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Site Assessment using Echo Sounding, Side Scan Sonar and Sub-bottom Profiling

by

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NUTC
R338

A National University Transportation Center at Missouri University of Science and Technology

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Technical Report Documentation Page

1. Report No. NUTC R338	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Site Assessment using Echo Sounding, Side Scan Sonar and Sub-bottom Profiling		5. Report Date February 2014
		6. Performing Organization Code
7. Author/s Neil Anderson		8. Performing Organization Report No. Project # 00042502
9. Performing Organization Name and Address Center for Transportation Infrastructure and Safety/NUTC program Missouri University of Science and Technology 220 Engineering Research Lab Rolla, MO 65409		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTRT06-G-0014
12. Sponsoring Organization Name and Address U.S. Department of Transportation Research and Innovative Technology Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The primary objective of this research is to use multifaceted geophysical data techniques in order to better map karst terrain beneath standing bodies of water. This study may help providing stronger mapping techniques for future bridge and dam construction projects to utilize. In order to evaluate the foundation of existing infrastructure, primarily bridges and dams, and demonstrate the utility and cost-effectiveness, numbers of geophysical methods will be used to provide detailed subsurface information. These geophysical methods will be used to identify the channel bottom texture (sand, cobbles, riprap, etc.), mapping river beds, locate sediment stratifications, bedrock, locating springs, old river channels, karst terrain (voids or soil-filled solution cavities), fractures, and jointed rock.

17. Key Words Foundations, sonar	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.		
19. Security Classification (of this report) unclassified	20. Security Classification (of this page) unclassified	21. No. Of Pages 42	22. Price

Form DOT F 1700.7 (8-72)

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1. Project Summary

The current research project aims to help add to the existing knowledge of karst terrain beneath standing bodies of water in Missouri. It will utilize an integrated approach of geophysical techniques that incorporates several different mapping methods in order to provide a multifaceted and well-rounded data collection process. Data from different geophysical techniques can then be compared and contrasted in order to provide greater evidence for more accurate assumptions about the nature of the karst terrain under the designated study area. Using echo sounder, side scan sonar, sub-bottom profiling, and electrical resistivity tomography, this study will be able to thoroughly map subsurface terrain.

This research is heavily structured within relatively new techniques. It aims to use the geophysical methods in a more integrated way in order to better provide a model for future imaging and mapping processes for understanding karst terrain beneath standing bodies of water. Researching previous methods and the implications of understanding karst terrain has helped generate strength within this research.

As such, the research also has world-wide impacts on engineering and building practices. It can help establish a solid model for future building projects to use within the building of dams and bridges in known karst terrain. This will ultimately help increase the efficiency of such building projects and help avoid catastrophes of leaks, breaks, and collapses. In addition, in order to drill a horizontal pipe beneath standing bodies of water, it is important to characterize the sub surface layers (clay, sand, or bedrock) and to select the layer which is softer to drill throughout. That allows making the drilling process easier, less cost, and time effectiveness.

2. Project Description

2.1. Research Objectives

The primary objective of this research is to use multifaceted geophysical data techniques in order to better map karst terrain beneath standing bodies of water. This study may help providing stronger mapping techniques for future bridge and dam construction projects to utilize. In order to evaluate the foundation of existing infrastructure, primarily bridges and dams, and demonstrate the utility and cost-effectiveness, numbers of geophysical methods will be used to provide detailed subsurface information. These geophysical methods will be used to identify the channel bottom texture (sand, cobbles, riprap, etc.), mapping river beds, locate sediment stratifications, bedrock, locating springs, old river channels, karst terrain (voids or soil-filled solution cavities), fractures, and jointed rock.

2.2. Significance of Research

Geotechnical evaluation for foundation design for bridges and dams requires understanding of the characterization of the subsurface geological environment. Karst terrain considers a critical issue in Missouri State and also threatens the infrastructures. It is important to monitor the infrastructure below water and evaluate the channel bottom surrounding these items to ensure public safety. In addition, it is important to protect the infrastructure of damage, and keep the natural resource.

This research will significantly provide Missouri of Department of Transportation (MoDOT) a good image of the subsurface beneath the water to avoid any damage for the infrastructure and will provide Missouri Department of Natural Resource useful information of the leakage of water to keep the natural resource. Development of building projects on karst terrain may cause catastrophic collapse. Missouri is a state that is unfortunately familiar with tragedies associated with the destruction of infrastructure systems within its karst terrain regions. In fact, Williams and Vineyard (1976) documented 97 catastrophic collapses in Missouri karst terrain area in the Twentieth Century (Williams & Vineyard, 1976). Often, these collapses have been associated to man-made developments that have cause dewatering, vibration, or dangerous level of water saturation caused by infrastructure development and agricultural practices.

In many instances, these collapses could have been prevented stronger and more efficient method for mapping karst systems (Williams & Vineyard, 1976). As such, it is clear that more innovative technologies need to be implemented in the region to better forecast the presence of karst systems that may lead to a catastrophic collapse within the state of Missouri. It is crucial that “the risks of potential future subsidence must be defined for potential owners so that they can make rational decisions about the amount of risk they are willing to accept” (Urich, 2002). This research aims to provide future contractors and the state of Missouri with much needed information about the subsurface features of karst terrain in the region.

Geophysical methods like (echo sounder, side scan sonar, sub-bottom profiling, and resistivity marine) have several significant geological and geotechnical applications over water. Echo sounder is efficient in showing the depth standing bodies of water, as well as the angles of slopes on the bottom surface, which helps define the nature of the water bottom features (Land & Paull, 2000). This also helps to give some information about what is on the ocean floor as well. Thus, echo sounders can give brief information about the presence of things like pipes or cables. In addition, echo sounders are often used by commercial vessels for navigation purposes (Smith, 2013). They help larger commercial vessels obtain water depths to ensure they do not run into water too shallow to allow for safe passage across oceans and larger lakes.

Side scan sonar can be used to detect objects on the seafloor, making it useful in detecting both depressions and dangerous objects for water navigation, but also man-made objects like pipes and archeological finds. Side scan sonar devices are also used in Acoustic Bottom Classification (ABC), which helps monitor the topography of ocean habitats in order to increase the efficiency of environmental monitoring for benthic habitat mapping (Suthard, Dougherty, & Andrews, 2011). This essentially allows researchers to keep track of habitat changes in some of the ocean's most vulnerable ecosystems, like the reefs in tropical waters. Side-scan sonar devices have also been used to track seismic activity and geological formations along the ocean floor. The GLORIA side scan sonar device uses low frequencies to help collect data for vast areas. Its technology is used by the United States Geological Survey in order to detect images and changes on the continental shelves (United States Geological Survey, 2013). Moreover, it is a technology that has been used in underwater archeological investigations since the 1950s. Side scan sonar devices help archeologists in greater detail and in larger applications, allowing them to detect certain objects of interest underwater in greater detail and accuracy than with other technologies, like echo sounders (Wilson, 2011). The technology is especially useful in conditions with low visibility. Its ability to detect underwater objects also allows it for use in mapping of construction sites as well. It can help assist builders in survey potential build sites, locating any geological or man-made features, like pipes, which would need to be removed before construction can begin.

Sub bottom profiling is often used to detect underground structures and deposits within more shallow waters. This makes sub-bottom profiling a good technology to use within applications for investigation stream and bridge scour, as well as leaking dams. The ability to focus on a great detail in the shallower water helps uncover problem issues with leaking dams and scour activity surrounding bridges and other structures that may cause unpredicted results if not detected upon early. Sub-bottom profilers are often a crucial tool for the mapping of underwater terrain in order to prepare for the construction of large building projects, like dams and bridges (Sea Vision, 2007). Sub-bottom profilers are also often used in detecting seismic activity under the river floor. They help provide a very detailed investigation for how sediment changes can suggest the presence of fault lines and other seismic activity (Savini, 2011). The technology is also efficient at helping map underground surface structures and can detect depressions signifying the presence of karst systems. They are also used to locate pipeline underwater as well as covered objects that lay just beneath the first few layers of sediment.

Resistivity Marine method has proven itself quite useful within archeological investigations in the past as well. The resistivity technology was used to locate buried objects under the soft, sandy seabed, which then alerted archeologists as to where would be the best sites to dig along the stretch of the coast. The fact that resistivity can provide such a detailed description of the changes in sediment materials suggests that it is an efficient method for mapping out depressions within karst systems (McGrath et al., 2002). This can also be used to detect the presence of fault systems, as the electrical charges would be able to detect the voids within a fault structure based on the resistivity changes of the sediments present both around and in the fault itself. Resistivity is also a method for locating underwater subsurface systems, like karst systems. The technology can help uncover clear changes within the resistivity of the sediment, which can then be calculated in order to make assumptions about the size and depth of these underground structures.

2.3. Present State of Knowledge

Previous research has illustrated the need for integrated approaches at mapping karst systems. This helps make mapping of geophysical techniques more efficient because they can be double checked with other data collection methods. This current research aims to test a new and highly integrated combination of geophysical techniques in order to provide the best potential model for karst terrain that is needed for modern development in karst terrain areas in Missouri and elsewhere.

3. Literature Review

3.1. Background

Karst terrains are natural topographies that are created by weather and other erosion sources underneath the ground or underneath the bottom of standing bodies of water (Figure 1). They are often formed in limestone, gypsum, and other rocks where the bed rock has been eroded into a variety of sinkholes, caves, and underground fissures. Within these underground structures, "weathering is concentrated along joints and bedding planes of the limestone, producing a number of different sculptured features from the effects of solution" (Thorpe & Thorpe, 2011).

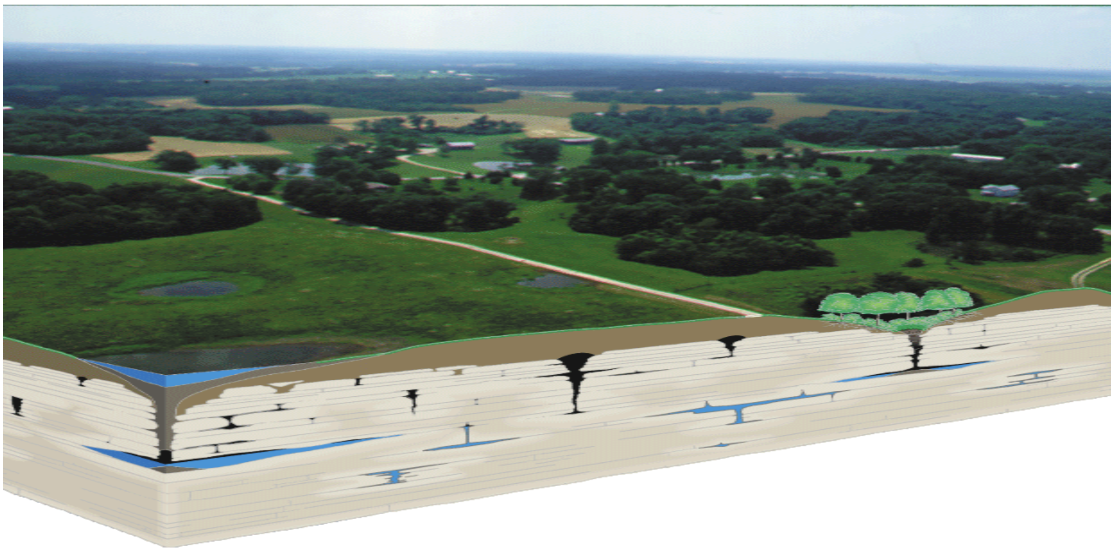


Figure 1: A slice through Karst in southwestern Illinois (ILLINOIS STATE GEOLOGICAL SURVEY).

As such, voids, depressions, and pockets are created underground that can have huge complications for building an infrastructure programs and projects above the surface. In karst terrain regions, "normal groundwater modeling methods are difficult to apply to missing problems in a karst aquifer due to the heterogeneity of system since flow in the conduits does not obey Darcy's law" (Lee & Krother, 2001). Darcy's Law helps explain the natural movement of water through any sort of porous medium through an equation that correlates the two. The rate of water discharge through the medium is determined how thick the liquid's viscosity is in relation to the pressure drop.

Missouri is a state with a rich karst system network. Perry County alone holds the Central Perryville Karst and Mystery Rimstone Karst with hundreds of km in mapped passages (Burr et al., 2001). In fact, the karst system in Perry County actually has its own unique environment with grotto scalping living in the underground cave systems (Burr et al., 2001). It is also important to understand whether or not a karst system serves as an underwater conduit, especially in regards to dam building, as conduits can drain water reservoirs.

3.2. Karst Systems and Human Development: Potentially Disastrous Implications

Building and construction projects can be in danger when working on karst terrain that is littered with sinkholes and caves. This goes for building projects both on land and above standing bodies of water. For example, bridges are difficult to build and maintain when on complex karst terrain regions. Karst terrains create a situation where the bridge piers are unstable (figure 2). The foundations of the bridges can be subjected to sinkhole collapse (Xeidakis et al., 2004).

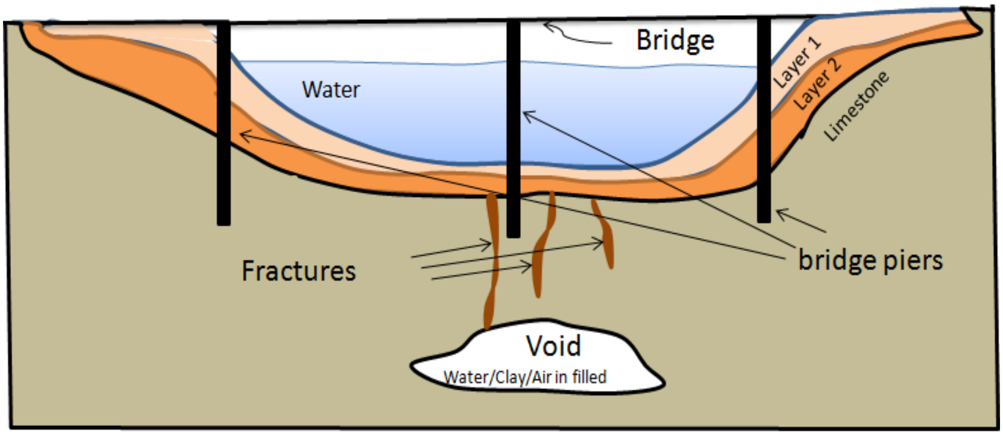


Figure 2: A sketch of bedrock fractures that may make the bridge piers unstable.

Dams are also vulnerable to the impacts of karst terrains. Building on karst terrain is difficult for any type of projects, yet the building of dams proves even more problematic. Essentially, working with considerable structural loads is very dangerous on karst terrain. Most dams are between 100 m and 200 m high, and require tons of material to hold back the forces of the water. Since dams require enormous weight in building materials in concrete, they do not fare well when built on karst terrain land (Ford & Williams, 1994). Dams built on karst terrains often witness leaks in the foundations and abutments. Fissures and underground structures serving as conduits for the movement of groundwater can cause serious engineering complications for dam projects (Davies, 2012). Here, the research suggests that “caves and fissures give rise to serious problems in foundations and abutments of dams with reservoir tightness, stability of bridge piers, and stability of cut slopes” (Davies, 2012). Dam sites built on karst terrain are also often affected by water loss from the reservoir (Xeidakis et al., 2004). Water is funneled out of reservoirs through the underground system of fissures and caves which act as conduits. One tragic example of a dam project gone awry because of karst complications was the Hales Bar Dam in Tennessee in the 1940s. The builders knew the area was on karst terrain, and so went forth to fill in the bulk of the subsurface voids underneath the planned project. The time table and budget of the project had to be extended dramatically, and ended up taking eight years and 11.5 million dollars (Ford & Williams, 1994). Still, even after extensive filling, leaks continued to plague construction of the dam. There can also be problems associated with not only dams built on karst terrain, but even near it.

Lateral leakage can be seen in dams built in areas where karst terrain is just upstream (Ford & Williams, 1994).

Building dams on karst terrain requires a lot of pre-planning and extra effort. Builders have to spend time and money filling in the larger subsurface voids with concrete or by using extremely long foundation posts that dig deep beneath the karst terrain under the top layers of sediment (Xeidakis et al., 2004). It requires much more effort than traditional building projects. As the research suggests," if the dam sites with limestone or dolomite must be used, the preferred location will be where there is a simple geological structure, the least karst development and fissure frequency, and where there are shales or some other aquiclude strata at shallow depth so that a grout curtain can be extended to them economically" (Ford & Williams, 1994). Thus, it is crucial for contractors to understand the nature of the terrain before even starting on planning dams and bridge projects.

Karst systems can have a detrimental impact on any type of building project (Urich, 2002). As such, the United States has conducted unprecedented research on the nature of how urban developing can be impacted by subsurface karst terrains to deal with how to develop karst terrain. There are entire towns and cities which reside on top of complex karst terrains, where sinkhole flooding is just a natural part of the hydrologic ecosystem, as seen in the case of Bowling Green, Kansas (Urich, 2002). In cities and regions with these subsurface karst terrains, it is difficult to avoid potentially contaminating the groundwater with the urban pollutants that come from above. In Bowling Green, Kansas, the city is helpless to defend the complex underground karst terrain from being tainted by pollutants which then filter into the groundwater source. This gets even more difficult in situations of large storms or flash flooding, where rain water runs through the streets and fields, picking up urban and agricultural pollutants as it continues to then funnel deep into the underground sinkholes and cave systems of the karst subsurface structure (Urich, 2002). Additionally, the filling of sinkholes to facilitate urban development can also prove problematic, even for the larger karst terrains. According to the research, "sinkholes were filled by developers and homeowners, and runoff was directed into adjacent sinks which were unable to handle the increased discharge" (Urich, 2002). This often leads to situations where the overflowing sinkholes collapse and can have huge detrimental impacts on urban landscapes and increase flooding in neighborhoods.

A number of other man-made development projects are also at risk if located on top of a karst structure. A previous site here in Missouri was created within a mature dolomite karst terrain. Unfortunately, the site had numerous sinkholes and cave systems, which made any future work within the landfill dangerous, as it might have leaked into other ground water sources from the karst terrain underneath (Urich, 2002). A thorough investigation was conducted in order to determine just how large the karst terrain was and to see if any of its features were working as a conduit for water, in which case would have increased the potential for the landfill material above to leak into the groundwater. This investigation used "fracture traces analysis, natural potential and resistivity surveys, and regional potentiometric data analysis" (Urich, 2002). From this incredibly integrated approach, it was determined that water under the surface was being channeled through the karst terrain, which made any future use of the landfill dangerous. The area still has to be monitored in regards to groundwater pollution and potential sinkhole collapses (Urich, 2002). Without the use of integrated and multifaceted techniques to map the true size and nature of the karst terrain in this instance, the situation might have become direr, with greater potential risk of the landfill caving in from sinkholes, or pollutants being seeped into the groundwater over an extended period of time.

There are also agricultural implications for karst systems found under or around farming regions. The pollutants from agriculture can easily permeate into underground karst systems. Surface run off from farms can inject pesticides and animal waste into valuable groundwater resources (Urich, 2002). As such, “livestock exclusion is one practice of keeping animals away from water bodies and areas subject to erosion. In karst, sinkholes and cave entrance should be declares off-limits” (Urich, 2002). It is important for agricultural land owners and developers to utilize efficient karst mapping techniques in order to ensure that the pollutants from agricultural use is not sinking deep into groundwater systems. Unfortunately, “sinkholes, a prominent feature of karst terrain, allow sediments and chemicals to be directly injected into the groundwater without the filtration associated with non-karst regions” (Burr et al., 2001). Thus, the state of Missouri needs to be aware of karst terrains in order to help avoid polluting groundwater.

Faults and other seismic activity underneath bodies of water can cause a real danger for a foundation of bridges and dams. However, it can be a reason of leaking dams or bridges failure (Figure 3).

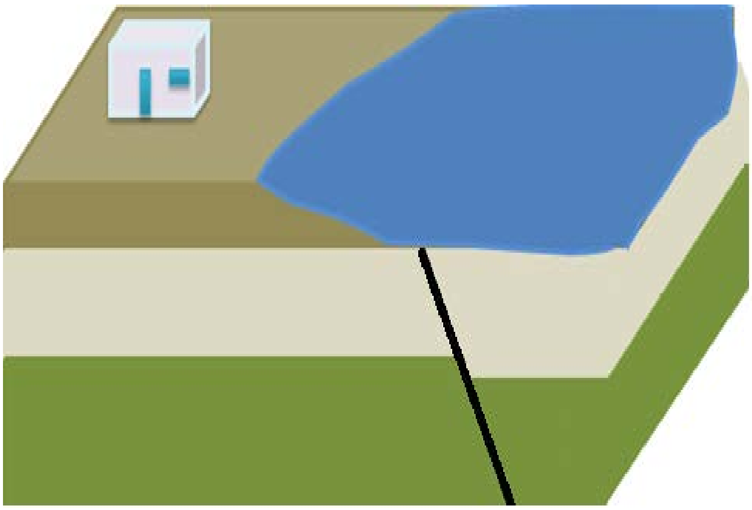
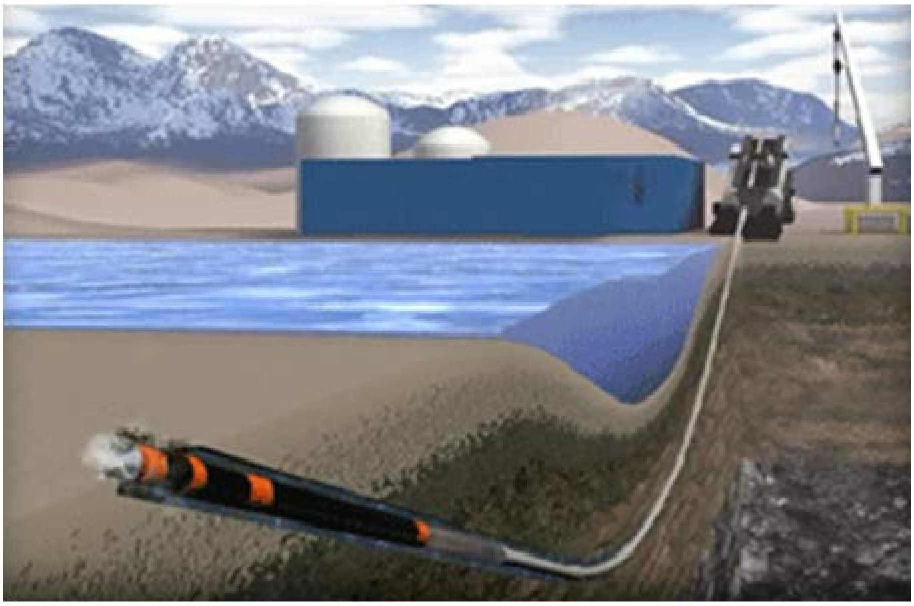


Figure 3: A sketch of fault system underneath the bodies of water.

Scour surrounding the foundation bridges is another reason of bridge failure. The scour occurs during the flood when the flow water removes sediment beds around the foundation. "In the United States, approximately 95% of failed highway bridges constructed over waterways have been related to scour around the bridge piers" (Wightman et al., 2003).

Vertical and horizontal drilling underneath bodies of water demands understanding of the subsurface. In the vertical drilling, borehole core and riverbed sediments samples are not good choices to characterize the subsurface, due to the high cost and the time consuming. In addition, these traditional methods do not give an accurate image of the variation of riverbed sediments. In horizontal drilling, drilling without knowledge about the subsurface is critical issue. That may cause problems for the drillers when they face the hard rocks like damage the equipment. Therefore, using the geophysical methods help to determine the best location to drill. That may reduce the cost and the time.



http://www.groundeffectsdirectionaldrilling.com/directionaldrilling.htm

Figure 4: Ground effects directional drilling.

3.3. The Need for Integrated and Efficient Mapping of Geophysical Techniques

There is evidence illustrating how integrated models of geophysical methods are best for mapping potentially dangerous karst areas. McGrath et al. (2002) used microgravity, along with electrical resistivity tomography techniques to efficiently map out the details of two karst systems in Europe.

Essentially, the more multifaceted approach helps better map such complicated geophysical structures underground. Using integrated approaches allows for a better understanding, because one method may help fill in the gaps presented by another. McGrath et al. (2002) suggest that “integrated geophysical methods provide an alternative to grid (or random) drilling for the detection and mapping of subsurface karst topography”. Using such multifaceted techniques helps allow researchers to avoid the pitfalls of random drilling. The more techniques used, the more detailed the research can get in regards to specifying the exact location of the karst terrain and to develop the data explaining its core elements and measurements. As the researchers increase the number of methods used for mapping purposes the accuracy of readings also improves. Integrated approaches often prove essential in working with complicated karst terrains as well. It is clear that “multiple traverses with closely spaced gravity stations, i.e. grids, result in useful spatial redundancy and improved data accuracy, which can be used to separate the anomalies caused by an ensemble of cavities from geological or topographical background noise and permit the utilization of inversion techniques" (McGrath et al., 2002). Some of the more traditional techniques cannot tell all the information needed to properly understand the nature of karst terrain technology.

Kruse et al. (2006) conducted a study in Florida to test the usefulness of ground penetrating radar in clay-rich environments, but also in order to test the methods efficiency in imaging individual fractures and conduits that were actually far deeper below the primary depression that was already recognized by prior research. Ground penetrating radar (GPR) is an excellent technique for mapping sinkholes in karst terrain. However, it is often inefficient at being able to determine whether or not the sinkhole is a strong conduit for underground water flow. As such, higher-resolution imaging is often needed in tandem with ground penetrating radar techniques. As such, it is clear that there needs to be a more multifaceted approach to mapping karst terrain in order to truly understand the specific details of the karst terrains beneath the surface level. To make up for any potential limitations, Kruse et al. (2006) used ground penetrating radar in conjunction with resistivity methods. With this more integrated approach, researchers were better able to model and map not only the main deposit, but also the various smaller conduits underneath and surrounding it within the larger karst terrain.

Nitsche et al. (2004) used side scan sonar, sub-bottom profiling, and high-resolution bathymetry with several gravity cores and grab samples to obtain more information of sedimentary environments in subaqueous settings from the Haverstraw Bay section of the Hudson River Estuary. The grain size composition of the sediments can be distinguished by using the differences in acoustic backscatter strength. The result of the interpretation of the three acoustic methods reveals the differences in bottom roughness and sediment compaction which are caused by the spatial variations in the modern dispositional environments. Moreover, eight different sedimentary classes were distinguished from the acoustic methods and sample data sets. In addition, the results of this study give a good understanding of the dynamic processes including contemporary deposition, erosion, and sediment migration in sand waves for of the Hudson River Estuary all of this processes can link to many of the classes. This study also gives the improvements of the acoustic backscatter data interpretation from fine grained sedimentary environments.

Rollet et al. (2007) used four acoustic methods (new sub-bottom profiler, multibeam bathymetry, side-scan sonar, and echo-sounder) in the northern Arafura Sea, offshore Northern Australia to identify the shallow gas and fluid migration under the sea floor. In this study, geochemical analyses of sampled sediments were taken. However, new geological data and a seismic stratigraphy were obtained for the youngest units in the Money Shoal Basin. The combination of methods helped increase the accuracy of mapping methods.

Clearly, using geophysical techniques to facilitate smarter urban development that works in tandem with natural karst terrains proves incredibly beneficial for the homeowners and residents living on top of such subsurface systems. Efficient mapping of geophysical techniques can save thousands of dollars in damage and even prevent injuries and deaths. Working with a number of techniques can help prevent catastrophes. In order to find more success in groundwater modeling, prior research has asserted that mapping techniques are "necessary to understand the geochemical evolution of mixing water in these karst settings" (Lee & Krother, 2001).

3.4. Conventional Approaches to Working in Water

Some unusual hazards may happen when a person works over water includes (rivers, streams, lakes, seas). As a result, several precautions must be taken during working on water where a fall into water may happen and sinking. Some instructions should be provided for the people who will work over water:

1) Getting a license for driving the boat.
2) Follow the speed limit inside the water.
3) Wearing a life jacket, and avoid wearing heavy clothing which will increase the weight for the person that makes the ability to swim impossible.
4) Keep electrical cable away from water that may damage the geophysical equipment.
5) Avoid working in very shallower water where the boat cannot pass safely.

4. Methodology

4.1. Introduction

Each geophysical method measures either direct or not direct one or more of the physical properties of the earth materials. The physical properties like (conductivity, electrical resistivity, seismic velocity, and density) of the earth materials differ from rock to rock or even at the same type of rock, due to several parameters like (moisture, salinity, clay content, lithology, and temperature) (Figure 5 & Table 1). For instance, the differences of the resistivity and seismic velocity values between dry and saturated sand can be notice.

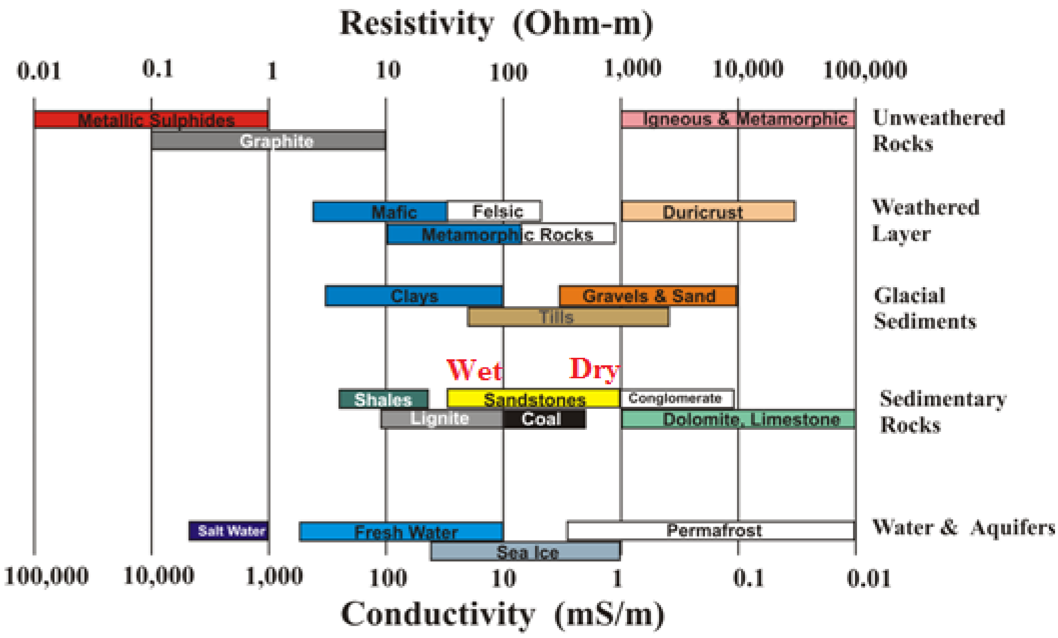


Figure 5: Typical ranges of electrical resistivity (ohm-m) or conductivity (mS/m) for selected Earth materials (Palacky 1988).

Table 1. Typical values (averages and/or approximate ranges) of elastic constants, density, Poisson's ratio and seismic wave velocities for some selected materials, unconsolidated sediments, sedimentary rocks of different geologic age and igneous/plutonic rocks. (compiled from Hellwege, 1982; Castagna et al., 1985; Lillie, 1999; and Wikepedia).

Material or Geologic Formation	Bulk Modulus in 10^9 Pa	Shear Modulus in 10^9 Pa	Density in kg m^{-3}	Poisson Ratio	v_p in km s^{-1}	v_s in km s^{-1}	v_p/v_s
Air	0.0001	0	1.0	0.5	0.32	0	∞
Water	2.2	0	1000	0.5	1.5	0	∞
Ice	3.0	4.9	920	-0.034	3.2	2.3	1.39
Clastic sedimentary rocks					(1.4-5.3)		
Sandstone	24	17	2500	0.21	4.3	2.6	1.65
Salt	24	18	2200	0.17	4.6 (3.8-5.2)	2.9	1.59
Limestone	38	22	2700	0.19	4.7 (2.9-5.6)	2.9	1.62
Granite	56 (47-69)	34 (30-37)	2610 (2340-2670)	0.25 (0.20-0.31)	6.2 (5.8-6.4)	3.6 (3.4-3.7)	1.73 (1.65-1.91)
Basalt	71 (64-80)	38 (33-41)	2940 (2850-3050)	0.28 (0.26-0.29)	6.4 (6.1-6.7)	3.6 (3.4-3.7)	1.80 (1.76-1.82)
Peridotite, Dunit, Pyroxenite	128 (113-141)	63 (52–72)	3300 (3190-3365)	0.29 (0.26-0.29)	8.0 (7.5–8.4)	4.4 (4.0–4.7)	1.8 (1.76-1.91)
Metamorphic& igneous rocks					(3.8-6.4)		
Ultramafic rocks					(7.2-8.7)		
Cenozoic			1500-2100	0.38-<0.5	(0.2-1.9)		2.3 - 8
Cenozoic water saturated			1950	0.48	1.7	0.34	5
Cretaceous & Jurassic			2400-2500	0.28-0.43			1.8 – 2.8
Triassic			2500-2700	0.28-0.40			1.8 – 2.5
Upper Permian			2000-2900	0.23-0.31			1.7 – 1.9
Carboniferous				0.31-0.35			1.9 – 2.1

4.2. Acoustic Methods

Since the current research is going to work within areas of land with standing bodies of water, it is important to use underwater measurement techniques. Many of these techniques utilize sound waves as a way to measure and map the bottom surface of bodies of water. (Figure 6) acoustic energy moves through water as compressional waves (the velocity of shear wave in water equals zero), where the speed of the sound is affected by the conditions of the water and anything else it comes in contact with, like the structures on the bottom surface (Vaduva, 2000). Such conditions can impact the amplitude of the traveling sound wave. The distance between the pressure fronts on the wavelength can help to get information about depth, distance, and size of objects under water.

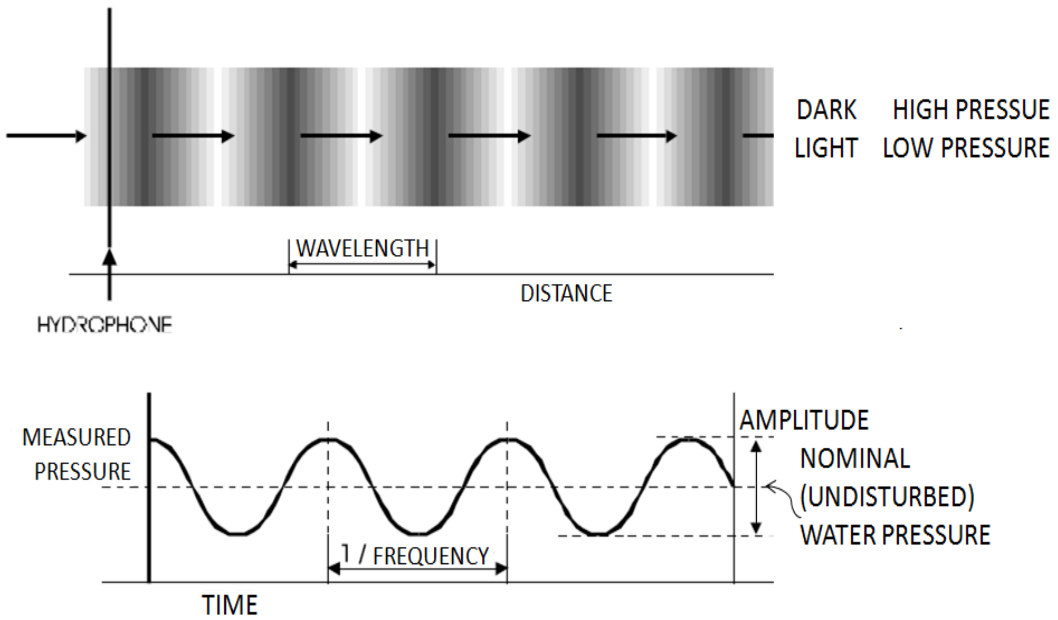


Figure 6: Components of a Sound Wave (Vaduva, 2000).

Acoustic energy measurements have long been used by researchers and scientists to map the floors of lakes, rivers, and oceans. Many of these techniques use techniques of measuring the echo of a sound in comparison of when and where that sound was first admitted (Figure 7). Vaduva (2000) states that “the sound energy is reflected back as an echo to a receiver system and the lapse in travel time from transmission to reception is converted into ranges” which can be manipulated to present a map image of the underlying surface layers. The changes in the wavelength of acoustic energy can thus be used by this current research to help map variations of subsurface components within karst terrain systems. Some of the acoustic waves are absorbed into new material it incidents, while some of these acoustic waves reflect, depending on the exact angle of incidence and an acoustic impedance of the interface. This process generates an echo, which can then be used by sonar devices to determine information about such underwater objects, like size and distance. The reflections can then be picked up by acoustical geophysical devices (Figure 8), like an echo sounder, side-scan sonar device, or sub-bottom profiler (Savini, 2011).

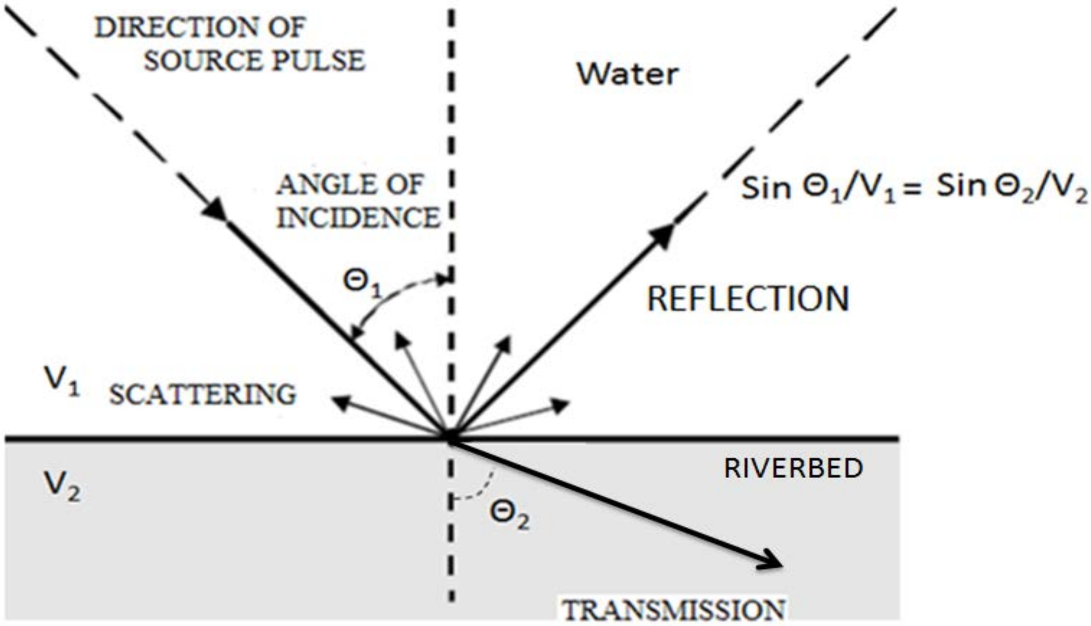


Figure 7: Components of an Echo Event on the Ocean Floor (Modified after Vaduva, 2000).

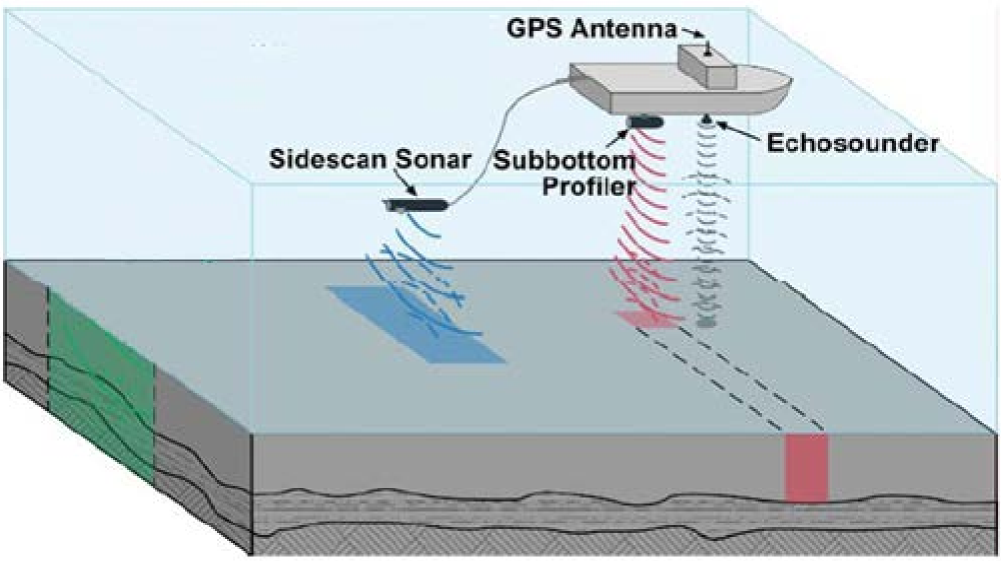


Figure 8: Acoustical geophysical methods for over-water surveys. (Modified after Savini, 2011).

It is important to consider that the penetration depth of acoustic energy depends on its frequency. Generally, Low frequency wave has a longer wavelenght that can provide a greater depth and a lower resolution than high frequency wave. In addition, the depth of the pentration can be determined by the type of the earth materials. For instance, the penetration of 3.5 KHz transducer in soft materials like clays and silts may exceed 100 meeter. On the other hand, compact sands and gravel tills may attenuate the signal and reuduce the depth of penetration.

The amount of reflected acoustic energy which is known as the reflection coefficient between two layers depends on the acoustic impedance for these layers. The acoustic impedance is defined as the multiple of velocity and density of the layers above and below the interface (Table 2).

$$Z= PV$$

Where:

Z = acoustic impedance (g/m^2s),
r = density of the material (g/m^3), and
V = velocity of sound through the material (m/s).

The amplitude refers to the maximum displacement of a periodic wave, or simply the height of a wave. From (Table 2), it can be seen that the high amplitude reflection may occur between water/limestone interfaces. The reflection coefficient can be calculated by using the below equation:

$$R= Z2-Z1/Z2+Z1=Ar/Ai$$

Where:

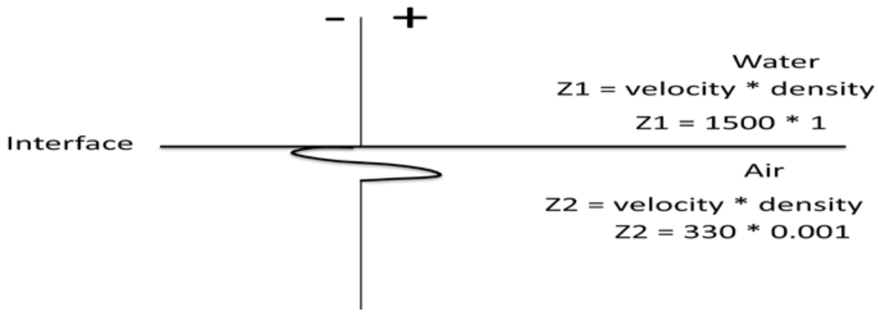
R = reflection coefficient for this interface,
Z_1, Z_2 = acoustic impedance of material above and below the interface, and
A_r, A_i = amplitude of the reflected and incident waves at the interface.

Table 2. Typical reflection coefficients [Modified from Sylwester, 1983]

Material	Reflection Coefficient
Water/Air	- 1.0
Water/Limestone	0.5
Water/Sand	0.3-0.4
Water/Clay or Silt	0.1-0.2
Water/Mud	0.05-0.1
Mud/Clay or silt	0.1
Clay/Sand	0.1
Sand/Limestone	0.2
Clay/Limestone	0.3
Sand/Granite	0.4

(Figure 9) is an example of the reflection coefficient between water/Air. By applying the previous reflection coefficient equation for the interface:

$$R= 0.33-1500/0.33+1500 =1499.67/1500.33 = -1$$



Figuer 9: The reflection coefficient of the interface between water/Air is -1.0.

Table 3. Comparison of Acoustic Tools

Source	Frequency (KHz)	Vertical Resolution	Penetration through riverbed (meter)
Side Scan Sonar	455 and 800	n/a	0
Echo Sounder	Broadband 83/200 Down scan 455/800	n/a	0 to few meter
Sub bottom Profiler	10	6 cm	40
Sub bottom Profiler	3.5	8 cm	<100

4.2.1. Echo Sounder

The first method to be used in this study is the echo sounder uses a high frequency ranges, also known as a fathomer method. It was originally developed at the turn of the Twentieth Century for use by the military in marine environments (Thorpe & Thorpe, 2011). Sound pulses are transmitted into the underground karst system, working with frequencies between 24 kHz and 340 kHz (Vaduva, 2000). By measuring the intervals between the sound emitted and returning echo, the tool can help provide the depth of the system and any major features that lie beneath the surface (Figure 10). Echo sounder "signals could be used to calculate transmissivity and permeability estimators" which can be used "to map and to draw a cross section of the case study site, which underline accurately the known karst conduit location and depth" (Vouillamoz, 2003). Echo Sounders often use a single beam to map the hydrographic elements of the bottoms of lakes, rivers, and oceans (Savini, 2011). As such, they are extremely accurate.

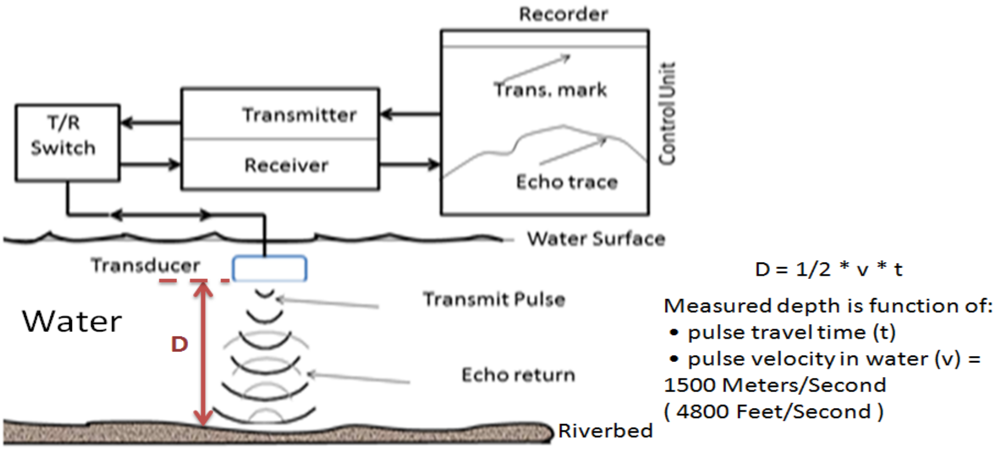


Figure 10: shows basic Echo Sounder Operation (Modified after Mueller & Landers, 1999).

They are particularly useful for this current research because they can show the depth and slop of the interior walls of karst systems (Land & Paull, 2000). Echo sounders have been used to map locations for oil prospecting, thus illustrating how they can be useful in working to map underground voids in karst terrain. They have been used successfully in previous research focusing on similar goals.

However, there are some limitations that would require a fathomer to be used in conjunction with another technology. It can only collect data from its immediate path, and is thus limited to the size and area it can map (Vaduva, 2000). Thus, research working with echo sounders alone would take much longer to cover a single area when compared to other technologies. As such, this current research will use a fathomer in conjunction with other measuring devices. Another limitation of echo sounders is that the system will not be able to measure the depths of water that are less than about 1 m.

4.2.2. Side Scan Sonar

A different sonar device that emits two identical beams that goes in opposite directions (Figure 11). This creates images of larger areas through emitting a cone-like pulse downwards. The pulse crosses over the bottom surface area at a wide angle. The method uses a “torpedo like tow fish” which can be dragged through the water (Nueman, 2013). The projectile scans the bottom surface area to generate pixels which can be transferred into a mapping image (Kvitek et al., 1999). Different very high frequencies between 200 KHz to 800 KHz can be used to image and provide a high resolution of the topography of the lakebed at different depths.

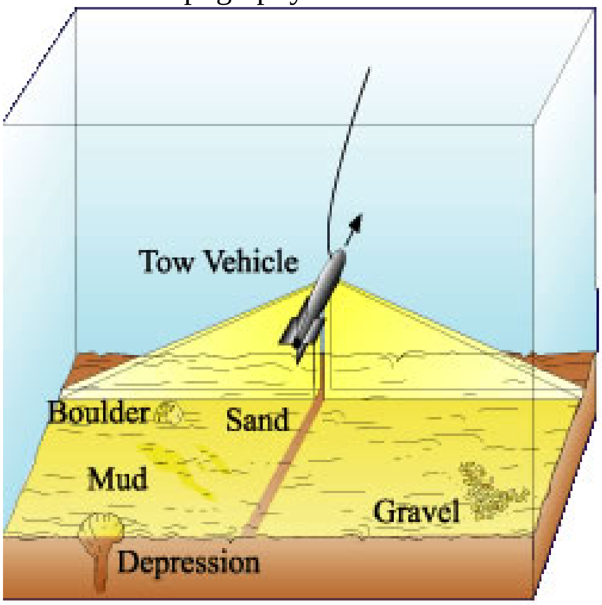


Figure 11: shows side scan sonar (Kvitek et al., 1999).

This is a highly effective imaging and mapping device that is now becoming much more widely available thanks to lowered costs associated with developing and using the technology (Nueman, 2013). According to the research, “the side-scan sonar provides an image (*sonograph*) from which an understanding of the nature of materials on the seafloor can be drawn” (Savini, 2011). Modern side scan sonar devices are much easier to use than previous generations of the technology, and are widely available to the public and researchers alike (Nueman, 2013). Another major benefit is that “sidescan sonar is the only technology capable of producing continuous coverage imagery of the seafloor surface at all depths” (Kvitek et al., 1999). Thus, it is a valuable tool for creating accurate images of the karst terrain systems underneath standing bodies of water.

4.2.3. Sub Bottom Profiling

Again, this method employs the use of sonar technology. It “draws upon the use of low frequency echo sounders that operate between 1 kHz and 20 kHz to penetrate into bottom sediments with the goal of developing high resolution subsurface imagery” (Sea Vision, 2007). In other words, the important advantage of using a low frequency echo sounder is to get a greater penetration depth of sediments underneath the lakebed. Again, sub-bottom profiling uses SONAR to create images of shallow subsurface structures beneath bodies of water, typically less than 100 meters in depth. As such, it can be utilized for the more shallow sections of the lake to be mapped in the context of this research. Previous studies have concluded that “in contrast to simple echo sounders that use acoustic energy reflected off the bottom to measure the depth, sub bottom profilers provide a record of acoustic energy reflected by layers beneath the seafloor” or other surfaces (Caress, 2010). Sub-bottom profiling uses lower frequencies, 1 kHz to 20 kHz frequencies, in order to allow the SONAR beams to penetrate (Figure 12). Modern sub-bottom profilers use sweep frequencies, also known as chirps, to transmit the pulses of energy across the bottom. Chirp sonars produce higher resolution images through the use of “match filtering (cross correlation) of the raw data with the source pulse” (Caress, 2010). These technologies are often “used for examining the high resolution sismostratigraphy of the seabed for better interpreting sedimentary processes acting upon the seafloor” (Savini, 2011). There are a number of benefits sub-bottom profiling has above other techniques. It works with larger areas at greater accuracy levels (Sea Vision, 2007). Most devices also have special software that allows raw data to be filtered to produce high resolution images, which can also be manipulated to focus on particular objects of interest (Sea Vision, 2007). It is a proven method for mapping terrain in preparation for bridge and dam building projects (Sea Vision, 2007). Yet, it too has some limitations, mainly acoustic interference because of the wide scope of the beam (Sea Vision, 2007). Its limit on depth is also a reason why it should not be used as a sole technique in most lakes.

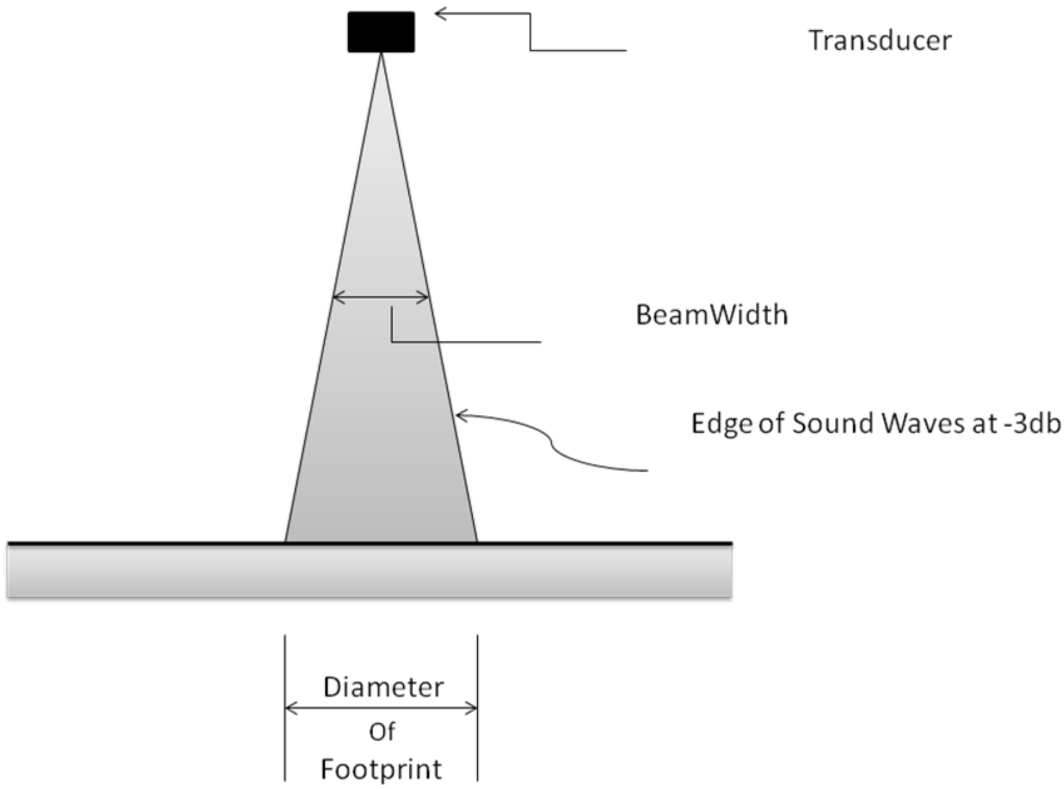


Figure 12: Illustrates the transducer beamwidth (Modified after Mueller & Landers, 1999).

The profiling beam pattern for 3.5 KHz and 10 KHz is unique and especially useful in a number of contexts. Lower frequencies have higher amplitudes when shot at smaller angles (Wunderlich & Wendt, 2004). At 3.5 KHz, there is a vertical beam pattern that sits rotationally around a symmetrical transducer axis. This allows for a wider breadth of surface to be detected by the beam, increasing the breadth of surface covered by a single transmission (figure 12).

As the frequency increases, the pulse width also changes. For example, at 8 KHz, the pulse width is at about 0.13 ms. At 10 KHz, the pulse width is at about 0.2 ms. 10 KHz frequency can be used at very shallow depths, even less than 5 meters and still have incredibly accurate sediment penetration because of their more concentrated beam patterns compared to 3.5 KHz beams. Lower frequencies tend to be able to penetrate into a greater depth of the sediment.

There are a number of benefits sub-bottom profiling has above other techniques. It works with larger areas at greater accuracy levels (Sea Vision, 2007). Most devices also have special software that allows raw data to be filtered to produce high resolution images, which can also be manipulated to focus on particular objects of interest (Sea Vision, 2007). It is a proven method for mapping terrain in preparation for bridge and dam building projects (Sea Vision, 2007).

4.3. Electrical Resistivity Tomography Method

This is a technique that does not rely on acoustic energy, but rather electrical current. According to the research, “resistivity profiling or imaging is a method for investigating the subsurface by measuring the capacity of earth materials to pass electrical current” (Frontier Geosciences, 2001). It provides information about soil and sediment type, along with uncovering the presence of any depressions or voids within the soil (Figure 13).

Electrical resistivity tomography is a traditional method that is often employed on dry land. Such a technique “utilizes measurements obtained on the ground surface to determine physical properties of subsurface materials” (Wei, 2011). ERT uses electrical charges to measure the nature and strength the current travels through various types of surfaces. Differing composition, pore space, and fluidity of substances will all show different current measurements. Probes are planted into the top layers of the ground with the spacing of the pairs of probes can impact the size and degree of the area being mapped. Here, Wei (2011) suggests that “most modern resistivity arrays combine lateral profiling with vertical soundings to generate a two-dimensional cross-section of resistivity information.” This will prove useful for the 2D images this research is aiming to compile. It is often used in urban areas to locate sinkholes beneath residences and commercial buildings (Wei, 2013).

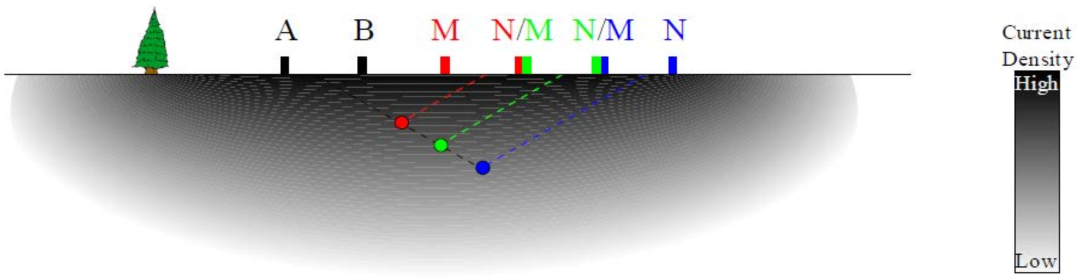


Figure 13: Multi-electrode dipole-dipole resistivity array (Frontier Geosciences, 2001).

Recent developments in the technologies driving electrical resistivity tomography have improved dramatically over the past several decades. In fact, these new innovations have increased the efficiency of most systems, and most commercially available systems are incredibly reliable (McGrath et al., 2002). Many of these new commercially available systems also have innovative and sophisticated mapping systems that use “inversion algorithms to produce electrical images that accurately model 2D and 3D sub-surfaces,” making analysis of ground tomography results much easier than when utilizing older, more traditional methods of gathering field data (McGrath et al., 2002). Unfortunately, most rocks and earth materials are poor conductors of electricity. As such, “the resolution of resistivity data decreases with depth because of the number of measured points decreasing with depth as a function of electrode spacing and electrode configuration” (McGrath et al., 2002). Moreover, when the nature of the rock changes the readings possible from within different porous materials in the earth also change. This is often the level of change needed to detect voids within rock materials in karst systems.

Marine resistivity testing takes these same principles and applies them to resistivity testing under water, which will be useful for this current research. Electrical resistivity testing is limited to surface levels because of the need to structure the probes within the earth. Yet, recent advances in technology have generated multi-electrode systems that can be used in bodies of water by submerging the electrodes under the surface of the water (Wei, 2011). Electrodes are towed through the water, which help cut set up time because there is no need to take down and set up electrodes after each and every measurement. One of these new advancements is Continuous Resistivity Profiling (CRP), which “is a new technique that uses an electrode array in constant motion to collect measurements every few seconds, generating a two-dimensional profile of sub-bottom sediments” (Wei, 2011). This current research will use this technique in conjunction with the others to create 2D images of the karst systems underneath the water (Figure 14). CRP technique measures depths of 12 feet, 30 feet, 60 feet, and 100 feet (includes water column).

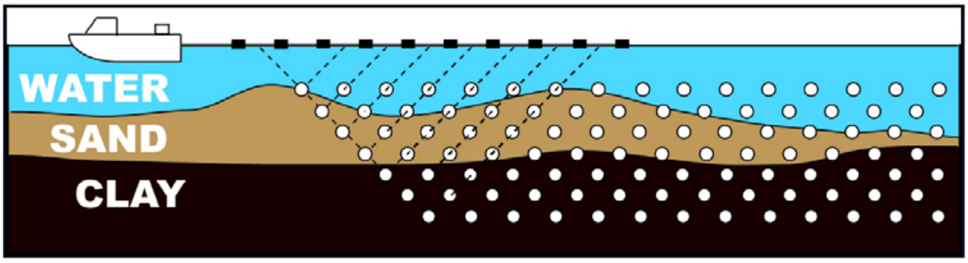


Figure 14: Sample setup of marine survey an array of electrodes towed behind a boat (Wei, 2011).

McGrath et al. (2002) have illustrated the success in mapping karst systems with the use of resistivity techniques. In resistivity methods, “artificially generated electric currents are introduced into the ground and the resulting potential differences are measured at the surface” (McGrath et al., 2002). The differences within the ground readings allows for researchers to construct vertical contoured sections of the ground area being examined, which help display karst sections and other subsurface abnormalities that may concern construction projects McGrath et al. (2002) assert that “deviations from the pattern of potential differences expected from homogeneous ground provide information on the form and electrical properties of subsurface inhomogeneities”. Resistivity results can often be used to help “further constrain the location and size of the cavities to enable robust inversions of the data for three dimensional inversions to give detailed configurations of the subsurface cave system” (McGrath et al., 2002).

Yang et al. (2002) also used Resistivity Image profiling (RIP) on water surface to study bottom structures of Lake Chung-Dah in Northern Taiwan and to examine the ability of using RIP technique to map the geology of the sub-water bottom. The reason of using this technique is that Standard Direct Current (DC) Resistivity Sounding is rarely used to describe underwater structures due to cost effective of the deployment of underwater electrodes. Moreover, RIP technique has two significant advantages high resolution and greater depth. In this study, the author used a pole-

pole configuration electrode array. In order to process the data of RIP, the author mentions that no need to correct the bottom topography and water body as required for DC technique. RIP results and comparing with well data describe efficiently the shallow sub-water stratigraphy of the lake rather than standard resistivity method.

Passaro (2007) utilized the marine electrical resistivity in (Salerno, Italy). The objective of using electrical resistivity over a submerged beach along the Agropoli shore was to locate buried archaeological objects beneath the sandy seabed. A shipwreck was found this a military vessel might sink in the Second World War during the Salerno landing operations of the allied forces. The extension of the shipwreck was provided by electrical resistivity data vertically and horizontally which is indicated by very low resistivity values (about 2-5 ohm-m). However, the extension of the shipwreck as obtained from Electrical Resistivity Tomography (ERT) and supported with Digital Elevation Model map which was extracted from the processing of bathymetric data was more than 30 m in the direction of NE-SW with 13 m width (Figure 15). Similarly, the magnetic data shows a magnetic anomaly with amplitude of about 1800 nT over the shipwreck. They could determine the boundary of the source by applying the computation of analytic signal method to the magnetic data. The final important result in this study is that marine geoelectrical methods provide a good result in searching of buried archeological targets, especially in very shallow water with sandy sea-bottoms which is hard to detect by seismic methods. In addition, this study recommends of using the different geophysical methods simultaneously to get better complete image, depth, and thickness of the buried object. Still, there are some drawbacks which can be mitigated through a more combined approach. The research suggests that “inversion modeling is time consuming but, on the other, the resolution of the technique is insufficient to discriminate between all possible geological conditions” (Frontier Geosciences, 2001).

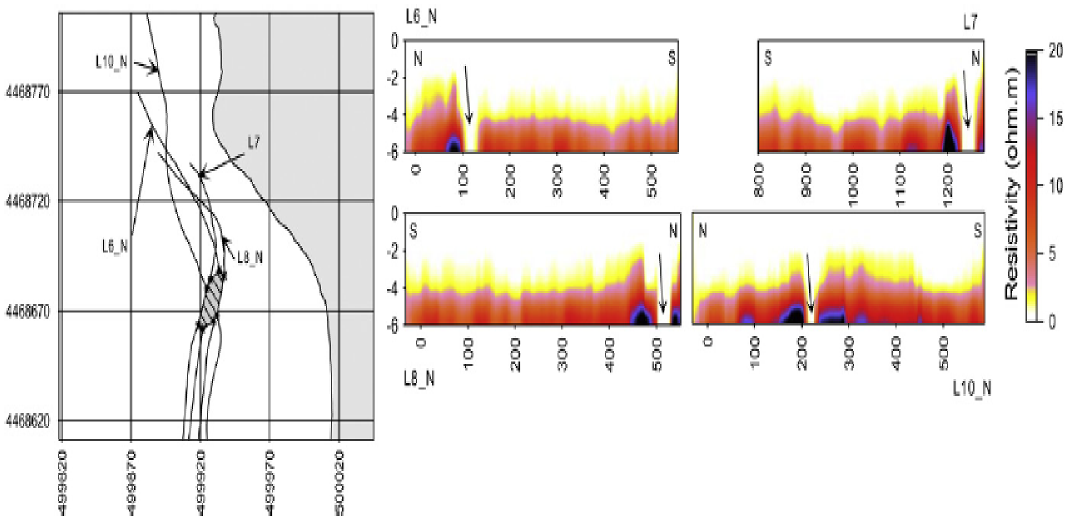


Figure 15: Navigation map and “picking” of the coordinates (latitude and longitude) corresponding with low resistivity anomaly in inverted resistivity profiles. Asterisks in the A frame correspond to the vertical stripes detected in four profiles (indicated arrows).The union of these points (filled polygon in leftmost frame) defines an area having an extension of about 25/30m along NE-SW,and13-15m along NW_SE. Datum isWGS84,projection is UTM (Zone33) (Passaro, 2007).

5. Geophysical Data Acquisition Equipment and Software

5.1. Introduction

The geophysical data acquisition will be recording and viewing in a real time. All geophysical equipment will provide continuous profiles and plan view images of the sub surface (Figure 16). The exact location of all geophysical data and tracking will be assigned on the map by using GPS (global positioning system). A 2D map for the sub surface will be provided. Data will be collected through an integrated approach, using echo sounder, sub-bottom profiler, side scan sonar, and marine resistivity testing. This allows the research to collect data from different sources, which can later be compared in order to produce more reliable maps of the karst terrain underneath standing bodies of water in Missouri.

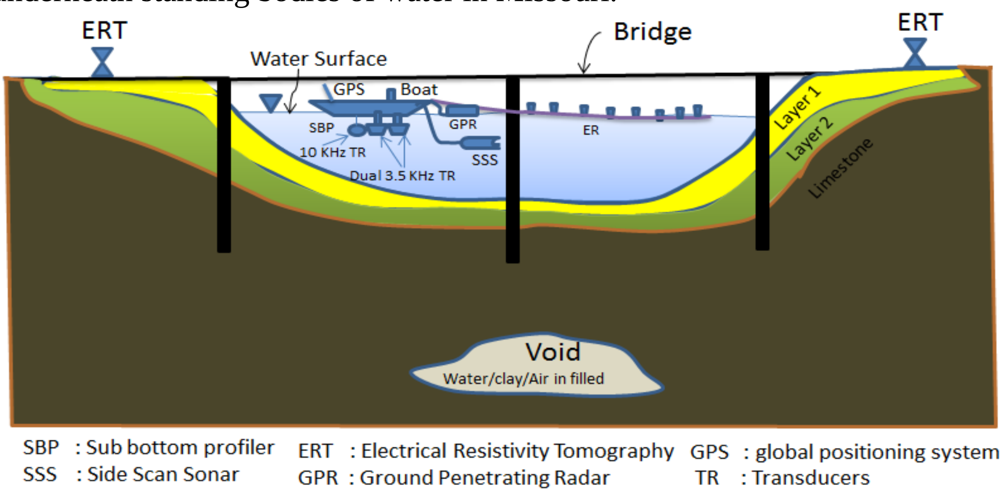


Figure 16: A simple model shows a demonstration of all geophysics surveys over water.

5.2. The Boat

The primary piece of equipment for this research is the boat which with the tests can be conducted. The model will be the Frontier 2070 CC Jon Boat, built in 2012 (Figure 17). It is from Lowe Boats and can carry 1,100 lbs.

Figure 17: The Frontier 2070 CC Jon Boat (Lowe Boats Inc.).

5.3. Sub Bottom Profiling Equipment

The acquisition equipment of sub-bottom profiler and bathymetric technique that will be used in this research is called BATHY-2010 system (Figure 18) which is comprised of the following electronic components:

- Bathy 2010 Data Acquisition System (Sonar/Sensor Unit)
- Dual TR-109 3.5 KHz Transducers (Beamwidth angle is 30°) and one 10 KHz transducer (Beamwidth angle is 10°)
- Junction Box Transducer

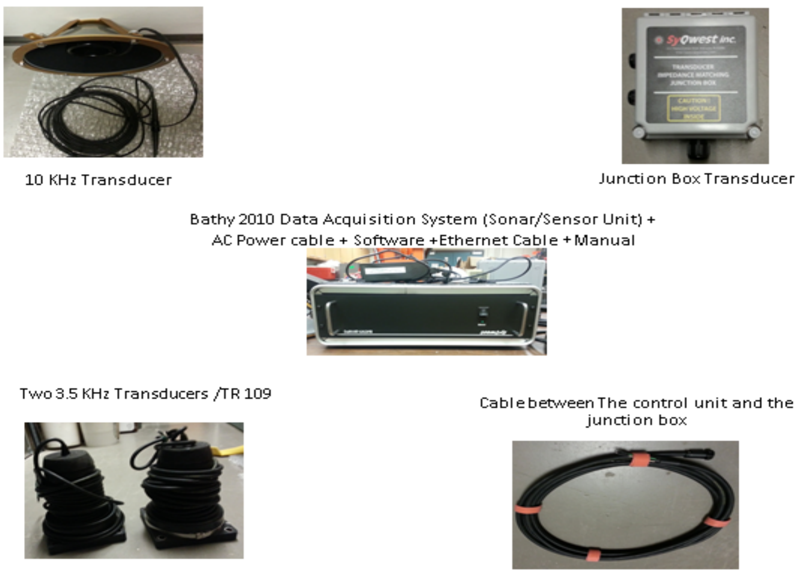


Figure 18: Bathy 2010PC™ CHIRP Sub Bottom Profiler and Bathymetric components.

The Sub bottom profiler and bathymetric acquisition software is called Bathy 2010 PC Acquisition (Figure 19). This software records the data in several formats (CSV, ODC, and SEGY) that can then be processed by using advanced seismic processing software like Reflexw.

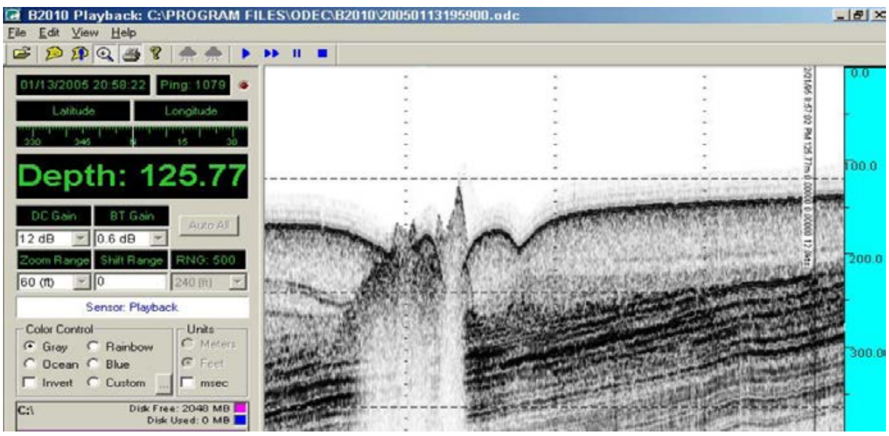


Figure 19: The sub bottom profiler and bathymetric acquisition software.

5.4. Echo Sounder Equipment

The echo sounder equipment is known as StructureScan HD with different frequencies broadband sounder 83/200 KHz and downscan imaging 454/800. This equipment measures the depth of water directly underneath the boat (Figure 20a). The maximum depth of downscan is 300ft/92m.

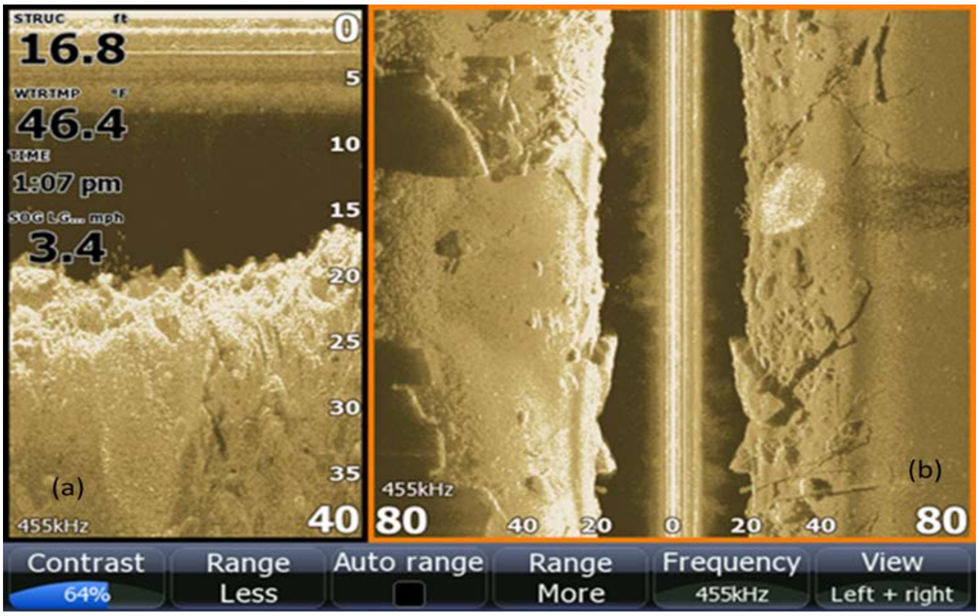


Figure 20: StructureScan HD data (a) downscan data, (b) side scan sonar imaging (Lowrance, Inc).

5.5. Side Scan Sonar Equipment

For Side Scan Sonar, two different equipment can be used. The first acquisition equipment is called yellowFin model 872 which is included three different types of frequencies (220 kHz/ 330 kHz/770 kHz) (Figure 21). This equipment can get 300 m depth with total coverage up to 1300 ft/400m. This equipment contains one transducer for each side, tilted down 20°. Side Scan Sonar acquisition software is “DiveLog3” from SeaSar. The second equipment is called StructureScan HD side scan sonar imaging system with 455 and 800 kHz transducer and total coverage up to 600 ft/183 m (Figure 20b).

Figure 21: Side Scan Sonar (Yellowfin) Model 872.

5.6. Seismic Processing

The goal of data seismic processing is to improve the reflection events. (Figure 22) shows the steps of seismic data processing which may apply all or some depending on the need (Sharma, 1997).

The steps of seismic data processing will be as a following:

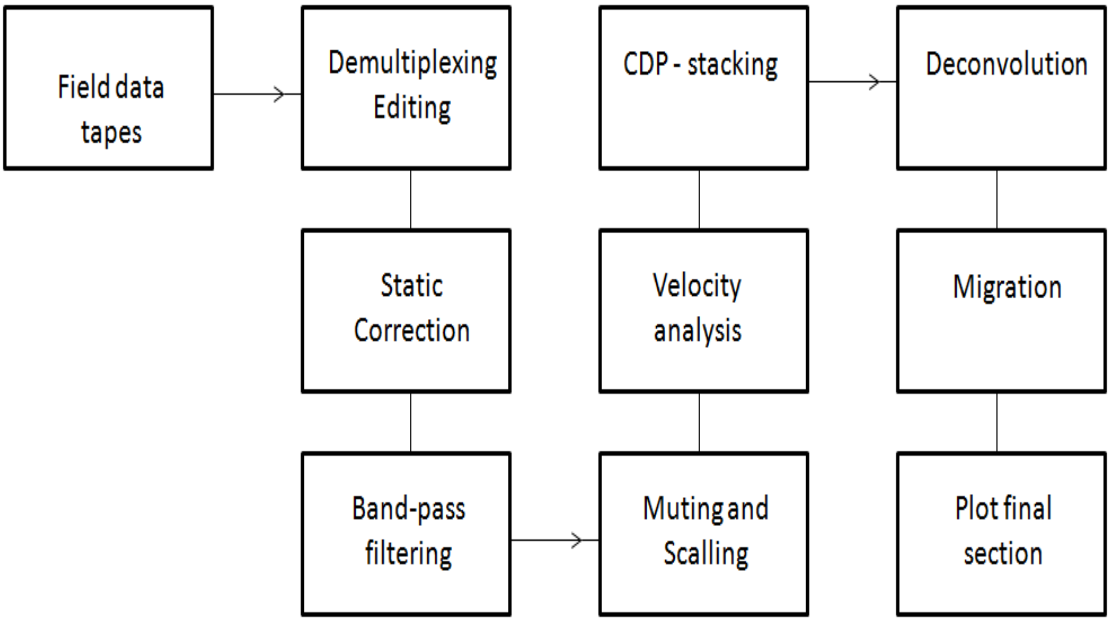


Figure 22: An overview of reflection seismic data processing. Data-processing flow is usually tailored to handle the requirements and problems of the individual data-set (Sharma, 1997).

5.7. Seismic Resolution

Basically, the definition of the resolution is that the ability to determine two targets from one another. That means that this ability makes the interpreter able to identify the minimal distance between two objects, and distinguish them individually.

5.7.1. Vertical Seismic Resolution

"The vertical resolution of an acoustic sub-bottom profiler refers to the minimum distance that can be visually distinguished in the image produced by the system" (Datasonics, 1996). Interestingly, seismic interpreters perceive resolution from a vertical sense; however, there is a limit to the horizontal width, which is possible to interpret using seismic data. The *Rayleigh Criterion* is the most popular method used in this case to determine the wavelength. The seismic measure is a wavelength, and in order to distinguish two reflective surfaces. *Rayleigh Criterion* suggests that they must be ¼ wavelengths in thickness. The main assumptions in this criterion are that seismic signal has one frequency seismic wave travel at one velocity, and there is a level background amounting to negligible seismic noise. Notably, the vertical resolution will decrease with the distance covered by the wave because attenuation reduces the higher frequencies generated (Liner, 2012). For instance, 3.5 KHz transducer with 8 cm resolution will be able to distinguish the layers which are not closer than 8 cm of each other. In case of the distance between layers are less than 8 cm, the system will not be able to determine the two layers and will consider them as one layer.

5.7.2 Horizontal Seismic Resolution and Fresnel Zone

On the other hand, horizontal resolution refers to the possibility of placing two reflective points horizontally, and distinguishes them as two separate points. It is possible to resolve the lateral extent features of rays because rays are thin, have unlimited frequencies, and do not have the capacity to distinguish all changes. In comparison with waveforms, which are non-planar, during the returning back of reflections, they do that in an interval of time. Owing to this interval, it is not possible to separate signals emerging at that time into their components. This helps in making the assumption that reflections can coincide in time to interrupt each other. The area that produces reflections is the one referred to as the First Fresnel Zone. It is the reflecting zone in the subsurface insonified by the first ¼ of a wavelength. However, if the wavelength happens to be larger than the zone, the resolution power becomes lower. Most importantly, the horizontal resolution relies on the frequency and the velocity (Yilmaz, 1988).

5.8. Electrical Resistivity Tomography Equipment and Software

For resistivity measurement, an AGI SuperSting will be structured on the boat connected to GPS and SONAR units to record location and water depth. The exact device is the SuperStingR8/IP multi-channel Direct-Current (DC) resistivity meter and switching box (Figure 23).

According to Wei (2011), "the system is comprised of a multi-channel Supersting resistivity meter, a waterproof Kevlar-strengthened electrode cable, and a Lowrance GPS/SONAR unit." The device uses a 12V battery (100W). The Supersting controls the injection of electricity through the cable and measures changes in voltage between pairs of electrodes. Then, GPS and SONAR units track the position and depth of the water within the limit of each measured cycle, which are approximately every four seconds. It uses an 11 electrode cable with two current electrodes and nine potential ones. This allows "for the collection of eight voltage measurements during each measurement cycle. Data collection speed is determined based on the necessary 'data density' for each project, but is typically on the order of 2-3 knots (3-5 km/hr)" (Wei, 2011). As such, when using slower speeds, more data can be recorded per mile, and faster speeds allow for more miles of data in a single day. Overall, the Supersting can store more than 79,000 measurements.

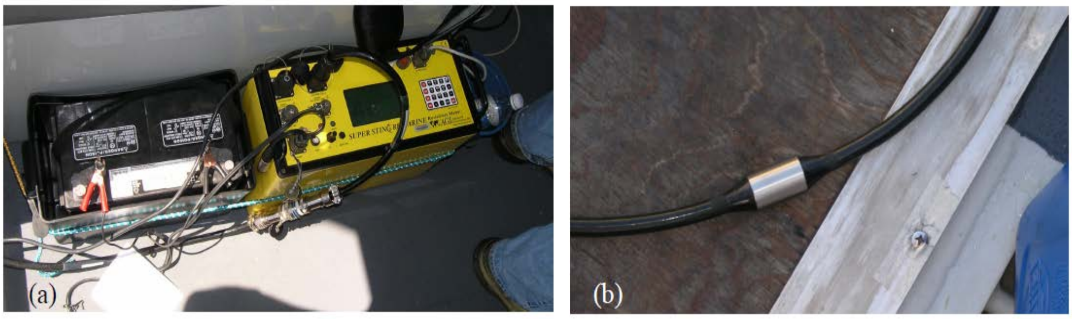


Figure 23: Equipment Photos (a) AGI Supersting Marine (b) stainless steel electrode on towed cable. (Enviroprobe Service, Inc.).

The data acquisition software to be used in this measurement will be the Marine Log Manager Software, which manages maps and processes GPS and Sting output files for later inversion. Additionally, Res2DInv processing software will also be used to compile map images from the raw data.

For electrical resistivity data processing, the data can be checked at the field to check the quality of the data. Sometimes, bad data is needed to be removed during using the software (Res2Dinv). However, usually no processing of the data is needed. The resistivity data are plotted a 2D section to form a pseudosection and create a 2D model (inversion).

5.9. Global Positioning System (GPS) and Others Equipment

In addition, the Lowrance HDS-10 Gen2 Fishfinder / Chartplotter will be connected to all Geophysical equipment. This equipment includes a built in internal GPS antenna, insight USA maps, and external GPS LGC-4000 – Baja (Figure 24). Moreover, temperature sensor will be used to measure the change of the river water temperature that may effect on the electrical resistivity and seismic data.

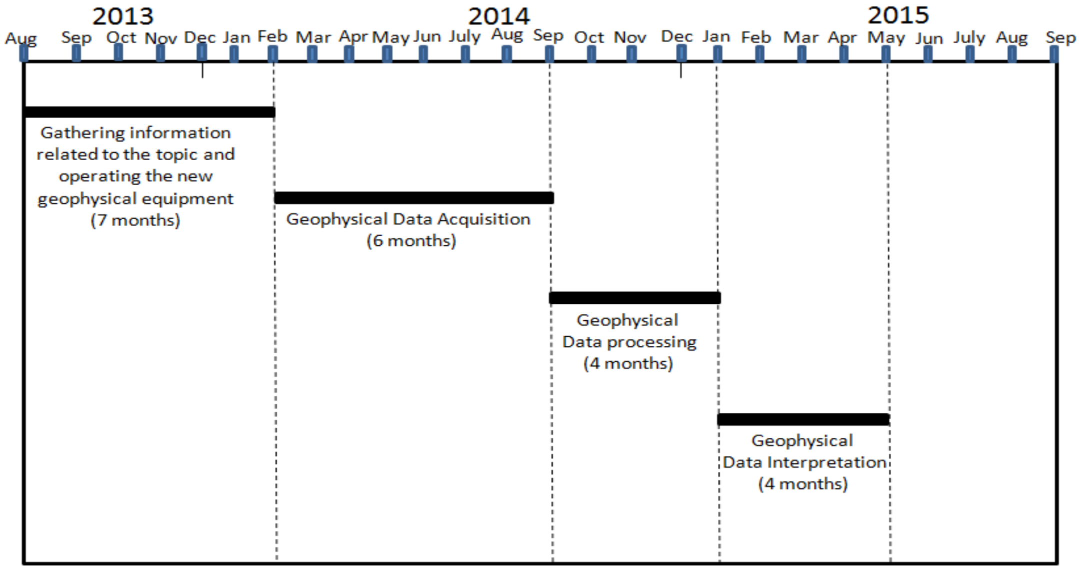
The external GPS LGC-4000 – Baja receiver is more accurate than the built in GPS antenna. Moreover, the external antenna gives a faster refresh and 5 times per second of update rate on position. It is important to set the external receiver near to the transducers to get more accurate location with water depth.

Figure 24: (a) Lowrance HDS-10 Gen2 Fishfinder / Chartplotter, (b) Downscan and sidescan transducers, (c) External GPS LGC-4000 – Baja, (d) Structurescan accessories, (e) Lowrance EP-80R temperature sensor (lowrance, Inc).

6. Data Interpretation

The data collected from individual techniques can then be combined and compared to provide the most accurate map of the karst system under the standing body of water. The integration of the geophysical data results and core drilling will produce detailed maps of bottom sediment and substrate. Thus, data interpretation will focus on using a variety of underwater acoustic methods and electrical sediment measurements for a truly in integrated approach to measuring and mapping the conditions of karst terrain below large bodies of standing water. Data from different techniques will be analyzed through software associated with each individual technology. 2D maps can then be generated with the results of the study area.

7. Work plan



As shown in the timetable above, this research will take several steps to achieve the objectives as the following:

First Step: Install the Lowrance HDS-10 Gen2 Fishfinder / Chartplotter GPS and all new geophysical equipment (side and down scan sonar, Electrical resistivity tomography, and Sub-bottom profiling) to the boat and test the equipment. In addition to gathering information related to the topic.

Second Step: Acquire the geophysical data for the designated sites.

Third Step: process the geophysical data and produce maps for all sites.

Fourth Step: interpret geophysical data results with the geological and coring information for each site.

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