THE BERMUDA CAVE AND KARST INFORMATION SYSTEM: A GIS DECISION-SUPPORT TOOL FOR CAVE AND KARST MANAGEMENT AND CONSERVATION

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Abstract

Bermuda is a densely populated island with approximately 65,000 inhabitants and 200 caves. These caves began forming about 1 million years ago, and many include passages with deep anchialine pools and extensive underwater networks. Bermuda's caves are significant for their numerous and delicate speleothems, as well as their large variety of cave-adapted life, making them globally recognized as a biodiversity hotspot. Many of these species were previously unknown, and 21 are currently listed as critically endangered under the Bermuda Protected Species Act in accordance with IUCN (International Union for the Conservation of Nature) criteria. Their importance as a part of Bermuda's natural heritage, the fact that they support approximately 25% of Bermuda's endemic fauna and that they contain the best-preserved archives of Bermuda's entire previous natural history (including biological, geological and palaeontological history) adds to their local significance. Unfortunately the rapid pace of development, which continues to escalate, as well as vandalism, pollution and other factors have significantly impacted and continue to threaten Bermuda's unique cave resources.

In 2002, the multidisciplinary Bermuda Cave and Karst Information System (BeCKIS) project was established, leveraging the efforts of professionals and volunteers alike into a common GIS database. BeCKIS has been used to establish baseline information from past observations, determine change over time, gain insight to the effects of development and landuse practices, and to create supporting documents and maps to increase public and governmental awareness. It is available and used by key resource managers to assist them in decision-making, with goals to continue evolving the GIS program further as an integral component of the decision-making process to yield policies and regulations that will preserve these unique cave resources.

Key words: island karst management, databases, GIS, karst hydrology, cave geology, cave history, cave biology, contaminants, law, Bermuda

Introduction

Bermuda is located in the western Atlantic Ocean 960 kilometers off the coast of North Carolina, United States. It is the second-most densely populated island in the world, with approximately 65,000 inhabitants in a land area of 53.7 km^2. Approximately 200 caves have been discovered in Bermuda, many of which are profusely decorated with delicate and unique speleothems. Many caves include passages which extend to sea level and contain deep anchialine pools and extensive underwater networks.

A large variety of cave-adapted life, including previously unknown species, has been found in these underwater caves. Of the species identified in Bermuda's caves, 21 are currently on the Bermuda Protected Species Act critically endangered species list. The high population density and resultant development pressures, vandalism, pollution and other negative factors have significantly impacted and continue to threaten Bermuda's unique cave resources.

While observation and explorations of Bermuda's caves date from the earliest days of human settlement, the fact that most of the caves form part of an extensive network of submerged passages has meant that cave research is limited to the skills of a select group of cave experts.

In early 2002 the Bermuda Cave and Karst Information System (BeCKIS) project was established with the primary goals of increasing public awareness of Bermuda's caves and cave life, increasing awareness of negative impacts on these resources, and promoting the scientific study of Bermuda caves. BeCKIS utilizes GIS software from ESRI, one of the early project sponsors, to maintain a database and inventory of cave locations and field observations.

The GIS is being used to establish baseline information from past observations, to query and analyze the data and to understand relationships with other geographic and hydrologic factors. The development of a GIS database also facilitates the production of high quality cartographic maps invaluable to record these features, understand their significance and relationships, and effectively communicate with others. The system has increasingly leveraged the efforts of professionals and volunteers alike, and represents a multi-national effort with partner organizations on both sides of the Atlantic including the Departments of Conservation Services and Planning and Environmental Protection in Bermuda.

BeCKIS is facilitated through the Bermuda Biodiversity Project (BBP) at the Bermuda Aquarium, Museum and Zoo. Established in 1997, the aims of the BBP are three fold: to collect and collate information on Bermuda's natural history, to identify gaps in the information and encourage collaborations to fill these gaps and to ensure that all the information is made available and widely disseminated.

Geology

Bermuda sits atop an extinct, volcanic seamount capped by limestone. During the Pleistocene approximately 1 million years ago, Bermuda's limestone caves began forming during glacial periods when sea level was as much as 120 m lower than present (Palmer et al. 1977) and the land mass was about 1,000 km^2 or 20 times larger than present. At this time, there would have been a sizeable, fresh, groundwater body, which resulted in the formation of the caves. Post glacial sea level rises subsequently led to large portions of these caves becoming drowned with seawater, which displaced the freshwater. This is evident by the presence of submerged stalactites and stalagmites, features in today's submerged caves. Sea levels have reportedly been as much as 22 m above present (Hearty et al. 1999).

Speleological History

Referenced in the writings of Bermuda's earliest explorers (Forney 1973, Iliffe 1993) the Island's caves have long been a feature of interest, a subject of scientific study, a place of refuge and of worship, an important natural resource for tourism and more recently a biodiversity hotspot and habitat of global significance.

In 1983 Dr. Tom Iliffe completed a two-year survey of cave features on the island, identifying 166 caves. The caves were evaluated and rated regarding specific factors, including vandalism, pollution, dumping, biological significance, threat, speleothems and others. Each cave was rated on a scale of one to five in each category. This information provided the valuable baseline data for developing the digital basemap of caves, and has also served as

a basis for continuing exploration, mapping and research activities.

Establishment of the Cave GIS

In 2001, several contacts were made that catalyzed a project trip in January, 2002, which brought together a small, but multi-national group of volunteers and professionals— cavers, cave divers, researchers, and students—to map caves and collect data to establish a baseline of information to date. The use of a Geographic Information System (GIS) was proposed to develop a Cave and Karst Information System to store cave location information, cave survey data and biological and other inventory data that had been collected.

The GIS would be used to store, manage, query, and analyze the data to understand relationships of these features to other geographic and hydrologic factors. Perhaps more importantly, it was hoped that this GIS information would be incorporated into the country's GIS, and become part of the policy and decision-making process to help preserve and protect these valuable resources. This system was named the Bermuda Cave and Karst Information System, or BeCKIS.

The initial step was to develop a GIS data layer from the information that Tom Iliffe had completed in 1983. Cave locations where obtained from derived XY coordinates that had been collected. These were imported into a GIS data layer, and attribute fields were added to store the evaluation ratings for the observed factors. Additional layers were obtained from the Bermuda Planning Department, or derived from available information. These layers included several layers of high-resolution imagery obtained at different times, geology, elevation models, parish boundaries, building footprints and others.

With the GIS foundation established, the

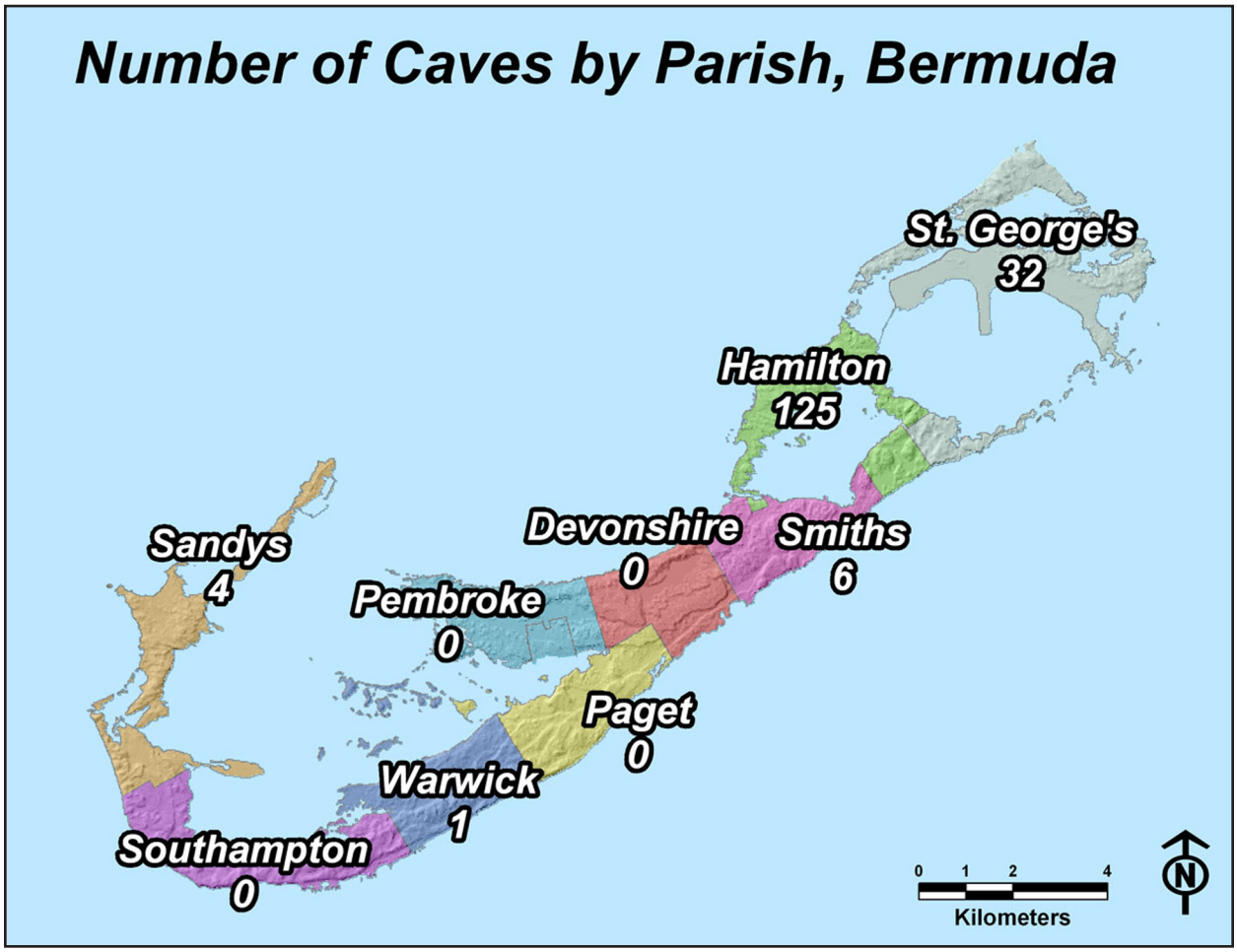

Figure 1 *GIS map showing the number of caves per parish based on the 1983 cave inventory. Note the high number of caves in Hamilton Parish, where the Walsingham limestone is found.*

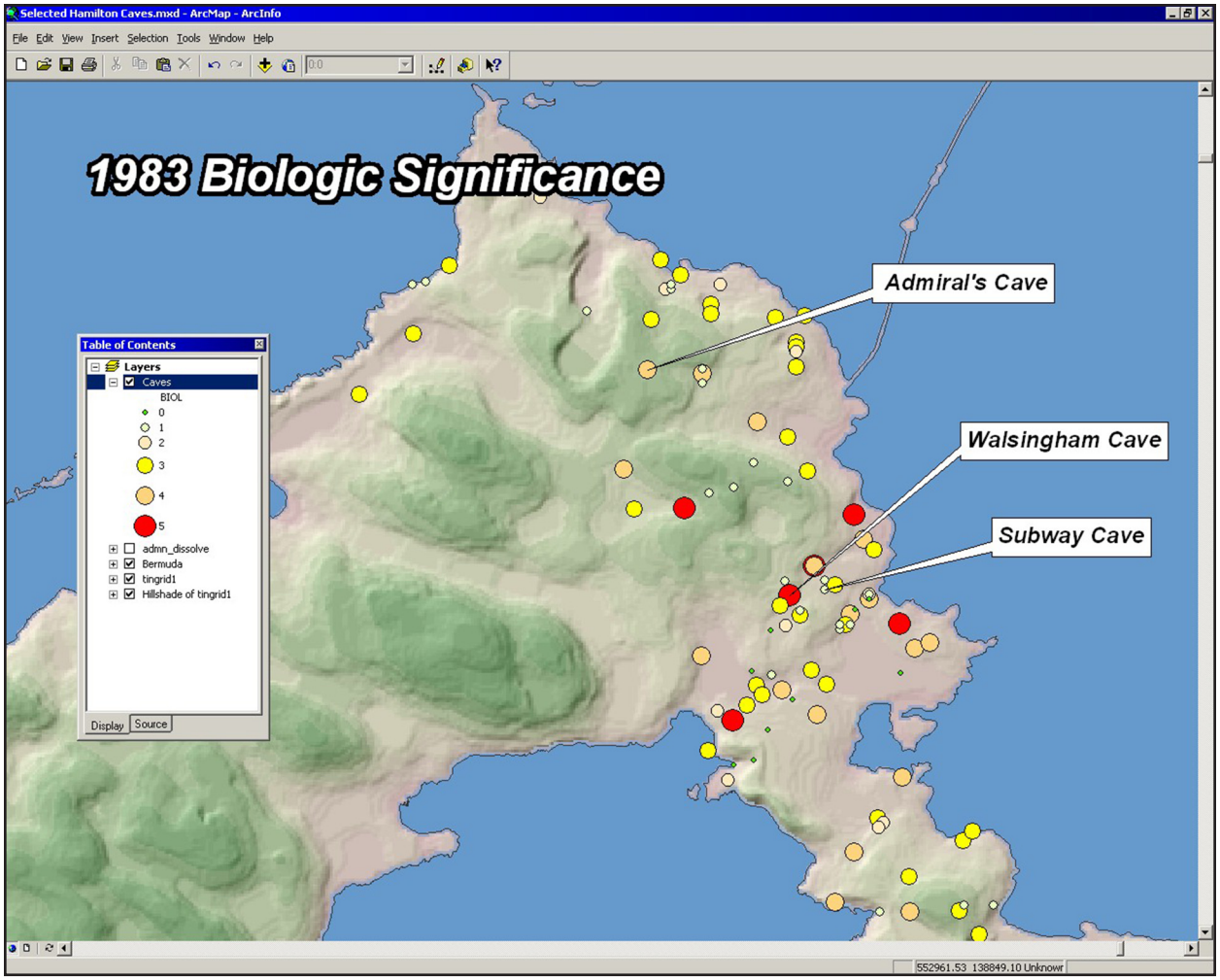

Figure 2 *Screen shot of GIS map of the northeastern portion of Hamilton Parish showing cave locations with graduated symbols indicating biological significance, based Iliffe's 1983 database.*

database was used in the production of a variety of high-quality cartographic maps. These maps included those showing the density of caves by parish, the relationships of caves to island geology, the proximity to housing and roads and thematic maps showing the inventoried cave factors (Figures 1 and 2). A variety of digital and hardcopy maps were authored and supported a variety of publications, public presentations, and inter- and intra-organization communications (Figure 3). These have played a key role in increasing the awareness of Bermuda's caves, and gaining an appreciation of their vulnerability.

BeCKIS Evolves

The BeCKIS has been leveraged for ongoing research and other activities, and has benefited as new information has been incorporated. In 2003, Darcy Gibbons completed her Master's thesis titled *An Environmental Assessment of Bermuda Cave Health* (Gibbons, 2003). Gibbons built upon the 1983 baseline evaluation with her own observations 20 years later. These provided insight to change and impacts over time, and added updated information including new GPS coordinates, elevation at each entrance, and new entries. Other graduate students are also building upon this information, and will in turn contribute to it.

But many challenges still remain. The intermittent nature of cave survey and study make it difficult to maintain continuity and pick up where previous work has left off. Definitive protocols for collection of cave survey and inventory information still need to be established, and ancillary information and content, such as photographs and cave maps still need to be integrated into the system. Some of this work has been prototyped with the georefer-

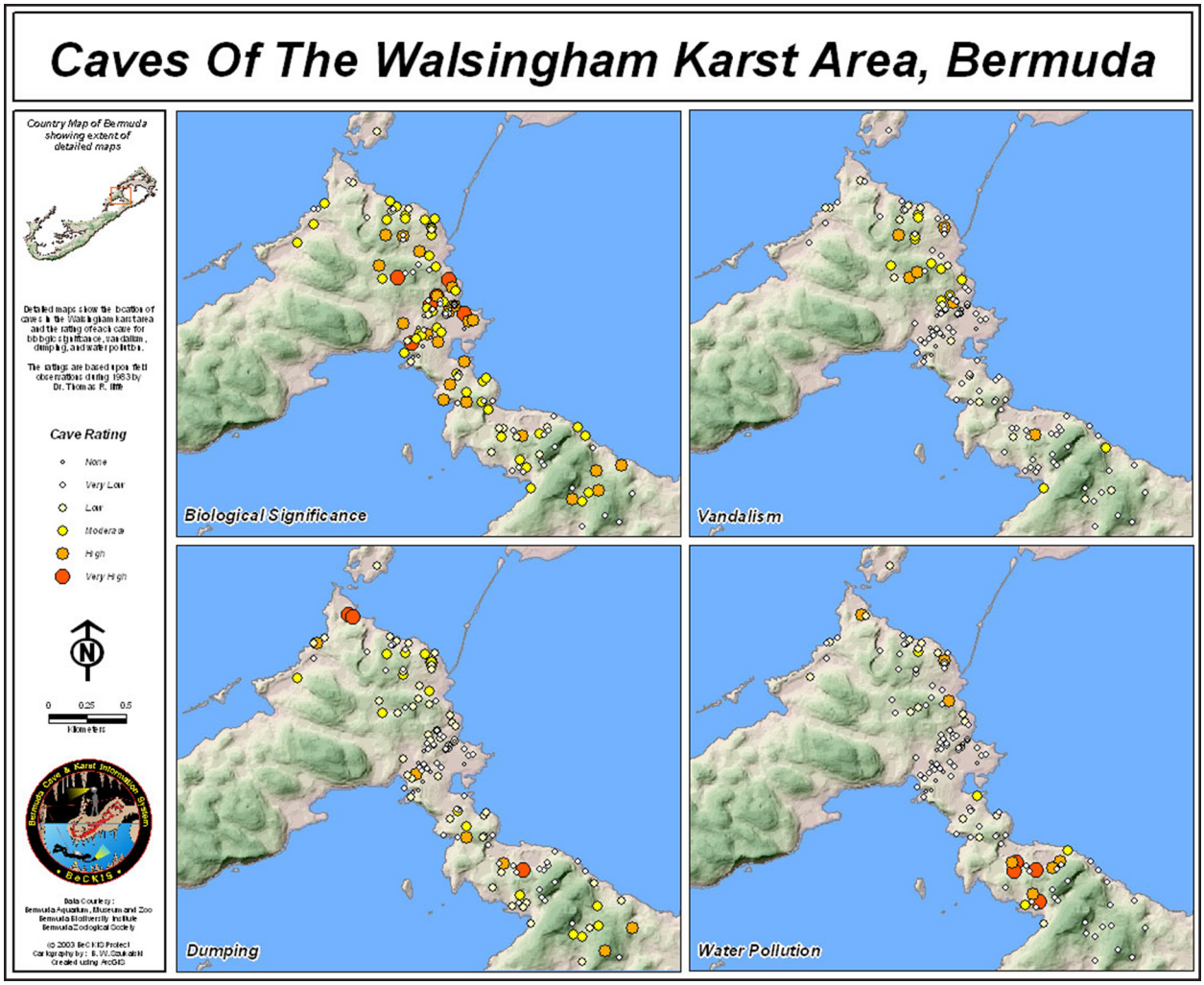

Figure 3 *A poster created from the GIS database showing cave locations and various evaluated parameters based on Iliffe's 1983 database.*

encing of the detailed plan maps of the surveyed caves, and the digitization of "cave footprints" from these maps showing in detail the proximity of caves to quarries, constructions, and injection wells, and providing additional information that can contribute to management and preservation (Figure 4). Despite the need for additional work, the BeCKIS provides a valuable foundation which should increase in value and use as additional information becomes incorporated.

Use within the Government and Policy

Under Bermuda's legislative framework, the Island's caves are afforded the highest level of protection through the Bermuda Planning Act 1999. Further protection has been afforded through the Protected Species Act 2003, which lists 23 of Bermuda's stygiobitic fauna and requires a cave fauna recovery plan to be implemented for these species. While this legislation provides a solid foundation for conservation, local resource managers have historically been challenged to ensure effective management, primarily because of a lack of information, or at least access to it. Clearly one of the most significant of these challenges relates to the extensive, submerged nature of the underwater passages.

Through BeCKIS, this information gap is being bridged. A key constraint at present is that there is no clearly defined understanding of what baseline conditions in the caves should be. It is challenging in the absence of this data, to accurately assess or predict human impacts. Further, without accurate mapping of the caves, implementation of policy is also compromised.

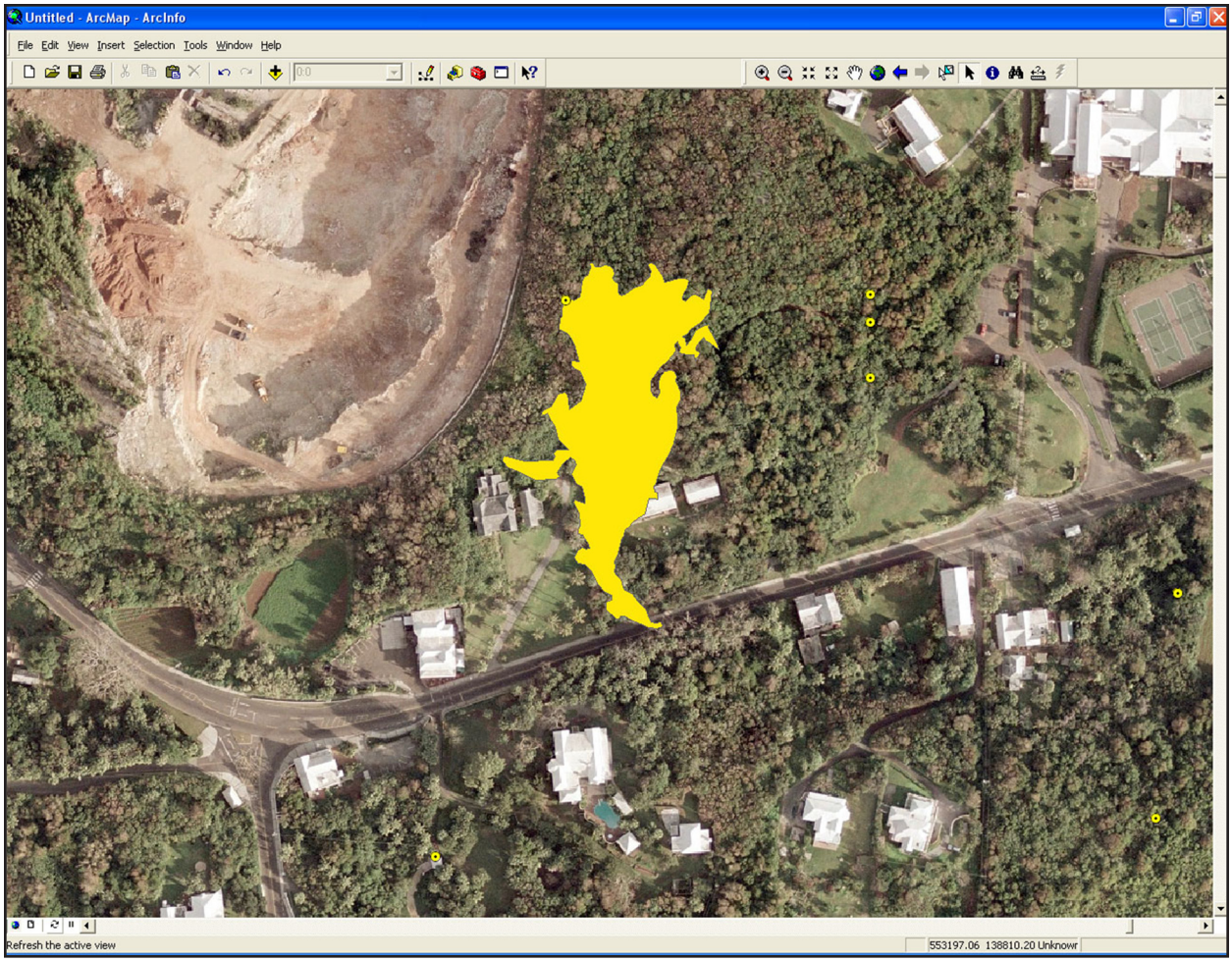

Figure 4 *The outline of Admiral's Cave, Hamilton Parish, derived from the final cave map. The map was scanned, georeferenced and digitized to create an overlay on the high-resolution aerial imagery.*

Through BeCKIS, ongoing research, targeted mapping expeditions and increased public awareness are all key activities that are strengthening our understanding of, and ability to manage Bermuda's unique cave systems. Integral to this is the use of a map-based system through which all the data being collated is made available to resource managers so that they are better able to make informed decisions that relate to planning zonings and construction activity, location of cesspits, drilling of freshwater wells, development of show caves for tourism, development of specific recovery plans and establishment of monitoring activities.

In 1990 the Geospatial Information Systems Committee was formed in Bermuda, initially as an interest group seeking support for GIS development within the Bermuda Government. Their focus has been the coordination of activities across the government to reduce duplication of effort and develop GIS resources. It is intended that through BeCKIS, we will continue to help evolve the GIS program further as an integral component of the decision-making process to yield policies and regulations that will preserve Bermuda's unique cave resources.

Summary

Bermuda's cave resources remain in the balance between human needs and preservation. The BeCKIS system has proven a valuable system for storing and managing cave and karst information, and has proven an effective tool for developing maps and for analysis that contribute to the decision-making process to yield policies and regulations that will preserve these unique cave resources.

Acknowledgments

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