BAHAMIAN CAVE AND KARST GEODATABASE, AND GIS
ANALYSIS OF SAN SALVADOR ISLAND, BAHAMAS

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A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Geosciences
in the Department of Geosciences

Mississippi State, Mississippi
August 2006
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A geodatabase and a data management program have been created to store and manipulate cave and karst feature data from the Bahamas. A geographic information system was used to recognize any spatial patterns in the cave and karst data from San Salvador Island. Elevation data for banana holes, vadose pits and flank margin caves were obtained from a digital elevation model and are consistent with values predicted by the Carbonate Island Karst Model. The slope and aspect of the hill on which a flank margin cave is found showed no relationship to cave sizes and shapes, emphasizing the hypogenic nature of flank margin caves. The digital elevation model further demonstrated the position of lakes on San Salvador Island during the last interglacial (OIS 5e) highstand, and the lack of flank margin caves along the shores of these lakes provides evidence for a paleoclimate on San Salvador Island similar to today’s.
DEDICATION

To my loving wife and family, without you this wouldn’t have happened.
ACKNOWLEDGEMENTS

First and foremost I would like to thank my committee members, John Mylroie, John Rodgers, and Bill Cooke, for all of their support. They have taught me everything I know about caves and GIS and I will remember them forever as exceptional mentors and friends. John M., I couldn’t have asked for a more supportive and attentive advisor – you have been the key to making this whole journey possible. John R. and Bill, you have given me great inspiration and shown me that it is possible to be good at everything. Special thanks to Joan M. for helping John M. make this all possible for me.

I would also like to thank all of my friends, both students and staff, within the Geosciences department for making my stay at Mississippi State as enjoyable as it was. Particular thanks go to Julie, Kevin, Athena, Brady and Kristen for the cookouts, parties and Thursdays at the Darkhorse – ingredients that were instrumental to the completion of this project.
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CHAPTER I

INTRODUCTION

Karst features have been documented in the Bahamas for over a century, and studied scientifically for three decades (Mylroie, et al., 1995b). Blue holes, caves, depressions and karren are all found throughout the Bahamas, and their mode of formation differs from that of “typical karst” found in continental settings (Vacher and Mylroie, 2002). With over 30 years of modern research on Bahamian caves and karst (Roth, et al., 2006), and the subsequent collection of data, the process of locating information can be laborious and inefficient. To date, there is no known single repository for Bahamian cave and karst information.

The first objective of this project is to collect as much of the available Bahamian karst data as possible into a single location so that future research may be performed more easily and efficiently. This will be accomplished with the use of a geodatabase, which allows one to store and manipulate geographic information. The second objective of this project is to perform an analysis of cave and karst features of San Salvador Island using a Geographic Information System (GIS) to correlate karst feature types with land surface features and characteristics. San Salvador currently has the most complete collection of GIS data and will therefore serve as a starting point for future GIS analysis of caves and karst in the Bahamas.
CHAPTER II
DESCRIPTION OF STUDY AREA

Geographic Setting

The Commonwealth of the Bahamas consists of an island chain (Figure 1) that extends from 21°N (Great Inagua) to 27.5°N (Grand Bahama/Abaco – Little Bahama Bank), and from 72°45’W (Mayaguana) to 80°30’W (Cay Sal). The Turks and Caicos Islands belong to the same island chain, but are a separate political entity. Other neighboring countries include Cuba to the southwest, the Dominican Republic to the south and the USA (Florida) to the northwest (Sealey, 1994).

The Bahamian archipelago covers an area of approximately 300,000 km$^2$, and of this area, 11,406 km$^2$ is subaerial land and the remaining 136,000 km$^2$ is submerged, shallow carbonate bank (Meyerhoff and Hatten, 1974). The two most northern islands, Grand Bahama and Abaco, are situated on the Little Bahama Bank, while North and South Andros Islands, New Providence Island, Eleuthera Island, Cat Island, Exuma Island, and Long Island all belong to the Great Bahama Bank (Sealey, 1994). Many of the southern Bahamian Islands such as San Salvador Island, Mayaguana, Crooked and Acklins Island, and Great Inagua are situated on their own platforms and are separated from other islands by deep channels (Sealey, 1994). San Salvador Island is located at approximately 24° N, 74.5° W.
The Bahamian climate is considered to be sub-tropical, “experiencing a warm temperate winter regime and a tropical summer regime” (Sealey, 1994, p. 109). While the Bahamas is a maritime country and does receive rain year-round, the country typically receives twice as much rain in the summer than in the winter. In general, due to its great latitudinal extent, the Bahamas can be divided into two distinct climatic regions. Northern islands such as Grand Bahama Island and Abaco Island typically receive more rain, have cooler winters, and have a positive water budget. Islands that are farther south tend to receive less rain, are generally drier and may have a negative water budget (Figure 2). That is, the southern islands tend to lose more water to evapotranspiration than they gain from rainfall (Sealey, 1994).
Figure 2  Climate map of the Bahamas showing yearly rainfall and potential evapotranspiration (P.E.T) (Modified from Whitaker and Smart, 1997)
**Geologic Setting**

The Bahamian islands are the exposed portions of thick carbonate banks, which make up the Bahamian Platform (Meyerhoff and Hatten, 1974). These banks are known to consist of at least 6 km of carbonate and evaporite sedimentary rock, with the possibility of another 5 km that have yet to be penetrated. According to Meyerhoff and Hatten (1974), the Bahamian region has been tectonically stable. Carew and Mylroie (1995) have supported this idea with field evidence such as coral reef and flank margin cave elevations, and have also suggested that subsidence is occurring at a rate of approximately 1-2 m every 100,000 years.

The carbonate rocks that make up the subaerial portion of the Bahamian islands are known to be entirely mid to late Quaternary in age. These relatively young rocks can be formed in many ways, including deposition of carbonate sediments by winds, waves and currents, or through the burial of coral reefs. There are two main landforms present throughout the archipelago: eolianite ridges, which provide the majority of the relief in the Bahamas and can reach elevations up to 63 m, and lowland areas, which are composed primarily of intertidal and subtidal deposits with some eolian deposits. Subtidal deposits were laid down during the last interglacial period, approximately 125,000 years ago (oxygen isotope substage 5e). At this time, sea level was approximately 4-6 m higher than present (Carew and Mylroie, 1997).
Hydrologic Setting

The hydrology of the Bahamian islands can be quite complex, and may vary drastically from one end of the archipelago to the other. According to Vacher (1988), the location and volume of fresh water within the carbonate islands are best described by the Dupuit-Ghyben-Herzberg model. This model suggests that a lens-shaped body of fresh water floats on top of marine water due to a difference in densities (Figure 3). It also predicts that the portion of the lens below sea level will be 40 times thicker than the portion of the lens above sea level. If there is a drastic and distinct transition from fresh to marine water, the boundary is referred to as a halocline (Davis and Johnson, 1989).

Based on their work on San Salvador Island, Davis and Johnson (1989) suggest that the conditions described by the Dupuit-Ghyben-Herzberg model are often not found in the field. The thickness of the fresh-water lenses may be influenced by factors such as climate and bedrock porosity (Whittaker and Smart, 1997). As was mentioned earlier, the islands in the northern part of the archipelago have a positive water budget and may result in a fresh-water lens beneath the entire land’s surface. In the south, where potential evapotranspiration exceeds mean annual rainfall, these lenses may be isolated beneath dune ridges. Permeability also plays a role in governing the thickness of the lens such that a higher permeability rock, or rock with conduits or fractures would have a thinner lens due to the increase in hydraulic conductivity (Davis and Johnson, 1989).

The presence of fresh water at the surface also varies greatly from the Northern to Southern islands. Inland areas that are topographically low may contain a surficial expression of the water table. These inland lakes may be fresh to slightly brackish in the
north, and are commonly saline to hypersaline in the south (Whittaker and Smart, 1997). Tidal creeks such as Stafford and Fresh Creeks on North Andros act as outlets to the ocean for the fresh water contained within the lens and depending upon tidal position, these creeks may be fresh/brackish to saline (Whittaker and Smart, 1997).

Figure 3  Simplified diagram of the fresh-water lens on a carbonate island (Modified from Mylroie and Carew, 1995)
CHAPTER III
BACKGROUND INFORMATION

Carbonate Island Karst Model

According to White (1988), landforms defined as karst form due to the dissolution of soluble bedrock material such as carbonates. Due to the unique hydrologic and geologic environments present on carbonate islands, “island karst” differs from karst found in a continental setting (including the interior of large islands such as Cuba or Jamaica). The Carbonate Island Karst Model (CIKM) explains the karst features and the processes by which they form on carbonate islands such as the Bahamas. This model is based on the following principles (Mylroie et al., 2004):

1. The mixing of fresh water and seawater, and the mixing of meteoric fresh water and phreatic fresh water occur at the boundaries of the fresh-water lens, resulting in solutions with increased dissolution capability.

2. Sea level has changed due to glacio-eustacy (over 100m in the Quaternary), producing horizons of dissolution features at varying elevations or depths.

3. Effects of sea level change can be over-printed by local tectonics, increasing the complexity of the record (this is not a factor in the Bahamas).
4. Karst found on carbonate islands is eogenetic. The rocks in which the karst forms are young and have never been buried beyond the range of meteoric diagenesis.

5. There are four main types of carbonate islands:
   a. Simple Carbonate Islands (Figure 4A) – no non-carbonates above sea level.
   b. Carbonate-cover Islands (Figure 4B) – non-carbonates covered by a carbonate veneer.
   c. Composite Islands (Figure 4C) – non-carbonates and carbonates exposed at the surface.
   d. Complex Islands (Figure 4D) – complex relationship between non-carbonates and carbonates resulting from faulting and interfingering of units.

As the Bahamas are composed entirely of carbonate material, according to the Carbonate Island Karst Model they qualify as Simple Carbonate Islands. Therefore, only features pertaining to this type of island will be discussed in this study. There are four main categories of karst found in the Bahamas: karren, depressions, caves and blue holes (Carew and Mylroie, 1997). In general, each type of karst forms as a result of different physical or chemical conditions, and as will be discussed below, features such as caves and blue holes may be polygenetic.
Figure 4  The four types of carbonate islands (Modified from Carew and Mylroie, 1997)
**Karren**

In the Bahamas, all precipitation falls directly onto a soluble, carbonate surface. These meteoric waters, made acidic by the absorption of carbon dioxide from the atmosphere and soils, expend the majority of their dissolution potential on karren and the epikarst (White, 1988). In general, karren refers to any small-scale dissolution formations located on bedrock surfaces as a result of “direct rainfall, sheet flow, channelized flow, or percolating flow” (White, 1988, p. 49). Karren features may range in size from millimeters to tens of centimeters. On exposed surfaces these features may be jagged, but under a soil mantle they may be smooth and curvilinear. Karren belong to the epikarst, which also includes any soil mantle as well as dissolution tubes, which carry water away from the karren into the subsurface (Taborosi et al., 2004).

**Depressions**

According to Mylroie and Carew (1995), closed contour depressions are one of the dominant karst landforms in the Bahamas. Unlike the classic closed depressions found within a continental setting (i.e. sinkholes), the origin of many of the depressions found on exposed carbonate islands is believed to be a factor of deposition. As a result, they are considered constructional, and not erosional. The majority of closed depressions in the Bahamas are actually inter-dune swales (Mylroie and Carew, 1995), and unlike depressions in a continental setting, the high primary porosity of Bahamian Carbonate rocks does not allow depressions in the Bahamas to holding water.

While the mode of depression formation is relatively consistent throughout the Bahamas, the degree to which the depression is maintained or modified can vary from
one end of the archipelago to the other, and is greatly affected by climate (Mylroie et al., 1995a). As was noted earlier, islands in the northern part of the archipelago have a positive water budget, and therefore tend to have a fresh-water lens under the entire island, including topographic lows. This may result in more vegetation than is typically found in the southern islands. The increased level of soil CO₂ that results from a greater amount of vegetation promotes the expansion and deepening of the depressions through karst processes. This has been demonstrated by the work of Mylroie et al. (1995a) in Bermuda. Conversely, in areas with negative water budgets, depressions tend not to be modified to the same degree as those found in the north. In addition to lower soil CO₂ levels, the hypersalinity of the lakes that are present in many of the topographic lows actually inhibits the dissolitional process and the depressions are therefore maintained in their original form over time (Mylroie and Carew, 1995).

Caves

In the Bahamas, there are a number of karst features that fall under the cave category. These include, but are not limited to, pit caves, banana holes, lake drains/discharge features, fracture caves, and flank margin caves. Pit caves are formed in the vadose zone by dissolution from meteoric waters, which are gathered into discrete point inputs. These vertical shafts, which are found most commonly on eolianite ridges, are usually deeper than they are wide and provide fast flow routes for water to the phreatic zone (Mylroie and Carew, 1995). They commonly form in a stair-step fashion and often do not reach the water table directly. By the time water reaches the bottom of the pit cave, it has often exhausted its entire dissolution potential, and therefore reaches
the water table by diffuse flow. Sizeable pit cave complexes are known to have
developed in eolianite ridges that are 125,000 years old, indicating relatively rapid
growth rates (Figure 5 and Figure 7) (Mylroie and Carew, 1995).

![Figure 5](Modified from Mylroie and Carew, 1995)

Banana holes are relatively small voids that have formed along the top of a fresh-
water lens that was present during the last sea-level highstand (approximately 125,000
years ago). The mixing of vadose waters and phreatic fresh waters may lead to a mixture
that is undersaturated with respect to CaCO₃, resulting in the formation of small voids. In
the Bahamas, these voids have formed under low elevation plains. The close proximity of
these voids to the surface often causes partial or complete collapse of the roof. These
features are generally circular or oval shaped, and can be up to 10 m wide and 5 m deep (Figure 6 and Figure 7). Banana holes are so named because thick moist soils often accumulate in the bottom of the depression, which have been exploited to grow banana and other specialty crops. The introduction of organics following roof collapse may also facilitate increased dissolution of the chamber floor by vadose waters (Harris et al. 1995).

Lake drains are poorly understood. They are cave conduits that connect inland lakes, ponds or blue holes to the ocean, providing an access route for marine waters. As they are connected to the ocean, they create varying degrees of tidal influence and salinity within the inland water body (Davis and Johnson, 1989).

Due to the steep sided nature of some of the carbonate platforms in the Bahamas, fractures may develop parallel to the bank margin as the bank begins to fail mechanically
Platform emergence and dissolution may play a role in weakening the rock in which fracture caves ultimately form, and while these fracture caves do not originate via dissolution, they do provide pathways for water into and out of the subsurface, and thus may undergo dissolution in the process.

Flank margin caves are large phreatic dissolution voids, and are considered to be hypogenic caves because their mode of formation is not directly tied to surface processes (Mylroie and Carew, 1995). By definition, flank margin caves form at the margin of the fresh-water lens, under the flank of the enclosing landmass, and in the Bahamas this is commonly a dune ridge (Mylroie et al. 1995a). It is at the margin of the fresh-water lens where two mixing zones converge, thus creating a region where dissolution is maximized (Figure 7). The first mixing zone is situated along the top surface of the fresh-water lens and contains a mixture of fresh waters from the vadose zone and the fresh-water lens. This situation is similar to that in which a banana hole forms. A second mixing zone is present at the bottom of the fresh-water lens where fresh water from the lens mixes with marine water. Even if both the fresh water and marine water are saturated with respect to CaCO$_3$ individually, mixing the two can result in a solution that is undersaturated, and therefore capable of further dissolution (Bottrell, et al., 1993).

Due to density differences, organic material may collect at either of the lens interfaces. The decay of this material may result in the production of CO$_2$, leading to further carbonate dissolution. Should sufficient material collect, the waters may actually become anoxic through complex reactions, producing sulfur that may combine to form even more acids and therefore driving more dissolution (Mylroie and Carew, 1995).
Flank margin caves initiate as small voids, which intersect other neighboring voids as they grow. Irregular, finger-like protrusions may also develop as a cave grows, possibly in directions of higher groundwater flow rate or due to irregularities in the rock (Mylroie et al., 1995a). This mode of formation results in a very distinct morphology, such as highly curvilinear surfaces and dead-end passages. Due to the shape and position of the fresh-water lens, these caves also have small vertical extents, but large lateral extents (Figure 8).
Figure 8  Map of a flank margin cave showing considerable lateral extent, but limited vertical extent.
Blue Holes

Blue holes are defined by Mylroie et al. (1995b, p.225) as “subsurface voids that are developed in carbonate banks and islands; are open to the earth’s surface; contain tidally- influenced waters of fresh, marine, or mixed chemistry; extend below sea level for a majority of their depth; and may provide access to submerged cave passages.” They have been documented in the Bahamas for over 100 years, and studied scientifically for 30 years.

Blue holes are named for their deep blue color caused by their great depth, and the term is generally associated with the Bahamas. According to Mylroie et al (1995b), there are four processes by which blue holes are believed to form: 1) Surface vadose karst features such as pits and sinkholes are flooded as sea level rises due to glacial-eustacy (Figure 9A), 2) Deep subsurface voids may prograde to the surface, or shallow subsurface voids may subside to greater depths as a result of sea level change, and then prograde upwards (Figure 9B), 3) Voids produced by dissolution along the ascending halocline of a fresh-water lens may enlarge to blue hole dimensions (Figure 9C), and 4) Flooded fissures may form due to the mechanical failure of carbonate bank margins (Figure 9D). A blue hole may be located inland, thereby termed an “inland blue hole”, or they may be found on the submerged bank, in which case they are termed “ocean holes” (Mylroie et al., 1995b, p.230-231).

Alternatively, Whitaker and Smart (1997) describe three general types of blue holes. The first kind consists of circular, vertical shafts and can be up to 200m deep. They refer to these as cenotes after similar features in the Yucatan Peninsula of Mexico. The
second type of blue hole is a laterally extensive but primarily horizontal cave system, which may be opened to the surface by roof collapse. The third type of blue hole develops linearly along bank-margin fracture systems, and tends to be vertically extensive. As Mylroie et al. (1995b) explain, the definition and use of the term blue hole has varied greatly over time and tends to depend upon the background of the author.

Cave Surveying

Cave surveying involves collecting data from within a cave that will later lead to the production of a map of that cave (Dasher, 1994). The survey process can be as simple as roughly sketching the inside of the cave, or as complex as making azimuth and inclination measurements with errors of less than 0.5 degrees, and distance measurements with errors less than a centimeter. The results of the survey range from a basic, 2D paper representation of the cave with little detail, to an advanced and highly precise 3D computer model.

The process of cave surveying generally involves using simple, durable, yet accurate instruments for measurement of length and orientation. Measurements of azimuth, inclination, and distance are taken between stations, which are generally situated at important locations such as passage intersections, or distinct features. This data will produce a line plot that shows the general shape of the cave. Often, a sketch of the cave interior is made at the same time the survey is taking place, so that once the survey data is reduced and the line plot is constructed, the sketch can be fitted to the line plot to create a relatively accurate and detailed representation of the cave.
Figure 9  Diagram showing four proposed methods of Blue Hole formation (Modified from Mylroie et al., 1995b)
Geographic Information Systems

A Geographic Information System, or GIS, is a computer based set of tools used to model and analyze geographic information (Ormsby et al., 2004). Digital representations of real world objects or situations can be incorporated into maps for visual interpretation, statistical analysis, etc. These maps are made up of a collection of layers, typically in the form of features or surfaces. Features and surfaces represent different methods for modeling the real world. Features generally represent discrete objects such as buildings, roads, and cities, whereas surfaces generally represent continuous information such as elevation, or temperature. It is possible, however, to model some objects using features or surfaces, depending on the purpose of the project.

The use of a GIS in the field of cave and karst science is becoming increasingly popular and they have proven to be invaluable in environment protection and resource management. For example, a GIS has been used to model and analyze the impacts of the proposed I-66 corridor on known cave systems in Pulaski County, KY (Florea et al. 2002). Many caves contain endangered species, which may be endemic to that particular cave, or rare formations that take thousands to millions of years to grow. GIS can help to alleviate the stress on cave resources, for example, by determining the least destructive location of the I-66 corridor. Other benefits of GIS in karst science include the area of public safety. Predicting areas prone to sinkhole collapse, or managing aquifer recharge areas such as the Edwards Aquifer, which supplies water to over 1.5 million people in San Antonio, TX are just a couple of examples of how this technology is extremely useful (Veni et al., 2001).
**Geodatabases**

A geodatabase is essentially a relational database that stores geographic information. It is based on the relational model of data introduced by Codd (1970). There are two main concepts in the relational model: relations, and relationships. Relations, or entities, are real world objects or concepts, and are often represented in the database as tables. In a relational karst database of the Bahamas, for example, islands and caves would be considered entities, and may therefore be represented by tables named ISLANDS and CAVES.

Each table in a relational database contains a set of properties, called attributes, which describe and/or identify each instance in the table. These attributes are each assigned to a column. Attributes are typically of a specific data type, such as integer or string, and restrictions may be placed on the possible values of an attribute. These restrictions, which are called domains, can help to reduce data entry errors and minimize internal contradictions. An example of a domain might be cave type, such as flank margin cave, vadose pit, or banana hole. Each instance is stored in a row, or tuple, in the table, and in the relational data model, no two tuples may contain exactly the same combination of attributes (Gao, 2005).

A primary key is an attribute, or set of attributes that uniquely identifies a tuple. For example, an ID value may be assigned as an identifier, which may involve suffixing the table name with “id” (i.e. CAVE_ID), and in this case the primary key would be the single CAVE_ID value (Gao, 2005). A tuple may also contain a combination of attributes that acts as an identifier, called a multivalued key. A multivalued key may be more
descriptive of the entity type it identifies, but it may also limit the ability to update those
attributes. A surrogate key may be used instead, which is essentially a computer-
generated value that will act as the primary key. Each entity type may also have more
than one key, and in this case, each key is called a candidate key. In the relational data
model, no primary key can have a null value, which is referred to as the entity integrity
constraint (Gao, 2005).

Relationships are associations among two or more entities. In the Bahamian
relational karst database example above, the ISLAND and CAVE tables may be related
because an island may contain caves, and each cave belongs to an island. This is an
example of a one-to-many relationship because each cave may only belong to one island,
but an island may contain many caves. Other types of relationship types include one-to-
one, and many-to-many (Peterson, 2002). One-to-one relationships are not often used,
except in unusual circumstances. Many relational database management systems
(RDBMS) do not support many-to-many relationships directly. Instead, a combination of
one-to-many tables linked by a junction table may be used (Gao, 2005). In a one-to-many
relationship, the table on the “one” side of the relationship is generally referred to as the
parent table, while the table on the “many” side is referred to as the child table. To
establish a relationship, the primary key from the parent table must exist in the child table
as a foreign key (Figure 10). Just as is the case with primary keys, foreign keys may not
contain null values. It is possible for a table to be a child table in one relationship, and a
parent table in another relationship (Peterson, 2002).
In designing a database, steps must be taken to properly organize the data into tables so that there is a minimum amount of redundancy. This process of data organization is called normalization, and helps to reduce problems with data consistency. The degrees of database organization are referred to as normal forms, and range from first normal form (1NF) to fifth normal form (5NF). The normal forms are cascading, meaning that in order for a database to be in 2NF, it must first be in 1NF, and so on. First normal form requires that all repeating attributes are removed and placed in a separate table (Figure 11A). Second normal form requires that redundant data be removed and placed in a separate table (Figure 11B). To be in third normal form, all columns not dependant on the primary key are removed (Figure 11C). Fourth normal form involves isolating independent multiple relationships, and the fifth normal form isolates semantically related multiple relationships. In most cases it sufficient for a database to be in 3NF. Proceeding to 4NF and 5NF may result in reduced system performance such as increased query processing times (Peterson, 2002).

Figure 10  Example of a one-to-many relationship; the primary key (PK) in the parent table is present in the child table as a foreign key (FK)
Queries and other data access processes are most often accomplished using Structured Query Language (SQL – pronounced “sequel”). SQL is a database independent language, meaning that it functions within a variety of database applications. There are actually three sub-languages contained within SQL. Data Definition Language (DDL) involves the creation, alteration, and deletion of tables and columns. Data Manipulation Language (DML) involves the “select”, “insert”, “update”, and “delete” commands responsible for manipulating data within tables. Data Control Language (DCL) involves granting data manipulation permissions to certain users, and is only available in limited database applications (Peterson, 2002).

A geodatabase applies the technology of the relational data model to the realm of geographic data, and it provides a central repository from which to manage these data (Zeiler, 1999). Benefits of the geodatabase model include more accurate data entry and editing, users work with more intuitive data objects, features have a richer context due to the ability to model topological and spatial relationships, and overall better maps can be made, just to name a few.

In the Bahamas, Robinson and Davis (1999) created a GIS database for San Salvador Island. Some of the data layers in this project included cave locations, roads, contours, settlements, archaeological sites, beaches, wetlands, and lakes. The San Salvador GIS Database is presented as an ArcView project. Roth (2004) created an inventory of many of the cave and karst features of the Bahamas. To date, no known karst geodatabase has been created for the entire country.
Figure 11 Methods for normalizing databases relations. (A) Converting to first normal form (B) Converting to second normal form (C) Converting to third normal form (Modified from Toepke, 2006)
CHAPTER IV

METHODOLOGY

Data Collection

Cave and karst data for the Bahamas was collected from a variety of existing sources, including previous Master’s Theses and various other publications. Some caves were located, mapped, and added to the database as a direct result of fieldwork related to this thesis. This information included cave names, locations, cave maps, and other distinguishing features. GIS data was obtained from sources such as the existing San Salvador Island GIS database and the USGS.

Geodatabase Development

The collection of data concerning each cave and karst feature was stored in a geodatabase to promote efficient viewing and editing of the data. This information was then extracted from the database to produce layers for the GIS that dynamically respond to changes in the database. The attributes that were stored for each karst feature include the UTM zone, UTM datum, location based on UTM coordinates, location accuracy, feature name, feature type, the island on which the feature is located, elevation, survey grade, penetration direction, and relative path names to store the location of html pages and map images for each image where available. The attributes were stored in a table called Bahamas_Karst.
A new geodatabase was created in ArcCatalog 9.0 (ESRI, 2005). Microsoft Access (Microsoft, 2000a) was used as the Database Management System (DBMS), and the database is in third normal form (3NF). In order to maintain 3NF, the island on which a cave is located, the type of karst feature, the survey grade, and the location accuracy information were stored in the master cave table as codes (Tables 1 – 4).

Table 1  Islands currently included in the Bahamian Cave and Karst database, and their corresponding island codes

<table>
<thead>
<tr>
<th>Island Name</th>
<th>Island Code</th>
<th>Island Name</th>
<th>Island Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaco Island</td>
<td>AB</td>
<td>Long Island</td>
<td>LI</td>
</tr>
<tr>
<td>Acklins Island</td>
<td>AC</td>
<td>Mayaguana</td>
<td>MA</td>
</tr>
<tr>
<td>Bimini</td>
<td>BI</td>
<td>North Andros Island</td>
<td>NA</td>
</tr>
<tr>
<td>Cat Island</td>
<td>CA</td>
<td>New Providence Island</td>
<td>NP</td>
</tr>
<tr>
<td>Crooked Island</td>
<td>CR</td>
<td>Rum Cay</td>
<td>RC</td>
</tr>
<tr>
<td>Eleuthera Island</td>
<td>EL</td>
<td>South Andros Island</td>
<td>SA</td>
</tr>
<tr>
<td>Exuma Island</td>
<td>EX</td>
<td>San Salvador Island</td>
<td>SS</td>
</tr>
<tr>
<td>Grand Bahama Island</td>
<td>GB</td>
<td>Turks and Caicos Islands</td>
<td>TC</td>
</tr>
<tr>
<td>Great Inagua</td>
<td>GI</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 2  Feature types currently included in the Bahamian Cave and Karst database, and their corresponding codes

<table>
<thead>
<tr>
<th>Feature Type</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banana Holes</td>
<td>BH</td>
</tr>
<tr>
<td>Blue Holes</td>
<td>BL</td>
</tr>
<tr>
<td>Closed Depressions</td>
<td>CD</td>
</tr>
<tr>
<td>Collapse Features</td>
<td>CF</td>
</tr>
<tr>
<td>Discharge Features</td>
<td>DF</td>
</tr>
<tr>
<td>Flank Margin Caves</td>
<td>FM</td>
</tr>
<tr>
<td>Man-made Features</td>
<td>MM</td>
</tr>
<tr>
<td>Non-karst Features</td>
<td>NK</td>
</tr>
<tr>
<td>Perched Caves</td>
<td>PC</td>
</tr>
<tr>
<td>Sea Caves</td>
<td>SC</td>
</tr>
<tr>
<td>Tafoni Caves</td>
<td>TF</td>
</tr>
<tr>
<td>Unknown Origin</td>
<td>UK</td>
</tr>
<tr>
<td>Vadose Pit</td>
<td>VP</td>
</tr>
</tbody>
</table>

### Table 3  Location accuracies currently included in the Bahamian Cave and Karst database, and their corresponding codes

<table>
<thead>
<tr>
<th>Location Accuracies</th>
<th>Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS locations +/- 5 m</td>
<td>1</td>
</tr>
<tr>
<td>GPS locations +/- 10 m</td>
<td>2</td>
</tr>
<tr>
<td>GPS locations +/- 25 m</td>
<td>3</td>
</tr>
<tr>
<td>GPS locations +/- 50 m</td>
<td>4</td>
</tr>
<tr>
<td>GPS locations with unknown accuracies</td>
<td>5</td>
</tr>
<tr>
<td>Topographic map locations</td>
<td>6</td>
</tr>
<tr>
<td>Other map locations</td>
<td>7</td>
</tr>
<tr>
<td>Estimated locations</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 4 Survey Categories currently included in the Bahamian Cave and Karst database, and their corresponding codes

<table>
<thead>
<tr>
<th>Survey Category</th>
<th>Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>No survey</td>
<td>0</td>
</tr>
<tr>
<td>1: sketch with no measurements</td>
<td>1</td>
</tr>
<tr>
<td>2: better than grade 1 but less than grade 3</td>
<td>2</td>
</tr>
<tr>
<td>3: Angles +/- 2.5°, distance +/- 20 cm</td>
<td>3</td>
</tr>
<tr>
<td>4: better than grade 3 but less than grade 5</td>
<td>4</td>
</tr>
<tr>
<td>5: Angles +/- 1°, dist +/- 0.3 cm</td>
<td>5</td>
</tr>
<tr>
<td>6: better than grade 5</td>
<td>6</td>
</tr>
<tr>
<td>Surveyed but grade unknown</td>
<td>7</td>
</tr>
</tbody>
</table>

These codes were then linked to child tables by one-to-many relationships. The island shape layer also included island codes instead of full island names to minimize data redundancy. A simple form was also created from which users may view or update cave information. Domains were included to ensure that coded information is not entered erroneously.

In order to view the cave and karst features in a GIS, the Bahamas_Karst table was added to the working dataframe in ArcMap (ESRI, 2005). UTM coordinates were then viewed as X-Y data with the Easting coordinates used as the X-value, and the Northing coordinates used as the Y-value. The final step before viewing the features was to select the projection in which the data will be viewed. All GIS layers used in this project were in the NAD 1927 projection, which is based on the Clarke 1866 datum. This is the same datum on which all maps in the Bahamas are based, and should therefore minimize data entry errors for future additions. The resulting “Bahamas_Karst” layer displays all of the Bahamian karst features in the geodatabase, which can then be subset to individual islands using an SQL definition query.
A simple polygon layer representing the shape of each island in the archipelago was also added to the database. This information was obtained from a USGS geodatabase titled “Geology, Oil and gas Fields, and Geologic Provinces of the Caribbean Region” by French and Schenk (2004). This data was used to provide a simple background on which the cave and karst feature data were displayed for the purpose of map production.

**GIS Analysis**

**Creation of a Digital Elevation Model**

As previously noted, Robinson and Davis (1999) published a GIS database for San Salvador Island that includes layers such as cave locations, contours, and lakes. This existing data was used in conjunction with recent additions to perform an initial analysis of cave and karst features on the island and to demonstrate the value of the geodatabase and its potential for future analysis.

The first step in the analysis was to create a digital elevation model (DEM). This was necessary in order to obtain elevation data for all of the karst features. The data on which the DEM was based was a layer called “ContoursTemp”, which was made from the “Contours” layer, “Coastline” layer, and “Lakes” layer from Robinson and Davis (1999). The original “Contours” shapefile contained contour lines with values in feet, therefore metric measurement was not used at this point. Contour lines in this layer had an interval of 10 feet, and ranged in elevation from 10 feet to 120 feet. As some karst features are found between zero and 10 feet in elevation, the “Lakes” layer and “Coastline” layer were used to create contour lines with zero elevation. This was
accomplished by adding all three layers to the active dataframe, and editing the “Contours” layers by copying all of the polygons from the “Lakes” layer, and the polygon that represented the coastline to a copy of the “Contours” layer. These polygons were then given a value of zero in the CONTOUR column of the “Contours” layer’s attribute table. The edits were saved and the shapefile was renamed as “ContourTemp”, which contained contour lines with an interval of 10 feet, and a range of zero to 120 feet. Layers were later converted to metric values.

The digital elevation model was created from the CONTOUR data in the “ContoursTemp” layer via two methods (Figure 12). The first method involved an inverse distance weighted interpolation of point data created from the contour lines. A temporary raster layer was created by converting the contour lines to raster. A 10 m cell size was used, and each pixel in the layer that represented part of a contour line had a value equivalent to that of its corresponding contour line. The raster layer was then converted back to a feature file, with point features representing the location of the centroid of each of the “contour line” pixels. The layer containing all of the new points was saved as “Contour_pts.”

The “Contour_pts” layer was then divided into two subsets. The “training” subset consisted of 90% of the original points and served as the input data for the interpolation. The interpolation based new pixel elevation values on the pixel’s 100 nearest neighbors and used a power of “2” within the calculation. The resulting raster had a cell size of 10 m and was saved as “idw_100pts.” The remaining 10% of the points in the “test” set was used to test the accuracy of the interpolated values, as will be explained later.
The second method used to create a digital elevation model from the “ContourTemp” layer first involved creating a triangulated irregular network (TIN). The TIN was then converted to a raster, and saved as “tin2dem.”

Figure 12 Flowchart showing two processes used to create digital elevation models from a contour line shapefile

Comparison of Digital Elevation Models

In order to compare the two digital elevation models, their elevation values were compared to the original elevation values found in the “test” subset, which had been subset from the “Contour_pts” layer. Originally, the “Contour_pts” layer contained over 160,000 pts. The “test” subset contained 10% of the points, or approximately 16,000 points. Five subsets were then created from the original “test” subset, with the new “training” subsets containing 95% of the points, and the new “test” subsets containing...
The new “training” subsets were discarded, resulting in five testing sets of approximately 800 points. These five sets were labeled truth_pts1, truth_pts2, truth_pts3, truth_pts4, and truth_pts5.

A zonal function was then used to extract elevation data from each of the digital elevation models. Zonal functions extract values from a raster layer based on an input “zone dataset” layer. A “truth_pts” subset was used as the zone dataset, the PT_ID attribute as the zone field, and the DEM as the value raster. The result was a DBF file containing elevation data from the DEM at locations corresponding to those points in the zone dataset. This procedure was repeated for all five subsets and for both DEMs. The elevation data from the DBF files were then copied to a Microsoft Excel (Microsoft, 2000b) spreadsheet for comparison. The five subsets were considered “truth” for each test, and the amount to which each DEM varied from the true values was calculated for each point in the set. The root mean square error was used to compare each DEM, which was calculated by summing the squares of each point’s deviation from the expected value, dividing by the number of points, and then taking the square root of the fraction.

Comparing Karst Feature Elevations

Once the most suitable DEM was determined it was used to calculate the elevation of each karst feature on San Salvador Island. This was accomplished using a zonal function. First, the “Bahamas_Karst” layer was subset to display only features on San Salvador Island using a definition query in the layer’s property menu. This data was then exported to a shapefile called “SS_karst”. The San Salvador karst layer was then subset to display one of three different karst types: flank margin caves, banana holes, and
vadose pit caves. Again, this was accomplished using a definition query. Once the “SS_karst” layer was subset to a specific karst type, a zonal function was used to extract elevation data for each feature. The karst layer was used as the zone dataset, name as the zone field, and the digital elevation model of San Salvador as the value raster. The process produced a DBF file containing elevation data for each of the karst features. This process was repeated for each of the three karst types, and the DBF files were then converted to Microsoft Excel (Microsoft, 2000b) workbook (*.xls) files for easier manipulation. Feature elevation data were then plotted for each of the karst types in order to compare the characteristics of each karst type visually.

Comparing Flank Margin Cave Morphologies and Topographic Attributes

Tests were performed to correlate the morphologies of flank margin caves to spatial properties such as slope, aspect, and elevation. Perimeter, footprint area, and the resulting perimeter to area ratios for 20 caves were obtained from a previous study by Roth (2004). Entrance types were determined from the available cave maps. Cave entrances were classed as horizontal if the majority of the entrances were horizontal, vertical if the majority of the entrances were vadose pits or breakdowns, or mixed if there were equal numbers of horizontal and vertical entrances (Table 5). Roth (2004) calculated footprint area as the cave’s total area minus the area of bedrock columns, and total perimeter as the outside perimeter of the cave plus the perimeter of bedrock columns within the cave.
Table 5  Cave entrance types

<table>
<thead>
<tr>
<th>Cave Name</th>
<th>Entrance Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closet Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Reckley Hill Pond Maze Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Midget Horror Hole</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Emerald Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Bug City Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Crescent Top Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Reckley Hill Pond Water Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Dance Hall Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>George Storr's Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Dripping Rock Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Altar Cave</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Pipe Cave</td>
<td>Mixed</td>
</tr>
<tr>
<td>Chinese Firedrill Cave</td>
<td>Mixed</td>
</tr>
<tr>
<td>Blowhole Cave</td>
<td>Mixed</td>
</tr>
<tr>
<td>Major's Cave</td>
<td>Mixed</td>
</tr>
<tr>
<td>Garden Cave</td>
<td>Mixed</td>
</tr>
<tr>
<td>Beach Cave</td>
<td>Mixed</td>
</tr>
<tr>
<td>Granny T's Cave</td>
<td>Vertical</td>
</tr>
<tr>
<td>Old Bottle Cave</td>
<td>Vertical</td>
</tr>
<tr>
<td>Lighthouse Cave</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

Slope was obtained by taking the first derivative of the digital elevation model. The output of this process was a raster layer with each pixel containing a slope value. A zonal function was then used to extract the slope value at each cave location. Aspect was calculated from the DEM, and again a zonal function was used to extract aspect values for each cave. Cave perimeters, areas, and perimeter to area ratios were each plotted against slope, aspect, and elevation in Microsoft Excel (Microsoft, 2000b) to determine if any relationships existed.

Histograms of total hill slope and aspect for San Salvador Island were also created by calculating the total land area within each classification. The slope layer was classified
into intervals of 10%, with all slopes above 100% classified as a single group. This layer was then masked to select only slopes below 10 m in elevation, as well as to remove Holocene dunes and members of the Cockburn Town formation. The total number of pixels for each slope classification were obtained from the attribute table and multiplied by 100 m² to calculate area for the histogram. The aspect layer was reclassified into the eight cardinal directions (with 45° coverage for each direction), and a ninth classification for flat areas. This layer was then multiplied by a mask to remove areas above 10 m, Holocene dunes and members of the Cockburn Town formation, which could not participate in flank margin cave development as they are too young. The total number of pixels in each classification were obtained from the attribute table and multiplied by 100 m² to calculate total area for the histogram.

The digital elevation model was also used to display the position of cave and karst features relative to sea level during the last interglacial highstand (OIS 5e). Because sea level during the last interglacial highstand is predicted to be 6 m above current level, but there has been approximately 2 m of subsidence in the Bahamas since then, the “virtual” sea level in the GIS was raised 4 m. Any pixels in the DEM containing a value less than 4 m were colored blue, while the remaining pixels varied in colors to represent the elevation above sea level.

Creation of a Simple Database Management Program

In order for the Bahamian Cave and Karst database to be effective and efficient, it must be easy to update and edit, and should be at least minimally self-sufficient. The most basic way of editing this database is to open the database file in Microsoft Access
(Microsoft, 2000a) directly. This provides a user with direct access to all of the database’s tables, forms and queries, but requires that the user maintain a minimum level of knowledge with the Microsoft Access program.

To simplify the process of data entry, a Bahamian Cave and Karst program has been created to provide a user-friendly environment for users who are less familiar with MS Access (Microsoft, 2000a). The program was written using the Visual Basic .NET (Microsoft, 2003) software and is directly linked to the database. It provides a simple data entry form into which the user will enter pre-defined data requirements and will not require the user to manipulate the database environment at all. Domains similar to those used in the geodatabase creation ensure that the user enters the appropriate type of data, thereby maintaining the integrity of the database. The program requires the user to fill a minimum number of fields within the data entry form in order to further maintain database integrity. In non-critical fields, a default value is provided as a “no data” value.

The data entry form allows a user to upload a map of the karst feature, which is automatically copied to the appropriate directory within the project file structure. The location of the file is stored within the database. Features with no map are assigned an image stating that no map is available for the feature.

The Bahamian Cave and Karst (BCK) program works in conjunction with a web page structure, which is used as a simple display tool for data such as island and karst feature maps. If a new feature is added to the database using the BCK program, the program automatically creates a web page for that feature and inserts a hyperlink into the appropriate parent island page. The new feature web page displays either the map of the
feature or the “no map” image, depending on the path that has been stored in the database. The BCK web pages are also used as an access point to other types of files such as GIS map files, cave survey and sketch files, autocad files, and even available literature specific to an island or feature. The initial web page structure was created using Microsoft FrontPage (Microsoft, 2000c). In order to perform more complicated tasks within the database, such as adding a new feature type, a user is required to edit the database directly. This also applies to the web pages. Making advanced changes to the web page layout will have to be done in an HTML editor.
CHAPTER V

RESULTS

Data Collection. Geodatabase Development, and Data Accessibility

Currently the Bahamian Cave and Karst Database contains 217 karst features from nine islands (Table 6). Each feature in the database includes information such as UTM zone, UTM datum, location based on UTM coordinates, location accuracy, feature name, feature type, the island on which the feature is located, elevation, survey grade, penetration direction, and relative path names to store the location of html pages and map images for each image where available.

Table 6 The number of cave and karst features currently present in the Bahamian Cave and Karst Database, sorted by island

<table>
<thead>
<tr>
<th>ISLAND</th>
<th>FM</th>
<th>BL</th>
<th>BH</th>
<th>CF</th>
<th>DF</th>
<th>SC</th>
<th>VP</th>
<th>TF</th>
<th>PC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaco</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>14</td>
<td>1</td>
<td>33</td>
</tr>
<tr>
<td>Cat Island</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Crooked</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Eleuthera</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Exuma</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Long Island</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>New Providence</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>South Andros</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>San Salvador</td>
<td>25</td>
<td>1</td>
<td>42</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>59</td>
<td>0</td>
<td>0</td>
<td>131</td>
</tr>
</tbody>
</table>
The geodatabase consists of six main data tables. The Bahamas_Karst table shares one-to-many relationships with the Islandcodes table, the Accuracy_Information table, the Cave_Type table and the Survey_Grade table. The Bahamas_Boundaries table shares a one-to-many relationship with the Islandcodes table (Figure 13). Information in the Bahamas_Karst table can be edited directly in Microsoft Access (Microsoft, 2000a), or through the use of the Bahamian Caves and Karst (BCK) Program (Figure 14). The BCK program allows the user to view all of the records in the database and add or edit records as necessary. Links are also available to view the cave and karst feature web pages, as well as to open the MS Access file containing the database. The web pages are openly accessible, whereas the record editor and MS Access link require the user to input a password in order to gain access.

The cave and karst web page collection contains a homepage from which users may navigate to individual island pages. Each island page contains hyperlinks to the cave and karst features on that island (Figure 15). A user may also access other data such as cave survey files, cave sketch files, AutoCAD files, GIS files, and scientific literature pertaining to the study area.
Figure 13  The six main tables in the Bahamian Cave and Karst database, and their relationships

Figure 14  Screenshot of the Bahamian Cave and Karst program
Two digital elevation models were created in this project from a shapefile containing contour line data using two different methods. An inverse distance weighting interpolation was used as the first method, and a raster created from a triangulated irregular network comprised the second method for DEM generation. The two DEMs were compared based on the root mean square error from five separate tests. Each of the DEMs was compared to five test sets containing 800 “truth” points. The DEM generated from the TIN had an average root mean square error of 0.54 meters, whereas the DEM created using the IDW interpolated had an average root mean square error of 1.0 meters. The DEM created from the TIN (tin2dem) had superior RMSE and was chosen for elevation analysis in this project. The results of the comparison are illustrated in Table 7.
Table 7  Results of the root mean square error comparison between digital elevation models

<table>
<thead>
<tr>
<th>Test Set</th>
<th>Root Mean Square Error (ft)</th>
<th>IDW_100pts</th>
<th>Tin2dem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pts_test1</td>
<td>2.96</td>
<td>1.61</td>
<td></td>
</tr>
<tr>
<td>Pts_test2</td>
<td>3.32</td>
<td>1.88</td>
<td></td>
</tr>
<tr>
<td>Pts_test3</td>
<td>3.56</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>Pts_test4</td>
<td>3.56</td>
<td>1.94</td>
<td></td>
</tr>
<tr>
<td>Pts_test5</td>
<td>3.19</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td><strong>3.31</strong></td>
<td><strong>1.78</strong></td>
<td></td>
</tr>
</tbody>
</table>

Comparing Karst Feature Elevations

Elevations for banana holes, vadose pits and flank margin caves, the three prominent karst feature types on San Salvador Island, were extracted from the “tin2dem” DEM. The elevation values for each feature type were plotted to show any trends in the data. Banana hole elevations show an obvious plateau at approximately 5 – 6 meters. Of 42 features, only seven are more than two meters above or below this plateau (Figure 16). Vadose pit caves range in elevation from one to 26 meters, with a small plateau at approximately six meters (Figure 17). Flank margin cave elevations range from zero to nine meters, but all but three of the 25 features are below seven meters (Figure 18). Figure 19 shows a comparison of banana hole, vadose pit and flank margin cave elevations. If flank margin cave elevations are plotted against cave size rank and P/A ratios as determined by Roth (2004), neither chart shows an obvious relationship (Figure 20). As the distribution of elevations is not normal, Spearman’s rho was used to describe correlation. Rank vs. Elevation and P/A vs. Elevation have correlation values of 0.288 and –0.251 respectively, again showing no relationships.
Figure 16  Chart showing banana hole elevations on San Salvador Island, Bahamas
Figure 17  Chart showing vadose pit elevations on San Salvador Island, Bahamas
Figure 18  Chart showing flank margin cave elevations on San Salvador Island, Bahamas
Figure 19  Chart showing comparison of banana hole, vadose pit and flank margin cave elevations
The “tin2dem” digital elevation model has also been used to display the spatial patterns of the cave and karst features depicted in Figures 16 - 18 above. By reclassifying the raster layer it can be used to represent the topographic setting on San Salvador Island as it would have appeared during the last interglacial highstand (Figure 21). One can see that most of the flank margin caves are located at the shoreline, banana holes are found primarily on broad, flat terraces, and vadose pits do not demonstrate a preference for any specific topographic condition. From the DEM one can also see that during the last interglacial highstand there were at least four sizable lakes on San Salvador Island. No flank margin caves are found on the shore of any of these lakes.
Figure 21  Map of San Salvador Island showing positions of cave and karst features relative to sea level during the last interglacial highstand (arrows indicate position of isolated lakes)
Comparing Flank Margin Cave Morphologies and Topographic Attributes

Flank margin caves can have a great variety of shapes and sizes, and can be found in a variety of topographic conditions within a limited elevation range throughout San Salvador Island. Where data were available, morphological properties such as perimeter, area, perimeter to area ratio, and entrance type for each cave were plotted against topographic conditions such as slope and aspect to determine if topography controls the shape and size of a cave in any way.

Slope

When a cave’s primary entrance type is plotted against slope, the graph shows that horizontal, vertical, and mixed entrance types may be found in similar hill slope conditions (Figure 22). Horizontal entrances are the most common, and can be found on slopes ranging from 4.5 % to over 150 % (degrees slope). Mixed entrance types are the second most common, and can be found on slopes ranging from 0 % to nearly 70 %. Caves that have mostly vertical entrances are the least common on San Salvador Island, and can be found on slopes ranging from 25 % to 50 %.
All of the flank margin caves on San Salvador Island for which perimeter and area values are available were ranked based on cave footprint area by Roth (2004). According to Roth (2004), the smallest flank margin cave on San Salvador Island is Granny T’s Cave, whereas Lighthouse Cave is the largest. If cave ranks are plotted against slope, the chart does not show any obvious relationships, which is also supported by a Spearman’s correlation coefficient of 0.029 (Figure 23). Dance Hall cave, which is ranked 13th in size shows the greatest slope at approximately 153%, whereas Blowhole Cave, which is ranked 10th in size, shows 0% slope. Lighthouse Cave has a slope at the main entrance of
and Granny T’s Cave has a slope of 25 %. The histogram of cave slopes appears to be positively skewed, which reflects the obvious poisson distribution of hill slopes for the entire island (Figure 24). The majority of the caves on San Salvador Island (65 %) are found on slopes less than 50 %, with a median slope of approximately 45 %.

If cave perimeter and footprint area as calculated by Roth (2004) are each plotted against slope, the perimeter and area shapes are similar, but neither appears to be related to the steepness of the hill slope on which on the cave is found (Figure 25). Perimeter vs. slope and area vs. slope show no correlation with Spearman’s correlation coefficients of 0.235 and 0.026 respectively. Dividing the cave’s perimeter by its area gives a ratio that roughly describes the shape and bedrock column content of the cave. A cave that has a high perimeter to area ratio generally contains many columns, a highly irregular outline, or long, narrow passages. A cave that has a low perimeter to area ratio generally has fewer columns and approaches a circular chamber shape. All of the caves on San Salvador Island with a perimeter to area ratio greater than or equal to 1.0 are found on slopes greater than approximately 20 %, whereas caves with a P/A ratio less than 1.0 may be found on slopes ranging from 0 % to nearly 90 % (Figure 26). The Spearman’s correlation coefficient for this comparison is 0.305, showing no correlation.
Figure 23  Chart showing hill slope at a cave’s entrance plotted against the cave’s size rank
Figure 24  Histogram showing distribution of cave slopes on San Salvador Island compared to the total distribution of hill slope by area
Figure 25 Chart showing cave perimeter and area plotted against the slope of the hill on which the cave is found.
Figure 26  
Chart showing cave perimeter to area ratio plotted against the slope of the hill on which the cave is found
Aspect

Aspect refers to the direction that a hill slope surface is facing. A histogram of cave aspects was created to determine whether the orientation of the eolian dunes in which flank margin caves form control cave formation (Figure 27). The histogram appears to be bimodal and negatively skewed. The two modes appear at the South and Northwest aspects while no caves exist on a slope with a Northeast aspect. The pattern approximately resembles the overall distribution of slope aspects on San Salvador Island (Figure 27).

If cave aspects are plotted over the entire 360° azimuth, all but five caves appear on a slope with an aspect between 180° and 360° (Figure 28). This illustrates the relative distribution of aspects and the clumping of caves at aspects of approximately 180-190° and approximately 300-320°. There is an obvious gap between approximately 10° and 110°. When cave size rank and P/A ratio is plotted against aspect, there does not appear to be any relationship (Figure 29), which is supported by Spearman’s correlation coefficients of 0.194 and –0.203 respectively.
Figure 27  Histogram of cave slope aspects on San Salvador Island compared to total area for each aspect
Figure 28  Distribution of cave aspects through 360 degrees
Figure 29  Chart showing size rank and aspect plotted against slope aspect
CHAPTER VI

DISCUSSION

Data Collection

Over 200 cave and karst features from nine Bahamian islands have been recorded and included in this project. Most of these features are found on only a few islands, and this is generally accepted as the result of an explorational bias. Many islands are remote and difficult to reach or have limited resources available for researchers. Islands such as Abaco Island and New Providence Island, however, are more easily accessible and already have established research communities. San Salvador Island is home to the Gerace Research Center, which provides researchers with access to resources that may not typically be available elsewhere in the Bahamas. The presence of the research center combined with the relatively small size of the island means it is no coincidence that more cave and karst features have been found on San Salvador Island than all of the other islands combined. Because San Salvador contains the majority of the known karst features in the Bahamas, and GIS data were readily available, San Salvador was chosen as the representative island for cave and karst GIS analysis in the Bahamas.

While the volume of data collected for this project is not exhaustive, the number of resources from which the data originated emphasizes the need to create a single repository for that information. Not only will this make future research more efficient and
complete, but it will also provide a standard by which new data is recorded, thereby 
eliminating inconsistencies. Maintaining the database digitally will ensure that the 
information can be easily shared, or protected, as necessary. It also facilitates database 
maintenance because editing data is much easier when done digitally.

Geodatabase Development and Database Accessibility

A simple database in 3NF consisting of six tables was created to store the cave 
and karst data for the Bahamas. The main Bahamas_Karst tables stores all of the main 
information for each feature, while the remaining five tables store supplemental data such 
as island codes, survey grades etc. While this collection of data was sufficient for the 
analysis performed in this project, the database can be expanded to include more detailed 
information such as landowner information, survey teams, biologic contents, 
archeological relevance, etc. A major benefit of storing the feature attributes in a 
geodatabase rather than in a shapefile is that the data within the database can be easily 
updated, and the changes are automatically reflected in the GIS layers. This process is 
further simplified with the use of a simple data entry/editing program such as the 
Bahamian Cave and Karst Program.

The Bahamian Cave and Karst program developed for this project provides a 
simple means by which data can be entered into the database, and ensures that 
information is entered correctly. As it is the initial version of the program, functions 
available in the program are relatively simple. User defined data are simply added to or 
edited within the database. If the information is a new addition, the program will create a 
new web page for the feature, including a map of the feature if available. The new page is
then linked to the appropriate island page so as to maintain navigation within the web page collection.

Currently the feature name and map image are the only user-defined data added to a feature’s web page and no functions are currently available within the program to handle or manipulate GIS data layers. Future versions of the program may provide the opportunity to include feature descriptions, comments, photos, or links to scientific literature, as well as allow a user to add new feature classes to the database or store new shapefiles within the file structure.

A major limitation to the current version of the program is the inability to edit the cave and karst feature web pages without interfering with the function of the BCK program. Currently the BCK program makes edits to an existing web page based on the HTML structure of that page. Altering that structure without altering the code structure of the BCK program would cause the program to not function properly. Future editions of the BCK program may include a simplified HTML editor so that users may alter a webpage within the BCK program while maintaining the program’s functions. The potential to expand the functionality of the program is only limited by the needs of the researchers using the database.

**Digital Elevation Model Creation and Comparison**

The digital elevation model used in this analysis was created from a GIS layer containing polygons representing contour lines. These contour lines were digitized using topographic maps of the island. While other methods are available for the production of digital elevation models, digitizing topographic maps is relatively inexpensive, especially
if one already possesses the maps. It is likely that any new elevation data for the Bahamas, at least initially, will be in the form of contour lines or points generated from topographic maps. It is possible that the methods used to create the DEM for this analysis will be used for future DEM production when nationwide elevation data becomes available.

Of the two methods discussed in this analysis, the DEM generated from the triangulated irregular network (TIN) proved to contain the least amount of error when tested against known values. A TIN is commonly created using contour lines as input values, and in doing so, generates a surface with realistic slopes between contour lines. This “realism” carries over to the raster version of the surface in smoother transitions between elevations (Figure 30).

The inverse distance weighting interpolator used to create the second digital elevation model is an exact interpolator. This means that the surface created by the interpolation will adhere to the original input elevations almost exactly. In order to compare the two DEMs in an unbiased manor, the interpolated DEM was created using only 90% of the elevation points from the “contour_pts” layer as described above. The remaining 10% of the points were used to evaluate how well the DEM predicted elevations between input points.
As the TIN is generated directly from the contour lines, the inherent error in the TIN-derived DEM is created during the conversion from TIN to raster. On the other hand, in order to interpolate a DEM from contour lines, the contour lines must first be converted into a vector point file. This process involves two steps in which error is created (Figure 31). These two steps effectively shift the position of the original contour line creating inconsistencies between the new point values and the original contour line values.
Another problem inherent in the interpolated DEM is that unlike the TIN-derived DEM, which generally creates smooth transitions in elevation, the interpolated DEM has a tendency to join two relatively flat areas with a steep “cliff”, usually between two contour lines (Figure 32). Because the input points are not evenly distributes about the map, but instead occur in long lines of points with the same values, there are areas on the map where the nearest 100 neighbors all have the same value. This produces “flat” areas next to the contour lines. There are also narrow areas between contour lines in which some of the neighbors are from the upper contour, while the rest are from the lower. This produces abrupt changes in elevation and creates the stair-step appearance of the DEM. While the interpolated DEM can be expected to be relatively accurate near the contour lines, it is obvious that the interpolation method creates unrealistic topography between
contour lines. Surface analysis functions such as slope and roughness would be highly unreliable if created from the interpolated DEM.

Figure 32  Map showing abrupt elevation changes located between contour lines generated by the IDW interpolation

**Comparing Karst Feature Elevations**

A major characteristic used to describe many karst features is their elevation above sea level. As mixing fresh and marine water is a major proponent for carbonate dissolution according to the Carbonate Island karst Model (CIKM), sea level, or elevation relative to sea level is an important classification method for karst features in the Bahamas. According to the analysis of cave and karst features on San Salvador Island, all three of the karst feature types examined fit the Carbonate Island Karst Model as described above.

The majority of Banana Holes on San Salvador Island are found in an obvious horizon on broad flat terraces. As the methods described above involve extracting Banana
Hole elevation based on the land’s surface according to the digital elevation model, most Banana Holes are represented at approximately five to six meters in elevation (Figure 16). These elevation values describe the maximum elevation of the banana hole “chamber”. Dissolution of the original chamber would have occurred at the top of the fresh-water lens, and then due to the relative thin layer of bedrock above the void, progradational collapse would have exposed the void to the surface. The Dupuit-Ghyben-Herzberg model suggests that the top of the fresh-water lens roughly approximates mean sea level. Based on this model, banana hole position may be used as an indicator of past sea levels, or conversely, a digital elevation model may be used to predict areas that may be more likely to contain banana holes. The five banana holes located above 10m in Figure 16 are from the Robinson and Davis (1999) database and their description as banana holes is suspect. It is possible that these five features are vadose pits or progradational collapse features.

Analysis of vadose pit elevations shows that vadose pits may be found at most elevations, with essentially no preference for one specific elevation. This enforces the CIKM description of vadose pit formation. As pit dissolution is obviously not tied to sea level, and therefore mixing zone position, the formation of vadose pit must be entirely caused by dissolution from meteoric waters. This creates a problem in terms of predicting the most likely locations for these features. As rainfall is generally evenly spread throughout an island’s surface, one cannot designate an area most likely to be affected. The depth of a vadose pit, however, is limited by the thickness of the material in which it forms. One would therefore expect the deepest pits to form on or near dune ridges.
Flank margin cave elevations have also shown to be highly predictable. According to the CIKM, flank margin caves should be found between one and seven meters above current sea level. Analysis showed that all but three of the flank margin caves on San Salvador Island fell within this range based on elevations provided by the digital elevation model. Two of the three caves that did not fall within the expected range can be easily explained. The location of Hurricane cave was approximated from a topographic map. On an eolian dune, a location that is off by mere meters may change the elevation of the feature a meter or more. It is possible that the lack of positional accuracy accounts for an elevation of 8.08 m for Hurricane Cave. Lighthouse Cave’s elevation of 8.35 m is most likely the result of an explorational/technical bias. Lighthouse Cave is nearly unique on San Salvador in that all of its entrances are vertical vadose pits, meaning that the “entrance” to the cave is actually higher than the cave chamber itself. The GPS coordinate would have been taken at the surface directly above the cave, resulting in an elevation that is higher than expected according to the DEM. South Breezy Hill Cave is not so easily explained. Its elevation may be an artifact of the DEM creation, or South Breezy Hill Cave may not be a true flank margin cave. Small caves have been found at higher than expected elevations on other islands, and the phenomenon is generally contributed to the perching of a fresh-water lens atop an impermeable terra rosa paleosol.

Elevation as a prediction tool is much more effective for flank margin caves than for other karst features. As was discussed earlier, elevation can be used to predict banana hole locations to some degree, but due to the relatively large areas of low lying terraces on Bahamian islands, elevation is not as “precise” a predictor for banana holes as for
flank margin caves. The relatively narrow elevation “window” in conjunction with the fact that nearly all caves must be found at the periphery of an eolian dune effectively eliminates much of the exposed land surface. This is not to say that locating caves on large islands with extensive dune networks would not be laborious, but it gives researchers a place to start. With the ability to “virtually” raise sea level within the GIS, researchers will also have a visual aid to determine where to start looking.

**Flank Margin Cave Morphologies: Is There Topographic Control?**

Even with nearly three decades of research, explaining the variety of flank margin cave sizes and shapes is still difficult. In this project a simple analysis was performed to attempt to link various cave morphological characteristics to patterns in topography. Slope and aspect were the two main topographic attributes used for comparison, both of which were generated from the DEM. Cave perimeters and areas were obtained from a previous study. Entrance types were determined from the available cave maps.

Perimeter, area, and the perimeter to area ratio were used to quantify a cave’s shape. The perimeter to area ratio is particularly descriptive in that caves with similar extents but different shapes would have very different perimeter to area ratios. Flank margin caves on San Salvador Island demonstrated perimeter to area ratios that ranged from 0.2 to almost 3.0. Some of the caves were single, narrow passages, some were single round rooms, and some were large multi-chamber caves with many bedrock columns.
One might expect hill slope to have some control on the erosional processes that expose flank margin caves and make them accessible to exploration. A cave formed in a gently sloping hillside should be breached more quickly than one formed in a steep hillside merely because less material must be removed before the cave is exposed. A cave formed in a steep hillside would also be expected to last longer because it might be less prone to mass wasting processes such as ceiling collapse. These patterns, however, are not evident in the GIS analysis of cave sizes or shapes compared to hill slope. The fact that most caves are located on slopes less than 50 – 60 % reflects the distribution of slopes on the island. The histogram of hill slopes by area on San Salvador Island demonstrates a classic poisson distribution (Figure 24). The large majority of the slopes are less than 50 %.

It is possible that location error inherent in the GPS location data affected slope values for the caves. Errors of only a few meters could have overestimated or underestimated the slope values for some or all of the caves in the study. It is also difficult to assign a slope value to a cave that is located in a steep or vertical cliff face. Caves that are found on a steep cliff likely receive a slope value corresponding to the areas directly adjacent to the cliff. These areas can be nearly flat, thus giving the cave an erroneous and deceiving slope value.

The GIS data may also include error because much of the data was digitized by hand from original sources. Due to the lack of benchmark elevation data, the DEM values could not be “ground-truthed”. The DEM values were further compromised by large gaps between the original contour lines. As digitizing an entirely new elevation layer for San
Salvador would have been extremely time consuming, it was not completed as part of this project.

On San Salvador Island there is an obvious pattern in the orientation of the dune ridges, which is due to seasonal weather patterns in the area. The histogram of flank margin cave aspects (Figure 27) demonstrates that in general the Northwest and Southeast aspects are the two preferential aspects on which caves are formed. These preferred aspects appear to roughly correlate with the front and back slopes of the dune ridges that dominate the island landscape. It is logical that more caves should be found on the sides of the dune that are parallel to the dune axis simply because there is more available space. It is interesting that the majority of flank margin caves on San Salvador Island are found on aspects between 180 degrees and 360 degrees. As this study included only 20 flank margin caves on one island, analysis of other caves on other islands may help to support and explain these findings. No relationships were found between cave size or shape and slope aspect. The failure of the flank margin caves to correspond to any of the measured topographic conditions does support the flank margin caves as being hypogenic, that is, decoupled from direct surface hydrology, as the CIKM predicts.

Topography may indirectly control flank margin cave formation by creating situations unsuitable for dissolution. As discussed earlier, at least four lakes were present on San Salvador Island during the last interglacial highstand. The presence of these lakes is supported by Hagey and Mylroie (1995), who used molluscan fossils as indicators of lake and lagoon positions during the OIS 5e highstand (Figure 33). No molluscan fossil sample sites are located on the four lakes indicated in Figure 33, suggesting that these
lakes may have been too saline to support the marine animals. The DEM used in this study illustrates that no flank margin caves are located on the shores of any of these lakes. If conditions on San Salvador during the last interglacial highstand were similar to the conditions on the island today, it is possible that the lakes at that time were at least somewhat hypersaline. As is evident from work by Mylroie et al. (1995a) in Bermuda and the Bahamas, hypersalinity can negatively affect dissolution of carbonate material, and may possibly explain the lack of flank margin caves on the few lakes that existed on San Salvador approximately 125,000 years ago. The data therefore lead to a paleoclimatic conclusion.
Figure 33  Map showing the position of isolated lakes during the OIS 5e highstand and the locations of samples taken by Hagey and Mylroie (1995)
CHAPTER VII
SUMMARY AND CONCLUSIONS

Cave and karst data from the Bahamas has been successfully incorporated into a simple geodatabase, making this data easily accessible for future research. The incorporation of a user-friendly data management program ensures that new data will be affectively and efficiently added to the database. While this collection is not exhaustive, or even representative of all types of karst features, it provides a framework for including any type of karst feature.

The use of a geodatabase also makes the cave and karst data readily available for GIS analysis. The simple analysis performed in this project has shown the utility of a GIS for working with cave and karst data. Through the use of GIS, the data collected from karst features on San Salvador Island supports the Carbonate Island Karst Model and provides a tool for illustrating potential locations of new karst features.

The first step to performing the GIS analysis involved creating a digital elevation model from a contour lines layer obtained from a previous study. Two methods of DEM creation were explored in this project. The first involved interpolating elevations using an inverse distance weighting interpolation. The second involved creating a triangulated irregular network (TIN), and then converting the TIN to a raster layer representing elevation. The two DEMs were compared based on their average root mean square error.
and the TIN-derived DEM was determined to be more accurate with a RMSE of 0.54 m, versus a RMSE of 1.0 m for the interpolated DEM. The TIN-derived DEM was then used to determine elevation values for karst features and to create slope and aspect maps of San Salvador Island.

Based on the elevation data collected in this study, a GIS can be used to generate maps illustrating the association between elevation and the sea levels associated with the last interglacial highstand, which can then serve as a guide to the potential locations of flank margin caves or banana holes. This is not only important for future research, but may be used for urban planning or land use zoning. Overlaying the karst feature maps with maps of current and future buildings or infrastructure will allow users to identify problem areas and possible prevent any property damage or even personal injury.

Using the data collected in this study, an example of a simple model that could be used to designate possible locations of karst features is as follows:

Flank Margin Caves:

- Found at elevations between approximately 1 and 7 meters.
- Most often found along the lee slope of a dune ridge
- Not found on the shore of inland lakes that would have been present during the last interglacial highstand (in areas with a negative water budget)
- Show no relationship to overlying topography, supporting their genesis as hypogenic caves.
Banana Holes:
- Found at elevations between approximately 1 and 6 meters
- Most often found on the flat, lowland terraces (low slope)

Vadose Pits:
- The deepest pits are generally found on dune ridges

This project has also identified weaknesses in the use of GIS data for the analysis of cave and karst data. The quality of the analysis is limited by the quality of the available GIS data and the quality of the cave and karst data itself, some of which was collected or created nearly 30 years ago. For example, the accuracies of feature locations vary almost as much as the features themselves, making slope and aspect values extracted from a DEM less reliable. The DEM itself was created using contour lines digitized from topographic maps, introducing a degree of potential human error.

While this study found no significant relationships that might explain the variance in karst feature morphologies, specifically those found in flank margin caves, the production of more accurate and precise GIS data might elicit more useful results. For example, the use of Airborne LiDAR data or high-resolution multi-spectral imagery could be used to accurately characterize the island surface, thereby improving the quality of the DEM. The new values could then be “ground-truthed” to validate them. The accuracy of the karst feature locations could also be improved using more advanced GPS technology.

The fact that no significant relationships were found between cave morphologies and topographic conditions supports the CIKM description of flank margin caves as
being hypogenic. The presence of isolated hypersaline lakes on San Salvador Island during the last interglacial highstand has paleoclimatic implications. The data suggest that during the OIS 5e San Salvador Island had a negative water budget climate that could have produced hypersaline lakes, similar to conditions found there today.

Once elevation data is available for more of the Bahamian islands, it should be used to perform analyses similar to those done in this study to refine the use of GIS as a prediction and modeling tool.
REFERENCES


