Predictive Modeling Of Sinkhole Hazards Using Synthetic Aperture Radar Interferometry (Insar) Subsidence Measurements And Local Geology

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PREDICTIVE MODELING OF SINKHOLE HAZARDS USING SYNTHETIC APERTURE RADAR INTERFEROMETRY (INSAR) SUBSIDENCE MEASUREMENTS AND LOCAL GEOLOGY

A Thesis
presented in partial fulfillment of requirements
for the degree of Master of Science
in the Department of Geology and Geological Engineering
The University of Mississippi

by
W. GABE POWELL
May 2016
ABSTRACT

The mining of salt domes provides economically important resources through salt and brine production and storage of petroleum products as part of the U.S. Strategic Petroleum Reserve. In order to assess the risk to nearby communities for potential of salt dome collapse, it is important to understand the growth of the Bayou Corne sinkhole and the conditions surrounding the Napoleonville Salt Dome that may have exacerbated its formation.

The Bayou Corne sinkhole in Assumption Parish, Louisiana has been expanding since it formed overnight on 2 August 2012. Growing from slightly over 2 acres to more than 30 acres today, the sinkhole has forced the evacuation of approximately 350 local residents and threatens transportation on the nearby Highway 70 hurricane evacuation route. The sinkhole was caused by solution mining of a brine well (Oxy-Geismar Well 3), expanding the subterranean storage cavity too close to the edge of the salt dome. This caused a sidewall collapse into the storage cavity and a rapidly growing sinkhole. The response to the Bayou Corne sinkhole collapse has involved 12 local/state agencies and five federal agencies. The State of Louisiana initiated a $12 million lawsuit against the proprietor of the well, Texas Brine, to recoup much of the State’s costs for response to the sinkhole collapse. The potential for future subsidence in the Bayou Corne area continues to pose a risk to residents. To mitigate this risk, it is important to understand and identify the risk of collapse of caverns on mined salt domes.
The ability of Interferometric Synthetic Aperture RADAR (InSAR) to measure surface subsidence, coupled with the available geologic and anthropogenic data for the Bayou Corne sinkhole, were used to develop a predictive, sinkhole hazard assessment model. Results suggest that, even without subsidence data, Oxy-Geismar Well 3 could have been identified as a cavern with a high moderate risk of collapse prior to its actual collapse in August 2012. The inclusion of UAVSAR subsidence data increased modeling accuracy and elevated the failed cavern’s risk of collapse to the highest level. Of concern is the identification of nearby Oxy-Geismar Well 1 as a cavern with a high potential for collapse, while the cavern is currently still intact. Two other nearby caverns, Oxy-Geismar Wells 2 and 9, were also identified as areas of concern with elevated probability of collapse.
OBJECTIVE

The objective of this study was to create a decision support framework to analyze geology, topography and mining designs along with subsidence data to better understand sinkhole hazard formation risk on mined salt domes. The framework allows Louisiana parishes and Mississippi counties to better understand the risk of sinkhole formation in the areas near salt dome mining. The decision framework was developed and tested through a geologic investigation of the Bayou Corne sinkhole designed to operationalize interferometric synthetic aperture radar (InSAR) data as a tool to map subsidence and use a geologic and anthropogenic context to better understand the sinkhole’s formation and growth. The primary model input was ground subsidence as detected by InSAR data collected by the UAVSAR platform (Uninhabited Aerial Vehicle Synthetic Aperture Radar). Other model inputs included characteristics of the proposed/actual mining well (e.g. depth, type of mining activity) and the spatial relationship on the salt dome for other geologic and anthropogenic factors (e.g. distance from well to top of dome and edge of dome).
DEDICATION

This work is dedicated to my wonderful wife and three amazing children. Without your love and support, I fear I would not only fail, but also cease to be.

ACKNOWLEDGEMENTS

Special thanks to Cathleen Jones, Darlene Easson, my committee members (Bruce Davis, Greg Easson and Lou Zachos), Dianne Welch, Aubrey Bolen, Ron Blom, Terry Panhorst and, last but, by no means least, my fellow graduate students. Without the unique input, advice and support provided by each of you, the pursuit of this Masters Degree would have been an insurmountable task.

UAVSAR data courtesy of the NASA Jet Propulsion Laboratory
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CHAPTER 1: INTRODUCTION

Study Site: Bayou Corne, Louisiana Sinkhole

The Bayou Corne sinkhole in Assumption Parish, Louisiana (Figure 1.1) has been expanding since it formed overnight on 2 August 2012. Growing from slightly over 2 acres to more than 30 acres today, the sinkhole has forced the evacuation of approximately 350 local residents, destroyed extensive areas of marsh and trees, and threatened transportation on nearby Highway 70 (for more statistics on the current sinkhole status reference Table 1.1) (Louisiana Department of Natural Resources Office of Conservation, 2014). The sinkhole was caused by brine well (Oxy-Geismar Well 3) solution mining that expanded the subterranean storage cavity too close to the edge of the Napoleonville Salt Dome. Expanding the well too close to the edge of the salt caused a sidewall collapse in the storage cavity and a rapidly growing sinkhole (CB&I, 2013).

Residents of Bayou Corne notified local parish officials of bubbling in the waterways around Bayou Corne on 31 May 2012, over two months prior to the actual collapse (Kent et al, 2013). A parish emergency was declared on 19 June 2012 and active monitoring of the area began on 22 June 2012 (Assumption Parish Louisiana, 2012). As part of the monitoring, the US Geological Survey evaluated six seismograph stations and confirmed reports of ongoing seismic activity, but could not identify the cause (Kent et al, 2013). After the sinkhole was discovered on
3 August 2012, Louisiana officials declared a state emergency (see Table 1.2 for a more complete timeline of sinkhole related events).

Figure 1.1. Bayou Corne Sinkhole Growth October 2012 to April 2014 (Miller Engineers and Associates Inc., 2014)
### Table 1.1 Bayou Corne Sinkhole: Current Situation

- Sinkhole area: >~29 acres (CB&I, March 11, 2014)
- Subsidence zone: ~23 acres (CB&I, March 11, 2014)
- Total area: ~52 acres (Louisiana Department of Natural Resources Office of Conservation, March 11, 2014)
- Depth: ~260 feet deep (CB&I, March 11, 2014) (Maximum depth of 440 feet reached on 04 October 2012 according to DNR Survey 2014)
- Maximum potential size (estimate): ~40.6 acres (Louisiana Department of Natural Resources Office of Conservation, February 19, 2013)
- Most probable potential size (estimate): ~11.5 acres (Louisiana Department of Natural Resources Office of Conservation, February 19, 2013)
- Closest potential approach to community (estimate): ~1,300 feet (Louisiana Department of Natural Resources Office of Conservation, February 19, 2013)
- Mandatory evacuation ordered by Assumption Parish still in effect (Louisiana Department of Natural Resources Office of Conservation, February 19, 2013)
  - ~150 homes, 350 people affected by order
- Salt cavern breached ~1 mile beneath surface (Kent, Dunaway, Osborne, & Mugnier, 2013)
- Cavern remains unstable (Kent, Dunaway, Osborne, & Mugnier, 2013) with potential for continued subsidence (Louisiana Department of Natural Resources Office of Conservation, February 19, 2013)
- Earthen berm built around sinkhole to avoid environmental contamination
- Berm has subsided up to 10 feet in areas (Kent, Dunaway, Osborne, & Mugnier, 2013)
- Crude oil and natural gas continues to move to sinkhole surface from deep formation(s) (Louisiana Department of Natural Resources Office of Conservation, February 19, 2013)
  - 19 wells venting natural gas from beneath the aquifer (Kent, Dunaway, Osborne, & Mugnier, 2013)

The brine cavern collapse is the first in Louisiana in the modern regulatory era and only the second in the state’s history (the first occurred in 1954) (Louisiana Department of Natural Resources Office of Conservation, 2013). Response to the Bayou Corne sinkhole collapse has involved 12 local/state agencies and five federal agencies (Louisiana Department of Natural Resources Office of Conservation, 2013) and resulted in civil penalties against Texas Brine totaling $260,000 (Louisiana Department of Natural Resources Office of Conservation, 2013). The state of Louisiana has initiated a $12 million lawsuit against Texas Brine to recoup much of the State’s costs for response to the sinkhole collapse (Nazaryan, 2013). The total cost to Texas Brine for continued monitoring, analysis, containment, remediation and reparations is unknown.
Table 1.2. Bayou Corne Sinkhole Timeline

- 1982: Oxy-Geismar Well No. 3 permitted for solution-mining of brine (Kent, Dunaway, Osborne, & Mugnier, 2013)
- 1995: Texas Brine received permission from Louisiana Department of Natural Resources to store Naturally Occurring Radioactive Material (NORM) in the well (Kent, Dunaway, Osborne, & Mugnier, 2013)
- 2010: DNR issues permit to mine a section of salt above the existing cavern roof (~3,400 feet deep) (Kent, Dunaway, Osborne, & Mugnier, 2013)
- June 2011: Texas Brine notifies DNR that integrity of the well had been lost. Wellbore above the cavern was plugged with cement (Kent, Dunaway, Osborne, & Mugnier, 2013)
- May 2012: Parish officials were notified of areas of bubbling spots in the Bayou Corne and Grand Bayou waterways (Kent, Dunaway, Osborne, & Mugnier, 2013)
- June 2012: Parish Emergency Declared (Kent, Dunaway, Osborne, & Mugnier, 2013)
- June 28 2012: Louisiana Department of Conservation (DOC), Office of Environmental Protection and Department of Environmental Quality agents inspected well sites (Louisiana Department of Natural Resources Office of Conservation, February 19, 2013)
- August 01 2012: DOC met with Texas Brine on abandoned cavern “Oxy 3” (Louisiana Department of Natural Resources Office of Conservation, February 19, 2013)
  - Texas Brine salt dome expert consultant assessed cavern collapse probability as “exceptionally low”
  - Mechanical integrity of well determined as “sound” through productive history
  - Cavern measured at 3,400’ feet deep and identified as deeper than any known cavern failure impacting the surface in international record
  - Vertical seismic profile indicated possible sidewall proximity to salt dome edge. No guidance was issued identifying sidewall as collapse threat.
  - Cavern identified as having never been used for natural gas storage and considered an unlikely source to feed the widespread bubbling sites
- August 02 2012: 372’ diameter sinkhole forms overnight. State emergency declared (Kent, Dunaway, Osborne, & Mugnier, 2013)
- August 2012: “Mandatory” evacuation ordered for >150 residents (Kent, Dunaway, Osborne, & Mugnier, 2013)
- May 2013: Containment levee built around the sinkhole to prevent further environmental contamination (Kent, Dunaway, Osborne, & Mugnier, 2013)
- June 2013 to present: Sinkhole expansion continues and cavern instability persists

The potential for future subsidence in the Bayou Corne area continues to pose a risk to residents (Louisiana Department of Natural Resources Office of Conservation, 2013). With 20 hydrocarbon storage and 33 brine caverns on the Napoleonville Salt Dome alone (Figure 1.2) (Louisiana Department of Natural Resources, 2015), the potential for cavern collapse and sinkhole growth is an issue that may eventually affect many residents residing over the Napoleonville Salt Dome or other mined Gulf Coast salt domes. To mitigate this risk, it is
important to establish a method to better understand sinkhole hazard formation risk on mined salt domes.

Figure 1.2. Napoleonville Salt Dome Activity (Louisiana Department of Natural Resources, 2015)

Gulf Coast Salt Domes

The Gulf of Mexico coastal plain of Louisiana and Mississippi has many salt domes created as Jurassic age salt deposits were deformed and rose toward the land surface, piercing and deforming the overlying sediments (Law Engineering Testing Company, 1981). Salt domes play an important economic role in the Gulf Coast region. They are sites of numerous natural resources (e.g. salt/brine, natural gas, oil). Once mined, the properties of salt caverns make them desirable as storage areas for hazardous waste or petroleum products. Removal of the salt from within the salt domes creates voids that reduce the ability of the salt dome to support the
overlying material. When the weight of the overburden is greater than the structural strength of the underlying, mined salt dome, the surface will subside or collapse. Subsidence is a more gradual manifestation of subsurface deformation than the near instantaneous (especially in relative geologic time) formation of a sinkhole that occurs with cavern collapse (Seni et al, 1985). The potential to predict collapse through identification of precursory surface deformation or subsidence exists as demonstrated by UAVSAR interferometry of the Bayou Corne sinkhole (Figure 1.3) (Jones & Blom, 2014).

![Figure 1.3. Differential interferogram showing pattern of precursory surface deformation. Interferogram formed from images of Bayou Corne site acquired on 23 June 2011 and 2 July 2012 (Jones & Blom, 2014)](image)

*The Napoleonville Salt Dome*

The Napoleonville Salt Dome is located in southeastern Louisiana and covers an area of approximately 14.2 square miles at a measured depth of 7,000 feet (Figure 1.4). The top of the
salt occurs at a depth of 1000 feet and covers an area of approximately 10.5 square miles (Appendix A). The town of Bayou Corne, LA is located over the western edge of the Napoleonville Salt Dome. Mining at the edge of salt domes has been identified as the most problematic location in which to operate (Hart et al, 1981). Problems that may occur when drilling within 300 feet of the edge of a salt dome are related to the increased potential of encountering a shear zone between the salt and surrounding sediment. Potential problems include leaks of gases, brines and hydrocarbons; slabbing of the roof and pillars; gas blowouts; and pressure pockets (Hart et al, 1981).

The Napoleonville Salt Dome and other Gulf Coast salt domes have moved either in the form of a gradual shift towards the Gulf of Mexico or subsidence and collapse (Fort & Brun, 2012) (Halbouty, 1967) (Hudec et al, 2013). While the coastward shift is a relatively slow and gradual movement caused by the one degree dip toward the Gulf of Mexico basin (Law Engineering Testing Company, 1981), movement caused by subsidence and collapse is generally more rapid and pronounced. Historically (i.e. 1995 to 2012), the greatest subsidence has occurred in the relative center of the top of the Napoleonville Salt Dome and remained at rates less than 1 inch per year (Figure 1.4). In 2011, increased subsidence began occurring on the western edge of the dome only a few hundred feet from the site where the sinkhole formed in 2012 (Figure 1.5). The new peak subsidence center for 2011 was identified as Oxy-Geismar Well Number 1, which registered 1.1 inches of subsidence from September 2011 to August 2012 (Ratigan J. L., 2012). Oxy Well 1 is approximately 1/4 mile east of Oxy-Geismar Well 3, the likely cause of the sinkhole collapse (Kent et al, 2013).
Figure 1.4. Precision Level Measured Subsidence Rates from 1995 through 2012 (Ratigan J. L., 2012)
Figure 1.5. Precision Level Measured Subsidence Rates for 2011 (Ratigan J. L., 2012)
CHAPTER 2: LOUANN SALT DEPOSITION AND GULF COAST SALT DOME FORMATION, SALT DOME MECHANICS AND THE NAPOLEONVILLE SALT DOME

The Gulf of Mexico coastal plain of Texas, Louisiana and Mississippi has many salt domes created as Jurassic age salt deposits were deformed and rose toward the land surface, piercing and deforming the overlying sediments (Pierce & Rich, 1962). Salt deposition occurred in a proto-gulf that became the Gulf of Mexico and was covered during expansive periods of erosion and sedimentation. Salt’s ductile properties and low density allowed it to move surface-ward and form diapirs (domes). Those salt domes play an important economic role in the Gulf Coast region. They contain numerous natural resources (e.g. salt/brine, natural gas, oil). Once mined, the properties of salt caverns make them desirable as storage areas for hazardous waste and petroleum products (Seni et al, 1985). Today, salt domes are economically important as resources for salt and brine and for storing petroleum products as part of the U.S. Strategic Petroleum Reserve. A misunderstanding of salt and salt dome characteristics may lead to mismanagement of the resource and potentially catastrophic results with dramatic consequences for local, state or national economies.

Louann Salt Deposition

Louann Salt exists all along the Gulf Coast from Texas to Florida (Figure 2.1). Louann Salt deposition began nearly 170 million years ago during the formation of the Gulf of Mexico (GOM). During this time, the North American continent and Mexico’s Yucatan peninsula began to
separate (Hudec et al., 2013). This separation created a void that filled with seawater to form a proto-Gulf (Figure 2.2). Due to the location of this relatively contained, shallow sea, the GOM in its early stages has been described as a back arc basin (Figure 2.3) (Stern & Dickinson, 2010). In this backwater basin setting, the Louann Salt was deposited. After the opening of the early GOM, seawater flowed into the restricted basin only to be unable to egress. The trapped seawater evaporated, leaving behind evaporates, most particularly salt (Ajdukiewicz et al., 2010). As the inflow-evaporation cycle repeated over millions of years, the Louann Salt filled the GOM during deposition to near sea level (Hudec et al., 2013).

![Louann Salt layer coverage of the Gulf of Mexico](image)

**Figure 2.1.** Louann Salt layer coverage of the Gulf of Mexico (NOAA, 2014)
Figure 2.2. (a) 163 ma: Gulf of Mexico at the start of salt deposition (b) 161 ma: Gulf of Mexico at the end of salt deposition (Hudec et al, 2013)

Figure 2.3. Illustration of the Gulf of Mexico as a backwater basin (Stern & Dickinson, 2010)
Sedimentation

After deposition of the Louann Salt sediment that was deposited in the GOM basin. Fed by erosion from the Appalachian and Rocky Mountains, the sediment accumulated up to 40,000 feet thick in some areas, especially in the northern third of the Gulf Coast Salt Dome Basin (GCSD) (Hudec et al, 2013). Sediment accumulation came in undulating waves of sand, silt, clay, volcanic material and other constituents of continental crust.

Periods of sedimentation coupled with the GOM’s perpetually warm (relative to the period) climate created ideal conditions for the formation of vast deposits of petroleum and natural gas. One of the significant erosional periods for petroleum formation, and perhaps the most researched, is the Miocene. Approximately 23.8 to 5.3 million years ago (ma), the extensive erosion from the North American Continent sent sediment into the GOM trapping ancient marine organisms (e.g. plankton) on the seafloor (Dribus et al, 2008). The remnants of these ancient organisms eventually formed a significant portion of the GOM’s oil reserves resulting in extensive exploration/exploitation of Miocene formations.

Salt Tectonics (Movement and Diapirism)

The sediment that was deposited within the GOM basin and on the coastal plain are far from static, fixed features in the geologic landscape. The overlying sediment is mostly unconsolidated, has little strength and is still subsiding. After deposition, during periods of seafloor spreading, the salt and overriding sediment slowly moved towards the deeper parts of the GOM basin leaving a thinner section at the landward end and a thicker section seaward (Hudec et al, 2013). The Louann Salt is less dense than its overlying layers of sediment. It is this
lower density that gives the salt buoyant properties when compared to the overlying sediment and the potential to move upwards towards the surface and through the overlying sediments (Figure 2.4) (Fort and Brun, 2012).

Salt cannot force its way towards the surface based on the weakness of the overlying strata alone. The properties of salt allow it to form vertical columns, or diapirs. In reference to geologic time, salt has more of the properties of a glacier (at surface temperatures and pressure) or highly viscous magma (at deep subsurface temperatures and pressure) (Fort & Brun, 2012). The properties from the ionic bonding of the sodium and chloride give salt a unique crystalline structure that is relatively weak (Tarbuck et al, 2013). While the crystalline structure of salt is weak in the sense of resisting movement, it gives salt the ability to withstand compressional forces. Therefore, salt tends to deform in a viscous manner, but maintains a relatively constant density despite its stratigraphic depth. Since most other sedimentary rocks have a tendency to increase in density with increasing depth and pressure, salt, with its ability to resist density changes, becomes more dynamic in comparison (Voosen, 2010).
Diapir formation was once attributed to a violent intrusion of salt through the overlying layers (Voosen, 2010). Diapirism has since been identified as a more gradual process. Salt’s viscous and buoyant characteristics encourage it to move upward through overlying sediment. Salt finds its way vertically through Gulf Coast Salt Basin sediment through weak areas created as the sediment moves laterally (Fort & Brun, 2012). At times, the diapirs would halt their vertical movement and move horizontally creating salt layers. Salt also moved toward the surface during sedimentation. As pore water migrated out of the sediments over the underlying Louann Salt during the lithification process, some subsidence of the sediment occurred. This subsidence also gave rise to diapirs as the salt displaced the subsiding sediment. One example of a salt diapir is the Napoleonville Salt Dome (NSD).
The Napoleonville Salt Dome

Due to the recent formation of a 30+ acre sinkhole on its western edge, the NSD has received more attention than many other salt domes in the U.S. The NSD is a shallow dome, extending in a relatively vertical profile to within 689 feet of the surface (Figures 2.5 and 2.6) (Halbouty, 1967). It is located in southeastern Louisiana and covers an area of approximately 14.2 square miles at a measured depth of 7,000 feet (Figure 2.7). The top of the salt occurs at a depth of approximately 700 to 1000 feet and covers an area of approximately 10.5 square miles (Appendix A). Since the NSD’s initial uplift, it has moved either as a gradual shift towards the Gulf of Mexico or subsidence and collapse. While the coastward shift is a relatively slow and stable movement caused by the one degree dip in that direction (Law Engineering Testing Company, 1981), movement caused by subsidence and collapse is generally more variable and pronounced. Historically (i.e. 1995 to 2012), the greatest subsidence has occurred in the relative center of the top of the salt and remained at rates less than 1 inch per year (Figure 2.7) (Ratigan, 2012). In 2011, subsidence began occurring on the western edge of the dome only a few hundred feet from the site where the sinkhole formed in 2012 (Figure 2.8) (Ratigan, 2012). The new peak subsidence center for 2011 was identified as coincident with the Oxy-Geismar Well 1, which registered 1.1 inches of subsidence from 2011 to August 2012 (Ratigan, 2012). Oxy-Geismar Well 1 is approximately 1/4 mile east of Oxy-Geismar Well 3, and is the likely cause of the sinkhole collapse that formed in August of 2012 (Louisiana Department of Natural Resources Office of Conservation, 2013). The community of Bayou Corne, LA and Oxy-Geismar Well 3 are located on the western edge of the Napoleonville Salt Dome. Mining at the edge of salt domes has been identified by Hart and others (1981) as the most problematic location in which to operate.
Problems that may occur when drilling close to the edge of a salt dome are leaks of gases, brines and hydrocarbons, joints and fractures, slabbing of the roof and pillars, gas blowouts and pressure pockets and shear zones (Hart et al, 1981).

Figure 2.5. Napoleonville Salt Dome illustration (not to scale) (Assumption Parish Louisiana, 2012)
Figure 2.6. Seismic cross section of Napoleonville Salt Dome (Louisiana Department of Natural Resources, 2014)
Figure 2.7. Precision Level Measured Subsidence rates from 1995 through 2012 (Kent et al, 2013)
Figure 2.8. Precision Level Measure Subsidence Rates for 2011 (Kent et al, 2013)
Salt Dome Mechanics

There are numerous uses for salt domes in addition to the brine solution mining that caused the Bayou Corne sinkhole. Two of the most contentious uses are based on salt’s ability to form large, self-healing storage caverns: 1) storage of toxic waste and other hazardous materials and 2) storage of oil and natural gas. Salt domes are often considered for storage caverns because salt is highly impermeable and possesses the ability to self-heal (i.e. close cracks). As one of the most ductile minerals, it readily deforms in low temperature/pressure settings (Johnson, 1971). Unfortunately, salt domes as a system have a unique response to stress (i.e. load) that makes their selection as storage locations a complex process.

Based on the aforementioned properties of salt, salt domes exhibit two primary mechanical behaviors: creep and dilation. Creep occurs when salt domes are subjected to asymmetrical stress. Due to salt’s ductile nature, the stress tends to cause the salt to migrate towards the area of least stress (Figure 2.9) (Ratigan et al, 1993). Dilation is an overall volumetric increase in the salt dome caused by a reduction in confining pressure at the sides of the dome. The drop in confining pressure allows the salt dome to dilate by creating micro-fractures within the salt that increase the salt dome’s overall porosity (Ratigan et al, 1993). When the weight of the overburden is greater than the structural strength of the underlying, mined salt dome, the surface will subside or collapse.
Figure 2.9. Illustration of the results of salt’s dynamic ability to creep (Cox & Killalea, 2014)

Conclusion

The Gulf Coast Salt Basin of Texas, Louisiana and Mississippi is rich in resources influenced by the movement of the Louann Salt through the overlying sediments. The Jurassic age deposition of evaporates, primarily salt, in a proto-gulf led to the formation of the Louann Salt. The unique characteristics of salt allowed it to move in response to pressure from overlying sediment and form diapirs throughout the region. Manifestations of salt in a domal form create numerous economic opportunities for the region and the nation. However, they must be properly managed and exploited to avoid damage to the environment and economy of the region and nation. All of the characteristics of salt and salt domes must be considered when exploiting resources provided by the salt or undesired consequences could occur in the form of surface subsidence or catastrophic collapse.
CHAPTER 3: SYNTHETIC APERTURE RADAR ATTRIBUTES AND APPLICATIONS

Polarimetric Synthetic Aperture Radar (PolSAR)

Radar polarimetry (“polar”: polarization + “metry”: measure) is the science of acquiring, processing and analyzing the polarization state of an electromagnetic field” (Pottier & Ferro-Famil, 2008). As an active form of remote sensing, PolSAR waves interact with different targets/surfaces in unique and specific manners. The results of the interactions are called backscatter. When the polarized waves from the radar backscatter that make it back to the radar sensor are analyzed, the resulting information (in the form of phase and amplitude values) is highly dependent on the shape (orientation and geometry) and dielectric constant (reflectivity) of the target (Pottier & Ferro-Famil, 2008). Radar waves are often polarized in horizontal and vertical orientations (Figure 3.1). Analysis of backscatter from different combinations of polarizations (e.g. HH, HV and VV) generally results in more effective extraction of the phase and/or amplitude values from a specific polarization combination (Figure 3.2).

Figure 3.1. Vertical and Horizontal Polarization of Radio Waves (Jet Propulsion Laboratory California Institute of Technology, 2014)
PolSAR platforms utilize a variety of radar wavelengths (Figure 3.3). The three most common are X-band (λ≈3.2 cm), C-band (λ≈5.6 cm) and L-band (λ≈23.5 cm) (Lillesand & Kiefer, 1994). L-band was selected for use in this study due to two main attributes: 1) its ability to penetrate tree canopies and 2) its ability to minimize the effects of surface roughness because of its longer wavelength. In contrast to optical remote sensing platforms and even shorter wavelength (e.g. X-band and C-band) SAR platforms, L-band PolSAR penetrates tree canopies and allows backscatter to contain information derived from its interaction with targets at or near ground level (Figure 3.4) (Waring, et al., 1995). Surface roughness for SAR data is relative to the wavelength of the sensor. A surface is considered rough when its features on the surface are greater than half of the SAR wavelength (Figure 3.5) (Farr, 1993). The land surfaces in and around the Bayou Corne sinkhole consist of varied terrain that interacted as a moderately rough surface.
for the L-band acquisitions. Moderate diffusion of the PolSAR data renders significantly different returns than that of a relatively smooth surface (e.g. the water filling the Bayou Corne sinkhole) (Figure 3.5) (Farr, 1993). When diffusion occurs from numerous different angles and directions due to small-scale irregularities in the surface, it introduces noise (i.e. speckle) in the image (Ulaby, Moore, & Fung, 1986). This speckle noise, resulting from variations in the amplitude and phase of the returned waves, gives radar images a grainy appearance. When the majority of pixels on a surface experience amplitude and phase changes, between acquisitions, to the extent that they are incomparable across acquisition dates, the surface is said to have “lost coherence” (Jones, 2015). Loss of coherence is a particularly common problem when imaging areas with extensive vegetation, high soil moisture or standing water (e.g. Bayou Corne, LA).

Figure 3.3. SAR Sensors Available for Commercial Applications by Wavelength (TRE, 2015)
Interferometric Synthetic Aperture Radar (InSAR)

When two PolSAR images for the same location are differenced, an interferogram is created (Figure 3.6). By subtracting the phase and amplitude values of a more recent PolSAR
image from that of an older PolSAR image, an interferogram attempts to capture the change in those values over time. For pixel based assessments of changes in phase or amplitude resultant from true changes in the phenomena of interest, coherence must be maintained between the two images. When measuring changes, such as ground subsidence, it is often necessary to compare PolSAR images acquired several months, and possibly, over a year apart to achieve levels of subsidence detectable by the applied sensor. Since loss of coherence may be driven by surface changes due to vegetative growth, rainfall or disturbances caused by agricultural practices, successful applications of InSAR are most prevalent in arid climates with little rain or vegetation or vegetated areas with hard targets (e.g. corner reflectors) not susceptible to temporal decorrelation (Table 3.1). However, use of L-band systems has led to successful applications of InSAR in more temperate regions (Table 3.1). Of utmost importance for this study is the success in measuring surface deformation/subsidence for the Bayou Corne sinkhole using the UAVSAR L-band platform (Table 3.1) of (Jones and Blom, 2014).

![Interferogram of the San Andreas Fault in California](image)

**Figure 3.6. Interferogram of the San Andreas Fault in California** (Jet Propulsion Laboratory California Institute of Technology, 2014)
### Table 3.1. Previous Research Related to InSAR Subsidence Measurement/Monitoring

<table>
<thead>
<tr>
<th>λ</th>
<th>Platform</th>
<th>Location</th>
<th>Climate</th>
<th>Range of Subsidence Measured</th>
<th>Period of Study</th>
<th>Key Finding</th>
<th>Major Issue/ Recommendation or Solution</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>UAVSAR</td>
<td>Bayou Corne, LA, USA</td>
<td>Subtropical</td>
<td>&lt;28 cm</td>
<td>JUN 2011 – OCT 2014</td>
<td>InSAR is a viable method for sinkhole hazard monitoring pre and post formation</td>
<td>Loss of coherence/ Long periods between acquisitions to allow subsidence extent to overcome coherence loss</td>
<td>(Jones &amp; Blom, 2015)</td>
</tr>
<tr>
<td>L</td>
<td>UAVSAR</td>
<td>Bayou Corne, LA, USA</td>
<td>Subtropical</td>
<td>≤26 cm</td>
<td>JUN 2011 – JUL 2012</td>
<td>InSAR has potential to identify sinkhole development before surface collapse</td>
<td>Loss of coherence/ Further investigation</td>
<td>(Jones &amp; Blom, 2014)</td>
</tr>
<tr>
<td>L</td>
<td>ALOS PALSAR</td>
<td>Sumatra and Java Indonesia</td>
<td>Tropical</td>
<td>≤22 cm/yr</td>
<td>2007 - 2009</td>
<td>L-Band enabled large scale deformation mapping in tropical areas and agreed with GPS observations</td>
<td>Ascending only acquisitions prevented separation of horizontal and vertical displacement/ Assumed horizontal displacement was negative due to historic GPS data</td>
<td>(Chaussard et al, 2013)</td>
</tr>
<tr>
<td>L</td>
<td>ALOS PALSAR</td>
<td>Central Mexico</td>
<td>Semi-arid to Subtropical</td>
<td>&lt;35 cm/yr</td>
<td>FEB 2007 - JAN 2011</td>
<td>L-band InSAR is effective for regional subsidence monitoring across a varied landscape</td>
<td>Ascending only acquisitions (except Mexico City) prevented separation of horizontal and vertical displacement/ Separated horizontal and vertical displacement for Mexico City and assumed remainder of area had similar trend</td>
<td>(Chaussard et al, 2014)</td>
</tr>
<tr>
<td>L</td>
<td>ALOS PALSAR</td>
<td>Wink and Daisetta, TX, USA</td>
<td>Arid and Subtropical</td>
<td>&lt;30 cm/yr</td>
<td>JAN – JUL 2007 and DEC 2006 – APR 2008</td>
<td>InSAR detected vertical movement over a large area surrounding Wink sinkholes</td>
<td>No subsidence detected at Daisetta/ Author’s note: Attempting InSAR collection with a higher resolution platform (PALSAR = 10m², UAVSAR = 6m²) and/or a track perpendicular to PALSAR track (ground movement is difficult to detect if in along track direction) may yield subsidence measurements</td>
<td>(Paine et al, 2009)</td>
</tr>
</tbody>
</table>
Table 3.1 (continued). Previous Research Related to InSAR Subsidence Measurement/Monitoring

<table>
<thead>
<tr>
<th>λ</th>
<th>Platform</th>
<th>Location</th>
<th>Climate</th>
<th>Range of Subsidence Measured</th>
<th>Period of Study</th>
<th>Key Finding</th>
<th>Major Issue/ Recommendation or Solution</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C and L</td>
<td>ERS-1 ERS-2 ENVISAT ALOS PALSAR</td>
<td>Ebro Valley, Spain</td>
<td>Semi-desert/ Semi-arid</td>
<td>&lt;17 mm/yr</td>
<td>JUL 1995 – APR 2010</td>
<td>InSAR suitable for analyzing active dissolution-induced subsidence</td>
<td>Decorrelation (Loss of coherence) – 70% more sinkholes identified with traditional methods/ Incorporate geologic data and supplement with traditional inventory mapping methods</td>
<td>(Galve et al, 2015)</td>
</tr>
<tr>
<td>C</td>
<td>ERS-1 ERS-2</td>
<td>Jiangsu Province, China</td>
<td>Subtropical/ Continental</td>
<td>&lt;30 mm</td>
<td>JUL 1995 - MAY 2000</td>
<td>InSAR obtained nearly identical measurements of surface deformation over a large area as ground monitoring techniques</td>
<td>Loss of coherence/ Areas that lost coherence were removed from the study</td>
<td>(Hongdong et al, 2011)</td>
</tr>
<tr>
<td>C</td>
<td>ERS-1 ERS-2</td>
<td>Jiangsu Province, China</td>
<td>Subtropical/ Continental</td>
<td>&lt;30 mm</td>
<td>JUL 1995 - MAY 2000</td>
<td>InSAR obtained nearly identical measurements of surface deformation over a large area as ground monitoring techniques</td>
<td>Loss of coherence/ Areas that lost coherence were removed from the study</td>
<td>(Hongdong et al, 2011)</td>
</tr>
<tr>
<td>X</td>
<td>TerraSAR-X</td>
<td>Carajás Province, Brazil</td>
<td>Tropical</td>
<td>&lt;39.59 cm / &lt;37 cm/yr</td>
<td>MAR 2012 – APR 2013</td>
<td>Surface deformation best monitored with combination of InSAR and in situ monitoring</td>
<td>Effectiveness limited over rapidly changing surfaces (low coherence)/Coordinated, near daily collections using all available space based systems</td>
<td>(Paradella, et al., 2015)</td>
</tr>
<tr>
<td>Ku 1.67 - 2.5 cm</td>
<td>Ground based (GB)</td>
<td>Elba Island, Italy</td>
<td>Subtropical/ Mediterranean</td>
<td>&lt;28.5 mm</td>
<td>JAN 2013 – NOV 2014</td>
<td>GB InSAR feasible for sinkhole monitoring and early warning</td>
<td>Loss of coherence/ Emplacement of corner reflectors</td>
<td>(Intrieri, et al., 2015)</td>
</tr>
</tbody>
</table>
The Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) platform is an airborne platform that utilizes an L-band radar antenna (24 cm wavelength). It was designed to study earth science with potential for emergency response applications (Jet Propulsion Laboratory California Institute of Technology, 2014). The L-band antenna (Figure 3.7) images the ground with a 0.5m range resolution and 1.5m azimuth resolution that results in ground projected pixels approximately 6m by 6m. With a collection swath of 20km by 100km, the UAVSAR platform generates approximately 55.6 million pixels per scene. Guided by a precision autopilot system, the UAVSAR platform can duplicate flight paths +/-10m facilitating PolSAR collection for the creation of interferograms.

Figure 3.7. UAVSAR L-band Antenna applications (Jet Propulsion Laboratory California Institute of Technology, 2014)
Previous successes in subsidence measurement using InSAR are sure to continue as the methods becomes better understood and more systems become commercially available. Lessons learned from the development and application of UAVSAR data and other L-band systems is aiding the ongoing development of the United States’ first space based SAR platform, NISAR (NASA-ISRO Synthetic Aperture Radar). Like UAVSAR, NISAR will be designed to aid the study of the earth and assist with hazard response/mitigation. A partnership between NASA and the Indian Space Research Organization, NISAR is set to launch in 2020 with two onboard sensors (L-band and S-band) and a potential ground resolution of 5-10m². Methods discussed in the next chapter will illustrate methods to process and analyze InSAR data.
CHAPTER 4: DATA DEVELOPMENT

The Bayou Corne sinkhole in Assumption Parish, LA was used as a case study to develop the model to understand risk of cavern collapse on mined salt domes. An analysis of subsidence/ground movement using UAVSAR data was conducted beginning with the initial signs of precursory surface deformation, through sinkhole formation and ending with the last data collection in 2014. Subsidence was mapped through analysis of raster UAVSAR images with a phase component (i.e. interferograms). The phase component was translated into a subsidence measurement using the wavelength of the radar (24 cm). Interferograms were then analyzed to detect ground level change (i.e. subsidence) and map the change in elevation over the time period. Subsidence contours were then analyzed in the context of local geology, mining design and activity. Finally, a model for sinkhole formation hazard on mined salt domes was generated from the results.

Specific Tasks

1) Data acquisition (Figure 4.1)
   a. InSAR raster scenes with phase data created by NASA JPL (Table 1)
   b. Supporting data collected or created and compiled (Table 2)
      i. Geologic data
      ii. Land cover (LC) data
      iii. Sinkhole growth surveys
      iv. Mining data

2) Data preprocessing/processing: Defining the Case Study Area (Figure 4.1)
   a. Define geologic setting of Napoleonville Salt Dome
      i. Thickness of [salt dome] overlying surficial material
      ii. Depth to clay confining layer
b. Define subsurface topography of salt domes
   i. Depth to top of salt
   ii. Salt dome shape (location of edge of salt)

c. Define anthropogenic activity
   i. Well depths
   ii. Type of activity (e.g. solution mining, brine or petroleum storage)
   iii. Land cover (vegetated, barren, water or urban/developed)

d. Measure subsidence using InSAR data

3) Data analysis/modeling (Figure 4.1)
   e. Correlate subsidence to the geologic and anthropogenic inputs
   f. Weight relevant factors affecting subsidence and generate spatially oriented decision model

4) Test model using the 53 mined caverns on the Napoleonville Salt Dome and the known collapse of Oxy-Geismar Well 3 (Figure 4.1)

Table 4.1. **UAVSAR InSAR Pairs for Napoleonville Salt Dome** (NASA Jet Propulsion Laboratory, 2015)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Flight ID</th>
<th>Data take ID</th>
<th>Date Acquired</th>
<th>Flight ID</th>
<th>Data take ID</th>
<th>Date Acquired</th>
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<td>11038</td>
<td>7</td>
<td>2011-06-23</td>
<td>12053</td>
<td>12</td>
<td>2012-07-02</td>
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<tr>
<td>InSAR</td>
<td>12053</td>
<td>12</td>
<td>2012-07-02</td>
<td>12115</td>
<td>9</td>
<td>2012-10-26</td>
</tr>
<tr>
<td>InSAR</td>
<td>12115</td>
<td>9</td>
<td>2012-10-26</td>
<td>13134</td>
<td>4</td>
<td>2013-07-24</td>
</tr>
<tr>
<td>InSAR</td>
<td>13053</td>
<td>2</td>
<td>2013-04-03</td>
<td>13134</td>
<td>4</td>
<td>2013-07-24</td>
</tr>
<tr>
<td>InSAR</td>
<td>13134</td>
<td>4</td>
<td>2013-07-24</td>
<td>13163</td>
<td>4</td>
<td>2013-10-29</td>
</tr>
<tr>
<td>InSAR</td>
<td>13163</td>
<td>4</td>
<td>2013-10-29</td>
<td>14036</td>
<td>7</td>
<td>2014-04-09</td>
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<tr>
<td>InSAR</td>
<td>14036</td>
<td>7</td>
<td>2014-04-09</td>
<td>14161</td>
<td>7</td>
<td>2014-10-28</td>
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Figure 4.1. Research Methods Flowchart
<table>
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<th>Data</th>
<th>Type</th>
<th>Date</th>
<th>File Name</th>
<th>Source</th>
<th>Online Access</th>
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<tbody>
<tr>
<td>Background imagery</td>
<td>.jpeg's digitized to rasters</td>
<td>Varied</td>
<td>Varied</td>
<td>Google Earth</td>
<td>NA</td>
</tr>
<tr>
<td>UAVSAR InSAR data</td>
<td>raster with phase data</td>
<td>2011-2014</td>
<td>Varied</td>
<td>NASA JPL</td>
<td><a href="http://uavsar.jpl.nasa.gov/cgi-bin/data.pl">http://uavsar.jpl.nasa.gov/cgi-bin/data.pl</a></td>
</tr>
<tr>
<td>Napoleonville Salt Dome contours</td>
<td>Paper map</td>
<td>2013</td>
<td>Napoleonville Salt Structure Map and Cavern Maximum Radii</td>
<td>Louisiana Department of Natural Resources Office of Conservation Mining and Injection Division</td>
<td>None – available in paper copy at LDNR in Baton Rouge, LA</td>
</tr>
<tr>
<td>Mining/well data</td>
<td>Tabular – individual well info (e.g. coords) accesible by hyperlink</td>
<td>2014</td>
<td>NA</td>
<td>Louisiana Department of Natural Resources Office of Conservation</td>
<td><a href="http://sonlite.dnr.state.la.us/sundown/cart_pro/d/cart_con_injwlbypsh2">http://sonlite.dnr.state.la.us/sundown/cart_pro/d/cart_con_injwlbypsh2</a></td>
</tr>
<tr>
<td>Overlying geology</td>
<td>.pdf</td>
<td>2013-2014</td>
<td>StructureContourIsopach.pdf</td>
<td>Louisiana Department of Natural Resources</td>
<td>NA – received via email</td>
</tr>
<tr>
<td>Subsurface mining cavern boundaries</td>
<td>Paper map</td>
<td>2013</td>
<td>Napoleonville Salt Structure Map and Cavern Maximum Radii</td>
<td>Louisiana Department of Natural Resources Office of Conservation Mining and Injection Division</td>
<td>None – available in paper copy at LDNR in Baton Rouge, LA</td>
</tr>
<tr>
<td>Land cover</td>
<td>30m raster</td>
<td>2014</td>
<td>Generated from LANDSAT 8 OLI imagery</td>
<td>USGS Global Visualization Viewer (GLOVIS)</td>
<td><a href="http://glovis.usgs.gov/">http://glovis.usgs.gov/</a></td>
</tr>
</tbody>
</table>
Step 2: Defining the Case Study Area: Overlying Geology, Salt Structure and Mining Activity

The intent of this study was to create a functional tool that municipalities with limited resources (e.g. computing/GIS capabilities and personnel) may use to estimate the risk for subsidence on mined salt domes and identify potentially hazardous areas that warrant further investigation (e.g. collection of UAVSAR data or installation of GPS reference stations). For this portion of the research, spatial analysis was conducted in ArcMap™ 10.2.2 (Figure 4.1). Data for all variables were extracted to raster surfaces with identical grids covering the top of the salt dome. The resulting grid for each attribute had approximately 6.5 million 5’ by 5’ cells, each with an, attribute specific value. The potential range of values for each attribute was then indexed into five categories (high risk = 5, high moderate risk = 4, moderate risk = 3, low moderate risk = 2 and low risk = 1) and assigned a value based on the assessed risk for subsidence/collapse (e.g. for land cover: standing water = high risk = 5 and impervious cover = low risk = 1). When possible, break points for risk classes were identified from state (Louisiana Department of Natural Resources Office of Conservation, 2015) or international (Warren, 2006) regulations governing mined salt domes. The map algebra feature (Figure 4.2) in ArcMap™ was then used to weight the influence of each variable (initially in the absence of subsidence data) and calculate an overall risk value for each cell. Resulting total risk values were mapped and compared to historic subsidence as estimated from UAVSAR InSAR data.

\[ \text{Risk level} = (\text{Proximity to edge of salt} \times 0.3) + (\text{Mining activity} \times 0.19) + (\text{Proximity to other caverns} \times 0.14) + (\text{Cavern volume} \times 0.13) + (\text{Depth to salt} \times 0.1) + (\text{Thickness of confining layer} \times 0.1) + (\text{Land cover} \times 0.04) \]

Figure 4.2. Map Algebra for Weighted Risk Calculations
Overlying Geology and Salt Structure

Three geologic attributes of the NSD were identified as having impact on the potential for collapse: location of the edge of the salt, depth to the top of salt and depth to the base of the clay confining layer. Since the NSD, and many other salt domes, are somewhat bulb shaped (i.e. larger at the top that at the bottom), three dimensional modeling of the salt contours is likely not possible in a local government GIS division. To overcome the issues that accompany creating a three-dimensional representation of the salt dome, the edge of salt contour and extents of the underground caverns were mapped in two-dimensional space. While avoiding 3D surface modeling for some attributes will introduce a degree of error, it will still allow for the model to serve as a functional tool for municipalities with limited GIS/computing capacities.

The edge of salt contour was defined as the most restrictive contour (i.e. smallest polygon) created from multiple salt dome depth contour lines (largely the -1000’ and -7000’ on Figure 4.3). The “near” function in ArcMap™ was then used to assign a distance from the most restrictive salt edge contour to each of the 6.5 million cells in the gridded surface. The processing extent and cell size/mask for the edge of salt contour near analysis (and all other attribute layers) was modified to coincide with the study’s 6.5 million cell gridded surface. Based on distances identified in Louisiana Administrative Code (LAC) 43:XVII governing salt solution mining and hydrocarbon storage (Chapters 33 and 3 respectively), risk categories for the proximity to the edge were established (Table 4.3) and mapped (Figure 4.4).
**Figure 4.3.** Most restrictive edge of salt contour

**Table 4.3.** Break points for risk associated with proximity to the edge of salt

- <100' (<30.48m) = High Risk (5)
- 100.01’ – 200’ (30.49 – 60.96m) = High Moderate Risk (4)
- 200.01’-250’ (60.97 – 76.2m) = Moderate Risk (3)
- 250.01’-300’ (76.3 – 91.44m) = Low Moderate Risk (2)
- >300’ (>91.44m) = Low Risk (1)
Figure 4.4. Proximity to the Edge of Salt on the Napoleonville Salt Dome

The depth to the confining layer surface utilized interpolated stratigraphy data obtained from over 75 wells recorded in a structure contour map developed by the Louisiana Department of Natural Resource (LDNR) (Table 4.2). The data extracted from the LDNR structure contour map provided base of clay elevation at most of the wells on the NSD. Data for the depth to top of salt elevations were extracted from the LNDR’s Napoleonville Salt Structure Map for each of the 53 cavern locations (Figure 4.3). The two layers of elevation data (in feet below the surface) were extracted from the LDNR map and recorded in tabular form in Microsoft® Excel®. Most well locations did not contain data for every layer (e.g. depth to salt and base of clay). Therefore, the
data layers were recorded in separate tables each associated to other layers via a primary key to reduce the duplication of data, ensure referential integrity, and eliminate interpolation issues created by null values. To serve as the primary key when normalizing the data, a text field containing the unique well serial numbers was added to each data set.

Unfortunately, well location datasets currently available for Assumption Parish are outdated and incomplete. The well location shapefile obtained from the LDNR only contained 22 of the approximately 75 wells depicted in the LDNR map. Before the newly created data table for NSD geology could be joined (via table join) to a shapefile containing the point locations for each well/cavern, the missing well locations had to be plotted. The additional location data were generated by georeferencing the LDNR map and adding well locations at each of the missing data points. To create a single dataset to enable interpolations, the two well/cavern datasets were merged into a single shapefile. That shapefile was clipped to the extent of the georeferenced JPEG (from the original LNDR map). The individual spreadsheets (i.e. two data layers in third normal form) were converted to a dbf2 file in ArcMap™ and joined (via table join) to the merged, clipped well location shapefile.

Spatial accuracy of the original, incomplete LNDR Assumption Parish well location shapefile is unknown. However, when compared to LANDSAT 8 OLI data from October of 2014, the points appear to fall within the correct pixel for the well location on the OLI image (Figure 4.5). The same was true for data points generated from the georeferenced map. Since all assessed points fell within the proper 30m pixel of the LANDSAT 8 OLI image, it is probable all spatial data is within 30m of the correct location. Spatial accuracy within 30m is more than
adequate for interpolation of stratigraphy from less than 100 data points over an area of almost 11 square miles.

Figure 4.5. Example of spatial accuracy for LNDR well location shapefile: Location of data point of Oxy-Geismar Well 3 in reference to Bayou Corne sinkhole and LANDSAT 8 OLI pixel

Top of salt and base of clay interpolations were conducted using kriging. As a geostatistical method, kriging assesses the statistical relationships among the data points. As with many interpolation methods, kriging assumes that surface variations may be explained through a correlation of directions and distance between data points. Kriging differs from other interpolation methods, because it applies a multistep process that utilizes exploratory statistical analysis to fit a mathematical equation to a set number of points (ESRI, 2015). It is most
applicable when the data contains a distance or direction bias and is, therefore, the interpolation method of choice for many geologists.

Since no overriding trend was known to exist in the surficial geology of the NSD, the default method, ordinary kriging, was utilized. A spherical semivariogram model was applied, because stratigraphy, by its very nature, consists of layered data delineated by measured elevations below the ground surface, (Figure 4.6). The spherical model is best for stratigraphy interpolations since it assumes spatial correlation decreases until it reaches zero. The point at which each data layer was assessed to equal zero was input as the partial sill (Table 4). Sill values were assumed to occur beyond the measured extent of the well data. Range values (i.e. the distance at which the sill is reached) were held constant at a value provided by the LDNR (i.e. 5000 ft) (Table 4.4). No nugget value was assessed so the partial sill in effect became the actual sill (Figure 4.7).

Table 4.4. ArcMap™ 10.2.2 Interpolation Parameters

<table>
<thead>
<tr>
<th>Data Layer</th>
<th>Kriging Method</th>
<th>Semivariogram Model</th>
<th>Lag Size</th>
<th>Major Range</th>
<th>Partial Sill</th>
<th>Nugget</th>
<th>Search Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base of Clay</td>
<td>Ordinary</td>
<td>Spherical</td>
<td>500 ft</td>
<td>5000 ft</td>
<td>490 ft</td>
<td>0</td>
<td>12 Points</td>
</tr>
<tr>
<td>Top of Salt</td>
<td>Ordinary</td>
<td>Spherical</td>
<td>500 ft</td>
<td>5000 ft</td>
<td>1000 ft</td>
<td>0</td>
<td>12 Points</td>
</tr>
</tbody>
</table>
Once interpolated surfaces were created for the top of salt (Figure 4.8) and base of clay (Figure 4.9) elevations, both surfaces were indexed into the five risk categories. For the base of clay elevation, it was assumed that more distance to the base of the confining layer equated to a larger layer of plastic overburden above the salt dome. The more plastic overburden that exists above a salt dome cavern, the lower the risk of a sudden collapse (Warren, 2006). Since no published data was found quantifying the level of overburden required to reduce the risk of sudden sink hole collapse, break points were created relative to the depth of the confining layer for the NSD (-89’ to – 204’) (Table 4.5) and mapped (Figure 4.10).
**Figure 4.8. Depth to Top of Salt on the Napoleonville Salt Dome**

**Figure 4.9. Depth to the Base of the Clay over the Napoleonville Salt Dome**
**Table 4.5. Break points for risk associated with depth to base of confining layer (clay)**

- `<50' (-15.24m) = High Risk (5)
- `-50.01' - `-75' (-15.25m - -22.86m) = High Moderate Risk (4)
- `-75.01' - `-125' (-22.87m - -38.1m) = Moderate Risk (3)
- `-125' - `-175' = (-38.11m - -53.34m) = Low Moderate Risk (2)
- `>175' = Low Risk (1)

**Figure 4.10. Risk Associated with Depth to the Base of the Clay (Confining Layer) over the Napoleonville Salt Dome**

For the top of salt elevation, 3 factors were incorporated into the development of break points for risk values: the LAC 43:XVII regulatory prohibitions for mining within 300 feet of the edge of a salt dome (waiverable to -100'), the maximum depth of the confining layer (-204') and the range of depths to the top of salt for the caverns in the NSD (-672' to -855'). It was assumed that piercing the top of the salt could have collapse inducing effects similar to piercing the side.
of a salt dome. It was also assumed that salt dome pirecement of the confining layer would allow natural solution mining through the introduction of surface water. Therefore, these two factors were considered when developing risk index break points relative to the top of salt elevations for the NSD (Table 4.6 and Figure 4.11).

Table 4.6. Break points for risk associated with depth to top of salt

- < -200’ = High Risk (5)
- -200.01’ - -400’ = High Moderate Risk (4)
- -400.01’ - -600’ = Moderate Risk (3)
- -600.01’ - -800’ = Low Moderate Risk (2)
- >-800’ = Low Risk (1)

Figure 4.11. Risk Associated With Depth to the Top of Salt on the Napoleonville Salt Dome
The only significant issues encountered during the overlying geology/salt structure interpolations related to the extraction of data from the original LDNR maps. Once the data were recorded, the next step was verifying all data were in the proper form (i.e. third normal with the correct text or numeric cell format). Until the formatting was correct, joining the tabular data to the spatial data was not possible. Georeferencing also presented the possibility for introduction of error. Accurately georeferencing the LDNR map took multiple attempts. Eventually, through the use of 11 control points, residual errors were brought below 9 feet with a total RMS error of 6.69.

**Mining Design**

Three mining design attributes were identified for the NSD that may impact the potential for collapse: type of mining activity, proximity of one cavern to another and individual cavern volume. Data for all three attributes were calculated using the maximum radius for each of the 53 caverns on the NSD. Maximum cavern radii (i.e. cavern boundaries) were digitized from the Napoleonville Salt Dome Structure Map (Figure 4.3). It is understood that the salt caverns exist in a three-dimensional space and each have a unique shape. However, to maintain spatial analysis that may be conducted at the “laptop level”, cavern boundary polygons were plotted in two dimensions. This eliminated the need for volumetric, three-dimensional modeling of salt caverns and will facilitate future applications of these methods by a larger audience.

Cavern volumes and mining activities were obtained from the LDNR in a shapefile format containing a point location for each cavern (Table 4.2). For both layers (i.e. cavern volumes and mining activities), a spatial join was conducted to assign the activity and volume attributes to the
corresponding cavern boundary polygon. The set of polygons for each attribute was then converted to a raster layer matching the previously created grid (5’ by 5’ cells). Cavern proximity was calculated (via a “near analysis”) between cavern boundary polygons and each 5’ by 5’ cell in the grid.

Break points were then identified and risk values assigned to all cells for each attribute. Cavern volumes are not regulated in the United States; however, they are regulated in Germany. Over time, Germany has increased the maximum allowable salt cavern volume from 350,000 m³ (2,935,245 bbl) to 500,000 m³ (3,144,905 bbl) to 700,000 m³ (5,870,490 bbl) (Warren, 2006). Dividing Germany’s historical regulated cavern volumes into 5 risk categories worked well with the NSD’s caverns that range from 203,246 (32,314 m³) to 36,584,377 bbl (5,816,451 m³). The resulting risk classes are detailed in Table 7 and mapped in Figure 4.12.

Table 4.7. Break points for risk associated with salt cavern volume

<table>
<thead>
<tr>
<th>Volume Range</th>
<th>Risk Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;700,000m³ (5,870,490 bbl)</td>
<td>High Risk (5)</td>
</tr>
<tr>
<td>575,000.01-700,000m³ (4,822,188.01 - 5,870,490 bbl)</td>
<td>High Moderate Risk (4)</td>
</tr>
<tr>
<td>475,000.01-575,000m³ (3,983,546.01 - 4,822,188 bbl)</td>
<td>Moderate Risk (3)</td>
</tr>
<tr>
<td>350,000.01-475,000m³ (2,935,245.01 - 3,983,546 bbl)</td>
<td>Low Moderate Risk (2)</td>
</tr>
<tr>
<td>&lt;350,000m³ (2,935,245 bbl)</td>
<td>Low Risk (1)</td>
</tr>
</tbody>
</table>
Break points for cavern proximity were derived from regulations (i.e. LAC 43: XVII, Chapter 33) requiring caverns to be a minimum of 200’ apart unless a waiver is approved. The waiverable proximity limit is not defined. The minimum waiverable distance to mine near the edge of salt (100’) was considered when developing break points for collapse risk associated with cavern proximity (Table 4.8). Risk associated with cavern proximity is mapped in Figure 4.13.
Table 4.8. Break points for risk associated with cavern proximity

- < 130’ (<39.62m) = High Risk (5)
- 130.01’-150’ (39.63 – 45.72m) = High Moderate Risk (4)
- 150.01’-180’ (45.73 – 54.86m) = Moderate Risk (3)
- 180.01’-200’ (54.87 – 60.96m) = Low Moderate Risk (2)
- >200’ (>60.96m) = Low Risk (1)

Proximity of Mined Caverns on the Napoleonville Salt Dome

Since four types of mining/industrial activities (i.e. active solution mining, liquid storage, gas storage, and abandoned/capped/plugged) are common on salt domes, break points were established for risk values assigned to the activity layer. As an overt effort to expand cavern dimensions, active solution mining has the potential to create conditions for a rapid collapse of the cavern (e.g. pierce the side of the salt dome or expand the cavern beyond its structural limits).
Solution mining to expand the cavern at Oxy-Geismar Well 3 likely caused the loss of cavern integrity that actually led to the Bayou Corne sinkhole. Abandoned and capped wells are considered to have the second highest associated risk of collapse for two reasons: 1) an empty cavern has no internal support from the outward pressure of stored materials 2) abandoned caverns have the potential to have been abandoned due the presence of conditions that suggest a loss of integrity is possible. Oxy-Geismar Well 3 sat empty for over one year prior to its collapse. Caverns utilized for storage have the lowest probability of collapse due to the support provided by the stored material. More dense materials (e.g. liquid petroleum), when filling the cavern to capacity, provide a high level of internal support. Gas, when stored at high pressures, also provides internal support, however, in the event of a breach of the top of the salt dome, gas will escape and the internal pressure/support will decrease. Figure 4.14 and Table 4.9 depict the risk assigned to each mining activity.
Figure 4.14. Risk Associated with Mining Activity on the Napoleonville Salt Dome

Table 4.9. Break points for risk associated with mining activity

- Active Solution Mining = High Risk (5)
- Abandoned/capped and plugged = High Moderate Risk (4)
- Gas Storage = Moderate Risk (3)
- Liquid Storage = Low Moderate Risk (2)
- NA = Low Risk (1)

Step 2: Defining the Case Study Area: Land Cover

The land use land cover (LULC) changes over the top of salt domes have the potential to affect sinkhole formation and expansion. Changes in LULC, especially deforestation and urbanization, can increase the movement of surface water (Wagener, 2007). Strong ionic bonds between the sodium and chlorine ions that form salt are broken with relative ease by highly polar
solvents such as water; therefore, an increase in surface water volume has the potential to infiltrate to the top or side of a salt dome and contribute to a natural form of solution mining of the underlying salt (Martinez et al, 1998). Erosion of additional portions of the underlying salt dome can increase the probability of sinkhole formation and exacerbate its growth once formed. Understanding LULC changes prior to a sinkhole’s initial precursory surface deformation will allow for more accurate modeling of future sinkhole hazards.

The objective of this portion of the study was to quantify the LULC changes (from 2011 to 2014) over the NSD area in order to determine if LULC change contributed to the formation of the Bayou Corne sinkhole. LULC change was not deemed significant from 2011 to 2014. The objective was achieved through a comparison of LULC as created from LANDSAT 5 TM and LANDSAT 8 OLI data for June 2011, September 2013 and October 2014. Use of LANDSAT data, with its 30 meter ground resolution allowed for the classification of approximately 16,000 pixels over the top of the NSD. The 30 meter resolution of LANDSAT data was deemed sufficient for LULC classification of the NSD due to the minimal change in land cover and general lack of developed areas across the salt dome. For areas with greater variation in land cover, especially the presence of urban development, higher resolution data (e.g. National Agricultural Imagery Program data with a 1 meter ground sample distance) may be required to adequately assess LULC. LULC for each image was quantified from supervised classification results. The final classification schema utilized four cover classes [i.e. dense vegetation (mostly forest), sparse vegetation (mostly agriculture), bare soil (mostly fallow agriculture) and water]. Total area for each cover class was measured and compared across years to generate a percent change for each cover class for the entire study period.
Minimum distance supervised classification techniques in ERDAS Image 2013 resulted in classification accuracies from 84% to 90%. The only discernible land cover change over the top of the NSD was the approximately 30 acre increase in water cover due to the formation of the sinkhole itself. All other variations were attributed to seasonal changes in agricultural practices and do not provide value as a change parameter in a hazard model.

LANDSAT 5 TM, Enhanced Thematic Mapper (ETM) and LANDSAT 8 OLI imagery for four dates covering 2011 to 2014 were reviewed. Cloud cover and scan line corrector (SLC) errors limited the available scenes to three dates: 04 June 2011 (LANDSAT 5 TM), 04 September 2013 (LANDSAT 8 OLI) and 25 OCT 2014 (LANDSAT 8 OLI). Bands (LANDSAT 5 = 2, 3 and 4; LANDSAT 8 = bands 3, 4 and 5) for green, red and near infrared (NIR) were stacked for each imagery date to create three false color infrared (IR) images. Each image was subset using topography to capture the area around the NSD. The resulting subset covered an area approximately 25 mile (north to south) by 15 mile (east to west) bounded by local rivers, streams and lakes (Figure 4.15).

![Subset of (left to right) 04 June 2011 (LANDSAT 5 TM), 04 September 2013 (LANDSAT 8 OLI) and 25 OCT 2014 (LANDSAT 8 OLI) False Color IR image vicinity of the NSD](image)
Once subset, multiple attempts were made to classify the 2014 image into five land cover classes (i.e. water, dense vegetation, sparse vegetation, bare soil and urban/developed). Supervised classification methods were utilized due to the availability of similar acquisition dates (i.e. 04 April 2011, 12 March 2013 and 08 December 2014) for detailed imagery of the area. Similar acquisition dates were utilized to minimize classification errors due to seasonal changes in agricultural practices and natural vegetation. Ten training areas of interest (AOIs) were identified for each class, except built up/developed areas. Due to the limited development in the scene, the urban class was limited to five training AOIs.

Supervised classification of the five class land cover scheme was attempted using both maximum likelihood and minimum distance parametric decision rules and default settings for non-parametric decision rules for the 2014 image. Classification results were qualitatively assessed through visual comparison to the original LANDSAT image and to Google Earth imagery.

The maximum likelihood decision rule highly over classified built up areas, while the minimum distance decision rule was better at classifying built up areas, but significantly over classified the urban areas. The over classification of urban areas occurred in conjunction with the under classification of areas of sparse vegetation and barren land, resulting in the classification of some sparsely vegetated/bare areas as urban. The classification inaccuracies were likely due to the relative absence of built up areas in the imagery for training and because the available urban training areas were small communities largely composed of sparse vegetation and bare ground land cover classes. Therefore, the built up/developed class was removed from the classification scheme and both classification methods (i.e. maximum likelihood and minimum
distance decision rules) were recalculated with only four classes. If the need arises to identify built up areas from the four class classification scheme, they may be inferred from a mix of multiple classes (especially bare soil and sparse vegetation) occurring in a single area.

Minimum distance was identified as the optimal parametric decision rule and a further attempt to improve classification accuracy was conducted using a parallelepiped non-parametric decision rule and parametric rules for overlap and unclassified decision rules. While classification results appeared very similar when visually compared to those of the minimum distance decision rule with default settings, the default settings appeared to yield a slightly higher classification accuracy. The similarity of classification results required further scrutiny to identify the optimal decision rule (Figure 4.16).

Figure 4.16. Minimum distance supervised classification results for 25 OCT 2014 (LANDSAT 8 OLI) imagery using (left to right) default settings and additional parallelepiped/parametric rules (dark green = dense vegetation, light green = sparse vegetation, tan = bare soil, blue = water)

To more thoroughly assess classification accuracy for the two variations of the minimum distance decision rule, the image was subset to an ellipse following a 2 mile buffer that
approximately corresponded with the -1000 foot top of salt contour for the NSD. Fifty random sample points were generated within the ellipse to compare the classified classification results to the original 2014 LANDSAT 8 image and the corresponding GE imagery (Figure 4.17). The minimum distance decision rule with the default configurations was identified as the most accurate, because it correctly classified 90% of the pixels represented by the 50 random points. The minimum distance, parallelepiped rule was slightly less accurate, correctly classifying 84% of the sample pixels.

![Figure 4.17. 50 random sample points over the 25 October 2014 LANDSAT 8 image](image)

The most successful supervised classification method, minimum distance with default settings, was repeated for the 25 mile by 15 mile subsets of the other two images from 04 April 2011 and 12 March 2013. When possible the original training AOIs were utilized to generate new
signature files associated to each individual image. When necessary the training AOIs were modified to account for temporal changes in land cover. Cloud cover in the 2013 image necessitated the creation of cover classes for clouds and their resulting shadows. Upon visual comparison to original images and GE imagery, the resulting classification accuracies were similar to that of the 2014 image (Figure 4.18).

Figure 4.18. Supervised classification results for (left to right) 04 June 2011 (LANDSAT 5 TM), 04 September 2013 (LANDSAT 8 OLI) and 25 OCT 2014 (LANDSAT 8 OLI) images vicinity of the NSD (dark green = dense vegetation, light green = sparse vegetation, tan = bare soil, blue = water, white = clouds, gray = shadow)

To compare supervised classification results of the three images (i.e. 2011, 2013 and 2014), the attribute tables had to be normalized so that each image had the cover classes represented by the same value (i.e. dense vegetation = 1, sparse vegetation = 2, bare soil = 3, water = 4). Once the attribute values were normalized, the images were once again clipped to the two mile elliptical buffer (Figure 4.19). After a visual assessment of the 2013 image, it was determined the clouds (and corresponding shadows) over the NSD had the caused too many classification errors to warrant further comparison. Land cover change was therefore, only assessed for the 2011 and 2014 images. Two methods were utilized to assess the land cover change: 1) the change detection feature in ERDAS Imagine® 2013 and 2) change in area
calculations as derived from pixel counts. To optimize visualization of classification results, the classified images were further clipped to an area encompassing the NSD -1000 foot top of salt contour as determined from Figure 4.3. Pixel count calculations (i.e. number of pixels per class, total area of each class and change in cover area) were conducted for both sets of subset images (i.e. two mile elliptical buffer and top of salt buffer). Due to similarities in the results, only the results for the top of salt images are discussed.

![Supervised classification results for the 25 OCT 2014 (LANDSAT 8 OLI) image](image)

*Figure 4.19. Supervised classification results for the 25 OCT 2014 (LANDSAT 8 OLI) image (dark green = dense vegetation, light green = sparse vegetation, tan = bare soil, blue = water)*

Change detection results clearly depicted the formation of the Bayou Corne sinkhole (Figure 4.20), while other LULC changes showed no distinct pattern. Comparison of pixel counts was required to yield greater insight as to the quantification and possible causation of the land cover class changes between 2011 and 2014.
Figure 4.20. ERDAS Imagine® change detection results for the 04 June 2011 and 25 October 2014 classified images (blue > 10% increase, red > 10% decrease)

Results from pixel counts of the 2011 clipped (to the top of the NSD) image show that the 2011 image had 2242 acres of dense vegetation, 684 acres of sparse vegetation, 141 acres of bare soil and 119 acres of water (Figure 4.21 and Table 4.11). Results from pixel counts of the 2014 image, clipped to the top of the NSD, shows that the 2014 image had 2349 acres of dense vegetation, 297 acres of sparse vegetation, 389 acres of bare soil and 151 acres of water (Figure 4.22 and Table 4.12). When comparing 2011 to 2014, dense vegetation increased by 107 acres (4.8%), sparse vegetation decreased by 387 acres (56.5%), bare soil increased by 248 acres (176.6%) and water increased by 31 acres (26.3%) (Table 4.10).

Table 4.10. Comparison of land cover class changes from 04 June 2011 to 25 October 2014

<table>
<thead>
<tr>
<th>Class</th>
<th>Area Change (ac)</th>
<th>Direction</th>
<th>Area Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Veg</td>
<td>106.9717545</td>
<td>increase</td>
<td>4.771352048</td>
</tr>
<tr>
<td>Sparse Veg</td>
<td>-386.521641</td>
<td>decrease</td>
<td>-56.3871178</td>
</tr>
<tr>
<td>Barren</td>
<td>248.192262</td>
<td>increase</td>
<td>176.5822785</td>
</tr>
<tr>
<td>Water</td>
<td>31.3576245</td>
<td>increase</td>
<td>26.25698324</td>
</tr>
<tr>
<td>Sum</td>
<td>-1.7053E-13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The decrease in sparse vegetation and increase in bare soil is likely due to seasonal changes in agricultural practices. In June, most fields are actively growing and contain crops planted earlier. In October, most crops have been harvested and many fields are covered in crop residue or bare soil. Crop residue and bare soil have similar spectral characteristics in the green, red and NIR bands resulting in fields covered in plant litter after the late summer/fall harvest being classified as bare soil. The majority of the 31 acre increase in water is almost certainly due to the formation of the Bayou Corne sinkhole. Forming in August 2012, the sinkhole grew to almost 30 acres by the end of 2014. Rainfall for the periods one month prior to image acquisition likely resulted in only a slight increase of water cover in 2014. From 11 May 2014 to 11 June 2014, the area received 1.97 inches of rain. The majority of that rain fell towards the end of the 32 day period. From 25 September 2014 to 25 October 2014, the area received 3.39 inches of rain, with the majority of it falling in the beginning or middle of the 32 day period. Although the area received 1.42 inches more of rain in 2014, the earlier rainfall dates (as compared to 2011) likely reduced its impact on land cover classification.

![Figure 4.21](image.png)

**Figure 4.21.** Results from pixel counts of the 04 June 2011 clipped (to the top of the NSD) LANDSAT 5 TM image (dark green = dense vegetation, light green = sparse vegetation, tan = bare soil, blue = water)
Table 4.11. Results from pixel counts of the 04 June 2011 clipped (to the top of the NSD)

<table>
<thead>
<tr>
<th>Class</th>
<th># of Pixels</th>
<th>Area (m)</th>
<th>Area (ac)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Vegetation</td>
<td>100812</td>
<td>9072900</td>
<td>2242</td>
</tr>
<tr>
<td>Sparse Vegetation</td>
<td>3074</td>
<td>2766600</td>
<td>684</td>
</tr>
<tr>
<td>Barren</td>
<td>632</td>
<td>568800</td>
<td>141</td>
</tr>
<tr>
<td>Water</td>
<td>537</td>
<td>483300</td>
<td>119</td>
</tr>
<tr>
<td>Sum</td>
<td>14324</td>
<td>12891600</td>
<td>3186</td>
</tr>
</tbody>
</table>

Figure 4.22. Results from pixel counts of the 25 October 2014 clipped (to the top of the NSD)
LANDSAT 8 OLI image (dark green = dense vegetation, light green = sparse vegetation, tan = bare soil, blue = water)

Table 4.12. Results from pixel counts of the 25 October 2014 clipped (to the top of the NSD)

<table>
<thead>
<tr>
<th>Class</th>
<th># of Pixels</th>
<th>Area (m)</th>
<th>Area (ac)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Vegetation</td>
<td>10562</td>
<td>9505800</td>
<td>2349</td>
</tr>
<tr>
<td>Sparse Vegetation</td>
<td>1336</td>
<td>1202400</td>
<td>297</td>
</tr>
<tr>
<td>Barren</td>
<td>1748</td>
<td>1573200</td>
<td>389</td>
</tr>
<tr>
<td>Water</td>
<td>678</td>
<td>610200</td>
<td>151</td>
</tr>
<tr>
<td>Sum</td>
<td>14324</td>
<td>12891600</td>
<td>3186</td>
</tr>
</tbody>
</table>

Based on these results, it is unlikely that LULC changes contributed to the formation of the Bayou Corne sinkhole or affected its rate of expansion. Changes in LULC, as quantified from the 2011 and 2014 LANDSAT images, were minimal. Other than a 31 acre increase in the water cover class that is attributed to the formation of the sinkhole, no significant changes to land cover occurred. What variations were observed are likely attributed to seasonal changes in agricultural
practices from June (2011) to October (2014). While LULC change is not necessarily applicable in modeling growth for the Bayou Corne sinkhole, it may serve as an input for modeling sinkholes in other areas. Supervised classification methods utilized in this study should be considered for LULC classifications and change comparisons in future sinkhole hazard studies.

As there was minimal change in LULC over the NSD from 2011 to 2014, only the 2014 LULC data was utilized in the hazard model. Supervised classification results of the 25 October 2014 image (2 mile elliptical buffer) were clipped and gridded to match the study AOI grid of 6.5 million 5’ x 5’ cells (Figure 4.23). Since the greatest influence of land cover on mined salt caverns is its influence on the infiltration of surface water that may promote dissolution of the salt surrounding the cavern, results were then reclassified into 3 classes (pervious, impervious and surface water) (Joseph Martinez, 1998). Standing water has the highest potential for natural solution mining of salt caverns through groundwater infiltration and was given the highest risk factor (Table 4.13). Risk associated with land cover over the NSD is shown in Figure 4.24.
Table 4.13. Break points for risk associated with land cover class

- Water = High Risk (5)
- NA = High Moderate Risk (4)
- Pervious Cover (Dense/Sparse Veg and Barren: 1,2,3) = Moderate Risk (3)
- NA = Low Moderate Risk (2)
- Impervious Cover = Low Risk (1)

Figure 4.23. Land Cover over the Napoleonville Salt Dome
Step 2: Defining the Case Study Area: Measuring Subsidence with InSAR data

Processing UAVSAR Interferograms: Phase Data Extraction (MATLAB®)

The first step in mapping subsidence from UAVSAR interferograms is to extract the desired phase data from the InSAR files. Raw UAVSAR InSAR pairs contain both amplitude and phase data in a single file, the .grd file. The .grd UAVSAR file is a list of floating point complex numbers without any header records. The floating point complex numbers are a list of real and imaginary numbers for amplitude and phase data created by subtracting data recorded during the later SAR acquisition from data recorded during the earlier acquisition. The NASA Jet
Propulsion Laboratory (JPL) developed a MATLAB® script (Appendix A) to read the two column array of 32-bit floating point numbers and automate the isolation of the phase data (with values ranging from π to –π) required to measure subsidence/surface deformation.

Processing UAVSAR Interferograms: Header Creation (ENVI®)

The phase data isolated by the MATLAB® script does not contain header data, as such; a header must be created before the files may be opened in most common image processing/GIS software packages. The header information ties the single band phase data file to a geographic reference point and defines its length and width (lines and sample numbers) for ground projection. The steps required to create a header in ENVI® Classic are listed in Appendix B.

Processing UAVSAR Interferograms: Export to ArcMap™ (ENVI®)

Once the headers were created in ENVI® Classic, the *.grd files were opened in the 32-bit version of ENVI®. This version was utilized because it has the option to export the files directly to ArcMap™ as georeferenced TIFF images. The file opened as a temporary file in ArcMap™ and were saved as *.tif files before proceeding.

Processing UAVSAR Interferograms: Normalizing Phase Data (ArcMap™)

Each InSAR geoTIFF was then clipped to the study AOI of approximately 6.5 million 5’ x 5’ cells. Each image was then normalized to a stable reference point on the ground in order to adjust all subsidence values in relation to a fixed point of zero subsidence within the AOI. Dow Storage well number 972001 (91°7’6.082”W 30°0’53.556”N) was selected as the reference point for zero subsidence due to its low risk for subsidence as determined by the initial predictive
model calculations, its relatively central location on the NSD, and because it has the lowest level of measured subsidence across the NSD (Figure 4.25). The pixel value was identified at the 972001 well location for each InSAR pair (Table 4.14) and subtracted from all other pixels within the same image subset to normalize the phase values across that particular image.

Table 4.14. Normalized Reference Point (Well 972001) Pixel Values

<table>
<thead>
<tr>
<th>InSAR Image</th>
<th>Initial Pixel Value</th>
<th>Raster Calculator Function</th>
<th>Final Pixel Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-23-11 to 7-2-12</td>
<td>-1.711173</td>
<td>-1.711173</td>
<td>0</td>
</tr>
<tr>
<td>7-2-12 to 10-26-12</td>
<td>1.545801</td>
<td>-1.545801</td>
<td>0</td>
</tr>
<tr>
<td>10-26-12 to 4-3-13</td>
<td>-1.520205</td>
<td>-1.520205</td>
<td>0</td>
</tr>
<tr>
<td>4-3-13 to 7-24-13</td>
<td>-0.262957</td>
<td>-0.262957</td>
<td>0</td>
</tr>
<tr>
<td>7-24-13 to 10-29-13</td>
<td>-0.262957</td>
<td>-0.262957</td>
<td>0</td>
</tr>
<tr>
<td>10-29-13 to 4-9-14</td>
<td>-0.698302</td>
<td>-0.698302</td>
<td>0</td>
</tr>
<tr>
<td>4-9-14 to 10-28-14</td>
<td>1.792913</td>
<td>1.792913</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4.25. Precision Level Measured Subsidence Rates from 1995 through 2012 and Dow Storage Well 972001 (Kent et al, 2013)
Processing UAVSAR Interferograms: Re-wrapping Phase Data (ArcMap™)

After the pixel values were normalized, they were “re-wrapped” to fall within the range of -3.14159 to 3.14159 (-π to π) and then doubled to achieve the -2π to 2π range that equates to a full interferometric phase unwrap. The math involved in this process was executed by creating a series of grids using ArcMap’s™ Raster Calculator. The four step process is detailed in Figure 4.26. The final interferometric phase values are listed in Table 4.15.

"Grid1" = The grid of phase values.

**Step 1**: Create a new grid (“Grid2”) using the command string: "Grid1"/math.pi

This calculates how many times π will divide into the values in “Grid1”.

Example: A “Grid1” pixel value = -4.14159. “Grid2” = -4.15169/3.14159 = -1.31831

**Step 2**: Create a new grid (“Grid3”) using the command string:

Con("Grid2">=0,"Grid2"-RoundDown("Grid2"),"Grid2"-RoundUp("Grid2"))

This calculates the remainder of Step 1 with the correct sign (+ or -) for rewrapping.

Example: “Grid3” = -1.31831 – -1 = .31831

**Step 3**: Create a new grid (“Grid4”) using the command string: "Grid3"*math.pi

This recalculates the correct phase values between + π and − π.

Example: “Grid4” = .31831*3.14159 = 1

**Step 4**: Create a new grid (“Grid5”) using the command string: “Grid4”*2

This doubles the values from Step 3 placing them in the range of -2π to 2π.

Example: “Grid5” = 1*2 = 2
Table 4.15. Rewrapped Pixel Values (-2π to 2π)

<table>
<thead>
<tr>
<th>InSAR Image</th>
<th>Normalized Pixel Value Range</th>
<th>Final Pixel Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-23-11 to 7-2-12</td>
<td>-1.4304 to 4.85271</td>
<td>-2.86079 to 6.28315</td>
</tr>
<tr>
<td>7-2-12 to 10-26-12</td>
<td>-4.68737 to 1.59575</td>
<td>-6.28297 to 3.19151</td>
</tr>
<tr>
<td>10-26-12 to 4-3-13</td>
<td>-1.62139 to 4.66177</td>
<td>-3.24277 to .28297</td>
</tr>
<tr>
<td>4-3-13 to 7-24-13</td>
<td>-2.87856 to 3.40454</td>
<td>-5.75712 to 6.28313</td>
</tr>
<tr>
<td>7-24-13 to 10-29-13</td>
<td>-2.87856 to 3.40454</td>
<td>-5.75712 to 6.28313</td>
</tr>
<tr>
<td>10-29-13 to 4-9-14</td>
<td>-2.44328 to 3.83985</td>
<td>-4.88656 to 6.28316</td>
</tr>
<tr>
<td>-9-14 to 10-28-14</td>
<td>-4.93449 to 1.34867</td>
<td>-6.28317 to 2.69734</td>
</tr>
</tbody>
</table>

Processing UAVSAR Interferograms: Mapping Subsidence (ArcMap™)

Attempts were made to automate contouring of measured subsidence using processed interferometric phase values, numerous contour intervals (i.e. 1, 2, 6 and 12), and multiple interpolation methods (i.e. spline and inverse distance weighted). All attempts were unsuccessful due to the high levels of speckle noise in the InSAR data. Speckle was so prevalent (due to poor coherence resulting from collection in the swampy, vegetated terrain of southeastern Louisiana), it was also determined that application of low pass filters would not improve the results of automated contouring of subsidence data. The subsidence was visually interpreted for each image and manually contoured.

Manual contouring was conducted while the applicable InSAR layer was open in ArcMap™. Layers for locations of wells, the sinkhole and NSD contours were not displayed to limit bias during visual interpretation of subsidence data. Manual contouring resulted in a single polygon that defined the outermost boundary of the measured subsidence for each InSAR image (Figures 4.27 and 4.28 and Appendix C). The resulting polygons were compared to the subsidence depicted in corresponding interferograms from Jones and Blom (2015) and evaluated in the presence of actual sinkhole and Ox-Geismar Well 3 locations to ensure contouring accuracy. A
single value estimating the amount of subsidence/surface deformation was approximated from a crude survey of phase values for pixels at the inner boundary of the subsidence polygon (Table 16). The area of each polygon was calculated in ArcMap™ to chart the growth of the collapse subsidence over time (Table 4.16 & Figure 4.29). A final, comprehensive subsidence polygon was created to depict the extent of subsidence surrounding the Bayou Corne sinkhole that has occurred inclusive of the time period covering initial precursory surface deformation and the most recent interferogram (6-23-11 to 10-28-14) (Figures 4.30 and 4.31 and Appendix D). The total subsidence polygon was created by stacking the six individual subsidence contours (i.e. polygons) and drawing a bounding polygon around the perimeter created by the collective, stacked subsidence contours.

Figure 4.27. UAVSAR Interferogram (June 2001 to July 2012) over the Napoleonville Salt Dome
Figure 4.28. Map of surface deformation prior to the formation of the Bayou Corne sinkhole created from UAVSAR Interferogram (June 2001 to July 2012)

Table 4.16. Bayou Corne Sinkhole Subsidence Zone Growth as Measured by UAVSAR InSAR

<table>
<thead>
<tr>
<th>InSAR Image Acquisition Dates</th>
<th>Subsidence Zone Size (ac)</th>
<th>Change From Previous Mo (%)</th>
<th>Subsidence Amount (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-23-11 &amp; 7-2-12</td>
<td>38.2</td>
<td>NA</td>
<td>28^1</td>
</tr>
<tr>
<td>7-2-12 &amp; 10-26-12</td>
<td>58.5</td>
<td>53.1</td>
<td>9.9</td>
</tr>
<tr>
<td>10-26-12 &amp; 4-3-13</td>
<td>67.5</td>
<td>15.4</td>
<td>10.1</td>
</tr>
<tr>
<td>4-3-13 &amp; 7-24-13</td>
<td>64.1</td>
<td>-5.0</td>
<td>6.1</td>
</tr>
<tr>
<td>7-24-13 &amp; 10-29-13</td>
<td>40.2</td>
<td>-37.3</td>
<td>7.5</td>
</tr>
<tr>
<td>10-29-13 &amp; 04-9-14</td>
<td>31.1</td>
<td>-22.6</td>
<td>6.7</td>
</tr>
<tr>
<td>4-9-14 &amp; 10-28-14</td>
<td>31.2</td>
<td>0.3</td>
<td>9.0</td>
</tr>
</tbody>
</table>

^1From Jones & Blom, 2015. Precursory surface deformation too great to measure within a single phase unwrap.
Figure 4.29. Bayou Corne Sinkhole Active Subsidence Zone Size in Acres

Figure 4.30. Subsidence Zones for the Napoleonville Salt Dome
Once a comprehensive subsidence polygon was created, proximity to ongoing subsidence (defined by the comprehensive “total subsidence” contour) was calculated using a near analysis between the comprehensive total subsidence polygon and each 5’ by 5’ cell in the grid. A spatial join was then conducted to add the correct subsidence proximity attribute value to the each polygon representing a mined salt cavern.

Break points for proximity to surface deformation/subsidence were derived using the same methods and regulatory references (i.e. LAC 43: XVII, Chapter 33) as cavern proximity. The LAC 43: XVII requires caverns to be a minimum of 200’ apart unless a waiver is approved. The
waiverable proximity limit is not defined. The minimum waiverable distance to mine near the edge of salt (100’) was considered when developing break points for collapse risk associated with cavern proximity to subsidence (Table 4.17). Risk associated with proximity to ongoing subsidence on the NSD is mapped in Figure 4.32.

Table 4.17. Break points for risk associated with proximity to surface deformation/subsidence

- < 130’ (<39.62m) = High Risk (5)
- 130.01’-150’ (39.63 – 45.72m) = High Moderate Risk (4)
- 150.01’-180’ (45.73 – 54.86m) = Moderate Risk (3)
- 180.01’-200’ (54.87 – 60.96m)= Low Moderate Risk (2)
- > 200’ (>60.96m) = Low Risk (1)

Figure 4.32. Risk Associated With Proximity to Ongoing Subsidence on the Napoleonville Salt Dome
Step 3: **Modeling: Overlying Geology, Salt Structure and Mining Activity**

Once all risk layers were created, map algebra (Figure 4.2) was then used to weight the influence of each variable (in the absence of subsidence data) and calculate an overall risk value for each cell. Resulting total risk values were mapped and compared to historic subsidence as estimated from UAVSAR InSAR data. Model results are discussed in Chapter 5: Results and Discussion.

Step 3: **Modeling: Subsidence, Overlying Geology, Salt Structure and Mining Activity**

Three experiments (Formulas 2-4) were conducted to determine the optimal way to weight the influence of all variables (including ongoing subsidence) on the risk of collapse for each cavern on the NSD. Map algebra equations (Figures 4.38-4.40) were modified slightly to adjust the influence of each variable during total risk calculations. Results for each model are discussed in Chapter 5: Results and Discussion.

### Formula 2

\[(\text{Proximity to ongoing subsidence} \times 0.33) + (\text{Proximity to edge of salt} \times 0.2) + (\text{Mining activity} \times 0.13) + (\text{Proximity to other caverns} \times 0.095) + (\text{Cavern volume} \times 0.085) + (\text{Depth to salt} \times 0.07) + (\text{Thickness of confining layer} \times 0.07) + (\text{Land cover} \times 0.02) = \text{risk level ranging from 1 to 5}\]

**Figure 4.38. Map Algebra Formula 2 for Weighted Risk Calculations**

### Formula 3

\[(\text{Proximity to ongoing subsidence} \times 0.33) + (\text{Proximity to edge of salt} \times 0.2) + (\text{Proximity to other caverns} \times 0.13) + (\text{Mining activity} \times 0.095) + (\text{Cavern volume} \times 0.085) + (\text{Depth to salt} \times 0.07) + (\text{Thickness of confining layer} \times 0.07) + (\text{Land cover} \times 0.02) = \text{risk level ranging from 1 to 5}\]

**Figure 4.39. Map Algebra Formula 3 for Weighted Risk Calculations**

### Formula 4

\[(\text{Proximity to ongoing subsidence} \times 0.33) + (\text{Proximity to edge of salt} \times 0.2) + (\text{Mining activity} \times 0.13) + (\text{Cavern volume} \times 0.095) + (\text{Cavern proximity} \times 0.085) + (\text{Depth to salt} \times 0.07) + (\text{Thickness of confining layer} \times 0.07) + (\text{Land cover} \times 0.02) = \text{risk level ranging from 1 to 5}\]

**Figure 4.40. Map Algebra Formula 4 for Weighted Risk Calculations**
CHAPTER 5: RESULTS AND DISCUSSION

Modeling: Overlying Geology, Salt Structure and Mining Activity

Initial modeling without a weighted subsidence input identified Oxy-Geismar Well 3 as the cavern with the greatest potential (i.e. high moderate risk) for subsidence/collapse (Figure 5.1). Oxy-Geismar Well 1 was also identified as having a high moderate risk of subsiding/collapsing (Figure 1). Both wells were identified as high moderate risk, largely due to their proximity to the edge of the salt dome (Figure 5.1). Since there is minimal risk of piercing the edge of the salt for caverns greater than 300’ from the edge (Louisiana Department of Natural Resources Office of Conservation, 2015), proximity to the edge of the dome did not play a role in risk calculations for the remaining caverns. From a risk standpoint, the relatively uniform geology (i.e. depth to the top of salt and depth to base clay) and land cover of the area, did not significantly impact the total calculated risk. The assignment of a moderate or low moderate risk (in the absence of a weighted subsidence variable) for the remainder of the caverns was most influenced by a combination of the variability among mining activities, proximity to other caverns and total cavern volume.

When the initial model results were compared to the subsidence estimates from the UAVSAR data, subsidence occurred in an area of high moderate risk as identified by the model (Figure 5.1). As expected, the collapsed cavern (Oxy-Geismar Well 3) and its northern neighbor (Oxy-Geismar Well 1) garnered a high moderate potential for collapse, the highest of all caverns.
on the NSD. This formula will allow municipalities to assess their risk for subsidence/collapse of caverns on mined salt domes through geospatial analysis of readily available information (e.g. salt dome contours and cavern statistics) even if subsidence data is unavailable. It will also allow municipalities to identify high risk areas for further monitoring (e.g. remote sensing collection) to refine modeling results. Using this analysis, the Oxy-Geismar Well 3 would have been assigned a high probability of collapse. Based on these initial results, it was assessed that incorporation of ongoing subsidence data into the model was required to increase its accuracy. Map algebra formulas 2, 3 and 4, discussed in the next section, are attempts to include subsidence in the model and manipulate the weights to achieve the highest possible risk factor for Oxy-Geismar Well 3.

**Figure 5.1. Initial Modeling Results for Risk of Mined Cavern Collapse Compared to Ongoing Subsidence on the Napoleonville Salt Dome**

- **Explanation**
  - Low Moderate Risk
  - Moderate Risk
  - High Moderate Risk
  - High Risk
  - Zone of Subsidence
  - Edge of Salt

*Subsidence as contoured from UAVSAR data collected June 2011 through October 2014*
**Modeling: Subsidence, Overlying Geology, Salt Structure and Mining Activity**

Since formula 1 (no subsidence data) did not produce a “high” assigned risk for Oxy-Geismar Well 3, attempts were made to adjust the weighting of different factors including ongoing subsidence as a factor. Proximity to ongoing subsidence and proximity to the edge of the salt dome were deemed the most influential variables in cavern collapse. Proximity to ongoing subsidence was selected as the most influential variable because it is an actively occurring phenomena on the NSD and was shown to have occurred immediately preceding the collapse of the sinkhole (Jones & Blom, 2014). Proximity to the edge of the salt dome was selected as the second most influential due to the increased potential for piercing the edge of the salt dome as caverns, or subsiding areas approach the edge of the salt. For all three formula variations, proximity to ongoing subsidence and proximity to edge of the salt dome remained the most heavily weighted variables (Table 5.1). For formula 2, all other variables remained the same as formula 1. Formulas 3 and 4 varied the influence of proximity to other caverns, mining activity and cavern volume on the risk of cavern collapse (Table 5.1).

Formulas 2 and 4 both assigned a high to high moderate risk to Oxy-Geismar Wells 3 and 1 (Figures 5.2 and 5.3). Formula 3 rendered a high moderate risk assignment similar to that of Formula 1 where the subsidence data was absent (Figures 5.4 and 5.1). Upon final review, Formula 2 was selected as the most effective weighted model for predicting cavern collapse on a mined salt dome. The success of formula 2 is attributed to the order of influence of its top five variables (Table 5.1).
<table>
<thead>
<tr>
<th>Variable #</th>
<th>Formula 2</th>
<th>Formula 3</th>
<th>Formula 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(Proximity to ongoing subsidence*.33)</td>
<td>(Proximity to ongoing subsidence*.33)</td>
<td>(Proximity to ongoing subsidence*.33)</td>
</tr>
<tr>
<td>2</td>
<td>+ (Proximity to edge of salt*.2)</td>
<td>+ (Proximity to edge of salt*.2)</td>
<td>+ (Proximity to edge of salt*.2)</td>
</tr>
<tr>
<td>3</td>
<td>+ (Activity*.13)</td>
<td>+ (Proximity to other caverns*.13)</td>
<td>+ (Activity*.13)</td>
</tr>
<tr>
<td>4</td>
<td>+ (Proximity to other caverns*.095)</td>
<td>+ (Activity*.095)</td>
<td>+ (Cavern volume*.095)</td>
</tr>
<tr>
<td>5</td>
<td>+ (Cavern volume*.085)</td>
<td>+ (Cavern volume*.085)</td>
<td>+ (Proximity to other caverns*.085)</td>
</tr>
<tr>
<td>6</td>
<td>+ (Depth to salt*.07)</td>
<td>+ (Depth to salt*.07)</td>
<td>+ (Depth to salt*.07)</td>
</tr>
<tr>
<td>7</td>
<td>+ (Thickness of confining layer*.07)</td>
<td>+ (Thickness of confining layer*.07)</td>
<td>+ (Thickness of confining layer*.07)</td>
</tr>
<tr>
<td>8</td>
<td>+ (Land cover*.02)</td>
<td>+ (Land cover*.02)</td>
<td>+ (Land cover*.02)</td>
</tr>
<tr>
<td></td>
<td>= risk value ranging from 1 to 5</td>
<td>= risk value ranging from 1 to 5</td>
<td>= risk value ranging from 1 to 5</td>
</tr>
</tbody>
</table>

Table 5.1. Comparison of Weighted Model Formulas (Variations from Formula 2 in Red)

---

**Risk of Mined Cavern Collapse on the Napoleonville Salt Dome**

*Subsidence as contoured from UAVSAR data collected June 2011 through October 2014

**Explanation**
- Low Moderate Risk
- Moderate Risk
- High Moderate Risk
- High Risk
- Zone of Subsidence
- Edge of Salt

**Figure 5.2. Formula 2 for Risk of Mined Cavern Collapse on the Napoleonville Salt Dome**
Figure 5.3. Formula 4 for Risk of Mined Cavern Collapse on the Napoleonville Salt Dome

Figure 5.4. Formula 3 for Risk of Mined Cavern Collapse on the Napoleonville Salt Dome
Variable 1: Proximity to Subsidence

Ongoing subsidence must remain the most influential variable since it has been shown to be a precursor for collapse. Not all collapses are known to have precursory surface deformation, but when surface deformation on a salt dome has occurred, collapse has followed (Jones & Blom, 2014).

Variable 2: Proximity to the Edge of the Salt Dome

Regulatory and scientific literature suggest piercing the edge of the salt dome leads to cavern collapse (Louisiana Department of Natural Resources Office of Conservation, 2015) (Warren, 2006). Therefore, proximity to the edge of the salt dome remains the second most heavily weighted variable.

Variable 3: Mining Activity

The most probable situations involving the initial, sudden collapse of a cavern include the dissolution of the structural salt surrounding the cavern, whether by natural or unnatural causes. Anthropogenic causes come, in a large part, in the form of active solution mining and are the reason mining activity is the third most heavily weighted variable.

Variable 4: Cavern Proximity

Cavern proximity, as the final spatial variable address in this study that is regulated in the United States, received the fourth highest weight. It is important to note that inaccuracies created by using a two-dimensional model for the cavern diameters instead of modeling them in three-dimensions, diminish the accuracy of this variable and warrant additional investigation.
when two-dimensional modeling suggests a collapse is possible. It is also important to understand that a cavern collapse may expand or shift the boundaries of a cavern requiring the creation of an updated cavern boundary polygon (by redrawing cavern boundary polygons to match the most current cavern data) and recalculation of the cavern proximity risk layer.

**Variable 5: Cavern Volume**

Cavern volume, with its status as a regulated variable in Europe, rounds out the top five most influential variables as weighted in Formula 2.

Model results suggest Oxy-Geismar Well 1 will collapse if the subsidence zone surrounding Oxy-Geismar Well 3 continues to expand. Implications of study results are discussed further in Chapter 6: Recommendations and Conclusions.
CHAPTER 6: RECOMMENDATIONS AND CONCLUSIONS

Recommendation: Expand Study to Additional Locations

The successful modeling of the potential for mined cavern collapse on the Napoleonville Salt Dome shows promise for applicability on other mined salt domes. While the model is difficult to test without collapse of additional caverns, its application on other Gulf Coast salt domes may lend valuable information and insight as to its effective implementation.

While the Napoleonville Salt Dome is the only Gulf Coast salt dome with a recent, mining induced sinkhole formation, it is not the only salt dome with readily available, historic UAVSAR data. Two additional salt domes with mining activity exist and have the potential for use of UAVSAR InSAR subsidence data for sinkhole hazard modeling (Figure 6.1). The Chacahoula Salt Dome to the south of the NSD has one well with corresponding UAVSAR InSAR (Figure 6.2) and the White Castle and Darrow Salt Domes to the north have four wells each with similar data (Figures 6.3 and 6.4). These additional sites, coupled with the conditions on the Napoleonville Salt Dome, provide additional locations with which to refine the decision support model.

Recommendation: Update Cavern Proximity Data

To realize the stated objective of this study and create a decision support framework to analyze geology, topography and mining designs along with subsidence data to better understand sinkhole hazard formation risk, the model must identify caverns with a high potential for collapse with relative accuracy. The size and depth of the Bayou Corne sinkhole and that of
Oxy-Geismar Well 3 are continually changing as suggested by the UAVSAR measurement of ongoing subsidence. However, the cavern boundaries were mapped before the collapse. As the zone of disturbed rock expands around Oxy-Geismar Well 3, the effective boundary of its cavern likely also expands. To enable accurate assessment of surrounding caverns for their potential to collapse, it is necessary to incorporate accurate cavern boundaries into the weighted calculations.

Figure 6.1. Salt Dome Activity near the Bayou Corne Sinkhole (18). Numbers correspond to locations in Figures 2-4. Green = UAVSAR InSAR available, Red = No UAVSAR available (Louisiana Department of Natural Resources, 2015)
Figure 6.2. Chacahoula Salt Dome Activity – UAVSAR exists for northernmost well (Well location at the edge of the UAVSAR collection swath may minimize effectiveness of InSAR subsidence analysis) (Louisiana Department of Natural Resources, 2015)

Figure 6.3. White Castle Salt Dome Activity – UAVSAR data exists for 4 Wells (well location at the edge of the UAVSAR collection swath may minimize effectiveness of InSAR subsidence analysis) (Louisiana Department of Natural Resources, 2015)
Conclusions

Success of the Model

The ability of InSAR to measure surface subsidence, coupled with the available geologic and anthropogenic setting data for the Bayou Corne sinkhole, allowed for the development of a predictive, sinkhole hazard assessment model.

Results suggest that, even without subsidence data, Oxy-Geismar Well 3 could have been identified as a cavern with a high moderate risk of collapse prior to its actual collapse in August 2012. The inclusion of UAVSAR subsidence data increased modeling accuracy and elevated Oxy Gesimar Well 3’s risk of collapse to the highest level. The inclusion of subsidence data in all tested...
models resulted in the identification of Oxy-Geismar Wells 1, 2, 3 and 9 as high or high moderate risk of collapse. All other wells were assigned a moderate or low moderate risk of collapse.

Data Suitability and Potential for Error

As an operational model designed to function within the constraints (e.g. personnel and computing limitations) found in many municipalities, the results are intended to serve as indicators of a potential collapse and allow affected communities to focus further, in depth assessments and monitoring on the suspect wells. Therefore, actual risks of collapse for individual caverns may be different than those modeled, but generalized areas of concern identified on the salt dome should still accurately depict risk trends.

All data incorporated into the model should be available, in some form, for most mined salt domes on the Gulf of Mexico Coastal Plain. In Louisianna and Mississippi, the majority of the data (e.g. cavern attributes, mining activity and well logs for stratigraphy) may be acquired online (http://sonris.com or http://gis.ogb.state.ms.us). Prior to the collapse of the NSD, the most difficult data to acquire would have been accurate salt dome contours. Originally, and only somewhat accurately mapped in 1960, the NSD was not remapped until 2013, after post-collapse investigations commenced. While the accuracy of salt dome contours presents an opportunity for modeling error (e.g. inaccurate assessment of a cavern’s distance from the edge of the salt), problems also arise from the 2-dimensional application of the model when assessing collapse potential on a 3-dimensional salt dome.

Two-dimensional modeling creates the potential for inaccurately predicting the collapse of a well (i.e. false positive or type 1 error) when, in fact, a neighboring well possesses a higher
risk of collapse. A possible type 1 error exists with the identification of Oxy-Geismar Well 1, a cavern that is currently still intact, as possessing the greatest potential for collapse. When the NSD is viewed in 3 dimensions, it appears possible that an expansion of the Oxy-Geismar Well 3 cavern could pose a more significant threat to Oxy-Geismar Well 2 than to Well 1 (Figure 6.5). The similar subteranean elevations of Wells 2 and 3 place the 2 wells in closer actual proximity that of the 2D model. The shallow depth of Well 1 increases its actual distance from Well 3 as compared to the 2D model. The true proximity of Wells 2 and 3, at similar depths, may give Well 2 a higher probability of collapse (due to the influence of continued subsidence at Well 3) than the much more shallow Well 1.

Figure 6.5. Mined Caverns near the Bayou Corne Sinkhole as Viewed Looking North (CB&I, 2013)
The inclusion of subsidence data in all tested models resulted in the identification of Oxy-Geismar Wells 1, 2, 3 and 9 as high or high moderate risk of collapse. All other wells were assigned a moderate or low moderate risk of collapse. The modeling efforts of this study have successfully achieved the stated objective and are ready for operational use for by communities desiring to capitalize on the exploitation of salt domes.


LIST OF APPENDICES
APPENDIX B. MATLAB® SCRIPTS FOR UAVSAR PREPROCESSING
Appendix B. MATLAB® Scripts for UAVSAR Preprocessing (Courtesy of Dr. Cathleen Jones, NASA JPL)

The MATLAB® script was executed by starting MATLAB® and navigating to the directory with the m-file (MATLAB® script file) and the data file(s) (*.int.grd). The script runs on all applicable files within the directory folder. Then the m-file was opened in the MATLAB® editor. Clicking the 'Run' icon caused the script to generate separate phase (*.phs.grd) and amplitude (*.amp.grd) files in the original folder directory. The phase files were selected for header creation.

```matlab
% cpx2realampphase
% handle = 'int_*_looks';
% inhandle = 'int';
handle = '*int.grd';
inhandle = 'int';
outdir = './';
outhandle1 = 'amp';
outhandle2 = 'phs';
nsamp = 25581;
inlist = dir(handle);
if ~isdir(outdir); mkdir(outdir); end;
for ii=1:numel(inlist)
clear cdat rdat idat adat phdat cpxdat
infile=[];
outfile=[];
tmp = char(inlist(ii).name);
infile=cellstr(tmp);
fdat = fopen(infile{1},'r');
if (fdat < 0); fprintf(['Error in opening file ',infile{1},'\n']); break;
end;
fprintf(['infile: ',infile{1},'
'])
cdat = fread(fdat,[2*nsamp,inf],'real*4');
close(fdat);
ntot = size(cdat,1)*size(cdat,2);
rdat = cdat(1:2:ntot);
idat = cdat(2:2:ntot);
rdat = reshape(rdat,nsamp,ntot/nsamp/2);
idat = reshape(idat,nsamp,ntot/nsamp/2);
cpxdat = complex(rdat,idat);
phdat = angle(cpxdat);
adat = abs(cpxdat);
outfile=strcat(outdir,strrep(infile{1},inhandle,outhandle1));
odat = fopen(outfile,'w');
fwrite(odat,adat,'real*4');
close(odat);
outfile=strcat(outdir,strrep(infile{1},inhandle,outhandle2));
odat = fopen(outfile,'w');
fwrite(odat,phdat,'real*4');
close(odat);
end
```

Figure B.1. MATLAB® Script for Phase Extraction
cdat = fread(fdat,[2*nsamp,inf],’real*4’); Reads 2 column x nsamp rows array of 32-bit floating point numbers

handle = ‘*int.grd’; Wildcard name of the input file(s)

inhandle = ‘int’; Part of the output file name

outdir = ‘./’; Output directory - same directory as input in this case - add a path if another directory

OUTHANDLE1 = ’amp’; Part of the amplitude output file name

outhandle2 = ’phs’; Part of the phase output name

nsamp = 25581; Number of data records (rows)

Figure B.2. MATLAB® Code Explained
APPENDIX C. STEPS TO CREATE A HEADER FILE FOR UAVSAR DATA
Appendix C. Steps to Create a Header File for UAVSAR Data (Courtesy of Dr. Cathleen Jones, NASA JPL)

Step 1 - Open Envi

Step 2 - File>Open Image File

Step 3 - Select the .grd file (the one in which a header file needs to be created) from its directory and open it. This header box will open.

Step 4 - Open the corresponding .ann (the one which corresponds to the .grd file). There is one .ann file per three polarizations for each specific flight. The metadata needed to create the header file is located in the .ann file.

Step 5 - We need to fill in Samples, Lines, Bands, and we need to change the Data Type to Floating Point. Leave everything else as the default.

Step 6 - Find the number of pixels per column and row in the .ann file, which corresponds to Samples and Lines, respectively. Make sure to get the number for the grd file and not the SLC,
MLC, or DAT files. In the below picture the two numbers are highlighted. Enter in these numbers to their corresponding areas, Samples and Lines.

Step 7 - Enter in 1 for Bands and leave Offset blank, a zero will be filled in automatically. Change Data Type from Byte to Floating Point. Here is an example.
Step 8 - Click Edit Attributes > Map Info... A new box appears. Here we need to enter in Lat and Long coordinates, as well as X and Y Pixel Size. The Image X and Y coordinate of Tie Point will remain the default of 1.5.
Step 9: Find X and Y Pixel Size in the .ann file, see below. For this project, the X and Y Pixel Size will remain the same, \textbf{0.000055560}. Enter in this number for the X and Y Pixel Size.

\begin{verbatim}
  dat.row.mult         (m/pixel)   = 7.2
; DAT S (azimuth) Slant Post Spacing (cannot be displayed in mdx)
  dat.col.mult         (m/pixel)   = 4.99654098
; DAT C (range) Slant Post Spacing (cannot be displayed in mdx)
  grd_pwr.row.mult (deg/pixel) = -
  0.000055560         ; GRD Latitude Pixel Spacing
  grd_pwr.col.mult (deg/pixel) = -
  0.000055560         ; GRD Longitude Pixel Spacing
  grd_mag.row.mult (deg/pixel) = -
  0.000055560         ; GRD Latitude Pixel Spacing
  grd_mag.col.mult (deg/pixel) = -
  0.000055560         ; GRD Longitude Pixel Spacing
  grd_phase.row.mult (deg/pixel) = -
  0.000055560         ; GRD Latitude Pixel Spacing
  grd_phase.col.mult (deg/pixel) = -
  0.000055560         ; GRD Longitude Pixel Spacing
  hgt.row.mult (deg/pixel) = -
  0.000055560         ; HGT Latitude Pixel Spacing
  hgt.col.mult (deg/pixel) = -
  0.000055560         ; HGT Longitude Pixel Spacing
  slc_mag.val.size (bytes) = 8
; SLC Bytes per pixel in file
  slc_phase.val.size (bytes) = 8
; SLC Bytes per pixel in file
  mlc_pwr.val.size (bytes) = 4
; MLC Bytes per pixel in file
\end{verbatim}
Step 10: Find the Approximate Upper Left Lat and Long coordinates in the .ann file and enter them into their corresponding places, Longitude measuring E and W with Latitude measuring N and S. For this project, Longitude will be negative denoting West and Latitude will be a positive number denoting North. See below for a complete dialogue box.

; post-processing parameters

Number of Range Looks in MLC   (-) = 3
Number of Azimuth Looks in MLC  (-) = 12
Number of Range Looks in GRD   (-) = 3
Number of Azimuth Looks in GRD  (-) = 12
Ground Projection Method   (4) = Nearest Neighbor
DEM Used in Ground Projection (6) = SRTM1 v2
DEM Datum                   (6) = WGS-84
DEM Source                   (6) =
DEM Original Pixel Spacing (arcsec) = 1
Slope Calibration in GRD (6) = No

Approximate Upper Left Latitude (deg) = 30.01178000
Approximate Upper Left Longitude (deg) = 91.97050800
Approximate Upper Right Latitude (deg) = 30.33028200
Approximate Upper Right Longitude (deg) = 91.53262300
Approximate Lower Left Latitude (deg) = 28.75435000
Approximate Lower Left Longitude (deg) = 90.77650500

![Edit Map Information Dialog Box](image_url)
Step11- Hit OK

Step12- Hit OK again

Step13- The file is now loaded into Envi's available bands list. A header file was created in the same folder as the grd file that was opened. You can use this previously created header file to create the other two for the different polarizations. Steps below.

Step14- Open the remaining two .grd files that need a header file by following steps 1-3 above. The header info box will appear as it did in the first case. Instead of entering the information manually, we can use the recently created header file to create these two new header files.

Step15- Select Input Header Info From > Other File.

Step16- A new dialogue box appears in which you can select the recently created header file as your import file. Select it. See below

Step17- Hit OK. The information will be added to the header info dialogue boxes.

Step18- Hit OK again and the file will be loaded into the Envi available bands list.

Step19- Repeat steps 15-18 to complete the header file for the third and final polarization.
APPENDIX D. UAVSAR INTERFEROGRAMS OF THE NAPOLEONVILLE SALT DOME AND CORRESPONDING SUBSIDENCE CONTOURS
Appendix D. UAVSAR Interferograms of the Napoleonville Salt Dome and Corresponding Subsidence Contours

Interferogram* (June 2011 to July 2012) of the Napoleonville Salt Dome

Explanation
- Edge of Salt

Interferogram Jun '11 - Jul '12
Interferometric Phase (radians)
- High : 6.28315
- Low : -2.86079

Subsidence* (April 2014 to October 2014) of the Napoleonville Salt Dome

Explanation
- Surface Deformation Jun '11 - Jul '12
- Edge of Salt

Interferogram Jun '11 - Jul '12
Interferometric Phase (radians)
- High : 6.28315
- Low : -2.86079
Interferogram* (July 2012 to October 2012) of the Napoleonville Salt Dome

* As derived from UAVSAR InSAR data

Subsidence* (July 2012 to October 2012) of the Napoleonville Salt Dome

* As derived from UAVSAR InSAR data

Explanation

Interferogram Jul '12 - Oct '12
Interferometric Phase (radians)

High : 3.19151
Low : -6.28297

Contoured Subsidence* (July 2012 to October 2012) of the Napoleonville Salt Dome

* As derived from UAVSAR InSAR data

Subsidence Jul '12 - Oct '12

High : 3.19151
Low : -6.28297
Interferogram* (October 2012 to April 2013) of the Napoleonville Salt Dome

Explanation
- Edge of Salt
- Interferogram Oct '12 - Apr '13
  - Interferometric Phase (radians)
    - High : 6.28318
    - Low : -3.24277

Subsidence* (October 2012 to April 2013) of the Napoleonville Salt Dome

Explanation
- Subsidence Oct '12 - Apr '13
- Edge of Salt
- Interferogram Oct '12 - Apr '13
  - Interferometric Phase (radians)
    - High : 6.28318
    - Low : -3.24277
Interferogram* (April 2013 to July 2013) of the Napoleonville Salt Dome
* As derived from UAVSAR InSAR data

Subsidence* (April 2013 to July 2013) of the Napoleonville Salt Dome
* As derived from UAVSAR InSAR data
Interferogram* (July 2013 to October 2013) of the Napoleonville Salt Dome

* As derived from UAVSAR InSAR data

Subsidence* (July 2013 to October 2013) of the Napoleonville Salt Dome

* As derived from UAVSAR InSAR data
Interferogram* (October 2013 to April 2014) of the Napoleonville Salt Dome

Explaination

Interferogram Oct '13 - Apr '14
Interferometric Phase (radians)

High : 6.28316
Low : -4.88656

* As derived from UAVSAR InSAR data

Subsidence* (October 2013 to April 2014) of the Napoleonville Salt Dome

Explaination

Subsidence Oct '13 - Apr '14
Edge of Salt

Interferogram Oct '13 - Apr '14
Interferometric Phase (radians)

High : 6.28316
Low : -4.88656

* As derived from UAVSAR InSAR data
Interferogram* (April 2014 to October 2014) of the Napoleonville Salt Dome

* As derived from UAVSAR InSAR data

Explanation

Interferogram Apr '14 - Oct '14
- High : 2.69734
- Low : -6.28317

Subsidence* (April 2014 to October 2014) of the Napoleonville Salt Dome

* As derived from UAVSAR InSAR data

Explanation

Subsidence Apr '14 - Oct '14
- High : 2.69734
- Low : -6.28317
APPENDIX E. SUBSIDENCE ON THE NAPOLEONVILLE SALT DOME FROM APRIL 2011 TO OCTOBER 2014
Appendix E. Subsidence on the Napoleonville Salt Dome from April 2011 to October 2014

Surface Deformation on the Napoleonville Salt Dome (June 2011 to July 2012) as Contoured from UAVSAR InSAR Data

Subsidence on the Napoleonville Salt Dome (June 2011 to October 2012) as Contoured from UAVSAR InSAR Data
Subsidence on the Napoleonville Salt Dome
(June 2011 to April 2013)
as Contoured from UAVSAR InSAR Data

Explanation

- Mined Caverns
- Surface Deformation Jun ’11 - Jul ’12
- Subsidence Jul ’12 - Oct ’12
- Subsidence Oct ’12 - Apr ’13
- Edge of Salt

Subsidence on the Napoleonville Salt Dome
(June 2011 to July 2013)
as Contoured from UAVSAR InSAR Data

Explanation

- Mined Caverns
- Surface Deformation Jun ’11 - Jul ’12
- Subsidence Jul ’12 - Oct ’12
- Subsidence Oct ’12 - Apr ’13
- Subsidence Apr ’13 - Jul ’13
- Edge of Salt
Subsidence on the Napoleonville Salt Dome
as Contoured from UAVSAR InSAR Data

Explanation
- Mined Caverns
- Subsidence Jul '13 - Oct '13
- Surface Deformation Jun '11 - Jul '12
- Subsidence Jul '12 - Oct '12
- Subsidence Oct '12 - Apr '13
- Subsidence Apr '13 - Jul '13
- Edge of Salt

Subsidence on the Napoleonville Salt Dome
(June 2011 to October 2013)
as Contoured from UAVSAR InSAR Data

Subsidence on the Napoleonville Salt Dome
(June 2011 to April 2014)
as Contoured from UAVSAR InSAR Data
Subsidence on the Napoleonville Salt Dome
(June 2011 to October 2014)
as Contoured from UAVSAR InSAR Data
VITA: W. GABE POWELL

Experience

Senior Intelligence Officer (S2)
April 2013 – July 2014

4th Maneuver Enhancement Brigade, 1st Infantry Division Fort Leonard Wood, MO

- S2 for 2600 Soldier Maneuver Enhancement Brigade consisting of two Engineer Battalions (BN), a Military Police BN and a Brigade Support BN with units postured to deploy in support of global/national defense and regionally aligned force requirements
- S2 for 2900 Soldier Brigade Task Force supporting Joint Task Force Civil Support as a deployable Department of Defense Chemical, Biological, Nuclear, Radiological Response Force (DCRF)
- Developed and recommended Commander’s Critical Information Requirements (CCIR)
- Coordinated multi-source intelligence/information analysis that answered CCIR
- Commended for efforts as Brigade S2 at Vibrant Response 2013 DCRF certification exercise
- Advised Commander regarding current intelligence estimate
- Worked closely with BN S2s as the Brigade Physical Security Manager, Security Manager, and Intelligence Oversight Officer
- Oversaw career development of 4 Intelligence Officers and 10 enlisted Intelligence Soldiers

Intelligence, Surveillance, Reconnaissance Collection Manager
December 2008 – November 2012

1st Brigade, 25th Infantry Division Fort Wainwright, AK

- Brigade Intelligence, Surveillance and Reconnaissance (ISR) Collection Manager for a Stryker Brigade Combat Team consisting of three Infantry Battalions, a Field Artillery Battalion, an Armor Squadron, a Brigade Support Battalion, and a Brigade Troops Battalion with over 4,200 Soldiers in a forward deployed environment and a garrison environment postured to deploy in support of Alaska defense, global defense, and regionally aligned force requirements
- Responsible for development of a training plan to enable brigade information collection support for decision making, targeting, and operations planning and execution during deployments
- Developed, reviewed and recommended priority intelligence requirement (PIR) for the Commander. Coordinated collection of multi-source intelligence that answered CCIR
- Developed ISR plan to conduct intelligence preparation of the operational environment (IPOE)
- Provided the Commander with the current enemy situation and updates to the intelligence estimate
- Responsible for property accountability and maintenance as the 184th Military Intelligence Company Executive Officer
Experience (con’t)

**Instructional Assistant: Analytical Statistics and Principles of Government**
August 2007 – May 2009
Texas State University  Department of Political Science  San Marcos, TX
- Peer reviewer for *Armed Forces and Society*
- Tutored, mentored and counseled students concerning performance and potential
- Developed testing materials
- Received training or experience in:
  - Blackboard  > TRACS  > SPSS  > Grant Application Management System (GAMS)

**Satellite Communications Operator/Maintainer**
February 2005 – August 2007
Charlie Company  3rd BDE Special Troops Battalion (82D ABN)  COB Speicher, Iraq
- Designed and implemented 3rd Brigade Satellite Transportable Terminal standard operating procedures for Task Force Lightning, Operation Iraqi Freedom 2006-2008
- Supervised satellite communications hub in support of Hurricanes Katrina and Rita relief efforts
- Special Troops Battalion Noncommissioned Officer of the Quarter
- Maintained serviceability and accountability of over $4 million of US Army Property
- Fielded new Satellite Transportable Terminal communication equipment and trained personnel to deployable status within 2 months of equipment issue
- Unit Movement Officer for Operation Iraqi Freedom 06-08 deployment
- Conducted numerous combat patrols in support of Operation Iraqi Freedom 06-08
- Assisted Military Transition Team (MiTT) to train and develop Iraqi Army assets
- Supervised communications security/counter surveillance measures for multiple MiTT missions and combat patrols

**Graduate Research Assistant**
August 2001 – December 2003
Mississippi State University  Department of Agriculture  Starkville, MS
- Investigated the “Remote Sensing of Soil Physico-Chemical Properties and Their Use in Agricultural and Environmental Applications” (Funded by: NASA’s Stennis Space Center Commercial Remote Sensing Program)
- Designed, conducted, analyzed, and presented scientific research
- Received training or experience in:
  - ArcGIS 8.1  > eCognition  > Viewspec Pro
  - ArcMap  > ERDAS Imagine  > Quatro Pro 10
  - Hyperspectral Signal Analysis Toolkit  > Statistical Analytical Software (SAS)
**Civilian Education**

**Master of Science in Engineering Science - Geology**  
August 2014 – May 2016  
University of Mississippi - Oxford, MS  
- Thesis Title: "Predictive Modeling of Sinkhole Hazards Using Synthetic Aperture Radar Interferometry (NSAR) Subsidence Measurements and Local Geology"  
- Geospatial technology emphasis  
- Taught remote sensing and imagery analysis lab  
- GPA: 4.0

**Master of Public Administration**  
August 2007 – May 2009  
Texas State University - San Marcos, TX  
- Thesis Title: "Identifying Land Use/Land Cover (LULC) Using National Agriculture Imagery Program (NAIP) Data as a Hydrologic Model Input for Local Flood Plain Management"  
- Urban and Environmental Planning Minor: Emergency management emphasis  
- Research cited on Wikipedia and in numerous other publications  
- GPA: 4.0

**Master of Science in Weed Science**  
August 2001 - December 2003  
Mississippi State University - Starkville, MS  
- Research cited in *Weed Science*  
- Research published in Southern and Mississippi Weed Science Society conference proceedings  
- Remote Sensing and Spatial Technology (GIS) emphasis

**Bachelor of Science in Agriculture**  
August 1996 - May 2001  
Tennessee Technological University - Cookeville, TN  
- Environmental Science emphasis

**High School Diploma**  
August 1991 – May 1996  
Cookeville High School - Cookeville, TN

**Military Education**

**Military Intelligence Captains Career Course**  
November 2012 – April 2013  
- Alpha Company 111th Military Intelligence Battalion - Fort Huachuca, AZ  
  - 95% GPA  

**Military Intelligence Officer Basic Course**  
July 2008 – November 2008  
- Charlie Company 111th Military Intelligence Battalion - Fort Huachuca, AZ  
  - 99% GPA (Top in class)

**Modern Army Combatives Program Level I Instructor Certification**  
September 2009
Military Education (con’t)

Anti-Terrorism Officer Level II Certification
December 2010

Defense Intelligence Agency Intelligence Collection Managers Course
April 2010

Satellite Communications Operator/Maintainer Advanced Individual Training
July 2004 – December 2004
Charlie Company 551st Signal Battalion Fort Gordon, GA
- Honor Graduate

Basic Airborne Training
January 2005 – February 2005
Bravo Company 1-507th Parachute Infantry Regiment Fort Benning, GA

Basic Combat Training
April 2004 – June 2004
Alpha Company 1-38th Infantry Regiment Fort Benning, GA
- Distinguished Graduate

Awards
- Featured in USGIF Trajectory article (2014 Issue 4) as a “Future GEOINT Leader”
- Recognized by Pentagon for leading one of the most efficient/effective ISR/Collection Management programs in all of Operation Enduring Freedom (2012)
- National Training Center Outstanding Augmentee Trainer of the Rotation (2014)
- Texas State Brightest Star Achievement Award (2008)
- United States Army Cadet Command Superior Cadet (2007-2008)
- Scottish Rite Scholastic Excellence Award (2008)
- Military Officers Association of America Exceptional Military Leadership Medal (2008)
- United States Army Green to Gold Active Duty Option Scholarship (2007-2009)
- United States Geospatial Intelligence Foundation Graduate Scholarship (2007 & 2014)
- Society of American Military Engineers Scholarship (2007)
- Army Commendation Medal (4 Awards) & Army Achievement Medal (3 Awards)
- 1st Place ROTC Ranger Challenge Patrolling Competition (2008)
- First Place Southern Weed Science Society Poster Contest (2002)
- Full Academic Scholarship - Tennessee Technological University (1996-1997)
- Noncommissioned Officer of the Quarter - 505th Parachute Infantry Regiment, 82nd Airborne Div (2006)
- Noncommissioned Officer of the Month - 505th Parachute Infantry Regiment, 82nd Airborne Div (2006)
Military Training

- Vibrant Response 2013 and numerous other DoD CBRN Response Force training exercises
- Toxic Environment Training – Battle Field CBRN Defense – Fort Leonard Wood, MO
- Numerous DCRF Response training exercises
- National Training Center Deployment Readiness Exercise
- Master Reference Terminal Operator Course
- HMMWV & MTV Driver’s Training
- Joint (Deployment) Readiness Training Center Rotation 06-06
- 3rd BDE, 82D Deployment Certification Exercise
- 2nd BDE, 82D Deployment Certification Exercise
- Numerous Field Training and Switching Exercises
- Ranger Challenge Team (Texas State ROTC Battalion)
- Equal Opportunity Awareness Training
- Risk Management Training
- Technical Transportation of Hazardous Materials

Civilian Training

- Beginning TRACS Workshop
- Student Worker Safety Training Workshop
- Utilizing Handheld Computers and GPS for Field Mapping
- Introduction to Hyperspectral Signal Analysis Toolkit
- Radioactive Materials Laboratory Training
- Risk Management Training Intervention Program (TIPS)
- Hazardous Waste Operations and Emergency Response (not current)
- Black Belt in Zen Bu Do and Okinawan Kempo

Conferences

- Association of Environmental and Engineering Geologists 2015 (Presenter)
- USGIF GEOINT 2015 (Presenter)
- USGIF’s GEOINT 2007 (Attendee)
- Stennis Space Center Collaborator Exposition 2003 (Presenter)
- Southern Weed Science Society 2002 (Attendee), 2003 (Presenter)
- Mississippi Weed Science Society 2003 (Presenter)
- Mississippi Water Resources Research Institute 2003 (Attendee)
- ESRI National Convention Recap 2003 (Attendee)
- Mississippi Weed Science Society Roundtable 2002 (Attendee)
- Kappa Sigma Fraternity Leadership Conference 2001 (Attendee)
- American Society of Agronomy 2000 (Speaker)
Professional Affiliations

- 82nd Airborne Division Association
- American Association of Petroleum Geologists
- Association of the United States Army
- Veterans of Foreign Wars
- American Society for Photogrammetry and Remote Sensing
  > Vice President and charter member - MSU chapter
- Kappa Sigma Fraternity
  > Vice President - Tennessee Technological University Chapter
- United States Geospatial Intelligence Foundation

Publications


- MS Thesis Title (2016): “Predictive Modeling of Sinkhole Hazards Using Synthetic Aperture Radar Interferometry (InSAR) Subsidence Measurements And Local Geology”

- MPA Thesis Title (2009): "Identifying Land Use/Land Cover (LULC) Using National Agriculture Imagery Program (NAIP) Data as a Hydrologic Model Input for Local Flood Plain Management"
Publications (con’t)


- Powell, W.G. (2003). First Place Graduate Student Poster Award. 56th Annual Meeting of the Southern Weed Science Society of America, Houston, TX.


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