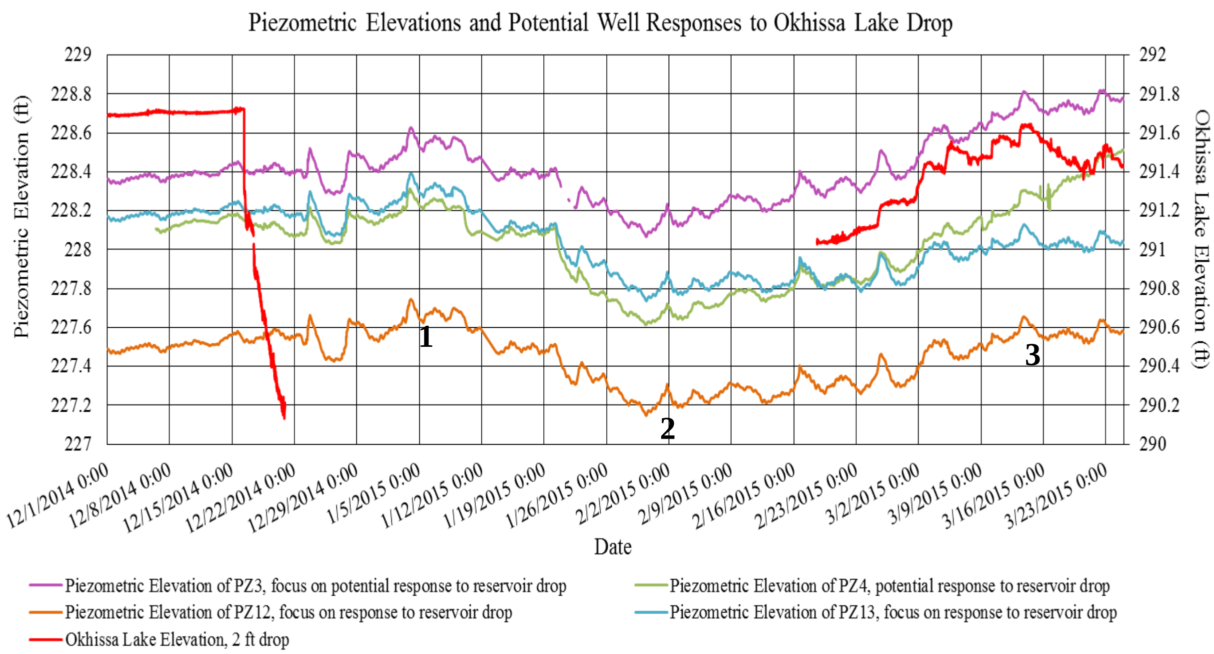

Figure 4.15: Intentional drawdown and potential piezometer (PZ) response (5 minute).

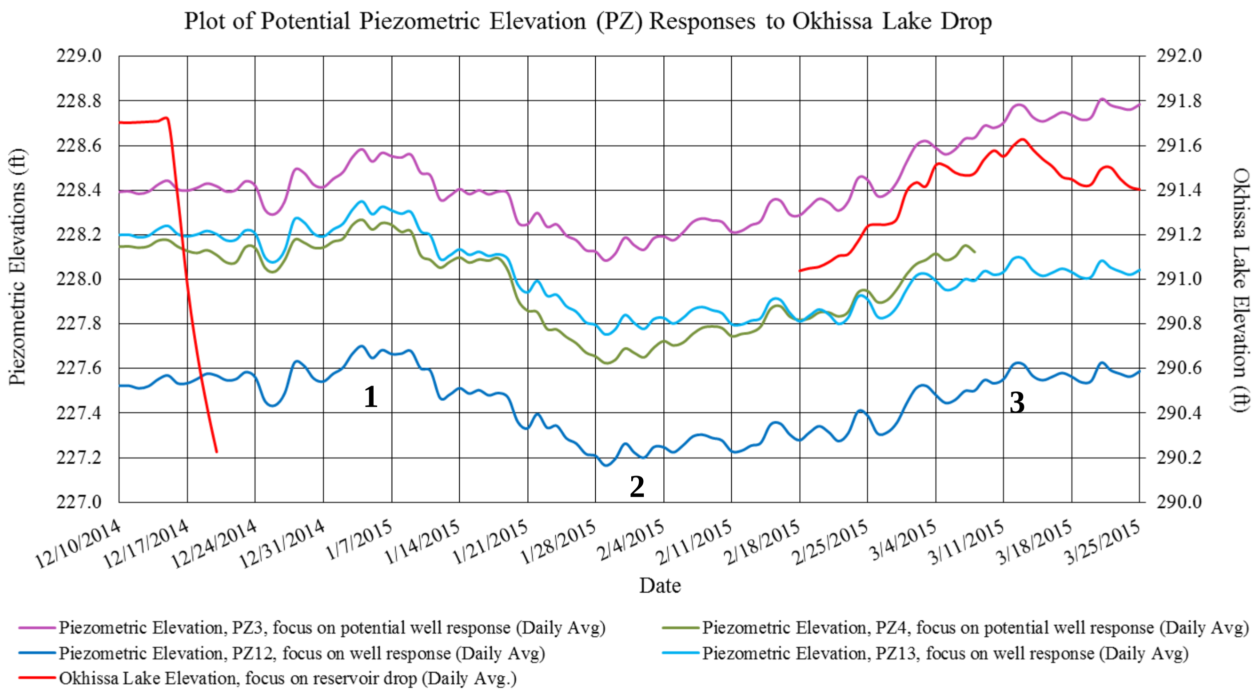

Figure 4.16: Intentional drawdown and potential piezometer (PZ) response (daily average).

4.2 Correlation Analysis

The correlation analysis has several advantages over the typical time history plots (Gall, 2007). Correlation analysis is a reliable, simple and practical approach for estimating groundwater level responses for proper planning and management of groundwater (Sahoo & Jha, 2015). A scatter plot of piezometer water level readings (dependent variable, e.g. GOW and PZ) versus reservoir water level (independent variable, e.g. Okhissa Lake) can be used to determine if the reservoir is influencing the piezometer water levels and if there are factors other than reservoir water level that influence the piezometer water levels. The changes with time in the relationship between piezometer and reservoir water level is a correlation or hysteresis plot (Carter, Hosko & Rubertis, 2000). The correlation plot is underutilized, but provides more insightful information in comparison to a time history plot (Gall, 2007).

4.2.1 Time Segmentation

Three principle factors govern time segmentation of collected data for correlation analysis. The first factor that requires separating the data in different time segments is the time-gap effect. This factor is applicable when the reservoir and piezometer levels are not recorded at the same time. The time-gap effect can be interpreted as a false time lag between the piezometer and the reservoir (Gall, 2007). The time-gap effect segment removes the false lag from the correlation plot. The time-gap effect is not an issue for the real-time monitoring system operating at Okhissa Dam, as each installed sensor is collected on a five minute schedule.

The second data segmentation factor is the scale effect. The selection of a too-detailed scale for the piezometer readings will exaggerate the piezometer reading variation. The full scale of the VW piezometers installed in the Casagrande standpipes is -14.50 to 50.76 psi (-100 to 350 kPa) and therefore an accuracy of 0.151 feet (0.046 m) or 1.8 inches (4.57 cm). The reservoir sensor scale is ± 0.1% of 10.15 psi (70 kPa), which is an accuracy of 0.023 feet (0.007 m) or 0.28 inches (0.71 cm) (Geokon, 2012). To check the scale effect of the Okhissa Dam monitoring system, a section of data was selected from the time history plots, from September 5, 2014 through October 1, 2014. This segment of data includes minimal rainfall events, thus isolating the potential influence from precipitation and focusing on the effect from the reservoir levels. The recorded water level measurements of piezometer (PZ3, PZ4, PZ12, and PZ13) water level versus reservoir water level is shown in Figure 4.17.

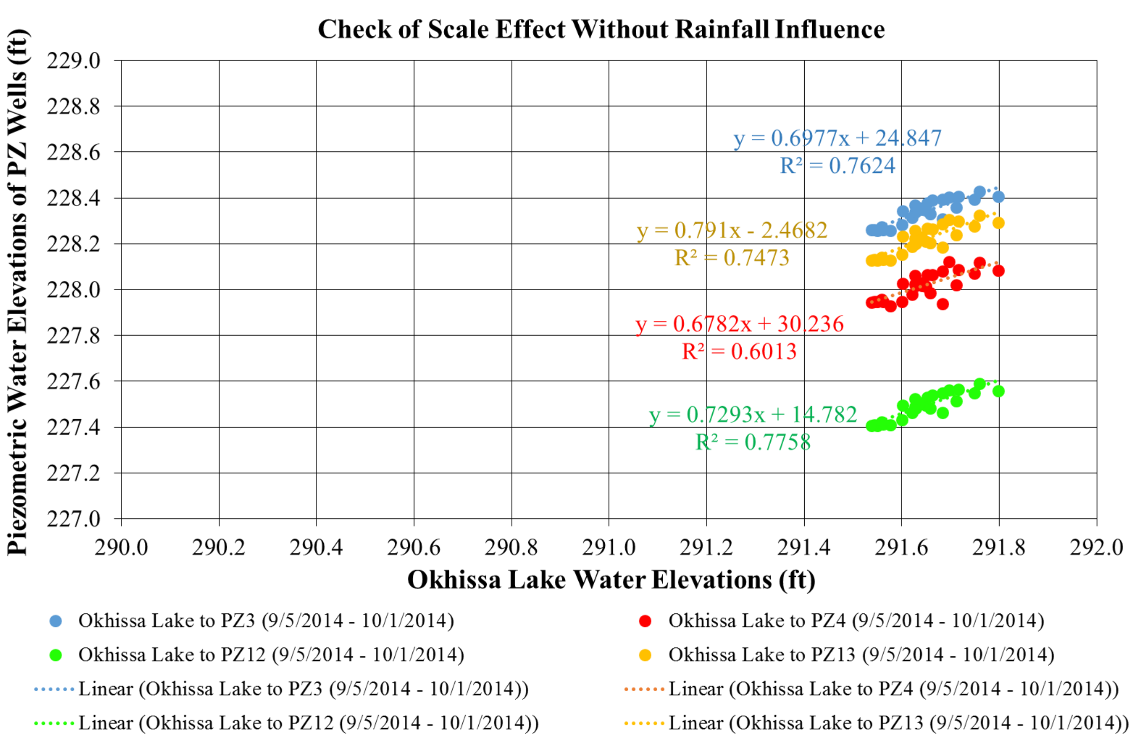

Figure 4.17: Reservoir and piezometer (PZ) relationship to determine if scale effect exists.

A scale effect is present if a slope of zero exists in the relationship of reservoir level and piezometer level. The relationship from September 5, 2014 through October 1, 2014 shows a correlation between the piezometer water level and the reservoir water level, and it is concluded that the scale effect is not an issue. Furthermore, the scale effect is not present because the range of collected piezometer and reservoir water levels is greater than the accuracy of the vibrating wire piezometers.

The third factor that requires time segmentation of the data is associated with changes in the system that significantly affects the correlation (Gall, 2007). These changes include factors that affect the phreatic line in the dam or foundation (e.g.: intentional lowering of the reservoir water level in December) and any alterations made to the piezometers (e.g.: recalibration, sensor replacement, changes in signal cable length). Figure 4.18 displays correlation plots for each piezometer. The blue data was collected with the originally installed reservoir sensor before its signal cable was severed and red data represents the current sensor, installed on February 18, 2015. The effect of replacing the reservoir sensor and the lowering of the reservoir clearly causes a redistribution of the data.

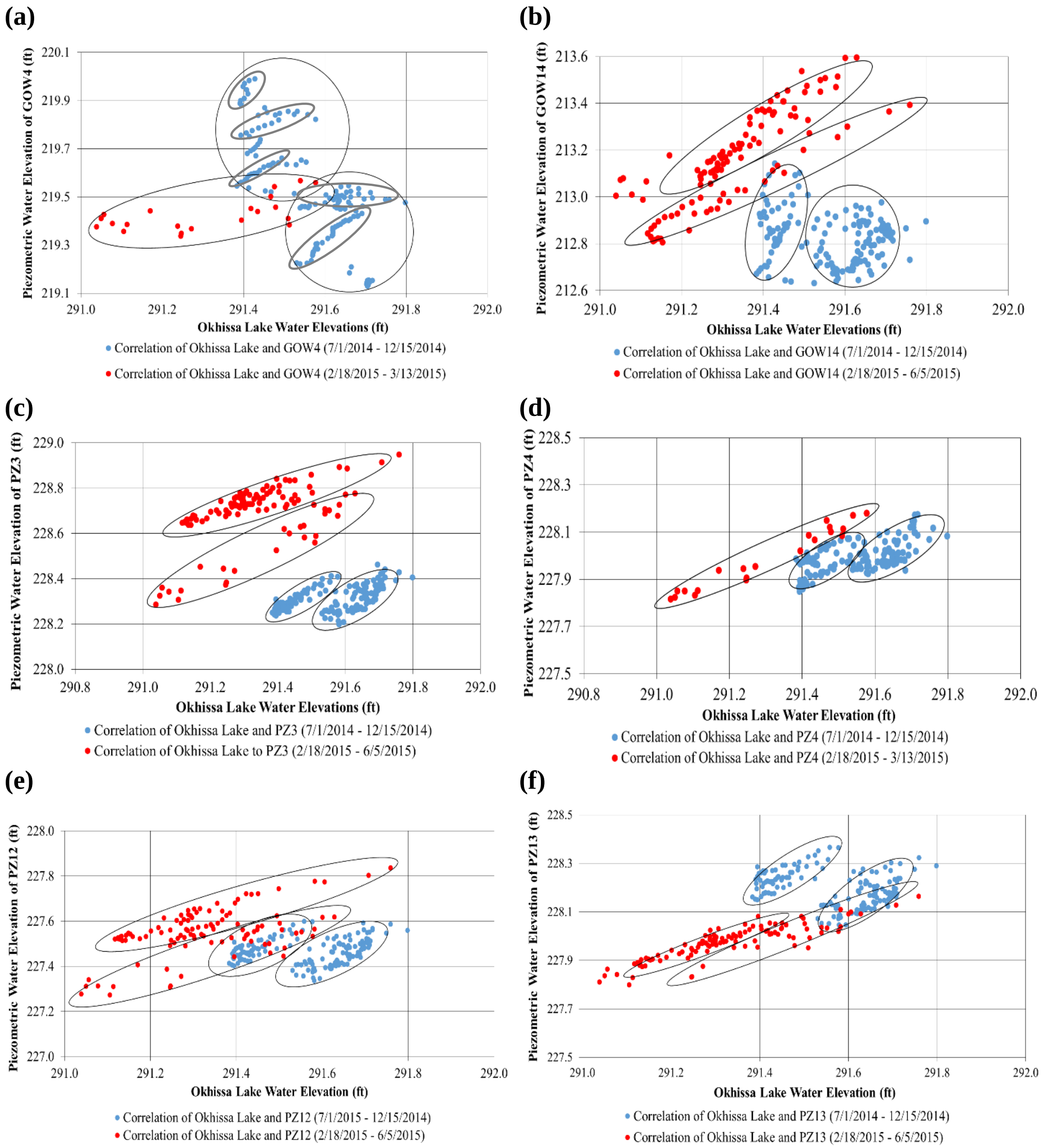

Figure 4.18: Piezometer and reservoir relationship: (a), GOW4; (b), GOW14; (c), PZ3; (d), PZ4; (e), PZ12; (f), PZ13.

The inspection of Figure 4.18 reveals additional time segmentation is needed, due to the formation of distinct clusters for both the original reservoir sensor (blue) relationship and the relationship corresponding to the current reservoir sensor (red). Two distinct blue clusters (July 1, 2014 to December 15, 2014) are revealed in the piezometer and reservoir level relationships in Figure 4.17. The two blue clusters are a result of a change in the monitoring system. The reservoir sensor recorded a higher water level because the cable slipped down on September 3, 2014. This is consistent with the scatter plot results as the cluster after the slip is shifted to deeper reservoir water levels. This redistribution of data for the blue is seen across all the piezometer and reservoir water level relationships because the reservoir level is the common factor. The result of this change requires a time segmentation on September 3, 2014, as the reservoir sensor established a new deployed elevation. Additional time segmentation is needed for the red data (February 18, 2015 to June 5, 2015) in Figure 4.18 because of a system change. The time history plot of the recorded reservoir data shows an abrupt decrease in the reservoir level on March 13, 2015. The reason for this sudden change in reservoir level is not known. However, the evaluation of Figure 4.18 clearly shows the need for an additional segmentation in the red data as two distinct clusters are displayed. The relationship between piezometer (GOW4) and reservoir level in Figure 4.18(a) indicates additional time segments are needed. The cause(s) of the additional segmentations within the previously segmented blue data is unknown. The segmented red data in Figure 4.18(a) and Figure 4.18(d) contains less points as a result of inaccurate data due to a malfunctioning charge controller. A minimum of 12V is required to be supplied to the sensor node called GOW4 and PZ4 to accurately record measurements.

4.2.2 Linear Regression Analysis

Linear regression analysis provides information that quantifies the relationship between piezometer water levels and reservoir water level. The outputs of regression analysis include: the coefficient of determination (R^2), coefficient of correlation (R), and the slope of regression (m). The qualitative and quantitative evaluation of regression analysis and its outputs provides valuable information in determining if communication at the Okhissa Lake site exists between the reservoir and groundwater.

The R^2 value is a key output of regression analysis. The coefficient of determination is the square of the R value and ranges from zero to one. The fit of the linear regression model is assessed by R^2, which represents the proportion of total variation of the dependent variable accounted for or, explained by the independent variables (Sahoo & Jha, 2015). A high R^2 value means a high level of confidence in the model and the model's ability to predict future piezometer levels based on current reservoir water levels. For example, a R^2 value of 0.85 means that 85% of the variance in piezometric levels is predictable from reservoir levels. The value of R^2 is determined by Microsoft Excel® using a linear regression analysis. The mathematical determination of R^2 is defined as:

$$R^2=\left\{\left(\frac{1}{N}\right)*\frac{\Sigma\left[(x_i-\bar{x})*\left(y_i-\bar{y}\right)\right]}{\left(\sigma_x-\sigma_y\right)}\right\}^2 \tag{4.2}$$

where, N = number of observations used to fit the model, x_i is the initial observed reservoir water level, $\bar{x}$ is the mean reservoir water level, y_i is the initial observed piezometric water level, $\bar{y}$ is the mean piezometric water level, σ_x is the standard deviation of reservoir water level, and σ_y is the standard deviation of piezometric water level.

A correlation coefficient (R) is the correlation between the observed value of a dependent variable (piezometer water level) and the value of the independent variable (Sahoo & Jha, 2015). The magnitude of R depends on the hysteresis within the relationship. The value of R reveals how closely or not at all the two variables are related to one another and quantifies the hysteresis formed by the plotted data. The factors affecting the spread of the hysteresis are: whether other sources are affecting the piezometer levels (e.g.: rainfall), a lag in the piezometer response, and the distance the piezometer is from the influencing source. The correlation coefficient is mathematically defined as:

$$R=\frac{n(\Sigma xy)-(\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2-(\Sigma x)^2][n\Sigma y^2-(\Sigma y)^2]}} \tag{4.1}$$

where, n is the number of data pairs, x is the reservoir level, and y is the piezometer level (Davis, 2002). The value of R ranges from $-1 \leq R \leq +1$, the signs are used to show a negative or positive correlation. The magnitude of R indicates the whether or not there is linear dependence between piezometer and reservoir water levels. The R value is determined by using the CORREL function in Microsoft Excel®. The R value is also calculated by taking the square root of the R^2 value. The criteria for defining the meaning of a particular correlation coefficient is displayed in Table 4.1.

Table 4.1: Defining coefficients of correlation (Davis, 2002)

Coefficient of Correlation (R)	**Description**
0 - 0.1	No Correlation
0.1 – 0.5	Weak Correlation
0.5 – 0.8	Moderate Correlation
0.8 – 1.0	Strong Correlation

The resulting slope (m) of a linear relationship is a ratio of the rate of change that the y values fluctuate in comparison to the x values (Davis, 2002). A slope of approximately zero indicates the reservoir is continuing to fluctuate without the piezometer responding to the changes, and indicates communication is not occurring. A slope of approximately one, indicates the fluctuations of the piezometer are equal to the reservoir level and clear communication potentially exists. The slope of a regression greater than one suggests the piezometer is acting independently from the reservoir, and the fluctuations seen in the piezometer may be attributed to a different source (e.g.: rainfall).

The simultaneous evaluation of R^2, R, and m is vital in determining if communication exists at the Okhissa Lake site between the reservoir and piezometers. The fluctuations measured at Okhissa Lake are minimal. The relationship between piezometer water level and reservoir water level is plotted on a scale of 0.2 feet (0.061 meters) or 2.4 inches (6.1 centimeters). A conclusion of communication at Okhissa Lake is not considered to be a concern in the dam's efficiency, due to the near constant water levels. The criteria for determining communication is shown in Table 4.2.

Table 4.2: Summary of potential communication criteria.

Degree of Communication	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Slope (m)
None	0 - 0.1	0 - 0.1	0 – 0.1
Weak	0.1 - 0.5	0.1 – 0.5	0.1 – 0.5
Moderate	0.5 - 0.8	0.5 – 0.8	0.5 – 0.8
Strong	0.8 - 1.0	0.8 – 1.0	0.8 – 1.0

4.2.3 Piezometer (GOW) Water Levels versus Reservoir Water Levels.

The relationship between reservoir level and piezometer (GOW4) displays six sections of time segmented data. Each of these segments are analyzed using regression analysis. The piezometer (GOW4) is located at the toe of the downstream embankment, 287 feet from the centerline of the dam and 460 feet west of the principle spillway. The relationship between reservoir level and piezometer level (GOW4) is presented in Figure 4.19. A summary of results for this relationship is displayed in Table 4.3.

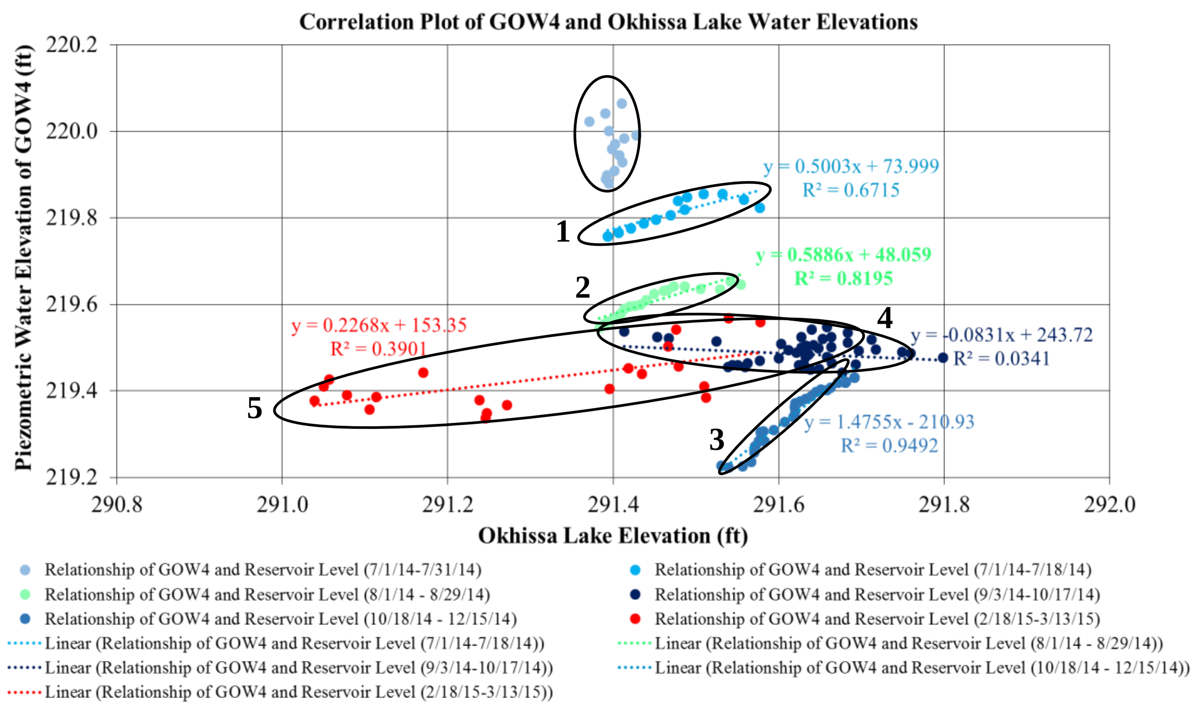

Figure 4.19: Relationship between reservoir level and piezometer (GOW4).

Table 4.3: Summary of reservoir level and piezometer (GOW4) relationship.

Time Segment	Time Segment	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Line of Regression Slope (m)
7/1/14 – 7/18/14	1	0.67	0.81	0.50
7/18/14 – 7/31/14	No Connection, this segment is indicated by the circled cluster.			
8/1/14 – 8/29/14	2	0.82	0.92	0.59
8/31/14 – 10/17/14	4	0.034	0.18	-0.083
10/18/14 – 12/15/14	3	0.95	0.97	1.5
2/18/15 – 3/13/15	5	0.39	0.62	0.23

The time segments that indicate communication are July 1, 2014 through July 18, 2014 (1), August 1, 2014 through August 29, 2014 (2), and October 18, 2014 through December 15, 2014 (3). The segments (1, 2, and 3) in Figure 4.19 do not form an elliptical hysteresis, but rather aligned segmentations. This indicates minimal lag in the piezometer (GOW4) response due to reservoir level changes. The results of the slope for segment 1 and 2 show the reservoir level is increasing by a rate that is twice as large as the increase rate of the piezometer (GOW4), indicating moderate reservoir influence on the water level of the piezometer (GOW4). The value of the slope, for time segment 3, shows the piezometer (GOW4) water level increasing at the same rate as the reservoir level. Time segment 3 is during a series of precipitation events (seen in the time history plots), as indicated by the slope value of 1.48, meaning the piezometer (GOW4) is experiencing a greater change than the reservoir. Based on this analysis, time segments 1, 2, and 3 indicate communication is a factor between piezometer (GOW4) and reservoir. However, segments 1, 2 and 3 are over short periods of time, thus possibly skewing the results of the correlation analysis to show potential communication.

Time segments from August 31, 2014 through October 17, 2014 (4) and February 18, 2015 through March 13, 2015 (5) displays zero to minimal potential for reservoir and piezometer (GOW4) communication. The effect of precipitation must be isolated in the correlation analysis to determine if the results indicating communication between piezometer (GOW4) and reservoir level are connected due to rainfall.

The piezometer (GOW14) is located 530 feet downstream from the centerline of Okhissa Lake dam and 300 feet west of the principle spillway. The plot of the piezometer (GOW14) water level versus reservoir water level is shown in Figure 4.20. A summary of the quantitative results of this relationship is displayed in Table 4.4.

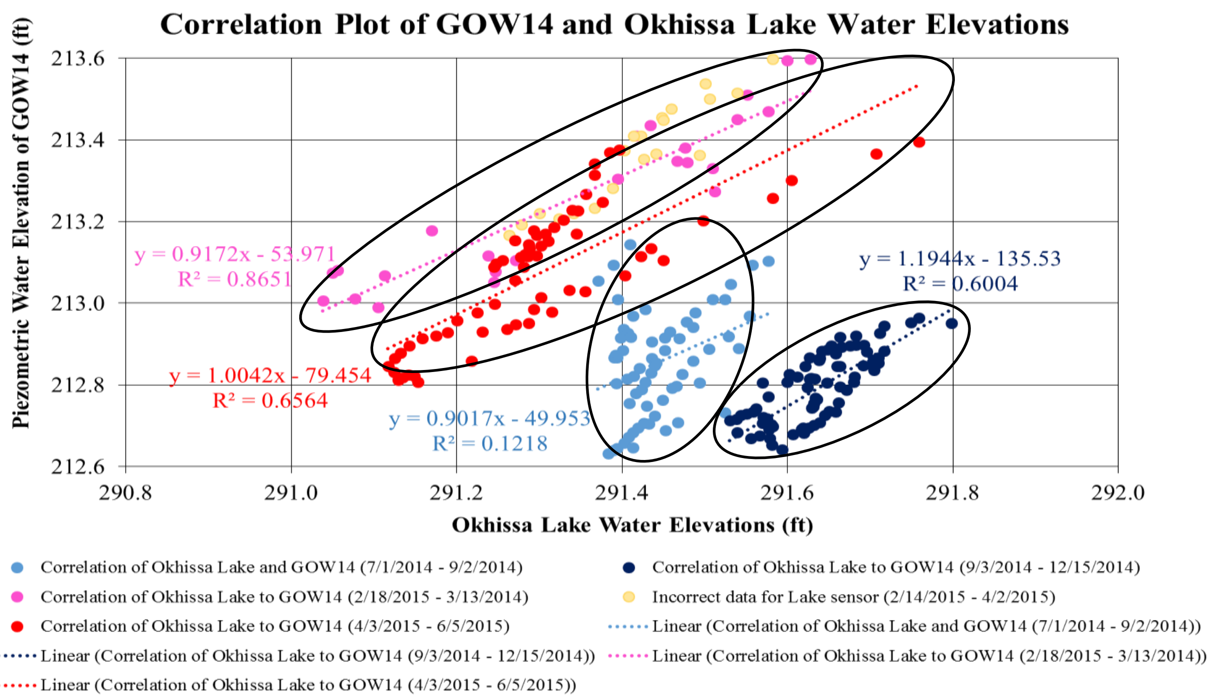

Figure 4.20: Relationship between reservoir level and piezometer (GOW14).

Table 4.4: Summary of reservoir level and piezometer (GOW14) relationship.

Time Segment	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Line of Regression Slope (m)
7/1/14 – 9/2/14	0.12	0.35	0.90
9/3/14 – 12/15/14	0.60	0.79	1.2
2/18/15 – 3/13/15	0.87	0.93	0.92
4/3/15 – 6/5/15	0.66	0.81	1.0

The relationship between reservoir water level and piezometer (GOW14) water level reveals more consistent results in comparison to the previous relationship of reservoir water level and piezometer (GOW4) water level data from July 1, 2014 through September 2, 2014 indicates a relationship between the reservoir and piezometer (GOW14) is not present. The R^2 value of 12% for this particular linear regression model is unable to confidently predict future piezometer levels as they relate to reservoir levels. The data segment from September 3, 2014 through December 15, 2014 shows a slightly stronger hysteresis and a higher linear dependency. This segment of higher correlation could be attributed to more frequent rainfall during this time period. The quantitative evaluation of the data segment from September 3, 2014 through December 15, 2014 in Table 4.4 shows moderate communication between the reservoir and piezometer (GOW14) based on the linear regression analysis results.

The data from February 18, 2015 through June 5, 2015 meet the criteria for communication between the reservoir and piezometer (GOW14) and form an elliptical hysteresis envelope. The hysteresis indicates precipitation is affecting the linear dependency for these segments in Figure 4.20. These data segments are during the rainy season and contain higher precipitation values in comparison to the previous segments from July 1, 2014 through December 15, 2014.

The qualitative and quantitative relationship of the segments from February 18, 2015 through June 5, 2015 3 reveal a moderate level of communication between the reservoir and piezometer (GOW14) based on the linear regression analysis.

The relationship between the piezometers monitoring the phreatic aquifer water levels versus reservoir water levels must be evaluated with respect to precipitation. The variations of the water-table level of an unconfined aquifer due to rainfall are complex (Viswanathan, 1983). The rate of infiltration depends upon several parameters and variables. The most important of these are the soil moisture levels of the unsaturated region, and the amount of surface cover.

The complexity of properly accounting for aquifer infiltration was alleviated by isolating rainfall events to determine if communication with the reservoir exists. The relationship between piezometer (GOW14) water level and reservoir water level shown in Figure 4.21 focuses on the influence of precipitation at Okhissa Dam. A summary of quantitative results for the relationship of piezometer (GOW14) water level versus reservoir water level is shown in Table 4.5.

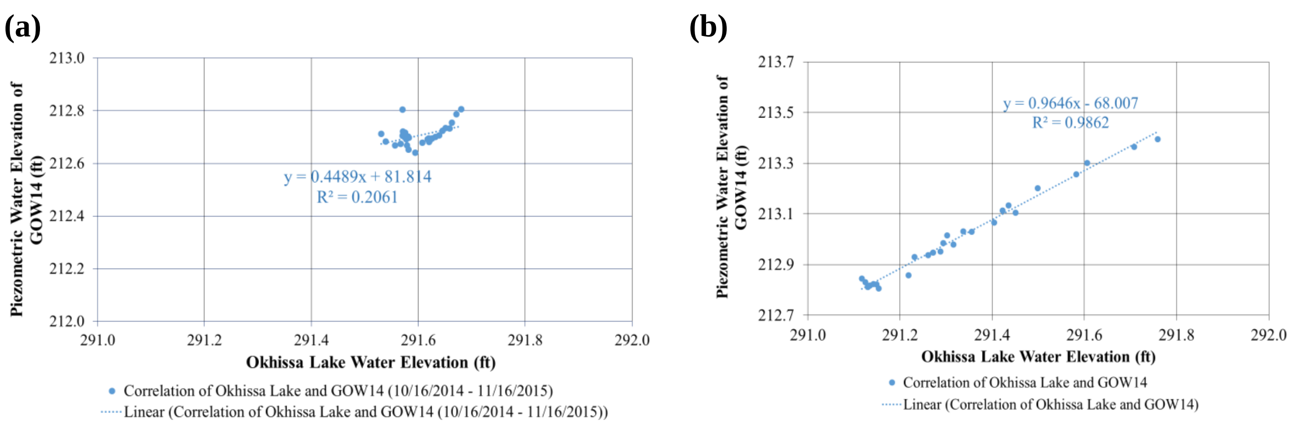

Figure 4.21: Reservoir level and GOW14 relationship: (a), without rainfall; (b), including rainfall events.

Table 4.5: Summary of reservoir and piezometer (GOW14) relationship to precipitation events.

Time Segment (precipitation in inches)	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Line of Regression Slope (m)
Minimal Precipitation	0.21	0.45	0.45
Multiple Precipitation Events	0.99	1.0	0.96

The results of the relationship in Figure 4.21 reveal the piezometer (GOW14) water level is influenced by precipitation, and not communication from the reservoir. The time segment of minimal precipitation (Figure 4.21(a)) indicates communication between the piezometer (GOW14) and the reservoir does not exist. The added effect of precipitation (Figure 4.21(b)) shows an aligned data set rather than a hysteresis. The correlation analysis reveals the piezometer (GOW14) and the reservoir are both affected by precipitation. The reservoir is not the primary contributor to piezometer (GOW14) water levels and the slurry trench is effective in cutting off communication from the reservoir.

4.2.4 Piezometer (PZ) Water Levels versus Reservoir Water Levels

The piezometer (PZ3) is located 311 feet downstream from the centerline of Okhissa Dam and 200 feet west of the principle spillway, along the toe of the downstream embankment. The qualitative results of piezometer (PZ3) water levels versus reservoir water levels is shown in Figure 4.22. A summary of quantitative results of the relationship between piezometer (PZ3) water levels and reservoir water levels are displayed in Table 4.6.

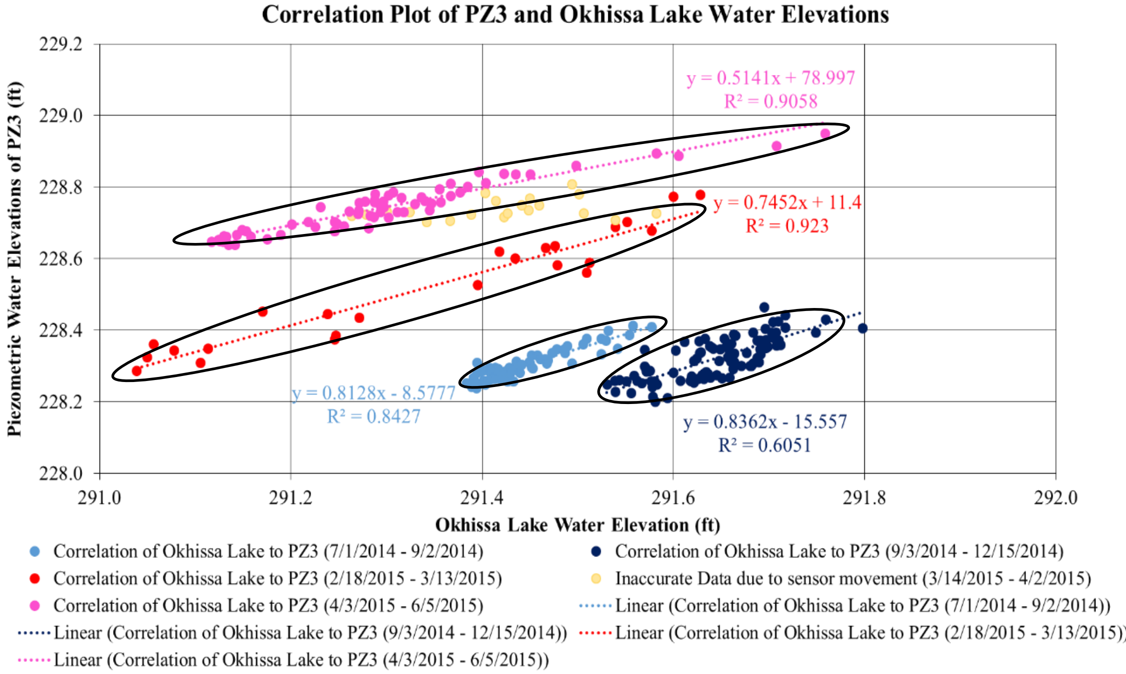

Figure 4.22: Relationship between reservoir level and piezometer (PZ3).

Table 4.6: Summary of reservoir level and piezometer (PZ3) relationship.

Time Segment	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Slope of Regression (m)
7/1/14 – 9/2/14	0.84	0.92	0.81
9/3/14 – 12/15/14	0.61	0.78	0.84
2/18/15 – 3/13/15	0.92	0.95	0.75
4/3/15 – 6/5/15	0.91	0.95	0.51

The relationship between reservoir level and piezometer (PZ3) water level shows the piezometer water level is influenced by the reservoir and communication is present. The quantitative results in Table 4.6 from the linear regression analysis indicate moderate communication exists and the reservoir is contributing to the piezometer (PZ3) water levels.

Piezometer (PZ4) is located 292 feet downstream from the centerline of Okhissa Lake dam and 460 feet west of the principle spillway along the downstream toe. The results of the correlation of piezometer (PZ4) water levels versus reservoir water levels are shown in Figure 4.23 with a summary of quantitative results displayed in Table 4.7.

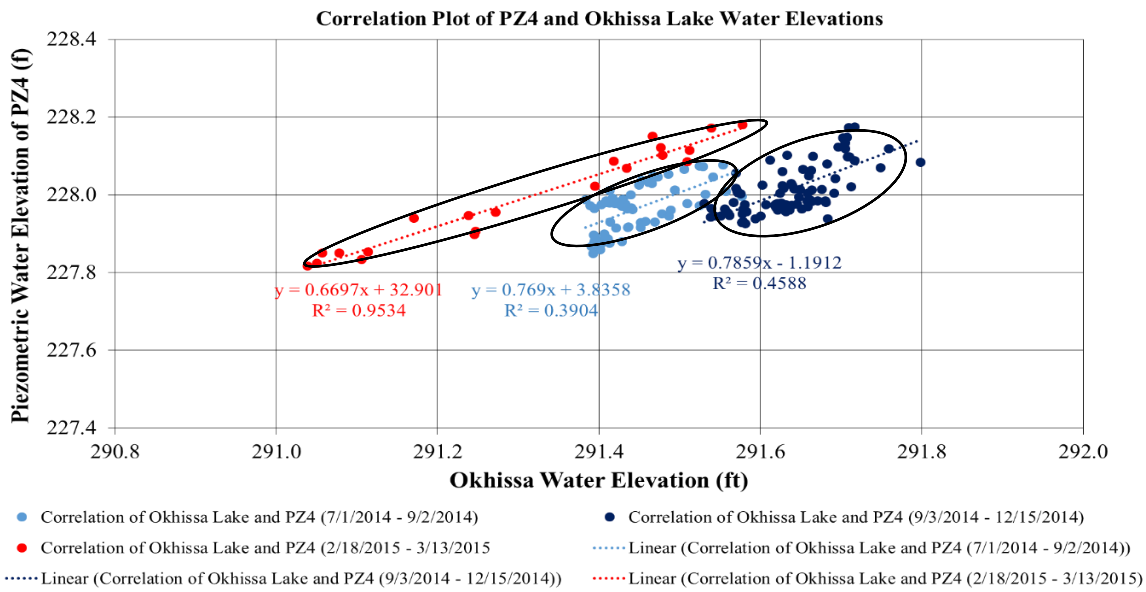

Figure 4.23: Relationship between reservoir level and piezometer (PZ4).

Table 4.7: Summary of reservoir level and piezometer (PZ4) relationship.

Time Segment	**Coefficient of Determination (R^2)**	**Coefficient of Correlation (R)**	**Slope of Linear Regression (m)**
7/1/14 – 9/2/14	0.46	0.68	0.79
9/3/14 – 12/15/14	0.39	0.62	0.79
2/18/15 – 3/13/15	0.95	0.98	0.67

The qualitative results in Figure 4.23 show a larger hysteresis in comparison to piezometer (PZ3) in Figure 4.22. The quantitative results displayed in Table 4.7 show weak to moderate communication exists.

The linear regression analysis from February 18, 2015 through March 13, 2015 shows strong communication between the reservoir and piezometer (PZ4). The limited data may be skewing the linear regression analysis results, showing communication exists for this segment.

The piezometer (PZ12) is located 391 feet downstream from the centerline of Okhissa Lake dam and 243 feet west of the principle spillway. The qualitative results of piezometer (PZ12) water level versus reservoir water level is shown in Figure 4.24 and a summary of the quantitative results of this relationship is displayed in Table 4.8.

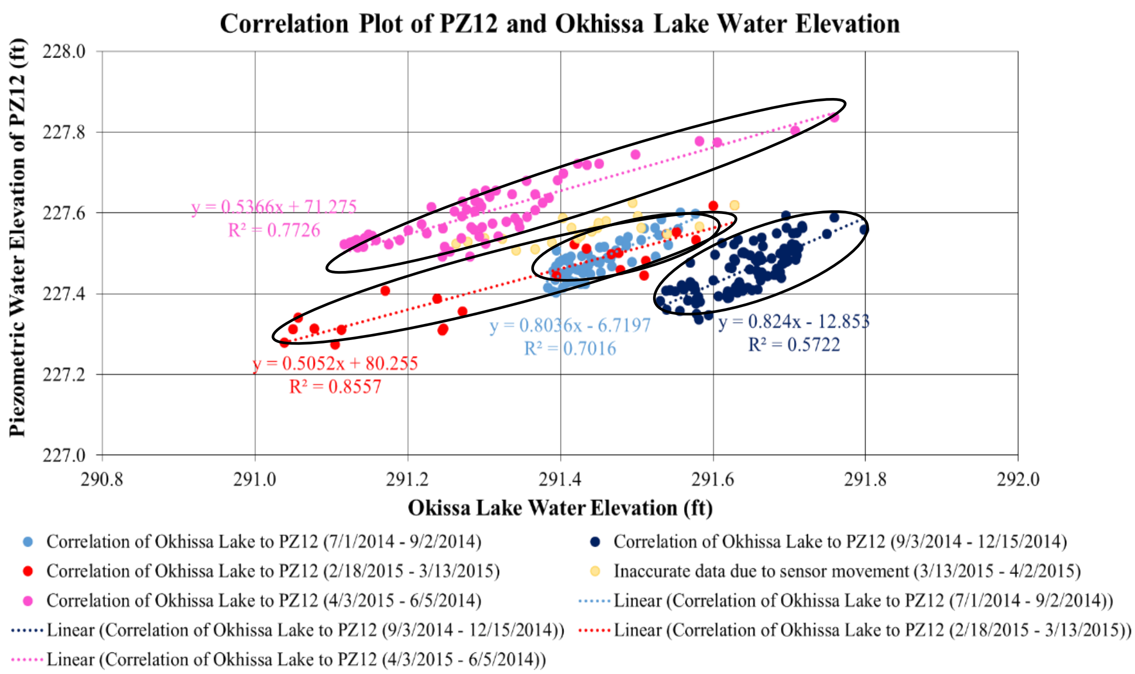

Figure 4.24: Relationship between reservoir level and piezometer (PZ12).

Table 4.8: Summary of reservoir level and piezometer (PZ12) relationship.

Time Segment	**Coefficient of Determination (R^2)**	**Coefficient of Correlation (R)**	**Slope of Linear Regression (m)**
7/1/14 – 9/2/14	0.70	0.84	0.80
9/3/14 – 12/15/14	0.57	0.76	0.82
2/18/15 – 3/13/15	0.86	0.91	0.50
4/3/15 – 6/5/15	0.77	0.88	0.54

The results of Figure 4.24 show a larger hysteresis in comparison to piezometer (PZ3) but similar to piezometer (PZ4). The larger hysteresis for the relationship of piezometer (PZ12) water level and reservoir water level is attributed to the increased downstream distance from the reservoir, than the previous piezometer (PZ3 and PZ4) locations. The larger distance leads to an increase in the lag of the piezometer's (PZ12) response. The quantitative results of linear regression analysis reveal a moderate level of communication between the reservoir and piezometer (PZ12).

Piezometer (PZ13) is located 302 feet downstream of the centerline of Okhissa Lake dam and 340 feet west of the principle spillway. The qualitative display of piezometer (PZ13) water level versus reservoir water is shown in Figure 4.25. A summary of the quantitative results from the linear regression analysis is displayed in Table 4.9.

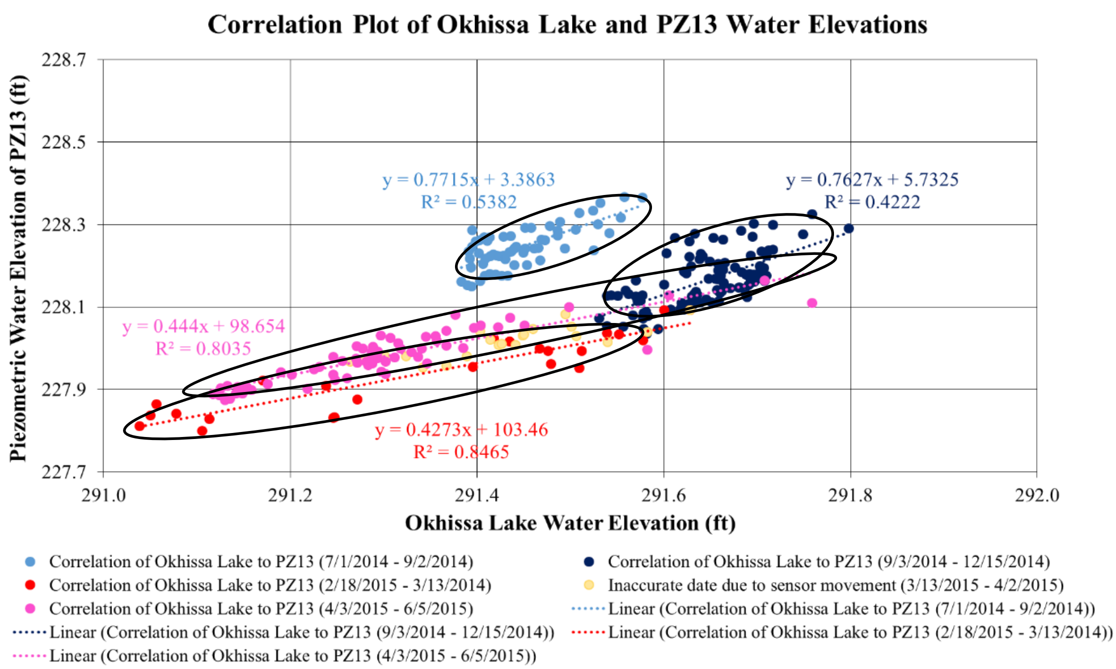

Figure 4.25: Relationship between reservoir level and piezometer (PZ13).

Table 4.9: Summary of reservoir level and piezometer (PZ13) relationship.

Time Segment	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Slope of Linear Regression (m)
7/1/14 – 9/2/14	0.54	0.73	0.77
9/3/14 – 12/15/14	0.42	0.65	0.76
2/18/15 – 3/13/15	0.85	0.92	0.43
4/3/15 – 6/5/15	0.80	0.89	0.44

The evaluation of Figure 4.25 indicates communication between the reservoir and piezometer (PZ13).

The linear regression analysis from February 18, 2015 through June 5, 2015 shows a weak to moderate level of communication between the piezometer (PZ13) and reservoir. A smaller hysteresis is seen in these particular segments in comparison to the segments from July 1, 2014 through December 15, 2014, meaning the reservoir has a stronger influence on piezometer (PZ13) water level. The results of the linear regression analysis from February 18 through June 5, 2015 in Table 4.9 displays a high level of confidence to predict future piezometer (PZ13) water levels from reservoir water levels (R^2). The high R values are evidence there is strong linear dependency between piezometer (PZ13) water level and reservoir water level. The values of the slope display a weak rate of change. The reservoir has a greater increase in water level than the increase in piezometer (PZ13) water level.

Each plot of the relationship of reservoir water levels and piezometer water levels shows weak to moderate communication based on the results of the linear regression analysis. The changes in reservoir and piezometer water levels are on the scale of 2.4 inches (6.1 cm) over the course of a year.

Precipitation is not anticipated to affect the piezometer (PZ3, PZ12, and PZ13) water levels directly due to the confinement of the clay layer. The influence of rainfall could increase the correlation due to its influence on reservoir water levels, and those fluctuations are anticipated to affect the piezometer water levels. Figure 4.26 displays a relationship with minimal rainfall (a) and a relationship with a series of precipitation events (b). A summary of quantitative results is displayed in Table 4.10.

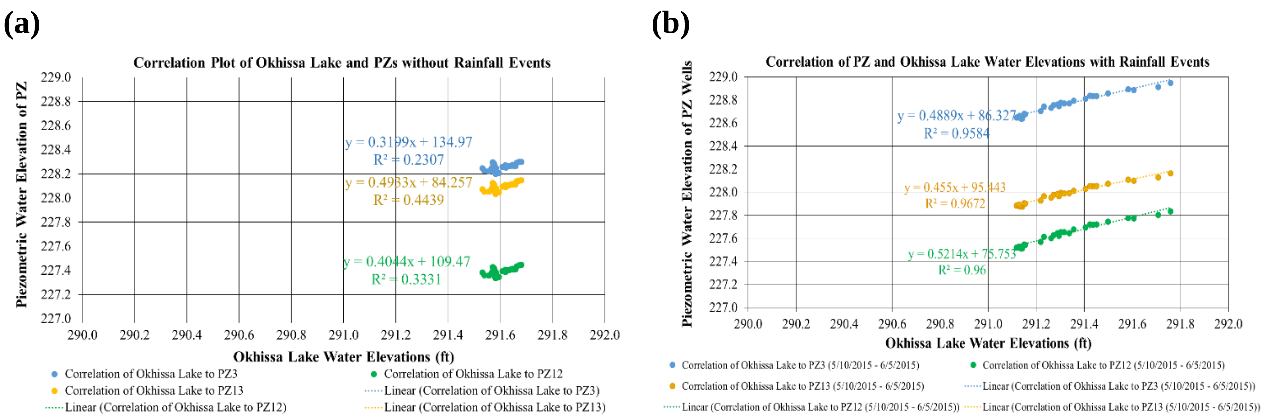

Figure 4.26: Relationship between reservoir and piezometer levels (a), without rainfall; (b), with rainfall events.

Table 4.10: Summary of reservoir and piezometer (PZ) relationship as a function of rainfall.

Time Segment	Piezometer	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Slope of Linear Regression (m)
(a) 10/16/14 – 12/15/14	PZ3	0.23	0.48	0.32
	PZ12	0.44	0.66	0.49
	PZ13	0.33	0.57	0.40
(b) 5/10/15 – 6/5/15	PZ3	0.96	0.98	0.49
	PZ12	0.97	0.98	0.45
	PZ13	0.96	0.98	0.52

The relationship between piezometer (PZ3, PZ12, and PZ13) water level and reservoir water level in Figure 4.25(a) reveals a very weak level of communication. However, the addition of rainfall results in a highly correlated relationship. The slope remains relatively constant with or without the influence of rainfall, reinforcing the previous conclusions that the changes in reservoir water level are influencing the piezometer (PZ3, PZ12, and PZ13) water levels. The addition of rainfall to the physical system causes an increase in reservoir water level, and the fluctuations of the reservoir are seen in the piezometers (PZ3, PZ12, and PZ13), creating a highly correlated relationship. The quantitative results in Table 4.10 for the relationship of piezometer (PZ3, PZ12, and PZ13) water level versus reservoir water level shows precipitation events significantly increase the future predictability of piezometer levels (R^2), and the linear dependency shown by the correlation value (R). The conclusion is the reservoir is influencing the piezometer water levels to some extent, based on the strong correlation and linear slope of the relationship.

The final analysis relates the confined aquifer (PZ4 and PZ14) to the phreatic aquifer (GOW4 and GOW14). The goal of this analysis is to see if there is any communication between to the two aquifers using the water levels of two paired wells. The qualitative results of this relationship are shown in Figure 4.27. A summary of the quantitative results are displayed in Table 4.11.

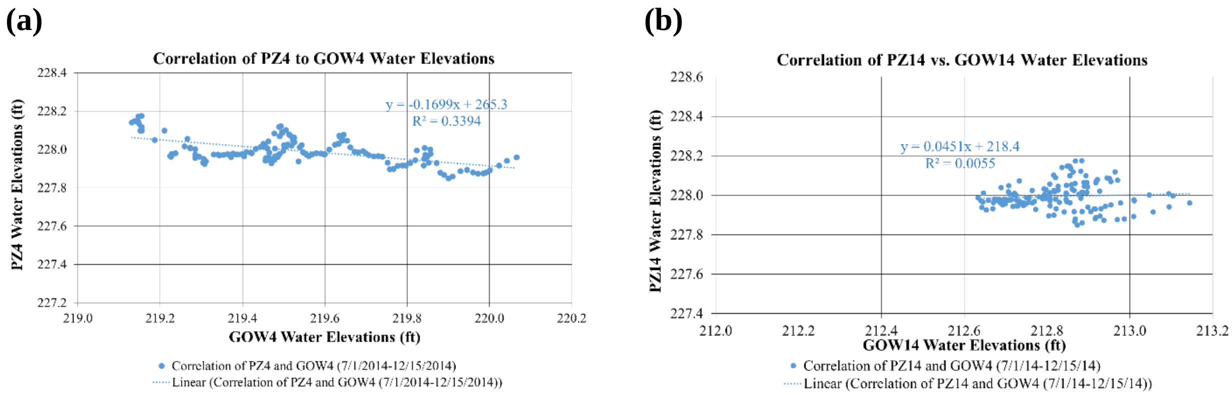

Figure 4.27: Piezometer relationship (PZ vs. GOW): (a), GOW4 and PZ4; (b), GOW14 and PZ14.

Table 4.11: Summary of piezometer relationship (PZ vs. GOW).

Time Segment	Piezometer Relationship	Coefficient of Determination (R^2)	Coefficient of Correlation (R)	Slope of Linear Regression (m)
(a) 7/1/14 – 12/15/14	PZ4 vs. GOW4	0.34	0.58	0.17
(b) 7/1/14 – 12/15/14	PZ14 vs. GOW14	0.006	0.077	0.045

The results of the statistical analysis is that no communication is present between the two aquifers at Okhissa Dam.

The Okhissa Lake water elevation is controlled and remains relatively constant. Projects of constant water levels do not typically call for a correlation plot, but rather a time history plot is sufficient (Gall, 2007). A statistical method for Okhissa Lake dam using linear regression analysis reveals if communication exists between the reservoir and piezometers. The relationship between piezometer water levels (GOW4 and GOW14) versus reservoir water level shows communication exists as a result of rainfall. The statistical linear regression analysis between reservoir water level and piezometer (PZ3, PZ12, and PZ13) water levels reveal weak to moderate communication is present.

The final relationship between piezometer (PZ4 and PZ14) water levels versus piezometer (GOW4 and GOW14) water levels reveal there is no communication between the two aquifers at the Okhissa Lake site. It is concluded that the linear regression technique serves as a cost effective and efficient modeling tool (Sahoo & Jha, 2015).

4.3 Calculation of Piezometric Threshold Levels

A successful early warning system detects and provides notification of a dam failure event with adequate warning time to allow for safe evacuation of the downstream community at risk (Myers & Dutson, 2002). Threshold levels are developed to assist in determining if readings are approaching a level which cause concern regarding the stability of the earthen dam. The threshold value is a reading that indicates a significant departure from the expected range of collected readings and prompts corrective actions to be taken. These actions may include: double checking the readings, checking the instrumentation, increasing surveillance, field investigations, or emergency action (USSD, 2011). The potential development of heave and uplift conditions are the driving factors to establish threshold levels for the Okhissa Lake site.

Heave is a condition in cohesionless soils involving vertical seepage forces acting on soil grains. The vertical seepage gradient is continually increasing during a heave event until the effective stress of the soil becomes nearly zero. At this point of zero effective stress in the soil, there is a volumetric increase of soil in addition to a dramatic increase in permeability. This event is a possibility at Okhissa Lake dam as it is built on a cohesionless foundation. The representation of a heave event is shown in Figure 4.27.

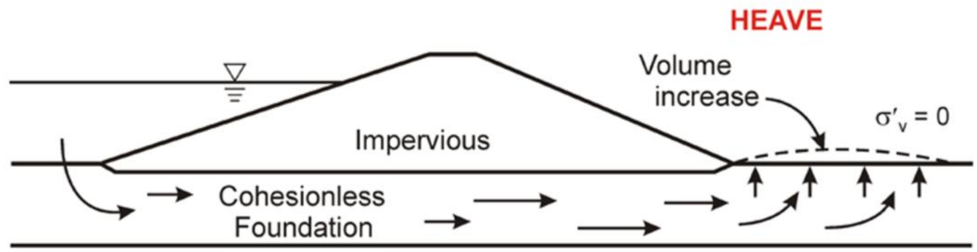

Figure 4.28: Heave at the toe of an embankment dam (Pabst, 2013).

The calculation for the factor of safety with respect to heave for cohesionless soils is defined as the ratio of the critical gradient (I_c) and the predicted vertical exit gradient (I_e). I_c is the critical gradient (pore pressure has increased to equal overburden pressure) at which heaving occurs.

$$I_c = \frac{\gamma_b}{\gamma_w} \tag{4.3}$$

where, γ_b is the buoyant unit weight of soil, and γ_w is the unit weight of water.

$$\text{Factor of Safety} = \frac{I_c}{Ie} \tag{4.4}$$

The value of the vertical exit gradient is estimated from piezometric data. Depending on the state of knowledge about a given site condition there can be significant uncertainty with the estimated values of the gradients, thus the resulting factor of safety. The factor of safety against heave, when large, represents an assurance that vertical exit gradients will not be sufficient enough to create heaving at a seepage exit point (Pabst, 2013).

Uplift occurs for dams built on top of a confined aquifer, with an impermeable foundation. A schematic of a typical uplift condition is displayed in Figure 4.28. The attribute for uplift to occur at a dam site consists of a confining layer, such as a clay, as the dam's foundation. The clay layer is the contributing factor to the development of high pore water pressures in the underlying pervious strata.

When this pressure becomes large enough to overcome the weight of the confining soil layer, this is known as an uplift condition. Additionally, the calculation of uplift in comparison to heave is a more conservative result (Pabst, 2013).

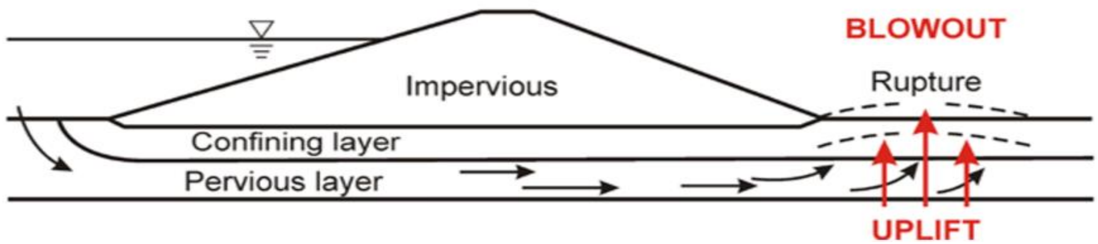

Figure 4.29: Uplift condition of embankment dam (Pabst, 2013).

The design factor of safety against hydrostatic uplift is recommended to be greater than or equal to (≥) 1.4. A higher factor of safety may be required if a potential dam failure would have a catastrophic effect on human health or the environment (Ohio EPA, 2004). A piezometric cross section with the appropriate labeled inputs for determining threshold levels as they relate to piezometer measurements is displayed in Figure 4.30.

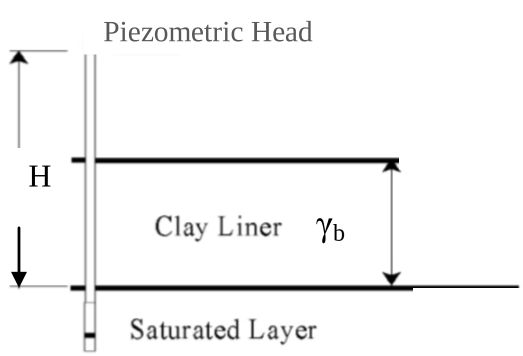

Figure 4.30: Piezometric cross section with input labels.

Factors of safety against heave and uplift for vertical seepage conditions are not factors of safety against structure failure. However, they provide useful information regarding stability and serve as a basis for relief well system design. For cohesionless soil (e.g.: sands, gravel, etc.), the effective stress factor of safety against heave (zero effective stress) is evaluated by comparing the vertical hydraulic "exit" gradient to the critical hydraulic gradient. The condition for saturated confining soil (e.g.: clay) seepage conditions the effective stress factor of safety against uplift is formulated in terms of weights and forces (Guy, Ider, & Darko-Kagya, 2014).

A factor of safety that results in 1.0 means over the burden pressure (σ) is equivalent to the pore water pressure (u) (Ohio EPA, 2004). The recommended minimum factor of safety criteria against uplift is 1.4, and is calculated by:

$$\gamma_L \times H_L > 1.4\left(\gamma_w \times H_P\right) \tag{4.5}$$

where, γ_L is the unit weight of the clay layer, γ_w is the unit weight of water, H_L is the thickness of the total overburden material, and H_P is the peizometric water head (Ohio EPA, 2004).

The site investigations previously conducted at the Okhissa Lake focused on the condition for uplift (Templeton, 2012). The equation used to obtain the factor of safety against uplift is simple, but effective. The equation used by Burns Cooley Dennis, Incorporated in their investigative report is:

$$\text{Factor of Safety} = \frac{z \times \gamma_b}{H \times 62.4} \tag{4.6}$$

where, z is the thickness of the overburden, γ_b is the buoyant unit weight of overburden in pounds per cubic foot (pcf), H is the excess head above ground surface, and the input value of 62.4 is the unit weight of water in pcf.

The numerator of Equation (4.6) represents the total stress of the overburden (σ) and the denominator represents the pore water pressure (u). A rearrangement of variables in 4.6 is done to determine the excess head amount according to a factor of safety of 1.5 and 1.0:

$$H=\frac{z\times\gamma_b}{FS\times 62.4} \tag{4.7}$$

Equation (4.7) calculates the excess head in feet of the piezometer as it relates to the input factor of safety values. The threshold value in terms of water elevation is obtained by adding the ground surface elevation at each particular well to the calculated excess head.

The significance in determining the piezometric threshold elevations for Okhissa Lake and the instrumented PZs and GOWs is to establish a warning element for conditions of uplift for the installed real time monitoring system.

The warning level criteria for the Okhissa Lake piezometers was established in 2012 by Burns Cooley Dennis, Incorporated using a hydrostatic uplift factor of safety calculation, due to the potentially high uncertainty in the heave condition calculation. The warning levels were calculated for a hydrostatic uplift factor of safety of 1.5 and 1.0 for each PZ and GOW well. A resulting factor of safety of 1.5 indicates a condition that is less safe than intended by the design, but does not indicate a condition of failure. A factor of safety of 1.0, indicates uplift is imminent. If this condition occurs, proper emergency action should be implemented.

The overburden thickness (z) is obtained from bore logs when the PZ and GOW standpipes were installed by Burns Cooley Dennis and the NRCS.

The buoyant unit weight (γ_w) is estimated at a uniform value of 57.6 pound per cubic foot (pcf). The measurement of piezometric head (H) is recorded by the real time monitoring system and implemented into the LoggerNet® monitoring program to record a real time factor of safety and serves as the system's real time warning element. The results of the factor of safety against uplift are presented in Table 4.1, along with the input values.

Table 4.12: Table of piezometric warning levels.

Well Station #	Overburden Thickness (Z)	γ_b (pcf)	γ_w (pcf)	GSE (ft)	Warning Level (Factor of Safety 1.5), ft	Warning Level (Factor of Safety 1.4), ft	Warning Level (Factor of Safety 1.0), ft
PZ-1	3	57.6	62.4	253.8	255.6	255.8	256.6
PZ-2	14	57.6	62.4	235.8	244.4	245.0	248.7
PZ-3	33.5	57.6	62.4	225.7	246.3	247.8	256.6
PZ-4	28	57.6	62.4	229.3	246.5	247.8	255.1
PZ-5	26	57.6	62.4	260	276.0	277.1	284.0
PZ-7A	25.7	57.6	62.4	247.7	263.5	264.6	271.4
PZ-8	14	57.6	62.4	209.4	218.0	218.6	222.3
PZ-11	24.5	57.6	62.4	219.6	234.7	235.7	242.2
PZ-12	17.8	57.6	62.4	225.7	236.7	237.4	242.1
PZ-13	32	57.6	62.4	224.9	244.6	246.0	254.4
PZ-14	34.5	57.6	62.4	220.1	241.3	242.8	252.0
GOW-1	11	57.6	62.4	216.5	223.3	223.8	226.7
GOW-2	0	57.6	62.4	213.9	213.9	213.9	213.9
GOW-4	6	57.6	62.4	228.2	231.9	232.2	233.8
GOW-6	13	57.6	62.4	224.5	232.5	233.1	236.5
GOW-11	0	57.6	62.4	219.7	219.7	219.7	219.7
GOW-14	7	57.6	62.4	220.1	224.4	224.7	226.6

The calculated piezometric warning levels are set as threshold water elevations for the Okhissa Lake warning system, and are shown is columns 6, 7, and 8 of Table 4.1. These threshold water elevations serve as the real time warning element for the monitoring system at Okhissa Lake and will trigger an alert to dam officials when each threshold level is reached.

The variable of recorded piezometeric head allows for a continuous real time update of the factor of safety calculation against uplift conditions.

4.4 Slope Stability Analysis

Embankment dam engineering has evolved over many centuries with the major developments occurring since the 1940s with the development of soil mechanics and geotechnical engineering. Many aspects of the engineering principles of dams are readily analyze, such as slope stability (Foster, Fell & Spannagle, 2000). Slope stability is the potential of soil covered slopes to withstand movement causing failure. The stability of a slope is determined by the balance of shear stress and shear strength (Das, 2010). Slope failures occur when changes in the shear stress or shear strength destroy the equilibrium of the soil mass. Slope stability is a critical analysis that is necessary in the design and longevity of an earthen dam. A slope stability analysis determines if a particular slope of known soil can withstand a series of imposed conditions, such as: external loads, slope steepening, undercutting, rapid drawdown, or earthquakes (Li & Desai, 1983). The key indicator in slope stability analysis is the factor of safety, which is commonly defined as the ratio of the resisting shear force to the driving shear force along a failure surface (Oh & Lu, 2015). The resisting shear forces must be greater than the driving shear forces for the analyzed slope to have stability. The stability of a slope is conveyed by geotechnical engineers through a factor of safety, defined as:

$$\text{Factor of Safety} = \frac{\Sigma R}{\Sigma D} \tag{4.8}$$

indicating, the factor of safety is the ratio between the forces and moments resisting (R) movement and the forces and moments driving (D) movement (Das, 2010).

The factor of safety must meet or exceed specific minimum factor of safety values such as the ones displayed in Table 4.13 for earthen dams. The highlighted section is the criteria used for the slope stability analysis of Okhissa Lake dam, as it was designed by the NRCS.

Table 4.13: Summary of earthen dam factor of safety criteria for slope stability (USSD, 2007).

Agency	Loading Condition	Stress Parameter	Factor of Safety
NRCS	Steady Seepage-Normal Pool	Composite	1.5
	Rapid Drawdown	Composite	1.2
USACE	Long-term (steady seepage)	Effective	1.5
	Sudden Drawdown	Total and Effective	1.3
USBR	Steady-State Seepage	Effective	1.5
	Operational – Rapid Drawdown from Normal Pool	Effective or Undrained	1.3
FERC	Steady Seepage – Max. Storage Pool	Effective and Total	1.5
	Sudden Drawdown from Max. Pool	Effective and Total	1.1
Tennessee Valley Authority (TVA)	Steady Seepage – Normal Operating Condition	Total	1.5
	Sudden Drawdown	Total	1.2

Limit equilibrium methods are widely used for analyzing slope stability and designing engineered slopes (Oh & Lu, 2015). There are five primary limit equilibrium methods within slope stability analysis: ordinary method of slices (OMS), Bishop, Janbu, Spencer, and Morgenstern and Price. The limit equilibrium methods use a slicing technique to analyze the potential failure surface in a slope (Das, 2010). Each slice is then analyzed using principles of force and / or moment equilibrium (Oh & Lu, 2015). The various interslice forces considered in limit equilibrium are shown in Figure 4.31. The limit equilibrium methods differ from one to the other by each one having its own advantages and limitations.

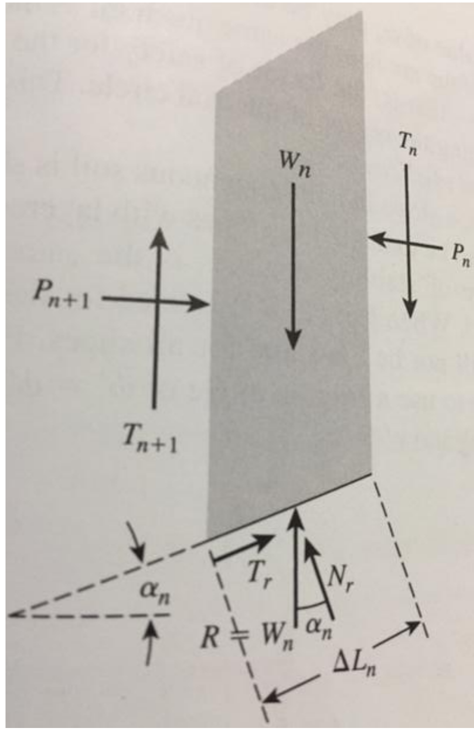

Figure 4.31: Forces acting on a slice for slope stability analysis (Das, 2010).

The first analysis method is the ordinary method of slices (OMS). OMS does not take into account any of the interslice forces and fails to satisfy force equilibrium for the slide as well as for individual slices. This method is advantageous as it is one of the simplest procedures as it assumes a circular slip surface (Das, 2010). The next type of slope stability analysis is the simplified Bishop method. The simplified Bishop accounts for the vertical interslice shear force (T_n in Figure 4.31) to some degree, they are accounted for by a resultant horizontal interslice (Das, 2010). Bishop's method satisfies the equilibrium of moment but not the equilibrium of forces. The third analysis type is Janbu's method. This method uses the horizontal forces equilibrium equation to obtain the factor of safety. It does not include the interslice forces in the analysis but accounts for its effect using a correction factor. The correction factor is related to cohesion, angle of friction (e.g.: soil strength parameters) and the shape of the failure surface (Rahman, 2012).

The fourth analysis type is Spencer's method, and it is a very accurate method that satisfies both equilibrium of forces and moments and is applicable for any slip surface shape. The basic assumption of this method is that the inclinations of the side forces are the same for all slices. The final analysis type is Morgenstern and Price. Morgenstern and Price proposed a method that is similar to Spencer's method, except the inclination of the interslice resultant force is assumed to vary (Rahman, 2012). A summary of aspects for each analysis type is displayed in Table 4.14.

Table 4.14: Summary of slope stability analysis methods (USSD, 2007).

Procedure	Overall Moment	Individual Slice Moment	Vertical Force	Horizontal Force
Ordinary Method of Slices (OMS)	Yes	No	No	Yes
Modified Bishop	Yes	No	Yes	No
Janbu	Yes	Yes	Yes	Yes
Spencer	Yes	Yes	Yes	Yes
Morgenstern-Price	Yes	Yes	Yes	Yes

The selected analysis type for the slope stability analysis of Okhissa Lake dam is Spencer's method. Spencer's method satisfies all conditions of equilibrium, thus is the most accurate method. The USACE deems any analysis method other than what accounts for all equilibrium conditions may involve significant inaccuracies (USACE, 2003).

The software program GeoStudio Slope/W 2012® student version is used for evaluating the stability of Okhissa Dam. GeoStudio 2012® student version has certain limitations, specifically the limit of three materials for the model. The slope stability analysis of Okhissa Lake dam is an approximation due to consolidating the number of material variations used for the actual construction of the dam.

The geometry of the cross-section of Okhissa Lake dam was obtained from the dam design plans shown in Figure 4.32. The design height of the dam is 87 feet according to the cross-section plan. The dam's base width is approximately 650 feet with a crest width of 30 feet.

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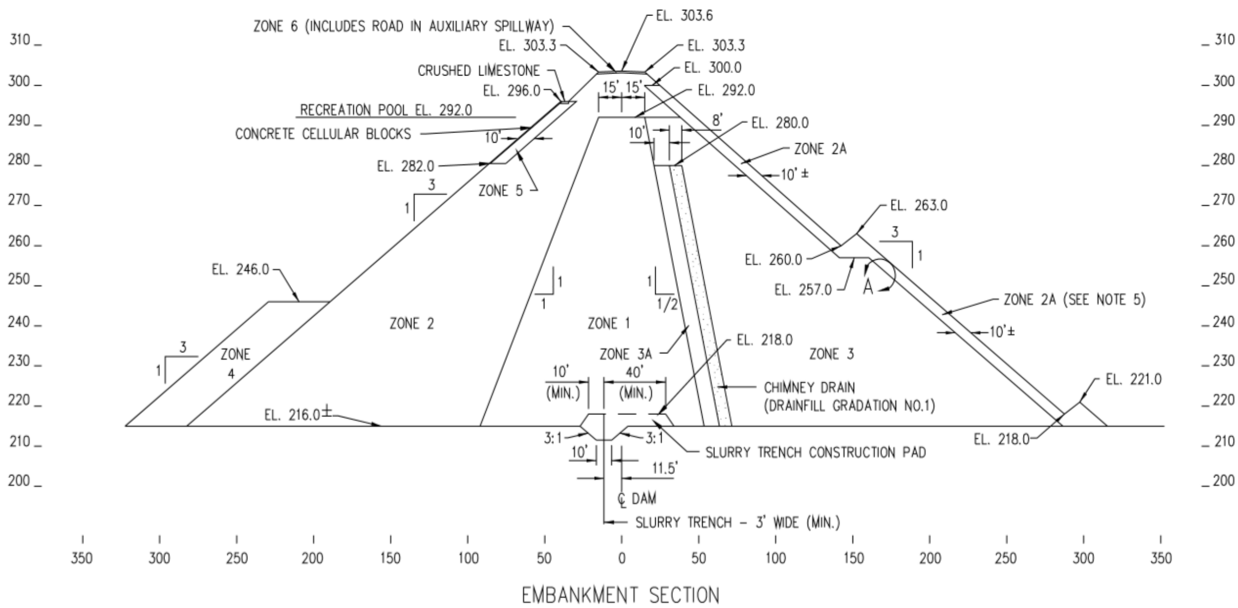


Figure 4.32: Okhissa Dam cross-section design drawing (Spencer Engineers, 1999)

Okhissa Dam is a clay core dam with a course grained shell or embankment. The clay core material (CH) was selected to use for the slope stability analysis of Okhissa Lake dam due to its high strength and low permeability. The soil boring summary completed by the NRCS in 2000 provides the classification of the embankment material to be composed of a sandy clay (SC) and silty sand (SM). The selected material of the embankment for the slope stability analysis of Okhissa Lake dam is SM. The design base elevation of Okhissa Dam is 216 feet, and the soil profile in Figure 4.33 displays the foundation material of the dam.

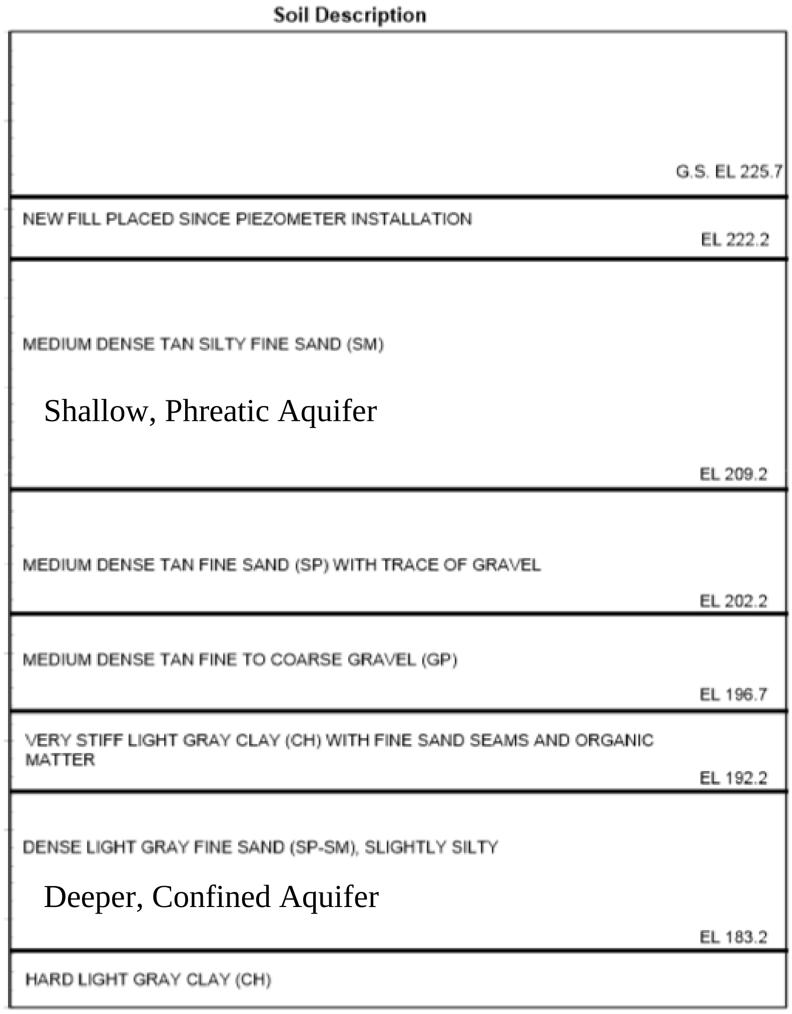


Figure 4.33: Soil profile from piezometer (PZ3) boring log (Templeton, 2012).

Okhissa Dam is built on a pervious foundation consisting of alluvial material. Okhissa Lake dam uses a soil bentonite slurry trench (cutoff wall) to restrict groundwater flow through the relatively pervious foundation material (Rice & Duncan, 2010). The slurry trench extends approximately 30 feet from the foundation of the dam to the confining clay boundary. The foundation of Okhissa Lake dam is composed primarily of permeable material such as sands and gravels.

The three components of Okhissa Dam deemed the most essential for modeling in GeoStudio 2012® are the clay core, shell (embankment), slurry trench, and foundation material. These four features were narrowed down to three material inputs: the clay core, slurry trench, and confining clay layer are classified as a clay (CH). The embankment material is input as a silty sand (SM), and the phreatic and confined aquifer material is input as a poorly graded silty sand (SP-SM). The model as drawn in GeoStudio 2012® is displayed in Figure 4.34. The elevation (y-axis) is offset by 194 feet, to calculate the true elevations 194 feet is added to the y-axis value.

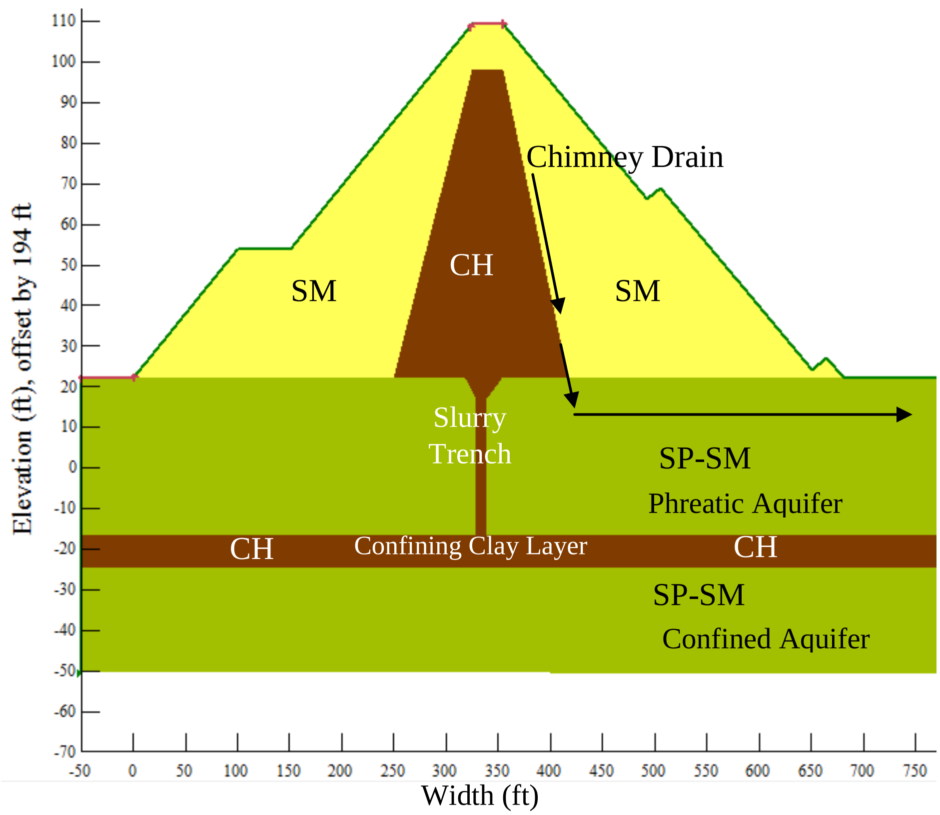


Figure 4.34: Okhissa Dam cross-section as modeled (GeoStudio 2012®).

The soil parameters needed for slope stability analysis are strength parameters and include cohesion (c) and internal friction angle (ϕ) and unit weight (γ). The material properties for the soils in the slope stability analysis of Okhissa Lake dam were determined from previous engineering soil sampling and testing at the Okhissa Lake site. The properties were obtained from the NRCS Soil Mechanics Report of Okhissa Lake, 1996.

The material properties used were obtained from an effective stress, consolidated undrained (CU') triaxial test. The practice of the NRCS for impervious soils is to use values between the triaxial test results of both a CU' test and a consolidated drained (CD) test in the case of CD soil strength parameters are greater than the CU soil strength parameters.

The condition of the CD material parameters being less than CU' material parameters, the CD results are used. The CD test results were not available during this project, and the CU' soil strength parameters were used. The slope stability analysis of free-draining soils, such as the embankment material (SM) and foundation material (SP-SM), calls for the use of CD triaxial test results (USSD, 2007). The CD triaxial test results were not available and the results from a direct shear test were used for the embankment and foundation materials. The moist unit weight (γ) of each material was used, as the dam cross-section will be modeled under saturated conditions. The soil strength parameters are displayed in Table 4.15.

Table 4.15: Soil properties of slope stability analysis (NRCS Soils Report, 1996).

Material	Max Dry Unit Weight (pcf)	Optimum Moisture (%)	Max Wet Unit Weight (pcf)	Effective Cohesion (psf)	Effective Angle of Friction (ϕ')	Test Type
CH (Clay Core, Cutoff Wall, Foundation Layer)	91	29	117.39	375	17.5	CU (effective stress)
SM (Embankment Soil)	102.6	0.53	103.14	0	35.5	Direct Shear
SP-SM (Aquifer Material)	106.6	0.43	107.06	0	30	Direct Shear

The stability of the upstream and downstream slopes of a dam embankment is analyzed for the most critical or server loading conditions that may occur during the life of the dam.

The loading conditions typically include: end of construction, steady-state seepage, rapid or sudden drawdown, and earthquake (USSD, 2007). The case of Okhissa Lake dam the critical conditions modeled are the case of steady-state seepage and rapid drawdown.

4.4.1 Analysis of Downstream Slope

The first analyzed condition of Okhissa Dam is steady-state seepage with the reservoir level at maximum normal pool. Long term stability computations are performed for conditions that will exist an extended length of time after construction for steady state seepage, or hydrostatic conditions to develop (USACE, 2003). After a prolonged storage of the reservoir water, water percolating through an embankment dam will establish a steady-state condition of seepage. The upper surface of this seepage is called the phreatic line. Steady-state seepage analysis is typical for the stability of the downstream slope of the dam embankment since this is the loading condition that the dam will experience the most. The results of the steady-state seepage condition are shown in Figure 4.35.

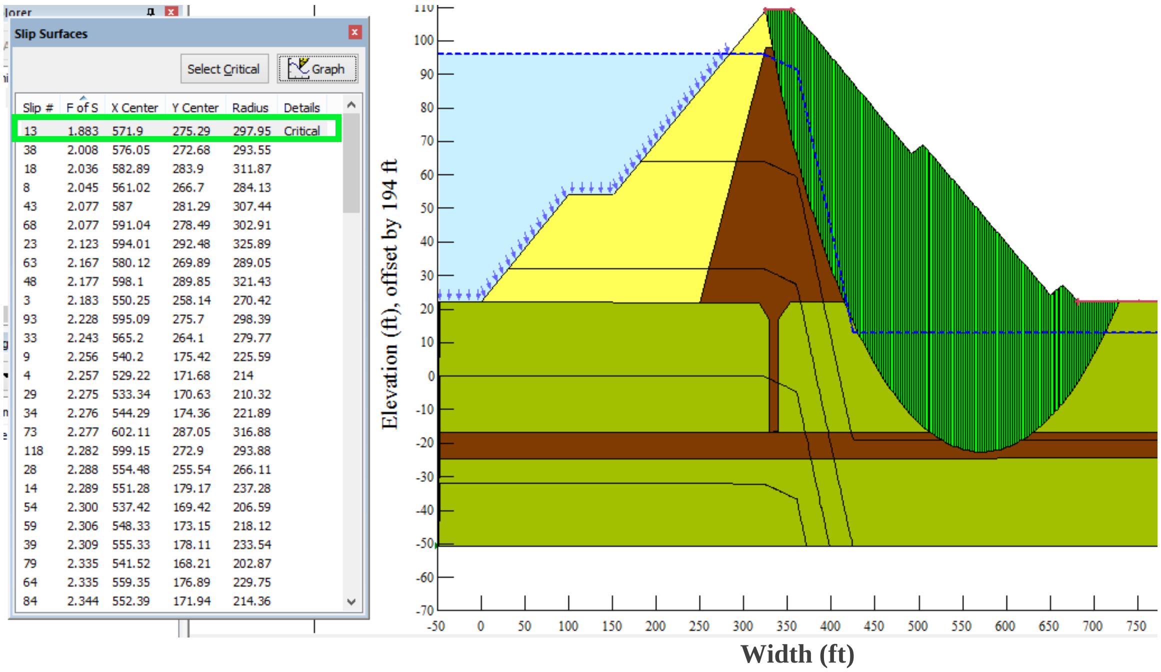
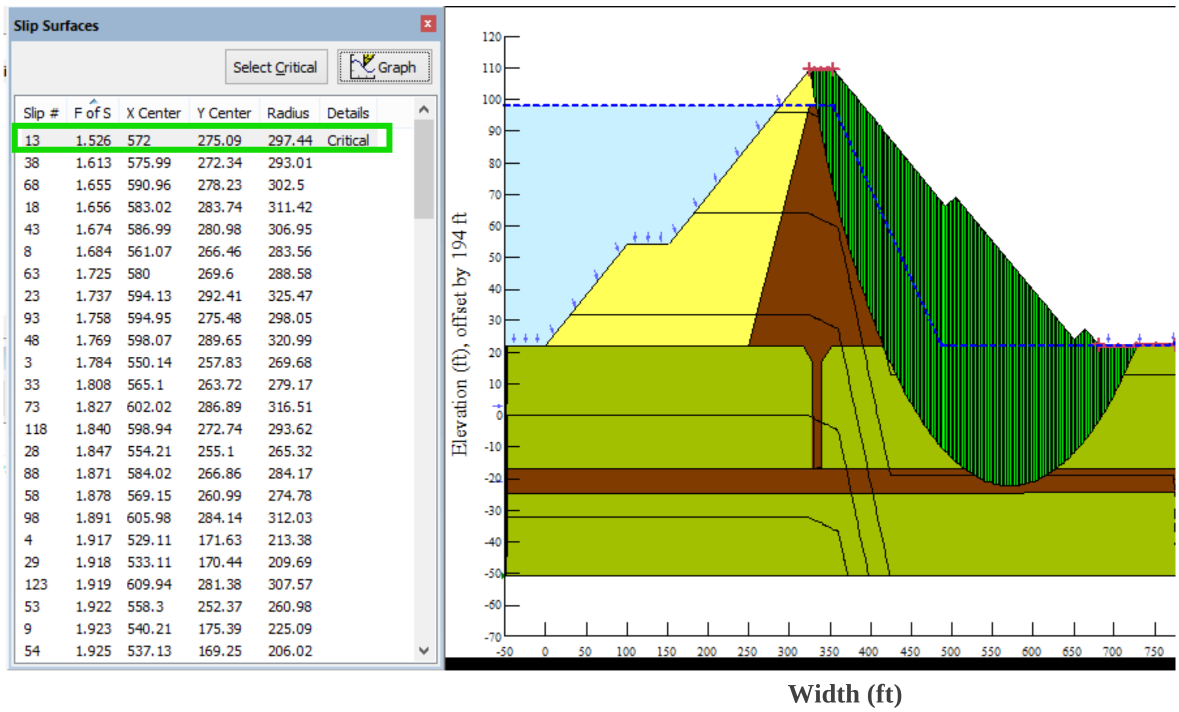


Figure 4.35: Downstream slope stability analysis (GeoStudio, Slope/W®).

Steady state seepage of Okhissa Dam was analyzed using GeoSlope 2012® with a water elevation of 292 feet (maximum normal pool). The chimney drain is not specifically shown in the model, but is taken into consideration by dropping the piezometric line out of the downstream slope and draining through the pervious foundation material. The result of the steady-state seepage analysis with maximum normal pool loading condition is a critical (lowest) factor of safety of 1.8. The minimum criteria set by NRCS for this particular loading condition is 1.5 (Table 4.1), the dam is safe and has stability by exceeding the required minimum design factor of safety.

The determining factor for downstream slope stability is the effective operation of the clay core and chimney drain. Figure 4.36 displays the piezometric line at the maximum normal pool elevation of 292 feet. The piezometric line crosses the embankment at an elevation 292 feet and decreases slightly once the clay core is encountered.

The conditions shown in Figure 4.36 simulate the chimney drain partially blocked allowing pore water to seep into the downstream embankment and pore pressure to form in the downstream slope, resulting in a critical factor of safety of 1.52. These conditions result in a reduction of the downstream slope stability of Okhissa Lake dam. The critical components for the stability of the downstream slope is cutting off pore water influence from the reservoir by the use of the clay core and the effective operation of the chimney drain.



Slip #	F of S	X Center	Y Center	Radius	Details
13	1.526	572	275.09	297.44	Critical
38	1.613	575.99	272.34	293.01	
68	1.655	590.96	278.23	302.5	
18	1.656	583.02	283.74	311.42	
43	1.674	586.99	280.98	306.95	
8	1.684	561.07	266.46	283.56	
63	1.725	580	269.6	288.58	
23	1.737	594.13	292.41	325.47	
93	1.758	594.95	275.48	298.05	
48	1.769	598.07	289.65	320.99	
3	1.784	550.14	257.83	269.68	
33	1.808	565.1	263.72	279.17	
73	1.827	602.02	286.89	316.51	
118	1.840	598.94	272.74	293.62	
28	1.847	554.21	255.1	265.32	
88	1.871	584.02	266.86	284.17	
58	1.878	569.15	260.99	274.78	
98	1.891	605.98	284.14	312.03	
4	1.917	529.11	171.63	213.38	
29	1.918	533.11	170.44	209.69	
123	1.919	609.94	281.38	307.57	
53	1.922	558.3	252.37	260.98	
9	1.923	540.21	175.39	225.09	
54	1.925	537.13	169.25	206.02	

Figure 4.36: Conditions for minimum factor of safety criteria (GeoStudio 2012, Slope/W®).

Increasing the groundwater elevation does not have an effect on the slope stability of the downstream embankment. Okhissa Dam was modeled for groundwater levels at the surface and the results show a factor of safety that exceeds the minimum design criteria. The current factor of safety readings, using Equation (4.7), indicate Okhissa Dam has a high level of slope stability.

4.4.2 Analysis of Upstream Slope

The stability of the upstream embankment slope for the condition created by a rapid drawdown is analyzed for the water level in the reservoir to the reservoir level at the lowest gated or ungated outlet (NRCS, 2005). Rapid drawdown stability computations are performed for conditions occurring when the water level adjacent to the slope is lowered rapidly. For analysis purposes, it is assumed that drawdown is very fast, and no drainage occurs in materials with low permeability. Materials of a free draining nature (e.g.: permeability greater than 10^{-4} cm/sec) are assumed to drain during drawdown and the drained strengths are used (USACE, 2003). This loading condition is the normal operating case for pumped-storage reservoirs where the drawdown of the reservoir, up to 5 to 10 feet per hour, occurs daily (USSD, 2007). Lake Okhissa is not a pumped-storage reservoir, but could experience a rapid drawdown if repairs or inspections were needed to the principle spillway riser, or to the upstream slope of the dam. A 54 inch slide gate at the base of principle spillway riser enables the reservoir to be completely drained. The results of the rapid drawdown loading condition is shown if Figure 4.37.

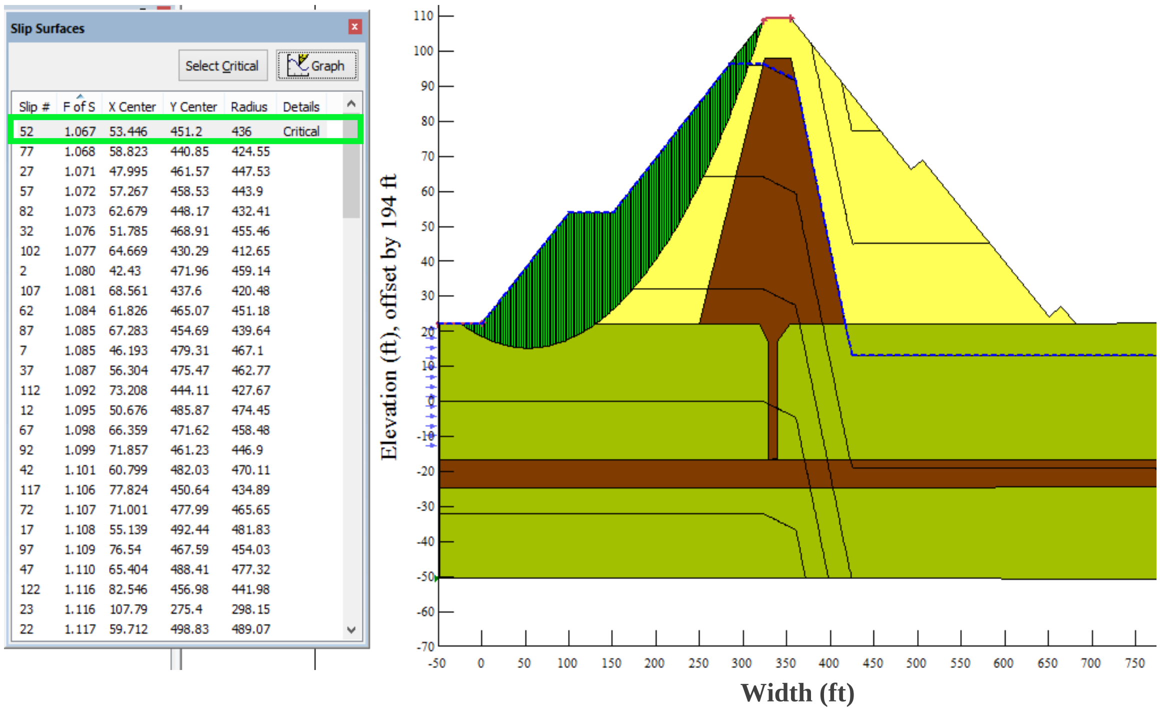


Figure 4.37: Upstream slope stability analysis (GeoStudio 2012, Slope/W®).

The result of the rapid drawdown of Okhissa Lake dam is a critical factor of safety of 1.06. This value does not meet the criteria set by the NRCS of 1.2. This condition is an extreme case, the phreatic line elevation starts at the base of the Okhissa Lake model, and is plotted along the surface of the upstream slope. This condition would exist if the drawdown was near instantaneous and embankment material were not of a free draining material. The pore-pressures within the upstream embankment would dissipate some as the reservoir level would drop at a more gradual rate and allow some pore pressure to fall out of the upstream slope material. The imposed condition of the phreatic line in this model is not a realistic case, Figure 4.38 demonstrates a more reasonable rapid drawdown loading condition.

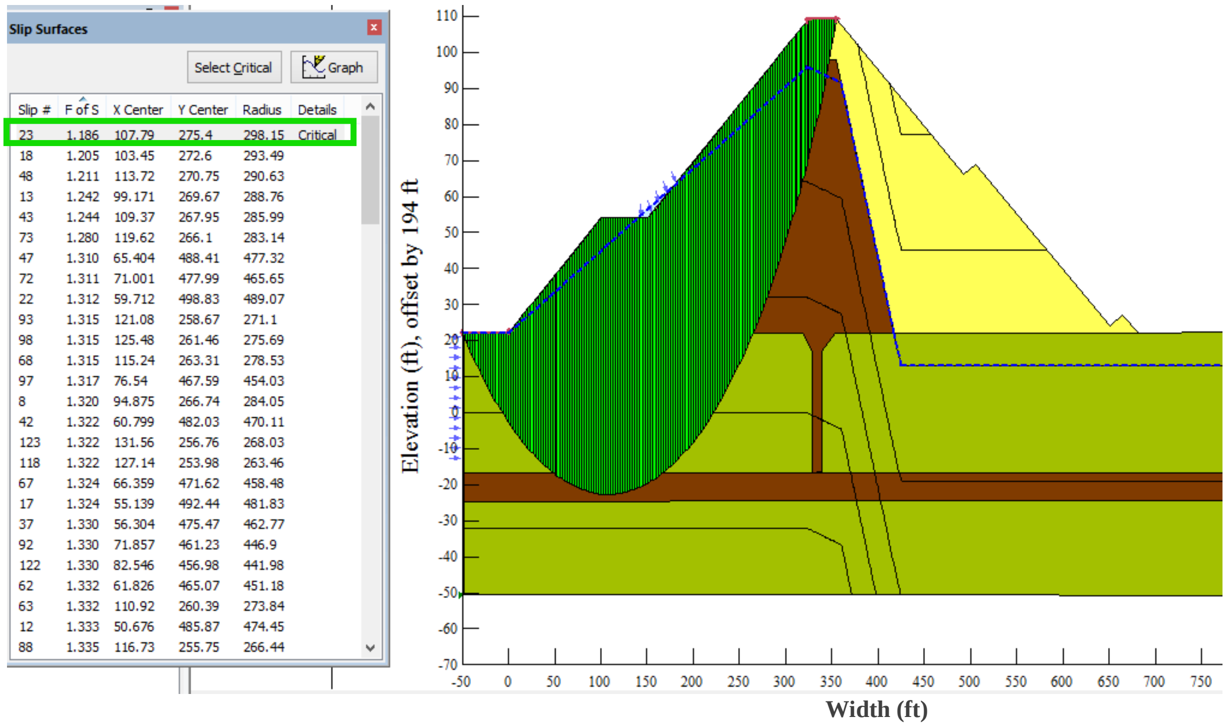


Figure 4.38: Steadier drawdown of Okhissa Lake (GeoStudio 2012, Slope/W®).

The results of the second case of the rapid drawdown reveal a critical factor of safety of 1.18. This critical factor of safety does not meet the required factor of safety criteria of 1.2. Considering the material and region approximations used for this model, Okhissa Lake dam is stable. This loading condition is more realistic and conservative, providing more reasonable results in comparison to the analysis in Figure 4.37. The pore pressures of the upstream soil may even be less for a rapid drawdown condition for Okhissa Lake dam. The consideration of the approximations made and the embankment soil type, Okhissa Lake dam is stable under the loading condition of rapid drawdown.

A third rapid drawdown scenario was created using GeoStudio Slope/W® to find what the maximum drawdown Okhissa Lake dam can have for this model to meet the minimum factor of safety criteria of 1.2. Figure 4.39 displays the results of a rapid drawdown of sixty feet from maximum normal pool.

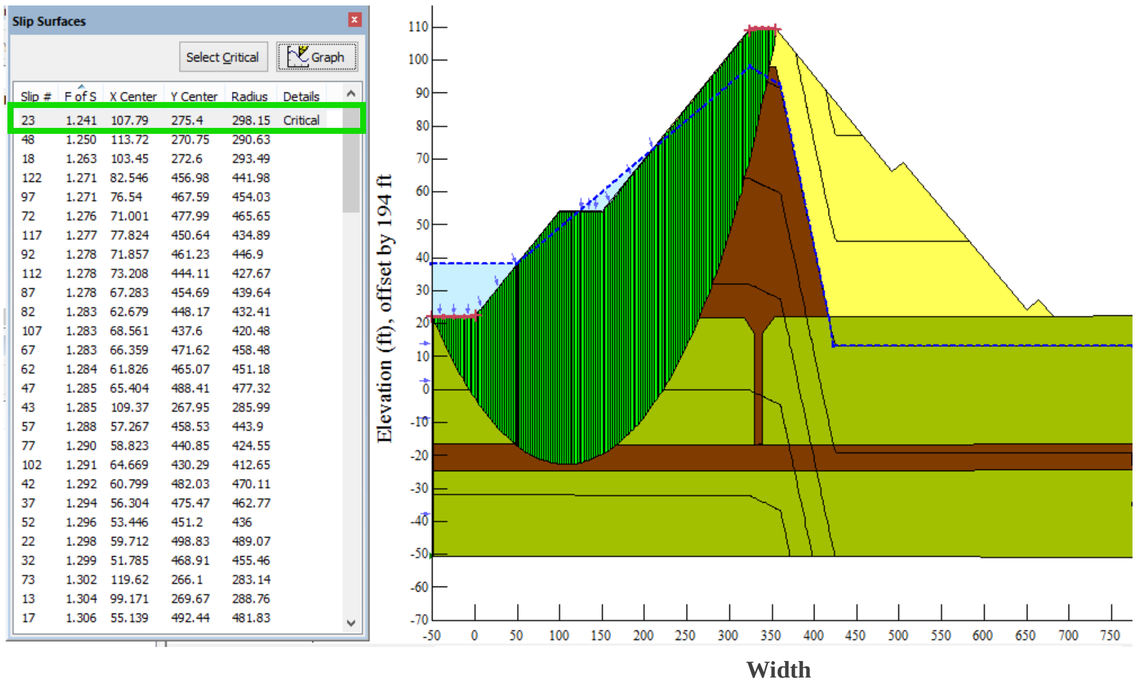


Figure 4.39: Steady drawdown of 50 feet (GeoStudio 2012, Slope/W®)

The results indicate a critical factor of safety value of 1.24, which meets the minimum factor of safety criteria set by the NRCS. A comparison between the results in Figure 4.38 and Figure 4.39 for this model of Okhissa Lake dam, indicates slope stability of Okhissa Lake dam is compromised in the event of a complete drawdown, as the factor of safety falls below 1.2. A resulting drawdown pool elevation of 232 feet maintains a satisfactory factor of safety and still allows inspections or repairs to be conducted.

The dam at Okhissa Lake meets the minimum factor of safety criteria for the conditions of steady state seepage and rapid drawdown. A drawdown of Okhissa Lake to an elevation of 232 feet is recommended over the complete drawdown if repairs to the downstream face or a thorough inspection is needed based on the results of this model. The minimum factor of safety criteria is achieved and a reduction of downstream slope stability results when a simulation of an inefficient chimney drain is modeled.

The type of instrumentation installed at Okhissa Dam could be expanded to include additional vibrating wire piezometers that are installed in the dam embankment. The additional installed sensors would monitor both the upstream and downstream slope of Lake Okhissa dam to plot a real time phreatic line. This application would be beneficial in analyzing the efficiency of the dam (e.g.: clay core and chimney drain) and the behavior of the phreatic line. If the phreatic line is detected on the downstream slope, this would indicate the chimney drain may not be properly draining. Real time data collection of the phreatic line through the dam would reveal how the soils behave during an event of rapid drawdown, and how effectively the embankment soils are draining. Additionally, a running real time slope stability analysis during significant events (e.g.: excessive rainfall, drawdown, etc.) is possible by continuous monitoring of the phreatic line.

5. CONCLUSIONS

The National Inventory of Dams states there are approximately 78,000 earthen embankment dams across the United States, which makes up nearly 87% of the total number of dams (NID, 2015). The majority of these dams have approached their initial design life of 50 years and require thorough inspections to assure their structural integrity and safety to the public. The traditional approach to asses a dam's performance and efficiency is by visual inspection, but internal failure mechanisms may not be detected by these visual inspections.

The causes of dam failures include: overtopping, foundation defects, seepage and piping, and through the conduits and valves. Visual inspections may not be able to detect these issues until the situation has progressed to an advanced stage that compromises the integrity of the dam. A monitoring system detects dam deficiencies in an early state, which may allow for remediation action to be taken before the dam reaches a critical state.

The goal of the research at Okhissa Dam was to install a wireless, portable real-time monitoring system and determine if communication between the reservoir and groundwater aquifer is present. The failure type of interest at Okhissa Dam is foundation defects, driven by uplift pressures, which affect the slope stability.

The desired features for this monitoring system include: portable, wireless real-time monitoring and warning system that has remote data collection. The primary sensor type selected for this research was the vibrating wire piezometer to continuously monitor reservoir water level and piezometer water levels.

This sensor was selected because of its accuracy and its ease of incorporation into a wireless, real-time monitoring system (Bartholomew, Murray & Goins, 1987). The location of installed instrumentation includes: six confined aquifer wells (PZ), three phreatic wells (GOW), and Okhissa Lake. Additional sensors include an electronic, tipping bucket rain gage, atmospheric temperature and relative humidity probe, and an atmospheric barometric pressure sensor. The real-time monitoring system provides continuous data which enables the establishment of time history plots as well as correlation plots. The continuously collected data is viewed in real time on the monitoring system's webpage, http://ncpa.olemiss.edu/okhissa-lake-dam-monitoring-system/.

The time history plots are evaluated to determine trends in the data. The correlation plots are used to conduct a linear regression analysis to determine if communication is present between the reservoir and the downstream aquifers. The measured rainfall data is incorporated into the correlation analysis to understand the impact precipitation has on the relationship between piezometer levels and reservoir water level. The results of the relationship between piezometers (GOW) and reservoir level, shows the reservoir water levels are not impacting the shallow phreatic aquifer water levels. However, the reservoir is potentially influencing the piezometer (PZ3, PZ12, and PZ13) water levels based on the results of the analysis in this research. The linear regression analysis reveals moderate communication is potentially present between the reservoir and piezometers (PZ3, PZ12, and PZ13). Rainfall is the driving mechanism to water level changes at Okhissa Dam. Without rainfall the system is at steady state with minimal changes in both the reservoir and piezometer. Precipitation increases the reservoir water levels, which in turn appears to be increasing the piezometer water levels of the confined aquifer. The rate of change remains relatively constant whether or not precipitation is a factor.

The final linear regression analysis of two sets of paired wells (PZ4 vs. GOW4 and PZ14 vs. GOW14) does not reveal any communication.

Water elevation thresholds were established to add a real time warning element to the monitoring system at Okhissa Dam. This criteria focused on the ratio of overburden pressure (e.g.: soil material on top of the aquifers) to the pore water pressure of each well. A situation resulting in the pore water pressure equaling or exceeding the pressure of the overburden soil demonstrates an uplift event and slope failure. The water level thresholds for the piezometers (PZ and GOW) correspond to a factor of safety of 1.5 (alert of changing conditions), 1.4 (design criteria minimum), and 1.0 (impending dam failure). This warning element is specific to this system's monitoring capabilities and site conditions. An alert is sent to the dam officials as each threshold water level is reached. The threshold water level alert is seen by indicator lights on the public webpage display of incoming data. A green light indicates the factor of safety is above 1.5, a red light indicated the factor of safety is at or below the design criteria of 1.5. The calculated warning level thresholds are also used to evaluate the slope stability of Okhissa Dam. The comparison of the current piezometric readings to the threshold levels yield results of stable conditions against uplift as well as slope stability.

A slope stability analysis was conducted for Okhissa Dam, under the conditions of steady state seepage and rapid drawdown. GeoStudio Slope/W® student version was used to complete this analysis, but it is restricted to the use of three soil materials. The condition of steady state seepage at maximum normal pool analyzes the stability of the downstream slope. The design criteria for this particular condition is a factor of safety of 1.5, and the critical factor of safety from the analysis is 1.71, exceeding the design criteria. Increasing the pore water levels of the downstream groundwater does not affect the slope stability of Okhissa Dam.

The measured factors of safety indicate Okhissa Dam has a high level of slope stability. The factor of safety is reduced if seepage into the downstream embankment occurs. This seepage would occur if the clay core is cracked and the chimney drain is potentially clogged with sediment, allowing pore water to build in the downstream slope. The stability of the downstream slope depends on the effective operation of the clay core and chimney drain.

The second analysis of slope stability included two cases of a rapid drawdown event, which requires a factor of safety of 1.2. The first rapid drawdown event plots the piezometric line along the upstream slope, resulting in a factor of safety of 1.06. This event is not completely feasible as the slope consists of a free draining soil type and much of the pore water pressure along the slope would drain out of the soil. The second analyzed loading condition demonstrates a more realistic situation. The soil along the slope is partially drained, resulting in a factor of safety is 1.17, slightly lower than the design criteria of 1.2. The results are attributed to the approximation of material zones, which was required use of the limited student version of GeoStudio Slope/W®. The soil data for Okhissa Dam was limited, and the behavior of the piezometric line through the upstream slope was unable to be accurately predicted. The pore pressures may be lower in a rapid drawdown of Okhissa Lake, thus increasing the factor of safety. In the event of a reservoir drawdown, based on this slope stability analysis, it is suggested the reservoir be reduced to a water level of 232 feet to maintain the minimum required factor of safety of 1.2.

Suggestions for future work include installing the portable monitoring system at a dam that has known communication between the reservoir and downstream groundwater where water levels fluctuate on a minimum scale of one foot (Carter, Hosko & Rubertis, 2000).

This installation would validate the benefits of a real time monitoring system and analysis procedures in determining if the reservoir is contributing to aquifer water levels and to what extent. Further analysis should be done in order to gain knowledge of the piezometer response lag to changes in the reservoir level. An analysis method could be implemented to determine the influence factors or percentage of impact that individual water level contributor (e.g.: reservoir water level or precipitation) has on the aquifer water levels (Parks, 2012). A seepage analysis using GeoStudio Seep/W® could be performed to further understand the behavior of the dam and how various reservoir and aquifer water levels impact the performance of the dam. The final suggestion for future work is an expansion of the current monitoring system. The current monitoring system is capable of an expansion to include additional vibrating wire piezometers or other sensor types.

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VITA

Corey Hamil enrolled at The University of Mississippi in the fall of 2009. As an undergraduate, Corey worked as a student researcher for the School of Engineering and interned with the Mississippi Department of Transportation (MDOT). He was an integral part in his university, serving as President for the Engineering Student Body, ASCE and ITE. He earned a Bachelor's of Science in Civil Engineering (B.S.C.E.) in May of 2012 and continued his education at The University of Mississippi by enrolling in the Civil Engineering graduate program. He obtained a Master's of Science in Civil Engineering (M.S.C.E.) with an emphasis in Geotechnical Engineering from The University of Mississippi in August 2015. He has worked for MDOT as an Engineer in Training (E.I.T) and recently accepted a position as a Staff Geotechnical Engineer with GeoEngineers in Baton Rouge, Louisiana.