A CASE HISTORY OF A LARGE KARST INVESTIGATION

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Abstract

A geotechnical karst investigation (i.e. identification of cavities, fractures and collapse zones) is undoubtedly one of the most difficult subsurface investigations: a real needle in the haystack problem. This paper summarizes the strategy and results of one of the largest and most comprehensive karst investigations in the country. The data utilized on this project included a wide range of data types, scale (regional, local and site-specific details), depths and measured parameters.

The site occupies approximately 130 acres in west-central Florida and was previously used as a phosphate refining plant. The plant has been demolished and remediation of the site is planned. Since the site is located in a regionally karst-prone area, the geology and hydrogeology need to be accurately characterized and a karst risk assessment made prior to the remediation efforts.

The shallow geology (upper 20 feet), was densely-sampled by EM31 and ground penetrating radar along lines spaced 10 feet apart (virtually 100% site coverage). Deeper geology was densely-sampled (to depths of 80 feet and more) with 2D resistivity imaging data, microgravity data and marine seismic reflection data in the adjacent river. These sets of data provided total coverage of the 130-acre site from which background and anomalous conditions were readily identified. Monitoring wells, Geoprobe pushes, rotosonic drilling and geophysical logging were then completed in anomalous and background areas defined by the surface geophysics and were used to provide detailed geologic and hydrologic data.

Appropriate and adequate data from a variety of sources and measurements were integrated to improve our understanding of site conditions. By themselves, each set of data provide a limited understanding of site conditions. However, combined, these data sets provide a powerful base of information in which to design and execute a remediation for the site and enable a reasonably accurate risk assessment to be made. When multiple sets of data agree, our interpretation is significantly improved and reliable risk assessments can be made.

Background

The site is located in the northwest corner of Pinellas County, Florida adjacent to the Anclote River (Figure 1). The site occupies approximately 130 acres and was previously used as a phosphate refining plant. The plant was in operation from 1947 to 1981. The plant production facilities and most of the buildings have been demolished and removed from the site. This site is a superfund site and a Record of Decision (ROD) was issued in 1998 that outlined the remediation for the property. However, because the site is located in a regionally karst-prone area, the geology and hydrogeology need to be accurately characterized and a karst risk assessment made prior to the remediation efforts (O'Brien &Gere, 2003).

Strategy

The project objectives were to identify the possible presence of both shallow and deep karst features at the site. A variety of conditions exist at the site and include buildings, foundations of abandoned structures, buried utilities, disposal areas, ponded waste materials, and areas of saltwater intrusion. Because of these conditions, it was recognized the no single technique or measurement would be effective over 100% of the site. Therefore, a strategy that integrated a wide variety of data was employed. The variety of data included different data types, different scales of measurement, various depths of measurement and different parameters being measured.

While much of the investigation utilized non-invasive geophysical techniques, other data sources were also used. These data sources included regional literature, existing site-specific reports, existing wells, aerial photo analysis, sinkhole databases, Geoprobe direct push, rotosonic drilling and laboratory analyses. The integration of a wide source of data increases the overall confidence in the final conclusions at the site. Figure 2 illustrates the strategy used on this project.

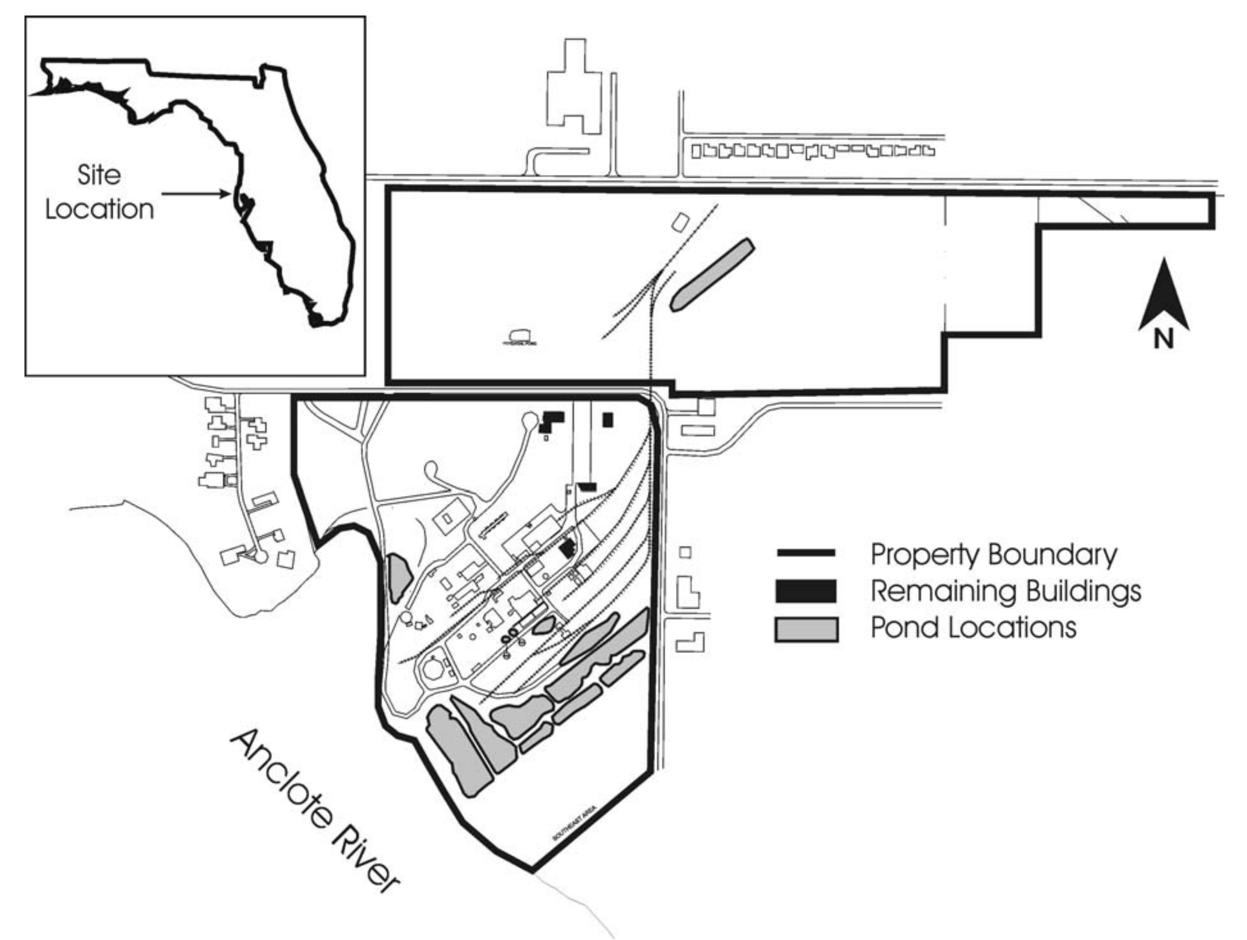


Figure 1: Site map

Appropriate, Adequate, Accurate Data

Fundamentally, all data acquired must meet three basic criteria, appropriate, adequate and accurate for the site and the project objectives (Yuhr, 1998). The techniques chosen for this project are all appropriate and meet at least one project objective and provide redundancy of measurements for correlation purposes. Table 1 lists the variety of measurements acquired at this site for the purposes of assessing karst conditions.

The data acquired must be spatially adequate, both laterally and vertically, to detect the targets of interest. The shallow geology (upper 20 feet), was densely-sampled by EM31 and ground penetrating radar along lines spaced 10 feet apart (providing virtually 100% site coverage). The shallow geophysical data measure a smaller volume of the subsurface with the capability of detecting smaller zones of soil raveling, dipping strata and voids.

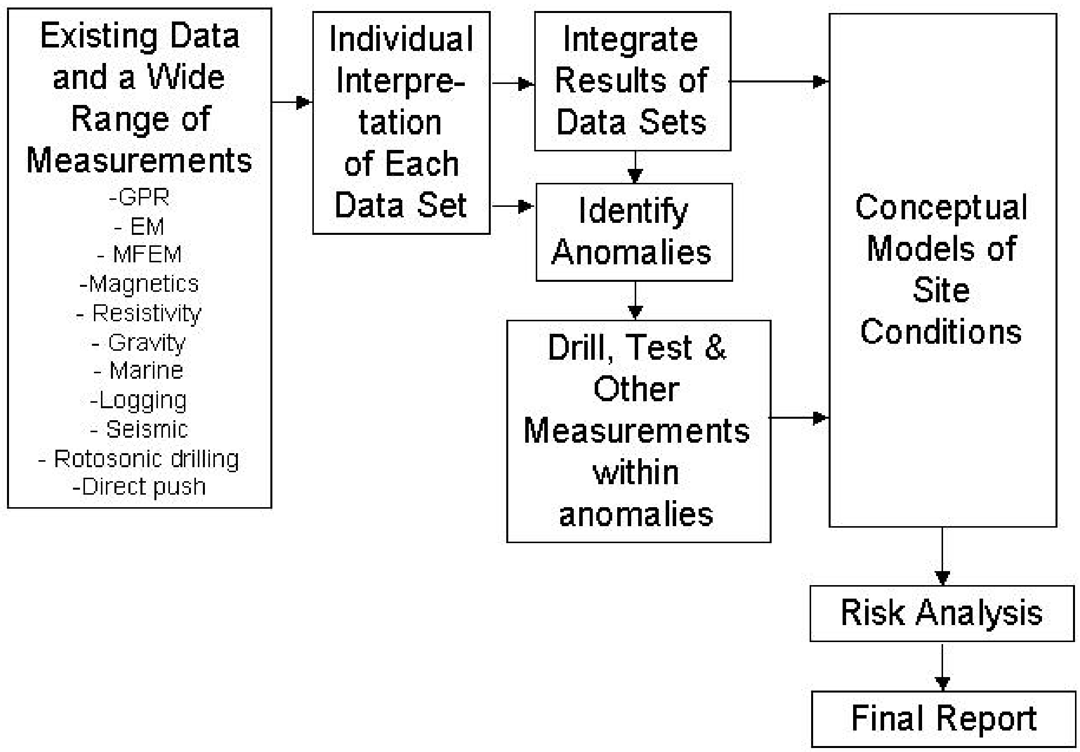


Figure 2: Strategy used for overall site characterization

Deeper geology was densely-sampled (to depths of 80 feet and more) with 2D resistivity imaging data, microgravity data and marine seismic reflection data. The deeper geophysical data measure a larger volume of the subsurface and was acquired at a wider line spacing of 100 feet. The deeper geophysical data provided the capability of detecting larger and deeper geologic conditions including the continuity of the deeper strata, lateral variations in an unconformity, zones of paleo-karst collapse and water filled cavity systems. Monitoring wells, Geoprobe direct pushes (150 locations), rotosonic drilling (22 locations) and geophysical logging (82 locations) were then completed in anomalous and background areas defined by the surface geophysics and were used to provide detailed geologic and hydrologic data.

This site also required data to be temporally adequate (over time). Temporal data for the project included site specific aerial photos of plant operations, a sequence of aerial photos dating back to the 1920's and a review of the available sinkhole databases providing information on the frequency of sinkhole collapse.

The final requirement is that of accurate data. Detailed standard operating procedures (SOP) were written and included in the Work Plan for the project. Each person acquiring data followed the SOP to provide quality control for a given technique. In addition, a third party consultant was contracted to provide quality assurance on all measurements made. With the criteria for appropriate, adequate and accurate data being met, the project was assured a solid base of data that could then be integrated and interpreted.

Table 1: Summary of New Measurements

Measurement	Maximum Depth of Measurement	Parameter Measured	Density of Measurements	Number of measurements
Ground Penetrating Radar	24 feet	Responds to changes in dielectric constant	Continuous data along lines spaced 10 feet apart	90 line miles of data
Electromagnetics (EM31)	20 feet	Electrical conductivity and the presence of metals	Continuous data along lines spaced 10 feet apart	110 line miles of data
2D Resistivity Imaging	80 feet	Electrical resistivity	20-foot electrode spacing along lines spaced 100-feet apart	10 line miles of data
Microgravity	>100 feet	Responds to variations in bulk density of subsurface materials	40-foot station spacing (60% of site), 20-foot station spacing (40% of site), along lines spaced 100-feet apart	1826 station measurements over 10 line miles of survey lines
Marine Seismic Reflection	150 feet	Responds to changes in velocity	Within accessible areas of Anclote River and selected bayous	About 10 line miles
Geophysical Logging - natural gamma - induction - gamma-gamma - neutron	Depth of well (ranged from 10 to 156 feet)	Probe specific - clay content - conductivity - density - porosity	Existing wells 36 New MW 24 Test borings 22	82 wells
Geoprobe Direct Push Electrical Conductivity	To refusal or a maximum depth of 40 feet	Electrical resistivity/ conductivity	Locations throughout site selected based upon various objectives	150 pushes
Rotosonic drilling	75 to 156 feet	Provided 3-inch soil cores	Locations throughout site selected based upon various objectives	22 test borings
Vertical seismic profiling	75 to 156 feet	Variations in velocity	Selected test borings	-- test borings
Crosshole seismic	75 feet	Variations in velocity	One set of 3 test borings	One location
X-ray diffraction	NA	Mineralogy and % clay content	A few samples of semi-confining layer	6 samples
C-14 dating	NA	Approximate age of material sampled	Peat material within paleocollapse	2 samples
Permeameter Testing	Samples of the semi-confining layer	Hydraulic conductivity	1-foot sections from 7 locations	7 samples
Hydrometer (sieve analysis)	Samples of the semi-confining layer	Variations in grain size	Semi-confining layer Existing test borings 9 (2 samples each) New test borings 7 (2 samples each)	32 samples from 16 locations

Hydrogeologic Conditions

An initial conceptual model of the hydrogeologic conditions at this site was developed early in the project with limited data. Then, as additional data were acquired, the conceptual model was revised. The final conceptual model of site conditions is illustrated in Figure 3. There is a layer of surficial sands (5 to 25 feet thick), which contains the surficial aquifer. Underlying the surficial aquifer is a semi-confining layer. Below the semi-confining layer are the Tampa and Suwannee Limestones. The Tampa Limestone contains the upper Floridan Aquifer.

Three of the key geologic features of interest at this site are:

- The thickness and continuity of the semi-confining layer;
- The possible presence of shallow, cover karst features; and
- The possible presence of deeper paleo-karst features.

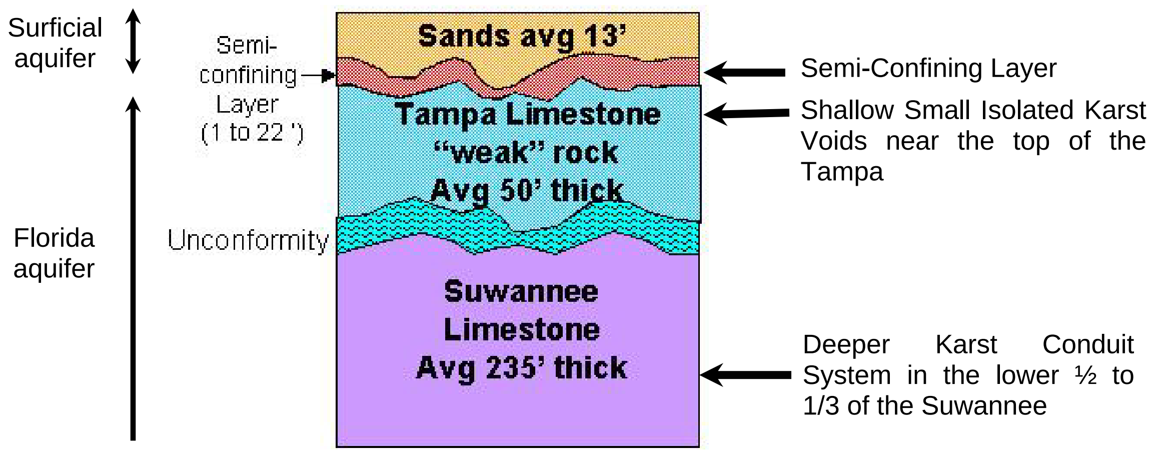


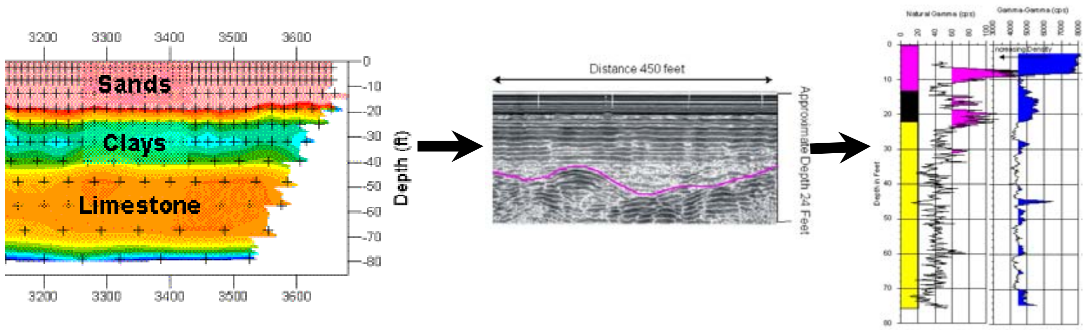
Figure 3: Final conceptual model of geologic conditions

Semi-Confining Layer

The semi-confining layer actually consists of two different sources of fine-grained materials and clays. The upper portion of the semi-confining layer was deposited at the base of the surficial sands which grade into a sandy clay. The lower portion of the semi-confining layer was created due to weathering of the Tampa Limestone and consists of a weathered limestone residuum with clay. The higher clay content from both of these layers results in a lower permeability and forms the semi-confining layer at the site.

The semi-confining layer was identified in a variety of measurements (Figure 4):

- 2D resistivity imaging was able to confirm the overall presence of the semi-confining layer over much of the site, but not provide detailed depths;
- ground penetrating radar was able to map the top of the semi-confining layer over much of the site and showed the variability of this layer laterally across the site;
- Geophysical logs (natural gamma and induction) were able to indicate the presence and thickness of the semi confining layer in both existing and new wells and test borings. These measurements provided very detailed profiles showing the vertical variability in thickness and composition;
- Geoprobe direct push electrical conductivity (DPEC) was used to confirm the presence of the semi-confining layer where the surface geophysical techniques provided limited information.



2D Resistivity Imaging Ground Penetrating Radar Geophysical Logs

Figure 4: Multiple techniques were used to characterize the semi-confining layer

This layer was found to be variable in depth, thickness and clay content, but was found to be laterally continuous throughout the site, except in those areas of paleo-collapse.

Further characterization of the impeding nature of the semi-confining layer was completed by laboratory analysis. Samples of this layer were acquired with rotosonic drilling and submitted for pressurized permeameter analysis. These samples were also used for particle size analysis. Initial data indicated that the semi-confining layer was, in fact, 3 orders of magnitude less permeable than the overlying surficial aquifer.

Shallow Cover Karst Features

Based on regional characterization of the area (Sinclair and Stewart, 1985), typical sinkholes are cover subsidence sinkholes. These features are formed when the relatively thin layer of sandy soils migrates into random dissolution voids within the upper Tampa Limestone. These features are typically 10 to 20 feet in diameter and 10 to 20 feet deep. This characterization is supported by the site-specific geologic setting, review of sinkhole databases, newspaper reports and observed local sinkhole activity.

Observations, historic records and the geophysical data collected on-site did not indicate any previous shallow karst collapse features or recent karst activity (i.e. raveling soils, dipping strata). Random, localized low density zones were observed in the geophysical logs across the site within the upper Tampa Limestone. Any one of these features could potentially receive migrating soils from above. The presence of the semi-confining layer acts as the barrier, preventing the overlying sandy sands from migrating into the upper Tampa Limestone.

Deeper Paleo-Karst Features

Surface observations and aerial photo interpretation indicated only two karst feature on the perimeter of the site: a sinkhole pond and Meyers Cove within the adjacent river. There were no visual indications of karst activity on-site. However, microgravity data identified areas of low gravity values (indicating areas of low density materials or possible cavities). Direct push electrical conductivity (DPEC) measurements were then used to determine if these low gravity areas were due to a shallow or deep features. Direct push electrical conductivity measurements were made across the gravity anomalies to a depth of 40 feet. These data indicated that the semi-confining layer was missing throughout the area of low gravity values.

Figure 5 is an example of one of the low gravity areas identified on-site. It is located along the eastern edge of the property and extends off-site. All invasive measurements were limited to on-site access and were located throughout the low gravity area. Numerous DPEC measurements were acquired to map the area that was missing the semi-confining layer.

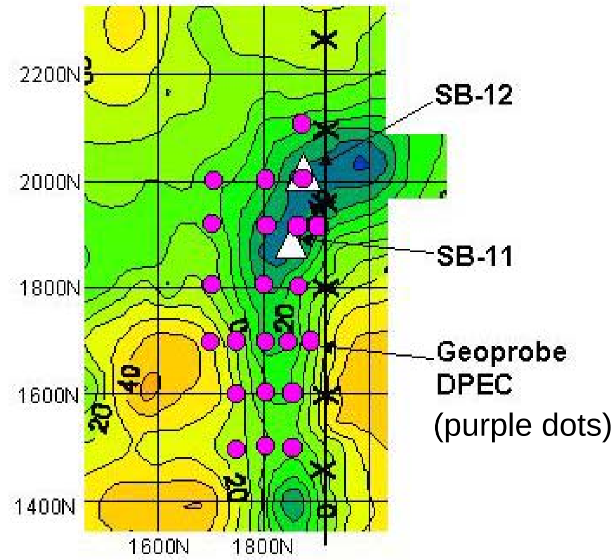


Figure 5: Example of gravity low with follow-up measurements

Two deep borings were located within the lowest gravity values measured. The borings were made using the rotosonic drilling method which provided a 3-inch soil core. Within the low gravity area, the borings indicated layers of organic materials at depth, where the Tampa and Suwannee Limestones should have been. These borings were then geophysical logged, which confirmed that the semi-confining layer was missing and detected significant low densities with depth. This area was interpreted to be a paleo-karst collapse area based upon the missing semi-confining layer, the missing limestone, the low density zones and the presence of organic materials. Finally, C-14 dating of the organics within the paleo-collapse feature indicated that the collapse occurred more than 40,000 year ago. Integration of these data clearly defined the spatial extent, geologic character, and age of these paleocollapse zones (Figure 6).

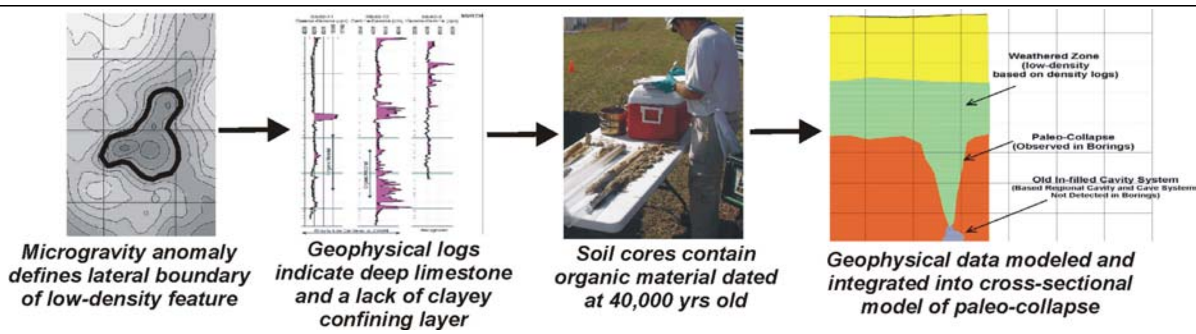


Figure 6: Interpretation of the paleo-collapse feature based upon gravity, DPEC, borings and geophysical logs.

Risk

Data from a wide variety of sources and measurements were integrated to improve our understanding of site conditions. When combined, these data sets provide a powerful base of information in which to evaluate subsurface conditions, design and execute a remediation for the site and enable a reasonably accurate risk assessment to be made. When multiple sets of data agree, our interpretation is significantly improved and reliable risk assessments can be made.

Various risk factors (factors which could cause collapse to occur) were identified and given a subjective rating or risk. Each risk factor and its rating was then backed up by a variety of data which reduced the subjectiveness of our opinions (Benson, et al, 2003).

Conclusions

The semi-confining layer is critical to the site for two main reasons: contaminant transport and downward material transport into local voids. The presence of an impeding layer between the surficial aquifer and the Upper Florida aquifer provides protection to the lower groundwater resource. The presence of the semi-confining layer also prohibits the loose surficial sands from migrating into the shallow, small voids or low density zones which lie within the upper Tampa Limestone, just beneath the semi-confining layer.

While the site lies within a karst-prone area, previous small, shallow karst features were not identified in the data collected at this site. Larger, deeper paleo-karst features were identified and characterized on-site. Two of these features have a surface expression (the sinkhole pond and Meyers Cove), while no surface expression was observed at the others.

The knowledge, tools and experience to solve the problem of locating, mapping and characterizing karst conditions are presently available. Many remote sensing, non and minimally invasive methods, as well as traditional boring methods of investigation can be applied to resolve karst problems.

Unfortunately, there are no technologies, procedures, guidelines, software or graphics that will, by themselves, minimize geologic uncertainties and improve upon inappropriate data, insufficient data, inaccurate data or poor critical thinking skills. What is needed is a simple back to basics multidisciplinary approach using good science to reduce the uncertainly to an acceptable level (Benson, et al, 1996).

This project provided appropriate and adequate data from a variety of sources, which were integrated to improve our understanding of site conditions. By themselves, each set of data provide a limited understanding of site conditions. However, combined, these data sets provide a powerful base of information in which to design and execute a remediation for the site and enable a reasonably accurate risk assessment to be made. When multiple sets of data agree, our interpretation is significantly improved and reliable risk assessments can be made (Yuhr, 1998).

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