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MAPPING EVERGLADES ALLIGATOR HOLES USING COLOR INFRARED AERIAL PHOTOGRAPHS

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Abstract—*Color infrared (CIR) aerial photographs were used to map alligator holes in a 2,442 km*^{2} *area (Water Conservation Area 3) of the Everglades. Open-water ponds appeared as clearly defined black spots on the photographs. Three types of alligator holes were identified based on differing CIR signatures: Type 1 holes were encircled by a bright red ring indicating a surrounding zone of woody vegetation (small trees and shrubs); Type 2 holes were not surrounded by a change in pixel brightness or tone, indicating a round open water pond within the existing vegetation matrix without a surrounding ring of woody vegetation; and Type 3 holes were immediately adjacent to elongated red ovals (small tree islands) formed from the construction of spoil banks and are termed "artificial holes." Eight hundred forty-five alligator holes greater than 5 m in diameter were mapped, including 309 Type 1, 331 Type 2, and 205 Type 3 holes. These alligator holes ranged from five to 15 m in diameter and 20 to 150 cm deeper than the surrounding marsh (n = 49). Based on the ground-truthing of 89 mapped alligator holes, 88 percent were successfully located in the field, 83 percent were correctly characterized, and the holes were found within 60 m, on average, of their map coordinates.*

American alligators (*Alligator mississippiensis*) in the Florida Everglades have the ability to alter the structure of the landscape (Craighead, 1968; Kushlan, 1974). Due to an alligator's large size and weight, and the soft, organic, peat sediments of central Everglades marshes, alligators maintain, and sometimes create, small ponds called alligator holes by wallowing into the peat, thereby mounding soil and vegetation around the perimeter. This causes significant topographic and hydrologic variation in an otherwise flat, shallow wetland landscape, resulting in increased vegetative and wildlife diversity (Craighead, 1971).

Alligator holes are approximately 1 m deeper than the surrounding marsh, reaching down to the limestone bedrock. They may range from 2 to 15 m in diameter and are found in a variety of major wetland habitats including sawgrass marsh (*Cladium jamaicense*), wet prairie (emergent rush marsh including *Eleocharis* spp. and *Rhynchospora* spp.), and slough [deeper water with floating aquatic plants such as spatterdock (*Nuphar luteum*), white water lily (*Nymphaea odorata*), floating heart (*Nymphoides aquatica*), and bladderwort (*Utricularia* spp.)]. Trees and shrubs, such as willow (*Salix caroliniana),* often take root on the raised banks surrounding alligator holes. In other cases, alligator holes may simply be small open water depressions hidden within the surrounding vegetative matrix. Once established, alligator holes are kept free from encroaching vegetation by the important maintenance activities of the resident alligator.

Alligator holes have long been hypothesized to provide critical dry season refugia for Everglades wildlife (Davis, 1943; Kushlan, 1974). As the surrounding marsh dries down, fish and other aquatic organisms concentrate in the alligator hole, becoming an important food source for nesting wading birds, and resident alligators. When water levels increase, surviving organisms reproduce and colonize surrounding wetlands. For this reason, alligator holes have been recognized as important components in the process of life and death within the Everglades ecosystem (Mazzotti and Brandt, 1994).

Although the importance of alligator holes in the Everglades is widely recognized, only one alligator hole has ever been quantitatively studied (Kushlan, 1972; 1974), and no inventory or mapping effort has been made. As a result, the significance of alligator holes to the overall structure and function of the Everglades is not known. The objective of this study was to find a simple procedure to identify, classify, and map alligator holes using CIR aerial photographs. To accomplish this, we asked several questions. Could alligator holes be identified from CIR aerial photographs? What size holes could be identified? How many types of alligator holes could be described? How accurate was the identification and location of alligator holes? Could this method be applied effectively over a large area?

MATERIALS AND METHODS—*Study Area*—This study focused on Water Conservation Area 3 (WCA 3), a 2,442 km^2 water impoundment that extends from the L-5 levee (Palm Beach County, Florida) in the north to U.S. 41 (Dade County, Florida) in the south (Figure 1). The major habitats of this shallow, peat wetland are sawgrass marsh, wet prairie, and freshwater slough, which are dotted with occasional tree islands (clumps of small trees and shrubs) (Jordan et al., 1997). Encompassing approximately one-third of the remaining Everglades fresh water marsh, the major functions of WCA 3 are water supply, flood control, public recreation, and wildlife habitat.

Data Sources—Alligator holes were mapped using color infrared (CIR) aerial photographs because they provided the necessary detail, were readily available, and covered the full extent of the study area. In addition, CIR photographs are superior to conventional color or black and white photographs for distinguishing between water and vegetation, which was critical for this study, (Schneider, 1966; Shima and Anderson, 1976; Howland, 1980). The CIR photographs, flown in September 1994, were obtained from the South Florida Water Management District (SFWMD). Accompanying the photographs were a set of ground control points (GCP's) that were collected by the SFWMD using a differentially corrected Global Positioning System (DGPS) and helicopter. Approximately four control points per photograph were flown and recorded as an image pinprick and as line-work on mylar overlays. Individual photographs were 9-by 9-inches at a scale of 1:24,000, resulting in a 3,025 ha photograph (5.5 km per side). A total of 180 photos were used to map WCA 3.

Pilot study—A pilot study was conducted within WCA 3 on a 250 km^2 area to determine if alligator holes could be successfully identified from the CIR aerial photographs. Fourteen photos were professionally scanned at one-meter ground resolution (40 μm) and stored on CD-ROM. The resulting digital color infrared (DCIR) raster images were approximately 100 Mb each. The DCIR images were imported into EASI/PACE (PCI Geomatics, Ontario, Canada)

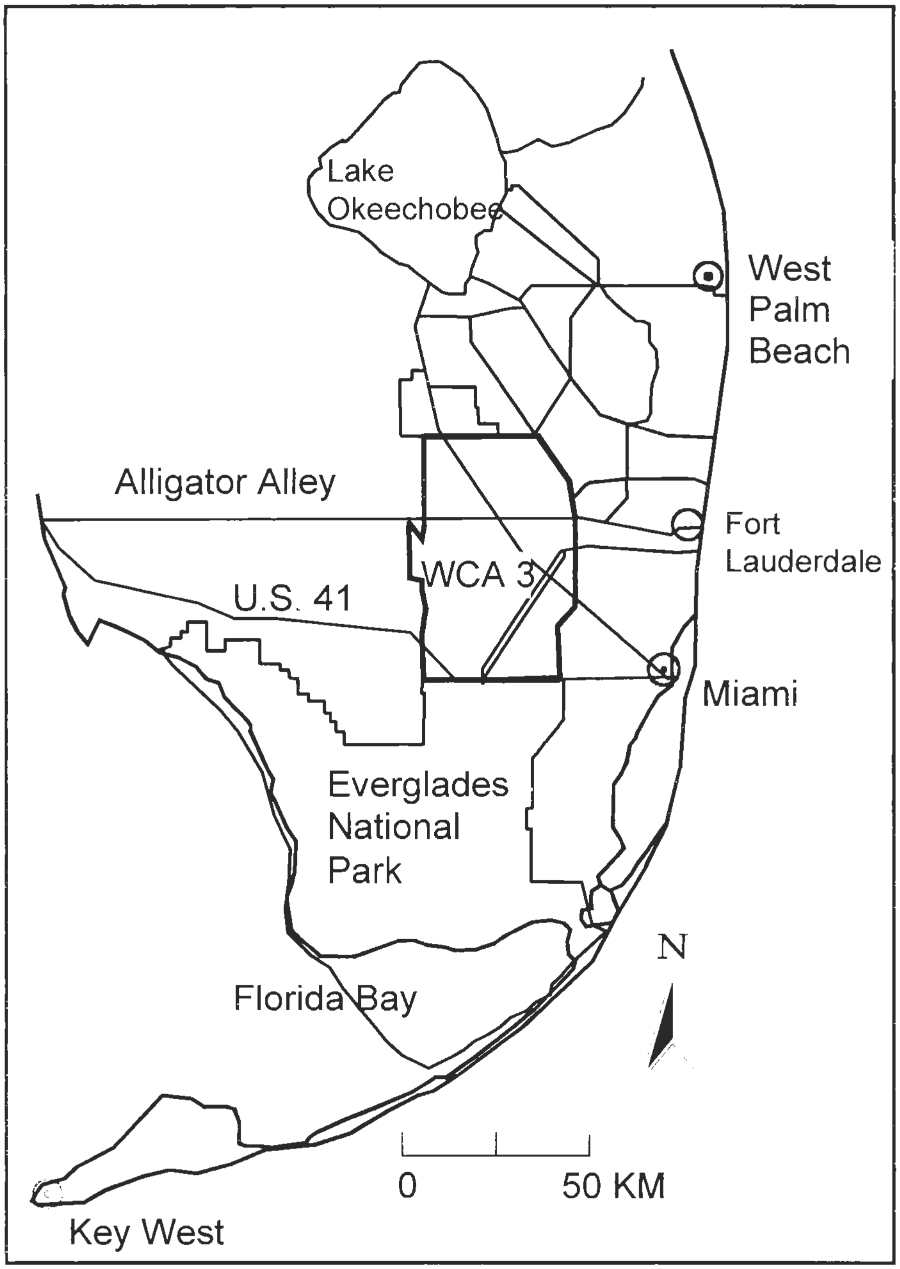

FIG. 1. Location of Water Conservation Area 3 in southern Florida.

image processing software and georeferenced in the Universal Transverse Mercator (UTM) ground coordinate system (Zone 17) tied to the North American Datum of 1983 (NAD 83) using the GCP's supplied by the SFWMD.

Potential alligator holes were identified on the positive CIR film as small, dark, open-water areas and subsequently located on the DCIR images on the computer. A light table and magnifying loupe assisted in the identification of alligator holes from the CIR photos in positive transparency format. Color inkjet printouts of digital alligator hole enlargements were used to record field characteristics associated with the holes such as open water, sawgrass, woody vegetation, and shadows. The printouts contained a UTM grid for navigation to a specific alligator hole with a DGPS and airboat or all-terrain vehicle. This information assisted in classifying alligator holes into different types, and determining the minimum pond size that can be interpreted from the photographs.

Mapping WCA 3—After the pilot study demonstrated the potential of CIR photography for mapping alligator holes, a manual interpretation (U. S. Fish & Wildlife Service, 1994) of all air photos covering WCA 3 was then conducted. With the aid of a light table and magnifying loupe, potential alligator holes were located on each of the original 1:24,000 scale diapositives and plotted on 9-by 9-inch clear acetate overlays with a fine point permanent marker (0.4 mm nib). In addition, the location of the four GCP's, airboat trails, and canals were plotted on the overlay for each photo.

To increase the amount of ground control per overlay (four GCP's are minimal), while reducing the number of overlays for computer processing, 20 adjacent overlays were assembled into a mosaic by lining up common control points, airboat trails, canals, and alligator holes. A second, continuous, transparent overlay then was placed over the mosaic, and all alligator holes, airboat trails, canals, and the 20 control points were retraced onto a final single sheet. The large overlays were photographically reduced to 8½-by 11-inch paper maps to accommodate the page size of the scanner. Each reduced line drawing was scanned as a sharp black and white drawing at 75 dpi creating a digital raster image. Once scanned, the digital line drawings were imported into EASI/PACE image processing software and georeferenced using the ground control coordinates collected by the SFWMD. Coordinates were entered from the keyboard and assigned to their respective tick marks recorded on the digital line drawings. The image was georeferenced using a second order polynomial solution and a nearest-neighbor resampling algorithm.

The georeferenced images then were imported into SPANS geographic information system (GIS) version 6.0, and compared to an existing georeferenced canal vector layer (obtained from the SFWMD) to verify the success of georeferencing. To obtain a vector GIS layer of alligator holes that allowed the association of attribute information to individual alligator holes, a manual vectorization process was performed by on-screen digitizing a point layer of alligator holes (in addition to the study area boundary and major airboat trails). Field data collected during ground-truthing were linked to each alligator hole within the GIS database for subsequent analysis.

A random subset of a minimum of ten percent of potential alligator holes was ground truthed to evaluate the error of commission. Aerial photographs were randomly chosen, and all potential holes within that area were visited to maximize efficiency. Potential holes were navigated to using a DGPS and airboat. An alligator hole was determined to exist at the mapped location if three criteria were met. First, if a depression in the muck or limestone relative to the surrounding marsh was found. Second, if the depression had a definite round or oval boundary as indicated by the change in vegetation. Third, if the interior of the alligator hole had no emergent vegetation. Field information collected at the randomly selected alligator holes included pond length, width, and center depth, marsh water depth 10 meters from the edge of pond, field UTM coordinates, surrounding zonation of vegetation, and photographs.

Due to a lack of the ability to do aerial surveys the error of omission was not evaluated.

RESULTS—*Pilot study*—The identification of alligator holes was easier and more efficient using the positive CIR film, light table, and magnifying loupe than the DCIR images. The positive film under magnification revealed more detail than the 1-m DCIR images, and it was more efficient to manipulate the photos on the light table than to pan and zoom digital images in the computer. Within the 250-km^2 pilot study area, a total of 548 potential holes were identified from 14 CIR photographs. Twenty-three potential alligator holes were ground-truthed using the digital inkjet enlargements. The alligator holes were located by DGPS to within fifty meters of the computer-generated locations (varying from 0 to 26 m in the x direction and 0 to 50 m in the y direction). The root-mean square error (RMSE) was 15.1 m.

Investigation of the image spectral characteristics showed that open water appeared black, sawgrass was pink with mottled or rough texture, woody vegetation was dark pink to red with a rough texture, and cattail (*Typha domingensis*) was mixed, appearing as white, light pink, or red, depending on density, water depth, and other associated plants. The spectral signatures for open water and woody vegetation were consistent across the 23 printouts and could be readily identified. Five of the DCIR printouts with small islands of woody vegetation contained neither a clear round black spot on the image nor an open water pond in the field and were determined not to be alligator holes. These small islands of woody vegetation were specifically investigated to determine if alligator holes were present in areas where the CIR photographs did not reveal well-defined circular black spots indicating ponded water.

Information on the 1-m resolution DCIR printouts was compared to actual field values. There was no significant difference between the DCIR pond diameters and actual pond diameters (paired t-test, df = 21, P = 0.69), thereby validating the accuracy of the information obtained from photographs. The minimum pond size identified on the photographs was five meters in diameter. Nine unmapped alligator ponds, less than five meters across, were located in the field in close proximity (within 20 m) to larger ponds previously identified on the photographs.

Alligator holes were classified into three types based on different spectral characteristics on the CIR photos that resulted from varying physical and vegetative structure. Type 1 alligator holes were round open water ponds surrounded by either shrubs and trees, a ring of cattails, or a combination of both. They are identified on the photos as distinct black spots surrounded by an immediate red ring (darker in hue than the surrounding vegetation). Type 2 alligator holes were round open water ponds having a distinct boundary clearly offset from the surrounding vegetation matrix that are not surrounded by shrubs or trees. They were identified on the photos as distinct black spots within a red or pink matrix of marsh vegetation of varying intensity, and are not surrounded by a bright red ring. Type 3 alligator holes were termed "artificial" since they were formed from the construction of spoil banks, approximately 40 meters long by 15 meters wide, by digging up the muck with a drag line and piling it adjacent to the hole. A few hundred of these artificial islands were created in the 1970s for the benefit of wildlife (specifically deer) in times of extremely high water, and are found in close proximity (within 500 m) to each other as they string out from the levees. On the photos, Type 3 artificial holes were identified as round or elongated black spots of open water immediately adjacent to elongated islands of bright red woody vegetation. Only artificial islands that appeared to have an adjacent pond were mapped.

Mapping WCA 3—A total of 845 alligator holes were identified throughout WCA 3 from the 180 CIR aerial photographs. This includes 309 Type 1 holes with surrounding shrubs or trees, 331 Type 2 open-water ponds without a discernable ring of surrounding shrubs, and 205 Type 3 alligator holes at artificial islands (Figure 2).

A total of nine overlay-mosaics were created (20 overlays per mosaic) that covered the full extent of WCA 3. After the mosaics were reduced, scanned, and georeferenced, the resultant RMSE averaged four pixels for a thirty-meter resolution image (or 120 m on the ground). The canals on the georeferenced images were approximately within two pixels (sixty meters) of an existing georeferenced canal file (obtained from SFWMD), verifying both the georeferencing and the accuracy of plotting information on the acetate. This comparison of data sets indicated that the data manipulation (plotting information on acetate, recopying, reducing, and scanning) did not compromise its spatial integrity beyond the purposes of this study. In large part this is due to the very low topographic relief experience across WCA 3, resulting in minimal photogrammetric displacement of ground elements, but also important are care and precision when manually manipulating data.

A subset of the alligator holes was located in the field to assess the commission error of the alligator hole map. Out of a total of 89 mapped alligator holes that were searched for, 11 holes could not be located, resulting in an 88 percent commission rate for the map. For the individual alligator hole types, 90 percent (n = 42) of Type 1 was located, 74 percent (n = 27) of Type 2 was located, and 100 percent (n = 20) of Type 3 holes searched for was found. In addition, the commission error was not spatially independent. The majority of mis-commissioned holes (8 of 11 or 73 percent) were located in the southwest portion of the study area, a deep-water, open-slough region. The marsh water depth for the southwestern area (74 cm ± 16, n = 16) was significantly deeper (*t*-test, $P \leq 0.001$) than the central region of WCA 3 (40 cm ± 11, n = 10). No structures indicating an alligator hole were located for these eight potential holes, where it is likely that open water patches within the slough habitat were misidentified. The remaining three misidentifications, located in a northwestern sparse sawgrass marsh averaging 42 cm ± 12 water depth, were caused by round open water patches, averaging nine meters in diameter, but without depressions in the muck.

The accuracy of the identification of alligator holes was assessed by comparing the alligator hole classifications from the photographs to the vegetation zonation in the field (Table 1). Overall, 83 percent of the alligator

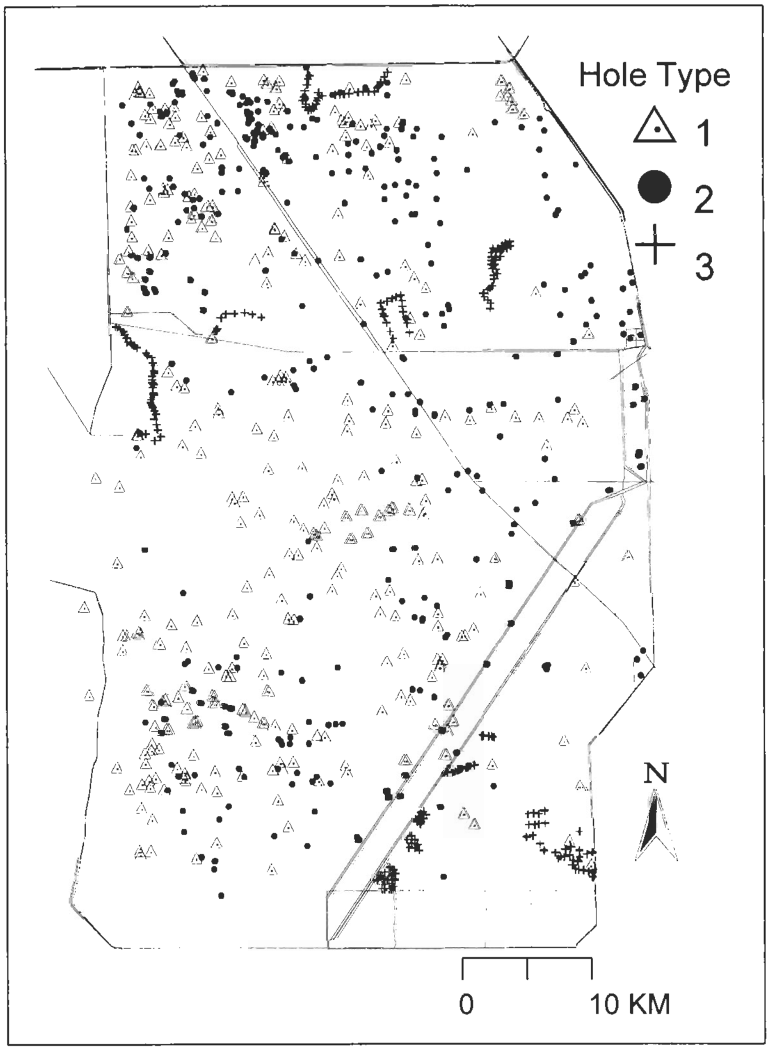

FIG. 2. Map of Everglades alligator holes. Type 1 holes were surrounded by small trees or shrubs, type 2 holes were in the marsh, and type 3 holes were associated with artificial tree islands.

holes investigated had physical characteristics that conformed to their identified types. Of the 38 Type 1 holes located in the field, 74 percent (28 holes) were correctly classified with surrounding trees and/or cattails, while low shrubs and sawgrass surrounded the remaining 26 percent (10 holes). Of the 20 Type 2 holes located, 85 percent (17 holes) were found in sawgrass, while 15 percent (3) were surrounded by a cattail stand and therefore misclassified. No Type 2 holes investigated were surrounded by trees. Fi-

TABLE 1. Classification error matrix to assess the accuracy of map types.

	Computer Classification (Column Total)			
Field Classification	Type 1	Type 2	Type 3	Row Total
Type 1	20	0	0	20
Type 1 (cattail)	8	3	0	11
Type 2	10	17	0	27
Type 3	0	0	20	20
Column Total	38	20	20	78
Classification Accuracy	28/38 74%	17/20 85%	20/20 100%	65/78 83%

nally, all Type 3 holes investigated (20 holes) were located adjacent to artificial tree-islands, and were therefore correctly classified.

The spatial accuracy of the alligator hole locations was estimated, not only by the RMSE generated through the georeferencing process, but more importantly by comparing actual alligator hole ground locations to the computer generated estimate. The difference between the computer coordinates and those collected by DGPS in the field are plotted in Figure 3. The average error between coordinate pairs was 60 meters, distributed evenly in all directions. Therefore, the approximate spatial accuracy of the mapped gator hole coordinates is ±60 m.

Alligator holes ranged from five meters to over 15 m in diameter and 20 cm to 150 cm in basin depth (86 cm mean depth). A comparison of the surface area of open water shows Type 2 holes to be smaller (43 ± 33 sq m, $n = 21$) than Type 1 (74 ± 33 sq m, $n = 28$), (*t*-test, $P = 0.002$) (Figure 4). Large holes are generally deep, reaching the limestone substrate in approximately one meter, while small holes exhibit more variability. Most small, deep holes were located in cattail stands.

DISCUSSION—Color infrared aerial photographs (1:24,000) were a useful and efficient data source for mapping alligator holes over a large area. The methods described here can be used to map other areas of the Everglades. A total of 640 natural plus 205 artificial holes were identified using 180 photos over a 2,442 km^2 area. Three types of alligator holes were identified in this central Everglades area. In general, alligator holes with surrounding shrubs and trees (Type 1) tend to be larger and deeper than alligator holes without surrounding shrubs or trees (Type 2). Alligator ponds surrounded by cattail were classified as either Type 1 or Type 2, and it would be useful in the future to distinguish cattail zonation on the photographs. The third type of alligator hole (Type 3) is identified from its association with elongated, man-made, tree islands, and varies in size and shape from a few meters in diameter to over 40 meters in length (the size of the spoil bank).

It is likely that in other areas of the Everglades with more tree islands (Arthur R. Marshall Loxahatchee National Wildlife Refuge, Shark Slough

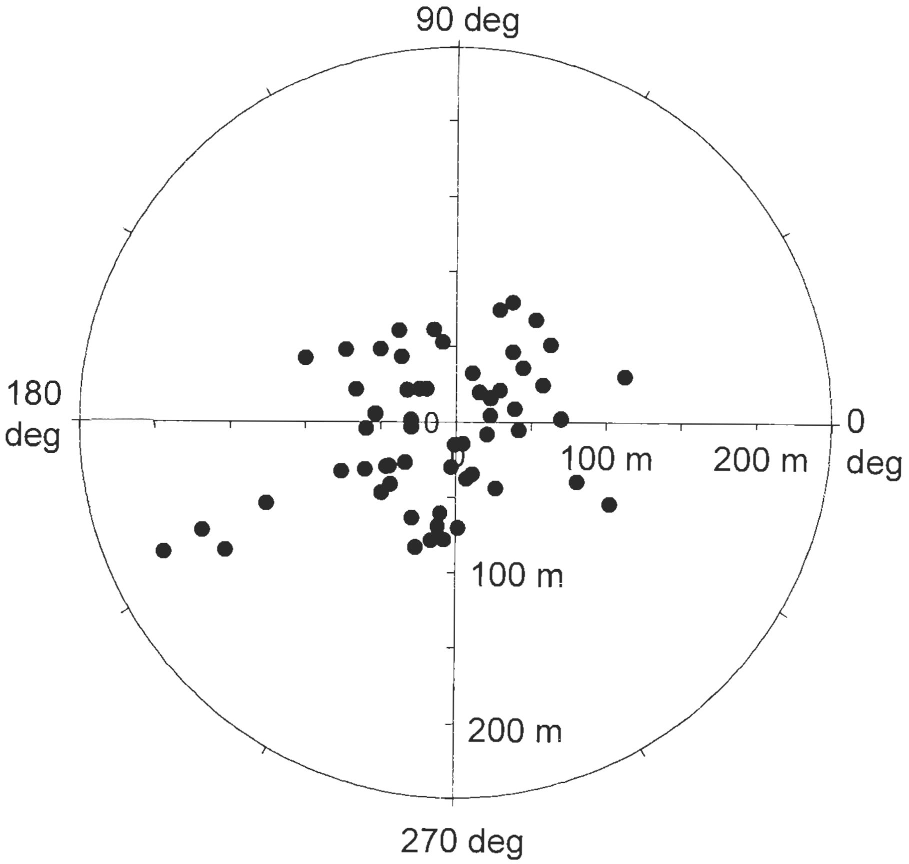

FIG. 3. Polar plot of the distance (meters) and bearing (degrees) errors for the computer generated alligator hole coordinates (UTM) as compared to actual field locations found during ground truthing. Average error is 60 meters.

in Everglades National Park) or a different substrate (rocky glades, Everglades National Park) there will be other types of alligator holes.

The error of commission for alligator holes depended on size, surrounding vegetation, and habitat (matrix vegetation). The majority of commission error was located in deep water, open slough habitat where breaks in the floating surface vegetation resulted in round open-water patches. In addition, round, vegetation-free patches were misidentified in shallow areas. These open patches may be caused from spot fires. The overall error of omission for the map was not determined, but alligator holes less than 5 m across were present though they were not mapped. While it is possible that larger alligator holes were also omitted it is likely that the majority of omission lies below the five-meter minimum-mapping threshold. A combination of aerial and ground surveys could be employed to investigate this error in detail. Because of the patchy, heterogeneous makeup of the marsh vegeta-

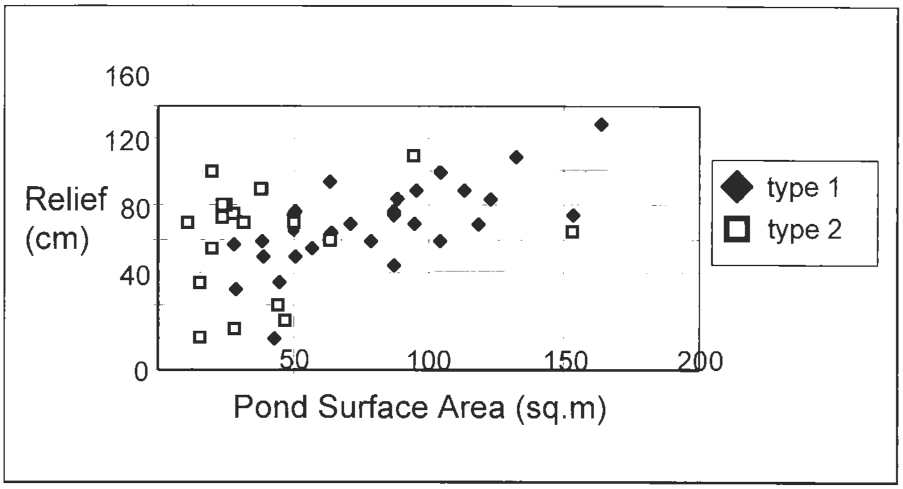

FIG. 4. Scatter plot of size vs. topographic relief (center pond water depth minus surrounding marsh water depth) for both Type 1 and Type 2 alligator holes.

tion, identification of entities this small would rapidly increase the error of commission. Small alligator holes with a distinct boundary were difficult to distinguish from small, irregular open-water patches within slough habitat that did not have a distinct vegetative boundary. Numerous potential alligator holes were identified during the pilot study in two areas of the marsh (approximately 25 km^2 each) where the sawgrass becomes patchy and merges into slough habitat. Investigation of these sites proved that caution should be applied when identifying small, round, open-water ponds as alligator holes in areas of patchy sawgrass and slough communities. After these sites were re-evaluated, the number of potential alligator holes within the pilot study area dropped from 548 to 173 holes.

The positional accuracy of the mapped gator hole locations was determined to be ± 60 m, based on comparison with field data. This positional accuracy could have been improved if the line work was scanned at a higher resolution, resulting in a smaller pixel size and if the overlay did not have to be reduced to 8.5 by 11 inches to fit the scanner. Nevertheless, the methods employed were sufficient for locating alligator holes in the field, and acceptable for compiling a relatively small-scale map of alligator hole point locations. The positional accuracy may not be sufficient for spatial analysis.

This mapping effort was accomplished with desktop computing systems, using PC image processing and GIS software. Management agencies will increasingly recognize the value of spatially analyzing environmental data. This study demonstrates an efficient, economical method for high resolution mapping over large spatial extent, and the value of integrating remote sensing and field biology in a GIS/GPS environment.

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