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Assessment of Three Mapping Techniques to Delineate Lakes and Ponds in a Canadian High Arctic Wetland Complex

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ABSTRACT. Recent evidence points to warmer and wetter conditions for Arctic regions. It is not clear how High Arctic environments, in particular extensive wetlands, will respond to these rapid changes. Sustainability studies of wetland complexes will require accurate mapping of water bodies (lakes, ponds, streams) over time. This information is critical to obtain reliable estimates of water inputs (e.g., snowmelt), outputs (e.g., evaporation), and storage, and to assess environmental change (e.g., pond desiccation, expansion, or both). Numerous tools and techniques are available to provide this information, though each approach has its benefits and limitations. In this study, we systematically explore the differences and similarities inherent in three different techniques used to delineate lakes and small ponds at an extensive wetland area near Creswell Bay, Somerset Island, Nunavut (72˚43′N, 94˚15′W). The mapping techniques compared are satellite mapping (extraction from a satellite-based land cover map), black-and-white aerial photography, and a topographic map sheet. Results indicate that while all three techniques could delineate large lake boundaries and their positions successfully, they differed in the number of ponds they delineated, as well as their boundaries and positions. A misrepresentation of water bodies can hinder hydrologic studies of Arctic water resources, and the results of this study emphasize the need to apply appropriate mapping techniques at different scales. The three mapping techniques are based on data from three different dates over several decades, so the different results also may indicate short- and long-term environmental change.

Key words: High Arctic hydrology, High Arctic lakes, ponds and wetlands, LANDSAT, landscape mapping, RADARSAT, remote sensing

RÉSUMÉ. Selon certaines observations récentes, les régions de l'Arctique pourraient connaître des conditions plus chaudes et plus humides. Cependant, nous ne savons pas comment l'environnement de l'Extrême-Arctique réagira à ces changements rapides, surtout dans les vastes terres humides. Les études de durabilité des complexes de terres humides impliqueront le mappage exact des nappes d'eau (lacs, étangs, cours d'eau) au fil des ans. Ces renseignements joueront un rôle crucial dans l'obtention d'estimations fiables des entrées d'eau (comme la fonte des neiges), des sorties d'eau (comme l'évaporation) et de l'emmagasinage d'eau, de même que dans l'évaluation des changements d'ordre environnemental (comme l'assèchement des étangs, leur agrandissement ou les deux). De nombreux outils et techniques permettent d'obtenir ce genre de renseignements, bien que chaque méthode soit assortie d'avantages et d'inconvénients. Dans cette étude, nous explorons de manière systématique les différences et les similitudes inhérentes aux trois techniques différentes employées pour faire délimiter les lacs et les petits étangs d'une grande région de terres humides près de la baie Creswell, sur l'île Somerset, au Nunavut (72˚43′N, 94˚15′O). Les techniques de mappage qui sont comparées sont les techniques par satellite (extraites d'une carte de la couverture terrestre par satellite), les photographies aériennes en noir et blanc et la carte topographique. D'après les résultats, même si ces trois techniques permettaient de bien délimiter les limites des lacs assez grands de même que leurs positions, ce n'était pas toujours le cas des limites et des positions des étangs. La mauvaise représentation des nappes d'eau pourrait nuire aux études hydrologiques des ressources aquatiques de l'Arctique. Les résultats de cette étude mettent donc l'accent sur la nécessité d'employer les bonnes techniques de mappage à différentes échelles. Les trois techniques de mappage sont fondées sur les données à partir de trois dates différentes au fil de plusieurs décennies. Les résultats différents pourraient donc indiquer des changements environnementaux à court et à long termes.

Mots clés : hydrologie de l'Extrême-Arctique, lacs, étangs et terres humides de l'Extrême-Arctique, LANDSAT, mappage du terrain, RADARSAT, télédétection

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INTRODUCTION

Recent climate change scenarios predict warmer and wetter conditions for Arctic environments. Air temperature and precipitation levels have already increased at a greater rate in the Arctic than in the rest of the globe, and environmental changes are appearing there. Snow cover duration is declining, and pond drainage has occurred with the disappearance of shallow permafrost in parts of northern Alaska (ACIA, 2004). Clearly, there is a pressing need to investigate how High Arctic environments, and particularly wetlands, respond to these rapid climatic changes. Wetlands are important ecological sites, providing food and water to migratory birds and northern fauna (Latour et al., 2005). They are also important for water storage, and they can modify water flow and often improve water quality. The role of wetlands as a sink for or source of greenhouse gases, or both, is also of interest (Woo and Young, 2003). Future hydrology and sustainability studies of extensive High Arctic wetland complexes will therefore require accurate delineation of water bodies (e.g., lakes, ponds, and streams) on a seasonal and annual basis. This information is required for credible estimates of water inputs (e.g., snowmelt), outputs (e.g., evapotranspiration), and storage, as well as to assess environmental changes such as pond desiccation or expansion. Numerous tools and techniques are available to provide this information, though each approach has it benefits and limitations.

Radar is excellent in its ability to differentiate water from land, making it suitable in hydrological studies for defining water boundaries and delineating inundated areas (Pietroniro et al., 1999). Since open water acts as a specular reflector in the microwave spectrum, it returns a very low radar backscatter signal. Flooded vegetation generally produces a medium-strength signal, and dry vegetation, a strong return signal, allowing for differentiation of water areas (Töyrä et al., 2001). While optical satellite data (e.g., from Landsat) is more commonly used for land classification, the high percentage and frequency of cloud cover found in the High Arctic limits the usefulness of optical satellites. Because of its longer wavelength, (5.6 cm in the C-band range), RADARSAT can penetrate cloud cover, providing more reliable image capture under changing atmospheric conditions (Campbell, 1996). RADARSAT also has frequent coverage of the Arctic areas as a result of the sub-cycles in the return interval (if the wide beam is chosen, daily coverage is possible), which makes it useful in identifying significant hydrological events (i.e., the snowmelt and runoff period, and summer flooding events induced by high rainfall). Important information on these hydrological events can also be obtained using combinations of spectral bands, including those out of the visible range such as near-infrared (NIR) and shortwave infrared (SWIR).

Another technique available for mapping is aerial photograph interpretation. While black-and-white aerial photographs can provide more spatial detail than some commonly used satellites, the information contained in the print photos is restricted by the narrower spectral band used in black-and-white aerial photography, which can cause interpretation difficulties. Bright grey levels can exist for both water and exposed rock terrain; the latter are due to spectral properties of the rock (limestone and beach sediments in the study area). For water, the incident angle of the sun may cause specular reflection of sunlight on the surface at the time of imaging, making it difficult to differentiate water from other terrain types on the print photos.

Topographic maps can be obtained for all areas of the Canadian High Arctic, with 1:50000 being the most detailed cartographic scale for this area. While these maps provide information on features such as ground relief and drainage patterns, they are limited by the scale at which they are created and the time dependency of the source of the data used to produce them, the original aerial photographs, and the ensuing cartographic interpretation of them. Specifically, potential errors can include scale errors (omission of detail), distortions in the photograph, shadows (obscuring the ground), and the interpreter's subjective identification of landforms (Gandolfi and Bischetti, 1997).

The objective of this study was to explore the differences and similarities inherent in three different techniques for delineating lakes and small ponds in a remote High Arctic location. The mapping techniques compared are satellite mapping (extraction from a satellite-based land cover map), black-and-white aerial photography, and a topographic map sheet.

STUDY AREA

The study area is an area of extensive wetlands located on the low-lying south side of Creswell Bay, Somerset Island, Nunavut, Canada (Fig. 1). Continuous permafrost (500 m thick) exists here, and the active layer reaches about 0.40 m in boggy areas and approximately 1.0 m in sandy and gravelly zones. There are no continuous climate records from Somerset Island, but the area is considered similar to Resolute Bay, Cornwallis Island (200 km to the north), with its long, cold, dry winters and brief, cool, damp summers (de March et al., 1977; Dyke, 1983). Resolute Bay has a mean annual temperature of -16˚C, with only July and August reaching mean temperatures above 0˚C. Annual precipitation is 150 mm, of which 69 mm falls as rain (MSC, 2002).

In the area of Creswell Bay, Dyke (1983) reports that the bedrock is a limestone and dolostone of Silurian (Read Bay and Cape Storm) and Ordovician (Allen Bay, Irene Bay, and Land River) formations—that is, continental shelf deposits. Surficial material is characterized by beach sediments (1 to 5 m thick) in the northern section and a till veneer (0.5 to 2 m thick) in the southern zone. Beach sediments form a ridge-swale topography, while the till

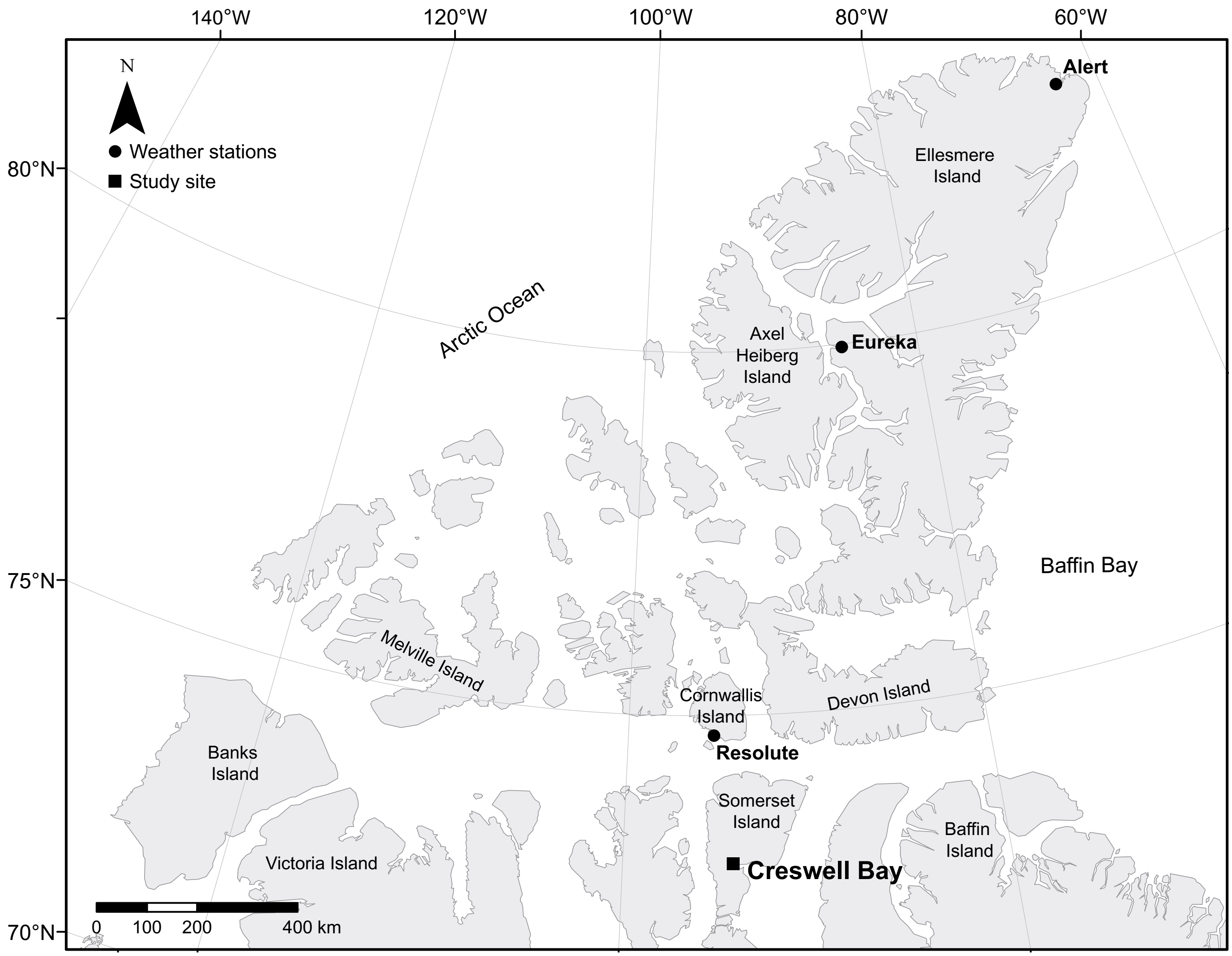

FIG. 1. Map of Canadian Arctic Islands showing the study site and weather stations. Study site is located near Creswell Bay (72.71˚ N, 94.25˚ W) on Somerset Island, Nunavut.

area has greater plant coverage of 30% to 60% (Dyke, 1983). Vegetation here has an average height of 59 mm and includes *Cassiope tetragona*, *Dryas integrifolia*, *Oxyria digyna*, *Pedicularis arctica*, *Saxifraga oppositifolia*, and *Salix arctica*, as well as a variety of wet meadow grasses, sedges, mosses, and lichens.

The target area covers roughly 23 km^2 and spans an elevation of 0 to 50 m above sea level. It is bounded by the following coordinates: upper left corner 72.73˚ N, 94.31˚ W (456549 E, 8071542 N, UTM Zone 15×) and lower right corner 72.69˚ N, 94.18˚ W (460712 E, 8065934 N, UTM Zone 15×). The site contains two contrasting landscapes, the northern part, which has been modified by beach and coastal processes, and the southern section, which shows more evidence of glacial and periglacial influence (M.-K. Woo, pers. comm. 2002). The northern coastal section has undergone isostatic uplift and has limestone bedrock and beach sediments and a ground cover composed mainly of rock, except for embayment areas found among the north-south ridges. Lakes and ponds in this area formed as a result of coastal processes and glacial action. The southern zone, which has been glaciated, is rocky, poorly drained, and generally well vegetated. It contains lakes and ponds formed as a result of glacial action, remnants of ponds formed behind an ancient lagoon, and ponds likely created by thermokarst action. To facilitate the discussion of the results, we will refer to the northern section as A, and subdivide the southern section into three areas: B – eastern, C – western, and D – southern (Fig. 2).

METHODS

This study comprised both summer fieldwork at Creswell Bay in 2002 to 2004 and analysis of remote-sensing imagery using one RADARSAT-1 image (9 July 2002), one Landsat 7 image (14 August 2000), and aerial photographs of the target area (11 August 1975). The main field season

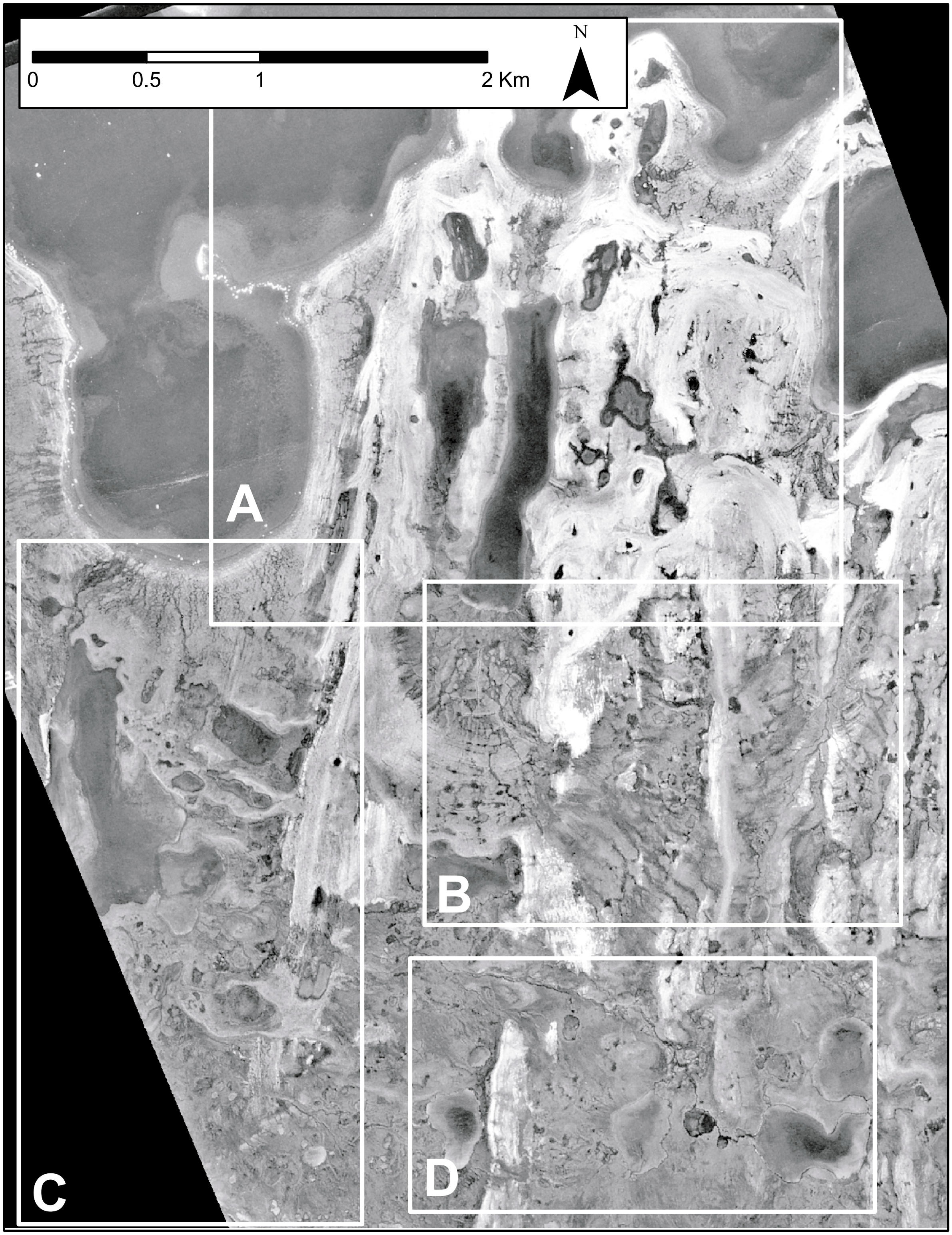

FIG. 2. Aerial photograph of the study area, with outlines of areas discussed: A) Northern section, B) Southern section – Eastern area, C) Southern Section – Western area, and D) Southern section – Southern area.

occurred from early to late July 2002. Additional training data and ground control points (GCPs) were obtained in mid-July 2003. Fieldwork in 2004 (mid-July to early August) assisted in the interpretation of the results.

Satellite Imagery

The water bodies were identified using a land classification map created from satellite imagery, which identified the four major land covers in the area (water, wetland, moist ground, and rock). The image used to create this map was a combination of shortwave infrared (SWIR) from Landsat (2.08–2.35 μm) and fine-beam radar from RADARSAT (F4 ≈ 45˚ descending, C band, HH-polarization – 5.6 cm). The combination of radar and SWIR was found suitable for identifying the land covers in the area, and it helped to eliminate misclassification of ice cover as a mixture of the ground covers, a problem experienced using RADARSAT alone. This combination also enhanced spatial detail since radar is good for defining water boundaries and has a finer spatial resolution than Landsat (7 m vs. 30 m). For this study, only one radar image was available for use. A combination of multi-angle or multi-temporal images might have provided the means to create a satellite-based classification map for the area using RADARSAT alone, rather than in combination with other imagery sources.

Since the RADARSAT image was obtained at the same time as the fieldwork program, ground conditions at the time of imaging were known. Image speckle, related to scattering within a resolution cell (Oliver and Quegan, 1998), was reduced using a 3 × 3 gamma filter, which minimizes image speckle but still allows high-frequency features, such as lake edges, to be preserved (Shi and Fung, 1994).

Registration of the Creswell Bay RADARSAT image was performed using a combination of GCPs obtained in the field with a handheld global positioning system (GPS error ≤ 5 m) and GCPs determined from a topographic map. As the study area is located in an Arctic wetland environment with few obvious GCPs and no existing corner reflectors, we followed a method described by Verbyla (1995) for similar terrain. Verbyla (1995) collected a number of GCPs that were distributed across the image, rejected the GCPs that contributed to high model residual error, and adjusted the model until an acceptable residual (i.e., ± 1 pixel) was obtained while retaining an acceptable number of GCPs for validation.

In order to avoid discrepancies around the coastlines and lake edges between the present-day positions and the locations based on the topographic map for the area (1:50 000; printed in 1978 and accurate to 1958), we used the centres of "stable" ponds as 12 additional GCPs. These small ponds are called "stable" because their shape and size as seen on the topographic map remains unchanged in the 2002 satellite imagery. Overall, this approach improved the registration accuracy. The root mean square error (RMSE), a measure of potential distortion between the original and the geometrically corrected images, was reduced to approximately 1.5 m (< ± 1 pixel), an accuracy comparable to that obtained by Verbyla (1995). A total of 21 GCPs were used in the final registration model, which (including potential GPS errors) created an overall error of 6.5 m or less.

The Landsat image required further image registration in addition to that which was provided with it because of conflicting map datums (NAD83 versus WGS84) between the Landsat and RADARSAT pre-processing methods. The Landsat image was registered to the geometrically corrected RADARSAT image at an acceptably low RMSE of less than 5 m.

The combined radar/SWIR image was classified into terrain classes on the basis of in-situ training data (e.g., ground type, vegetation height, moisture conditions) collected using a handheld GPS from within and adjacent to the target area (Kane et al., 2001). We chose a supervised classification method that used a maximum likelihood algorithm. Training data consisted of 206 sample points, and estimates of the means and variances of the terrain classes were used to estimate the probability that each pixel belonged to a particular category (Campbell, 1996). Validation of the classified map used the remainder of the ground data points not included in the training process (sample size = 86), and this resulted in an overall classification accuracy of 77% for the four land covers (water, wetland, moist ground, and rock). Accuracy was diminished by the difficulties in separating moist ground from wetland terrain. For the water class alone, however, user's accuracy (the percentage of a class that will correspond to the actual terrain type identified on the ground; see Campbell, 1996) was 95%. The classified water areas were then extracted and converted to a GIS vector file for comparison to the other mapping methods.

Aerial Photographs and Topographic Map

To gain more detailed ground information from the target area, we examined aerial photographs (1:20 000) taken on 11 August 1975. The two images were scanned into a digital format with a resulting pixel size of 2 m and geometrically corrected using the satellite image (image-to-image registration with the combined Landsat/RADARSAT image) with a resulting RMSE of under 3 m.

The ability to delineate boundaries of water bodies (e.g., lakes and ponds) from terrain is important in the context of Arctic wetland studies. Boundaries and shifting borders will often determine the appropriate application of a parameter in estimates of snowmelt and evaporation. For example, to model snowmelt in Arctic terrain, specific surface albedo and Priestley-Taylor α values are assigned to distinguish snow-covered from snow-free surfaces; and similarly, specific values are designated for dry and wet surfaces to model evaporation (Woo, 2004). However, this designation based on ground-type delineation can be compromised when using black-and-white aerial photography. Since only grey level values are contained in the digital version of the aerial photograph (as opposed to a range of spectral bands in an optical satellite image), an automated classification procedure cannot be used to separate the water bodies from the surrounding land areas. Specifically, in this study, tone alone could not delineate the lakes and ponds from surrounding terrain because of the wide range of grey-level values and the occurrence of light reflection from the water. Subsequently, the aerial photograph images were imported into a GIS program and digitized manually according to a subjective criterion

TABLE 1. Comparison of number of water bodies (lakes and ponds) and total area covered by water bodies mapped using three different methods. Water bodies only partially contained within the target area were not included in analysis.

	Satellite	Topographic Map	Aerial Photograph
Number of water bodies	408	175	262
Mapped water bodies as percentage of number mapped using the aerial photograph	156%	67%	[100%]
Total area covered by water bodies	1 683 401 m^2	1 673 762 m^2	1 642 563 m^2
Water-body area as percentage of that mapped using the aerial photograph	102.5%	102%	[100%]

based on both tone and texture. Water edges were delineated where there was a sharp contrast in grey values between the surrounding land and a water body (e.g., ponds appear dark within the rock areas, which are light in colour). In less distinct areas, such as ponds adjacent to wet meadows, texture differences were also considered: water bodies appear "smoother" than surrounding "rougher" ground. It was easier to define texture on the original aerial photographs than on the digitized versions, since spatial resolution is lost with magnification of the rasterized version. Where the grey-level values of the aerial photographs did not change sharply enough to demarcate boundaries, oblique colour aerial photographs of the study site, taken from low-level (200 m) helicopter flights in the summers of 2002 and 2003, were also used to help define edges. Yoshikawa and Hinzman (2003) also used a manual method for mapping water bodies from aerial photographs when dealing with defining the difficult threshold between ponds and marshes near Council, Alaska.

The water bodies on the topographic map sheet (Union River, 58B/11-1:50 000) within the target area were digitized manually and overlaid on the aerial photographs along with the extracted water class from the satellite image.

RESULTS AND DISCUSSION

Mapping the lakes and ponds in this low-gradient wetland complex by different methods 1) provides insight on which technique is most appropriate for a particular scientific objective or goal; 2) demonstrates the type of information potentially lost or gained by using different scales of imagery, as changing the resolution of the source imagery can lead to differences in mapped water body boundaries; and 3) reveals incidences of both short- and long-term environmental change and, in some cases, the associated processes involved. Table 1 presents the number of lakes and ponds mapped using the three different mapping techniques. In this analysis, the aerial photograph was assumed to have the "correct" number of lakes and ponds, and percentages are reported in relation to that number and area.

Occurrence and Areas of Lakes and Ponds

Using the water areas identified from the combination Radar/SWIR image returned 845 lakes and ponds. This number was initially suspect and considered to arise from the radar speckle that remained after filtering, or from misclassified radar pixels. In order to reduce the ponds influenced by radar speckle, the water bodies equivalent in area to one pixel were removed from the image. The remaining collection of lakes and ponds numbered 408 and covered an area of 1 683 401 m^2 (Table 1). The radar image was obtained while a large, widespread precipitation event was occurring throughout the Arctic Islands, and an automatic weather station near Resolute Bay recorded over 20 mm of rainfall on the same day the radar image was taken of Creswell Bay. The satellite overestimation of the number of lakes in relation to the aerial photograph (see Table 1) is partly explained by increased moisture and standing water on the ground, in particular in section A with its rocky ground cover. The wet season of 2002 likely filled depressions in this gravelly rock with water and returned a radar backscatter for water rather than rock. This type of depression storage after rainfalls has also been noted by Spence and Woo (2002) for a Precambrian landscape near Yellowknife, Northwest Territories. It was also confirmed for our study area during fieldwork in July 2004, when a similar high rain event occurred (more than 20 mm over two days). Small water bodies occurred after this prolonged rain but were intermittent in duration. Most small ponds disappeared via evaporation or vertical drainage a few days after the 2004 rain event.

These observations clearly show the potential ability of radar to identify the rapid response of Arctic wetland landscapes to short-term hydrologic events. The capability for radar to capture these expansion–contraction processes, if considered on a broader scale, could lead to improved estimates of evaporation or water storage on both a spatial scale (pond to catchments) and a temporal scale (day to seasons).

Figure 3 shows the frequency of water bodies in relation to size and mapping technique. Clearly, all methods are quite suitable for defining large water bodies (i.e., lakes and ponds larger than 10 000 m^2). The greatest variation in number of water bodies occurs with the smaller water bodies (less than 10 000 m^2). The high number of small satellite-mapped ponds can be seen clearly in Figure 3, especially for the two smallest categories (less than 100 m^2 and 100–1000 m^2). This dramatic departure from the results of the other two approaches is likely influenced by 1) the use of automated mapping techniques versus observation-based mapping techniques and 2) environmental changes in the landscape — both in the short term, and since 1958 (topographic map) and 1975 (aerial photograph).

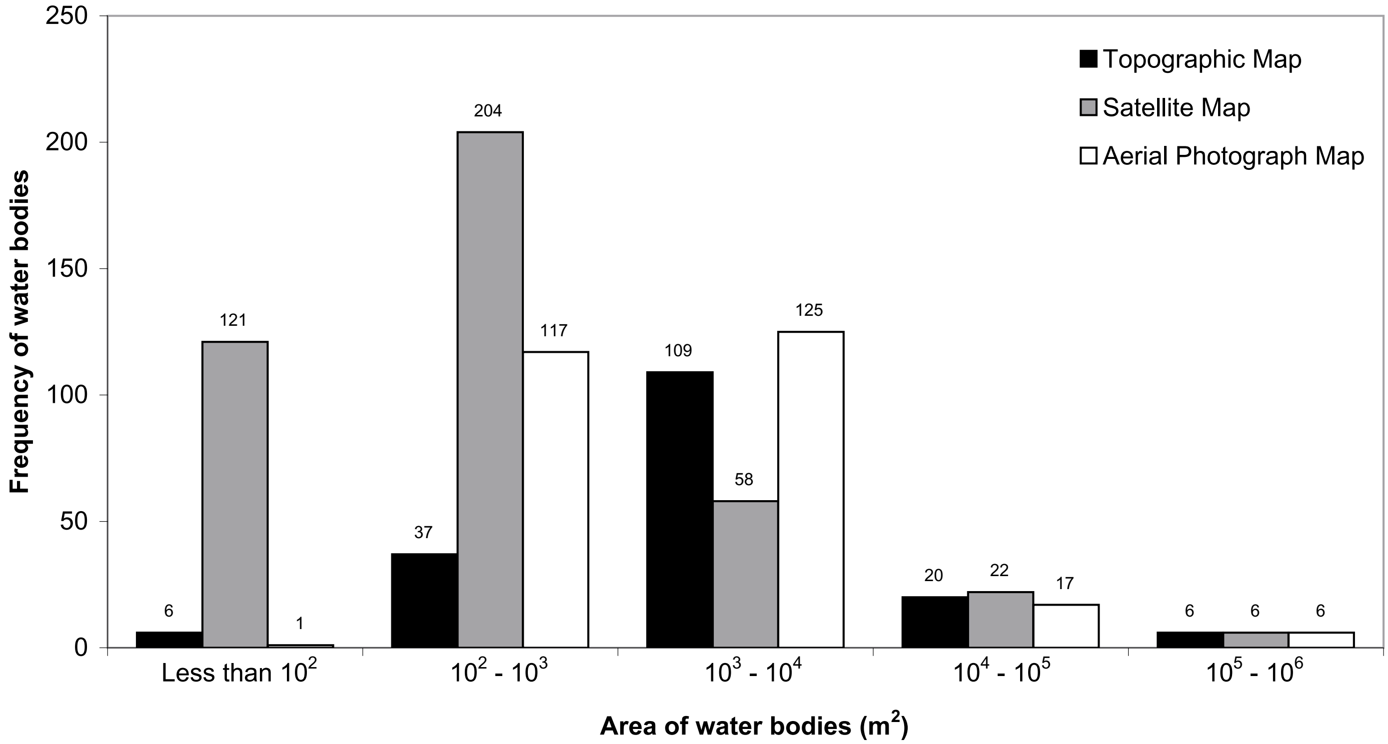

FIG. 3. Comparison of areal water body coverage (lakes and ponds) produced by the three mapping methods: topographic, satellite, and aerial photograph. The number of water bodies represented is shown above each bar.

The digitized map has 175 identified water bodies covering a total area of 1 673 762 m^2, compared to 262 identified water bodies covering 1 642 563 m^2 on the digitized aerial photograph. On the aerial photograph, objects that resembled potential water bodies but were very small (less than 100 m^2) were not digitized because their boundaries could not be well defined. If accounted for, these additional ponds might have reduced the discrepancy in pond number and area between the aerial photograph and the satellite imagery (see Table 1 and Fig. 3). The lower number of lakes and ponds identified in the topographic map compared to the aerial photograph (67% less) is likely a result of scale: 1:50 000 versus 1:20 000. At this coarser cartographic scale, many smaller water bodies are not identified on the topographic map. However, the total area covered by the water bodies as defined by the topographic map is greater than that of the aerial photograph. This implies an overestimation of areal coverage of ponds on the topographic map, which may stem from cartographic misinterpretation.

As mentioned earlier, large rainstorms (> 20 mm) such as those experienced during this study can increase the number of small ponds occurring over an area. The high rainfall in 2002 elevated soil moisture levels and filled depressions and low-lying areas. This pattern was confirmed when a rainfall event of similar magnitude occurred during the summer of 2004, highlighting the ability of radar to capture short-term terrestrial changes. Variation in frequency of small water bodies detected by all three methods also suggests the potential for long-term modifications to this landscape. Over a 25 to 40 year time span, such as that covered by the data sources used in this study, it is possible that some small ponds could have formed while other ponds dried up, disappeared, or merged into wet meadow patches (Woo and Young, 2003). Yoshikawa and Hinzman (2003) report ponds in Alaska draining in 1.5 years as a result of recent warming and disappearance of permafrost.

Locations of Lakes and Ponds

Generally, all three mapping methods indicate similar locations (based on visual criteria) for the larger lakes, although boundaries can vary in some cases. Greatest variation occurs with the smaller water bodies and likely results from the resolution of the different mapping methods. Hlavka and Dungan (2002) noted up to a 50% decrease in area covered by small tundra ponds south of Point Barrow, Alaska, as the imagery they were using was degraded spatially.

Section A (Northern Section): The positions of the lakes produced by the three mapping methods are more similar here than in the other three areas, likely as a result of the confining rock ground cover (Fig. 4). Some sections of the larger lakes show a lateral shift in shoreline position between the satellite and the aerial photograph; however, the smaller ponds in the bedrock areas show good boundary alignment. This pattern either suggests that lake edges are changing over time (e.g., possible infilling) or arises from the way the various methods determine boundaries. Lake edges found on aerial photo-

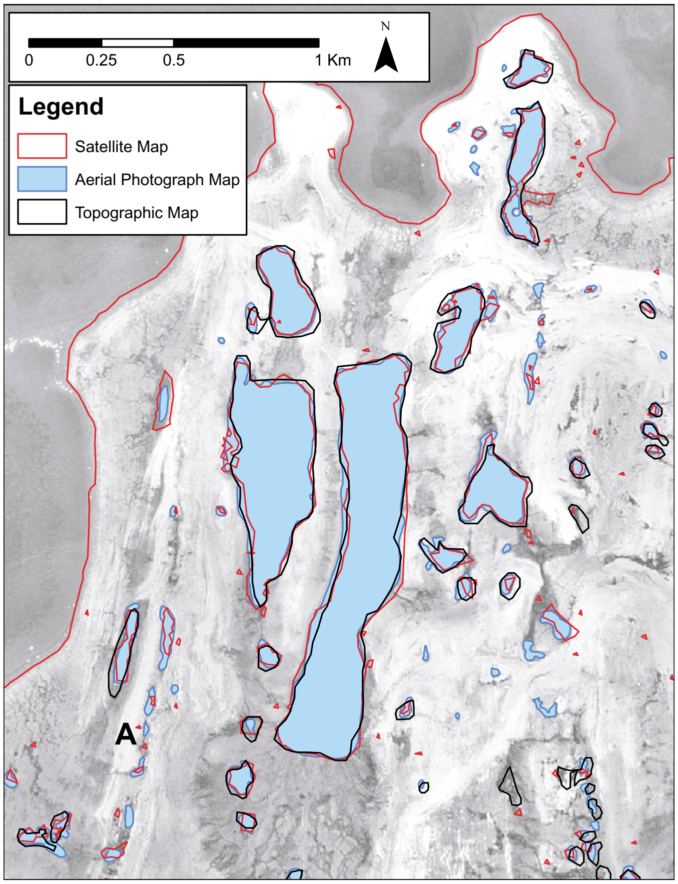

FIG. 4. Northern Section of the study area, showing the different results from the three mapping techniques, with the aerial photograph as the underlying image. Blue represents the lakes mapped on the aerial photograph; black lines, the lake boundaries on the topographic map; and red lines, the boundaries on the satellite map.

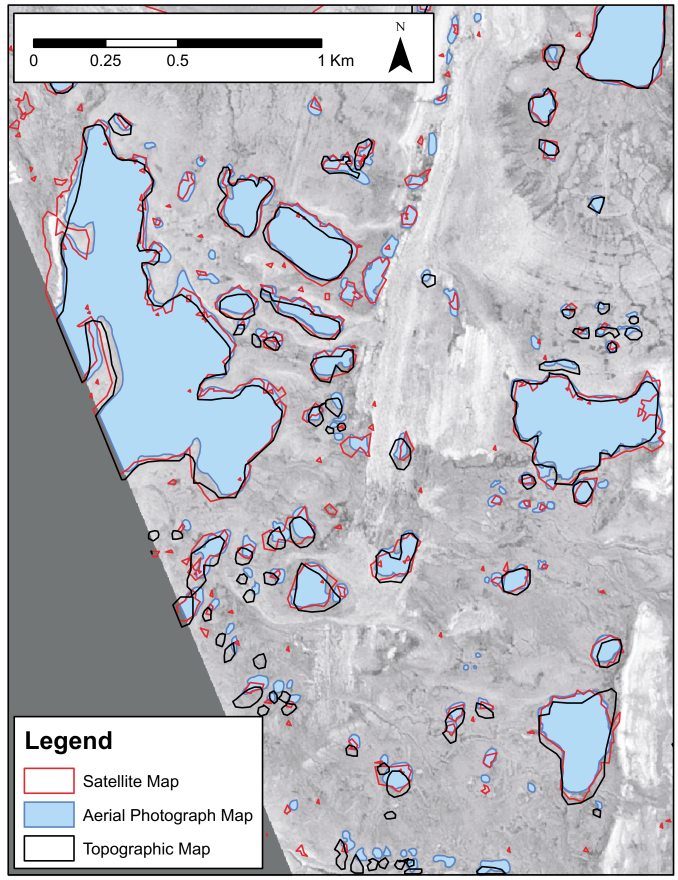

FIG. 5. Southern Section, Western area – Western portion of the study area showing the different results from the three mapping techniques, with the aerial photograph as the underlying image. Colour representation as in Figure 4.

graphs have smooth, natural edges. The satellite-mapped lakes are based on a rasterized image, and it is possible that some pixels were misclassified, resulting in a jagged shoreline. Lakes found on the topographic map are well aligned with those mapped by the other two methods, although shapes differ on the basis of scale. The topographic map also misses several small ponds, owing to its coarser scale. The satellite overestimation of small ponds in this section can be attributed to rain-induced, temporary ponds, as noted previously.

The most prominent discrepancy that emerged for this area involved the chain of small ponds found along the northeast-southwest bedrock ridge (the area has a series of bedrock steps) on the western side of the northern section (labelled "A" in Fig. 4). The satellite identified the general shape of some of these ponds, but they are absent from the topographic map. Ten ponds of similar type were mapped on the aerial photograph; of these, the topographic map showed only two ponds, while the satellite map indicated seven. The satellite map also underestimated the areal extent of these ponds in comparison to the 1975 aerial photograph. These water bodies are large enough to have been included on the topographic map (the map contains smaller ponds). Their absence suggests two possibilities: 1) the water bodies were dry when the 1958 aerial photographs used to create the topographic map were taken; or 2) a mapping error occurred. An aerial photograph from August 2000 that captured one of these ponds showed it to be quite shallow. Reconnaissance of this locale in 2004 also confirmed that many lakes and ponds are fed by perennial snowbeds, which often develop at breaks in slope as a result of the interaction between wind and topography that controls snow redistribution. Woo and Young (2003) indicate that these snowbeds can shrink considerably during warm summer periods and almost disappear. The absence of these ponds on the topographic map suggests that in 1958, the perennial snowbeds the ponds relied upon as a source of water were not of a sufficient mass to sustain the shallow water bodies lying downslope.

Section B (Southern Section-Eastern Area): An examination of the area east of the lagoon-type ponds shows a large discrepancy between all three methods and an overestimation by satellite imagery. The topographic map also misses three of the lagoonal ponds, while the satellite map overlooks 12 and the aerial photograph map fails to spot two ponds identified by the topographic map. Neither pond missed by the aerial photograph was captured by the satellite map, which suggests that the ponds were dried up at the time when the aerial photograph was taken (August 1975).

With respect to the position of the lagoonal ponds, the topographic map shows an offset of approximately 20 m to the east for several ponds. However, not all ponds in this area are shifted. A small pond just east of the lagoonal ponds has good east-west alignment between the topographic map and the aerial photograph, but north-south alignment is poor for the topographic map, which shows a northwest offset similar to that of the morainic lakes and ponds in the southern section. This pattern could possibly be a result of rectification errors, or possibly pond migration and encroachment by emergent vegetation. Pond migration has been observed in other northern areas such as the Alaskan North Slope, where ponds have been shown to form perpendicular to the prevailing wind direction (Carson and Hussey, 1962).

Section C (Southern Section-Western Area): The western portion of the mapped area (Fig. 5) shows more boundary agreement on the northeast sides of the satellite- and aerial photograph–derived water bodies than on their southwest edges. Several of these lakes and ponds have formed behind moraines to the northeast; hence, changes to their form would be more likely to occur on the southwest side, where no appreciable barriers exist. Observations in 2004 after a large rain event (> 20 mm) confirmed water spillage from these water bodies on the southwest edge into the adjacent wet meadow. It is likely that similar spillage in 2002 (a wet year) is the reason for the southwest boundary differences identified in this area.

Comparison of all map outlines shows digitized lakes from the topographic map to be located about 30 m to the southwest of their locations on the aerial photograph map and satellite map. This offset becomes especially pronounced for the smaller water bodies near the edge of the image. Many thermokarst ponds near the bottom of the image are not identified at all on the satellite map, and their position is substantially offset between the aerial photograph and the topographic map. Overall, the thermokarst-type ponds produce the worst match among the three mapping methods. Mapping errors are undoubtedly feasible, especially registration errors; however, modification of this permafrost landscape (e.g., drainage of ponds) within a short period is also possible (e.g., Kozlenko and Jeffries, 2000; Yoshikawa and Hinzman, 2003).

Section D (Southern Section-Southern Area): In this area, the boundaries mapped by all three methods of the northwest side of the larger lakes compare well; however, the aerial photograph and satellite maps show the lakes to be smaller on the southeast side. One hypothesis about this discrepancy is that since this area has gentle topography and lies at the bottom of a large slope, fine sediments may have washed down over time and settled near the shoreline, allowing vegetation to root and encroach on the shoreline. Smaller ponds in this area show a 15 – 30 m shift to the southeast between the topographic map and the aerial photograph, suggesting that the ponds in this low-gradient area have shifted over time. The mechanism for this shift is still not clear.

CONCLUSIONS

Since the radar/satellite method may have overestimated the ponds, and the topographic map may have had omitted some waterbodies, the lakes and ponds mapped from aerial photographs are considered most "accurate" for this study. However, aerial photographs can also present limitations, especially their lack of spectral data and problems in differentiating boundaries, particularly where water bodies grade into wetlands. The aerial photograph has much finer ground resolution than the satellite combination used, but the available aerial photographs are outdated (1975). Ideally, finer-resolution satellite imagery or more recent aerial photographs would be preferred for mapping small ponds; but low-level oblique photography, used in combination with the aerial photographs to update them, can provide a great deal of information on lakes and ponds and the recent changes that are taking place.

All mapping methods showed similar locations and areas covered for the larger lakes, but the shape and boundaries varied slightly for each method. These variations can likely be attributed to mapping errors and slow environmental changes. The "accuracy" of a particular mapping method is determined by the purpose for the mapping. If the given purpose does not involve accurately identifying the position of the small tundra ponds, then the use of topographic maps could be suitable, as the larger lakes were in good positional agreement with those mapped by the other methods. The smaller ponds are where the major discrepancies between methods became evident. Although these small ponds are evident at the aerial photograph scale (1:20 000), they become less apparent at the coarser scales, and overall, it proved difficult to map them accurately. Reasons for this difficulty include environmental changes over time and potential mapping errors. Some of these landscape alterations might have been from pond migration, expansion, and infilling, or from warm, dry summers that resulted in the disappearance of water bodies (through the disappearance of late-lying snowbeds and evolution of ponds into wet meadows).

Evidence of environmental change can be seen by comparing the results from the three mapping methods. The increased number of small ponds identified with the satellite map after a rainy period (2002) can be attributed to depression storage. In 2004, ponds of a similar nature persisted for days to several weeks before drying. The expanded boundaries of some of the moraine-dammed lakes also indicate potential seasonal changes in the water bodies that can be identified using satellite imagery. Higher water levels in 2002 (a wet year) spilled over into the wetland zone in an area where no confining moraine existed. The bedrock ponds missing from the topographic map (1958) but found on the aerial photograph map (1975) and the satellite map (2002) provide evidence of interannual variations in the environment. These bedrock ponds are reliant on the supply of meltwater from late-lying snowbanks, and wet and dry years can affect the persistence of these snowbanks, and hence pond sustainability.

The shifting locations of the small ponds may be evidence of long-term environmental changes. The time span between the topographic map and the satellite map is more than 40 years, and considerable discrepancies in pond occurrence are evident. While some of these differences could be attributable to mapping errors (e.g., photogrammetric or rectification errors), the landscape has undoubtedly been modified by periglacial processes (e.g., ground thaw, drainage, sedimentation, and encroachment).

Mapping from aerial photographs without the aid of field photographs can present difficulties in distinguishing the small ponds from the surrounding ground covers. These difficulties show the importance of carrying out fieldwork in combination with the application of remote mapping techniques. Improving on these methods could involve more complete field photograph coverage of the study area, more recent aerial photographs, and a finer resolution of satellite imagery.

This study also highlights the problems and difficulties of mapping water bodies at different scales. While some of the differences that occurred in delineating the lake edges using the three different methods (satellite, topographic map, and aerial photograph) could be a result of changes in the lake boundaries over time, the scale at which the water bodies were mapped plays an important role. Defining boundaries presents many difficulties, especially when manually mapping from an aerial photograph, since the decision where to draw the bounding line of the lake or pond is subjective. Moving up to the scale of the satellite imagery results in differing boundaries as well, since the lake edges are now defined as the edges of pixels that have been classified as water. As Woo (2004) discusses, changing the resolution of investigations through upscaling or downscaling is accompanied by a re-definition of some boundaries so that the consideration of boundaries and borders is integral to the issues of scale and scaling. A misrepresentation of water bodies can hinder sustainability studies of Arctic water resources, and our results emphasize the need to apply appropriate mapping techniques at different scales.

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