AN ASSESSMENT OF LANDSAT-5 THEMATIC MAPPER DATA FOR MAPPING AND MONITORING WETLANDS: SUMMARY REPORT

Geoffrey F. Tomlins
W. Sean Boyd

TECHNICAL REPORT SERIES No. 46
Pacific and Yukon Region 1988
Canadian Wildlife Service

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Geoffrey F. Tomlins[1]
and
W. Sean Boyd[2]

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This series may be cited as:

Tomlins, G.F. and W.S. Boyd. 1988.
An assessment of LANDSAT-5 thematic mapper data for mapping and monitoring wetlands: summary report. Technical Report Series No. 46 Canadian Wildlife Service, Pacific and Yukon Region, British Columbia.

1. B.C. Research Corporation, Vancouver, B.C.
2. Canadian Wildlife Service, Delta, B.C.

Published by Authority of the
Minister of Environment
Canadian Wildlife Service

Minister of Supply and Services Canada 1988
Catalogue No. CW69-5/46E
ISBN 0-662-16466-0
ISSN 0831-6481

Copies may be obtained from:
Canadian Wildlife Service,
Pacific and Yukon Region
P.O. Box 340,
Delta, British Columbia,
Canada V4K 3Y3

ABSTRACT

This report summarizes a previous, more detailed report on the use of Landsat Thematic Mapper (TM) data for mapping wetlands. Three study areas in British Columbia, Canada, were selected: the Estuarine system, at the mouth of the Fraser River in south-west B.C.; the Riverine system, a stretch of the upper Columbia River floodplain in south-east B.C.; and the Palustrine system, an area on the Fraser Plateau, in central B.C. For each study area, 1984 spring and fall TM data were registered together. Field surveys were undertaken in the spring and fall of that year to identify seasonal changes. Plant cover characteristics and other relevant information were collected from over 900 wetland and upland polygons which had previously been delineated from aerial photographs.

A comprehensive analysis of digital classification methods, and variables, was performed on TM data of the Estuarine system, using field survey data to quantify classification accuracies. The most significant parameter was the feature set. The TM 2, 3, 4 and 5 feature set (August data) provided equivalent or superior results to any alternative combination of TM bands, including 6-band feature sets and multi-temporal combinations. Supervised classification was superior to unsupervised, or semi-supervised methods. Results were optimized by development of a classification mask used to delimit the area classified. Other significant parameters included the number of signatures used in the classification and the signature threshold value. Application of a post-classification mode filter also improved the appearance of the final result and it increased classification accuracies. Thirty themes, at the species-association level of description, were classified at 85.4% overall class accuracy. Similar methods applied in the other study areas gave overall class accuracies of 92.5% (Riverine system, 16 themes) and 85.0% (Palustrine system, 18 themes).

Digitally enhanced colour composites for each wetland system were prepared at a nominal scale of 1:350,000. Sample wetland complexes were projected onto base-maps at scales of 1:15,000 to 1:50,000 and individual polygons interpreted. Due to the small sample size, we were unable to derive quantitative accuracy figures. However, larger wetland polygons (>5 ha) were easily delineated, and their distribution closely matched that obtained from aerial photography.

Ponds and lakes were easily classified or interpreted. In a sample area of the Palustrine system, water bodies were enumerated and results compared with the corresponding topographic map sheet. Ponds greater than 5 ha surface area (open water) were accurately mapped by digital methods; visual interpretation reliably identified ponds as small as 2.5 ha. Many other ponds identified by the TM data were not shown on the map.

RÉSUMÉ

Ce rapport est un résumé d'un rapport antérieur plus détaille sur l'utilisation des données du capteur thématique (TM) Landsat pour la cartographie des terres humides. Trois zones d'étude ont été choisies en Colombie-Britannique, Canada: le système estuarien, à l'embouchure du Fraser dans le sud-ouest de la C.-B.; le système fluvial, une section de la plaine inondable supérieure du Colombia dans le sud-est de la C.-B.; et le système palustre, une région du plateau du Fraser au centre de la C.-B. Pour chacun des secteurs à l'étude, on a enregistré sur un même support les données TM recueillies au printemps et à l'automne de 1984. Au cours de ces mêmes périodes, des études in situ ont été effectuées en vue d'identifier les changements saisonniers. Les caractéristiques de la couverture végétale et autres informations pertinentes ont été recueillies pour plus de 900 polygones en milieux humides et dans les terres hautes, lesquels avaient été d'abord délimités d'après des photographies aériennes.

Une analyse approfondie des méthodes de classification numérique et des variables a été effectuée sur les données TM du système estuarien, d'après les données recueillies lors de l'étude in situ, pour quantifier les degrés de précision de la classification. Le paramètre le plus important était le jeu de caractéristiques. Le jeu de caractéristiques TM 2, 3, 4 et 5 (données du mois d'août) a fourni des résultats équivalents ou supérieurs à toutes combinaisons de rechange des bandes TM, y compris les jeux de caractéristiques en bande 6 et les combinaisons multi-temporelles. La classification dirigée était supérieure aux méthodes de classification non dirigée ou partiellement dirigée. Les résultats ont été optimisés par le développement d'un masque de classification qui à sérvi a delimiter la zone classifiée. Au nombre des autres paramètres importants on compte le nombre de signatures utilisées pour la classification ainsi que la valeur de seuil de signature. L'application d'un filtre en mode post-classification a également permis d'améliorer l'apparence du résultat final ainsi que les degrés de précision de la classification. Trente thèmes, au niveau de description d'association des espèces, ont été classifiés avec une classe de précision globale de 85.4%. Des méthodes similaires appliquées dans d'autres secteurs d'étude ont donné des classe de précision globale de 92.5% (système fluvial, 16 thèmes) et 85.0% (systeme palustre, 18 thèmes).

Des compositions colorées et accentuées par techniques numériques pour chaque système de terres humides ont été préparés à une échelle nominale de 1:350 000. Des ensembles d'échantillonnage de terres humides ont été projetés sur des cartes de base de 1:15 000 à 1:50 000 et les polygones individuels ont été interprétés. En raison de la grandeur réduite des échantillons, nous n'avons pas été en mesure de calculer des valeurs quantitatives de précision. Toutefois, les polygones de terres humides plus grands (>5 ha) étaient facilement délimités et leur distribution correspondait étroitement à celles obtenues a partir de photos aériennes.

Les étangs et les lacs ont été facilement classifiés ou interprétés. Dans les zones échantillons du système palustre, les plans d'eau ont été répertoriés et les résultats comparés avec ceux d'une carte topographique correspondante. Les étangs dont la superficie dépassait 5 ha (eau libre) ont été cartographiés avec précision par méthode numérique; l'interprétation visuelle à permis d'identifier clairement des étangs aussi petits que 2.5 ha. De nombreux autres étangs identifiés grâce aux données TM n'apparaîssaient pas sur la carte.

ACKNOWLEDGEMENTS

Doug Gillespie, Canadian Wildlife Service Ottawa, and Clayton Rubec, Lands Directorate Ottawa, played key roles in the financing and guidance of the original research project. Evan McKenzie and Robert Hay assisted with data collection. Frank Ahearn, Canadian Centre for Remote Sensing Ottawa, provided comments on a previous version of this report. We thank them all.

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1. INTRODUCTION

1.1 Purpose of the Report

This report summarizes a previous, more detailed report on the use of Landsat Thematic Mapper (TM) data for mapping wetlands (B.C. Research 1986). The report addresses wildlife managers and other professionals who are contemplating the use of TM data as an aid in survey and management of wetlands. It describes the methods available for analyzing TM data and the results that can be expected. It also provides a summary of the inherent advantages and limitations of TM data.

The report will also be of interest to remote sensing specialists since it reports on comparisons between image interpretation and digital classification methods, and it provides quantitative evaluations of several digital processing techniques. Readers interested in more details are directed to the original research report.

1.2 Background

As awareness of wetland values has heightened and demands on wetlands for conflicting land-uses have increased, there has emerged a need for cost-efficient methods for their inventory and monitoring. Satellite remote sensing provides the capability of surveying very large areas of land at a much lower cost than traditional survey methods, and because of their re-visit capability, data are available on a current, regular basis. The satellite images are originally in digital form, which makes them suitable for integration into computer-based land information and management systems.

In March, 1984, the fifth in the series of Landsat satellites was launched carrying a new sensor called the Thematic Mapper (TM). Images acquired by the TM show the earth's surface in much greater detail than previous satellite sensors. A research study to investigate the role of TM data for the inventory and monitoring of wetlands was sponsored by the Canadian Wildlife Service (CWS) and by the Lands Directorate of Environment Canada. The research was performed by B.C. Research in co-operation with CWS.

1.3 Objectives and Scope of the Study

The principal objective was to investigate the TM in terms of its ability and feasibility for mapping wetland communities, distributions, and areal extents. Since wetland vegetation associations vary with biogeoclimatic zone and hydrology, three study systems were selected: Estuarine, Palustrine and Riverine systems. Also, since vegetation discrimination by remote sensing is affected by water level and plant stage-of-growth, multi-date analysis techniques were investigated.

Interpretation or classification of TM data can be performed by visual or computer-assisted methods, or a combination of both. Each approach has particular advantages and limitations. Another objective of this study was, therefore, to compare visual interpretation with digital classification.

1.4 Principles of Satellite Remote Sensing

The TM continuously measures, in seven wavelength bands, the amount of solar radiation reflected from the surface of the earth. The seven spectral bands are positioned in the visible, near infrared (NIR), short-wave infrared (SWIR), and thermal infrared (TIR) regions of the spectrum (Table 1).

TABLE 1
Spectral Bands of the Thematic Mapper

SPECTRAL BAND	WAVELENGTH INTERVAL (MICRONS)	REGION	PRIMARY RATIONALE FOR BAND SELECTION
TM1	0.45 - 0.52	blue-green	chlorophyll-carotenoid sensitivity
TM2	0.52 - 0.60	green	green region characteristics
TM3	0.63 - 0.69	red	chlorophyll sensitivity
TM4	0.76 - 0.90	NIR	sensitive to biomass
TM5	1.55 - 1.75	SWIR	sensitive to water in plant leaves
TM6	10.50 - 12.50	TIR	thermal properties
TM7	2.08 - 2.35	SWIR	geological applications, sensitive to water in plant leaves

The nominal spatial resolution of the TM is 30 m by 30 m, meaning that ground cover polygons less than 0.1 ha in area will not be detected by the satellite. In practice, ground targets should be greater than 0.5 ha for adequate resolution.

The continuous stream of image data received by the satellite is re-transmitted to ground receiving stations, where it is split into scenes representing 185 km by 185 km of ground area, or quarter-scenes of 105 by 88 km^2 (quadrants). The satellite orbit provides a re-visit cycle such that image data for any area of the earth are collected every 16 days, or 22 times per year. Each TM scene requires about 220 megabytes (MB) of computer storage. During ground processing, TM data can be transferred to photographic film (transparencies or paper prints), and imagery in a variety of photographic or digital formats can be acquired.

1.4.1 Options for Landsat Image Analysis: TM photo products are interpreted similar to aerial photographs. Major differences are the photo scale and the colour (or intensity in black-and-white products). Because of the large area coverage of the TM, a full scene represented on a 185 mm print would be at a scale of 1:1 million; a quadrant on a 420 mm print would have a scale of 1:250,000. Image colour depends on the spectral bands chosen to make the print. A print made from TM bands 1,2, and 3 would appear similar to a true-colour airphoto, while one produced from bands 2,3, and 4 would be similar to a false colour infrared (FCIR) airphoto. More unusual colours would be produced from TM 3,4, and 5 or from other band combinations, but those combinations often provide greater contrast between ground cover types than the more conventional true-colour or FCIR images.

TM digital data require specialized image processing systems for analysis. The system comprises the computer itself (often a high powered personal computer or general-purpose mini-computer), extra disk memory for storage of the TM data and processed results, and equipment for displaying the data in pictorial form on a high resolution colour monitor. Specialized software is also required for image correction, enhancement, classification, and other processing steps.

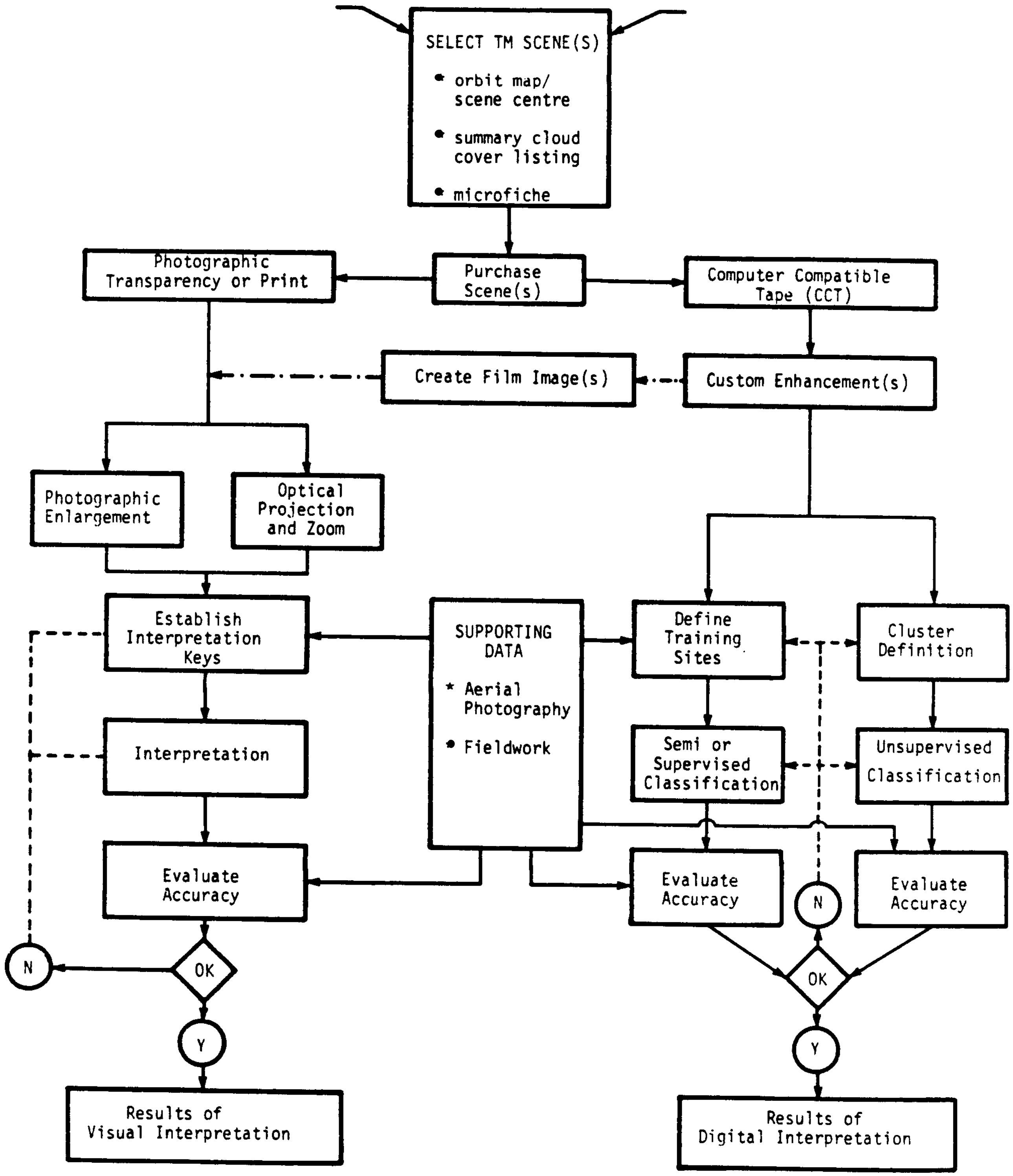
Digital processing allows for the maximum possible information to be extracted from the TM data. Images can be contrast enhanced to improve interpretation results. Custom enhancements can be easily developed for specific cover types (eg. vegetation enhancement, water enhancement). Different colour composites can be evaluated (eg. TM 1, 2, and 3 vs. TM 3, 4, and 5), or bands combined together by ratio or other arithmetic procedures. Statistical methods can be applied to the data to group together similar pixels, and automatically classify the total scene into various themes representative of ground cover classes. Following digital classification, thematic maps can be produced at any desired scale to show the distribution of plant community polygons, and reports can be generated providing area measurements by cover class.

Figure 1 summarizes the two main options (photo-interpretation and digital analysis) available for TM image analysis.

1.5 Literature Review

The first Landsat satellite was launched in 1972, carrying a multi-spectral scanner (MSS) which scanned the earth's surface in four broad spectral bands, at a spatial resolution of 80 m. Applications research for the MSS quickly followed, attracted by the very large area coverage (over 35,000 km^2/scale), the immediacy of the imagery, its up-date and monitoring potential, and its low cost (less than 1 cent/km^2). In the decade that followed, MSS data began to be used operationally to assess and monitor rangelands (Brown et al. 1983), for forest inventory and monitoring (Quenet et al.

FIGURE 1
Major Options for TM Image Analysis



1981), assessment of crop condition (Hickman 1984), and for reconnaissance level land cover classification and mapping (Oswald 1981). For those applications, the data had sufficient spatial and spectral resolution to provide the required information (Cihlar et al. 1985). The MSS was less successful for wetland mapping because of the smaller aerial cover of individual polygons. Some success has, however, been reported where wetland diversity is low and aerial coverage high, such as for reconnaissance surveys of mangrove swamps (Promanik et al. 1987), and for the inventory of peatlands (Dixon and Stewart 1984, Pala 1985).

The first Thematic Mapper (TM) was launched with Landsat-4 in 1982, but little TM data was captured due to spacecraft problems. About six months after the 1984 launch of Landsat-5, the TM started a new phase of applications research, because of its significantly enhanced spatial and spectral resolutions. In forestry, for example, Hopkins et al. (1988) determined that TM data could accurately discriminate level III forest type classes (species groupings), whereas MSS data were sufficient only for level II classification (hardwoods versus softwoods). The improved spectral range of the TM considerably enhanced its application in range management, particularly the inclusion of the two short wave infrared bands (Thomson et al. 1985). Similar expectations had earlier been forecast for wetland applications using simulated TM image data (Tomlins 1981), and ground radiometric surveys (Budd and Milton 1982).

The TM has been extensively used to map many different wetland habitats. Ormsby and Lunetta (1984) used digital TM data to prepare a land cover map of the Saginaw River basin, Michigan, and develop a distance model based on escape cover to show potential for food availability for whitetail deer. In the Mackenzie Delta, Jaques (1987) prepared enhanced imagery from digital TM data, from which he interpreted potential nesting and staging sites for shore birds. Throughout the central prairies of Canada and the U.S.A. Ducks Unlimited have recently started using TM data to inventory wetlands for waterfowl (Koeln et al. 1986). That large operational program covering approximately 900,000 km^2 from South Dakota to the boreal forests of Saskatchewan and Alberta requires processing of 60 full TM scenes. Each scene is digitally classified to produce wetland inventory maps at scales ranging from 1:24,000 to 1:250,000, together with statistical tables describing each wetland complex.

Other wetland TM investigations have been more restrictive in study area size. In a 1300 ha Delaware salt marsh, Gross et al. (1987) reported that the marsh grass *Spartina alterniflora* could be mapped, using the TM, at 87% accuracy, inclusive of commission and omission errors. Five other marsh communities were classified at accuracies ranging from 0-53%. They concluded that the TM offers success where monospecific vegetation dominates the wetland, as *S. alterniflora* occupied 40% of the area in large contiguous patches. The other marsh communities occupied between 1-11% of the area and each comprised several plant species. Lucy and Jensen (1987) observed similar results on the Santee Delta, South Carolina. A single-species low salt marsh was mapped at 92% accuracy, but three other communities, each with several plant species, had accuracies of 16-51%.

Processing methods for TM data have also received considerable attention. Some investigators reported that classification results using TM bands 2,3,4, and 5 are equal to, or better than classifications using all seven TM bands (Donogue and Shennan 1987, Atkinson et al. 1985). For visual interpretation of vegetation cover, the TM 3,4, and 5 colour composite has often been recommended (Thomson et al. 1985, Atkinson 1985), although Hopkins (1988) also noted that the visible (TM 1,2, and 3) or false-colour infrared (TM 2,3, and 4) composites may be superior for differentiation between major vegetation categories and mapping of cultural features. Multi-date TM images have been used to detect change (Jaques 1987) and have also been combined in attempts to improve classification accuracy (Thomson et al. 1985). The choice between visual interpretation and digital processing has been addressed by many investigators, but one particularly interesting study is reported by Snook et al. (1987). In their unusual investigation, high altitude photographs were digitized, classified by computer-assisted methods, and results were found to be superior to visual interpretations. In assessing costs of each method, the authors concluded that the value of computer classification increases with the size of the study area. For small study areas, digital methods are more costly than interpretation.

2. STUDY AREAS

2.1 Selection

British Columbia contains a variety of wetland types. Three study areas were selected for research, both to reflect their biophysical differences and because of the specific importance they have as wildlife habitats (Figure 2).

In the south-west corner of B.C., the Fraser River estuary supports large areas of fresh, brackish, and salt marshes, eelgrass beds, mudflats, and sandflats. The estuary is of prime importance to wintering and migrating birds and to salmonids. In south-eastern B.C., the upper Columbia River valley hosts a complex system of mudflats, marshes, ponds, lakes, and river channels which provide critical habitat for migrating birds and wintering ungulates. On the Fraser Plateau, in central British Columbia, glacial activity has left many depressions of varying sizes and depths which are commonly flooded in the spring. Those "potholes" and deeper lakes are important to breeding and migrating birds.

2.2 The Estuarine System

A 944 km^2 area at the mouth of the Fraser River was selected for study. The area includes parts of the city of Vancouver to the north and east, and is bounded by the Strait of Georgia to the west and south (Figure 2a). The Fraser estuary is a system influenced by tides and fresh water flow, both of which change constantly on daily and seasonal bases. On the foreshore, which extends from Sturgeon Bank in the north-west to Boundary Bay in the south-east, extensive sand- and mudflats have developed due to the accretion of sediments from the Fraser River. Much of that area has been colonized by marsh and eelgrass. Near the high tide demarcation, grass and herb meadows and low shrub thickets have established. Adjacent to the south arm of the Fraser River, and about 15 km inland, is a 40 km^2 peat bog, dominated by ericaceous shrubs and stunted lodgepole pine.

Foreshore gradients are very low and edaphic conditions change gradually across the intertidal platform. Mudflats and sandflats are mostly unvegetated; however, some cover by Ulva sp., Zostera sp., Enteromorpha sp., and/or filamentous algae does occur. In the west of the study area, mainly at Sturgeon Banks, the lowermost vegetation community is dominated by the bulrushes Scirpus americanus (seaward) and S. maritimus (landward), often in association with arrowgrass (Triglochin maritimum). Marshes dominated by the sedge Carex lyngbyei have developed on the upper reaches of the tidal flats, often with the bulrush S. lacustris and the cattail Typha latifolia close to fresh water influence. Also along the foreshore, between the homogeneous bulrush and sedge communities are transitional marshes with mixed species.

FIGURE 2
Study Areas

FIGURE 2a
Estuarine System

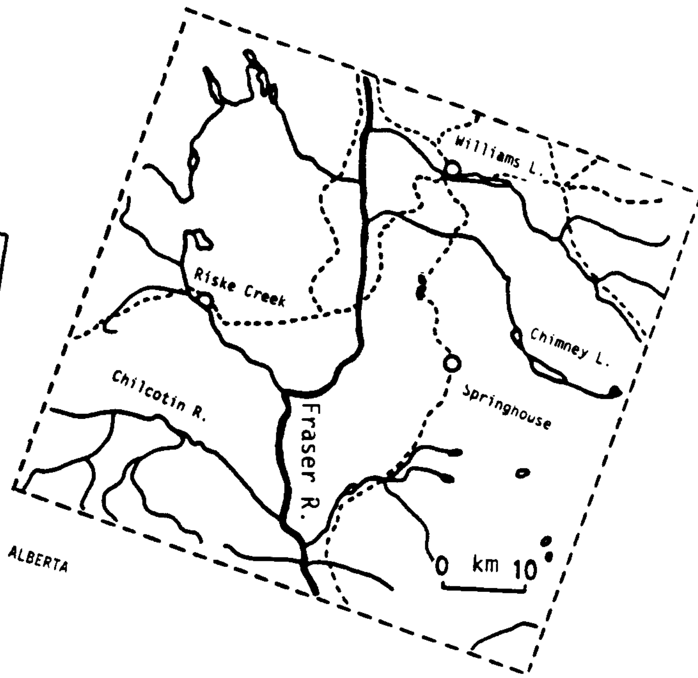


FIGURE 2c
Palustrine System

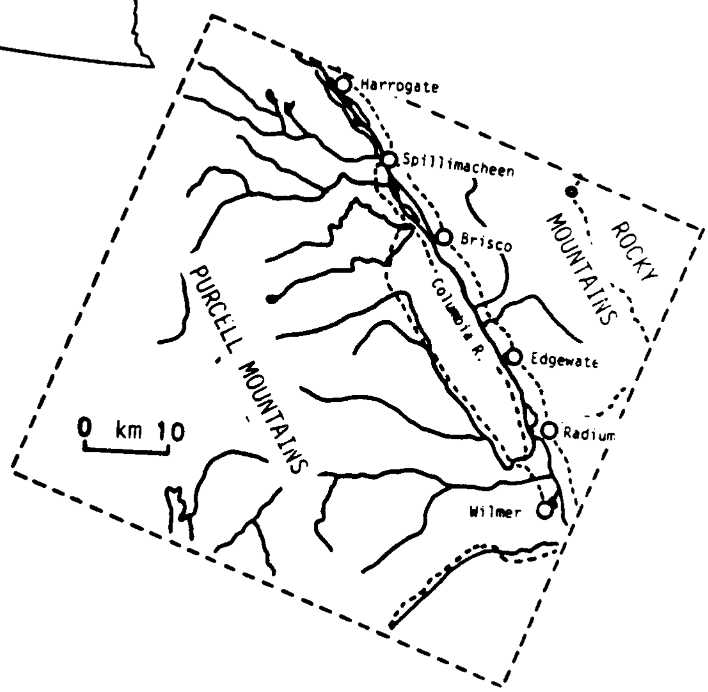


FIGURE 2b
Riverine System

In the south and south-east of the study area, at Roberts Bank and at Boundary Bay, salt marshes are dominated by Distichlis spicata and Salicornia virginica. Also, extensive Zostera marina and Z.japonica (eelgrass) beds are present in the subtidal and intertidal zones. Associated species include Ulva sp. and Enteromorpha sp. Driftwood areas dominated by beached logs are present in the upper extremes of salt marshes.

Meadow communities on higher, drier sites are rarely affected by tidal waters. They are dominated by grasses (Agrostis alba, Deschampsia cespitosa, Phalaris arundinacea), herbs (Trifolium sp., Ranunculus sp.), and rushes (Juncus effusus). Above the meadows are dense patches of raspberry and blackberry (Rubus leucodermis and R. ursinus), scotch broom (Cytisus scoparicus), and a discontinuous understory of rushes and grasses.

Upland areas are predominantly urban in the northern half of the study area, comprising part of Vancouver and the municipalities of Richmond and New Westminster. To the south are the fertile farmlands of Ladner, Delta and Surrey. Burns Bog, in the centre of the study area, is dominated by low ericaceous shrubs including blueberry (Vaccinium uliginosum), Labrador tea (Ledum groenlandicum), velvet-leaved blueberry (V. myrtilloides) and stunted lodgepole pine (Pinus contortus). Small deciduous, coniferous, and mixed forest stands are present in isolated areas throughout the study area, and fringing Burns Bog. Coniferous trees include Douglas fir (Pseudotsuga menziesii), Western Hemlock (Tsuga heterophylla) and Lodgepole pine (P. contortus). Alder (Alnus rubra) is the most common of deciduous trees.

2.3 The Riverine System

The riverine study area comprised a stretch of the upper Columbia River valley approximately 80 km long and 1.5 km wide between the town of Harrogate in the north-west and Columbia Lake in the south-east (Figure 2b). The floodplain, seasonally affected by river flooding, has a very gentle gradient through the area, resulting in the creation of extensive marshes, fens, ponds, and shallow lakes.

Water is the predominant cover in the floodplain. Numerous small ponds are support waterlily (Nuphar variegatum) or contain submerged aquatic vegetation (Chara sp., Myriophyllum sp., Potamogetum sp.). Sedge (Carex rostrata and C. aquatilis), horsetail (Equisetum fluviatile), and mixed horsetail/sedge marshes and fens are also predominant; less common are cattail (T. latifolia) and bulrush (S. lacustris) marshes.

Mudflats are common during periods of low river flow, some being vegetated by needle spikerush, (Eleocharis acicularis), marestail (Hippuris vulgaris), water buttercup (Ranunculus sp.), and grasses (Glyceria sp.). Unvegetated areas include river bars and lake edges with little or no vegetation cover.

Meadows occupy raised portions of the floodplain. Common plant species are grasses (Poa sp. and Calamagrostis sp.), sedges (Carex sp.) and herbs (eg. Potentilla anserina.)

At slightly higher elevations, shrub thickets are present adjacent to water bodies, along levees and on fluvial fans. Dominant plant species include willow (Salix sp.), water birch (Betula occidentalis), alder (Alnus tenuifolia), with minor rose (Rosa sp.) and cottonwood (Populus trichocarpa). Shrub understory is dominated by sedges, grasses, and herbs. Willow (Salix sp.), dogwood (Cornus stolonifera) and alder (Alnus sp.) shrubs often form the understory of forested deciduous habitat, namely large, mature cottonwood stands. In many of those areas, large trees have been felled by beaver.

Upland vegetation progresses from grasslands to forested areas. Grasslands are dominated by grasses (Poa pratensis, Agropyron spicatum, Stipa sp., Koeleria sp.), herbs (P. anserina, Antennaria sp.) and sagebrush (Artemisia frigida) with clover (Trifolium sp.) on moister sites. Most of the grasslands are grazed range or improved pasture, and some are cultivated for agricultural purposes. The deciduous forests are dominated by aspen (P. tremuloides), paper birch (B. papyrifera), and minor cottonwoods (P. trichocarpa) normally having a closed canopy. On the upland slopes, the closed coniferous forest is dominated by Douglas fir (P. menziesii), with white spruce (Picea glauca) evident on well drained portions of fluvial fans. There has been significant harvesting of the coniferous forest. The other major human activities are grazing on natural grasslands, sedge fens, and marshlands, and improvement of grasslands for pasture, forage, or grain crops.

2.4 The Palustrine System

The Palustrine study area comprised a 3775 km^2 area in the Cariboo-Chilcotin region, central British Columbia. Located on the Fraser Plateau, the study area is bounded by the city of Williams Lake to the north, the confluence of the Chilcotin and Fraser rivers to the south, Riske Creek to the west, and Chimney Lake to the east (Figure 2c). Elevation changes in the land are small, and the landscape is characterized by small ponds and lakes, many of which are seasonal.

The majority of open water bodies contain submergent vegetation, many with algal blooms. Other fresh water ponds and lakes support coontail (Ceratophyllum demersum), water milfoil (Myriophyllum exalbescens), pondweeds (Potamogetum sp.), brown moss (Drepanocladus sp.), filamentous algae, and minor species. The more saline ponds are dominated by widgeon grass (Ruppia occidentalis), water milfoil and pondweeds. A unique habitat is dead standing trees (snags) around the edges of many water bodies reflecting past fluctuations in climate and, therefore, water levels.

Marshes form narrow bands fringing the ponds and lakes. Characteristic emergents include bulrushes (Scirpus sp.), cattail (T. latifolia), large water sedges (C. aquatilis, C. rostrata, C. atherodes), rushes (Juncus sp.), spike-rush (Eleocharis palustris), and grasses. The area also contains many sedge dominated fens with a near total cover of Carex sp.

Both saline and fresh meadows are present. The most common species in fresh meadows are baltic rush (J. balticus), low sedges (C. praegracilis), grasses (Poa sp., Hordeum jubatum, Calamagrostis sp.), and forbs (P. anserina, Trifolium sp.). Saline meadows are dominated by salt tolerant grasses and to a lesser extent by salt-tolerant forbs.

Shrub dominated wetlands in the study area include shrub fens, shrub meadows and shrub swamps. The shrub fens support willows (Salix sp.) and dwarf birch (B. glandulosa) with a sedge and occasionally brown moss understory. Dwarf white spruce (P. glauca) trees are occasionally found growing among the taller (3-6 m) shrubs. The shrub meadows have an open canopy, and are dominated by low dwarf birch and, to a lesser extent, low willows ranging in height from 1-3 m. The shrub swamps are dominated by tall willows (3-10 m high).

Upland vegetation consists of grasslands and coniferous, deciduous, and mixed forest. The grasslands are distinguished by the presence of bluebunch wheatgrass (Agropyron spicatum), needle grasses (Stipa sp.), bluegrasses (Poa sp.), milk-vetches (Astragalus sp.) and other forbs.

The closed coniferous forest is dominated by Douglas fir (P. menziesii), lodgepole pine (Pinus contorta), and, in low-lying areas, white spruce. Open coniferous forest is predominantly lodgepole pine with an understory of kinnikinnick (Arctostaphylos uva-ursi), grasses, and forbs. Trembling aspen (P. tremuloides) is present in both open and closed deciduous stands. The closed stands also contained minor alder (A. rubus) and willows. Mixed forest species included lodgepole pine, Douglas fir, and aspen with an understory of kinnickinnick, shrubs, grasses, and forbs.

3. DATA COLLECTION AND PREPARATION

3.1 Field Surveys

Panchromatic and colour aerial photographs, at scales ranging from 1:5000 to 1:20000, were acquired for each study area (Table 2). They were used to select representative study sites, typically between 5-10 km^2 in area, for the detailed surveys. The study sites were located on NTS 1:50,000 scale map sheets for planning site access. Within each site, polygons of homogeneous plant associations were delineated on mylar. The polygons were divided into two categories: larger polygons (>2 ha) were identified for use as training sites during the TM classifications while smaller (<2 ha) and more numerous polygons were reserved for accuracy assessment.

Plant cover characteristics for more than 900 polygons were recorded during two seasons: (i) late spring/early summer, 20 May to 15 June 1984 and (ii) late summer/early fall, 25 August to 16 September 1984. Two 2-man crews recorded plant species cover-abundance and stage of growth in each polygon, along with other relevant information (see Appendix 1). The polygons were selected to include a variety of wetland habitat types, including shallow open water, emergent vegetation, unvegetated areas, and upland vegetation. Also included were areas modified by man.

3.2 Aerial Photography

The 185 mm format photographs, taken between 1975 and 1982, were supplemented with 35 mm oblique photographs taken from a rented light aircraft at 250 m and 1000 m altitudes. Those photographs were taken during the dates of fieldwork given above.

3.3 TM Data

Wetlands are highly dynamic. Both short-term effects, (eg. tide, rainfall), and seasonal phenomena, (eg. spring snow-melt), affect wetland community patterns in TM images. Therefore, two sets of TM data were acquired for each study area to investigate seasonal change. Microfiche images of all spring, summer, and fall TM data collected over the three study areas in 1984 were examined for cloud cover and distribution. No fully cloud-free images were available so quadrants were chosen for minimal cloud cover over the areas of specific interest (Table 2). For the Fraser estuary, the limitation of low tide conditions was included in the image specification.

All TM data were purchased in digital format as computer compatible tapes (CCT's). Photographic products were later produced from those data for photo-interpretation purposes.

TABLE 2
Ground Survey Dates, TM Data, and Aerial Photography

WETLAND SYSTEM	FIELD SURVEY (1984)	NUMBER OF POLYGONS SURVEYED	TM ACQUISITION (1984)	AERIAL PHOTOGRAPHY
Estuarine	June 11-15	232	Jul 10	185mm. 1979, 1982 Vert., color. 1:12,000
	August 25-29	97	Aug 11	35mm. 1984, oblique color & FCIR
Riverine	May 21-29	416	Jun 12	185mm. 1982. color and B&W Vert. 1:20,000, 1:5,000
	September 1-6	158	Aug 15	35mm. 1984. oblique color & FCIR.
Palustrine	May 30 to June 07	256	Jul 17	185mm. 1975 Vertical, color. 1:15,000.
	September 12-16	120	Sep 19	35mm. 1984, oblique color & FCIR

3.4 TM Data Pre-Processing

All digital processing was conducted on an image analysis system comprising PCI software and Adage display hosted on a VAX 11/780 mini-computer (Tomlins 1985). For each study area, overview scenes and full resolution sub-scenes of the TM quadrant were loaded from a computer compatible tape (CCT) to the video monitor. The TM quadrant contained 3500 by 2944 pixels, while the video display resolution was 1024 by 1024 pixels. For overview scenes, only every fourth pixel and fourth line were displayed on the monitor.

The TM data were provided by the Canada Centre for Remote Sensing, a division of Energy, Mines and Resources Canada, on a research basis, since production facilities were not yet available for data correction in 1984. The displayed images were of poor radiometric quality; scan line faults and severe striping were present in each image. Those faults were corrected by standard image processing methods.

3.4.1 **Master Files:** For the Estuarine study area (11 August data), a sub-scene was selected to include the fresh water, brackish, and salt marshes of interest. Boundaries were chosen to provide image data 1024 by 1024 pixels in size. The coordinates of those pixels were referenced to the CCT data and a disk file was created containing six of the seven TM spectral bands. The thermal band, TM 6, was not used due to its relatively poor spatial resolution (120 m). Many wetland polygons described during the fieldwork were less than 100 m wide and, therefore, would not have been resolved by TM 6 data.

A second disk file containing 10 June data of the Estuarine study area was similarly created. The June data were registered to the August data by developing an n-order polynomial transformation on 22 ground control points. Residual root mean square (RMS) registration errors were less than 0.5 pixels and 0.5 lines. The TM data were not registered to the UTM grid due to problems with the rectification software. The data sets thus retained rotational and other geometric errors.

The master data file for the Estuarine study area was 1024 by 1024 pixels in size and contained co-registered data in six spectral bands for both the June and August images. An equivalent volume was reserved for storage results of processing, so that the file required approximately 24 megabytes of disk space. Master data files were created in the same way for the Palustrine and Riverine study areas. Those files were four times larger than that for the Estuarine study area (96 megabytes each) since area coverage in each was 3775 km^2, (2048 by 2048 pixels).

3.5 TM Images

3.5.1 Video Display Photography: Different 3-band combinations and results of digital enhancement were photographed from the display as 35 mm format colour slides. Selected display images were also photographed with 60 mm format film.

3.5.2 Optronics Imagery: An Optronics film-writer was used to prepare 185 mm format positive film transparencies from custom-enhanced digital TM data. For the Estuarine data, four colour composite images were prepared from TM bands 1, 2, and 3 (both dates), TM 2, 3, and 4 (August only), and TM 3, 4, and 5 (August only). Image colour assignment was blue, green, and red respectively. The 3-band feature set for the Riverine data was TM 3, 4, and 5 (August data), and, for the July 17 Palustrine data, a TM 2, 5, and 4 composite was produced.

4. METHODS

4.1 Preamble

Digital classification and visual interpretation methods were compared (see Figure 3). Digital classifications, in particular, provide potentially valuable products. They show the distribution of different wetland habitats and other cover types in an area, and can also provide areal coverage data for individual and total polygons. They are also in suitable format for integration with other geographic information in a computer-based, land information and management system. However, before classified TM data can gain acceptance as a source of management information, the benefits and constraints of their use must be demonstrated and standard processing methods adopted. Accordingly, much of our work involved a quantitative evaluation of the different methods available for classifying TM data.

There are two basic approaches to digital classification; the unsupervised and the supervised methods. A third option, semi-supervised classification, is a derivative of the unsupervised approach. There are also many parameters and processing strategies available that can significantly influence classification results (Table 3). The effect of each of those factors on unsupervised, supervised, and/or semi-supervised classification was investigated using TM data of the Estuarine system. Results were subsequently applied to data of the Palustrine and Riverine systems.

4.2 Basis for Comparing Classification Results

Classified results (themes) were compared with wetland polygon data collected during the fieldwork. For each habitat or cover type, a digital "accuracy overlay" was prepared which identified the locations and areal coverage of two or more polygons. Those overlays were spatially registered to TM data in the master file. Each accuracy overlay contained 30-700 pixels, depending on the area and frequency of occurrence of the habitat. By overlaying the classified themes with the accuracy overlays, quantitative estimates of accuracy were obtained in the following way:

Class Accuracy: percentage of pixels that were correctly classified relative to one accuracy overlay, not including unclassified pixels;

Overall Class Accuracy: percentage of pixels that were correctly classified relative to all accuracy overlays, not including unclassified pixels;

Total Accuracy: percentage of pixels that were correctly classified relative to all accuracy overlays, with unclassified pixels assumed incorrect.

FIGURE 3
Organization of the Research

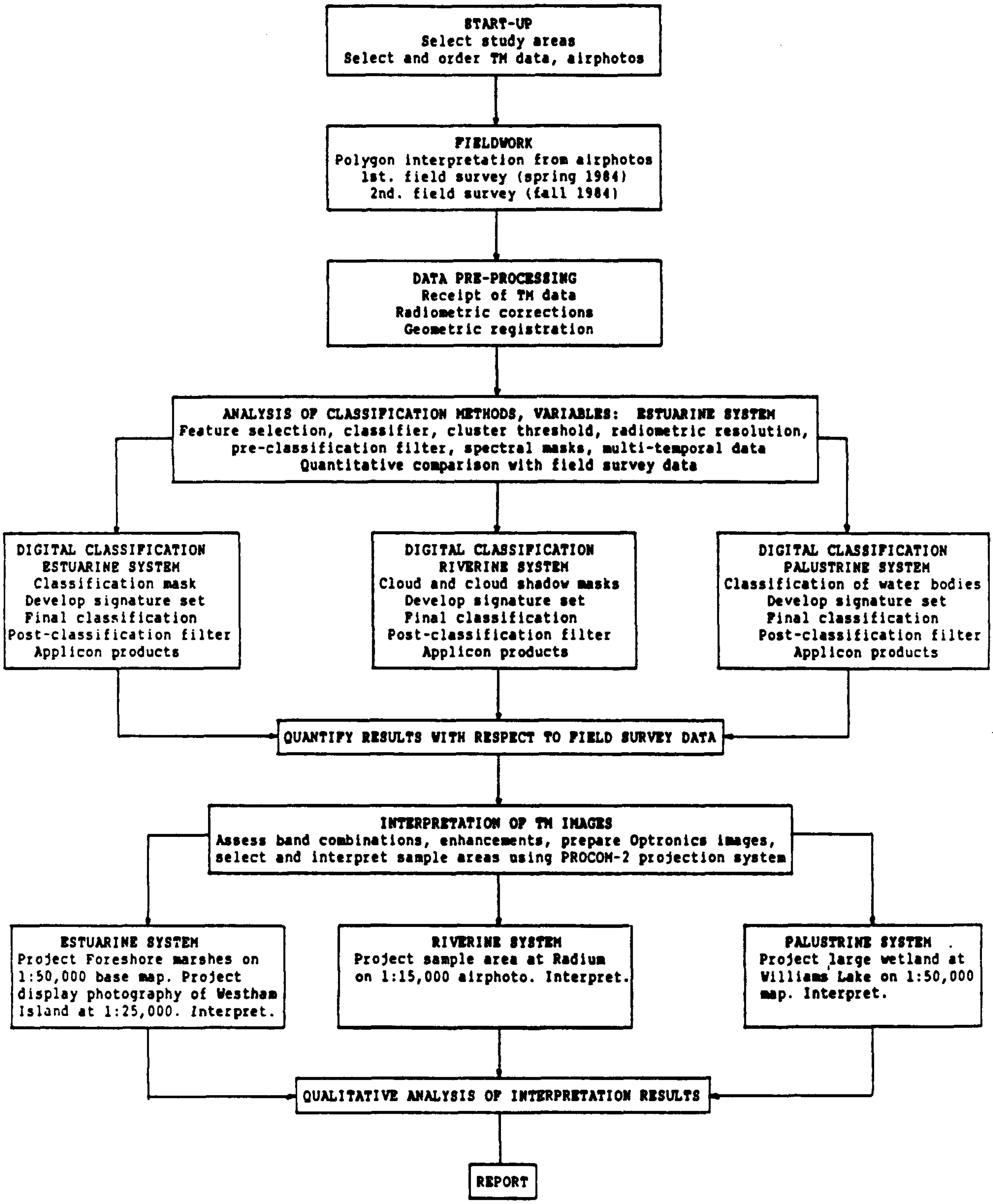


TABLE 3
Parameters and Processing Strategies that Influence Classification Results

PARAMETER	SUMMARY DESCRIPTION	APPLICATION U[1]	S-U[2]	S[3]	COMMENTS
Feature Set	Selection of image data on which classification is performed.	Y	Y	Y	May be original TM data, or pre-processed data (eg. TM bands, principal components).
Threshold Value	Defines limits to accept or reject classification of a pixel.	Y	Y	Y	High threshold values classify a greater proportion of total scene pixels.
Cluster Set or Signature Set	Selection of classification "keys" on which the classification is based.	Y	Y	Y	Each "key" defines a spectral pattern in 2 or more features.
Radiometric Resolution	Precision at which pixel clusters are defined.	Y	Y	N	Smooths the input data.
Pre-classification Filter	Application of a spatial filter to image data before classification.	Y	Y	Y	Smooths the input data, reducing spectral variance within a wetland polygon.
Multi-temporal Feature Set	Combination of selected features from 2 or more dates of imagery.	Y	Y	Y	Doubles (or triples..) the volume and cost of data. Shows differences between dates (plant phenology, water levels, etc.).
Post-classification Filter	Application of a spatial filter to classified result.	Y	Y	Y	Smooths the result, reducing the noisy appearrance caused by isolated pixels.
Cluster Mask	A spectrally-defined mask used to restrict clustering.	Y	Y	N	Clustering algorithm searches only for spectral patterns existing within the mask boundaries.
Classification Mask	A spatially-defined or spectrally-defined mask used to restrict classification.	Y	Y	Y	Classification is performed only on those pixels defined by the mask boundaries.

[1] - Unsupervised Classification
[2] - Semi-supervised Classification
[3] - Supervised Classification

4.2.1 **Theme, or Polygon, Combination:** Classified themes can range from the very general (eg. water versus land) to the very specific (eg. sedge meadow versus grass meadow) depending on the processing method and selected parameter values. Furthermore, themes resulting from unsupervised classifications are derived solely from analysis of TM spectral patterns. Those patterns may not correlate well with actual polygon data collected in the field. Comparisons between some classifications, therefore, required that individual themes and/or field polygons be combined.

4.2.2 **Accuracy and Level of Classification:** Very generalized themes, that are distinctive in TM bands, will normally report very high accuracy results when compared with merged field polygons. At higher levels of classification, more specifically defined themes are less easily differentiated by the TM, and accuracy decreases.

4.3 Selection of Feature Set

The fundamental variable in a digital classification is selection of the feature set (the number and composition of input TM bands or TM data-sets which have been prior-processed). A feature set analysis was performed using data of the Estuarine study area. Two techniques were investigated: correlation analysis and digital classification. First, 37 wetland polygons were located on the satellite image and the mean intensity of pixels in each spectral band determined. Inter-band correlations were calculated (SPSS-X, 1982). Secondly, 18 digital classifications were performed with different feature sets using supervised classification of an 8-theme classification system. The number of bands in those classifications ranged from three to six, and the composition of the different feature sets included both the raw TM data and principal component (PC) transformations (Fung and LeDrew 1987).

4.4 TM Classification of the Estuarine System

4.4.1 **Unsupervised clustering and classification:** Unsupervised clustering is the most automated, and the least subjective, of the classification methods. It was of particular interest because of its potential as an easily implemented standard method requiring minimum image processing expertise. A migrating-means clustering algorithm (Goldberg et al. 1975) was used to establish cluster centres of major spectral patterns in selected 4-band feature sets. Those values were submitted to one of two classifiers, the parallelepiped or the maximum likelihood classifier (Lillesand and Keiffer 1979).

The objectivity of the unsupervised method also made it the preferred technique for investigation of classification variables and processing strategy (Table 3). Multiple classifications were performed, keeping all variables constant other than the one under study. Those classifications were compared with each other and with the field survey data. Individual test objectives and methods are summarized in Table 4.

TABLE 4
Analysis of Classification Variables: Summary of Objectives and Methods

VARIABLE	OBJECTIVE	METHOD
Classification algorithm	Decide which classifier to use in subsequent work.	Parallelepiped versus maximum likelihood method.
Feature set	Select composition, and size, of feature set.	Inter-band correlation analysis on July and August data. Inter-image analysis. 18 digital classifications on selected feature sets.
Cluster threshold	Determine significance. Do large thresholds reduce class accuracies?	Compare 4 classifications (July data) at 3,5,7, and 9 standard deviations.
Size of cluster set.	Effect on level of classification and accuracy.	Comparison of 13 classifications on both the July and August data.
Radiometric resolution	Determine significance. Does reduced resolution change cluster set?	Compare 5 classifications (August data) at 5, 6, 7 and 8-bit resolution.
Pre-classification data-smoothing	Effect on level of classification and accuracy.	Average data variance using: (1) 3*3 mode filter, (2) 7-bit radiometric resolution, and (3) both. Compare classification results.
Multi-temporal feature sets.	Effect on level of classification and accuracy. Do data from 2 dates provide superior results than single-date data.	Combine July and August data into 6 separate 4-band feature sets. Classify on each, compare with result from single-date classification.
Clustering using Spectral Masks	Effect on level of classification and accuracy.	Comparison of classifications performed with, and without spectral masks.

4.4.2 Semi-Supervised Classification: Polygons of 16 wetland habitats surveyed during the fieldwork were identified on the TM image. The mean intensity of corresponding TM pixels for each polygon was determined in each of four TM bands. Those values were used to seed the clustering algorithm, at 6 and 7-bit radiometric resolutions. Classifications on those cluster sets were compared with results from the unsupervised method. Fourteen accuracy theme masks representing different wetland habitats were developed from the field survey data for accuracy assessment.

4.4.3 Supervised Training and Classification: A series of 14 supervised classifications was performed to examine whether this approach could discriminate wetland polygons at greater detail than the clustering method. Information from the previous work was used to guide processing methods and to set variable values.

Training sites and accuracy themes: Approximately 140 separate wetland polygons were mapped during the field surveys, of which as many as 48 were used to define the training sites for supervised classification. Most training sites comprised two or more polygons of the same cover type from disparate locations. Another 57 polygons representing 14 wetland habitats were used for accuracy assessment. The remaining field polygons were too small to be reliably identified on the TM image.

Classification Mask: A "classification mask" resulting from the unsupervised classification work was used in all classifications. TM pixels located outside of the area defined by that mask were excluded from the classification.

For verification of earlier results, classifications were conducted to investigate the significance of multi-temporal feature sets, signature threshold value, and the number and definition of signatures. Final products evaluated a post-classification mode filter for noise removal.

4.5 TM Classification of the Riverine System

Unsupervised, semi-supervised, and supervised classifications of TM data of the Riverine study area were compared. Results from the Estuary classifications were used for preliminary definition of parameter values and to guide processing strategy.

4.5.1 Differences between the Riverine and Estuarine Data: The Riverine data differed from the Estuarine data in two important ways. Firstly, the study area was four times the size of the Estuarine area, requiring a larger master file and much longer processing times. For efficiency, preliminary classifications were performed on a sub-scene of the master file containing 1024 by 1024 pixels (1/4 of total pixels). Accuracy evaluation was similarly restricted to that sub-scene. Having thus established classification parameters, a final classification was then performed on the entire scene. The second difference was the presence of extensive snow, ice, and cloud cover in both dates of the Riverine image. Attempts were made to eliminate the "snowpack-cloud" and associated "cloud-shadow" pixels using classification masks. Three methods were compared for generating masks: clustering, supervised training, and visual interpretation.

4.5.2 Unsupervised and Semi-Supervised Clustering: Unsupervised and semi-supervised classifications were performed on both the June and August data. The masks ensured clustering was limited only to those areas not affected by cloud. Trial classifications were performed at 5, 6, 7, and 8-bit resolution with and without pre-classification mode filtering.

4.5.3 Supervised Training and Classification: Four supervised classifications were performed on the 1024 by 1024 pixel sub-scene. Two of those classifications were performed using a TM 2, 3, 4, and 5 feature set from the August data. In the other two classifications, multi-date analysis was performed on data which had first been subjected to a principal component transformation. The effect of post-classification filtering using a 3 by 3 mode filter was also examined. Results from those classifications were then applied to the full study area. Classifications were restricted to areas not affected by snow, cloud, or cloud shadow.

Training sites and accuracy overlays: In the sub-scene used for preliminary classifications, 200 separate polygons had been described during fieldwork, many of which were very small. To ensure accurate representation in the TM data, a single-class classification was performed on each digitized polygon, and the result was visually examined. If the target theme appeared well classified, with few errors of omission, the polygon was saved for multi-class classification. If, however, the result omitted much of the target theme, an additional polygon was added and the classification repeated.

Fifty-seven of the original 200 polygons were used in the analysis: of those, 36 polygons were used to define training sites, leaving 21 polygons representing nine cover types for accuracy assessment.

4.6 TM Classification of the Palustrine System

4.6.1 Cloud and Cloud Shadow Problems: Cloud was present in both the July and September scenes of the Palustrine area. Both spectral classification and visual interpretation methods were investigated to develop "cloud" and "cloud shadow" masks. Because over 40% of the 19 September 1984 scene was affected by cloud or cloud shadow, multi-temporal classifications could not be performed. Further processing was restricted to the July data.

Open water bodies were very distinct in the displayed TM images. Small lakes and potholes are important habitat for aquatic birds. A more detailed analysis into the mapping of potholes and other water bodies using TM data was, therefore, performed on a 1024 by 1024 pixel sub-scene in the north-west of the study area, centered on Riske Creek.

4.6.2 Unsupervised Clustering, Full Study Area: A preliminary unsupervised classification of the July data was performed at 7-bit radiometric resolution on TM bands 2, 3, 4, and 5. Using the maximum likelihood classifier, with a cluster threshold of five SD's, nine themes were generated. Some of those themes were merged together into 6 spectral masks and secondary clustering was performed beneath each mask, generating a total of 41 separate clusters. Those were again submitted to the maximum likelihood classifier. Semi-supervised classifications were not performed.

4.6.3 Supervised Training and Classification, Full Study Area: Two supervised classifications for land cover themes were performed using the TM 2, 3, 4, and 5 feature set of the July data at signature thresholds of five SD's. Classification accuracies were estimated with and without post-classification mode filtering.

Training sites and accuracy theme masks: Although 250 polygons were ground surveyed, the small size and narrow width of emergent vegetation polygons severely limited the number of individual training sites available. Conversely, shallow open water and upland cover polygons were in abundance. In total, 91 separate polygons were digitized, each of which was individually classified using the TM 2, 3, 4, and 5 feature set at a signature threshold of three SD's. The results were visually examined and where satisfactory saved. Forty individual training sites were selected for multi-class classification. Accuracy evaluation was performed on 10 themes.

4.6.4 Classification of Water Bodies, Riske Creek Sub-Scene: Results from unsupervised clustering using a spectral mask, and from supervised training, were compared with NTS map-sheet 92 O15E. In addition, a visual interpretation for ponds and lakes was performed on the TM image displayed on the video monitor. A TM2 (blue), TM3 (green), and TM4 (red) colour composite was used for the interpretation.

4.7 Applicon Plots

Five Applicon ink-jet colour plots (60cm by 45cm) of the final supervised classifications for each study area, were prepared at scales ranging from 1:50,000 to 1:150,000. Another plot was prepared to illustrate differences in results from unsupervised, semi-supervised, and supervised classifications. A seventh plot showed the effect of post-classification filtering using a 3 by 3 and a 5 by 5 mode filter.

4.8 Interpretation of TM Images

4.8.1 Band Combination and Colour Assignment: There are 20 separate 3-band combinations that can be produced from six TM bands. Each combination can be colour coded in six different ways. If multi-temporal data are used, or if the data are ratioed or otherwise processed before producing film products, the possibilities for colour combination are infinite. The 35 mm format colour slides were used to compare and assess different 3-band combinations.

4.8.2 Enhancements: Raw TM data have low contrast, since sensor gains are established to image both very dark and very bright targets. Custom enhancements were created and the results
TABLE 9
photographed on the display. The enhancements investigated included linear and non-linear contrast stretch, band-ratio, and principal component combinations, and combinations of data from the two dates of imagery.

4.8.3 The Estuarine Study Area

In a sample area from Iona Island to Brunswick Point, foreshore and riverine marshes were interpreted at 1:50,000 scale from the four Optronics images using a PROCOM-2 image projection system. Major polygons evident in the projected image were delineated on a mylar overlay. A rectangular grid overlay was used to compare the interpretation with the airphoto polygons described during the field surveys.

Three 60 mm format transparencies photographed directly from the display were also interpreted using the PROCOM-2. Those slides showed Westham Island in three different combinations:

TM BANDS	COLOUR ASSIGNMENT	LABEL
1,2,3	blue, green, red	visible
3,5,4	blue, green, red	SWIR (short wave IR)
2,3,4	blue, green, red	FCIR (false colour IR)

Each slide was projected on a 1:25,000 base map and wetland polygons delineated onto mylar.

4.8.4 The Riverine Study Area: A sample sub-scene centred on the town of Radium Hot Springs was selected for image interpretation. The area was one of the study sites from which wetland cover had been interpreted using 1:15,000 scale aerial photography. The TM Optronics image (TM bands 3,5, and 4 at original scale 1:350,000) was enlarged more than 20 times to overlay the airphoto-derived polygons, and wetland polygons interpreted from that image were delineated on mylar.

4.8.5 The Palustrine Study Area: A large wetland on the Williams Lake Indian Reserve was projected from the Optronics image (TM 2, 5, and 4) onto a 1:50,000 scale base map. Polygon boundaries were drawn directly on the base map and compared with polygons mapped during the survey work.

5. RESULTS

Research results are presented in three formats. Analysis results from feature selection, and from other work related to classification variables, are summarized in mainly in graphic form (section 5.1). The final classification results for each study area are reported in tabular form (sections 5.2-5.4). Results of interpretation of TM images could not be quantified; subjective findings from that work are documented in section 5.5.

5.1 Classification Variables, Estuarine Data

5.1.1 **Feature Selection:** In the August data, high correlation was evident between the three visible bands (TM 1, 2, and 3), and also between the two short-wave infrared (SWIR) bands, TM5 and TM7. Visible and SWIR bands were poorly correlated, and TM4 showed no significant correlation with any other spectral band (Figure 4). Similar results were obtained for the July data. Multi-temporal results showed positive correlation between each TM band in each scene, with highest coefficients in the infrared bands TM 4, 5, and 7 (Figure 5).

Overall class accuracy marginally increased with expansion of the feature set (Figure 6), but total accuracy was adversely affected, as less of the image data were classified. The 4-band feature set of TM 2, 3, 4, and 5 achieved the highest overall class accuracy using the August data, and second highest in the July scene. That feature set also demonstrated a spike in the total accuracy trend at a similar amplitude to the 3-band feature sets.

Principal component (PC) classifications were less accurate than the original TM data (TM 2, 3, 4, and 5). Although the PC feature set required 20% less CPU time for classification, savings were more than offset by the labour and computing time required for the image transformation.

Following the above, all subsequent classifications were performed using TM bands 2, 3, 4, and 5.

5.1.2 **Unsupervised Clustering:** Because of the problems of comparing dissimilar themes and polygons (section 4.2.1), early classifications were simply evaluated on the basis of differentiating between wetland and upland cover.

Classification algorithm: With all other variables held constant, the parallelepiped method classified 21.3% more pixels than did the maximum likelihood method. However, wetland themes from the parallelepiped algorithm consistently overlapped upland areas. The maximum likelihood classifier was, therefore, used in all subsequent work.

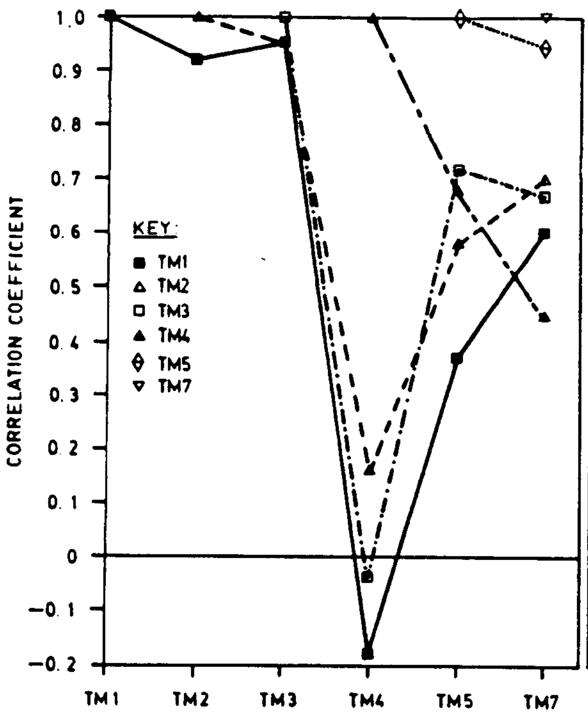


FIGURE 4
Correlation Between TM Bands
August 11 Data

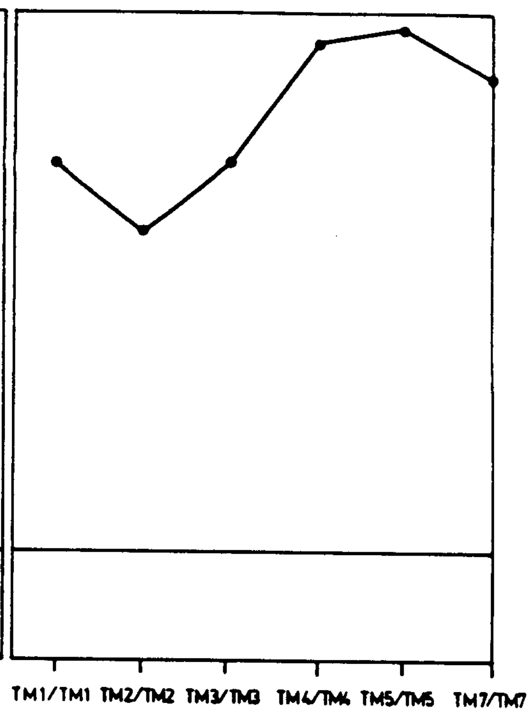


FIGURE 5
TM Band Correlation Between
July 10 and August 11 Data

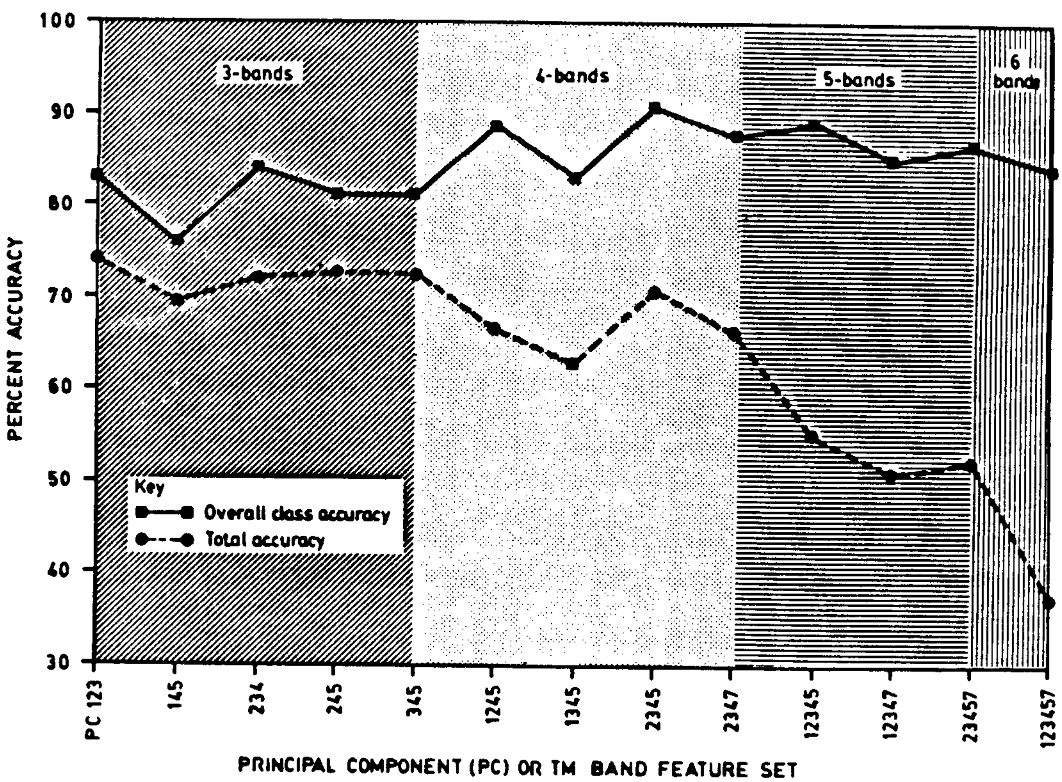


FIGURE 6
Classification Analysis for Feature Selection
(Results from 18 digital classifications of the Estuarine data. August normalized to the July results.)

Effect of cluster threshold value: An increase in threshold value from 3 to 9 SD's caused a 10% improvement in total pixels classified (Figure 7). There was a similar increase in total accuracy (86-95%), despite a slight reduction in overall class accuracy (97-96%).

Radiometric resolution for clustering: A reduction in radiometric resolution from 8-bits to 7-bits (128 gray levels) increased classification accuracies by 8-12% (Figure 8). Further reductions in radiometric resolution degraded the classification. The 7-bit resolution was, therefore, used in subsequent clustering analyses.

5.1.3 **Unsupervised Clustering Using Spectral Masks:** Spectral masks were prepared by pre-classifying the July image into five generalized themes. Two of those themes represented almost all of the tidal flat-low marsh and intertidal marsh communities in the study area. They also had similar, low radiance values in each of the TM bands. They were merged together into a "low radiance" spectral mask. A third theme, representing the distribution of "high marsh-upland grassland" areas, was labelled the "high radiance" spectral mask. Those two masks together represented both the spatial and spectral distribution of almost all wetland polygons in the study area, although the "high radiance" mask was contaminated by parkland, agricultural fields, and other upland areas.

Spectral masks improved the number of clusters found by the migrating means algorithm. They generated themes representing ground cover at much greater detail than classifications performed without the masks.

Size of the cluster set: Overall class accuracies of 94-97% were reported for a 2-theme classification, using five to eight clusters. When the search range for clustering was restricted by spectral masks, similar classifications provided between 10 and 17 themes. Some of those themes were merged together for comparison with the distribution of seven wetland polygon types. At that improved level of classification, overall class accuracies ranged from 76-83% (Figure 9). Also, since larger cluster sets classified more of the TM data, omission errors were reduced, and total accuracy figures approached overall class accuracy results.

Pre-classification smoothing of TM data: Size of the cluster set was also affected by smoothing the TM data prior to classification (Figure 10). Reducing radiometric resolution from 8-bit to 7-bit data caused two additional clusters to be found and it improved total and overall class accuracies by about 6-8%. Data smoothing using a mode filter also improved accuracies by 1-3%. However, when the two smoothing operations were combined, classification accuracies suffered.

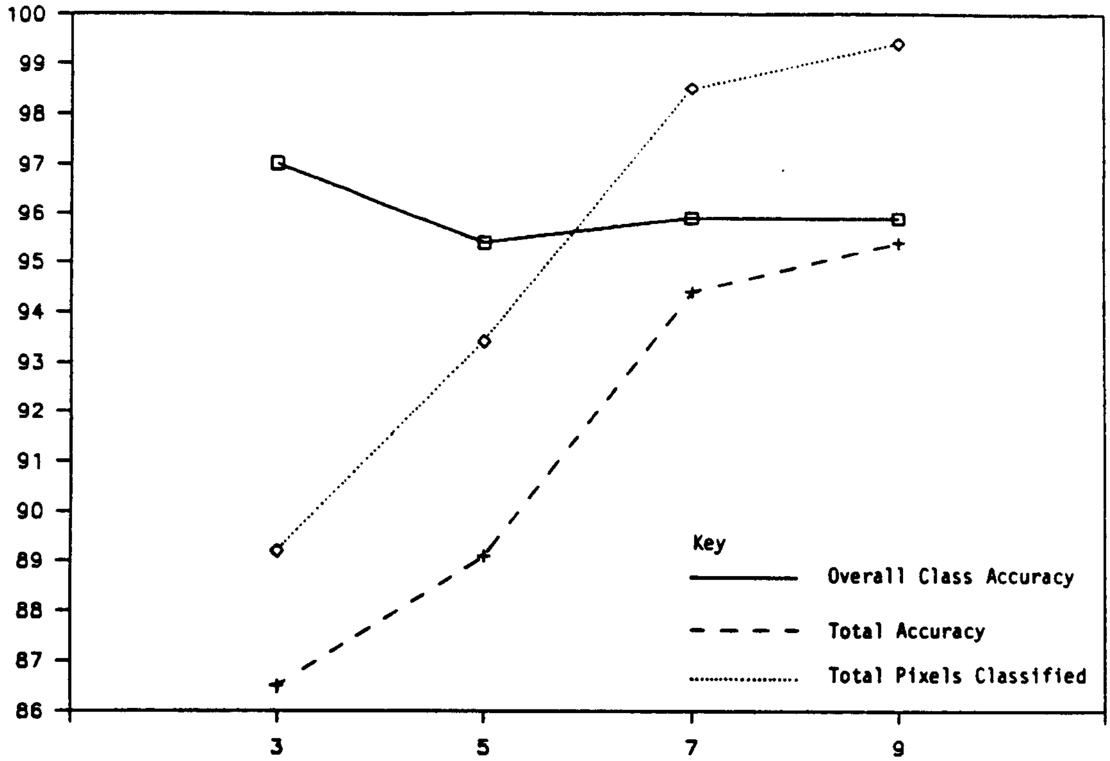


FIGURE 7
Effect of Cluster Threshold Value on the Accuracy of Unsupervised Classifications, Estuarine System

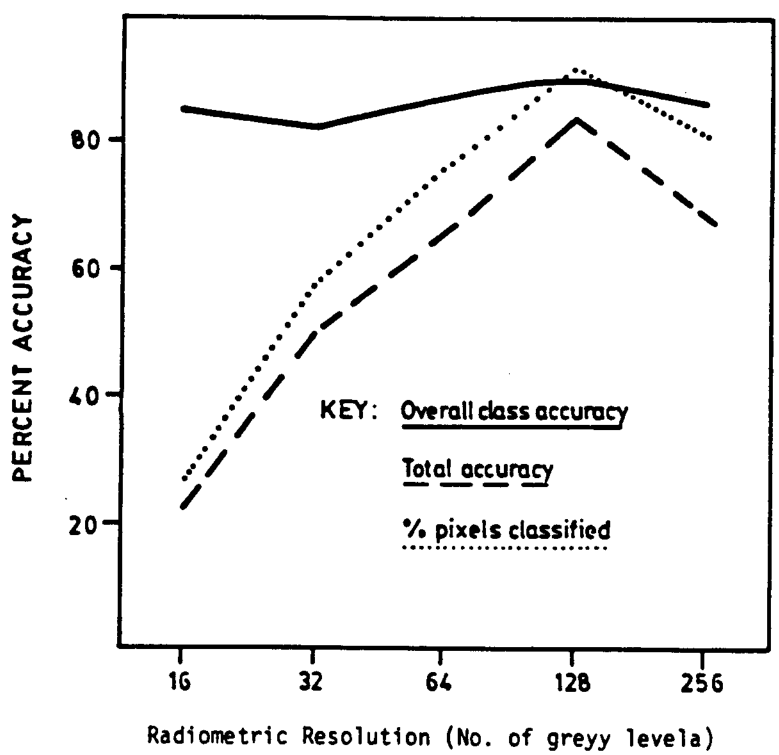


FIGURE 8
Effect of Radiometric Resolution on Histogram Clustering

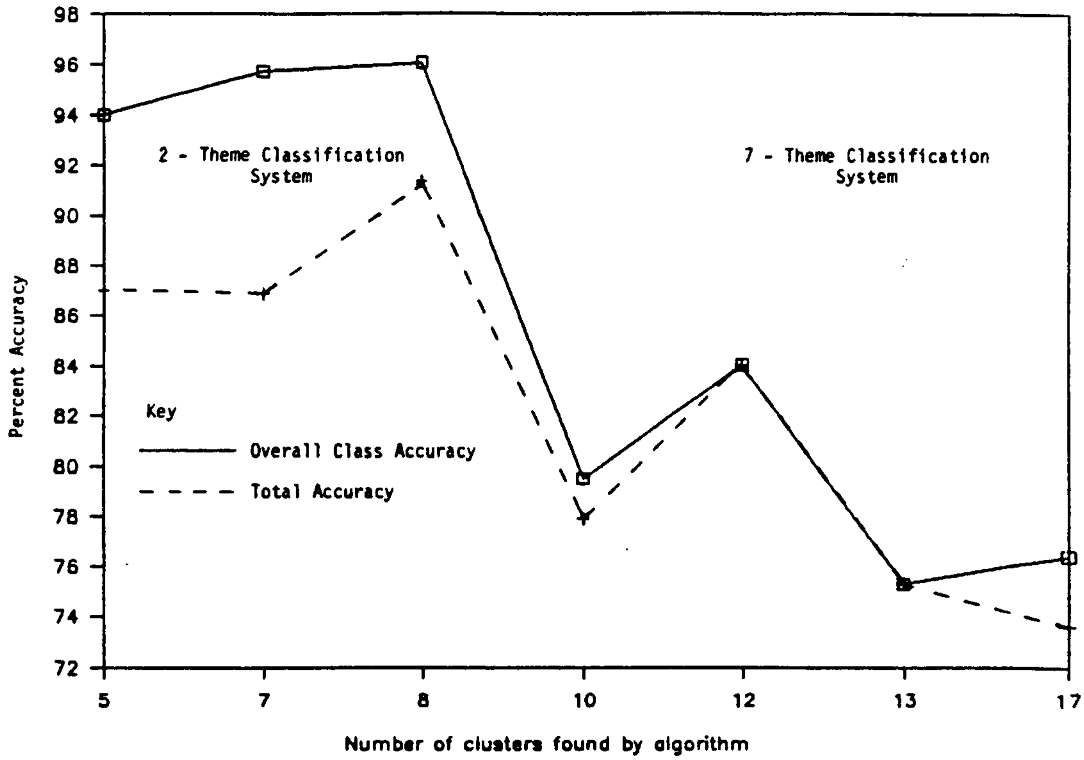


FIGURE 9
Effect of the Size of Cluster Set on the Accuracy of Unsupervised Classifications, Estuarine System

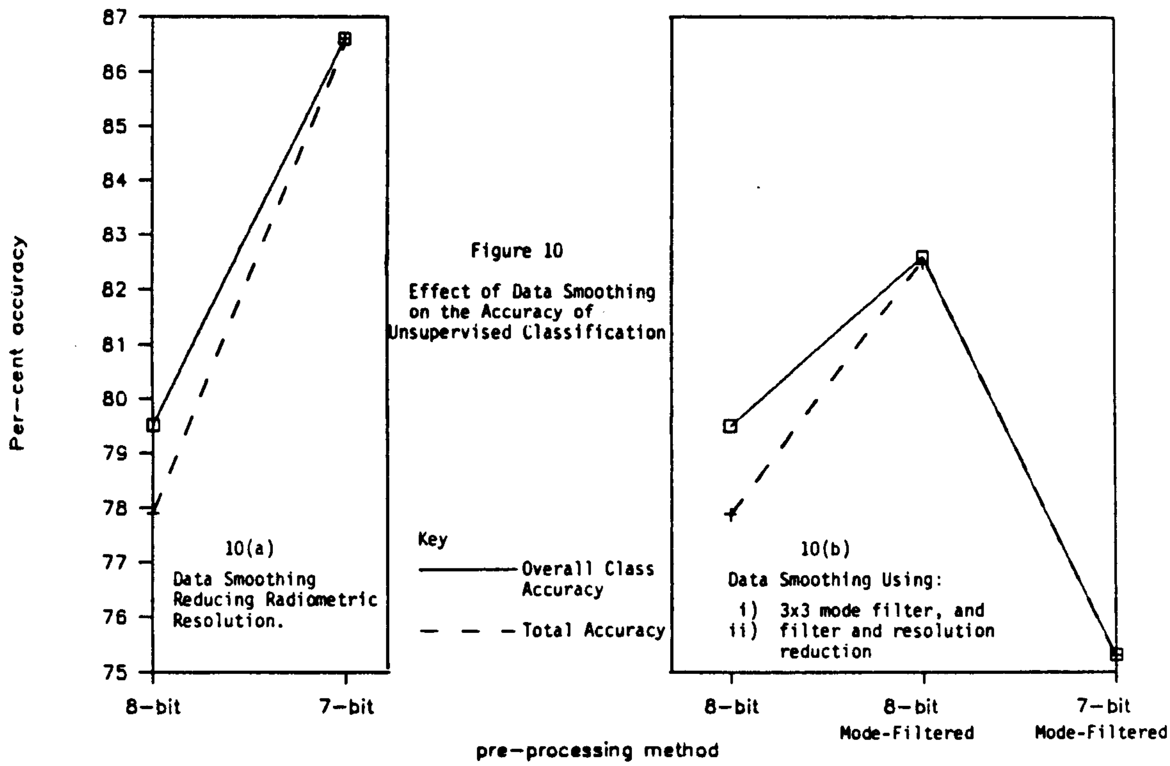


FIGURE 10
Effect of Data Smoothing on the Accuracy of Unsupervised Classification

Clustering using multi-temporal feature sets: No benefit was apparent for combining the July and August data (Figure 11). Only one of the multi-temporal feature sets provided better classification accuracy for eelgrass than the August data alone, and the difference between those was small. Not only are TM data costs doubled for multi-temporal analysis, but increased time and computer resources are required for geographic registration of the two data sets.

5.1.4 Semi-Supervised Classification

Results of semi-supervised and unsupervised classifications are compared in Table 5. Despite the initial seeding, considerable cluster movement away from the seeded values occurred. Following maximum likelihood classification, the themes were inconsistent with the seeded cover types, with the exceptions of eelgrass and salt-marsh cover. The 14 accuracy theme masks had to be merged into seven more generalized masks. Although accuracy results were generally lower than those from the unsupervised method, seven distinct themes were discriminated using semi-supervised clustering, three more than by unsupervised clustering. The semi-supervised method was not, however, capable of classifying the image at the desired species or species-association level of classification.

TABLE 5
Comparison Between Unsupervised and Semi-Supervised Clustering, Estuarine Data

RADIOMETRIC RESOLUTION	CLASSIFICATION METHOD	NO. OF CLUSTERS	NO. OF WETLAND THEMES	OVERALL CLASS ACCURACY	TOTAL ACCURACY %
7-bit	Unsupervised	9	4	90.9	80.3
7-bit	Semi-supervised	14	7	86.0	75.9
6-bit	Unsupervised	11	4	89.5	88.3
6-bit	Semi-supervised	15	7	85.1	81.1

5.2 Final Classifications, Estuarine System

The results of seven preliminary supervised classifications confirmed earlier findings that TM data of a single date provided better classifications than did combining data from two different dates (Figure 12). However, those results also demonstrated the importance of the image date. The August results were far superior to those obtained from the July data.

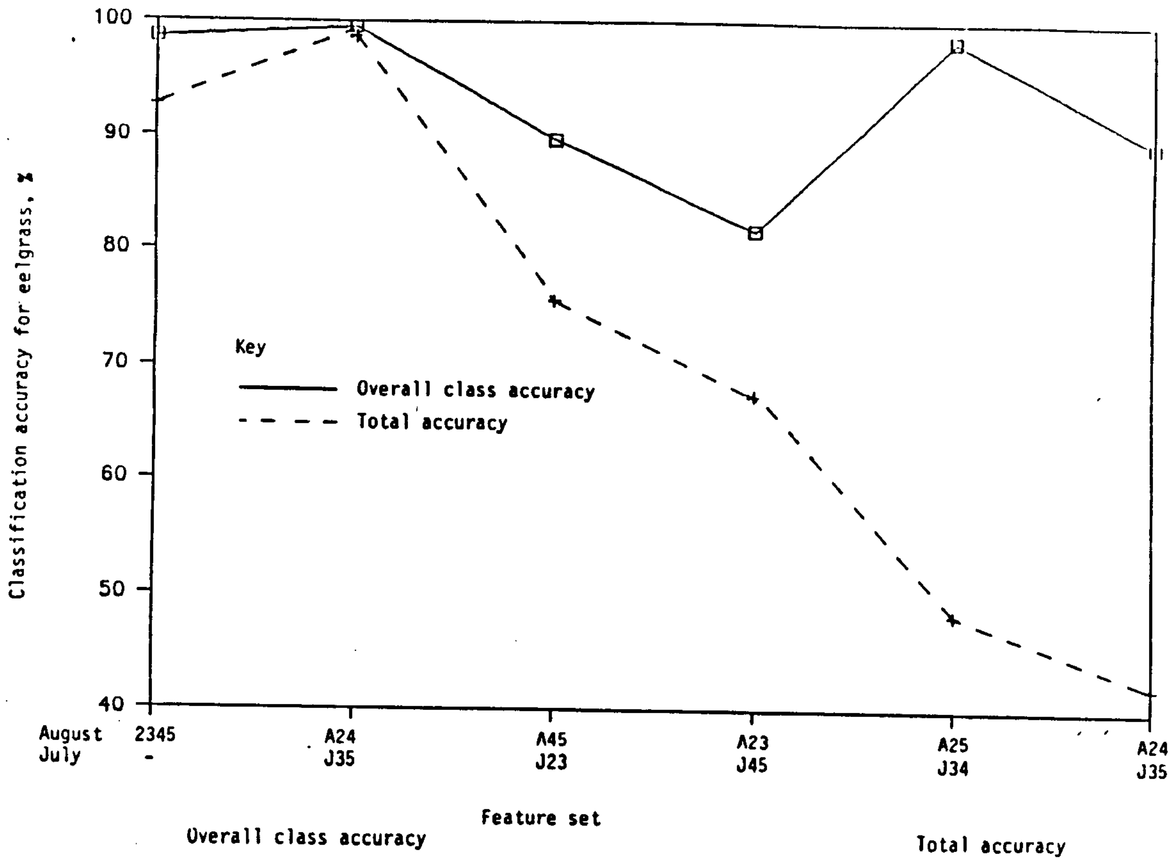


FIGURE 11
Accuracy of Classification of Eeelgrass (Zostera sp.) with Multi-Temporal Feature Sets Unsupervised Clustering, Estuarine System

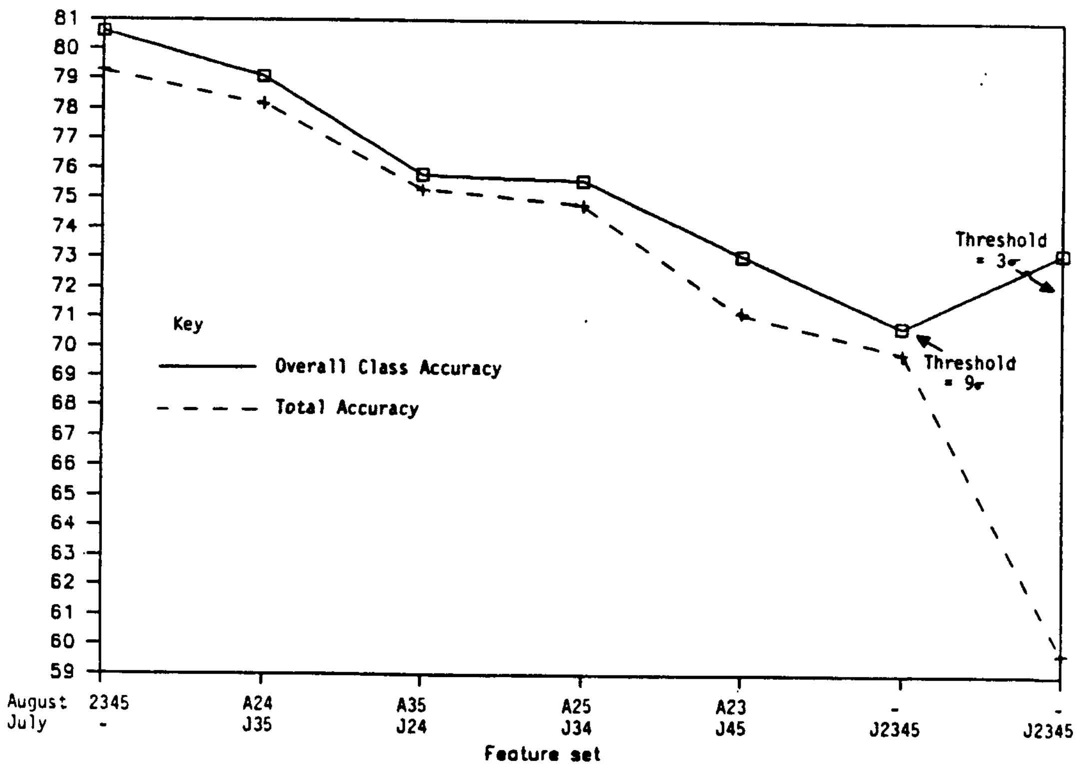


FIGURE 12
Accuracy of Multi-Temporal Feature Sets Supervised Classification, Estuarine System

All results suffered errors of commission, (ie. classified pixels for which no corresponding signature was used). That is shown for the July data (TM 2, 3, 4, and 5) by an increase in overall class accuracy when signature thresholds were reduced to three SD's. Those findings indicated that additional signatures were needed to reduce commission errors and thus increase total accuracy, while maintaining high levels of class accuracy.

Expansion of the signature training set: Examination of the classified themes showed that large areas of mudflats and some salt-marshes were left unclassified at three SD thresholds. Also, areas of woodland, heathland, peat cuttings and berry cultivation on Burns Bog were poorly classified. Additional signatures were developed and added to the 14-theme training set used previously. The final signature set totaled 30 signatures. Classifications were performed on those at threshold values from three to five SD's. Post-classification mode filtering was performed on the best of the results.

Final classifications were performed on the August data (TM 2, 3, 4, and 5 feature set). Total accuracy improved from 67.4% to 74.0% by increasing signature threshold to five SD's. That was consistent with an increase in total pixels classified (as defined by the classification mask) from 82.7% to 94.0%. There was no decline in overall class accuracy; it remained almost constant between 81.5% and 81.8%.

The post-classification mode filter improved the appearance of the final result by removing the noise (isolated pixels). The filter also improved the quantitative accuracy results; overall class accuracy increased to 85.4%, and total accuracy increased to 75.9%. Note that the accuracy of individual themes varied considerably (Table 6), ranging from 17.9% (Driftwood) to 98.9% (Zostera sp.).

5.3 Final Classifications, Riverine System

5.3.1 Elimination of Snowpack, Cloud, and Cloud Shadow Pixels: Both supervised training and clustering methods were tried without success to define masks for the elimination of snowpack, cloud, and cloud shadow pixels. Neither "cloud" nor "cloud shadow" could be accurately defined as spectral themes since the intensity values of those pixels varied with cloud density. The themes suffered either from large areas of omission (not enough classified) or from commission errors in which urban and other bright targets were confused with the cloud canopy. Low intensity areas, primarily water bodies, were confused with the "cloud shadow" theme.

The ice, snow, cloud, and cloud shadow areas were finally masked out using visual interpretation techniques. Full-resolution sub-scenes (1024 by 1024 pixels) were sequentially displayed on the video monitor and the cursor used to delineate the observed boundary of the snowpack, cloud, and cloud shadow canopy. In that way, a spatial mask defining snowpack, cloud, and cloud shadow pixels was constructed and loaded to the master file.

TABLE 6
Training Sites and Final Classification Results, Estuarine System
(Also shows merged polygons for 7-theme accuracy evaluation)

	DOMINANT GROUND COVER OF TRAINING SITE AND PERCENT COVER	NO. PIXELS TRAINING SITE	NO. PIXELS ACCURACY OVERLAY	AREA CLASSIFIED HA	CLASS ACCURACY %	ACCURACY OVERLAYS USED IN CLUSTERING TESTS
1	Mudflat, unvegetated	245	692	819	86.7	1 and 2 merged
2	Sandflat	201	184	1829	70.6	
3	Mudflat, saturated	429	-	3555	-	
4	Driftwood	91	162	452	17.9	yes
5	Vegetated mudflat, discontinuous *Ulva* sp.	155	-	581	-	
6	vegetated mudflat, filamentous algae	432	-	328	-	
7	*Scirpus americanus*, < 10%	270	621	663	87.4	7,8,10,11, and 12
8	*S. americanus*, 60-90%	207	245	419	86.9	merged
9	Transition, *S.americanus-S.maritimus*	622	-	936	-	
10	*S.maritimus-Triglochin maritimum-Puccinella* sp., 30-50%	347	480	186	88.3	
11	*S.lacustris*,45%	47	86	162	73.3	
12	*C.lyngbyei*, *Typha latifolia*, many minor sp., 90-95%	207	401	309	69.1	
13	*T.latifolia*, 60-100%	89	127	281	64.6	yes
14	*C.lyngbyei*, minor *T.maritimum*, *J.balticus*, 80-90%	58	-	204	-	
15	*Juncus effusus*-grass sp. 80-90%	90	108	800	49.1	15,17, and 18
16	Grass sp.-*J.effusus*, 80-90%	35	-	313	-	merged
17	*C.lyngbyei-Agrostis alba-Potentilla pacifica*, 95%	213	115	161	72.2	
18	*Triglochin maritimum*, *P.pacifica*,*E.palustris*, other sp., 100%	27	34	159	76.5	
19	*Distichlis* spp., 80-90%	230	380	165	94.2	yes
20	*Salicornia* sp., minor *Distichlis* sp. 80-90%	121	-	204	-	
21	*Zostera marina-Z.japonica*, 60-100%	290	618	488	98.9	yes
22	*Z.marina-Z.japonica*/cloud shadow	137	-	2728	-	
23	Upland barren area	267	-	191	-	
24	Peat cuttings, Burns bog	656	-	148	-	
25	Peat cuttings, Burns bog	657	-	295	-	
26	Heathland, Burns Bog	1248	-	368	-	
27	Woodland, Burns Bog	396	-	622	-	
28	Woodland, Burns Bog	232	-	122	-	
29	Berry cultivation, Burns Bog	940	-	513	-	
30	Open water	393	-	1236	-	

Overall class accuracy = 85.4% Total accuracy = 82.1%

5.3.2 Unsupervised and Semi-Supervised Classifications: No satisfactory results were obtained from the clustering method. In unsupervised classifications coniferous forest themes appeared in the Columbia River floodplain, while wetland areas appeared on upland slopes. In the semi-supervised classifications, cluster seeds often migrated away from the theme of interest. Quantitative accuracy evaluations were not performed because of the obvious errors.

Within-class spectral variability was the probable cause of the poor clustering results. In standing water bodies, for example, large fluctuations in water level gave rise to ponds ranging in depth from a few centimeters to one or more meters. They had sandy bottoms or were choked with floating or submerged vegetation. That diversity caused very high spectral variance in the TM data. The frequency of occurrence of many of the spectral patterns was insufficient for the clustering algorithm to work satisfactorily.

5.3.3 Training Sites and Accuracy Theme Overlays: Many themes were represented by more than one spectral signature to account for within-class spectral variation. Therefore, 33 separate signatures representing 16 themes were submitted to the classifier.

5.3.4 Supervised Classification: The multi-temporal feature set (PC 1, 2, 3) provided inferior results to classifications performed on the August data only (Table 7). That was consistent with findings reported earlier. Also substantiating the more detailed work on the Estuarine data, application of a post-classification mode filter increased classification accuracy. The best classification was obtained using a feature set of TM 2, 3, 4, 5 from the August data and applying a 3 by 3 mode filter to the result.

TABLE 7
Effect of Multi-Date Feature Set and Mode Filter Riverine System

FEATURE SET	IMAGE DATE DD-MM-YY	POST-CLASSIFICATION MODE FILTER	OVERALL CLASS ACCURACY %	TOTAL ACCURACY %
TM 2,3,4,5	15-08-84	none	88.4	87.5
TM 2,3,4,5	15-08-84	3*3	92.5	92.2
PC1,PC2,PC3	12-06-84 15-08-84	none	86.6	84.4
PC1,PC2,PC3	12-06-84 15-08-84	3*3	90.9	90.2

The final classification on the full 2048 by 2048 pixels in the data was performed using the parameters given above (Table 8). Accuracy estimates are assumed the same as for the 1024 by 1024 pixels sub-scene.

5.4 Final Classifications, Palustrine System

5.4.1 Elimination of Cloud and Cloud Shadow Pixels: Too many small clouds were distributed throughout the July 17 1984 scene for elimination by the visual interpretation method. Instead, five training sites representing different densities of cloud and cloud shadow were created for submission to subsequent multi-class classifications. Though not estimated in the final results (Table 9), residual confusion between clouds and urban areas, and between cloud shadow and open water, was evident. That supported the findings in the Riverine study area that cloud and cloud shadow pixels could not be entirely masked using TM spectral differences alone.

5.4.2 Unsupervised Classification: As had previously been found with the Estuarine and Riverine data, classification results could not easily be related to ground polygons. Certain themes were easily recognized as standing or permanently flowing water. Twelve separate themes were included within logged areas, and there was considerable confusion between regenerating clearcuts, agricultural fields, and vegetated wetland communities. Quantitative accuracy evaluations were not performed.

5.4.3 Supervised Training and Classification, Full Study Area: Training sites were developed for 18 themes (Table 9) and accuracy overlays for 10 of those. Results for total and overall class accuracy were identical, indicating optimum selection of signature set and threshold. Accuracies improved from 80-85% by application of a 3 by 3 post-classification mode-filter (Table 9). Individual class accuracies ranged from 5.5% (sedge fen, meadow) to 99.2% (mixed forest). Water themes ranged from 61.3% to 92.6%, with almost all of the errors due to misclassification between the four water themes.

Note that vegetated wetland cover was described in only one theme "sedge fen-meadow", and at 5.5% class accuracy, that theme was of no real value. Twelve training sites were initially developed for sedge, bulrush, and cattail marsh-fens, shrub-fens, shrub-carrs and wet meadows. Single-class classification of those provided very poor results. The bulrush and cattail marshes showed severe confusion with dry grasslands, urban, and other bare ground, possibly because of extensive dead biomass cover at the time of the satellite overpass. Shrub-dominated wetlands could not be separated from shrub-dominated logged areas, and the wet meadows also showed confusion with sedge fens, agricultural areas, and regenerating logged areas.

TABLE 8
Training Sites and Final Classification Results, Riverine System

	DOMINANT GROUND COVER OF TRAINING SITE AND PERCENT COVER	NO. OF SIGNATURES USED AND PIXEL COUNT FOR EACH NO.	MIN.	MAX.	NO. ACCURACY PIXELS	AREA CLASSIFIED HA	CLASS ACCURACY %
1	Clear water (Open & flowing), 0.2 to 4 m	4	50	301	525	5,170	96.8
2	Open water, submerged aquatic vegetation	2	41	75	-	244	52.4
3	Open water, emergent vegetation	3	20	82	42	605	-
4	Open water, floating vegetation	3	79	90	472	1,172	83.9
5	*Equisetum* marsh	2	41	130	107	1,498	73.8
6	*Carex* marsh/fen	2	32	43	46	1,013	93.5
7	Grassland, unimproved	2	42	140	-	2,828	-
8	Improved pasture, agriculture	5	48	540	399	7,833	99.5
9	Shrub thicket	1	45	45	19	4,389	0.0
10	Unvegetated land	2	45	64	-	615	-
11	Urban	2	36	141	-	879	-
12	Regenerating logged areas	1	67	67	-	6,069	-
13	Deciduous forest	1	46	46	242	3,699	93.8
14	Mixed deciduous-coniferous forest	1	116	116	-	11,505	-
15	Immature coniferous forest	1	39	39	399	4,221	87.3
16	Mature coniferous forest	1	231	231	-	18,493	-

Overall class accuracy = 92.5%   Total accuracy = 92.2%

TABLE 9
Training Sites and Final Classification Results, Palustrine System

	DOMINANT GROUND COVER OF TRAINING SITE AND PERCENT COVER	NO. OF SIGNATURES USED AND PIXEL COUNT FOR EACH NO.	MIN.	MAX.	NO. ACCURACY PIXELS	AREA CLASSIFIED HA	CLASS ACCURACY %
1	Open water, clear	3	119	703	724	3,197	78.6
2	Open water, marl	1	709	709	-	379	-
3	Open water, submerged/emergent aquatic vegetation	3	233	714	568	843	61.3
4	Permanently flowing water	2	123	720	1176	1,034	92.6
5	Open grassland, rangeland	5	26	374	2812	36,583	97.1
6	Recent clearcut	1	145	145	-	18,377	-
7	Regenerating clearcut	3	204	720	2512	68,167	81.9
8	Deciduous forest and shrub	1	38	38	-	6,022	-
9	Mixed coniferous-deciduous forest	1	215	215	1424	17,050	99.2
10	Open forest, selectively logged	1	720	720	-	43,949	-
11	Lodgepole pine forest	3	102	557	180	37,177	71.1
12	Douglas fir forest	3	720	720	-	90,490	-
13	Pasture and farmland	3	56	60	340	6,425	80.0
14	Sedge fen, meadow	2	31	159	360	10,927	5.5
15	Unvegetated (gravel, clay)	2	123	164	-	3,590	-
16	Urban	4	720	720	208	12,756	48.0
17	Cloud	4	119	720	-	14,646	-
18	Cloud shadow	1	720	720	-	5,136	-

Overall class accuracy = 85.2%   Total accuracy = 85.0%

5.4.4 **Classification of Water Bodies:** Digital classification of TM data is an accurate method for mapping bodies of open water that have minimum areas of 5 ha (Table 10). Classification accuracy falls off rapidly for smaller ponds. Visual interpretation techniques can be successfully used to identify ponds as small as 2.5 ha and if there is a-priori knowledge of the presence of a pond, TM interpretation methods could be used to monitor lakes as small as 1 ha.

TABLE 10
Inventory of Ponds and Lakes Using TM Data, Riske Creek Sub-Scene

	NUMBER OF LAKES IN THE MAP AND IMAGE AREA				
LAKE SURFACE AREA FROM MAP, (HA)	**MAP**	**UNSUPERVISED CLASSN. TM 2,3,4,5**	**SUPERVISED CLASSN. TM 2,3,4,5**	**INTERPRETATION OF TM 2,3,4 COMPOSITE**	
				Mapping	Monitoring*
< 1 ha	17	3	3	10	13
1.0 - 2.5	25	12	13	22	24
2.5 - 5.0	18	15	16	18	18
5.0 - 10.0	3	3	3	3	3
> 10 ha	7	7	7	7	7
Totals	70	40	42	60	65

* For monitoring, interpreter requires knowledge that a lake is, or was present. Interpretation would be very difficult for mapping purposes.

Some areas identified as water bodies by digital classification were not evident on the map. Many were misclassified pixels, such as "cloud shadow" or "north-west slope" pixels. However, 34 areas classified as lakes by the TM data (but which were not present on the map), were also interpreted as lakes by visual methods. Some of those lakes were adjacent to agricultural fields and may have been created for irrigation needs.

5.5 Interpretation of TM Images

5.5.1 **Band Selection and Colour Combination:** Some guidance to band selection for wetland interpretation was provided by the feature selection results, which concluded that 3-band composites should be produced from TM4, TM5, and one of the visible bands. Colour assignment (blue, green, red) to each band is largely subjective, depending on overall experience and personal preference. Our experience was that two combinations were of particular value:

VEGETATED WETLANDS	PONDS, LAKES AND COASTAL FORESHORE MARSHES
TM2 or TM3 .. blue	TM2 .... blue
TM5 .... green	TM3 .... green
TM4 .... red	TM4 .... red

5.5.2 **Enhancements:** Multi-temporal composites, ratioed data, and principal component transformations required extensive digital processing and were time-consuming and expensive. The linear contrast-stretch technique applied to single-date imagery was found to be simple to apply and effective at enhancing colour hues. That enhancement was applied to data of the three study areas before Optronics image production.

5.5.3 **The Estuarine Study Area:** Numerical accuracy results from interpretation of the Optronics imagery were very poor, although subjectively the TM interpretation appeared very satisfactory. The problem was mainly the relatively small sample size, compounded by differences in mapping scale. The numerous small polygons (<1 ha) interpreted from the airphotos were not evident in the TM image and the "incorrect" interpretation of those polygons biased the analysis. Also, boundaries of the TM and airphoto polygons were often dissimilar because of the different dates of image acquisition. Further attempts at quantifying interpretation accuracy were abandoned in favour of a subjective assessment of TM imagery for wetland interpretation.

Using the 60 mm transparency, the projected image overlaid the base map without evident registration, showing that simple photography from the display monitor can be used for interpretation. The visible composite (TM 1, 2, and 3) was best for delineating mudflats, sandbars, and Scirpus marshes, but higher marsh and meadow communities could not be differentiated. The SWIR composite (TM 3, 5, and 4) provided the opposite results, with good contrast between high marsh and meadow communities. The lower Scirpus sp. marshes, however, were very dark, and could not be differentiated from the unvegetated mudflats. The FCIR composite (TM 2, 3, and 4) was a good compromise in this type of wetland environment. High marsh and meadow communities were almost identical to the polygons described using the SWIR image. A broad band of S.maritimus on the foreshore of Westham Island was differentiated from the lowermost S.americanus stands, although less easily, and presumably with less accuracy, than with the visible composite. The main detraction of the FCIR image was the lack of a clear boundary between the ocean and saturated, unvegetated, tidal flat areas.

5.5.4 **The Riverine Study Area:** The pattern of the Columbia River as interpreted from the TM image very accurately overlaid the pattern delineated from the airphoto, despite the Optronics image having been enlarged more than 20 times. Ponds with at least 1 ha surface area were easily and accurately interpreted, and water lily cover was easily identified on larger (eg. 10 ha) ponds. Excellent interpretation results were also obtained for unvegetated areas of the floodplain, and for residential and commercial, industrial, agricultural, upland forest, and grassland classes. The smaller sedge marshes and meadow areas were less easy to interpret since image hues were not consistent. Emergent shrub-carr cover appeared as a different hue to other cover types but showed considerable variation, making interpretation difficult. Denser and tall shrub-thicket cover could not be differentiated from the deciduous forest bordering the Columbia River.

5.5.5 **The Palustrine Study Area:** Emergent wetland polygons interpreted from TM data showed little correspondence with the airphoto polygons. At the scale used (1:50,000), wetland vegetation communities on the Reserve appeared in various and intermixed hues of red which could not easily be interpreted.

Upland classes, including logged areas, grasslands, agricultural fields, and urban areas were easily discriminated, and although individual marsh, meadow, and shrub-carr polygons within the Reserve could not be mapped, the wetland as a land unit was very easily delineated.

6. DISCUSSION

6.1 Classification Method

In all three study areas, supervised classification provided superior results. Classes generated by this method were at similar level of detail as the wetland polygons delineated from airphotos. Overall classification accuracies were high, ranging from 85% in the Estuarine and Palustrine systems to 92% in the Riverine System. The unsupervised method was successful at simple discrimination between wetland and upland land cover, or for separating wetlands into a few major zones (eg. water, foreshore marshes, high marsh communities). Results from the semi-supervised method were unpredictable because of cluster migration from seeded values. The main value of clustering was to separate the image into spectral masks, certain of which were then combined into a spatial mask used to limit supervised classification.

6.2 Classification Variables

Of the variables investigated, the most significant was the feature set. The TM 2, 3, 4, and 5 feature set was used in final TM classifications for each wetland system. Other workers have found that set to provide results equal to, or superior to those derived from all seven TM bands (Donoghue and Shennan 1987, Atkinson et al. 1985). We found no benefit in using larger feature sets, multi-temporal feature sets, or performing the classification on transformed data (principal component).

Other significant steps were (1) training sites selected, (2) signature threshold value, and (3) post-classification filtering. We found that training sites were required for each different pattern discernable on the displayed TM image. When insufficient training sites were used, classification accuracies suffered.

Signature threshold value mainly affected the proportion of TM pixels classified. Once we had established sufficient training sites, the threshold was iteratively expanded until total accuracy approached, or equalled, overall class accuracy.

Post-classification mode filtering cleaned up the final result by elimination of noise. The filtered result also improved quantitative accuracy results. That was probably due to the manner in which accuracy was evaluated, since the comparative data (airphoto polygons) ignored small and isolated cover differences within the polygon.

6.3 Individual Class Accuracies

In each study area, wide differences in individual class accuracies were found. Large and homogeneous plant communities, ponds, and lakes were very well classified. In each system, classification accuracies of those were:

ESTUARINE:		RIVERINE:		PALUSTRINE:	
Mudflat	87%	Water	97%	Water	79%
Sandbars	71%	*Equisetum* marsh	74%		
Eelgrass	99%	*Carex* marsh	94%		
S. americanus	87%				
Distichlis spp.	94%				

Whenever small communities occurred, and in complex transition zones, the classification was poor. Since small (1-5 ha) polygons have a high proportion of mixed pixels along their boundary, their spectral reflectance is heterogeneous, and TM signatures are imprecise. Poor signatures also result from heterogeneous plant communities. Similar findings have recently been reported by Gross *et al*. (1987) and by Lacy and Jensen (1987).

High total and overall class accuracies were obtained. In the Estuarine system, where accuracies were quantified using wetland polygons only, overall class accuracy (85%) fairly reflected the range of individual class accuracies (49%-99%). In the Riverine system, overall accuracies also considered agricultural and forested upland cover, but four of the six wetland themes had individual class accuracies exceeding 70%. In the Palustrine system, the only wetland polygons that were well classified were ponds, lakes, and rivers. In that system, the reported results were biased by consideration of six upland themes.

Results from the Palustrine system demonstrated the spatial limitation of TM data for classifying small wetland units. On the other hand, those results also demonstrated the high value of the TM for mapping ponds and lakes having a surface area of 5 ha or more. Water strongly absorbs near infrared and shortwave infrared radiation. Zero or very low reflectance in TM bands 4, 5, or 7 thus indicates the presence of water. When combined with characteristic reflectance patterns in the visible bands, digital processing of TM data classifies the presence of water at accuracies approaching 100%. The lower accuracy figures reported in Tables 8 and 9 are due to our attempt to distinguish between different water types. Misclassified pixels were between water classes, rather than between water and land cover classes. One organization that has recognized the high value of TM data for mapping and monitoring water bodies is Ducks Unlimited. In early work which led to their current TM wetland mapping program for the northern prairie, TM digital classification methods provided 99.9% accuracy for open water (Hill 1985).

6.4 Image Date

Wetland mapping using TM data was very sensitive to image acquisition date. In the Palustrine system, for example, we observed more visible contrast between plant communities of the large wetland at Williams Lake Indian Reserve in the September data than in the July scene. Unfortunately, the extensive and dispersed cloud cover in the September data precluded its classification. Image acquisition date is extremely important in terms of both plant phenology and water level. Ducks Unlimited found that wetland vegetation growing in dry basins in late summer was very difficult to separate, using the TM, from agricultural areas or other dense vegetation (Koelne et. al. 1986). Use of spring imagery, when the basins contain water, would provide their accurate classification as wetlands. Unfortunately, cloud cover is more common during spring than in summer, but as the TM database expands, so too does the probability of finding cloud-free data.

6.5 Interpretation Products

We found no single best TM combination for wetland interpretation. The TM 1, 2, and 3 (as blue, green, and red) colour composite was similar to natural colour and simple to interpret. That was the best product for delineating tidal flats in the Estuarine system but vegetation contrast was poor. Maximum vegetation contrast was provided by the TM 3, 5, and 4 composite, but Scirpus marshes appeared similar to unvegetated mudflats. The false colour infra-red composite (TM 2, 3, and 4) was a good compromise in this system.

In the Palustrine and Riverine systems, composites containing one band each from the visible, near infrared, and short-wave infrared regions provided best discrimination between emergent wetland types. In the Riverine system, a TM 3, 5, and 4 composite was used: in the Palustrine system, a TM 2, 5, and 4 composite gave slightly superior contrast. Those same composites were found superior for vegetation studies by Atkinson et al. (1985), Thomson et al. (1985) and others.

Linear contrast stretch techniques were favoured over non-linear methods. Resulting enhancements were predictable and consistent. There was no danger of saturation of bright or dark targets.

Principal component enhancements, band-ratioed products, and composites produced from multi-date data were compared. Those enhancements often improved contrast between emergent wetland communities. However, considerable computer processing time was required and they were difficult to interpret.

6.6 Classification Versus Interpretation

Because of time constraints, we were unable to interpret any of the study areas in total. Sample areas were selected instead. Ease of interpretation depended on the image product used and on the type, areal extent, and dispersion of wetland cover. In the Riverine system, where wetland polygons are adjacent to each other along the floodplain, interpretation gave superior results when compared with digital classification. In the Estuarine system, interpretation was also expected to provide good results because of the large, continuous, and homogeneous nature of many wetland polygons.

However, visual contrast was poor between the lower *Scirpus* marshes and neighboring mudflats and image-to-film production reduced contrast even further. Because of those effects, interpretation results suffered. In the Palustrine system, interpretation was difficult because of the wide dispersion of ponds, lakes, and marshes throughout the study area.

7 CONCLUSIONS

7.1 Wetland Mapping

The TM is a valuable source of data for wetland mapping at scales of 1:50,000 or smaller, by digital or photo-interpretation methods. Within a wetland complex, mapping success depends on the area and homogeneity of individual polygons, and the spectral contrast between them. Water exhibits high contrast compared to vegetation or other neighboring cover, and ponds greater than 5 ha can be mapped by digital methods. Interpretation methods can also be used to map smaller ponds. Spectral contrast between other wetland components depends on size, plant/cover homogeneity, and phenology. Visual interpretation provides superior within-complex mapping capability.

The main limitation of the TM for mapping is spatial resolution, firstly with respect to small polygons and complex plant associations, and secondly as it affects perimeter pixels. Pixels on the perimeter of a polygon have mixed reflectance, and digital classifications of those pixels are often incorrect. Perimeter pixels also affect area measurement accuracies, since up to 80% of pixels in a 1 ha polygon may be on the perimeter. In contrast, polygons greater than 10 ha area have less than 20% of pixels located on the perimeter.

7.2 Wetland Inventories

The TM is a valuable source of inventory data, particularly for ponds and lakes. Digital classification of water bodies is simple, fast, and accurate providing cloud is absent from the scene. Lake surface area measurement constraints are as identified in the previous section. Digital classification is appropriate for large area inventories. In smaller study areas (250 km^2 or less) interpretation of TM photographic images is more efficient.

7.3 Wetland Monitoring

Since TM data are available on a regular basis, they are well-suited for monitoring applications. Given the existence of a base thematic map, image overlay methods can be used to highlight areas of change. Overlay can be performed digitally, in which case subtraction or ratio techniques can be used to display changes. Photographic products can be overlaid by the projection method, and interpretation of changes performed.

The comments made in sections 7.2 and 7.3 apply to TM monitoring applications. The stage of growth and dominance of species changes with season, and from year to year. In small and complex plant communities, the TM will not provide the needed spatial resolution. In large and homogeneous communities such as the eelgrass beds of the Estuarine system and the *Equisetum* and *Carex* marshes of the Riverine system the TM could provide information about significant changes in area cover.

Monitoring of water bodies may prove the most valuable role of TM data in wetland applications. The TM could provide pond and lake surface area information both across seasons and across years, as well as information on the distribution of water bodies. Spring distribution and surface area data are of importance to adult nesting waterfowl, whilst summer season data are important for brood pairs.

7.4 Digital Classification or Interpretation

We conclude that interpretation methods are best suited for detailed wetland mapping in complex wetland environments such as the Riverine system, or for polygon delineation in relatively small areas, less than 250 km^2. Large area wetland mapping, particularly for the enumeration, mapping, or monitoring of ponds and lakes, should be performed digitally.

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APPENDIX - 1

LANDSAT 5 WETLAND ASSESSMENT STUDY

WETLAND/UPLAND INVENTORY

WETLAND __ UPLAND __

Study Area Identification ____________________ File # ________

Observer ________________________________ Date __________

Location ____

Easting __________ Northing __________ Elevation (m) ______

Airphoto # ____________ Ground Photos # __________________

Notes on Access ____

____

Other Comments ____

____

____

____

Guidenotes

1. Changes observed in field relative to airphoto data to be sketched on mylar overlay.
2. Class: General descriptor at Level 1: e.g. Forest, Water, Emergent wetland, Transitional.
3. Sub-Class: General descriptor: e.g. Deciduous, Running Water, Sedge, Shrub.
4. Dimensions of polygons to be approximate - visual assessment.
5. Species cover and height to be approximate.
6. Homogeneity of dominant spp. to describe continuity as continuous or discontinuous.
7. Stage of growth as dormant, seedlings, mature, flowering, senascing.
8. Plant characteristics as vertical, leaning (angle?), prostrate.
9. Substrate nature as organic, silt/mud, sand, gravel, rocky, other (describe).
10. Average water depth to be given when small variations, e.g. shallow lakes. Range to be given for high depth variance, e.g. river.
11. Water clarity. Use secchi disc.
12. Land use or change: Describe modification to natural, steady-state land cover, human-induced (e.g. haying, logging, grazing) or natural (e.g. beaver-dam, bura, wild ungulate activity).
13. Comments: specific observations not described above, and/or expansion of above observations.

APPENDIX - 2

	POLYGON ___	POLYGON ___	POLYGON ___	POLYGON ___	POLYGON ___
CLASS					
SUB-CLASS					
APPROX. DIMENSIONS (meters)					
SLOPE (Upland)					
ASPECT (Upland)					
(1) DOMINANT SPECIES % Cover Height (m) Stage of Growth					
(2) SPECIES % Cover Height (m) Stage of Growth					
(3) SPECIES % Cover Height (m) Stage of Growth					
(4) MINOR SPECIES % Cover Height (m) Stage of Growth					
HOMOGENEITY OF DOM. SPP.					
PLANT CHARACTERISTICS					
SUBSTRATE NATURE					
SUBSTRATE EXPOSURE (%)					
AV. WATER DEPTH OR RANGE (m)					
WATER CLARITY (m)					
WATER CONDUCTIVITY (μ moles)					
WATER pH					
LAND USE OR CHANGE					
GROUND PHOTO #					
COMMENTS					