WETLAND INVENTORY AND MAPPING IN THE NORTHWEST TERRITORIES USING DIGITAL LANDSAT DATA

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ABSTRACT

The feasibility of using Landsat data as a basis for wetland inventory and mapping in the Northwest Territories (NWT) was assessed. Digital analysis of Landsat data was used to investigate wetland patterns and to map cover classes for three wetland areas in the subarctic and boreal wetland regions. The greater spatial and spectral resolution of thematic mapper (TM) data compared to Landsat multispectral scanner (MSS) data facilitated digital analysis and allowed differentiation of a greater number of wetland cover types. Enhancements produced using TM data provided abundant information about general land cover patterns and landscape heterogeneity, but classification products were superior for delineating and calculating areas of wetland cover types. From 8-13 cover types were produced for each wetland area by supervised classification using maximum-likelihood and parallelepiped classifiers, with 67%-89% overall classification accuracy.

Landsat data analysis provides a useful tool for mapping NWT wetlands. Potential users should be aware that a substantial investment of time and effort is required to produce maps with acceptable classification accuracies, and ground data collection is costly. However, in comparison with conventional mapping techniques which require intensive ground surveys or current aerial photography, analysis of satellite data is less expensive. The remote sensing approach is often the only feasible option for mapping remote wetland areas in northern Canada.

SUMMARY

The feasibility of using Landsat data as a basis for wetland inventory and mapping in the Northwest Territories (NWT) was assessed. Digital analysis of Landsat data on ARIES image analysis systems was used to examine land cover patterns for three wetland areas in the subarctic and boreal wetland regions. The information content of several image enhancement and classification products derived from Landsat multispectral scanner (MSS) and thematic mapper (TM) data was investigated, and the value of these products for wetland inventory and management in the NWT was evaluated.

Study areas included the Ramparts-Hume and Brackett Lake wetland complexes, which are in the low subarctic wetland region, and the Yellowknife-Rae wetland area, which is in the continental high boreal wetland region. The Ramparts-Hume and Brackett Lake areas lie in the Mackenzie River valley approximately 800km and 600km northwest of the Yellowknife-Rae area, respectively. Wetland areas were selected for study based on their known importance to wildlife, opportunities for field work, available reference data, and interest indicated by NWT waterfowl biologists.

Several digital image enhancement techniques were investigated, including contrast stretches (linear, piece-wise, power) and principal components (PC) analysis. PC

image enhancements and several contrast-stretched colour composites produced with TM data provided abundant information about general land cover patterns and landscape heterogeneity. Image enhancements are useful tools for studying wetlands at a reconnaissance level by providing a synoptic overview of land cover patterns. Initial study of wetland patterns should proceed using colour enhancements to identify dominant spectral patterns and spectral variability within study areas, and to stratify areas and select locations for ground study.

Digital analysis was used to produce supervised classifications for the three wetland areas using maximum-likelihood and parallelepiped classifiers. From 8-13 water and vegetation cover classes were mapped for each study area, with 67-89% overall classification accuracy. Two key features of supervised classification (which are not available using image enhancement) make this analysis technique valuable for wetland inventory and for wildlife management in general: (1) specific cover types can be mapped (depending on intended applications, availability of appropriate ground data and study area characteristics); and (2) calculation of the areal coverage by mapped classes can be achieved quickly, and summaries can be produced for entire mapped areas, subareas, or grid cells.

The final classification for the Ramparts-Hume wetland area was produced by supervised classification of MSS data

obtained in late August 1985, using a maximum-likelihood classifier and bands 1, 2, and 4. Eight cover classes were mapped for an extensive area (6,470 km^2) at 1:125,000 scale, including 2 water/wetland classes, 5 forest and shrubland cover types, and 1 class representing bare soil and rock. Low classification accuracy for the Ramparts-Hume wetland area limits the usefulness of the map for management purposes: overall classification accuracy was 67%; accuracies for individual classes ranged from 30-100%; and only 3 classes had accuracies greater than 70%.

Single-date classifications were pursued for the Brackett Lake area using Landsat TM data from two different dates, because haze on the first TM scene (from mid-July 1987) presented significant problems during classification. The final classification for the Brackett Lake wetland, which was produced using TM data from late July 1988, was mapped as 13 classes which represent: water with different turbidity, depth, and substrate characteristics (N=3); wetland vegetation and wetland/water mosaics (N=3); deciduous forest and shrubland (N=2); coniferous-dominated forest (N=3); and areas with little or no cover by vascular vegetation (N=2). The classification was produced using a maximum-likelihood algorithm with bands 2, 3, 4 and 5. Overall classification accuracy was 89%, and accuracies of individual classes were 78-100%. The Brackett Lake area (2,510 km^2) was mapped at 1:50,000-scale.

The Yellowknife-Rae wetland map (890 km^2 at 1:50,000-scale) portrays 8 cover classes with an overall accuracy of 82%, and individual class accuracies of 79-92%. Two cover classes represent each of the following categories: water, wetland vegetation, forest, and sparsely vegetated areas. The classification was produced using TM data (bands 2, 4, and 5) from mid-July 1987, and a parallelepiped algorithm.

The greater spatial and spectral resolution of TM data compared to MSS data was necessary for differentiating emergent and floating aquatic vegetation. The parallelepiped algorithm was valuable for classifying land cover in the particularly heterogeneous Yellowknife-Rae wetland area, where patches of important cover types were small and edge pixels between different cover types were plentiful. For the Brackett Lake wetland area, however, the advantages of the parallelepiped classifier were outweighed by the superior ability of the maximum-likelihood algorithm to discriminate wetland classes using 4 bands of TM data.

The study was conducted under difficult conditions which will likely exist for most wetland mapping projects in northern regions. Factors which presented problems included: (1) few suitable, cloud-free, summer Landsat scenes were available for the study areas, (2) available aerial photography was usually limited to relatively small-scale (i.e., approximately 1:60,000), out-of-date (i.e., at least 15 years old) black-and-white panchromatic

photographs, (3) topographic maps (1:250,000- and 1:50,000-scale) portray conditions existing 15-30 years before Landsat data used for this project were acquired, (4) no other reference data (e.g., resource maps) were available, and (5) access to study areas for collecting information about existing environmental conditions was difficult and expensive. Consequently, the data base used for producing classifications and assessing their accuracy consisted of relatively few ground data acquired during brief helicopter surveys and information obtained by interpretation of small-scale, outdated air photos.

Relatively large-scale (1:50,000 or larger) maps of wetland areas produced by analysis of Landsat TM digital data would be valuable for management of wildlife species associated with wetlands in the NWT. However, the limitations imposed by the logistical and financial requirements for working in extensive, inaccessible wetland areas should be considered during the planning stages of wetland classification and mapping projects. The lack of adequate ground data and reference materials was the single most important factor limiting the efficiency of producing classification maps with acceptable levels of accuracy. Collecting sufficient ground data to produce relatively detailed wetland maps accompanied by comprehensive descriptions of the ecological conditions represented by map units would require a significantly larger commitment of

resources (primarily funding and manpower) than that available during this study.

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INTRODUCTION

A large amount of data on seasonal use of NWT wetlands by waterfowl and other wildlife species has been collected during impact assessment studies (e.g., Mackenzie Valley pipeline corridor work) and annual surveys conducted by the U.S. Fish and Wildlife Service, the Canadian Wildlife Service, and the NWT Department of Renewable Resources. However, little information is available concerning the characteristics of NWT wetlands which determine their value for wetland-associated species. Furthermore, baseline habitat data necessary to monitor changes in wetlands resulting from natural causes and land use activities are not available.

Because of the large size of the NWT and inaccessibility of most of its wetlands, inventory of extensive areas using intensive field survey techniques is not feasible. Consequently, research was initiated by the NWT Wildlife Management Division, with the support of Ducks Unlimited Canada and Wildlife Habitat Canada, to investigate the feasibility of using data acquired by Landsat satellite sensors for inventorying and mapping NWT wetlands. Information describing land cover characteristics could be used to determine the regional distribution and abundance of wetland environments, to evaluate the potential of local areas as habitat for wildlife, and to assess the impact of habitat loss or alteration on wildlife. Information obtained from analysis of Landsat data has potential for facilitating and improving management of wetlands and wildlife in the NWT.

Numerous northern wetlands have been mapped using Landsat data by researchers studying wetland areas in northern Ontario (Kozlovic and Howarth 1977; Cowell et al. 1979; Pala 1982, 1983; Pala and Boissonneau 1982), Manitoba (Dixon and Stewart 1984, Stewart et al. 1986), and Alberta (Wickware and Howarth 1981, Palylyk 1985). (See Wakelyn 1987 for more details.) Wetland classes produced by classification of Landsat data are determined by the spectral characteristics and statistical properties of relatively few data (i.e., known ground sites), which are used to classify a comparatively large area. Landsat-derived wetland classes primarily describe surface features such as vegetation type and density, although other wetland characteristics influence spectral reflectance (e.g., moisture conditions, turbidity). Physiognomic type is usually the vegetation feature used to develop mapping units, which are modified by addition of terms describing edaphic, physiographic, and hydrologic conditions, when this information is available.

This study investigated the feasibility of using thematic maps derived from analysis of Landsat data to facilitate management of northern wetlands and wildlife. Specifically, project objectives were to:

(1) determine the type of information on wetland characteristics provided by visual interpretation of Landsat imagery (colour composites and image enhancements) and classification of Landsat digital data,

(2) assess the feasibility of mapping northern wetland areas using digital classification of Landsat data under constraints imposed by limited amounts of ground and reference data, and

(3) assess the potential value of Landsat-based wetland maps for managing wildlife populations and habitats in the NWT.

This report summarizes research undertaken to evaluate the application of remotely-sensed data for inventorying three northern wetlands in the boreal and subarctic regions of the NWT.

STUDY AREAS

Three wetland areas were selected for study based on: (1) their known importance to wildlife, (2) opportunities for field work during summer 1987, (3) available reference data, and (4) interest indicated by NWT waterfowl biologists (R. Bromley, R. Cole pers. comm.). Study areas included the Ramparts-Hume and Brackett Lake wetland complexes, which are in the Mackenzie River valley and the low subarctic wetland region, and the Yellowknife-Rae wetland area, which is in the continental high boreal wetland region (National Wetlands Working Group 1986; Fig. 1). In general, wetland formation in these regions is determined by the interaction of excess water and severe climate, which results in the development of permafrost and limits the growth of many plant species. Fen and peat plateau-palsa bog complexes are the most common wetland forms produced in the subarctic region, where northern ribbed fens often cover extensive areas. Wetland forms characteristic of the high boreal region include northern ribbed fens, horizontal fens, basin fens, peat plateaus and palsa bogs as small islands in fens, flat bogs, and basin bogs (National Wetlands Working Group 1988).

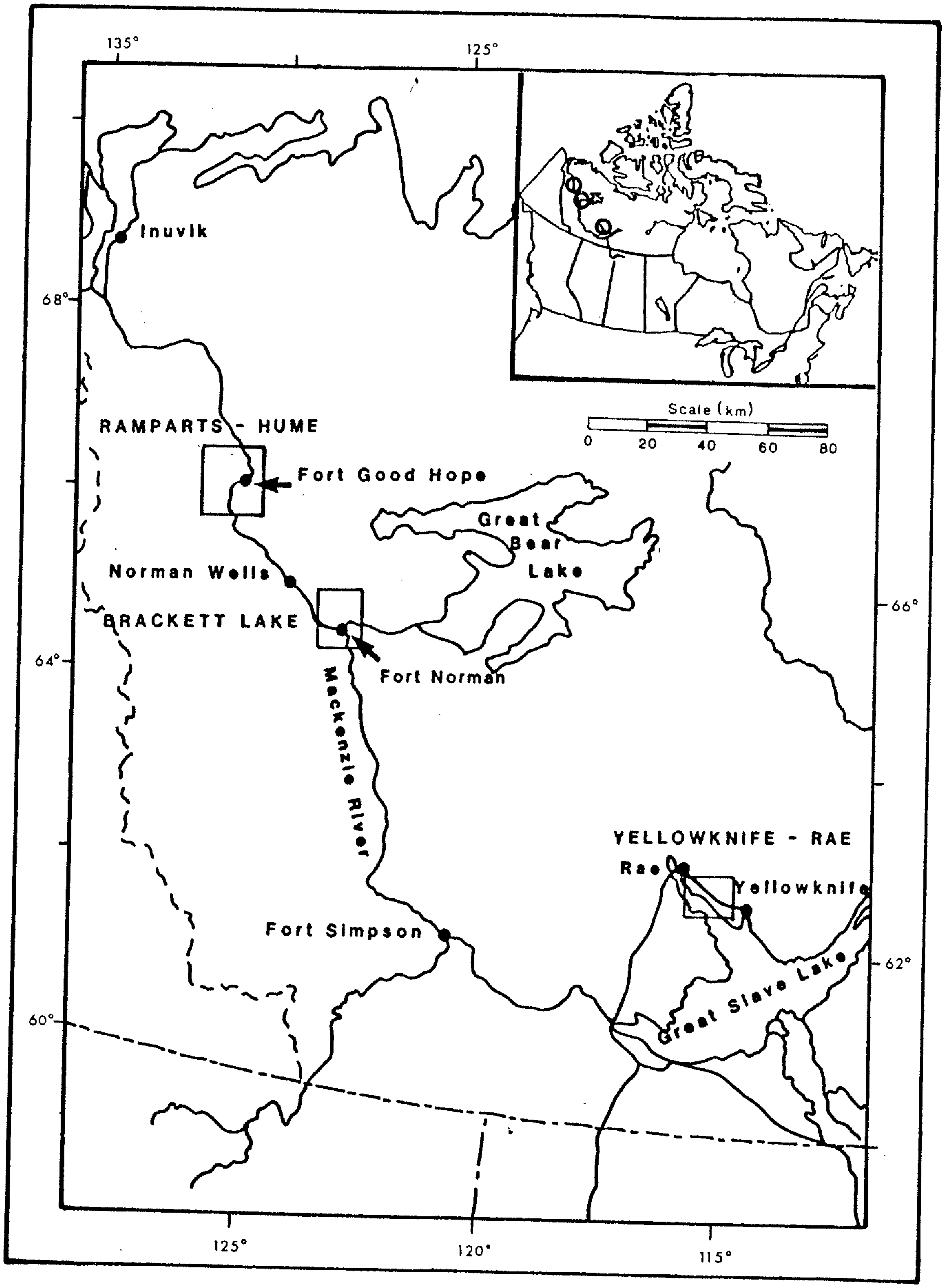

Figure 1. Location of study areas.

Ramparts-Hume

The Ramparts River area "has traditionally been considered the prime waterfowl area in the Mackenzie Valley" (Davis 1974: 64), although fires in the late 1960s/early 1970s apparently lowered the productivity of the wetland complex. Totals of 16, 7 and 0.4 waterfowl/km^2 were observed in the Ramparts River area during aerial surveys conducted in early June, mid-July, and late September 1972, respectively (Davis 1974). The Canadian Wildlife Service classified the Ramparts-Hume lowlands as primarily: (1) very good northern waterfowl habitat (Poston et al. 1973), (2) intermediate quality habitat for beaver and muskrat (Dennington et al. 1973), and (3) poor moose wintering habitat, with the islands in the Mackenzie River considered good moose wintering habitat (Prescott et al. 1973). Spawning and nursery areas for several fish species are located in the lower Ramparts and Hume rivers. The Ramparts-Hume lowlands are used annually by native families from Fort Good Hope for hunting, trapping, and fishing (Canada Department of the Environment 1976a, b).

The Ramparts-Hume wetland study area (Fig. 1) lies at approximately 66^o N 129^o W, and includes the community of Fort Good Hope within its boundaries. It occurs within the Peel Plain and Anderson Plain divisions of the Interior

Plains physiographic region (Douglas 1976). The lower Ramparts and Hume rivers meander through part of a glacial lakebed which characterizes the Peel Plain region, and have developed channels with broad floodplains. Small thermokarst lakes with irregular shorelines and often dense emergent vegetation occur at high density throughout the Ramparts-Hume lowlands (Poston et al. 1973). Topographic relief within the study area is relatively minor, with elevations ranging from sea level to 95m above sea level (asl) within the lowland, rising to uplands of about 155m asl.

This study area is included in the Lower Mackenzie section of the Boreal Forest region described by Rowe (1972). Transitional between boreal forest and tundra, the zone has been designated as subarctic forest (Mackenzie River Basin Committee 1981) and forest-tundra (Hernandez 1974). Zoltai and Pettapiece (1973) delineated two "land regions" within the study area, both characterized by extensive areas of black spruce (*Picea mariana*) - lichen (*Cladina*, *Cladonia*, *Cetraria* spp.) vegetation on imperfectly drained soils. Most of the area is included within a region characterized by paper birch (*Betula papyrifera*) - white spruce (*Picea glauca*) - poplar (*Populus balsamifera* or *P. tremuloides*) stands on well-drained sites, and black spruce - tamarack (*Larix laricina*) - shrub (*Betula* spp., *Salix* spp., ericaceous) - sedge (*Carex* spp.) or alder (*Alnus* spp.)

- willow vegetation on poorly drained sites. North of Ft. Good Hope, shrub birch predominates on poorly drained sites.

A large portion of this study area was burned by extensive fires around 1970 (W. Moore pers. comm.). Post-fire succession to black spruce-lichen forest on imperfectly drained land in this area may take 100 - 150 years (Zoltai and Pettapiece 1973). Although trees survived the fires on some wet sites (e.g., much of the Ramparts-Hume lowlands), and roots of some shrub species, (e.g., paper birch, willow, alder) likely survived in many areas, forest cover over vast areas will remain depleted for decades throughout the area (Zoltai and Pettapiece 1973).

Brackett Lake

The importance of the wetland habitat in the Brackett Lake area has been recognized by its designation as: (1) a proposed IBP site (number 24) by the International Biological Programme (Beckel 1975); (2) a key site for migratory birds by the Canadian Wildlife Service (McCormick et al. 1984); (3) good to excellent northern waterfowl habitat, with Brackett Lake serving as a critical concentration area of moulting and late summer staging waterfowl (Poston et al. 1973); and (4) the best available habitat for beaver and muskrat within the general area (Dennington et al. 1973). The area also provides fair moose wintering habitat (Prescott et al. 1973), spawning and nursery areas for a variety of fish species, and is a traditional native hunting, trapping and fishing area (Canada Department of the Environment 1976c). Davis (1974: 64) concluded that the Great Bear-Loche rivers area (which includes the Brackett Lake area) was "the most important waterfowl area in the Mackenzie Valley, south of the Delta, in 1972." The numbers of waterfowl observed during aerial surveys of the Great Bear-Loche rivers area in 1972 were significantly higher than for the Ramparts River area (86, 36, and 9/km^2 in June, July, and September, respectively; Davis 1974).

The Brackett Lake study area (Fig. 1) includes three wetland areas separated by rivers: the Loche-Brackett drainage basin, an area between the Great Bear and Mackenzie rivers, and an area immediately south and west of the Mackenzie River. These three areas are jointly referred to as "the Brackett Lake wetland area", which includes the community of Fort Norman within its boundaries, and is centred at approximately 65° N 125° 30'W.

Brackett Lake and its associated wetland complex occur in a valley between two ranges of the Franklin Mountains within the Mackenzie Plain division of the Cordilleran physiographic region (Douglas 1976). Thick ice-rich lacustrine sediments underlay the area, which is characterized by high density thermokarst lakes and generally poor drainage (Bostock 1976). Topographic relief within the wetland complexes is relatively minor, with elevations ranging from less than 100 to about 125m asl. Elevations increase substantially at the west and north-east margins of the study area, to over 600m asl along the southern ridges of the Franklin Mountains.

This study area occurs within Rowe's (1972) Upper Mackenzie section of the Boreal Forest region, and is dominated by vegetation similar to that of the Ramparts-Hume area. Forest cover is predominantly open, stunted black spruce-tamarack, with understory species including willow (*Salix* spp.), alder, ericaceous shrubs, *Sphagnum* mosses, and lichens. Poorly drained areas support little or no tree growth, and are dominated by mosses, lichens, and shrubs, with willow prevalent around margins of wetland basins (Poston et al. 1973). Dense stands of paper birch and poplar occur in some areas (e.g., along the Brackett River immediately south of Brackett Lake). Shallow ponds with irregular shorelines support an abundance of emergent and submergent plants (Poston et al. 1973).

Fires have altered the vegetation cover of several areas within the Brackett Lake wetland area. Current vegetation cover differs considerably among burned areas, according to the time elapsed since the burn (i.e., since 1968, 1971, or 1980) and various site factors. For instance, the southernmost, oldest burn (about 20 years post-fire; R. Lanoville pers. comm.) resulted in a dense cover of young spruce and tall shrubs, and an extensive, younger burn (16 years post-fire; W. Moore pers. comm.) between the Great Bear and Mackenzie rivers supports an open cover of primarily ericaceous shrubs, with charred peat still conspicuous.

Surveyors for the International Biological Programme (Cody et al. 1973) described five vegetation communities for the Brackett River floodplain area: sedge meadow (fen) and sedge lake margin, *Ledum* - *Cladonia* association, black spruce complex, regeneration after black spruce burn, and open water. Designation as an IBP site was based on the ecological value of the area and its potential scientific value with regard to several factors, including: various successional sequences (e.g., pond succession, post-fire regeneration), peat and permafrost landform, development of organic soils, the palynological record, and the northern limit of the range of *Salix athabascens*.

Yellowknife-Rae

The United States Fish and Wildlife Service completed intensive pond surveys in a 38.8 km^2 area straddling the highway between Yellowknife and Rae from 1962-1965 (Murdy 1962, 1963, 1964, 1965). Similar surveys have been conducted by the Canadian Wildlife Service since 1985 (R.

Cole, J. Hines pers. comm.). As a result, a large amount of information on use of ponds by waterfowl has been recorded for the area. Murdy's data (1965) indicates that more than 3,000 breeding pairs of 7-11 species of ducks produced almost 5,400 ducklings from this area during 4 seasons (1962-1965). He concluded that the area supports "a relatively high density of breeding ducks" (Murdy 1964: 54), which has been corroborated by subsequent studies (R. Cole, J. Hines pers. comm.). Breeding Bird Surveys (1988 and 1989) indicate that approximately 60 species of birds nest in the area adjacent to the highway between Yellowknife and Rae (R. Ferguson pers. comm.). This area has been used by residents of Yellowknife for recreational hunting since the 1940s, and by natives for traditional fishing, hunting, and trapping, primarily for waterfowl, moose, beaver, and muskrat (Canada Department of the Environment 1975).

The Yellowknife-Rae wetland study area (Fig. 1) differs markedly from the Ramparts-Hume and Brackett Lake areas, primarily as a result of differences in latitude and physiography. This study area lies at approximately 62° 30'N 115° W, about 800km and 600km southeast of the Ramparts-Hume and Brackett Lake areas, respectively. The Yellowknife-Rae area is in a transitional zone between the true Precambrian Shield (to the north and east) and the Interior Plains physiographic region, and is classified as part of the Bear-Slave Upland division of the Shield

(Bostock 1976, Douglas 1976). Outcrops of primarily granitic bedrock predominate throughout the study area, with the relative abundance of rock outcrop increasing to the northeast. Deep lacustrine silt was deposited throughout the area by a post-glacial lake (Murdy 1965). Topography is generally rolling, and topographic relief is relatively low. Elevations vary from about 160m asl adjacent to the highway to 235m asl in the uplands in the northeast corner of the study area.

The area is in the Northwestern Transition section of Rowe's (1972) Boreal Forest region, a zone of open subarctic woodland. The forest cover has been classified as unproductive immature mixedwood (W. Moore pers. comm.), which regenerated from fire in the late 1930s (Murdy 1965). Considerable diversity in vegetation cover exists as a result of variable moisture conditions and microclimate. Jack pine (Pinus banksiana) dominates on rock outcrops, sandy soils, and other well-drained sites. Dense stands of white spruce and paper birch/trembling aspen (Populus tremuloides) occur in riparian and other mesic areas. Black spruce forest and shrubby fens predominate on lowland, poorly drained sites. Shrubs include willow, alder, dwarf birch (Betula glandulosa), and numerous ericaceous species.

An abundance of ponds, lakes, and borrow pits occurs among the outcrops. Floating sedge mats, pond-lily (Nuphar variegatum), and various emergent and submergent plants are plentiful in wetland basins. Most of the borrow pits are in early successional stages of vegetation development and contain little aquatic vegetation relative to natural ponds. Vegetated ditches provide temporary wetland habitat during spring and early summer.

METHODS

Data Acquisition

Landsat Products and Reference Data

Suitable Landsat scenes were selected based on the following criteria: (1) <5% cloud cover over study areas, (2) image date during the period of primary phenological activity (i.e., July or August), and (3) imagery as recent as possible, given criteria 1 and 2. Specifications of imagery used in this study are provided in Table 1.

The most recent aerial photographs for the Ramparts-Hume and Brackett Lake areas were medium-scale (approximately 1:60,000) panchromatic black-and-white photos acquired in 1970 and 1971 (Table 1). Relatively recent (1984), large-scale (1:20,000) panchromatic black-and-white air photos were available for the Yellowknife-Rae wetland area. Additional reference data on land cover characteristics consisted of partial descriptions of the Ramparts-Hume and Brackett Lake areas by forest type maps produced by interpretation of 1970/71 air photos (Forest Management Institute 1974), and a limited amount of information collected about wetlands along the Yellowknife-Rae highway by Canadian Wildlife Service personnel in 1985 (R. Cole pers. comm.).

Table 1. Specifications of remote sensing products used for image analysis.

	Landsat Products[a]							Air Photos (B/W)	
Study Area[b]	LS	Sensor	TR	FR	Offset (sec) or Quad	Acquisition Date	Data Type	Date	Scale
Ramparts-Hume	4	MSS	57	14	-7	28/08/85	Print, CCT	July/71	1:60,000
Brackett Lake	5	MSS	55	14	+5	25/08/86	Transp.	July/70	1:60,000
	5	TM	54	15	5	20/07/87	CCT		
	5	TM	55	14	6	29/07/88	CCT		
Yellowknife-Rae	5	TM	46	16	3	12/07/87	CCT	July/84	1:20,000

[a] LS - Landsat satellite number; Sensor - Multispectral scanner (MSS), Thematic mapper (TM); TR - Track; FR - Frame; Offset in sec for MSS, quad no. for TM data; Data type - Print (color composite print, bands 1/2/4, 1:250,000 scale), CCT (computer compatible tape), Transp. (color composite transparency, bands 1/2/4).

[b] Study areas are shown in Fig. 1.

Field Work

Ground data were collected to provide information for visual interpretation of Landsat imagery and for digital classification of Landsat data. Sites were selected for ground data collection based on their appearance on air photos, topographic maps, and Landsat imagery, subject to the following criteria: (1) land cover was relatively homogeneous, (2) minimum size of homogeneous areas (3 x 3 pixels) was approximately 4.5 ha for MSS data and 0.8 ha for TM data, and (3) sites were located near obvious geographic features (e.g., lakeshores) to ensure that they would be easily recognized from the air and accurately located on imagery.

Surveys for collecting ground data were conducted by helicopter (3-5 hours/survey) for each study area and by automobile along the Yellowknife-Rae highway (2 days). Ground data were collected during the following periods: mid-July and late August for the Ramparts-Hume area; mid-June, mid-July, and late August for the Brackett Lake wetland; and early August for the Yellowknife-Rae area. Oblique colour photographs were taken of most sites, and general descriptions of vegetation species, forest cover density, moisture conditions, and local relief were recorded.

Landsat Data Analysis

A multistage approach was used to extract information from Landsat data. The first step was visual interpretation of Landsat imagery (colour composites and image enhancements), which provided information on general wetland patterns. This initial, synoptic view is particularly useful for relatively unknown areas of the NWT (e.g., areas for which recent aerial photography and topographic maps at scales greater than 1:250,000 are not available). In the second stage of wetland inventory, cover types of interest were identified and mapped using digital analysis of Landsat data, based on a limited amount of information describing land cover characteristics, which was collected during surveys (ground data) and by air photo interpretation.

Analysis of Landsat digital data was conducted using DIPIX System Ltd. ARIES-II image analysis systems at the Manitoba and Alberta Remote Sensing centres (MRSC, ARSC) and an ARIES-III at the NWT Centre for Remote Sensing (NWTCRS). Several image analysis techniques were evaluated to determine the information they would provide about wetlands given the limited amounts of ground and reference data available. For all three study areas, principal component

(PC) image enhancements and supervised classifications using a maximum-likelihood classifier were conducted. Supervised classification using a parallelepiped classifier was also investigated for the Brackett Lake and Yellowknife-Rae areas, and numerous contrast stretch enhancements were examined for the Brackett Lake area. The classification representing the known distribution and extent of cover types most accurately (assessed subjectively on the basis of available ground data) was used to produce colour plots for each study area, which were then subjected to error analysis. Thematic maps at scales of 1:50,000 and 1:125,000 were produced at MRSC using an Applicon ink jet printer-plotter and at NWTCRS using an ACT-II printer.

Image Enhancement

Image enhancements were used to increase apparent spectral contrast among cover types, and to improve the visual representation of Landsat data. Contrast stretch enhancements extend the range over which reflectance values are displayed, which facilitates visual interpretation. Principal component enhancement decreases spectral redundancy by compressing most of the variance within a relatively large number of correlated variables (i.e., 4 MSS or 6 TM bands) into a few uncorrelated variables. Principal components can be generated from the image statistics for an entire scene, or from training areas representing cover types of particular interest. A PC enhancement procedure described by DIPIX Systems Ltd. (1982) for general forest type mapping was conducted, and one principal component from each of three separate principal component analyses (from different training areas) were combined to produce a colour composite image.

Supervised Classification

Standard functional tasks available on the ARIES image analysis systems (DIPIX Systems Ltd. 1982) were used to produce supervised classifications (Fig. 2). Specific procedures are described below.

The supervised classification procedure uses information about known sites, which is supplied to the computer by the analyst, to establish the spectral attributes ("spectral signature") of each cover type of interest, and to classify each pixel in the image data set as the cover type it most closely resembles (Lillesand and Kiefer 1987). The analyst controls the classification by identifying the representative areas, or training areas, which are used by a computer algorithm to classify the study area. For this study, ground data obtained during field surveys and by air photo interpretation was the information base used to identify training areas. Vegetated sites were

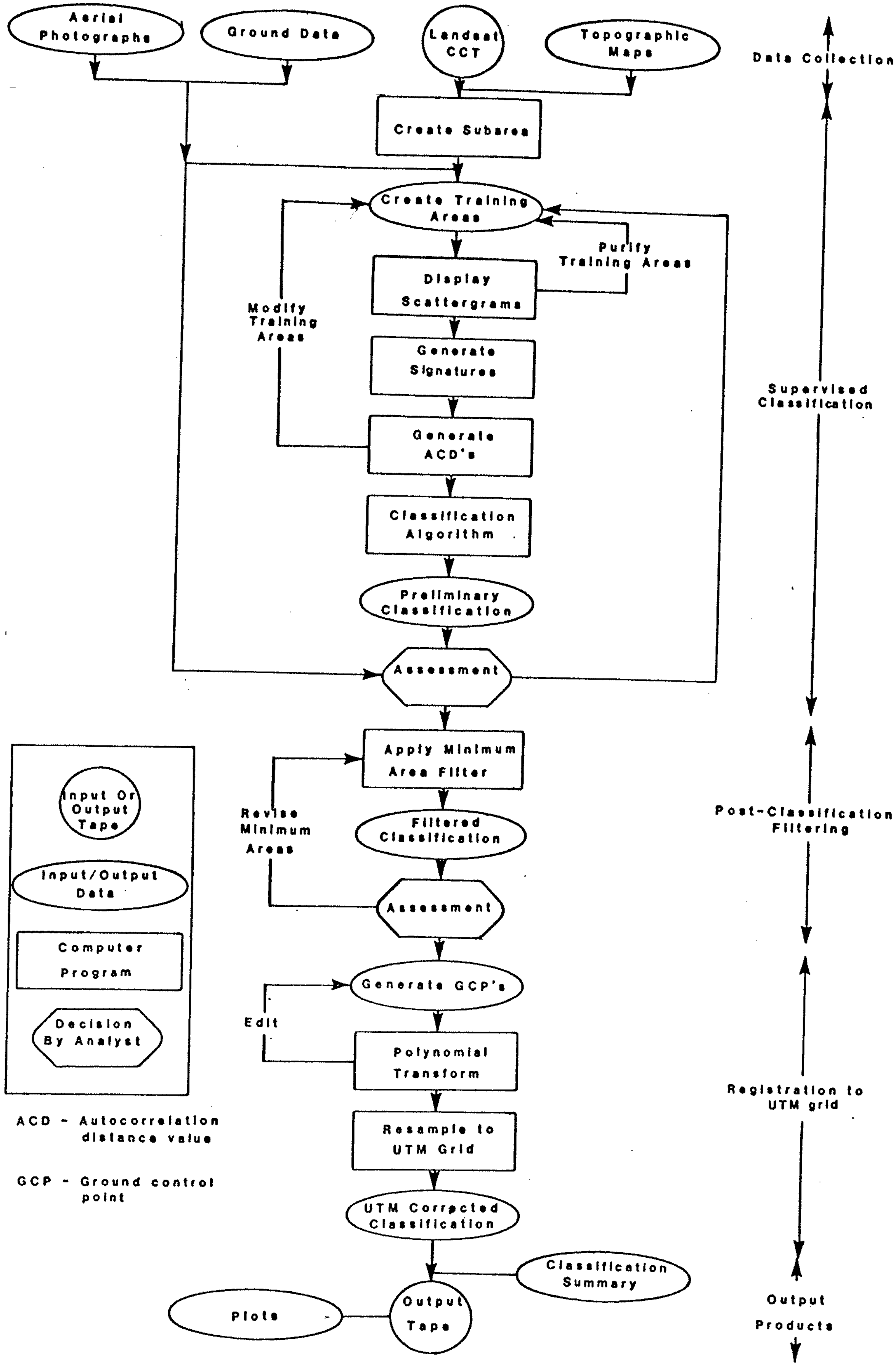

Figure 2. Flow chart of procedures followed for image analysis on ARIES systems (after Dixon et al. 1984).

designated by canopy cover (species and density) and understory vegetation (for sites with little or no tree cover). Waterbodies were described on the basis of estimated size, relative depth, sediment content, water colour, amount of submergent vegetation, and surface density of floating aquatic vegetation. Training area data sets of at least 1000 pixels per cover type were used whenever possible, and most training areas comprised 500 - 1500 pixels. Cover types were excluded from analysis when available data were insufficient to produce adequate training areas.

Supervised classifications were produced for the Ramparts-Hume and Brackett Lake areas using the maximum-likelihood classifier (MLC). Training areas were identified during interactive training while displaying 3 bands of data, and numerous changes in the composition of training areas were made prior to classification. Consistency of reflectance values included within training areas and apparent separability of cover types were monitored by displaying scattergrams during creation of training areas. Scattergrams showed the distribution of pixels in a training area in relation to spectral reflectance values for 2 bands of Landsat data at a time. Anomalous sites were identified and excluded prior to production of training statistics. When training areas were as "pure" as possible, spectral signatures were generated. Autocorrelation distances (ACD) were then calculated, to provide an additional measurement of the similarity of training area signatures. Training areas which exhibited significant correlations (>10%, ACD value <2.0) and had strongly overlapping scattergrams in all bands (>50%) were combined prior to classification. Spectral signatures for revised training areas were used to produce classifications by applying the maximum-likelihood classifier to all pixels within the study area.

The parallelepiped classifier (PPC) was used to produce supervised classifications for the Yellowknife-Rae area. The PPC was also used to modify training areas which had been created originally during interactive training using 1987 Landsat TM data for the Brackett Lake study area. Pixels with spectral intensity values which are identical to those delineated in a training area were classified as that class in near instantaneous or "real" time by the PPC. Training areas were revised periodically by changing single pixels or groups of pixels. For the Brackett Lake classification using 1987 data, the distribution of classes in the ongoing classification was monitored using scattergrams, because only 2 TM bands were used for training. In this manner, spectral separability of cover types could be examined prior to classification, overlap could be minimized, and confusion among cover classes in the final classification products was reduced as much as possible. Three bands (2, 4 and 5) were used for training during classification of the Yellowknife-Rae data, and no scattergrams were displayed.

Evaluation

Error Analysis

Error analysis is an integral part of the classification and mapping process. Mapping cover classes without assessing their accuracy is unsatisfactory, because users of the map have no indication of the likelihood that a particular patch of ground will resemble the cover type with which it is labelled. Accuracy for individual cover classes and for the entire study area should be assessed for every map which is intended for use in resource management. In general, accuracy will be higher with a few relatively simple, broad categories than with many complex cover types, all other factors being equal (Carter 1982).

Ideally, map accuracy should be assessed using a relatively large number of randomly selected test areas (e.g., >250 samples per class are necessary to estimate mean accuracy to within ± 5%; Schowengerdt 1983), and reference data should be independent of the data used to produce the classification. Unfortunately, ideal conditions rarely occur, methods used for assessing map accuracy vary considerably, and explanations are often insufficient (Palylyk 1985). Interpretation of map accuracy may be erroneously optimistic when high overall accuracy results primarily from a few easily recognized cover types (e.g., rivers, sandbars) and the range of accuracies for all classes is wide.

For this study, two types of error analysis were applied. "Consistency analysis" was conducted for the Ramparts-Hume area, because availability of few ground data precluded use of more sophisticated techniques. Homogeneous ground sites (including training sites) were compared with thematic maps to provide an indication of the consistency of the classifications, and to determine if serious problems existed with the provisional maps. Inclusion of training data in error analysis likely biased the results, but could not be avoided, because of the paucity of known ground points.

Standard accuracy assessment (Lillesand and Kiefer 1987) was conducted for the Brackett Lake and Yellowknife-Rae study areas. Known ground sites which were not used to produce the classification (i.e., sites not used as training areas) were identified on thematic maps, and the cover classes which were mapped for those sites were determined. Results were expressed as a confusion matrix, in which proportions of correctly classified pixels and errors of omission (e.g., pixels of class A incorrectly mapped as other classes) and commission (e.g., pixels of other classes incorrectly mapped as class A) were tabulated. Overall map accuracy was also calculated for each thematic map (i.e., [number of correctly classified pixels/total number of pixels checked] x 100).

Subjective Appraisal

The accuracy of the thematic maps and their potential value for management purposes were also evaluated qualitatively. Each classification was subjected to qualitative accuracy assessment at many stages in the image analysis process when the classification was compared to ground data. The degree of correspondence between a classification and the "true" land cover was the main criterion used to accept or reject the classification. A classification which subjectively appeared to be reasonably accurate was accepted as a final product for plotting, after which error analysis was conducted to obtain a quantitative evaluation.

The classification maps were subjectively evaluated by several resource managers (i.e., 3 wildlife biologists, 1 land use planner) to determine whether or not they would meet the needs of potential users. Input was requested concerning the apparent information value of the maps, applicability of this type of information to management problems, and suggestions for modifications which would increase their relevance to resource management in the NWT.

RESULTS

Ramparts-Hume

Image Enhancement

The Ramparts-Hume PC enhancement provided improved spectral contrast among cover types when compared with the original data, but was not a significant improvement over the colour composite print (1:250,000-scale) produced using MSS bands 1, 2 and 4. Consequently, no enhancement product was plotted for the Ramparts-Hume wetland.

Supervised Classification

Seventeen land cover types were initially selected for producing a supervised classification of the Ramparts-Hume area using MSS data (Table 2). Although many cover types were investigated, it was recognized that some of them would not be separable based on spectral reflectance values. A few cover types showed inconsistent spectral values or were too small to produce adequate training data (e.g., emergent vegetation), and were, therefore, excluded from classification. Scattergrams and ACD values indicated significant correlations among training area data for

Table 2. Comparison between land cover types of interest and map classes produced by supervised classification of Landsat MSS data for the Ramparts-Hume wetland area.

Group	Cover Type of Interest	Class[a]
Water	Deep, relatively clear ponds	2
	Deep lake/river (high sediment)	2
Wetland	Shallow, relatively clear water	1
	Shallow ponds with dense submergent vegetation	2
	Floating aquatic vegetation	2
	Emergent vegetation	2,4
Shrubland	Ericaceous shrubs dominant	6
	Mixed ericaceous/deciduous shrubs	6
	Regenerating burn	6
	Riparian/alluvial (willow)	5
Forest	Deciduous (paper birch, poplar)	5
	Riparian coniferous (white spruce)	3,4
	Nonriparian coniferous (black spruce)	3,4
	Mixedwood	3
	Open black spruce-lichen	7
Unvegetated	Rock outcrop	8
	Soil/mudflat	8

[a] Theme numbers correspond to those in Table 3.

several cover types, which were merged prior to classification. The resulting cover types included: deciduous forest and riparian willow; ericaceous, mixed, and regenerating shrubland (Fig. 3a); and rock outcrop and exposed mudflat (Fig. 3b). Shallow water with floating aquatic vegetation or conspicuous submergent vegetation could not be separated from coniferous forest or open water based on spectral reflectance alone (Fig. 3c). Several known sites with dense floating aquatic/submergent vegetation were delineated manually to produce the final classification.

Eight cover classes were mapped at 1:125,000-scale, including: 2 water/wetland classes, 5 forest and shrubland classes, and 1 class representing bare soil and rock (Table 3). The ericaceous shrubland and coniferous forest classes are by far the most extensive, comprising 53.7% and 25.8% of the classified area, respectively. The final 8 cover classes mapped for the Ramparts-Hume wetland area are described in Table 4.

The confusion matrix for the Ramparts-Hume area (Table 5) provides information about the numbers of known sites of each cover type which were correctly classified and mapped, and indicates that the classification is inadequate. Inclusion of training data produced biased results, and the true classification accuracy (calculated without inclusion of training sites) is likely lower than that reported in

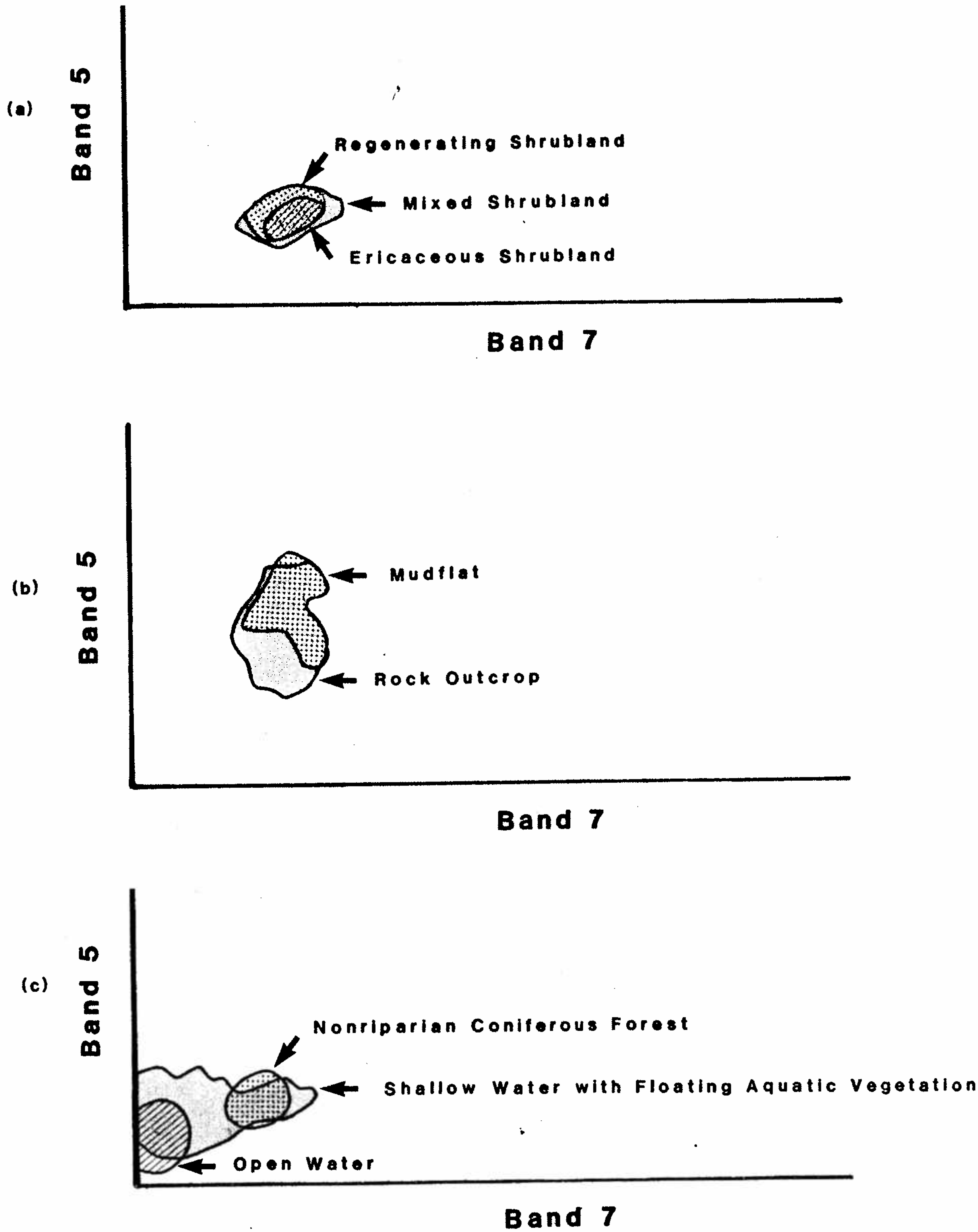

Figure 3. Scattergrams showing spectral overlap among training areas for the Ramparts-Hume wetland area.

Table 3. Classification summary for the Ramparts-Hume wetland area. (Supervised classification was produced using Landsat MSS data acquired 28 August 1985, to which a maximum-likelihood algorithm was applied.)

Class	Descriptor[a]	Area Classified		
		ha	% of Total	% of Classified Area
1	Open water (ponds/lakes)	24,833	3.0	3.8
2	Deep water/floating aquatic vegetation	25,007	3.0	3.8
3	Coniferous-dominated forest	60,594	7.3	9.3
4	Dense coniferous forest	106,342	12.9	16.5
5	Deciduous forest/willow	46,363	5.6	7.2
6	Ericaceous shrubland	347,281	42.0	53.7
7	Black spruce-lichen woodland/graminoid areas	33,800	4.1	5.2
8	Exposed soil/rock	2,712	0.3	0.4
	Total classified	646,932	78.2	99.9
	Unclassified[b]	179,591	21.7	-

[a] Cover class descriptions are provided in Table 4.

[b] Unclassified area is primarily outside the study area or Landsat imagery and is an artifact of mapping. Almost all of the mapped area was classified.

Table 4. Description of cover classes mapped for the Ramparts-Hume wetland area based on supervised classification of Landsat MSS data.

Class	Descriptor	Description[a]
1	Open water (ponds/lakes)	- relatively shallow water
2	Deep water/floating aquatic vegetation	- relatively deep, turbid water (Mackenzie River); waterbodies with dense cover of floating vegetation (consists of several known sites which were delineated manually)
3	Coniferous-dominated forest[b]	- upland and lowland spruce forest of variable density; dense mixedwood forest
4	Dense coniferous forest	- dense, tall, riparian white spruce forest; dense upland spruce; open water/emergent vegetation/upland vegetation mosaics
5	Deciduous forest/willow	- dense aspen and willow stands in Ramparts River lowland; alluvial pioneer willow, dwarf birch, and alder
6	Ericaceous shrubland	- ericaceous shrubs predominant, with other shrubs and standing dead trees often present; primarily consists of early successional stages following extensive fire; shrub density varies from open to dense
7	Black spruce-lichen woodland/fen	- continuous ground cover of lichen predominant, with sparse or no tree cover; sparsely treed or open shrubby fen, with low shrubs and sedges predominant; (trees, if present, primarily black spruce)
8	Bare soil/rock	- exposed mudflats in Mackenzie River; rock outcrop

Table 4. (continued)

[a] Vegetation densities:
(1) forest canopy cover - sparse (<10%), open (10-50%), dense (50-75%), closed (>75%).
(2) shrub/ground cover - sparse (10-25%), open (25-50%), dense (>50%).
(3) floating aquatic vegetation - dense (>50%).

[b] Distinction between coniferous forest classes (3 and 4) is not well-defined.

Table 5. Confusion matrix for Ramparts-Hume supervised classification (includes training data)[a].

Mapped Class[b]	Known Cover Type (no. of sites) 1	2	3	4	5	6	7	8	Total
1	15								15
2		3							3
3		1	3				1		5
4	1	2	4	10	3	7	1		28
5			1		10	5	3		19
6			2		3	27	5		37
7						1	12		13
8								2	2
Total No. Sites	16	6	10	10	16	40	22	2	122
Percent Correct[c]	94	50	30	100	62	68	54	100	

a Insufficient data precluded accuracy assessment without inclusion of training sites. Accuracy levels are biased and actual map accuracy is likely lower than suggested by these figures.

b Theme descriptions are presented in Table 4.

c Overall accuracy = $\frac{\text{No. sites correctly classified}}{\text{total no. sites}} \times 100 = 67\%$

Table 5 (Lillesand and Kiefer 1987, Schowengerdt 1983). Substantial misclassification occurred for turbid water/floating aquatic vegetation (class 2), coniferous-dominated forest (class 3), deciduous forest/willow (class 5), and black spruce-lichen areas (class 7). Although the majority of ericaceous shrubland (class 6) sites were mapped correctly, a large proportion was classified as dense coniferous forest (class 4) or deciduous forest/willow. Relatively high consistency exists for classification of known open water (class 1) and dense coniferous forest sites. Overall, 67% (82/122) of known sites were classified correctly.

Brackett Lake

Image Enhancement

The Brackett Lake PC colour enhancement produced using 1987 Landsat TM imagery provided information on general land cover patterns and heterogeneity and facilitated visual interpretation much more than any 3-band colour composite displayed on the colour monitor. The enhancement provided excellent contrast among forest and shrub cover types, and boundaries of regenerating burns were clearly evident. Deciduous and dense coniferous forest were consistently distinguishable. Cover types with sparse or no forest cover and conspicuous ericaceous shrub understory (e.g., spruce-lichen woodland and some regenerating burns) could be consistently distinguished from forested areas but not from each other. Water bodies were prominent, but floating aquatic and emergent vegetation could not be separated from adjacent cover types (i.e., open water and deciduous vegetation, respectively). The PC enhancement of the Brackett Lake area provided an excellent overview of land cover patterns at a reconnaissance level. However, it could not be used as the basis for delineating wetland cover classes.

Numerous contrast stretch enhancements were produced for the Brackett Lake area using 1988 Landsat TM imagery. Several 3-band colour composites which included combinations of power, linear, and piece-wise linear stretches provided abundant information about general cover type patterns, and were used for delineation of training areas during supervised classification. One 3-band colour composite was very similar to the principal components colour composite produced using 1987 data: band 4 power stretch/band 5 power stretch/band 3 linear stretch (red/green/blue). Replacement of band 3 with band 2 in this combination maximized contrast between wetland (particularly floating aquatic vegetation) and upland cover types. The band 4/5/2 enhancement facilitated visual interpretation of the Brackett Lake imagery, and was used for training area delineation.

Supervised Classification

Eleven land cover types were originally selected for producing a supervised classification for the Brackett Lake area using Landsat TM data (Table 6). The improved spectral and spatial resolution of the TM data (as compared to MSS data used for the Ramparts-Hume area) increased the potential for producing classifications with a larger number of wetland cover classes, at higher levels of accuracy.

Spectral overlap within several groups of cover types precluded separation of all classes, however. Problems were particularly evident during analysis of 1987 Landsat data, but were also encountered with data acquired in 1988. (The following examples pertain to analysis of 1987 data.) It was not possible to separate ponds with a dense cover (>50%) of floating aquatic vegetation from those with sparse-open cover (5 - 50%) of floating aquatics (Fig. 4a). Patches of emergent herbaceous vegetation were rarely large enough to be used for training areas, and mosaics of emergent vegetation/open water and sparse-open density floating aquatic vegetation/open water had reflectance values which were very similar to other land/water edge pixels. However, open water areas were generally distinct from vegetation/water mosaics and dense floating aquatic vegetation. A high degree of overlap (>50%) existed for the three original shrubland training areas (Fig. 4b).

Table 6. Comparison between land cover types of interest and map classes produced by supervised classification of Landsat TM data for the Brackett Lake wetland area.

Group	Cover Type of Interest	Theme[a] 1987	1988
Water	Deep lakes and ponds with low turbidity	6	3
	Deep, turbid lake/river	7,9	1
Wetland	Shallow, relatively clear water	6	2
	Shallow, turbid water	7	1
	Ponds with dense submergent vegetation	5,7	5,13
	Ponds with dense floating aquatic vegetation	5	5,13
	Ponds with sparse floating aquatic vegetation	5,7	13
	Emergent vegetation	5	5,13
	Treeless/sparsely treed shrubby fen or bog	12	6
Shrubland	Riparian/alluvial willow	1	7
	Ericaceous shrubland	1	8
	Dense mixed shrubland - advanced regeneration	1,10	8
	Open mixed shrubland - early/poor regeneration	11	8
Forest	Deciduous forest	4	7
	Riparian, mature white spruce	8	9
	Dense upland spruce	8	9
	Dense-open mixedwood	8	10
	Open lowland spruce (ericaceous understory)	8	10
	Black spruce-lichen woodland	2	11
Other	Rock outcrop	3	4
	Exposed soil/gravel/mudflat	3	4
	Lichen patches (no vascular vegetation)	3	12

[a] Themes mapped using 1987 or 1988 Landsat data. See Appendix A for results of analysis of 1987 data.

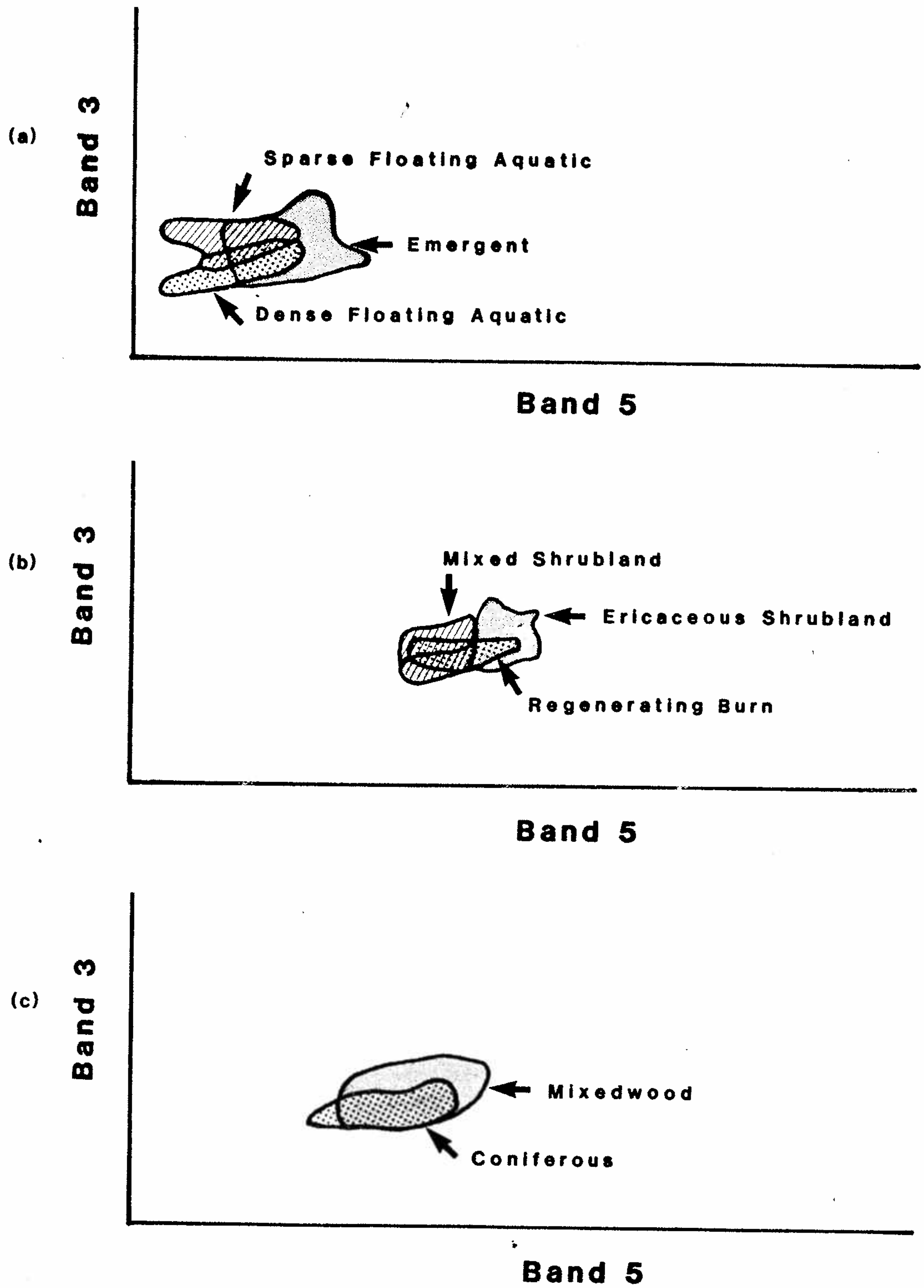

Figure 4. Scattergrams showing spectral overlap among training areas for the Brackett Lake wetland area using 1987 TM data.

Ericaceous shrub cover in combination with sparse stunted spruce, young spruce, other shrubs, or burned vegetation appeared to create spectral inseparability. Coniferous forest and mixedwood forest could not be separated (Fig. 4c), although dense deciduous forest and willow thickets were distinguished from coniferous and ericaceous-dominated shrubland types.

1987 Imagery

A great deal of difficulty was encountered while attempting to produce an acceptable classification for the Brackett Lake area using 1987 Landsat data. Several classification runs were made using maximum-likelihood and parallelepiped classifiers, with revisions made to training areas following each classification. Much of the problem resulted from high haze over the southwest one-third of the study area, which was caused by smoke from forest fires burning to the southeast, and possibly from high cloud cover. Classifications produced using bands 2, 3, 4 and 5 and the maximum-likelihood algorithm were consistently acceptable in haze-free areas, but were not adequate throughout the rest of the study area. Although some haze-related problems remained in parallelepiped-generated classifications, distortions were considerably reduced partially as a result of omission of band 2, which is quite sensitive to the presence of haze and clouds. A classification produced using bands 3, 4 and 5 and the parallelepiped classifier (with several manual modifications) was plotted and subjected to accuracy assessment.

Twelve cover classes were mapped at 1:125,000-scale for the Brackett Lake area using July 1987 TM data and ground data obtained in 1987. They represent 5 water/wetland types, 4 forest and shrubland cover types, 2 regenerating burn types, and bare soil/rock or lichen mat (Table 6; Appendix A). Accuracy assessment indicated that the classification was unsatisfactory. The confusion matrix (Appendix A) revealed significant problems: only 3 of 11 classes were mapped with accuracies >75%; overall map accuracy was unacceptable (62%); omission errors were >40% for 4 classes; and commission errors were >40% for 7 classes.

1988 Imagery

A second supervised classification was conducted using Landsat TM data acquired in late July 1988 and ground data obtained during 1987 and 1988 field studies. The absence of haze on the imagery and the availability of a greater amount of ground data were expected to facilitate successful classification of the Brackett Lake area. Previous attempts to classify the area showed that several cover types of interest would likely be spectrally similar (e.g., dense and open floating aquatic vegetation, various shrubland types, coniferous and mixedwood forest; Fig. 4). The extent to which this confusion resulted from problems caused by haze on 1987 imagery was not known, however.

Fifteen land cover types of interest were reduced to 13 classes (Tables 6,7) for mapping at 1:50,000-scale. Cover types which had substantial spectral overlap, as shown by scattergrams and low ACD values, were merged. In general, the final supervised classification for the Brackett Lake area did not differ substantially from the classification produced using 1987 Landsat data in terms of the classes which were mapped or the land cover patterns which were portrayed.

The final classes mapped for the Brackett Lake wetland area using Landsat TM data acquired in late July 1988 are described in Table 8. The wetland mosaic class could not be produced using training areas because of its spectral variability and the small size of relatively pure areas (e.g., emergent vegetation along the periphery of waterbodies). Class 13 (wetland mosaic) was mapped by systematically removing non-wetland mosaic pixels from unclassified areas, by ensuring they were classified as classes 1-12. This increased the variability of training areas for some classes, but did not significantly change training area statistics or the overall classification. Thus, the final areas mapped as "unclassified" pixels

Table 7. Classification summary for the Brackett Lake wetland area. (Supervised classification was produced using Landsat TM data acquired 29 July 1988, to which a maximum-likelihood algorithm was applied.)

Class	Descriptor[a]	Area Classified ha	Area Classified % of Total
1	Water - shallow/high turbidity	8,688	3.46
2	Shallow water - moderate turbidity	3,228	1.29
3	Water - deep/low turbidity	14,102	5.62
4	Exposed mud/rock	559	0.22
5	Wetland - dense floating vegetation	2,028	0.81
6	Wetland - mixed shrubland	14,819	5.91
7	Deciduous forest/shrubland	9,439	3.76
8	Shrubland - mixed/regenerating	16,656	6.64
9	Coniferous (upland spruce) forest	12,395	4.94
10	Coniferous-dominated forest	121,914	48.60
11	Spruce-lichen woodland	26,052	10.38
12	Lichen-bryophyte patches	3,140	1.25
13	Wetland mosaic (unclassified)	17,874	7.12
	Total	250,894	100.00

[a] Cover class descriptions are provided in Table 8.

Table 8. Description of cover classes mapped for the Brackett Lake wetland area based on supervised classification of Landsat TM data.

Class	Descriptor	Description[a]
1	Water - shallow/high turbidity	- waterbodies with high sediment loads, including the Mackenzie River; shallow ponds/lakes with inorganic (usually muddy) substrate
2	Shallow water - moderate turbidity	- shallow waterbodies with inorganic substrate and moderate sediment loads
3	Water - deep, low turbidity	- primarily ponds/lakes with relatively deep water, low turbidity, organic substrate, and $\geq$75% open water (i.e., <25% cover of floating aquatic vegetation)
4	Exposed mud/rock	- unvegetated sand, gravel, mud, and rock (e.g., alluvial mudflats, rock outcrops, airstrip)
5	Wetland - dense floating vegetation	- waterbodies with relatively large areas of continuous, dense cover of floating aquatic and emergent vegetation
6	Wetland - mixed shrubland (treeless bog/fen)	- variable wet areas dominated by graminoid, graminoid/ericaceous shrub, mixed ericaceous/tall shrub, and mixed graminoid/bryophytic species
7	Deciduous forest/shrubland	- closed stands of tall paper birch; dense, tall (usually alluvial) willow shrubland
8	Shrubland - mixed/regenerating	- variable species composition, depending on stage of post-fire succession; open medium - tall shrubs and short, young spruce; open - dense mixed ericaceous and tall shrubs; dense mixed shrubs and lichen hummocks; patchy and sparse mixed shrub/graminoid/bryophytic species

Table 8. (continued)

Class	Descriptor	Description[a]
9	Coniferous, upland spruce forest	- tall, dense upland/riparian/alluvial spruce (usually mature white spruce)
10	Coniferous-dominated forest	- stunted, lowland black spruce with continuous ericaceous shrub understory; young, dense, short spruce; open - dense mixedwood
11	Spruce-lichen woodland	- sparse - open, usually stunted black spruce with understory comprised primarily of relatively continuous lichen cover and sparse cover of ericaceous shrubs
12	Lichen-bryophyte patches	- relatively continuous, hummocky areas of lichen cover, or lichen/bryophyte mosaics, with little or no cover by vascular plants
13	Wetland mosaic	- variable mosaics of patchy wetland vegetation (including submergents and emergents) and shallow water; wetland/upland edges

[a] Vegetation densities:
(1) forest canopy cover - sparse (<10%), open (10-50%), dense (50-75%), closed (>75%).
(2) shrub/ground cover - sparse (10-25%), open (25-50%), dense (>50%).
(3) floating aquatic vegetation - sparse (<25%), open (25-50%), dense (>50%).

represent wetland mosaics and were labelled accordingly.

Accuracy assessment (Table 9) indicated that the final thematic map derived from 1988 Landsat TM data is acceptable, as all cover classes were mapped at accuracies >75% and overall map accuracy was 89%, compared to known ground sites. Although omission and commission errors were not generally large, commission errors for class 6 (wetland - mixed shrubland) were high, with few pixels from known sites with mixed shrubland cover available for assessment purposes. The spruce-lichen woodland cover class (11) was given a relatively high accuracy (80%), but this was based on few known sites. Other cover classes with apparently high accuracy levels based on relatively few assessment pixels were classes 1, 2, and 4, which are obvious features with distinctive spectral signatures. Although accuracy assessment based on a greater number of known sites more equally distributed among all cover classes would be desirable, the contingency table and subjective appraisal of the Brackett Lake wetland map indicated that it was generally acceptable.

Table 9. Confusion matrix for the Brackett Lake supervised classification.

Mapped Class	Known Cover Type[a] [no. pixels (%)] 1	2	3	4	5	6	7	8	9	10	11	12	Total[b]	Commission Errors
1	20 (100)												20	0 (0)
2		25 (100)											25	0 (0)
3			680 (99)		30 (17)								710	30 (4)
4				20 (100)									20	0 (0)
5			10 (1)		140 (78)								150	10 (7)
6						30 (100)	15 (6)	25 (8)		5 (1)		5 (2)	80	50 (62)
7							185 (80)	30 (10)		20 (4)			235	50 (21)
8								240 (80)				5 (2)	245	5 (2)
9					5 (3)				105 (84)	40 (8)			150	45 (30)
10					5 (3)		25 (11)		15 (12)	440 (87)	5 (20)		490	50 (10)
11								5 (2)	5 (4)		20 (80)		30	10 (33)
12							5 (2)					200 (95)	205	5 (2)
Omission Errors	0 (0)	0 (0)	10 (1)	0 (0)	40 (22)	0 (0)	45 (20)	60 (20)	20 (16)	65 (13)	5 (20)	10 (5)		
Total	20	25	690	20	180	30	230	300	125	505	25	210	2365	

[a] Cover type was identified for ground sites during field studies; descriptions are provided in Table 8. The accuracy of class 13 (wetland mosaic) was not assessed using known sites.
[b] Overall accuracy: (total no. correct pixels/total no. pixels) X 100 = 89%

Yellowknife-Rae

Image Enhancement

Neither of the two PC image enhancements produced for the Yellowknife-Rae area appeared to accentuate spectral contrast to a greater degree than the TM band 2/4/5combination with linear stretch. Therefore, the 3-band colour composite was plotted at 1;50,000-scale for use as a base image for this wetland area.

Supervised Classification

Fifteen cover types were initially identified for producing supervised classifications for the Yellowknife-Rae wetland area using TM data (Table 10). Problems in locating homogeneous patches of cover types sufficiently large for training area delineation were anticipated, because of the heterogeneous nature of the landscape. It was hoped that classification would be facilitated by the availability of relatively recent (1984), large-scale (1:20,000) air photos along the Yellowknife-Rae highway. Several cover types were not appropriate for producing adequate training data, because they occurred in small areas (e.g., disturbed areas, borrow pits), or they were visually indistinguishable from other cover types on Landsat imagery (e.g., willow vs. dense

Table 10. Comparison between land cover types of interest and map classes produced by supervised classification of Landsat TM data for the YelloWknife-Rae wetland area.

Group	Cover Type of Interest	Class[a]
Water	Very deep open water (Great Slave L.)	4
	Deep (>2m) open water	3
Wetland	Shallow (<2m) open water (pond/lake)	3
	Dense floating aquatic vegetation	1
	Sparse floating aquatic vegetation	1
	Sparsely treed/treeless fen	2
Shrubland	Ericaceous shrubs and lichen	2
	Dense medium-tall shrubs	2
Forest	Deciduous (paper birch, poplar)	5
	Mixedwood (deciduous/pine, spruce)	5
	Dense, tall white spruce	6
	Open jack pine	6
Sparsely Vegetated	Sparsely forested rock outcrop	7
	Disturbed areas/grassy areas	8
	Exposed gravel (highway, borrow pits)	8

[a] Classes correspond to those in Table 11.

white birch). Results for wetland-related cover classes were similar to those obtained for the Brackett Lake area. Ponds with open (25-50%) versus very dense (>75%) cover of floating aquatics could not be separated, but open water and emergent/dense floating aquatic vegetation were clearly distinguishable (Fig. 5a).

Low ACD values (<2.0) and significant overlap among scattergrams for training areas indicated that spectral similarity between several pairs of cover types could prevent their use as separate classes. Considerable modification of training areas and other changes resulted in increased separability for most types. For instance, spectral overlap among the original training areas for deciduous, mixedwood, and dense coniferous forest was high (Fig. 5b). Revision of training areas and merging deciduous and mixedwood classes resulted in improved spectral separability between deciduous/mixedwood and coniferous forest cover classes (Fig. 5c, ACD = 4.9). The open fen and ericaceous shrub-lichen classes remained spectrally inseparable, and were merged prior to classification. There was good separation between forest cover classes and the low shrubland/wetland class (ACD > 6.9, Fig. 5c).

"Edge" pixels between cover types created serious problems, particularly along borders among rock outcrops with sparse pine cover, open shrubland/fen, and dense deciduous stands. Several classifications produced using

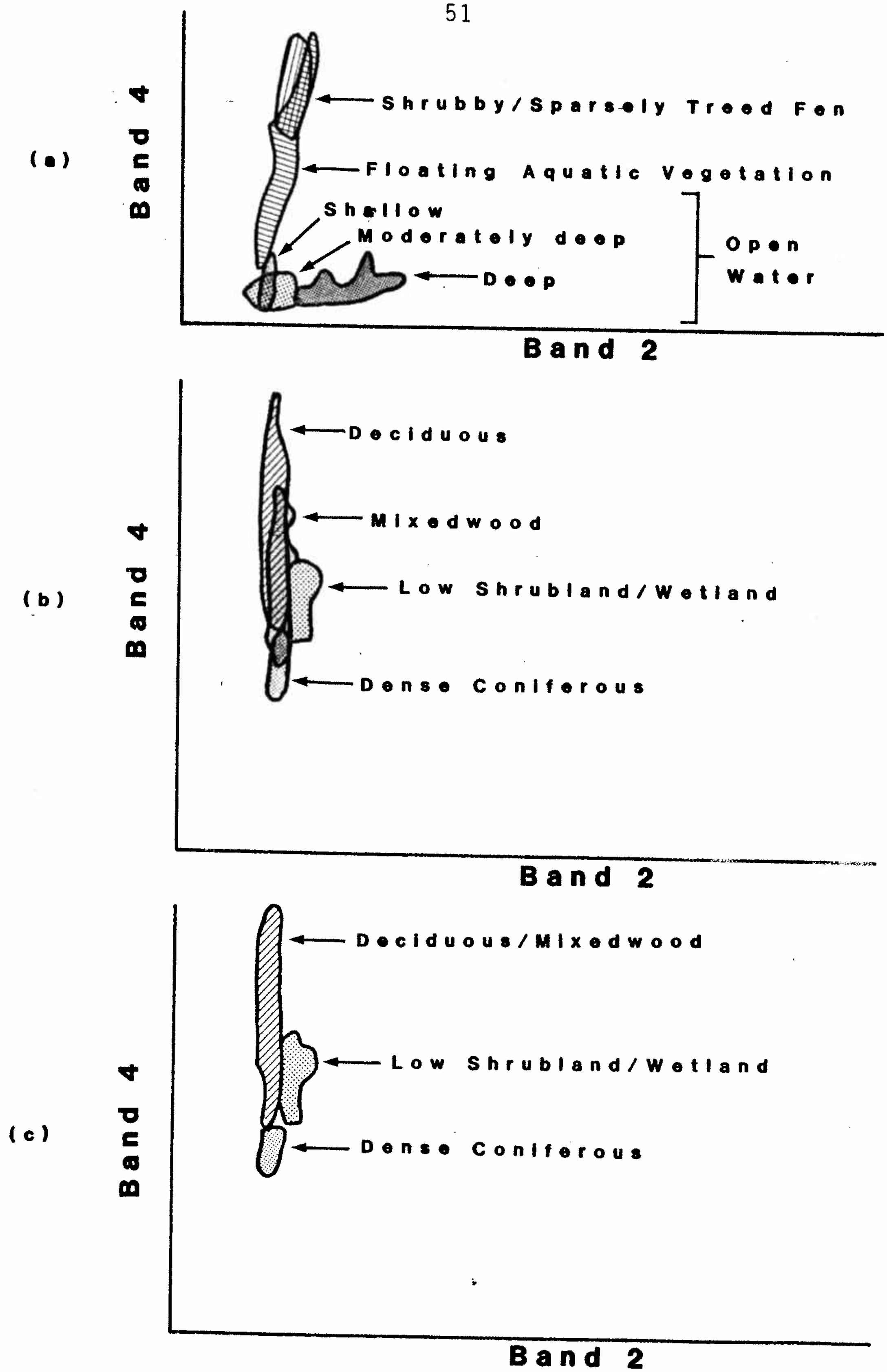

Figure 5. Scattergrams showing spectral overlap among training areas for the Yellowknife-Rae wetland area.

the maximum-likelihood classifier and modified training data exhibited the edge effect problem, with extensive areas incorrectly classified as shrubland/wetland. Consequently, the parallelepiped classification task (bands 2, 4, 5), in which single pixels can be added or subtracted, was used to remove edge pixels that were creating confusion. This classification was used to produce the colour plot for the Yellowknife-Rae area.

Eight cover classes were mapped at 1:50,000-scale for the Yellowknife-Rae wetland area using TM data (Table 10, 11). Four of these classes represented water or wetland cover types, two represented forest types, and two indicated the presence of substrate with little or no vascular vegetation (rock outcrop, highway/disturbed area). Deciduous/mixedwood forest and rock outcrop are the most prevalent, each comprising approximately one-third of the classified area. Small unclassified areas occur throughout, particularly on islands and shoreline of Great Slave Lake. The final classes mapped for the Yellowknife-Rae area are described in Table 12.

The confusion matrix (Table 13) shows that the thematic map produced for the Yellowknife-Rae area is acceptable, and that misclassification was primarily a function of land cover heterogeneity and the resultant abundance of edge pixels. Based on comparison with known ground sites, all cover classes were mapped with >75% accuracy (range 79 -

Table 11. Classification summary for the Yellowknife-Rae wetland area. (Supervised classification was produced using Landsat TM data acquired 12 July 1987, to which a parallelepiped algorithm was applied.)

Class	Descriptor[a]	Area Classified		
		ha	% of Total	% of Classified Area
1	Emergent or floating aquatic vegetation	5,911	6.2	6.6
2	Wetland/low shrubland	5,708	6.0	6.4
3	Open water - pond/lake/bay	5,165	5.4	5.8
4	Deep water	13,254	14.0	15.0
5	Deciduous/mixedwood forest	26,461	27.9	29.9
6	Dense coniferous forest	2,366	2.5	2.7
7	Rock outcrop	29,229	30.8	33.0
8	Highway/disturbed areas	609	0.6	0.6
	Total classified	88,703	93.4	100.0
	Unclassified[b]	6,291	6.6	-

[a] Cover class descriptions are provided in Table 12.

[b] Unclassified area was primarily outside Landsat scene. Almost all of the mapped area was classified.

Table 12. Description of cover classes mapped for the Yellowknife-Rae wetland area based on supervised classification of Landsat TM data.

Class	Descriptor	Description[a]
1	Emergent or floating aquatic vegetation	- shallow water with dense cover of floating aquatic vegetation; floating islands and other relatively large patches of emergent vegetation
2	Wetland/low shrubland	- sparsely treed and shrubby fens; untreed areas with ericaceous shrub and conspicuous lichen ground cover; rock outcrop/dense deciduous vegetation mosaics
3	Open water - pond/lake/bay	- very shallow (<2m) and shallow waterbodies (ponds, lakes, and bays of Great Slave Lake)
4	Deep water	- Great Slave Lake proper
5	Deciduous/mixedwood forest	- dense stands of paper birch, poplar, tall willow; mixed deciduous/spruce and deciduous/pine
6	Dense coniferous forest	- dense, tall spruce (often mature riparian white spruce)
7	Rock outcrop	- outcrops with little vascular vegetation and usually conspicuous lichen cover; outcrops with sparse cover of jack pine and variable lichen cover
8	Highway/disturbed areas	- highway roadbed and unforested right-of-way; gravel pits; relatively large borrow pits; highway/gravel/vegetation mosaics

[a] Vegetation densities:
(1) forest canopy cover - sparse (<10%), open (10-50%), dense (50-75%), closed (>75%).
(2) shrub/ground cover - sparse (10-25%), open (25-50%), dense (>50%).
(3) floating aquatic vegetation - dense (>50%).

Table 13. Confusion matrix for the Yellowknife-Rae supervised classification.

Mapped Class	Known Cover Type[a] [no. pixels (%)] 1	2	3	4	5	6	7	8	Total	Commission Errors
1	171 (81)	3 (1)	11 (13)	6 (1)					191 (8)	20 (10)
2		357 (85)		36 (4)		12 (4)		5 (4)	410 (18)	53 (13)
3	6 (3)	1 (0)	66 (79)	2 (0)				2 (1)	77 (3)	11 (14)
4	2 (1)	26 (6)		650 (81)	60 (22)				738 (32)	88 (12)
5	9 (4)	10 (2)		30 (4)	219 (79)			3 (2)	271 (12)	52 (19)
6	3 (1)	23 (5)		30 (4)		280 (84)			336 (14)	56 (17)
7				22 (3)		24 (7)	29 (88)	1 (1)	76 (3)	47 (62)
8	21 (10)	2 (1)	7 (8)	28 (4)		17 (5)	4 (12)	133 (92)	212 (9)	79 (37)
Omission Errors	41 (19)	65 (15)	18 (21)	154 (19)	60 (22)	53 (16)	4 (12)	11 (8)		
Total	212	422	84	804	279	333	33	144	2311[b]	

[a] Class numbers correspond to those in Table 11. Cover type was identified for ground sites during field studies; descriptions are provided in Table 12. The accuracy of class 8 was not assessed using known sites.

[b] Overall accuracy: $\frac{\text{total no. correct pixels}}{\text{total no. pixels}} \times 100 = 82\%$

89%), omission and commission errors were generally low (<25%, with 2 exceptions), and overall accuracy was 82%. Wetland cover classes (1 and 2) were mapped with >80% accuracy and low errors of omission (<20%) and commission (<15%). Substantial confusion occurred only for rock outcrop (class 7) and highway/disturbed area (class 8), which had large commission errors (62% and 37%, respectively). These errors resulted primarily from misclassificatiion of emergent/floating aquatic vegetation, small areas of Great Slave Lake and dense coniferous forest.

DISCUSSION

The type of information which can be extracted from Landsat imagery is determined by several factors, which include: (1) the spectral characteristics of the land surface at the time the satellite data is acquired, (2) the spatial and spectral distinctiveness of cover types which are of primary interest to the analyst, (3) the type and quality of Landsat data available, (4) the amount and type of ground data collected, and (5) availability of additional reference data. Differences in these factors determined the results of this study to a major extent.

The relative ease with which a satisfactory classification was produced for the Yellowknife-Rae area, compared to the Brackett Lake area, resulted primarily from differences in land cover characteristics and quality and quantity of ground and reference data. Although the Yellowknife-Rae area is very heterogeneous, the wetlands are mostly discrete patches surrounded by vegetation and rock outcrops with high spectral contrast. Cover types were easily differentiated on recent, large-scale air photos along the Yellowknife-Rae highway. The highway provided easy access to part of the area, and allowed most of the helicopter survey time to be used for collecting data on cover characteristics elsewhere within the relatively small (890 km^2) study area.

In contrast, few cover types in the comparatively large (2,510 km^2) Brackett Lake study area are spectrally distinct, and most of the area consists of wetland communities with no sharply defined boundaries. The distribution and density of plant species is determined primarily by the extent of permafrost and availability of moisture, and consequently, the vegetation changes along a gradient from the well-drained uplands to the successional thermokarst ponds. A large amount of analysis time was required to reduce the spectral variability within and the overlap among training areas for the Brackett Lake area, primarily because somewhat arbitrary boundaries were being imposed on an ecological continuum. Spectral overlap among cover types was common because vegetation cover types were differentiated primarily on the basis of relative amounts of a few key elements (e.g., black spruce, ericaceous shrubs, ground lichens), rather than distinct changes in species composition. A compounding problem was that reference materials available for the Brackett Lake area were inadequate, as they did not portray existing conditions, and air photos were relatively small-scale (i.e., approximately 1:60,000). Forest fires and pond succession produce substantial changes in a relatively short time (e.g., 20 years) in dynamic subarctic forest areas such as the

Brackett Lake study area (National Wetlands Working Group 1988).

Classification of the Ramparts-Hume area was subject to the same constraints as the Brackett Lake classification in terms of land cover characteristics and inadequate reference data. Additional problems were presented by the extremely limited amount of ground data collected (during a total of 6 hours of helicopter time on 2 surveys) for a large area (6,470 km^2), and the use of MSS data. The lower spatial, spectral, and radiometric resolution of the Landsat MSS sensor, compared with TM, was not sufficient for differentiating several important wetland cover types. With sufficient ground and reference data, Landsat MSS data could be used to map broad cover types for areas such as the Ramparts-Hume lowlands, but discrete wetland classes (other than open water) could not be mapped.

Mapping broad cover classes (e.g., deciduous vs. coniferous vs. wetland complex) using visual interpretation of Landsat MSS or TM transparencies would be the most cost-effective means to produce reconnaissance-level information on wetlands in the NWT. Colour TM enhancements plotted at 1:50,000-scale provide a synoptic view of relatively large areas, which could be used for assessing general land cover patterns, selecting survey routes, or locating areas for further habitat studies. They may also be used as base maps or navigational aids in areas which are not described by

1:50,000-scale topographic maps (Ferguson in prep.), or where recent fires have altered the land cover substantially.

From the standpoint of management programs for waterfowl, plots produced from Landsat TM data at 1:50,000-scale or larger have the greatest potential value. Enhancements and classification maps at smaller scales (e.g., 1:125,000) would not provide sufficiently detailed information to be useful for waterfowl population studies, although they may be useful for broad assessments of waterfowl habitat availability and distribution. Classifications produced from Landsat MSS data do not have much potential for facilitating waterfowl management, because limited spatial, spectral, and radiometric resolution prevent identification of important features (e.g., small ponds, shallow open water, emergent vegetation).

For areas known to be important to nesting or staging waterfowl, maps which could be used to estimate the relative level of primary productivity for individual waterbodies or to make inferences about waterfowl production would be useful. Relevant mappable features would include: open water, submergent vegetation, emergent and floating aquatic vegetation, sedge/cotton-grass (Eriophorum spp.) meadows, small nesting islands, and wetland complexes. This information also would be valuable for identifying habitats of high primary productivity in areas for which little or no information on use by waterfowl is available. Enhancements or thematic maps at 1:50,000-scale or larger could be used to stratify habitat prior to aerial waterfowl surveys or vegetation transects, and to plot locations of nests and observations of waterfowl. Operational use of these types of Landsat products could increase the efficiency and precision of surveys in the NWT.

Mapping land cover using Landsat data would be valuable for management of large mammal species generally associated with wetlands, such as moose and muskoxen. Information about the quantity and distribution of cover types would be useful for conducting surveys stratified by habitat type, which would increase survey efficiency significantly. Broad cover classes (e.g., deciduous and coniferous forest, open water) derived from visual interpretation of enhanced MSS or TM colour composite imagery may be satisfactory for stratification in some areas for some species (e.g., moose in the boreal forest). In other situations (e.g., muskoxen in the arctic tundra), however, requirements for more detailed mapping of spectrally complex habitats would entail supervised classification using TM digital data (Ferguson in prep.).

There is potential for using other remote sensing methods, in addition to those assessed during this study, to investigate wetland features of importance to waterfowl and other wildlife species in the NWT. The third stage of wetland inventory proposed for the NWT (Wakelyn 1988), which entails more intensive ground data collection, would provide relatively detailed data on the ecological characteristics of wetlands and uplands (e.g., soils, hydrology, physiography). This information could be used to describe complex wetlands and wetland patterns, and to assess the habitat suitability and productivity of individual wetland complexes for wildlife.

Research on the application of remote sensing methods for evaluating wetland characteristics is ongoing, although few proven techniques have been developed for operational use. The feasibility of using spectral reflectance measurements to identify hydrophytic vegetation (Best et al. 1981) and to estimate biomass of marsh vegetation (Hardisky et al. 1984) has been investigated for wetlands in the northern United States. The ability to measure these wetland features using analysis of Landsat data may facilitate wetland classification and mapping, and may be applicable to management of northern wetland areas. Characteristics such as water depth, turbidity, chlorophyll concentration, and water chemistry have been estimated using Landsat MSS data (Hoffer 1978, Howman et al. 1989, Vertucci 1989). The increased sensitivity of the TM sensor to turbidity levels was evident in this study, particularly for the Brackett Lake area. The improved resolution of the TM sensor provides opportunities to use Landsat data to monitor water quality parameters (Alfoldi 1982), and to assess features such as chlorophyll levels, from which an index to primary productivity or eutrophication of waterbodies could be derived (Hoffer 1978). Relatively detailed ground data would be required to assess the feasibility of estimating these features using TM data for northern wetlands, however, and development of an operational method for use in management would entail considerable time and effort.

RECOMMENDATIONS

The potential for successfully mapping any wetland area in the NWT using analysis of Landsat data depends primarily on information requirements for resource management, characteristics of the study area, and the resources available for analysis. In general, a mapping project has the greatest potential for "success" (i.e., mapping cover types of interest to users with high accuracy) for study areas which are quite well known (either through direct observation or reference data), and which have relatively uniform terrain and spatially and spectrally distinct wetlands. Use of high resolution, cloud- and snow-free Landsat TM data, which has been acquired under similar temporal and weather conditions as ground data, will increase the likelihood that favourable results will be obtained. (These Landsat data may not be available for all areas of interest in the NWT, particularly in coastal arctic regions.) It is important that information requirements be established cooperatively at the project planning stage by map users and remote sensing analysts, because users not familiar with the capabilities and limitations of mapping with satellite data often have unrealistic expectations (Lindenlaub and Davis 1978).

Even under these favourable conditions, a substantial investment of time, effort and financial resources is required to produce maps with acceptable classification accuracies. The logistical and financial requirements for working in extensive northern wetland areas should be considered during the planning stages of wetland mapping projects. The essential first step should be to assess whether or not a classification map derived from analysis of Landsat digital data is required to meet the information needs for resource management (Lindenlaub and Davis 1978, Philipson 1980). The next step should be to determine if adequate ground and reference data will be available for production of a classification map with acceptable accuracy. If these data will not be available, visual interpretation of Landsat imagery (transparencies or colour plots) should be used to obtain reconnaissance-level information on land cover patterns, and the Landsat classification approach should be delayed until sufficient ground and reference data can be obtained.

Two lessons learned during this feasibility study should be noted by anyone planning wetland mapping projects in the NWT. First, the lack of adequate ground data and reference materials was the single most important factor limiting the efficiency of producing classification maps with acceptable levels of accuracy. Prospects for achieving favourable results were significantly improved by the availability of good quality Landsat TM data (i.e., without the presence of haze or clouds), recent air photos at a relatively large scale (i.e., 1:20,000), and ground access to study areas. Second, collecting sufficient ground data to produce comprehensive descriptions of the ecological conditions represented by map units, similar to those produced for forested areas in Ontario (Pala and Boissonneau 1982) and for arctic tundra in Alaska (Walker et al. 1982) and the NWT (Ferguson in prep.), would require significantly larger commitment of resources (primarily funding and manpower) than that available during this feasibility study.

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APPENDIX A. Results of supervised classification for the Brackett Lake wetland area using 1987 Landsat TM data.

Table 1. Classification summary for Brackett Lake wetland area. (Supervised classification was produced using Landsat TM data acquired 20 July 1987, 1987 ground data and the parallelepiped algorithm.)

Class	Descriptor	Area Classified: ha	Area Classified: % of Total	Area Classified: % of Classified Area
1	Shrubland	35,069	12.0	12.8
2	Spruce-lichen woodland	38,064	13.0	13.8
3	Unvegetated rock/soil or lichen mat	1,202	0.4	0.4
4	Deciduous forest	10,680	3.6	3.8
5	Emergent or floating aquatic vegetation	11,985	4.1	4.4
6	Open water (ponds & lakes)	18,157	6.2	6.6
7	Water with sediment/haze	4,031	1.4	1.5
8	Coniferous-dominated/ mixedwood forest	139,789	47.7	50.7
9	Mackenzie River	7,863	2.7	2.9
10	Dense regeneration - spruce/tall shrub	3,602	1.2	1.3
11	Open regeneration/haze - low shrub/soil	4,279	1.5	1.6
12	Sedge fen - treeless or sparsely treed	560	0.2	0.2
	Total classified	275,281	94.0	100.0
	Unclassified[a]	17,409	6.0	-

[a] Unclassified area is primarily outside the study area or Landsat imagery and is an artifact of mapping. Almost all of the mapped area was classified.

Table 2. Confusion matrix for Brackett Lake supervised classification produced using 1987 Landsat TM data. Known sites were determined during 1988 field studies.

Mapped Class	Known Cover Type[a] [no. pixels (%)] 1	2	3	4	5	6	7	8	10	11	12	Total[b]	Commission Errors
1	455 (54)					15 (1)		95 (6)	140 (55)	65 (43)	2 (2)	772	317 (41)
2	40 (5)	300 (84)	10 (8)		60 (13)			126 (8)			2 (2)	538	238 (44)
3		15 (4)	100 (77)									115	15 (13)
4	40 (5)	25 (7)		160 (41)				72 (5)				297	137 (46)
5	10 (1)			5 (1)	333 (71)	320 (24)		50 (3)				718	385 (54)
6					45 (10)	865 (64)	75 (34)	5 (0)				990	125 (13)
7					25 (5)	150 (11)	145 (66)	10 (1)				330	185 (56)
8	95 (11)	15 (4)	20 (15)	110 (28)	5 (1)	10 (1)		1050 (70)	20 (8)		10 (10)	1335	285 (21)
10	20 (2)			115 (30)				95 (6)	30 (12)			260	230 (88)
11	170 (20)								65 (26)	85 (57)		320	235 (73)
12	10 (1)										85 (86)	95	10 (10)
Omission Errors	385 (46)	55 (16)	30 (23)	230 (59)	135 (29)	495 (36)	75 (34)	453 (30)	225 (88)	65 (43)	14 (14)		
Total	840	355	130	390	468	1360	220	1503	255	150	99	5770	

[a] The accuracy of class 9 (Mackenzie River) was not assessed using known sites.

[b] Overall accuracy: (total no. correct pixels/total no. pixels) X 100 = 62%