Final Report

Project No. WETLANDS2-EPA-06

REMOTELY MONITORING GREAT LAKES COASTAL WETLANDS USING A HYBRID RADAR AND MULTI-SPECTRAL SENSOR APPROACH

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1.0 Introduction

The focus of this project was to merge the capabilities of microwave (radar) and optical sensors to optimize satellite-based remote mapping and monitoring of coastal wetlands in the Great Lakes. The main goals were to develop techniques and demonstrate approaches to; (1) determine change over time in wetlands and adjacent uplands; (2) map extent of flooding in forested wetlands; and (3) merge Landsat and radar for improved wetland mapping capabilities.

Wetlands have historically been one of the most difficult ecosystems to classify using remotely sensed data. This difficulty is partially due to the high variability in wetland morphology. Wetlands can exist in many shapes and sizes, from open wet areas with sparse vegetative cover to densely forested areas with seasonal flooding. Vegetative cover ranges from low herbaceous, to shrubby, to forest. Synthetic Aperture Radar (SAR) and multispectral sensors complement each other in the classification of wetland ecosystems. Multispectral data can provide information on cover type and wetness information in open canopied ecosystems while SAR can provide flood condition and extent of flooding of forests and other closed canopy ecosystems. Another unique quality of SAR data is that it is an active system and thus is acquired independent of solar illumination and cloud cover. The fact that SAR penetrates cloud cover allows the data to be collected during specific conditions, this is especially important for seasonally flooded wetlands or tidally influenced wetlands.

Since the presence of standing water interacts with the SAR wavelengths differently depending on the dominant vegetation type, it is best to combine SAR data with optical and infrared data for vegetation mapping. A technique was developed to merge Landsat, JERS and Radarsat or ERS data for the mapping of Great Lakes coastal wetlands. By monitoring the wetlands over time with these sensors, one can determine change in wetland condition, change in landuse and adjacent habitat and produce indicators of wetland health (SOLEC indicators: Water Level Fluctuations 4861, Habitat Adjacent to Coastal Wetlands 7055, Nearshore Landuse Intensity 8132, Area Quality and Protection of Special Lakeshore Communitites 8129, Extent and Quality of Nearshore Natural Landcover 8136).

In this project, the approach developed for mapping land cover/ land use and wetlands as well as observing change varied by site. This variation was primarily due to the data availability and types of wetlands found at each test site. By analyzing a variety of data scenarios, we were able to develop more than one favorable approach for creating the various wetland products. When possible each approach was repeated at a second site to check for robustness of each approach. The main goals were to develop an optimum methodology for mapping coastal wetlands, extent of flooding, and monitoring change using medium resolution remote sensing, while keeping production costs minimal.

2.0 Site Selection

The criteria for site selection were to establish a diverse set of sites that included: (1) coniferous wetlands, hardwood bottomland forests, emergent wetlands, and boreal wetlands (Upper Peninsula), and (2) wetlands within urban areas and rural areas. These criteria allow us demonstrate the robustness of the mapping capabilities by choosing a variety of site conditions. We also chose sites where existing *in situ* data existed and/or sites that were the focus of ongoing studies (Table 1).

The Mackinac, Leelenau and Upper Peninsula (UP) sites all represent mostly rural to residential areas with some vineyards and orchards. Large areas of coniferous forested wetlands exist here along with some herbaceous wetlands. Lake St. Clair is a fairly large lake that forms as the St. Clair River travels between the Great lakes of Lake Huron and Lake Erie. The lake is bordered on the west by the State of Michigan and on the east by Ontario, Canada. This study site was chosen because it has a diverse selection of land cover including a large amount of urban and suburban areas, rural farm fields, and a large amount of wetlands (various species) that occur at the delta as the river enters the lake.

The Lake Ontario study site is located along the eastern shore in upstate New York. The study site is concentrated on the area between the lake shore and the Tug Hill Plateau (around the city of Watertown). This area was chosen because it is mainly rural, has isolated patches of vegetative wetlands, and has a relatively large amount of potentially forested wetlands. The Lake Ontario site is also mostly rural with lots of agriculture, but more emergent wetlands than forested. The Saginaw Bay study area is similar but was put on hold because there were only data available from JERS from the spring (March) of 1995 when the ground was wet from snowmelt such that all forests appear bright. The Lake St. Clair test site also only had JERS data available from March when the ground was wet from snowmelt and August when the ground was dry. However, at this site the JERS data were found useful in delineating marshlands with high biomass levels (especially *Typha* and *Phragmites).*

Table 1. List of test sites, general descriptions and investigators.

Test Site	General Description	Investigators
Leelanau Peninsula to tip of Lower MI and north into the Upper Peninsula	Area mostly rural to residential with vineyards/orchards A mix of coniferous forested and emergent wetlands.	Dennis Albert - wooded dune and swale sampling along the GL coasts. Don Uzarski -GLCWC Investigator
Saginaw Bay-Thumb area (*analysis put on hold)*	Emergent wetland, wet prairie and some forested wetland, lots of agriculture	Don Uzarski-GLCWC Investigator
Lake St. Clair	Urban area. Deciduous swamp and coastal marsh	Site visited by GDAIS staff in October 2003 Dennis Albert
Lake Ontario, near Watertown New York	Mostly emergent wetlands, some forested. Agriculture.	Marci Meixler, Cornell Univ. has ongoing studies in the wetlands, with detailed ground truth. Biocomplexity study--Mark Bain GLCWC Investigator.

3.0 Remote Sensing Data

3.1 Unique Nature of Sensors

The two types of sensors that were utilized in this study collect different information, yet this information is complimentary for land cover and, in particular, wetland identification. The Landsat sensor is an optical sensor that collects from the "blue" region of the spectrum through the thermal infrared region. It is a passive sensor, thus it collects the reflected/re-reradiated energy that comes from the earth's surface. The Landsat sensor is positioned such that it always collects in the nadir (straight down) position. This sensor was designed for vegetation applications and thus is able to effectively differentiate man-made features from natural features, as well as separate numerous vegetation groups, based solely upon spectral information. In this study, the seasonal dynamics (phenological cycle) are important in separating species groups that may have a similar spectral response on a single date.

In contrast, radars are active sensors that always collect at an angle off nadir. The active system creates its own energy field (microwave) and propagates that energy towards the target and collects the amount that is reflected back to the sensor. This microwave energy is sensitive to the dielectric constant which is unique to the material being imaged. One of the largest contributors to the dielectric constant is the amount of moisture in a material. Synthetic Aperture Radar (SAR) systems always operate at an angle and that incidence angle can vary by sensor (see 3.2 Radar Data Specifications). This off-nadir operation allows for biomass and structural aspects of the target material to be collected (such as roughness and stem density). Thus, the radar system allows for information to be collected that compliments the purely nadir, optical imagery of the Landsat imagery. Any classification system created to merge information from these two sensors needs to maintain and utilize their unique differences.

3.2 Radar Data Specifications

The JERS (L-band) sensor used for this project had Horizontal send and receive polarization and was operational from 1992-8. This sensor has a resolution of 30 m, incidence angle of 35º, and a footprint of 80 km x 80 km. To compliment these data, we also acquired some C-band (5.7 cm wavelength) radar data from the European ERS-1 and Canadian Radarsat satellites. The ERS-1 sensor has Vertical send and receive polarization and is collected at a central incidence angle of 23º. The Radarsat sensor has Horizontal send and receive polarizations. It also had pointing capabilities and can be collected in various modes and incidence angles. The data we received were of standard beam 7 mode, which has an incidence angle of 47º. Both C-band sensors have 30 m resolution and 100 km x 100 km footprints.

Three of the study areas around the Great Lakes were from a single track of the satellites, Mackinac, Leelenau and the UP. A list of all data obtained by site appears in

Table 2. For each date we also obtained climatological data from the National Climatic Data Center and Lake Water Level from the NOAA/NOS web site (National Water Level Observation Network data).

We also received two Envisat scenes from spring 2004. One from Lake St. Clair and the other from Mackinac. Unfortunately, these data arrived too late to be of use in the full analyses, but we conducted initial observations.

All of the radar imagery was georeferenced to the Landsat data. Both image data sets and all products covering Michigan are in the Oblique Mercator hotine projection with the GRS1980 spheroid and the NAD83 datum. This corresponds to the NWI data downloaded from the State of Michigan. All New York data sets were georeferenced to the UTM projection to correspond to NWI downloaded from the state of NY. The UTM data sets were georeferenced with the WGS84 datum and spheroid.

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Table 2. List of sites and Radar data obtained to map wetlands. Lake Levels are taken from the Mackinac City site (45º 46.7 N 84º 43.2 W), St. Clair Shores Site (42º 28.4N 82º 52.8 W), and Oswego, NY (43º 27.8 N 76º 30.7 W). Units are meters relative to IGLD.

Site	Sensor	Image Date (time GMT)	Weather	Lake Water Level
Leelenau Mackinac UP	JERS-1 L-HH	3 Nov 92 16:26	> 1" rain on 11/2	176.55 m
Leelenau Mackinac UP	JERS-1 L-HH	7 Sep 93 16:25	1/10 " rain	176.83 m
Leelenau Mackinac UP	JERS-1 L-HH	21 Oct 93 16:24		176.78 m
Leelenau Mackinac UP	JERS-1 L-HH	15 Apr 94 16:22	raining/ not frozen	176.67 m
Mackinac	ERS-1 C-VV	6 Sep 93 16:30		176.83
Mackinac	Envisat C-VV and C-HH	4 May 04 16:03		
Leelenau Mackinac UP	ERS-1 C-VV	13 Apr 94 16:30		176.63 m
Watertown, Lk Ontario	JERS-1 L-HH	11 Apr 93 15:49		75.35 m
Watertown, Lk Ontario	JERS-1 L-HH	8 July 93 15:49		75.28 m
Watertown, Lk Ontario	JERS-1 L-HH	17 Oct 93 15:49		74.58 m
Watertown, Lk Ontario	ERS-1 C-VV	17 Apr 93 15:53		75.46
Watertown, Lk Ontario	ERS-1 C-VV	7 Jun 93 15:50		75.49
Watertown, Lk Ontario	ERS-1 C-VV	25 Oct 93 15:50		74.56
Lake St. Clair	JERS-1 L-HH	28 Mar 95 16:16		175.17 m
Lake St. Clair	JERS-1 L-HH	10 Aug 98 16:30		175.52
Lake St. Clair	Radarsat S-7 C-HH	3 Oct 98 11:27		175.30 m
Lake St. Clair	Radarsat S-7 C-HH	27 Oct 98 11:27		175.11 m
Lake St. Clair	ERS-2 C-VV	4 Oct 98 16:16		175.31 m
Lake St. Clair	Envisat C-VV and C-HH	25 Apr 04 15:46		

3.3 Landsat Data Acquisitions

Potential Landsat change pairs were searched from the EOSAT archives, the University of Maryland ESDI site (free data), and from the Canadian Center of Remote Sensing web site (free data) to meet our criteria. Scenes representing seasons of varying lake water levels as well as leaf-on and leaf-off acquisitions within the same year were sought. It was attempted to find acquisitions coincident with the earlier radar data. However only one study site yielded a cloud free scene for these criteria (Lake Ontario). Each of the six study sites fall at the intersection of two Landsat rows, therefore, scenes were ordered with a 40% shift to the south so that only one image per study site was needed (Table 3). In addition, NALC triplicates for each Landsat path/row were acquired for $45 a dataset. This allows for comparison of NWI (mid-1970's) to Landsat MSS from the mid- 1970's.

Table 3. List of Landsat scenes acquired by study site with sources noted.

STUDY SITE	LANDSAT SCENES	SOURCES	
Upper Peninsula:	Path 22 Row 28		
	August 7, 1988	TM5	ESDI
	August 3, 2001	ETM+	ESDI
	July 11, 1974	MSS	NALC
	June 26, 1975	MSS	NALC
	June 28, 1985	MSS	NALC
	July 15, 1991	MSS	NALC
Mackinac:	Path 22 Row 28		
	August 7, 1988	TM5	ESDI
	August 3, 2001	ETM+	ESDI
	July 11, 1974	MSS	NALC
	June 26, 1975	MSS	NALC
	June 28, 1985	MSS	NALC
	July 15, 1991	MSS	NALC
Leelanau:	Path 22 Row 29		
	August 7, 1988	TM5	ESDI
	August 3, 2001	ETM+	ESDI

Study Site	Landsat Scenes	Sources
June 9, 1973	MSS NALC	
	June 10, 1973	MSS NALC
	June 28, 1985	MSS NALC
	July 15, 1991	MSS NALC
Saginaw:	Path 20 Row 29 and Path 20 Row 30	
	No Landsat Thematic Mapper data selected yet.	
	Path 20 Row 29:	
	July 31, 1975	MSS NALC
	August 8, 1975	MSS NALC
	August 20, 1986	MSS NALC
	August 20, 1992	MSS NALC
	Path 20 Row 30:	
	July 31, 1975	MSS NALC
	August 8, 1975	MSS NALC
	August 20, 1986	MSS NALC
	Sept 5, 1992	MSS NALC
Lake Ontario:	Path 16 Row 29 and Path 16 Row 30	
	June 24, 1993	TM USGS
	August 12, 2002	ETM+ USGS
	Dec 18, 2002	ETM+ USGS
	Path 16 Row 29:	
	August 19, 1972	MSS NALC
	July 23, 1986	MSS NALC
	August 3, 1990	MSS NALC
	Path 16 Row 30:	
	July 22, 1974	MSS NALC
	July 23, 1986	MSS NALC
	August 22, 1991	MSS NALC
Lake Saint Clair: Path 19 Row 30 and Path 19 Row 31		
Oct 30, 2000	ETM+ ESDI/CCRS	
March 23, 2001	ETM+ USGS	
August 30, 2001	ETM+ ESDI/CCRS	

No NALC data for Path 19 Row 30		
Path 19 Row 31:		
June 7, 1973	MSS	NALC
July 7, 1974	MSS	NALC
June 23, 1985	MSS	NALC
June 8, 1991	MSS	NALC

3.4 Study Sites, Data Availability and Approaches

To obtain the goals of this project, various approaches to wetland mapping, change detection and mapping flood extent were applied. The approaches applied at each test site varied by data availability and the types of wetlands that existed at each site. In some cases the constraints on data availability were priority and receiving station constraints, in other cases it had to due with difficulty in finding cloud-free images (Landsat), while in others it was budget constraints.

For the Mackinac, UP, and Leelenau sites we had only one season (summer) of Landsat imagery but from several different years (current and past data back to 1973). Since two or three seasons (leaf-on and leaf-off) of data are required for optimal classification mapping, the approach taken at these sites was to develop a cost-effective method for change detection using the anniversary date peak growing season imagery available. This approach was logical because there is no need to create past or current categorical maps at these sites since two good categorical maps already exist from the 1970's (NWI) and present (IFMAP).

Using the IFMAP as a current categorical map and NWI as the earliest date map, we recoded the maps to match categorically and then conducted a categorical change. We then used the Landsat data (current and 1973-4) to conduct a radiometric change analysis (change vector analysis). Finally, we put the two products together in a hybrid change analysis. This method makes use of existing products, while taking advantage of our hybrid change technique to determine real change (i.e. if there is a categorical change but not a radiometric change then it will be assumed to be no change).

For these same test sites we had four dates of JERS imagery. The radar data (from Fall 1992 to Spring 1994) were used to create an inundation map representing an average wetness year. It was determined that this was an average year based upon rainfall and lake levels and verified by communication with Thomas Rayburn. To do this a maximum likelihood classifier was used to map five (in one case 4) categories including low return (lakes and bare fields), low vegetation (such as fields), deciduous forest, coniferous forest, and woody wetland. We then used the NWI to grab only those woody wetland areas in the radar-derived maps that had previously been labeled as woody wetland in the NWI. Next we produced a flood extent map from the combined dates (1992-4) which represents an average year of wetness.

At the other two test sites (Lake St. Clair and Lake Ontario) we created current landuse/landcover (including wetlands) maps using radar and Landsat. Several techniques were considered and evaluated, but the best method appeared to be the simpliest; creating separate radar and Landsat landcover products and then merging them in a GIS. This method preserved the unique characteristics of each sensor. At these sites, we had C-band data to compliment the L-band which helps with mapping low herbaceous wetlands. It is important to note that the JERS L-band data, which are useful for mapping extent of forested wetlands, were from the mid-1990's. If a site was still forested in current imagery, then the extent of flooding was mapped using the JERS. The extent of flooding may eventually be updated with future L-band data (ALOS PALSAR to be launched in 2005).

4.0 Detailed Methods and Results of Hybrid Change

4.1 Hybrid Landcover Change - Wetlands

4.1.1 Hybrid Change Background Information

Generally, there are three approaches for detecting change: 1) categorical techniques, based on comparing categorizations of data collected on two different dates; 2) radiometric techniques, based on comparing the radiometric properties of data collected on two different dates; and 3) a "hybrid" approach, developed by GDAIS (heritage ERIM), which uses both categorical change and radiometric change. The new approach is a hybrid procedure because it effectively combines components of the two basic, but conceptually different, change detection procedures (i.e., categorical and radiometric) to extract information. This hybrid change detection procedure has significant advantages over using either procedure alone, because two tests are used to determine change (categorical and radiometric), thus reducing omission and commission errors.

Many errors in categorical change detection based on multispectral data are the result of inconsistent categorization between the first and second date. Inconsistent categorization occurs when a pixel that has not actually changed cover type between dates is erroneously assigned a different cover type label on each date. This may occur for two reasons, which may operate singly or together: 1) lack of perfect radiometric normalization between data sets, and 2) the signatures sets used to categorize the two data sets are not identical. Fortunately, this type of error can be effectively eliminated. This may be accomplished by examining the radiometric differences between dates of the pixels that have categorically changed between the data sets using CVA. The CVA results are tested to see whether the magnitude of the radiometric change between dates is greater than that which might be expected due solely to radiometric mismatches between the data sets. If the magnitude of the radiometric change does not exceed the specified "noise" threshold, then the pixel is considered unchanged, regardless of the categorical results. Note that it is not necessary that a threshold be specified that "perfectly" defines the magnitude beyond which real radiometric changes are found. Any threshold that eliminates "noise" changes, but which also does not eliminate changes of interest, is helpful in making the hybrid detection of change more accurate.

Radiometric change detection has been found to be a robust way of detecting all possible changes in land cover and land condition between two dates of Landsat data. However, except under special conditions, it does not provide unambiguous labels of the types of changes that have taken place. The addition of a categorical change test to a radiometric change detection provides a basis for assigning labels to radiometric changes that a radiometrically-based change detection technique usually cannot provide with as high a degree of specificity. Another benefit is that a combined radiometric and categorical change test will reduce errors caused by small radiometric changes due to changes in condition.

4.1.2 Change Detection Results in the UP, Mackinac and Leelenau Study Area

In order to update the NWI maps to reflect changes occurring in the UP, Mackinac and Leelenau study areas between the 1970s and 2001, the location and type of landcover change that had occurred within the separate study areas needed to be assessed. This was accomplished by conducting a categorical change between the NWI and IFMAP data.

First the NWI polygon coverage was rasterized and registered to match the IFMAP data. Then the IFMAP landcover categories were recoded to match the NWI landcover categories (Table 4). The wetland categories consisted of: forested, emergent, scrub-shrub, open water/unknown bottom, unconsolidated bottom, unconsolidated shore, aquatic bed, beach/bar, and flat. The two maps were combined to create a wetlands change map with "from" and "to" class labels.

Table 4. Recoding of IFMAP to match NWI attribute labels.

IFMAP	NWI
Low Intensity Urban	Uplands
High Intensity Urban	Uplands
Airports	Uplands
Roads/Paved	Uplands
Non-Vegetated Farmland	Uplands
Row Crops	Uplands
Forage Crops/Non-tilled Herbaceous	Uplands
Orchards/Vineyards/Nursery	Uplands
Herbaceous Open Land	Uplands
Upland Shrub / Low-density Trees	Uplands
Parks / Golf Courses	Uplands
Northern Hardwood Association	Uplands
Oak Association	Uplands
Aspen Association	Uplands
Other Upland Deciduous	Uplands
Mixed Upland Deciduous	Uplands
Pines	Uplands
Other Upland Conifer	Uplands
Mixed Upland Conifer	Uplands
Upland Mixed Forest	Uplands
Water	Open Water / Unknown Bottom
Lowland Deciduous Forest	Forested
Lowland Coniferous Forest	Forested
Lowland Mixed Forest	Forested

IFMAP	NWI
Floating Aquatic	Aquatic Bed
Lowland Shrub	Scrub-shrub
Emergent Wetland	Emergent
Mixed non-forest Wetland	Scrub-shrub
Sand / Soil	Unconsolidated Shore
Exposed Rock	Unconsolidated Shore
Mud Flats	Unconsolidated Shore
Other Bare / Sparsely Vegetated	Scrub-shrub

The post-categorical change map (Figure 1) exhibits a fair amount of change, much of which is insignificant. This can be attributed to several factors, including errors in the individual classifications, the re-labeling of landcover categories into classes that are not completely equal, and mis-registration between the maps. To reduce

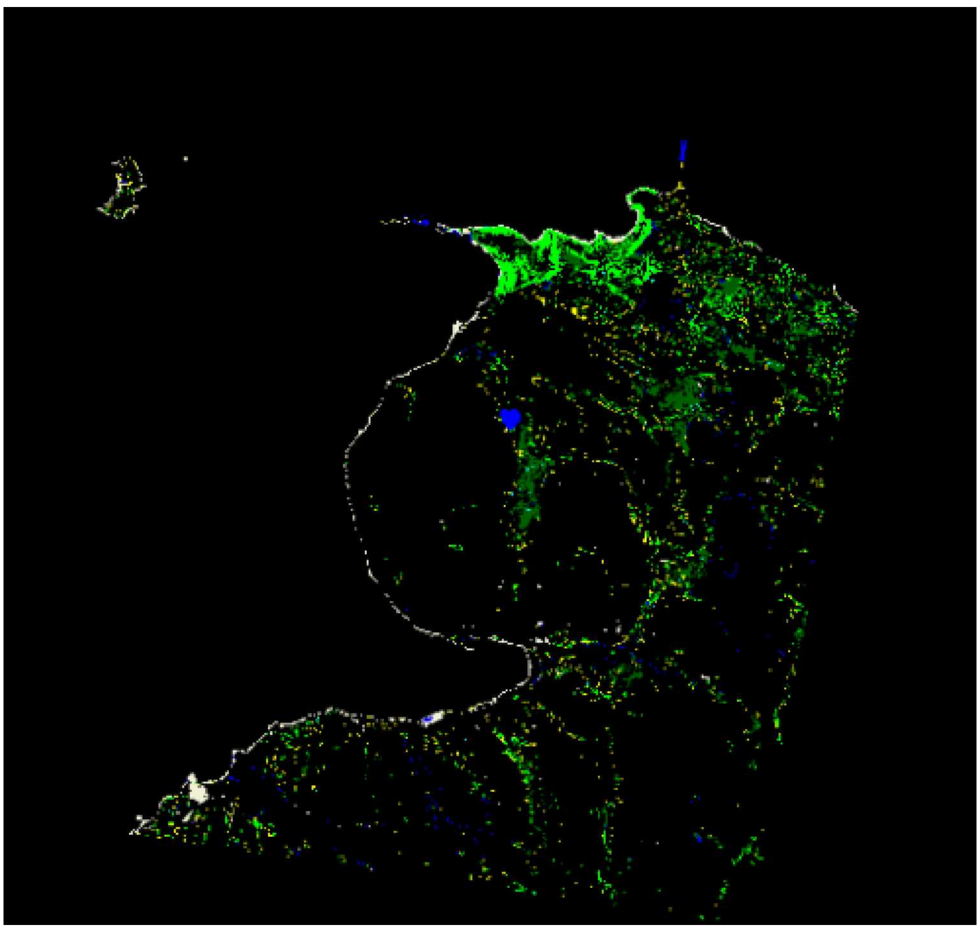


Figure 1. Post-categorical change map of Mackinac study site.

the amount of change identified to that which is most significant, radiometric change information was used to mask out changes of low magnitude. Since the early MSS scenes from the NALC datasets were acquired from about the same time that the NWI maps were created (early 1970's), they were utilized along with the most recent Landsat ETM+ images. Note that the Landsat scenes from both time periods were acquired mid-summer, July-August. MSS channels 1, 2, and 4 along with ETM+ channels 2, 3, and 4 were used since they represent similar portions of the spectrum. The MSS data were registered to the ETM+ data and resampled to a 60-m cell size. The ETM+ channels were then degraded by two to create a 60-m version of the image. The MSS channels were radiometrically balanced to the TM channels with a linear regression method. A change magnitude channel was then created by computing the Euclidean distance of the three spectral channel pairs. A threshold was then determined that best separated radiometric

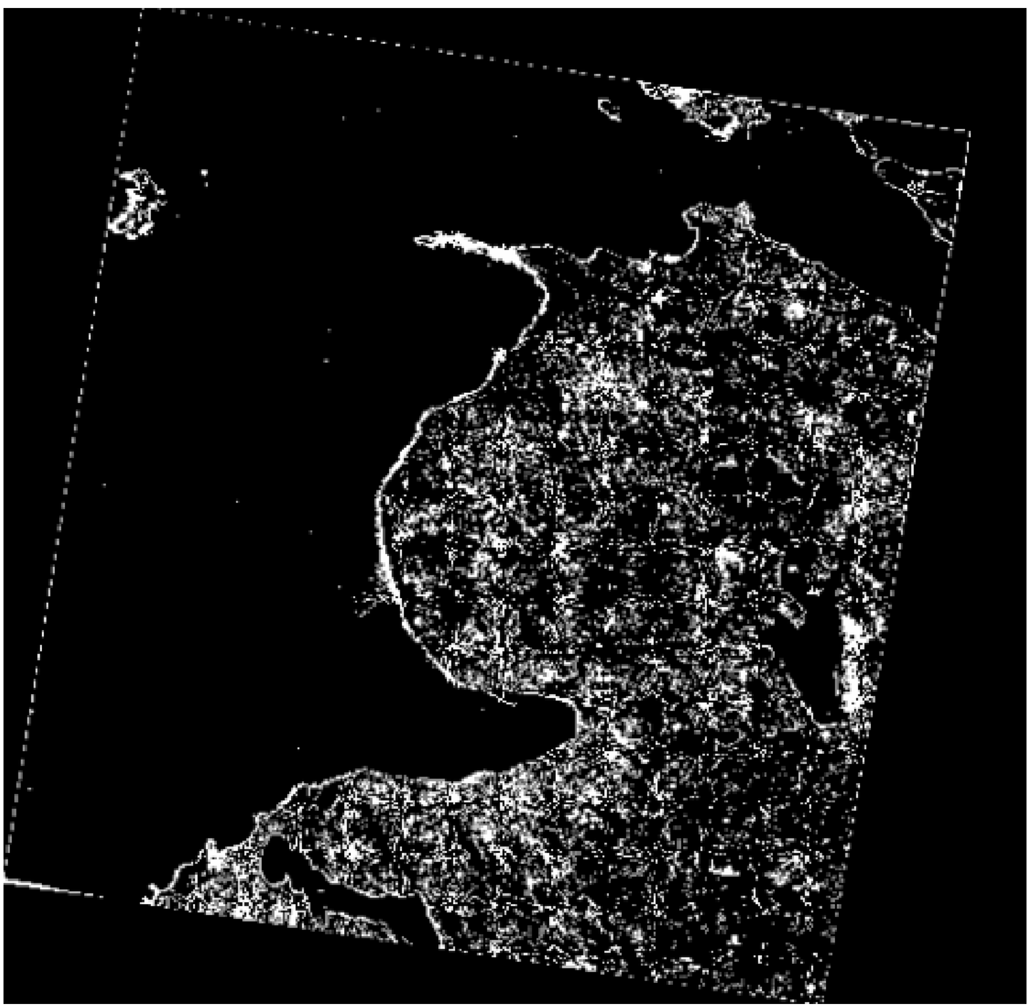


Figure 2. Change Magnitude channel of Mackinac study site.

changes of large magnitude that would be of interest from changes of small magnitude (Figure 2). A mask was generated from this threshold and applied to the categorical change map to create a hybrid change map (Figure 3).

The hybrid change product, MSS scene, ETM+ scene, and NWI vector coverage were displayed in separate viewers and linked together. A new vector coverage was created over the ETM+ scene. Areas of change were identified in the change image and investigated in both Landsat scenes to verify their occurrence. The change label was also checked to see if it made sense with the landcover appearance in both image dates. When a change was identified, the polygon for that feature was found in the NWI coverage and copied and pasted into the new (county-update) coverage. Edits to the polygon shapes were made and new polygons were drawn when necessary. Where clouds obscured the landcover in the ETM+ scene the change was not recorded.

The new wetland change polygons were then used to update the previous NWI coverage. This was accomplished by merging the change polygon coverage and the previous NWI coverage with the UNION command in ArcGIS. The attribute table of the new union coverage was modified with a new attribute *CLASS_ORG* to show the original class category. These updated NWI coverages by county are being delivered on CD-ROM. All changes to the NWI uplands category are evaluated in the next section (4.1.3 Hybrid Landcover Change - Uplands).

The hybrid change analysis resulted in 2.6% overall change to the nine counties covered by the study area. The total areas of change are presented in Table 5 below. The total area converted from wetland to upland in the change analysis was 2546 hectares (ha). Conversely, the area converted from upland to wetland was only three ha. 1304 ha changed from emergent to woody (shrub or forested) wetland and 7.2 ha changed from woody to emergent over the three decade change analysis. The area changing from wetland to open water (including aquatic bed) was 124 ha.

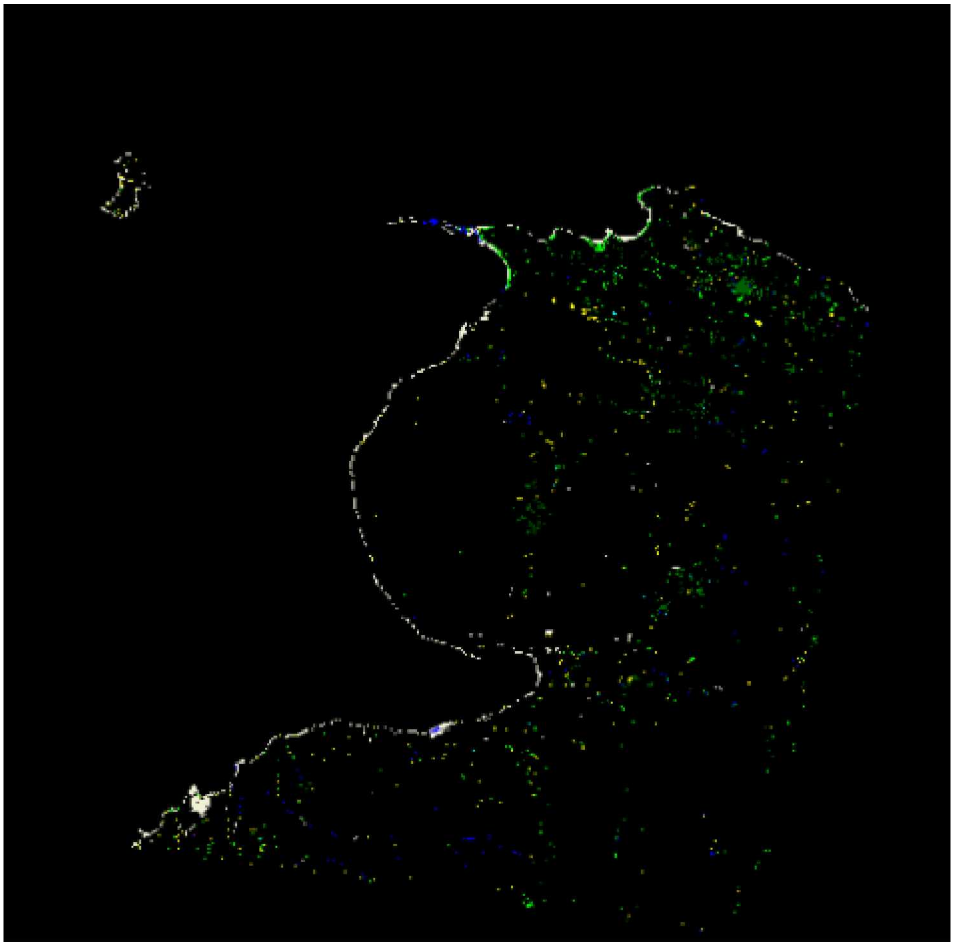


Figure 3. Hybrid change image of Mackinac study site.

Table 5. Summary of Original NWI class (from) and Updated NWI class (to) change categories for the wetland hybrid change analysis for the UP, Mackinac and Leelenau study areas. Nine counties.

Original Class	Updated Class	Area (hectares)
Emergent	Aquatic Bed	36.0
Emergent	Forested Wetland	83.3
Emergent	Open Water	5.2
Emergent	Shrub Wetland	1221.2
Emergent	Unconsolidated Shore	21.5
Emergent	Uplands	79.5
Forested Wetland	Aquatic Bed	87.6
Forested Wetland	Emergent	7.2
Forested Wetland	Open Water	55.8
Forested Wetland	Shrub Wetland	40821.6
Forested Wetland	Unconsolidated Shore	2.3

Original Class	Updated Class	Area (hectares)
Forested Wetland	Uplands	2366.9
Open Water	Forested Wetland	6.6
Open Water	Shrub Wetland	19763.4
Open Water	Unconsolidated Shore	3.1
Open Water	Uplands	12.3
Shrub Wetland	Forested Wetland	1215.1
Shrub Wetland	Unconsolidated Shore	2.9
Shrub Wetland	Uplands	87.3
Unconsolidated Bottom	Forested Wetland	0.6
Unconsolidated Bottom	Shrub Wetland	10.3
Unconsolidated Bottom	Open Water	9.0
Unknown	Uplands	533.8
Uplands	Forested Wetland	1.8
Uplands	Shrub Wetland	0.7

4.1.3 Hybrid Landcover Change – Uplands

A process similar to the wetland change process was used to assess change in the upland areas adjacent to wetlands. Since the NWI does not categorize different types of uplands, the MIRIS 1978 LULC coverages were obtained from the Michigan Geographic Data Library to use in our analysis. Raster files of the separate county coverages were generated at a 30-meter cell size. The MIRIS LULC categories were compared with the IFMAP LULC categories and a common set of categories were defined (Table 6). Both MIRIS and IFMAP coverages were recoded to reflect the new labels.

The separate NWI counties were mosaicked together and subsetted to the study site area. Areas less than 5 acres were eliminated by clumping the thematic layers and eliminating pixel clumps less than or equal to 16. The maps were combined to create a categorical change map from 1978 – 2001. An upland filter was created from the NWI raster files and dilated by 2 pixels to reduce edge effects. The filter was applied to the landcover change product to eliminate areas labeled as wetlands in the NWI. The same change magnitude mask that was used in the wetland change analysis was applied to each study site so that only changes of significant magnitude appear.

The hybrid change product along with the MSS and ETM+ scene were displayed in separate viewers and linked geographically together. A new coverage was created over the ETM+ image. The LULC change types were highlighted one at a time and evaluated in the Landsat change pair. Polygons were drawn over the ETM+ image where change occurred and a from-LULC and to-LULC attribute was populated for each. Air photos from terraserver.com were used to verify LULC labels.

These products were not used to update any coverage, but are being delivered as separate change polygons by county. These polygons may then be used to assess change occurring adjacent to existing wetlands and overall wetland health.

Table 6. Recoding of IFMAP and MIRIS to common categories

MIRIS LULC (1978)	MIRIS New LULC Label	IFMAP LULC (2001)	IFMAP New LULC Label
Broadleaved Forest (Generally Deciduous)	Deciduous Forest (700)	Low Intensity Urban	Urban (1)
Cropland, Rotation, and Permanent Pasture	Agriculture (300)	High Intensity Urban	Urban (1)
Herbaceous Rangeland	Herbaceous Rangeland (500)	Airports	Transportation, Communication, and Utilities (2)
Forested (wooded) Wetlands	Forested Wetlands (1000)	Roads/Paved	Transportation, Communication, and Utilities (2)
Orchards, Vineyards, and Ornamental	Orchards, Vineyards, and Nursery (400)	Non-Vegetated Farmland	Agriculture (3)
Residential	Urban (100)	Row Crops	Agriculture (3)
Lakes	Water (1300)	Forage Crops/Non-tilled Herbaceous	Herbaceous Rangeland (5)
Coniferous Forest	Coniferous Forest (800)	Orchards/Vineyards/Nursery	Orchards, Vineyards, and Nursery (4)
Shrub Rangeland	Shrub (600)	Herbaceous Open Land	Herbaceous Rangeland (5)
Non-Forested (non-wooded) Wetlands	Non-forested Wetlands (1100)	Upland Shrub / Low-density Trees	Shrub (6)
Permanent Pasture	Herbaceous Rangeland (500)	Parks / Golf Courses	Urban (1)
Transportation, Communication, and Utilities	Transportation, Communication, and Utilities (200)	Northern Hardwood Association	Deciduous Forest (7)
Other Agricultural Land	Agriculture (300)	Oak Association	Deciduous Forest (7)

MIRIS LULC (1978)	**MIRIS New LULC Label**	**IFMAP LULC (2001)**	**IFMAP New LULC Label**
Extractive	Sand/soil/open/exposed rock (1200)	Aspen Association	Deciduous Forest (7)
Industrial	Urban (100)	Other Upland Deciduous	Deciduous Forest (7)
Open and Other	Sand/soil/open/exposed rock (1200)	Mixed Upland Deciduous	Deciduous Forest (7)
Commercial, Services, and Institutional	Urban (100)	Pines	Coniferous Forest (8)
Sand other than Beaches	Sand/soil/open/exposed rock (1200)	Other Upland Conifer	Coniferous Forest (8)
Beaches and Riverbanks	Sand/soil/open/exposed rock (1200)	Mixed Upland Conifer	Coniferous Forest (8)
Reservoirs	Water (1300)	Upland Mixed Forest	Mixed Forest (9)
Confined Feeding Operations	Urban (100)	Water	Water (13)
Streams and Waterways	Water (1300)	Lowland Deciduous Forest	Forested Wetlands (10)
Forest Land	Mixed Forest (900)	Lowland Coniferous Forest	Forested Wetlands (10)
Bare Exposed Rock	Sand/soil/open/exposed rock (1200)	Lowland Mixed Forest	Forested Wetlands (10)
		Floating Aquatic	Non-Forested Wetlands (11)
		Lowland Shrub	Forested Wetlands (10)
		Emergent Wetland	Non-Forested Wetlands (11)
		Mixed non-forest Wetland	Non-Forested Wetlands (11)
		Sand / Soil	Sand/soil/open/exposed rock (12)
		Exposed Rock	Sand/soil/open/exposed rock (12)
		Mud Flats	Sand/soil/open/exposed rock (12)
		Other Bare / Sparsely Vegetated	Sand/soil/open/exposed rock (12)

The analysis of change in uplands for the three study areas resulted (Table 7) in most of the change occurring in forested land (coniferous and deciduous) being converted to herbaceous, most likely due to timber harvesting (5650 ha from mid-1970s to 2001). The conversion of land from a natural or agricultural category to urban was 1592 ha. The amount of land converted from an herbaceous or agriculture category to forest was 1470 ha.

Table 7. From-To change categories for the Upland hybrid change analysis for the UP, Mackinac and Leelenau study areas.

From-To Change Category	Area (Hectares)
Agriculture-Coniferous	224.0
Agriculture-Deciduous	168.5
Agriculture-Mixed Forest	26.9
Agriculture-Urban	456.1
Coniferous-Deciduous	627.2
Coniferous-Herbaceous	4452.5
Coniferous-Open	8.0
Coniferous-Shrub	349.4
Coniferous-Urban	26.5
Coniferous-Wetland	19.8
Deciduous-Agriculture	33.2
Deciduous-Coniferous	94.4
Deciduous-Herbaceous	1197.4
Deciduous-Open	45.0
Deciduous-Shrub	25.7
Deciduous-Urban	590.6
Herbaceous-Coniferous	598.6
Herbaceous-Forested	329.0
Herbaceous-Deciduous	76.1
Herbaceous-Mixed Forest	39.2
Herbaceous-Urban	137.4
Open-Coniferous	7.2
Open-Urban	349.0
Shrub-Deciduous	277.7
Shrub-Coniferous	285.2
Shrub-Urban	32.0

4.1.4 Evaluation of Hybrid Change Products

A comparison was made as to the percent area changed in each intermediate (categorical change and radiometric change) and final product (hybrid change) for each test site (Table 8). With categorical change the amount of change ranged from 4.4 to 14.5% and for radiometric change from 11.36 to 18.2%, but the final products showed only 1.3 to 3.8% change. This demonstrates the utility of hybrid change in reducing errors due to inconsistent categorical labels and in taking advantage of merging two methods of change detection.

Note that in all cases there was more radiometric change than categorical change and without explicit ground truth, these changes cannot be labeled because the categorical maps do not show a change. The most prominant reason for the higher radiometric change is phenological differences which were very noticeable in the UP dataset and likely in the other scenes since they were from the same dates. Landcover types that have not changed can appear radiometrically different if their condition has changed, such as senescent vegetation, or drought conditions. Also atmospheric conditions, clouds, haze, and shadow can cause some radiometric change. If changes in vegetation condition are of interest, then those change pixels can be focused on that did not have a categorical change but did have a radiometric change. The final hybrid change products created here record only the co-occurrence of radiometric and categorical change.

Table 8. Percent area changed in each of the raster products created using the hybrid change process.

	% Categorical Change	**% Radiometric Change (threshold)**	**% Hybrid Change**
Mackinac Wetlands	**4.43%**	Thresh = 20 **11.36%**	**1.3%**
Leelenau Wetlands	**9.17%**	Thresh = 30 **13.89%**	**1.45%**
Upper Peninsula Wetlands	**14.46%**	Thresh = 20 **18.2%**	**3.8%**

5.0 Initial Radar Analysis Results

The initial microwave portion of the project was funded by General Dynamics (GDAIS) and was completed in December 2003. The main focus of the GDAIS microwave study was to map forested wetlands along the coastal Great Lakes using the L-band (23 cm wavelength) sensor of the Japanese JERS satellite. At L-band, an enhanced signature is typically received from flooded forests which can be easily mapped. In addition, we found that at some test sites, tall and dense herbaceous vegetation also caused an enhanced signature at L-band. We found that different types of herbaceous wetlands with different degrees of flooding have unique signatures that can easily be mapped from a time-series of single channel L-band SAR imagery. By merging shorter wavelength C-band (5.7 cm wavelength) data with the L-band data at the herbaceous dominated wetland sites, we were able to map an even larger variety of wetland types. We were also able to determine changes in inundation associated with changes in lake level from the C-band SAR at the Lake St. Clair test site (Figure 6).

The results from the initial study are presented in the next few sections by site, starting with section 5.1. Further analysis was conducted after December of 2003 which built upon the initial study. The extended analysis included mapping of inundation extent in woody wetlands using the time-series of JERS data in the UP, Leelenau and Mackinac study areas, as well as, merging the radar with the Landsat to create new wetland landcover maps. These results are presented in sections 6.0 and 7.0 and products are being delivered on CD-ROM.

5.1 Lake St. Clair

For the Lake St. Clair site we had two JERS scenes (28 March 1995, 10 August 1998), two Radarsat scenes (3 and 27 October 1998), and one ERS scene (4 October 1998). We evaluated the SAR imagery and products by comparison to the NWI, IFMAP, field checks (October 2003) and expert field knowledge (Dennis Albert). Although the ancillary maps and field work show many forested wetlands within our study area (Figure 4), the dates of JERS imagery that we have show all of the forests the same, very bright in the spring (28 March 1995) and all are gray in the summer scene (10 August 1998). It is likely that all of the forests have a wet ground cover in the spring scene, there may even be wet, melting snow on the forest floor causing the enhanced signature from all of the forests, and in August all of the forests are dry with full foliage. However, the differences in backscatter in the tall herbaceous vegetation are apparent on these two dates, as well as in the Radarsat scenes. Figure 5 shows a red-green-blue composite of the 3 October 1998 Radarsat scene, 10 August 1998 JERS scene, and 28 March 1995 JERS scene, respectively. In this composite, the red/orange areas have strong return in the Radarsat C-band scene, indicating flooded non-forested vegetation conditions. The orange and green areas are also showing strong returns at L-band in the 10 August 1998 scene. There is a structural difference and/or water level difference between the green and orange sites because the green sites have low return at C-band (red). Dennis Albert met with us to investigate the variations in SAR backscatter within this scene as well as other test sites. He has done extensive field work in parts of all of our test areas. He helped us interpret the scene shown in Figure 5. We also conducted field checks of our own, but were unable to get into some of the sites, such as Dickinson Island (a location that Dennis Albert had visited). The orange areas of Figure 5 are interpreted as dominated by cattail (*Typha spp*.), and the green as *Phragmites* (*Phragmites spp*.) dominant. *Phragmites* tends to be taller/denser and occurs in less wet locations than cattail. The red areas of the image are shorter and sparser vegetation, thus they do not cause enhanced backscatter at L-band, only at C-band. The red areas along the fingers of the Delta are cattail and bulrush (*Scirpus spp*.) beds and the red area within Dickinson Island is a flood channel with wild rice (*Zizania aquatica*), open submergent and emergent vegetation (Dennis Albert). The dark area in the center of Dickinson island to the west of the kidney shaped forested wetland is a wet meadow and appears to be dry in our October 1998 C-band scene, it has strongest backscatter in the L-band spring scene (blue), but not enhanced backscatter. This combination of Radarsat and JERS allows for a good interpretation of this scene, discerning tall dense herbaceous vegetation from short sparse herbaceous vegetation, and different wetnesses and biophysical properties.

Unfortunately, the timing of the L-band data collections were not useful for forested wetland detection. We also obtained an ERS scene collected one day after the 3 October Radarsat scene (higher water level date), but the image shows no enhanced signatures from any of the wetland vegetation, only from a few agricultural fields. Further investigation of the ERS imagery over this test site should be conducted because the ERS imagery were found to be quite useful in monitoring hydropatterns in the wetland complexes of southern Florida (Bourgeau-Chavez et al. 2003).

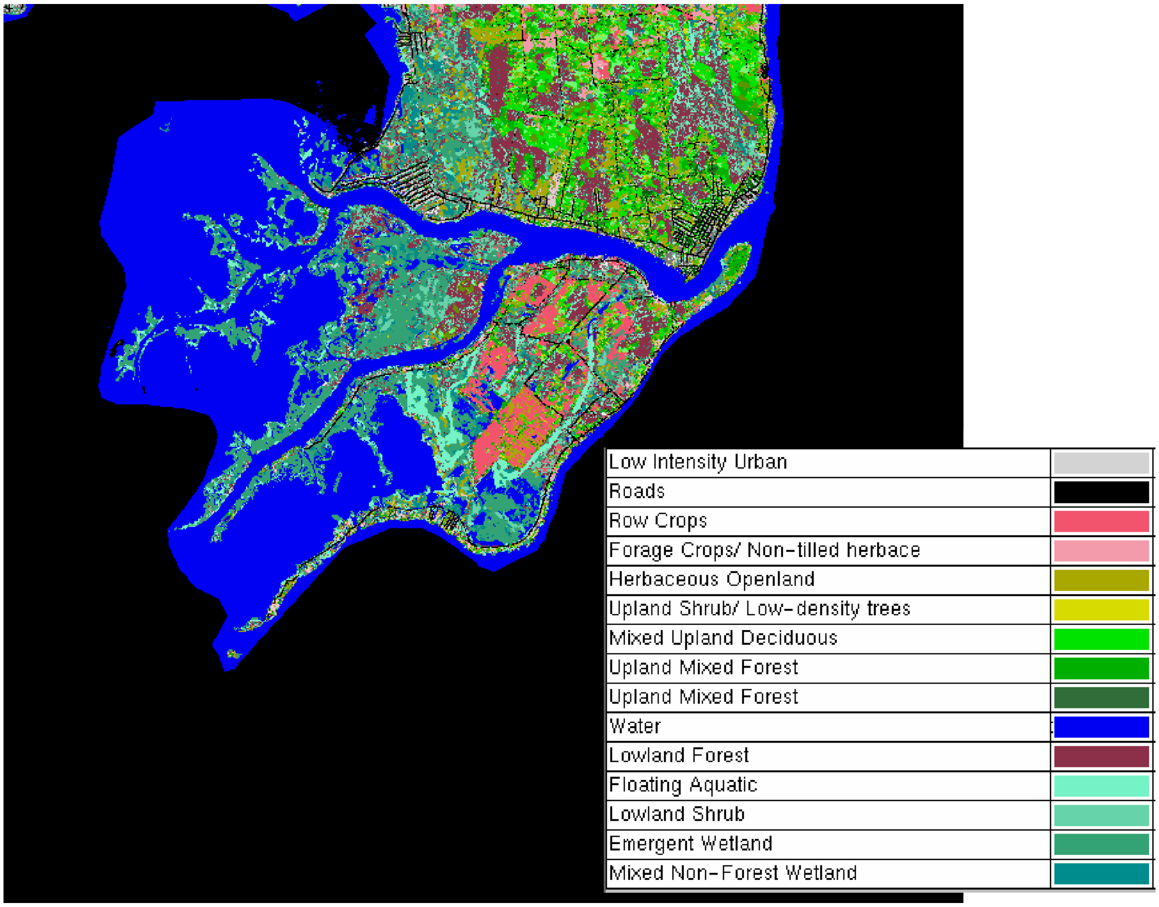


Figure 4. IFMAP of St. Clair River Delta. Some categories were combined for efficiency.

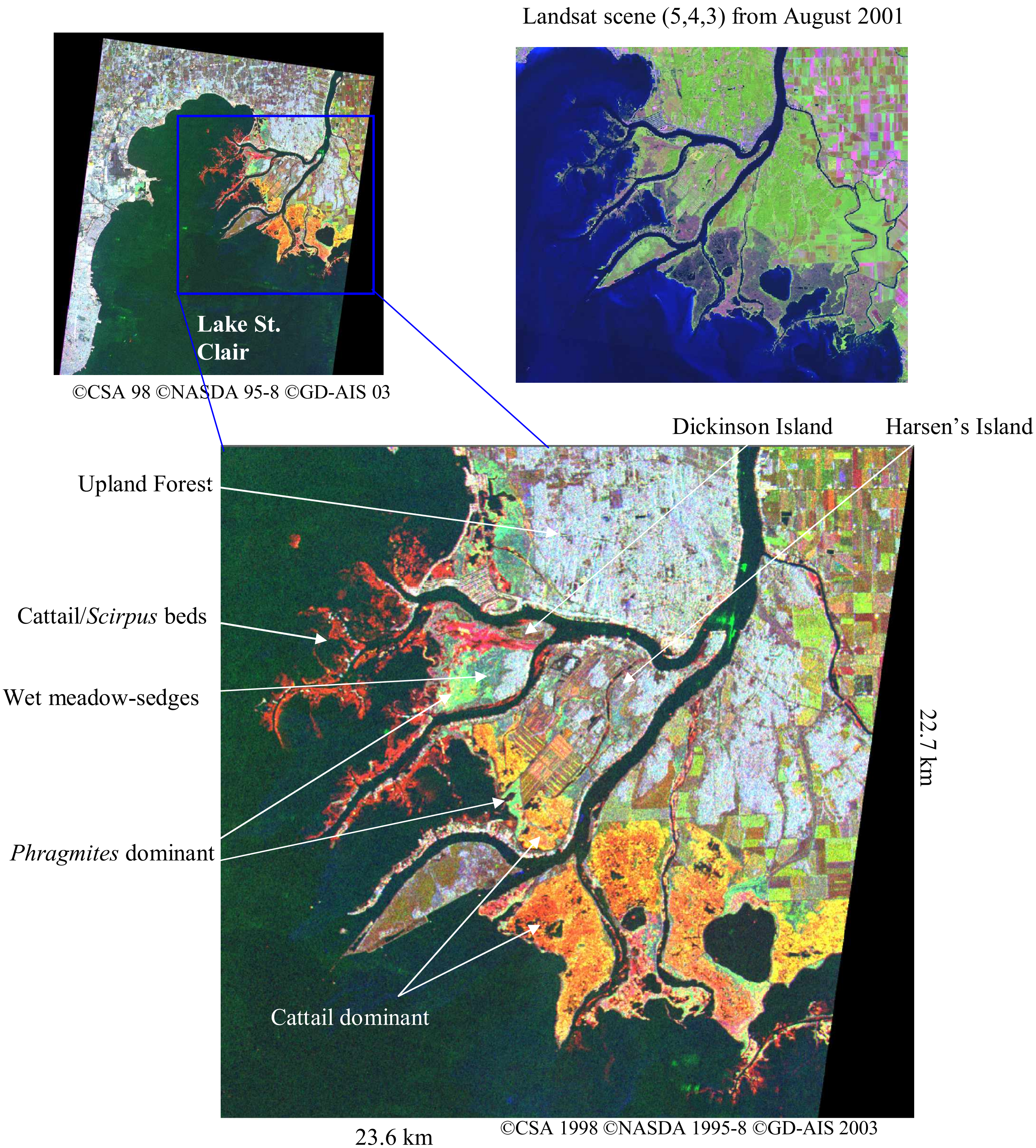
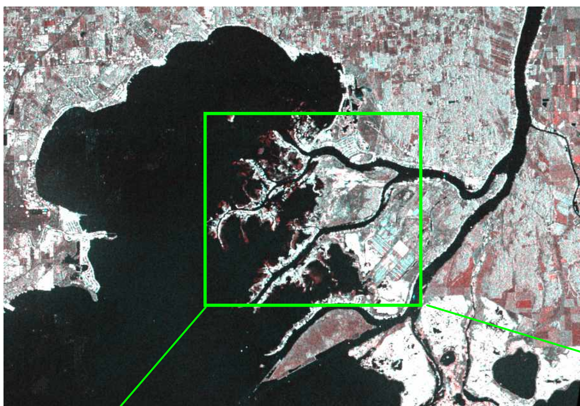


Figure 5. Lake St. Clair three date false color composite of Radarsat 3 Oct 98 (red), JERS 10 Aug 98 (green), and JERS 28 Mar 95 (blue). A 5,4,3 Landsat composite from August 2001 is shown for comparison.

We also found that the 19 cm difference in lake level on 3 October 1998 versus 27 October 1998 was apparent in the Radarsat imagery. Figure 6 shows a two-date false color composite of the 3 October 1998 (Cyan) and 27 October 1998 (Red) Radarsat scenes. The red areas along the fringes of the Delta showed a bright return on the second date (27 October) when the water level was 175.11 m indicating an enhanced signature due to low water levels, while on the first date (3 October) the water level was 175.30 m, 19 cm higher and likely covering a good deal of the vegetation resulting in a more specular response (low return). Most of these areas were found to be classified as open water in the IFMAP.



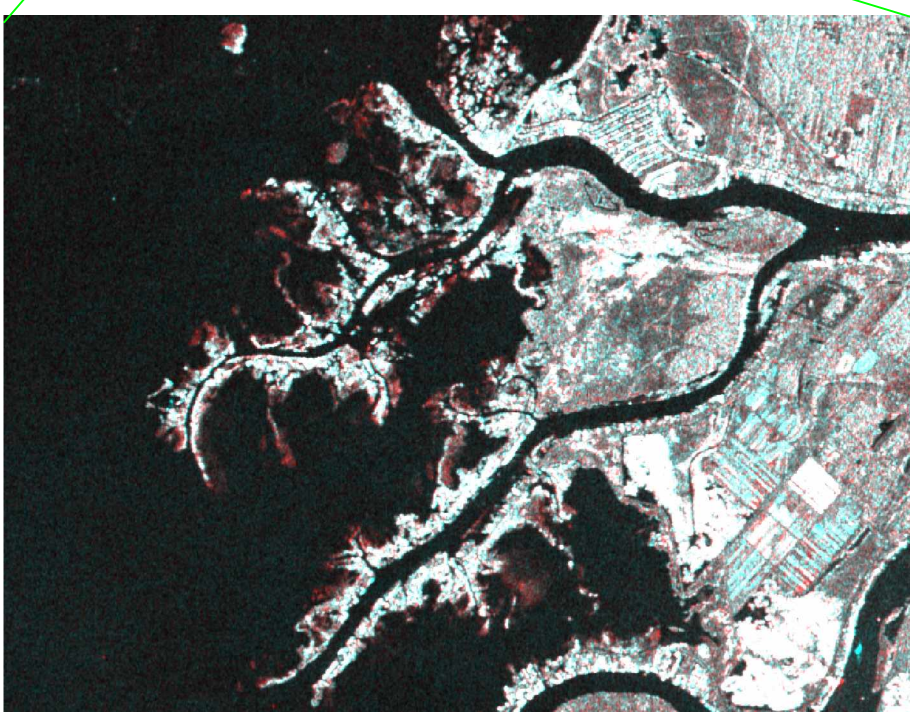


Figure 6. Two date false color composite of Radarsat imagery. Cyan is the 3 October 1998 image and red is the 27 October 1998 image.

5.2 Lake Ontario

At the Lake Ontario test site, we had an ideal seasonal data set with three images each of JERS and ERS from spring, summer and fall of 1993. Figure 7 presents

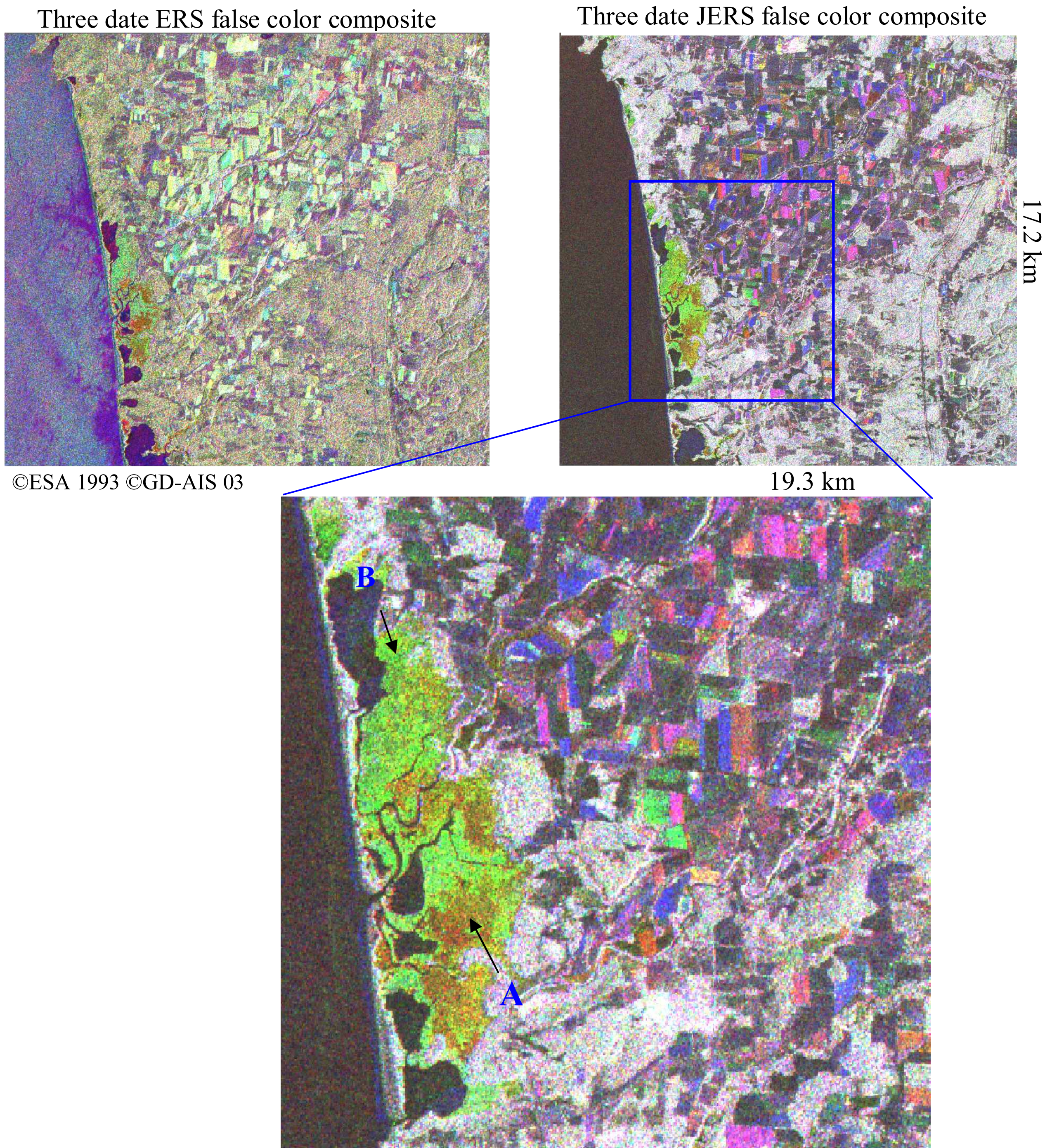


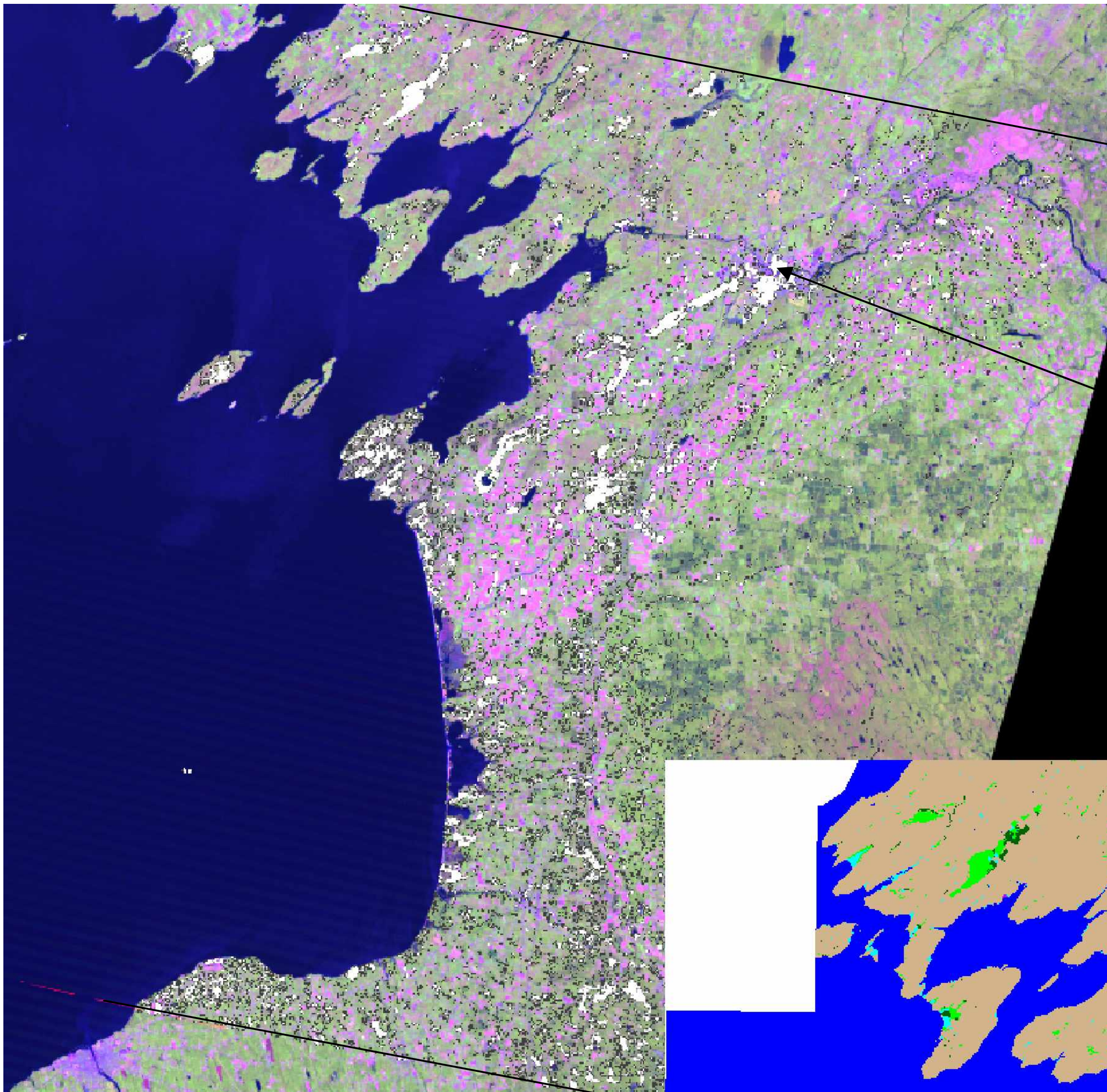
Figure 7. Three date ERS false color composite of 25 October, 7 June and 17 April 1993 ERS imagery over eastern Lake Ontario compared to a 17 October, 8 July and 11 April 1993 JERS composite. A and B are locations that were visited in November 2003.

false color composites of the two datasets. Both datasets highlight non-forested wetlands (based on NWI) as green and red shades. In the JERS data, these sites were dark from specular reflection in the April scene (blue), then some sites were bright in July (green in the composite) while other sites remained dark in July (red locations in the composite) and all sites were gray in October. In November of 2003 we conducted a field check to determine the difference between the red and green areas. The red area (A in Figure 7) was located at Sandy Creek and is featured in the left photo of Figure 8. This site was dominated by mixed grasses. It is likely that in the spring imagery the vegetation is fallen over with a high water level leading to specular reflection. The water level must still be high enough to cover much of the grasses and cause specular reflection again in the July scene, but when the lake water level drops to 74.58 m in October (70 cm drop), this site has more vegetation exposed and stronger backscatter. In comparison, site B (the northern site of Figure 7) contained a mixture of grasses, cattail and shrubs (Figure 8-red osier dogwood; *Cornus stolonifera*). This site was bright in the summer and gray in the fall in the JERS imagery. The water level in comparison to the vegetation was likely lower than at the other sites, causing the enhanced backscatter in July, but with lower soil moisture in the fall the site was gray. For the same two sites in the ERS, the Sandy Creek site was dark in the spring but the mixed shrub/herbaceous site was gray. In the summer the mixed shrub site was bright while the Sandy Creek site remained dark. In the fall all sites were gray. While similar patterns emerged for both sites, the contrast between the non-flooded adjacent forests and the wetlands is stronger with the JERS, making it easier to map the boundaries of the sites.

There are some forested wetlands within the Lake Ontario scene and they appear to be most notable in the April scene when the lake water level is the highest, and spring thaw has occurred and thus flooding is most likely. A comparison was made between assumed flooded forest and non-flooded forest for each JERS scene/date. The April scene had a 2.3 dB difference between flooded and non-flooded forest while the July date had only a 0.5 dB difference and the October date had a 1.7 dB difference. The April scene was then thresholded to values greater than that of the non-flooded forest. After median filtering the scene with a 5x5 window to remove speckle, the scene was overlaid on a 5,4,3 Landsat composite (Figure 9). The white areas of Figure 9 show the SAR-

Figure 8. Photo of grasses at Sandy Creek site (red) and red-osier dogwood at northern site (green).

derived potentially flooded forests. The backscatter from urban areas is also enhanced and has not been filtered from this scene. There are also white areas that are likely row plantings of trees. The row structure produces an enhanced return. The urban areas can be removed by using either the Landsat scene to mask forest from non-forest or by using the ERS C-band data. The C-band data will have enhanced backscatter for the urban area but not for the flooded forests. The extent of some of the enhanced signatures appears to be slightly greater than what is seen in the NWI for some of the sites (Figure 9).



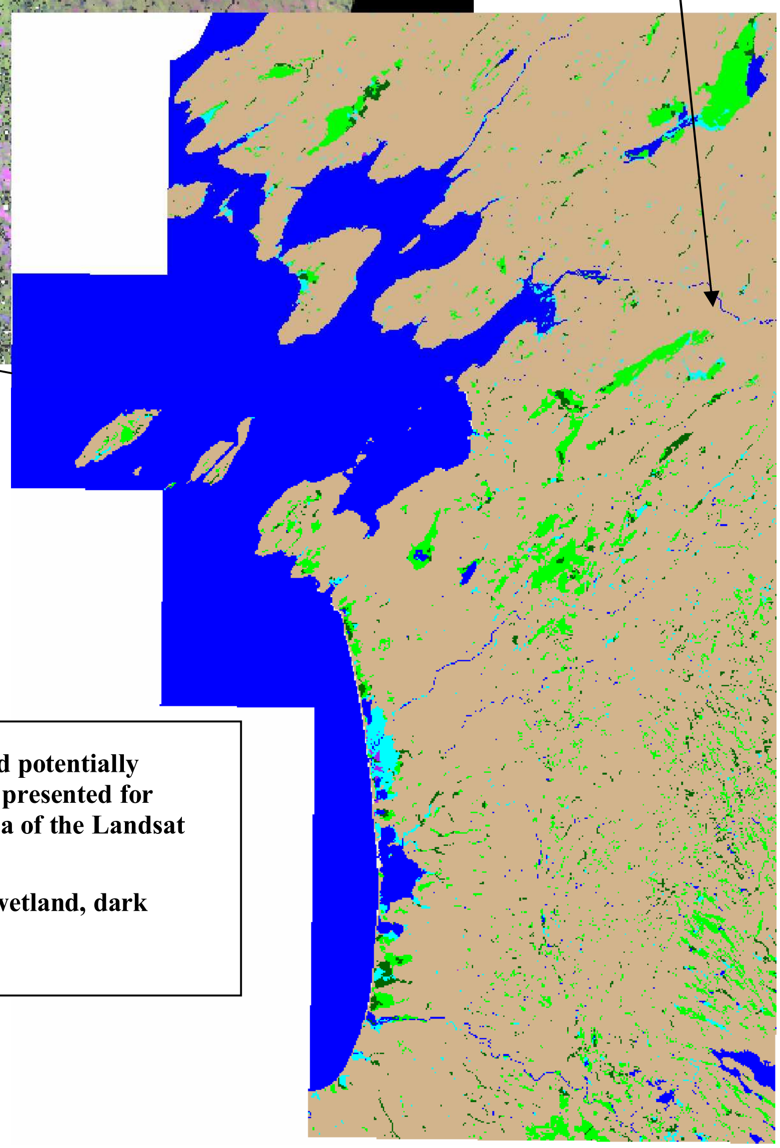


Figure 9. Landsat 5,4,3 composite with SAR-derived potentially flooded forests (white areas) overlaid. The NWI is presented for comparison. Note that the NWI is not the exact area of the Landsat scene.

NWI-blue=water, cyan=emergent, green=forested wetland, dark green=shrubby wetland, purple=floating aquatic.

5.3 Mackinac-Leelenau Site

The Mackinac JERS scenes were mosaicked to the Leelenau scenes prior to analysis. It was attempted to conduct analysis with the UP scene also mosaicked, but the differences in vegetation in the UP were great enough to result in less accurate maps of the Mackinac-Leelenau area. Thus they were kept separate.

The Mackinac-Leelenau (now referred to as Maclee) contains a number of diverse woody wetlands. From the false color composite presented in Figure 10, it is apparent that the pink-orange areas are primarily woody wetlands. The bright whitish areas are woody wetlands as well as urban areas. Some of the light green areas are mapped as woody wetland in the NWI and IFMAP, but other light green areas of Figure 10 are not wetland. Some of the green areas are pine plantations with row structure causing enhanced return. This was determined from air photos and classification on IFMAP.

To create a forested wetland map, an unsupervised maximum likelihood classifier was run on the four JERS scenes available over the Maclee site (Figure 11). The IFMAP is presented in Figure 11 for comparison to the JERS map. The IFMAP was recoded to reflect the JERS codes with the exception of shrubby wetlands being coded as orange on the IFMAP. With SAR we cannot separate shrub from forest. Also, emergent wetlands are cyan in the IFMAP but are not mapped in the SAR-derived map. There is a general agreement between the two maps but there is a scattering of a few pixels of orange in the SAR map that are likely agriculture or forest plantations. Overlaying a forest/non-forest mask from Landsat can eliminate the errors in the agricultural fields as well as the misclassified pixels in the urban areas (Figure 12). However, this mask will not eliminate the forest plantations. But since many are just a few isolated pixels, we could eliminate them from the map.

A validation of our SAR-derived map was made to the NWI (Table 9). 450 random points were selected from the maps and compared using the NWI as reference. The only problem with this comparison is that the NWI maps agriculture as upland and the SAR cannot distinguish between agriculture and open water (both result in low returns). So we expect quite a bit of error in the upland and open categories. Also, we cannot distinguish shrub from forest so those wetland types were combined into woody wetland. Lastly, we did not map emergent vegetation, but there is not much within our scene so that should not be a problem.

The results show 85% producer's accuracy for woody wetland and 39% users accuracy, 97 % producers accuracy for open areas with 48% users accuracy, and 45% producers accuracy for upland forest with 90% users accuracy. Producer's accuracy is the number of correctly classified pixels compared to the number of pixels chosen with that category from the new map (150), while user's accuracy is the number correctly classified versus the actual number of pixels with that category in the reference map.

It was noted by Dennis Albert that, particularly in the dune and swale areas, we sometimes overclassify the area of the wetlands. This is also apparent in the Landsat-derived IFMAP also, and is likely the result of the 30m resolution of the systems which are mapping dune and swale together in a single resolution cell. For this reason, Dr. Albert suggested that we map it as a complex. He noted that even with hi-resolution aerial photography in stereo that the dune and swale ecosystems are difficult to map.

Table 9. Accuracy assessment using the NWI as reference

	Reference Totals	**Woody Wetland**	**Emergent**	**Open water**	**upland**	**Total**
Woody wetland	**69**	**59**			**91**	**150**
Open (water and openland)	**74**	**1**	**1**	**72**	**76**	**150**
Upland forest	**302**	**11**	**2**	**2**	**135**	**150**

Red Green Blue False Color Multi-temporal JERS L-band Composite
Upper Lower Peninsula, Michigan

15 April 94   7 September 93   3 November 92

83 km

79 km

Figure 10. RGB Composite of 3 JERS image dates.

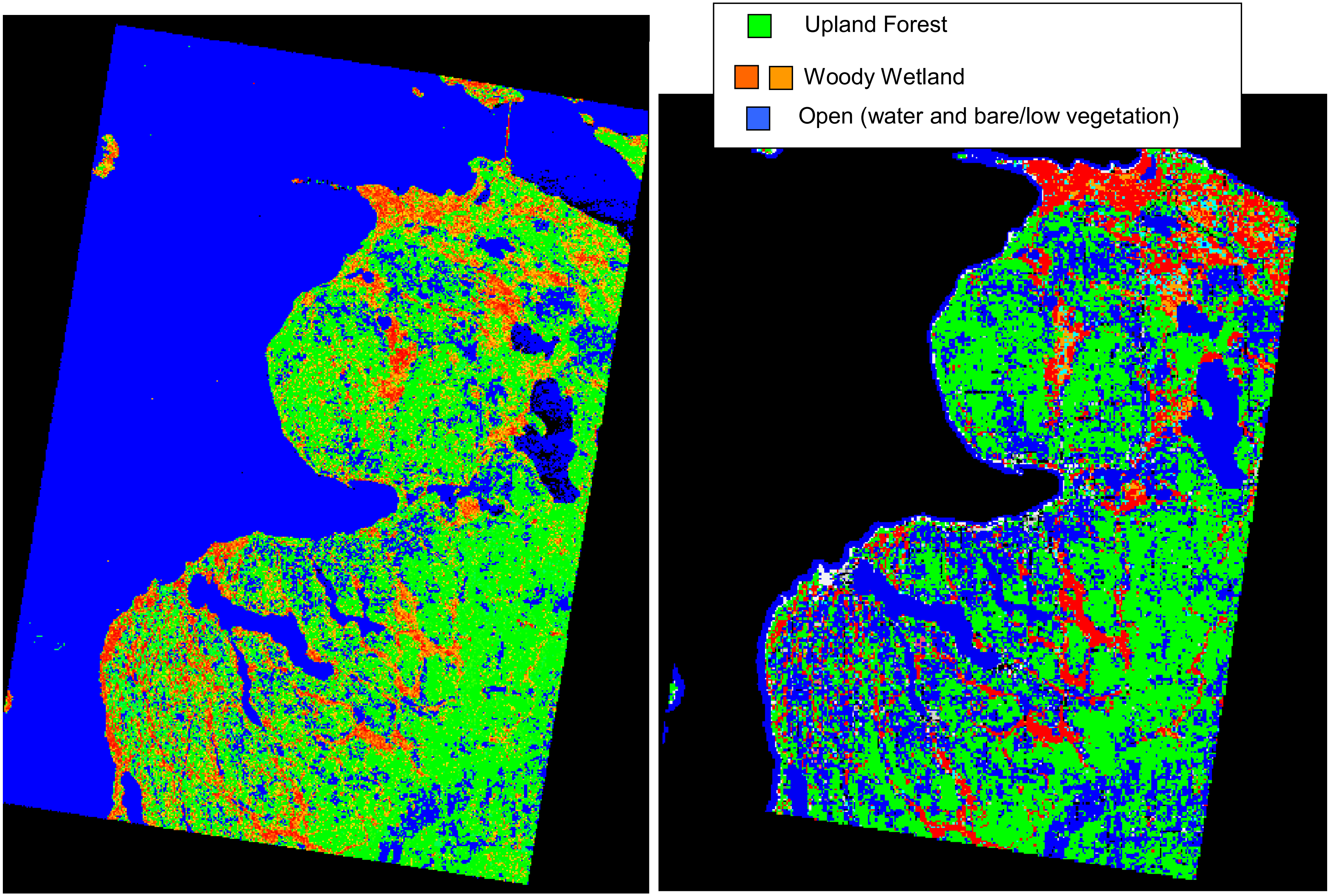


Figure 11. Four-Date JERS-derived Forested Wetland Map compared to IFMAP with similar categories. However, orange on IFMAP is shrubby wetland, cyan is emergent.

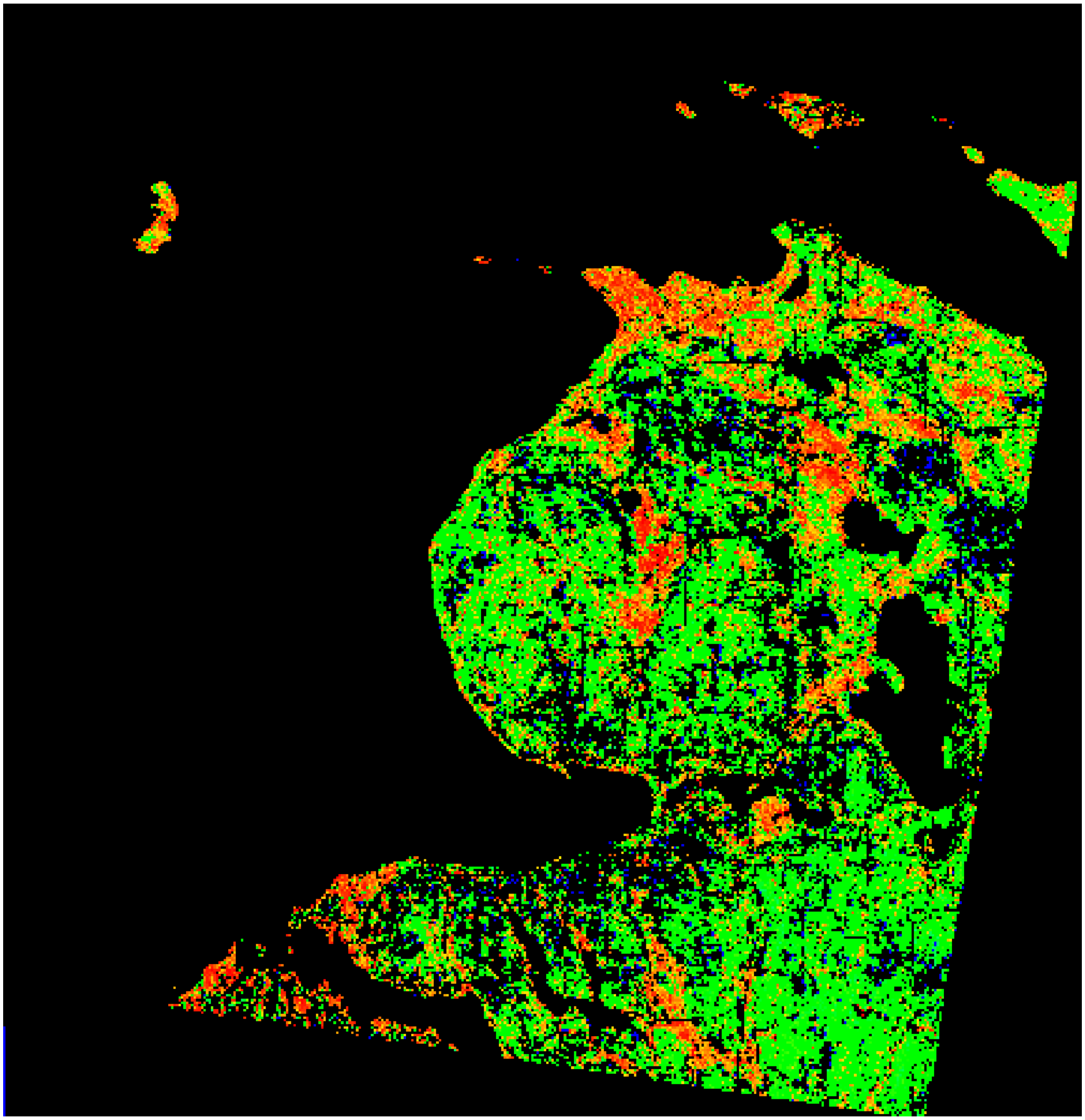


Figure 12. SAR-derived Forested Wetland Map with non-forested areas masked out. This area is smaller because the mask was only of the Landsat Mackinac scene and not the Leelenau.

6.0 Extent of Inundation Mapping with Multi-Temporal SAR Imagery

Under the current project, the JERS imagery from four dates spanning November of 1992 to April of 1994 were used to map extent of inundation for three study areas, the UP, Mackinac and Leelenau. Many different methods were evaluated for this analysis, including thresholding each image date as was done for the Lake Ontario study site in section 5.2, Figure 9. Since the contrast between the uplands and wetlands varies by date, a different threshold was needed for each date. This difference in contrast has to do with seasonal differences, including leaf-on versus leaf-off, moisture on the vegetation due to recent rainfall, and general environmental differences. Since the data were collected in the early 1990s, field truthing could not be conducted. However, lake levels and rainfall data show that the time period of our imagery represent "normal" conditions. While a single date of imagery would not necessarily be capturing the "normal" conditions of these years, a time series of imagery from spring, summer and fall would do a better job. Our database consisted only of fall and spring imagery, with no summer data available from these test sites by the JERS satellite. Although the dataset is not perfect, it captures a range of dates and conditions.

It was first attempted to merge the 4 individual date thresholded images to obtain the seasonal extent of flooding. However, in comparison to the multi-date composite image, it was clear that we were losing information. Wang (2004) used a thresholding method of JERS imagery to map extent of flooding in forested floodplains of North and South Carolina. Their goal was to create a single algorithm (threshold) to use on single date wet and dry season imagery. They compared their results to changes in river stage height and discharge and found good agreement. While this worked well for distinct wet and dry season imagery, it may not work as well in comparing more subtle differences between two wet or two dry season images. The brightness of the flooded forests changes with season, recent rainfall versus dry canopy conditions, and degree of flooding. Therefore, a single threshold would have to be chosen carefully to apply to all image dates and even then it is likely that some information would be lost or overestimated.

The multi-date composites of each study area were examined to determine the feasibility of a multi-temporal technique (see Figure 10 for example). In Figure 10, those areas of pink, orange, white and red are potentially flooded. It is fairly clear from the composites which areas are potentially flooded, and thus it was decided that a procedure may be devised to automatically extract the information needed

Since the composite images are showing us the potentially flooded areas, a categorical map could be made from these images to isolate those locations. The major sources of enhanced backscatter at L-band within these study areas are forested wetland, urban, and forest plantations. To eliminate errors due to urban a simple masking of the final product with a forest/non-forest mask would do, but it would not eliminate the errors due to the row structure of the pine plantations. Since the NWI is the basis of all wetland analyses, it was decided to use it to grab only those areas within a SAR-derived map that intersect an existing known forested wetland. This method eliminates urban and plantations. Another potential source of error is a ridge or hillside perpendicular to the line of sight of the radar. This also causes enhanced scattering and would most likely occur along coasts where there are exposed ridges not blocked by forest cover. This may cause issues in the dune and swale regions to some degree, or along the Lake Superior coast of the UP where rock outcrops occur. Using the NWI should filter most of these sources of error out.

6.1 Inundation Mapping Methods

The steps taken to create the inundation products were to first filter the radar imagery to reduce speckle. This was done in Imagine using the LeeSigma radar filter using first a 3x3 window and next a 5x5 window. The data were then converted from floating point to 16 bit since the maximum likelihood classifier in Imagine does not work well with floating point data. The maximum likelihood classifier was used to create 100 classes. These classes were then consolidated to 5 classes (and in the case of Leelenau 4 classes) to include: low return, low vegetation, deciduous forest, coniferous forest, and woody wetland. For the Leelenau study site, the first two classes were combined (low return and low vegetation). With L-band SAR the low return included bare fields, agriculture, and open water. Low vegetation was separated as the higher backscatter end of low return, which likely was vegetated. Woody wetland included forested and shrubby wetlands.

The new SAR-maps were visually checked against IFMAP, NWI and the original composite SAR imagery to determine if categorical boundaries were consistent. Adjustments to the woody wetland classes of the new products relied most-heavily on their comparison to the original composite SAR imagery. Next isolated pixels were removed by using the clumping and sieving tools of ERDAS Imagine.

Once these products were set, the woody wetland classes were extracted and overlaid on the NWI. Then only those areas of the new maps were kept that intersected an existing NWI "scrub-shrub" or "forested" wetland polygon. By doing this we eliminated areas of high return that were not wetlands. This is demonstrated in Figure 13 which shows the SAR-classification for the Mackinac study site with the potentially flooded woody vegetation in pink and red. The pink areas are those locations that did not intersect an NWI polygon that was labeled woody wetland (these areas were eliminated from the final map) while the red areas did intersect a polygon labeled "scrub-shrub" or forested wetland". Note that many of the pink areas eliminated from the woody wetland inundation map are adjacent to dark green areas which represent coniferous forests (Figure 13 zoom in). In many cases these areas were pine plantations. The row structure causes enhanced backscatter. This was determined from IFMAP labels and airphotos. Also, the NWI masking did not completely eliminate the urban areas in the Leelenau maps when there was a wetland directly adjacent to an urban area. Therefore some urban areas had to be further eliminated from the inundation maps, especially in the southern portion of the Leelenau scene. The resulting extent of inundation maps are presented in Figures 14-16. In these maps extent of inundation is overlaid on the corresponding NWI. The SAR-derived extent of inundation layers are being delivered on CD-ROM.

Note that a conservative approach was taken when mapping the extent of flooding at these sites. The boundaries of the NWI wetlands were often greater than the areas that appeared bright in SAR the imagery. In figure 10, the green areas near the pink areas are sometimes wetlands according to the NWI and IFMAP but other times they were coniferous forest in these references. Therefore these "green" areas were assumed to not be inundated during the SAR overpass collections of this study.

While these products cannot be validated per se, they serve as a starting point for a normal year, and can be checked against future imagery from the follow-on satellite to JERS, the Japanese ALOS PALSAR. Using the future satellite, which should be launched into orbit in early 2005, sites can be set up to field check and the methods used here can be applied to a seasonal set of imagery to map inundation extent. Next the

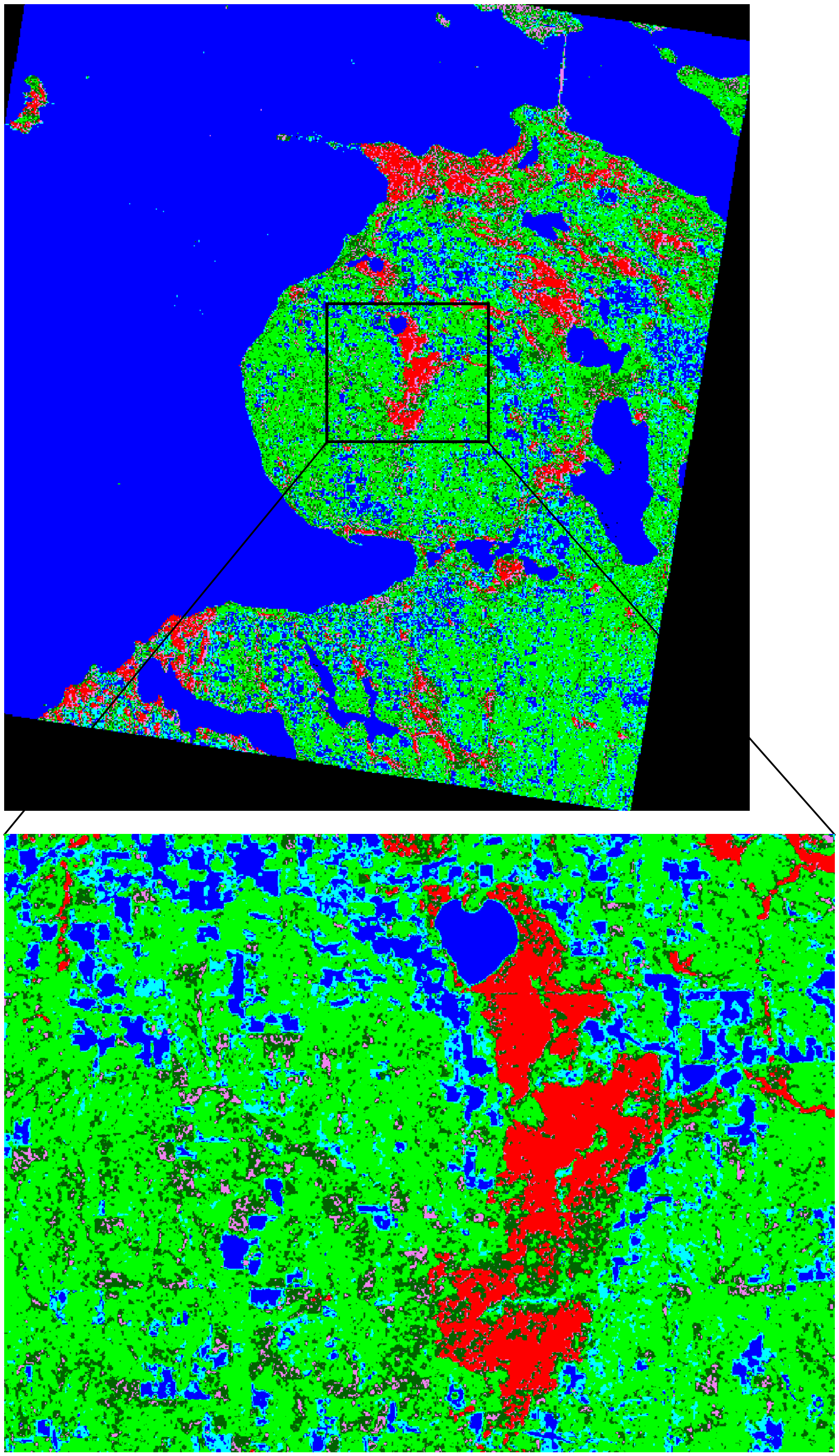


Figure 13. Four-date JERS classification with potentially flooded woody vegetation in pink and intersected areas with NWI in red. Blue represents areas of low return, cyan low vegetation, light green deciduous forest and dark green coniferous forest. Note that this figure was made prior to the removal of the city of Charlevoix.

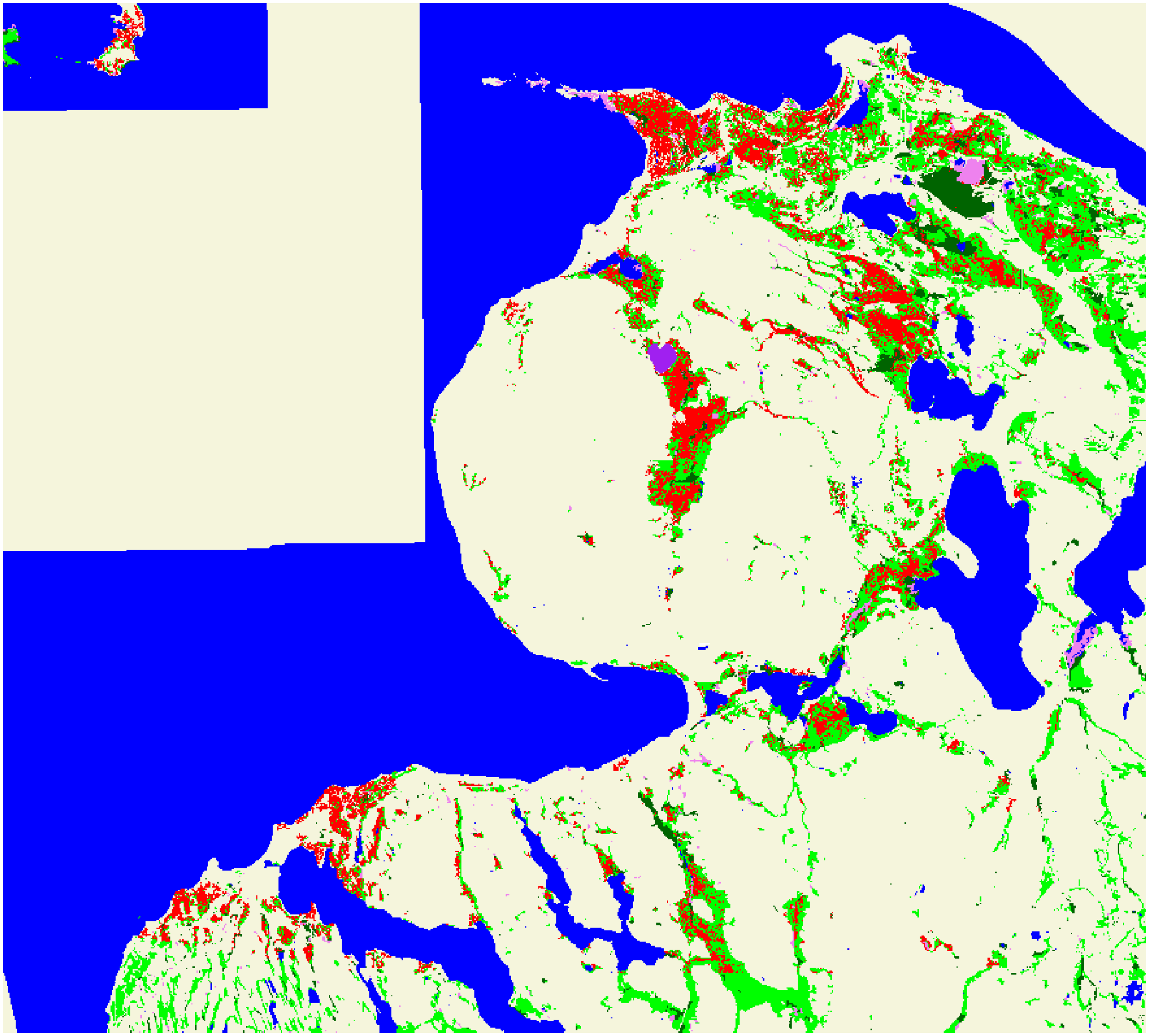


Figure 14. Extent of inundation in woody vegetation (red) overlaid on NWI for the Mackinac study area.

NWI-blue=water, pink=emergent, green=forested wetland, dark green=shrubby wetland, purple=floating aquatic.

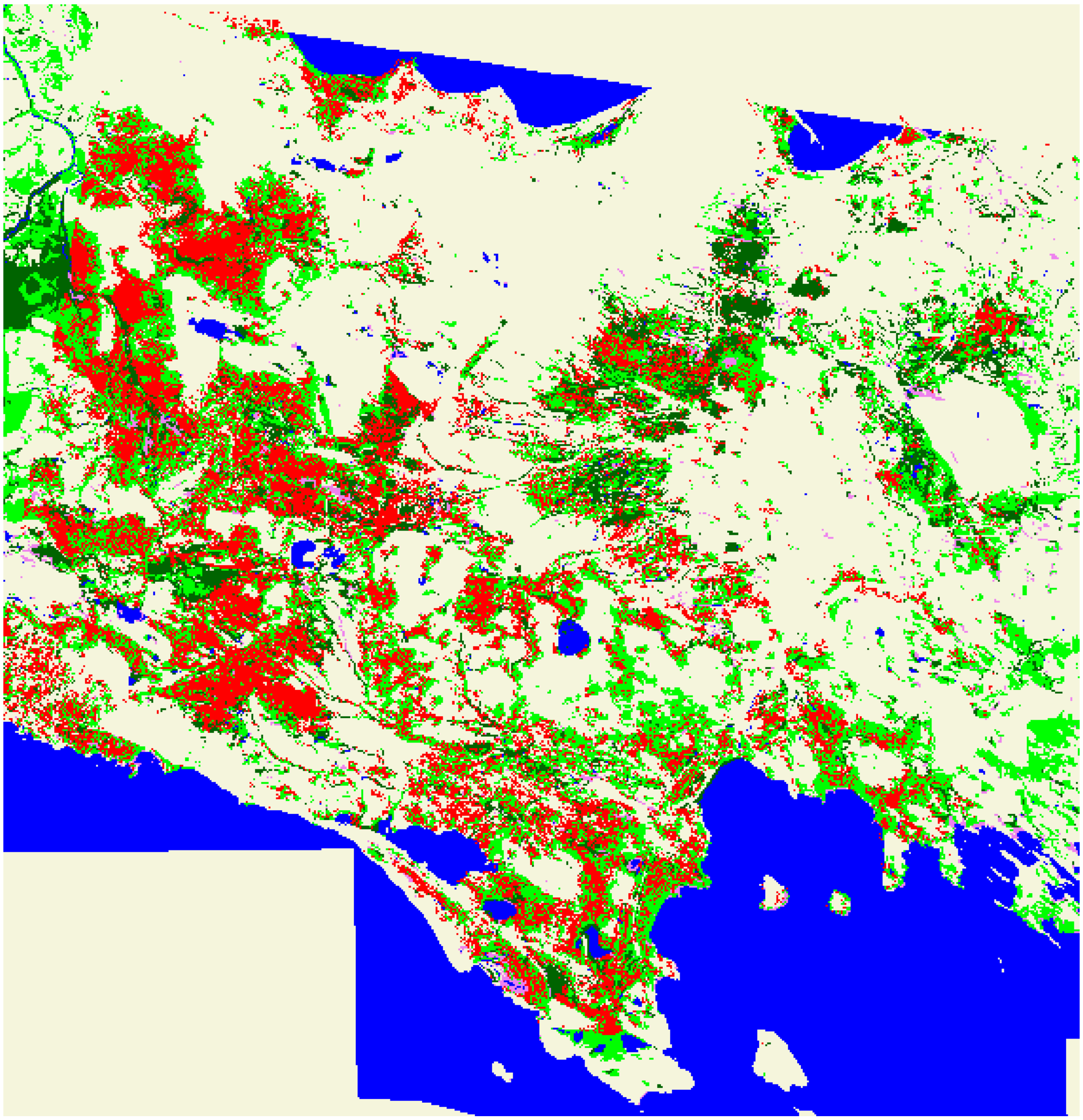


Figure 15. Extent of inundation in woody vegetation (red) overlaid on NWI for the UP study area.

NWI-blue=water, pink=emergent, green=forested wetland, dark green=shrubby wetland, purple=floating aquatic.

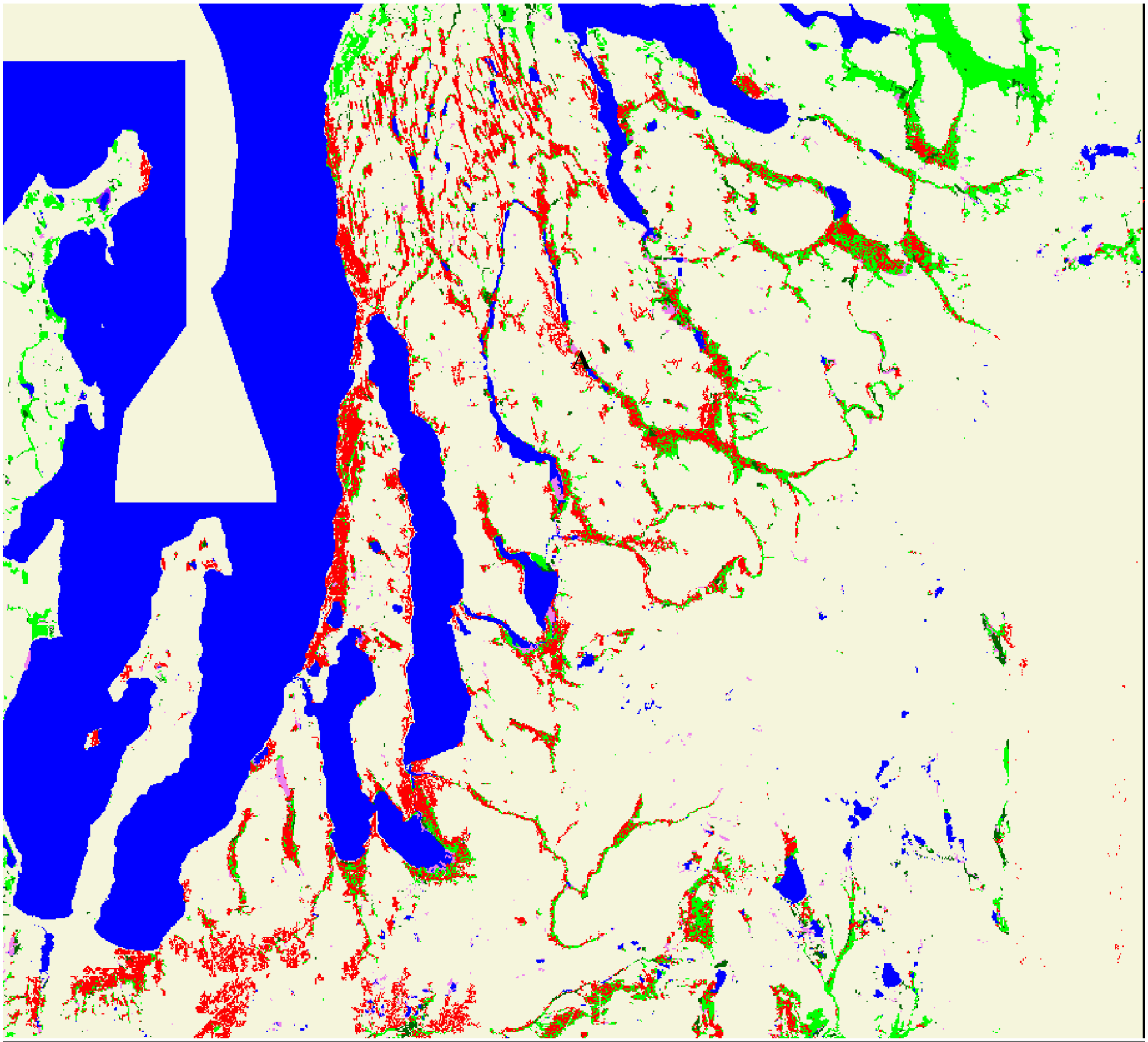


Figure 16. Extent of inundation in woody vegetation (red) overlaid on NWI for the Leelenau study area. Note that there may be errors in hilly regions adjacent to NWI wetlands since the SAR data often pick up strong reflections from hillsides perpendicular to the beam, such as location A above.

NWI-blue=water, pink=emergent, green=forested wetland, dark green=shrubby wetland, purple=floating aquatic

rainfall and lake levels can be checked to determine if it is a normal, wetter or drier than normal time period and the extents compared. Previous studies have also used the general changes in hydrology to validate changes in the flood extent maps that they created with SAR (Hess *et al.*1995, Townsend 2001, Wang 2004).

7.0 SAR and Landsat Fusion for Improved Wetland Mapping and Monitoring

Since the radar imagery and Landsat imagery compliment each other, it is fitting that the capabilities of each be merged. Each of these two sensor types has been proven in the past to provide information that is useful to the identification of land cover and wetlands but little research has been performed in the fusion of the data. Although several techniques were evaluated (see Lump Classification section 7.2.1 and Step-wise Classification section 7.2.2), the best process that we developed involved separate classifications of the Landsat imagery and the radar imagery into the most detailed classes possible with the SAR-derived classes complimenting the Landsat (Individual Classification and Recombination section 7.2.3). Next the two classifications were fused together, and the results visually interpreted to produce a final classification. This was the simpliest method and the most robust. The ultimate classification was assessed for accuracy by a comparison to currently available landcover datasets (in the absence of detailed ground truth information). The results were promising; with both examples producing an overall accuracy of about 70% compared to the reference data.

7.1 Study Sites, Image Datasets, and Reference Data

The two study sites that were analyzed for Landsat SAR data fusion were the Lake St. Clair and Lake Ontario test sites. Lake St. Clair was chosen because it has a diverse selection of land cover including a large amount of urban and suburban areas, rural farm fields, and a large amount of wetlands (various species) that occur at the delta as the river enters the lake. The Lake Ontario study was chosen because it is mainly rural, has isolated patches of vegetative wetlands, and has a relatively large amount of potentially forested wetlands. These two areas provide different sets of land cover classes and thus an opportunity to test the land cover identification algorithm. Note that, as stated earlier, the JERS data available over the Lake St. Clair site were from seasons not optimal for forested wetland detection, so forested wetlands were not identified in the corresponding classification. C-band data were ordered from leaf-off conditions to determine their utility in Great Lakes forested wetland delineation, however the forests must be too dense for canopy penetration with this 5.7 cm wavelength, because no enhanced backscatter was observed from Radarsat or Envisat data from spring collections. Townsend (2001) found Radarsat C-HH data to be useful for forested wetland delineation in southern bottomland forests, but those forests must have been of lower stature and more open canopied.

Over the two study sites there were many different image data sets available. The desired sets included seasonal Landsat and radar imagery (spring, summer, and fall) that were collected in the recent past. For the Lake St. Clair study site there were three Landsat images (collected from Landsat 7 ETM+) utilized: October 30, 2000, March 23, 2001, and August 30, 2001. There were a total of four radar scenes that were of interest: two JERS and two Radarsat. The JERS scenes were collected on March 28, 1995 and August 10, 1998. The Radarsat images (C-band, HH polarization) were collected on October 3 and October 27, 1998. Because of the close proximity in date between the two Radarsat images, only the October 3rd image was used in the processing. There are as many as 6 years between the JERS and Landsat collections but analysis of the imagery indicated that few major changes have occurred in this area. Also, due to the methodology, a site would first be checked for vegetation cover in the Landsat and then checked for flooding in the radar.

The Lake Ontario site had a seasonal set of images from the Landsat, JERS, and ERS sensors. The Landsat images were collected in 24 June 1993 (Landsat 5, TM), 12 August 2002 (Landsat 7, ETM+), and 18 December 2002 (Landsat 7, ETM+). There are nearly 10 years between the dates of collection but as with Lake St. Clair there appeared to be few major changes to the land cover within the study area and since the SAR imagery were from 1993, the Landsat 1993 image was included in the analysis. The JERS (L-band, HH polarization) was collected on 11 April, and 8 July and 17 October 1993. The ERS images (C-band, VV polarization) were collected on 17 April, 7 June, and 25 October 1993. In investigating the discrimination of landcover classes (especially wetland species) it seemed that the JERS imagery performed better than the ERS in most circumstances including the identification of flooded forests. But the ERS did provide some valuable information to discriminate low lying vegetation and improve the identification of urban areas. Thus, it was decided to utilize all three JERS bands and include a single ERS band (7 June) into the analysis. The June ERS image was least affected by wind on the water and the growing vegetation seemed most identifiable during this time period.

Reference data were chosen from the two study sites to provide training data for the classifications and to allow for testing. In both cases the most recent and most detailed land cover datasets were desired. At the Lake St. Clair study site the reference data were mainly provided by IFMAP (Integrated Forest Monitoring, Assessment and Prescription). This land cover data set is produced by the Michigan Department of Natural Resources. It is mainly based on the analysis of seasonal Landsat imagery (collected between 1997-2001), but is supplemented with selected high resolution images, existing land cover maps, and large amounts of field work. IFMAP provides a very detailed description of land cover but is only available for the Michigan portion of the study area. Thus, the bulk of the training samples were collected from the Michigan side of the study site and all accuracy assessment was limited to this side as well. Arzandeh and Wang (2003) created maps of the spread of *Phragmites* on the Canadian side of Lake St. Clair and a visual comparison was made with our resultant maps. The reference data gained from IFMAP was supplemented by the professional analysis of Dennis Albert, who has many years of experience studying this area and our field visits.

Unfortunately for the Lake Ontario study site, New York State does not offer a state-wide land cover product similar to IFMAP. For this study location, the National Land Cover Dataset (NLCD) seemed to be the best product available. The NLCD is created by the USGS and is based on Landsat imagery that was collected around 1992. Similar to IFMAP the imagery is supplemented by the incorporation of existing ancillary datasets. The class descriptions in the NLCD, since it is a national database, are not as detailed as that of IFMAP. To supplement the coarse nature of NLCD, high resolution Digital Ortho-Quarter Quads (CIR, 1m x 1m resolution) were utilized in questionable landcover areas. Also, field visits were performed at two locations that were of great concern (Figure 8). It should be noted that errors have been found in the NLCD dataset and a better source of reference data would be desirable. To supplement this dataset for validation, the new classification maps are compared to the NWI and to field data collected by Marci Meixler and Mark Bain of Cornell University for their biocomplexity study.

7.2 Sensor Fusion Classification Algorithms

Each of the three seasonal dates for the Landsat imagery was composed of 7 individual bands. The “blue” band (band 1) is generally not used in vegetative classification because it is often severely scattered by the atmosphere. The thermal band of the imagery was collected at a nominal resolution of 120-m x 120-m, but has been resampled to 30-m x 30-m. This resampling process provides a false sense of improved resolution, when in reality no additional data are created. Because of these limitations, the Landsat image sets were reduced from the original 7 bands to 5 bands per date, eliminating the blue band and the thermal band from further analysis. For a three date seasonal image set, that produced a 15-band image.

7.2.1 Lump Classification

Several different classification algorithms were developed and applied to the two study sites. Some of the results showed promise while others produced quite poor results. An initial method to classify the Lake St. Clair site was to layer stack (lump) all three dates of Landsat imagery (15-bands) and the three radar (2 JERS and 1 Radarsat) dates into a single 18-band image set. This image set was then classified using the standard maximum likelihood statistical classification algorithm. The training data for this example was taken from the reference datasets available. In this example, a 15 class result was produced. When the results of this technique were poor. It seems that the lumping of all the images together neutralized the unique aspects of the individual sensors, leaving many landcover features difficult to separate. Also, by lumping 15 landsat bands and only 3 radar bands, the information in the Landsat “overpowered” that of the radar, thus reducing any contribution that the radar may have to identify difficult land cover classes.

This lump classification process was performed a second time but for this example the number of Landsat images was reduced to a single band per date. The Near-IR band from each date (3 dates) were stacked with the three radar images, and classified according to the procedure above. The resulting product also showed poor classification results and thus this process was also abandoned.

7.2.2 Stepwise Classification

A second algorithm developed was designed to systematically step through the image, identifying a single land cover class, removing that class, and then continuing with another unique class. The process removed the most readily identifiable classes first, leaving only the more difficult (confused) classes for later in the classification. The advantage of this process is that by removing easily identifiable classes, the remaining pixels: (1) have fewer possible classes to belong; and (2) the removed pixels will not be mis-identified as a different class further in the processing. This process was initially established for the Lake St. Clair study site.

The most easily identifiable class in the imagery was that of open, standing water. This class was identified using a threshold (15) on the mid-IR (band 5) of the March image. This class of water was then removed. The forested areas in the image were identified next through a simple classification of forest and non-forest. The forested areas have a unique spectral return in the Landsat seasonal images, they were removed, leaving only non-forested areas remaining. (If it had been possible to identify forested wetlands with the SAR imagery available, then the forested areas would have been tested for flooded vs. non-flooded based on an L-band radar threshold). The non-forested areas were then separated into vigorous vegetation and non-vigorous vegetation based on a NDVI threshold (65) of the August Landsat image. Each NDVI group was further separated by applying a threshold of the total power of the radar (65). Pixels with a low vigor and a low total power were classified as cropland. Pixels with a low NDVI and a high total power were run through a maximum likelihood classification based on the radar imagery into the following classes: *Phragmites*, *Scirpus*, cattail, and urban. Pixels that had a high NDVI and a low total power were classified as woody vegetation (shrubland). Pixels with a high NDVI and a high total power were classified into suburban and row crops based on a simple maximum likelihood classification based on the Landsat August image.

This process held high hopes for being successful but it turned out to take a large amount of time and produced nominal results. The visual method to produce the thresholds at the various steps was very time consuming and was site specific. The resulting map was not as good as we had hoped. The results could have been improved if a large amount of time was placed in the threshold determination. Because of the transportability issue and the time-consuming nature of the methodology, this process was never applied to the Lake Ontario imagery.

7.2.3 Individual Classification and Recombination

The Landsat images and the radar images each have unique information that must be preserved to properly identify land cover conditions. Each of the unsuccessful examples above seemed to lose, or minimalize, the unique aspects of these sensors. The following "individual classification and recombination" algorithm was able to keep these differences and use them to discriminate land cover types. In this method each data set (Landsat (15-bands) and radar (3-bands)) were individually classified into land cover classes using the maximum likelihood algorithm (may be different classes) and then the results were combined on a pixel-by-pixel basis. The combined results were then analyzed and labeled as an ultimate land cover class through interpretation with the reference data. In the ultimate classification some land cover features were clearly identified by Landsat alone (such as water and forest), others by radar alone (such as *Phragmites* and *Scirpus*), but the majority were identified through the interaction between the two.

This process was first applied to the Lake St. Clair study site. First, the 15-band Landsat image was classified into 12 different land cover features using the maximum likelihood classification algorithm. The training sites for this supervised classification were collected from the reference data. The 12 classes created are shown in Table 10.

Table 10. Class descriptions for Lake St. Clair Landsat classification.

Class Name	Description
Water	Standing open water
High Density	Areas that are pre-dominantly composed of impervious surfaces

Class Name	Description
Urban	
Low Density Urban	Areas that have a mixture of impervious and landscape vegetation
Forest	Areas of continuous tree cover (all forests are deciduous in this area)
Emergent Wetland	Areas that have herbaceous vegetation and are wet during some parts of the year
Wetland Shrub	Areas that have woody vegetation (sparse) that are wet for some part of the year
Wetland-permanent	Areas that have low vigor herbaceous vegetation that are wet during all dates
Forage Crops	Cropland that is not plowed throughout or between seasons
Cropland 1	Four different examples of cropland, each identifying a different physical cycle (plowed vs. unplowed) or plant phenological cycle.
Cropland 2	
Cropland 3	
Cropland 4	

The second step of the process involved the classification of the 3-band radar image into 9 different classes. These classes were different than that of the Landsat imagery because the sensors are able to distinguish different phenomena. The classes for the radar classification are shown in Table 11.

Table 11. Class descriptions for Lake St. Clair radar classification.

Class Name	Description
Forest/Urban	Areas that are very bright on all dates of radar imagery
Phragmites	Wetland species that have high radar return in the summer L-band and a moderate return in the other radar dates.

Class Name	Description
Scirpus/ open submergent and emergent	Wetland species that are composed of short vegetation that has a low radar return in L-band imagery but a very high return in C-band
Cattails	Wetland species that are taller than the *Scirpus* and have moderate radar return in the spring L-band image and high returns in the summer L-band and fall C-band.
Wet Meadow	Areas of moderate radar return in all dates, indicating a woody species that may be wet at times
Forage Crops	Areas that are not harvested throughout the season and are well irrigated.
Cropland1	Three different examples of cropland, each identifying a different cycle of the farming process: some plowed, some growing, and some recently harvested.
Cropland2	
Cropland3	

The individual classification results were then recombined into a single classification. This was performed by recoding the 12-class Landsat classification into values of 10s (10, 20, 30…120) and recoding the radar classification into values 1-9. Then the values were added together on a pixel-by-pixel basis, producing possible values between 11-129. These recombined classes were then interpreted, by comparison to the reference data, and assigned into a final 11-class file. This final class identification relied on only the Landsat for some classes (such as water, forest, low density urban), only the radar for others (*Phragmites* and *Scirpus*), and a combination of both for the majority of the classes. The final classes are described below in Table 12.

Table 12. Combined Landsat and radar landcover results for the Lake St. Clair study site.

Class	Description
Water	Identified through the Landsat, regardless of the radar results
High Density Urban	Identified by an urban class in the Landsat imagery and a urban_forest (bright) from the radar class

Class	Description
Low Density Urban	Identified through the Landsat, regardless of the radar results
Scirpus	Identified through the radar classification and reinforced by being classified as a wetland/vegetative class in the Landsat imagery
Phragmites	Identified through the radar classification and reinforced by being classified as a wetland/vegetative class in the Landsat imagery
Cattail	Identified through the radar classification and reinforced by being classified as a wetland/vegetative class in the Landsat imagery
Wetlands_other	Identified as wetlands in the landsat imagery but is different than *Scirpus, Phragmites*, and cattail
Shrubland (shrub wetland)	Identified through a Landsat class of shrubland and forest and has a radar classification of wet meadow or shrubland
Cropland	Identified by the four cropland classes from the Landsat imagery and the three cropland classes from the radar classification.
Forage Crops/Low Herbaceous	Identified by landsat imagery (forage, row crop) and radar imagery (forage)
Forest	Identified through a Landsat imagery forest class (Note: if the radar were from a time when forested wetlands could be identified, this landsat class would be combined with a radar class)

7.2.3.1 Filtering of Classification Results

The pixel-by-pixel classification resulted in many isolated pixels that should be removed to improve the value of the resulting product. This was performed by first grouping (clumping) all adjacent pixels with the same value. Any group that contained less than 10 pixels was removed (sieved) while any group with more than 10 pixels was maintained. The removed areas were replaced with the value of the pixels that form the majority of the surroundings (5x5 filter). This process removed isolated pixels and small groups of pixels and replaced it with the surrounding values, thus improving interpretability of the resulting classification (Figure 17).

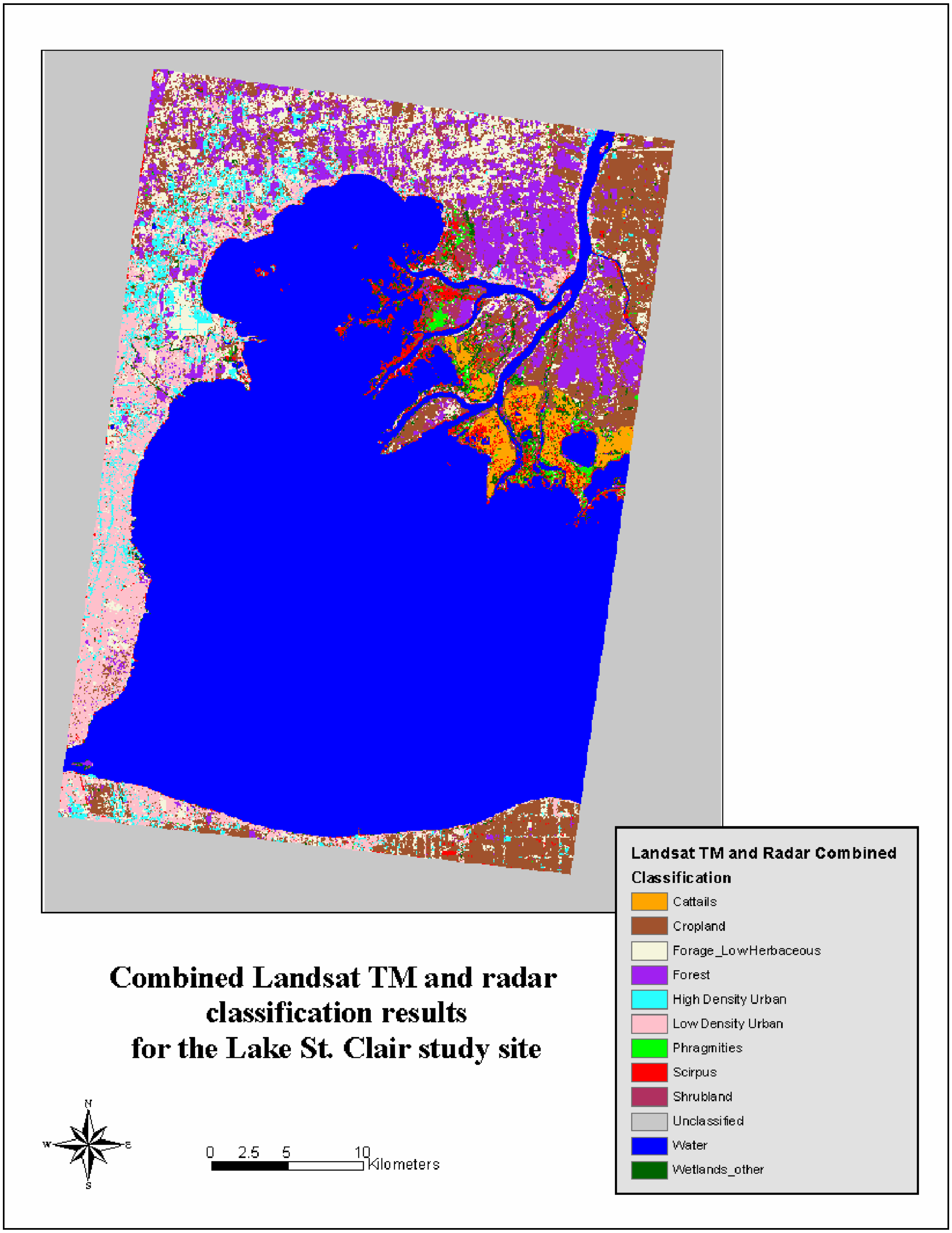


Figure 17. Landsat and SAR fused land cover classification results for the Lake St. Clair study area.

7.2.3.2 Accuracy Assessment

The assessment of the classification results was performed by comparing our map to IFMAP. First 10,000 random points were created across the image. Of these points 6686 were located in Canada and thus could not be compared to IFMAP, leaving 3314 random points. For each of the 3314 points the value from the IFMAP classification and the experimental classification were derived. Unfortunately, the class definitions from IFMAP do not perfectly align with that from the experimental classification, thus judgments needed to be made as to whether a pixel is “correct” or “incorrect”. In some aspects, such as tree species, the IFMAP is much more detailed than our experimental classification. In other aspects, such as wetland species, the IFMAP was much less detailed that our classification. The description below indicates which classes in IFMAP were considered correct for the experimental classification (Table 13).

Table 13. Linkage of experimental classification and IFMAP reference classes.

Experimental Class	IFMAP-1	IFMAP-2	IFMAP-3
Water	Water		
High Density Urban	High Density Urban	Roads/Paved	
Low Density Urban	Low Density Urban	Roads/Paved	
Scirpus	Floating Aquatic	Emergent Wetland	Mixed Nonforest Wetlands
Pharagmites	Floating Aquatic	Emergent Wetland	Mixed Nonforest Wetland
Cattail	Floating Aquatic	Emergent Wetland	Mixed Nonforest Wetland
Wetlands_other	Floating Aquatic	Emergent Wetland	Mixed Nonforest Wetland
Wet Meadow/		Lowland Shrub	Emergent Wetland

Experimental Class	IFMAP-1	IFMAP-2	IFMAP-3
Shrubland			
Cropland	Row Crops		
Low Herbaceous	Forage Crops	Open Herbaceous	Parks/Golf Courses
Forest	All Tree Species	Northern Hardwood Association	Lowland Deciduous

Using the descriptions above, an accuracy assessment was carried out on the 3314 random points identified. The overall accuracy was 65.6% across the United States portion of the image. Shown below is a break down of the accuracy assessment based on the 11 classes of the experimental classification (Table 14).

Table 14. Classification accuracy for combined Landsat and radar classification of the Lake St. Clair Site. Reference data were from IFMAP.

	IFMAP Reference																					
Classification	Canada	low density	high Density	roads/paved	row Crop	orchard	herbaceous	upland shrub	parks, GC	deciduous	pines	mixed forest	water	Lowland deciduous	floating aquatic	Lowland shrub	Emergent	Non-forested wetland	Bare sand/soil	bare/sparse veg	Total	Correct	User's Accuracy
water	5356	1	0	0	0	0	1	0	1	0	1	0	520	0	3	0	17	1	0	0	545	520	95.4
high Density	29	27	74	44	18	0	25	0	1	4	1	0	0	1	0	1	0	0	3	0	199	118	59.3
low Density	108	252	37	198	19	1	0	0	6	58	15	2	4	10	0	0	4	0	0	0	606	450	74.3
Scirpus, submergent, emergent	90	8	4	6	8	0	9	0	4	1	1	0	26	0	5	0	48	8	0	0	128	61	47.7
Phragmites	20	0	0	0	6	0	5	0	0	0	0	0	0	3	2	1	17	4	0	0	38	23	60.5
Typha	120	0	0	0	3	0	0	0	0	0	0	0	7	0	6	0	11	2	0	0	29	19	65.5
wetlands_other	70	4	4	3	3	0	4	0	0	5	0	0	22	7	14	3	29	5	0	0	103	48	46.6
wet meadow/ shrub	45	3	1	4	22	0	41	2	0	49	0	1	2	14	1	41	27	5	0	0	213	87	40.8
cropland	595	2	14	2	247	2	34	0	5	17	2	0	8	22	3	7	31	2	0	0	398	247	62.1
forage/low herbaceous	105	17	15	46	257	1	105	0	33	58	0	1	3	2	1	5	6	1	0	1	552	395	71.6
Upland Forest	148	10	2	5	21	0	37	8	1	174	0	3	0	185	14	16	12	3	0	0	491	196	39.9
TOTAL	6686	324	151	308	604	4	261	10	51	364	20	7	592	244	49	74	202	31	3	1	3300	2164	
Correct	exclude	252	74	242	504	0	105	8	33	173	0	3	520	199	27	41	132	24	0	0			
Producer's accuracy		77.8	49.0	78.6	83.4	0.0	40.2	80.0	64.7	47.5	0.0	42.9	87.8	81.6	55.1	55.4	65.3	77.4	0.0	0.0			65.6

As shown above the class that was most successfully identified was water with over 95% of the pixels correctly identified. Our classification did well with low density urban, cattail, *Phragmites*, low herbaceous, and cropland (all above 60% user's accuracy). There were some issues with the classification of *Scirpus* (47.66%), wetlands-other (46.60%) and wet meadow (42.25%). The issue with the wet meadow/shrub is confusion with tree species. This is a common point of confusion due to the fact that a shrub is in fact a small tree. As expected the spectral attributes of the two land cover classes significantly overlap. As for *Scirpus* and wetland-other both occur at the boundary between the land and the water and several areas are mis-identified as water in IFMAP. This may be caused by water level differences between the dates on which IFMAP was created and the dates analyzed using our approach (see Figure 6 for changes due to 19 cm difference in water level on two Radarsat collection dates). If the wetland areas identified as water in IFMAP are removed from the analysis of the wetland species, the overall result increased to nearly 72% correct. The results for the herbaceous wetlands after the water confusion is removed are shown in Table 15 below.

Table 15. Improvement of wetland classes with the removal of water confusion

Experimental Class	Number of points	Number Correct	Percent
Scirpus	102	61	59.6
Phragmites	38	23	60.5
Cattail	22	19	86.4
Wetlands-other	81	48	59.3

By removing the water classes from IFMAP, all of the wetland species improved significantly in accuracy with the exception of *Phragmites*, which remained the same. The largest improvement was seen in cattails which improved by over 20%, up to 86% correct.

A visual comparison was also made between our classification of the Canadian side of the study area and maps produced by Arzandeh and Wang (2002 & 2003) of Walpole Island, Ontario. In 2002 Arzandeh and Wang used a single Radarsat scene

(1997) and Landsat data (1997), separately, to create 2 classification maps with 8 categories including forest, built-up, swamp, tall grass, water, agriculture, cattail and *Phragmites*. Their areas of emergent wetland (cattail and *Phragmites*) correspond well with the areas that we have mapped as emergent. However, their maps lack the detail that we gained by combining multiple dates and two bands of SAR imagery with the Landsat. Their goal was to use texture analysis of a single date of SAR imagery to improve classification accuracy with a single date of SAR. Generally, more than one date of imagery is available, but for those cases when only one date of imagery exists or can be acquired their techniques would be useful. In the second article by Arzandeh and Wang (2003), satellite optical data were used over the same test site to determine the spread of *Phragmites* from 1992 to 1998. They used three different optical remote sensors (Landsat TM 1992, SPOT 1996 Landsat TM 1997 and IRS 1998) and the extent of spread was different for each year, each sensor, and each month of acquisition. Some areas showed increasing spread from year to year but other areas of spread increased and then greatly decreased in the subsequent year. The technique that they used was to create classification maps for each sensor, date, year, and then conduct categorical change between years to obtain the change maps that are presented in the article. As was demonstrated with the hybrid change techniques in section 4.1 of this report, categorical change alone can result in an overestimation of change. Lastly, Arzandeh and Wang (2003) combined the results from all sensors and years into a single map showing change from cattail to *Phragmites.* Using this map we visually compared our classification results in Ontario to their cattail and *Phragmites* map. Their map shows existing *Phragmites* in 1992 based on Landsat and then change from cattail to *Phragmites*, but not from other cover types to *Phragmites*. Many of the areas in their map correspond to ours, but on Seaway Island, we do not show any *Phragmites*, but their map shows more than 50% *Phragmites*. This island is used to dispose of dredge and we show it as "cropland" since it has similar spectral characteristics to the agricultural fields. We also show much more *Phragmites* on the lower portion of Squirrel Island than they do in their maps. We show a mixture of wetland types on this island (*Scirpus,* cattail, *Phragmites* and other wetland types) while they show it as pure cattail. We attempted to correspond with the authors of this article to determine where their *in situ* data were collected and to get their input on our map, but the corresponding author is on sabbatical for 6 months. Further investigation of these areas are needed.

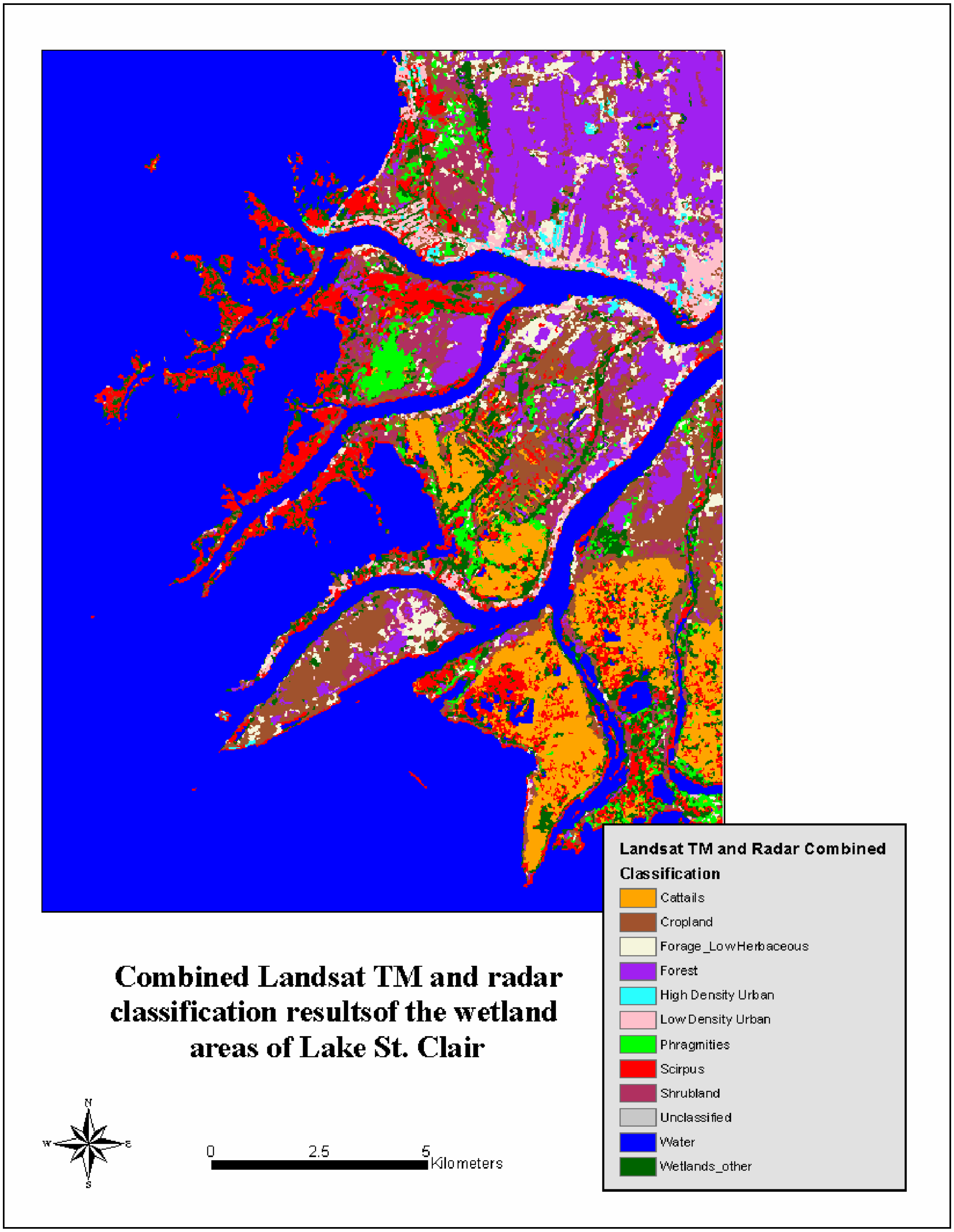


Figure 18. Subset of the Landsat and SAR fused land cover classification showing in more detail St. Johns Marsh, Dickinson Island, Harsen's Island and Walpole Island.

7.3 Lake Ontario Study Site

7.3.1 Landsat Classification

The individual classification and recombination algorithm proved to be the most successful of the approaches applied at the Lake St. Clair study site, thus it was applied to the Lake Ontario study site. Similar to the Lake St. Clair site, there was a three date (seasonal) set of Landsat images, each containing 7 bands. The “blue” and thermal IR bands for each date were removed from the analysis. The resulting 15-bands were layer stacked together and classified using the maximum likelihood algorithm. The reference data for this location were from the National Land Cover Database (NLCD) and from two known areas of investigation (field visits). The Landsat imagery was classified into 13 different landcover classes, which are described in Table 16.

Table 16. Classes for Landsat classification at the Lake Ontario study site.

Class	Description
Water	Areas of open standing water
High Density Urban	Areas that are predominantly composed of impervious surfaces
Low Density Urban	Areas that have a mixture of impervious and landscape vegetation
Deciduous Forest	Areas composed of trees that are deciduous
Coniferous Forest	Areas composed of trees that are evergreen
Mixed Forest	Areas composed of a mixture of deciduous and evergreen trees
Row Crops	Areas of fields that are planted with annual crops
Low Herbaceous	Areas of short vegetation (includes cropland) with high vigor.
Bare Soil	Areas of exposed soil, rock, and/or sand
Emergent Wetlands	Areas that have herbaceous vegetation and are wet during some parts of the year
Shrubland	Areas composed of short woody vegetation

Class	Description
Fields-Hay	Areas of herbaceous vegetation that has a lower vigor and are not harvested throughout the year, example hay field
Wetlands-other	Areas that are wet during parts of the year and have a combination of woody and herbaceous vegetation

7.3.2 Radar Classification

The Lake Ontario study site had four bands of radar imagery used in the classification. Three of these radar images were L-band, JERS imagery covering seasonal dates. The fourth was a C-band, ERS image collected on 7 June 1993. These four dates of imagery were layer stacked together and classified using the maximum likelihood classification algorithm. Using the NLCD as a primary reference, supplemented by the two areas that were field visited, the radar imagery was classified into 9 classes (Table 17).

Table 17. Classes for radar classification at the Lake Ontario study site.

Class	Description
Water	Areas of open standing water. This area is poorly identified because of the presence of waves in many of the image dates.
Urban/Flooded Forest	Areas that have very high radar return in all dates. These represent either urban areas or areas of forest that are flooded (forested wetlands)
Flooded Shrubland/ wet meadow	Areas composed of short woody vegetation, generally wet
Emergent Wetland	Areas of herbaceous vegetation that is predominately wet throughout the year
Forest1	Areas of non-flooded forest cover, this class covers the radar return in the higher elevations (Tug Hill area) of the imagery
Forest2	Areas of non-flooded forest cover that are found in the lower elevations, near the lake shore

Class	Description
Row Crop 1	Areas of field that are planted with annual crops, two classes to capture the different physical (plowing) and phenological differences of the fields.
Row Crop 2	
Herbaceous Field	Areas that have vegetation growing that is not plowed throughout the year, such as a hay field.

7.3.3 SAR-Landsat Fusion

Following the process used at the Lake St. Clair study site, the individual Landsat and radar classifications were combined into a single product. The Landsat classification were recoded to numerical increments of 10 (10, 20, 30,…130) while the radar results were recoded to ascending values between 1 and 9. The two results were then combined on a pixel-by-pixel basis, resulting in combinations with a range of values from 11 to 139. The combined values were then visually analyzed and placed into one of 12 final classes, as described in Table 18.

Table 18. Classes for the combined Landsat and radar classification at the Lake Ontario study site.

Class	Description
Water	Areas identified as water in the Landsat imagery, regardless of the radar classification
High Density Urban	Areas dominated by manmade materials, these areas were identified by high radar returns that were not forested areas in Landsat
Low Density Urban	Areas with a mixture of manmade features and landscape vegetation, these areas were mainly identified by the Landsat classification
Deciduous Forest	Areas of forest that lose their leaves throughout the season, identified through a combination of the Landsat and radar classifications
Coniferous Forest	Areas of evergreen forest, identified through the combination of classifications
Mixed Forest	Areas that are a mixture of coniferous forest and deciduous forest, identified through a combination of classifications

Class	Description
Forested Wetland	Areas are forest but have standing water on the ground throughout much of the year, identified as forest in the Landsat imagery and as urban/flooded forest in the radar imagery
Emergent Wetland	Areas of herbaceous vegetation that are wet at some times of the year, identified through the combination of radar classification and Landsat classification
Wetland-shrub	Areas of short woody vegetation that are wet at some points throughout the year, these are identified through the combination of sensor classification results.
Crop/pasture	Areas of herbaceous vegetation that are not plowed throughout the year, mainly identified through the Landsat classification
Bare Soil	Areas of exposed soil, sand, and/or rock, these areas were mainly identified through the radar and were confirmed by the Landsat classification
Row Crop	Areas that have herbaceous vegetation growing which is plowed at some point during the season. These areas were identified through a combination of the classification results.

The pixel-by-pixel classification for the Lake Ontario study site resulted in many isolated pixels. To improve the utility and interpability of the classification, the results were filtered by removing any contiguous areas that contained less than 10 pixels. These areas were then filled using the majority results (5x5 filter) from the surrounding pixels. The final map is presented in Figure 18.

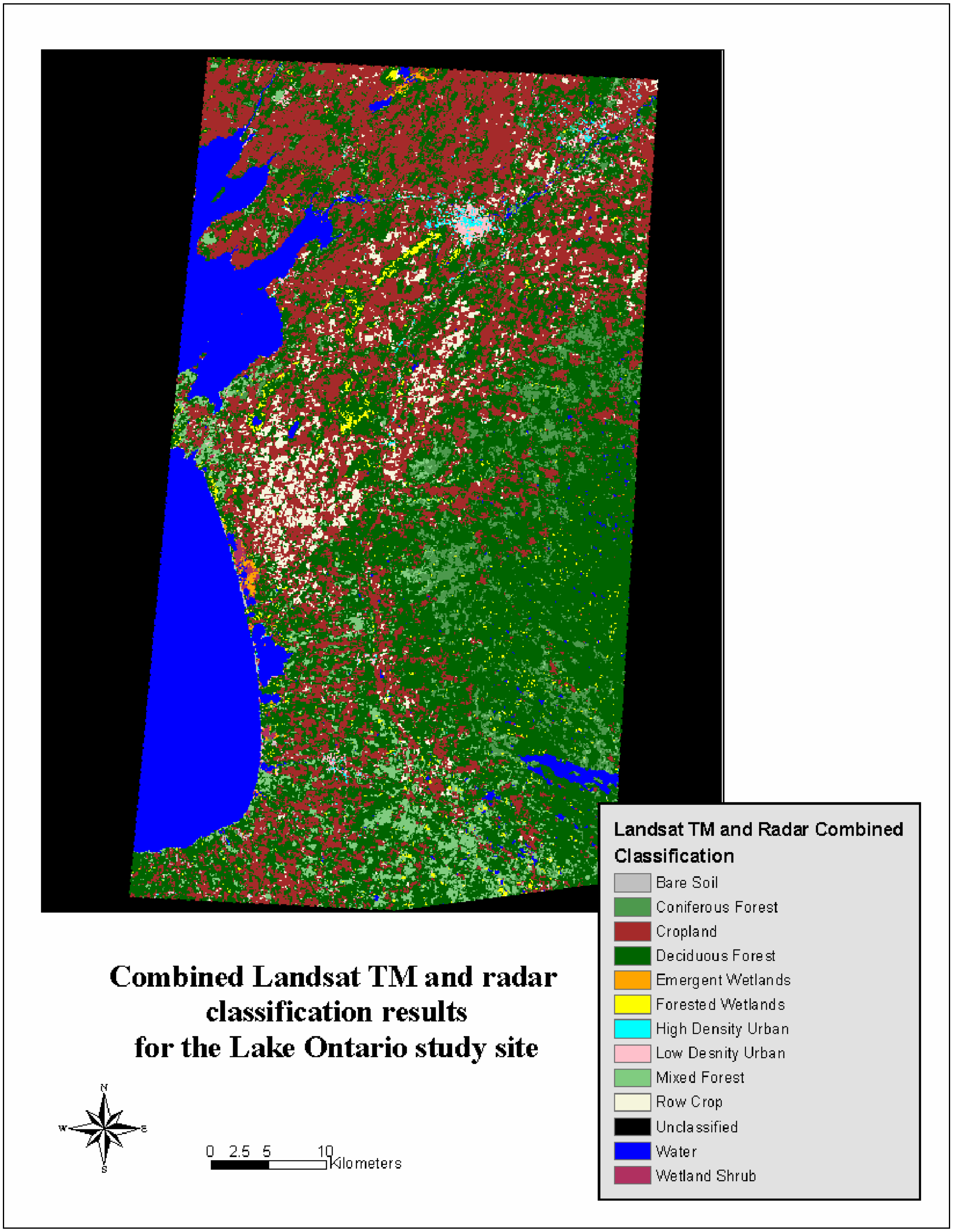


Figure 19. Landsat and SAR fused land cover classification of the Lake Ontario study area.

7.3.4 Accuracy Assessment

To assess the SAR-Landsat classification it was compared to the NLCD reference dataset. A test set of 5000 random point locations were created throughout the classified image. At each of these points the results of the experimental classification and the reference classification were derived. Similar to the Lake St. Clair study site, the class definitions between these two datasets do not perfectly match. The following Table 19 describes which NLCD classes were considered "correct" for each experimental classification result.

Table 19. Linkages between experimental classification and NLCD reference classes.

Experimental Class	NLCD-1	NLCD-2
Water	Water	
High Density Urban	High Density Residential	Urban
Low Density Urban	Low Density Residential	High Density Residential
Deciduous Forest	Deciduous Forest	
Coniferous Forest	Evergreen Forest	
Mixed Forest	Mixed Forest	
Forested Wetlands	Woody Wetlands	
Emergent Wetlands	Emergent Wetlands	
Wetland Shrub	Woody Wetlands	Emergent Wetlands
Crop/Pasture	Pasture/Hay	Row Crop
Bare Soil	Bare Rock	Strip Mines
Row Crops	Row Crop	

Using the descriptions above, an accuracy assessment was conducted on the 5000 individual points. Similar to the Lake St. Clair study, there were some areas where the wetland species were misclassified as water. This is most likely caused by different water levels during the imagery used to create the NLCD and our classification. To account for this, any wetland location that was classified as water (NLCD) was removed from the final analysis. This removed 60 points from the initial 5000, leaving 4940 points. The overall accuracy was 65.4% correct. The classification results for individual classes are presented in Table 20 below.

The classification compares best to the reference data in the classes of water, high density urban, crop/pasture, and row crops (all above 60% user's accuracy). The classes of deciduous forest and mixed forest also compared fairly well (50% user's accuracy or greater). The remaining classes do not correspond well to the reference data. Low density urban was most confused with deciduous forest (12 points out of 36). This may be because the majority of the vegetation in a residential setting is deciduous trees. Bare soil was completely misclassified, often confused with high density urban. This is expected since exposed sand or rock reflects a large amount of the energy incident upon it (both sunlight and radar). Since urban areas (predominantly concrete) have a similar response, it is not surprising that these two are confused. Since the wetland classes in our SAR-Landsat classification do not correspond well to those of the NCLD, we took a closer look at these wetland areas and questions were brought up concerning the accuracy of the NLCD. This dataset is national in coverage and is fairly general in its results. An example, centered around herbaceous wetland areas, is shown in Figure 20. This is the area that was field visited (Figure 8) and is the location of the biocomplexity study by Mark Bain.

Table 20. Accuracy assessment for the combined Landsat and radar combination at the Lake Ontario study site. Reference data are the NLCD.

	NLCD Reference															
Classification	Unclassified	Water	High Density Urban	Low Density	Bare	Transitional	Deciduous	Evergreen	Mixed Forest	Pasture	Row Crops	Recreation	Woody Wetlands	Emergent	Total	Correct	User's Accuracy
Water	1	682	1	3	1	0	23	3	11	11	1	1	4	3	744	682	91.7
High Density	0	0	8	0	0	1	1	0	0	2	1	1	0	0	13	8	61.5
Low Density	0	0	9	4	0	0	12	1	6	4	0	0	0	0	36	13	36.1
Deciduous	3	19	12	11	2	2	1245	41	249	391	62	1	79	4	2116	1245	58.8
Coniferous	0	2	0	0	2	2	85	96	14	0	1	0	6	0	206	96	46.6
Mixed Forest	1	0	1	2	0	0	45	20	94	13	4	0	9	0	188	94	50.0
Forested Wetlands	1	1	0	0	0	0	19	0	6	6	0	0	16	1	49	16	32.7
Emergent Wetlands	0	1	0	0	0	0	4	0	0	0	0	0	0	2	7	2	28.6
Wetland Shrub	0	2	1	0	0	0	4	1	2	1	0	0	0	1	12	5	41.7
Crop/Pasture	0	6	21	7	4	15	329	10	84	808	127	6	0	0	1402	935	66.7
Bare Soil	0	1	4	0	0	0	4	0	0	3	0	0	0	0	12	0	0.0
Row Crops	0	0	2	1	0	1	0	0	2	12	135	0	3	0	155	135	87.1
Total	6	714	59	28	9	21	1771	172	468	1251	331	9	117	11	4940	3231	
Correct	Exclude	682	17	4	0	Exclude	1249	96	94	808	262	0	16	3			
Producer's Accuracy		95.5	28.8	14.3	0.0		70.5	55.8	20.1	64.6	79.2	0.0	13.7	27.3			65.4

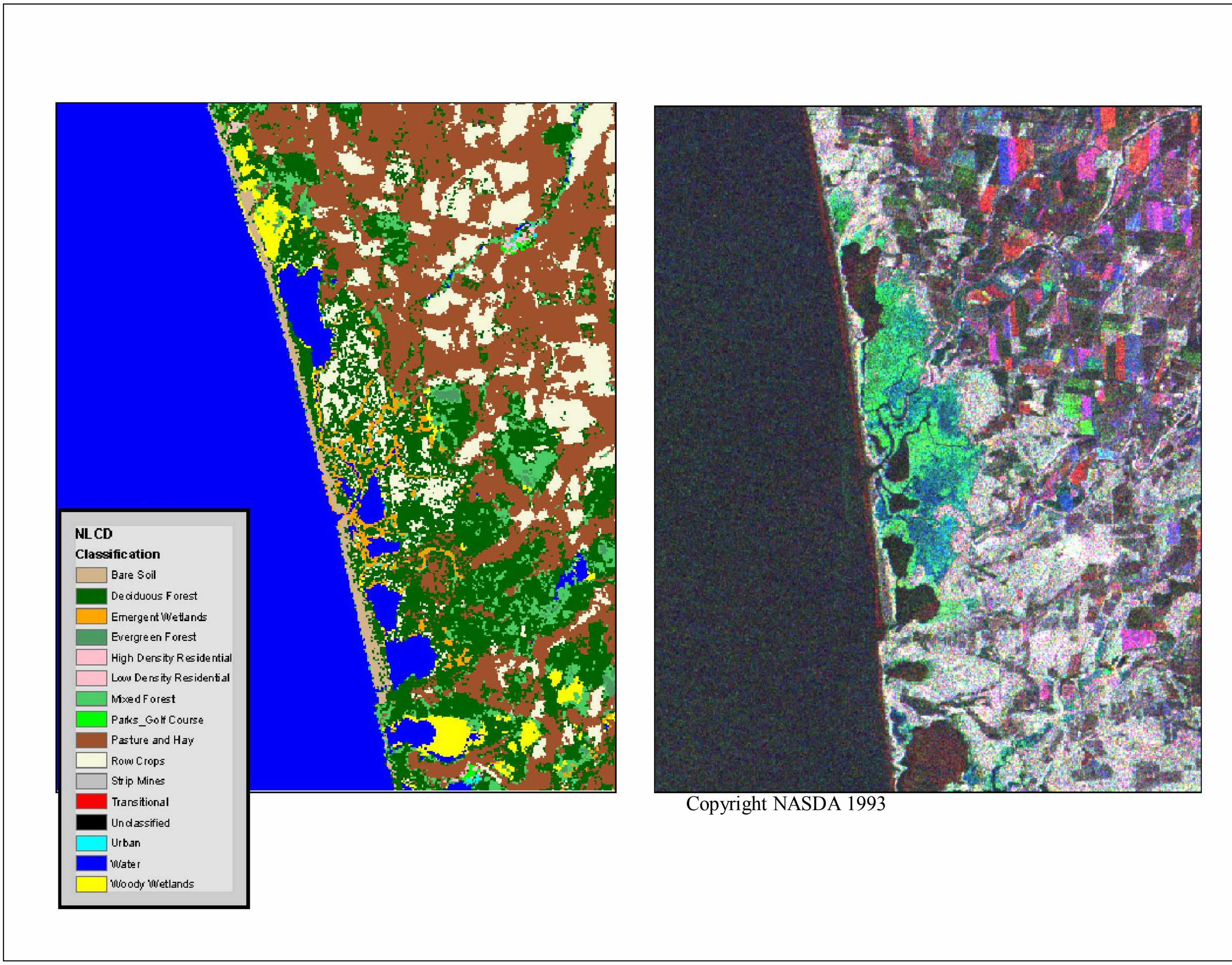


Figure 20. NCLD on the left and a three date L-band SAR composite from 1993. Possible land cover issues within the wetland regions of the NLCD.

In Figure 20 the areas of blue in the radar composite were identified as emergent wetlands by an on-site field collection. In the NCLD these areas are identified primarily as deciduous forest and row crops. Similarly, the green areas in the radar composite were identified as shrubby/woody or mixed wetland vegetation. The NLCD identifies these areas again as row crop and deciduous forest. This example shows that there are errors in the NLCD. And it should not be considered as an absolute land cover reference. We obtained field data from Mark Bain to conduct a validation on the areas of Figures 20 and 21. But first we conducted a comparison of our wetland classes to the NWI. It should be noted that the shrub and emergent wetland sites of figures 7&8 that were field visited, and that are labeled incorrectly in the NLCD as deciduous forest and cropland, are all labeled as emergent wetland in the NWI. The differences between some of the sites field checked and NWI may be due to changes in the wetland over the three decades since the NWI was created. The results of our comparison to the NWI (Table 21) had 94% overall accuracy, with all classes greater than 89% user's accuracy, except shrubby wetland.

Table 21. Accuracy Assessment for the Lake Ontario Study site using the NWI as reference.

	NWI Reference									
GD_class	Open Water	Aquatic Bed	Bare	Emergent	Woody Wetland	Urban	Unclassified	Total	Correct	User's Accuracy
Water	488	4	2	5	3	6	233	508	492	96.9
High Density Urban						11	4	11	11	100.0
Low Density Urban						28	6	28	28	100.0
Deciduous Forest (4)	8			14	127	1240	777	1389	1240	89.3
Coniferous Forest (5)	8			3		100	102	111	100	90.1
Mixed Forest (6)	8	0				96	74	104	96	92.3
Forest Wetlands (7)				1	71	5		77	71	92.2
Emergent Wetland (8)	2			71				73	71	97.3
Wetland Shrub (9)	2	2		6		3	2	13	0	0.0
Crop/Pasture (10)				8	6	1029	324	1043	1029	98.7
Bare Soil (11)			1			8	5	9	9	100.0
Row Crop (12)					1	139	28	140	139	99.3
Total	516	6	3	108	208	2665	Exclude	3506	3286	
Correct	488	4	1	71	71	2651				
Producer's Accuracy	94.6	66.7	33.3	65.7	34.1	99.5				93.7

The producer's accuracy in the wetlands was 34% for woody wetland and 66% for emergent. For the NWI woody wetlands, we labeled 127 out of 208 as deciduous forest. The problem likely lies in what areas were in fact inundated during the radar satellite collections. A wet, normal or dry year will provide different wetland extents. 66% for emergent wetlands is quite good, especially considering the likely changes of some of the wetlands labeled as emergent in the 1970s NWI to wetland shrub, as indicated by the field visits and point source field data of the biocomplexity study shown in Figures 20 and 21. The subset of the Landsat TM and SAR fused land cover classification on the left of Figure 21 includes an enlarged view of the field visited wetlands of Figure 8. Also overlaid are the point locations of the current biocomplexity study field locations (Mark Bain). The point colors indicate the dominant vegetation of each wetland type. The NLCD is also shown to the right in Figure 21, for comparison. The green biocomplexity study points represent cattail dominated wetlands which correspond to the wetland shrub (dark pink) areas in the Landsat-SAR fused classification and mostly deciduous upland forest (green) on the NLCD. It was noted in the Lake St. Clair study that cattail and other high biomass wetland vegetation cause an enhanced backscatter at L-band similar to forest or shrub vegetation. Therefore, the pink areas of our Landsat-SAR map should be labeled as shrub/high biomass herbaceous wetlands. The red points of the biocomplexity field locations represent mixed herbaceous wetlands which correctly correspond primarily to emergent wetlands (orange) on the Landsat SAR classification and on the NLCD (orange).

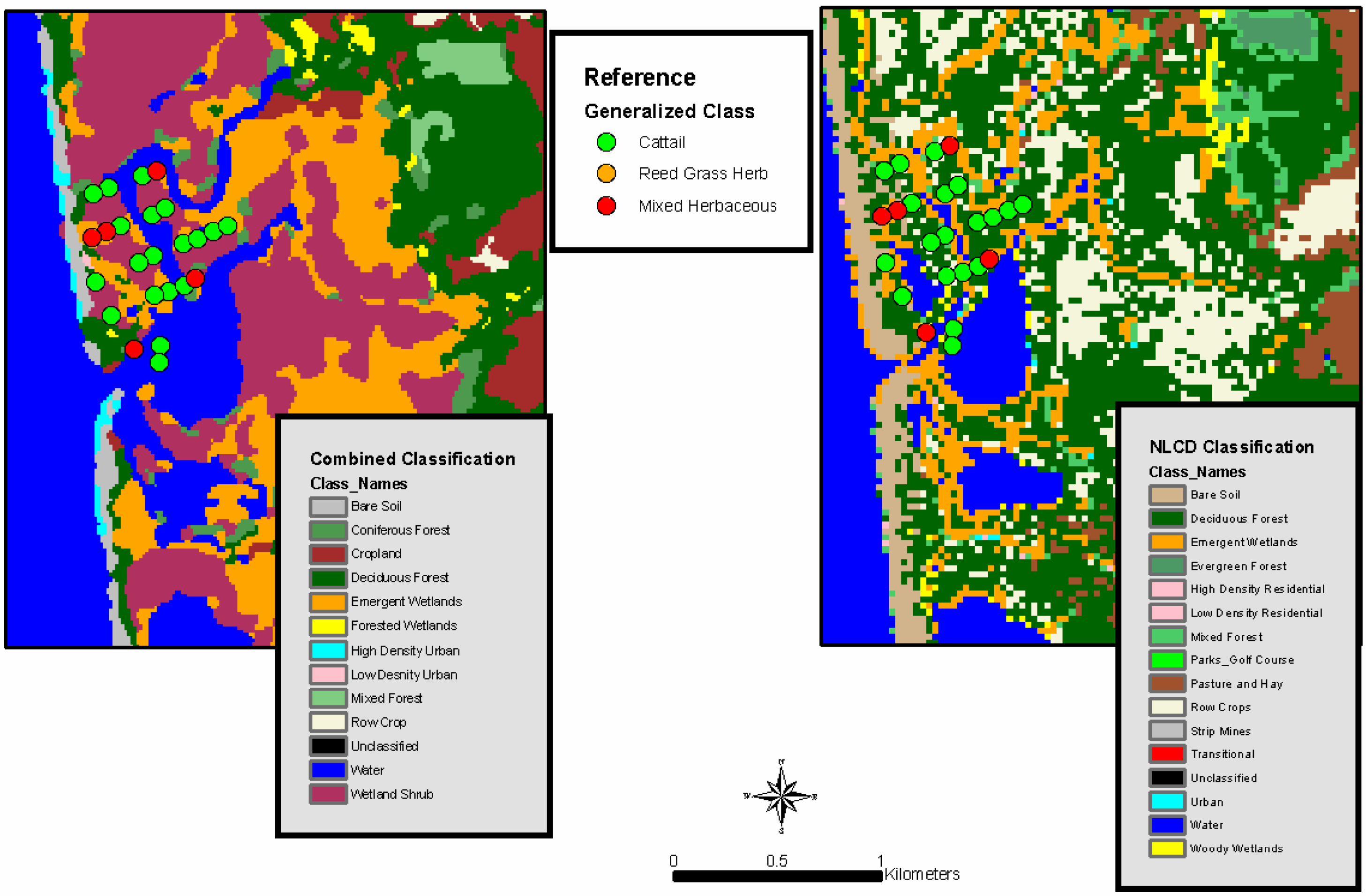


Figure 21. Subset of the Landsat TM and SAR fused land cover classification on the left, including an enlarged view of the field visited wetlands of Figure 8. Overlaid are the point locations of the current biocomplexity study field locations (Mark Bain). The point colors indicate the dominant vegetation of each wetland type. The NLCD is also shown to the right for comparison. The green points represent cattail dominated wetlands which correspond to the wetland shrub (dark pink) areas in the Landsat-SAR fused classification and mostly deciduous upland forest (green) on the NLCD. The red points correspond mostly to emergent wetlands (orange) on the Landsat SAR classification and to emergent on the NLCD (orange).

A validation analysis was conducted using all of the points of the biocomplexity study as reference (Table 22). Note that the areas from which these point reference data were collected are sometimes smaller than the 5 acre minimum wetland size that we were mapping. The pink areas of Table 22 represent the wetland types of the reference data considered correct for each of our Landsat SAR categories. The overall accuracy was 89%, with 67%, 89% and 91% user's accuracy in the wetland categories. The producer's accuracy ranged from 25 to 75% in the reference categories. Note that some of the sites fell on the edges of boundaries of open water/wetland or upland/wetland, and this may explain some of the misclassification into deciduous forest, coniferous forest, or water. Even slight errors in the geolocation of the northing and eastings of the study plots and/or in the georectification in the imagery could cause validation errors, especially when the plots are so small. Also, the extent of flooding at the time of the JERS overpasses may have affected what was labeled as wetland in our classification.

Table 22. Accuracy Assessment for the Lake Ontario Study site using the Cornell biocomplexity field data as reference

	Cornell/ESF Reference Generalized Description									
Classification	Cattail (Hybrid and Long Leaf)	P. Loosestrife Herbaceous	Reed Grass Herbaceous	Mixed Herbaceous	Alder Dominated Shrub	Mixed Woody Shrub	Mixed Wetland Forest	Total	correct	User's Accuracy
Deciduous Forest	3	1	1	5	2	2	5	exclude		
Coniferous Forest	3	0	0	3	1	2	0	exclude		
Forested Wetland	0	0	0	1	0	0	2	3	2	66.7%
Emergent Wetland	6	1	2	7	0	2	0	18	16	88.9%
Wetland Shrub	24	2	1	0	3	4	0	34	31	91.2%
Water	4	0	0	2	0	0	0	exclude		
Total	40	4	4	18	6	10	7	55	49	
correct	30.0	1	2	7	3	4	2			
Producer's Accuracy	75.0%	25.0%	50.0%	38.9%	50.0%	40.0%	28.6%			89.1%

7.4 Discussion of SAR-Landsat Fusion Results

In this analysis we found that the fusion of SAR and Landsat data can be difficult, yet the information derived from each is entirely complimentary. The final process developed was rather simple and involved the classification of each set of imagery individually and then recombining the categorical information and re-labeling into more specific classes. Since each sensor type produces unique information, it is the combined power that holds the greatest potential for improved land cover identification.

The algorithms developed here to improve land cover and wetland identification had overall good results for our two specific study locations. This is especially true considering the errors that we found in some of the reference data and problems with changing water levels. We found that the classification of water may vary significantly on different dates, thus affecting the classification of wetland areas. And with the radar, only those locations that were inundated during the satellite overpasses will be mapped as wetlands. The overall percent correct for the Lake St. Clair and Lake Ontario sites were 72% and 65.4-94% (NLCD-NWI as reference), respectively (when removing water edge effects).

The algorithms developed here provide a cost-effective, promising method for fusing optical Landsat and microwave radar imagery for the identification of land cover. The algorithms could be further refined, but the results thus demonstrate the unique capabilities of fusing optical and radar remote sensing imagery.

8.0 Review of Mapping Methods and Cost-Benefit Analysis

8.1 Comparison of Mapping Techniques

Many methods have been utilized for wetland mapping in the Great Lakes including air photo interpretation with ground truth, such as for NWI, and various Landsat techniques including a merged Landsat analysis with NWI, field truth and other ancillary data for IFMAP.

For the U.S. side of the Great Lakes, NWI serves as the base for wetland identification from the mid-1970's. For the Canadian side of the Great Lakes a coastal wetlands database is being created and updated based on air photo interpretation and ground truth merged with existing maps (Ingram et al, 2004). The most efficient method of wetland mapping and monitoring once these base maps are in place is change analysis. Using the methods described in section 4, two Landsat scenes may be used to detect radiometric changes from date 1 to date 2 and then categorical maps may be used to determine the from and to labels that go with these changes. As was shown in section 4.1.4 Table 8, using the radiometric change with the categorical change allows for reduction of change errors. For this analysis to work, it is important to get imagery from peak growing season and anniversary date data. For cases when a good second date categorical map such as IFMAP does not exist, there are several choices of methods for wetland mapping. The choice is dependent on the test site, availability of ancillary data, and the resolution desired. However, to monitor a regional area such as the Great Lakes, moderate resolution would be the best choice. Then those areas showing change can be reviewed more closely with higher resolution imagery or air photos and field truth, if necessary.

New methods for wetland mapping in Canada, where base maps don't exist, are under investigation, including a bottom-up Landsat classification in a GIS software package called eCognition. The eCognition GIS has a price tag as high as $15,000, but it allows the user to put the data into regions of various sizes for better mapping and to create a decision hierarchy unlike any other GIS package. Smith (2004) used Landsat imagery over boreal wetlands (fens, bogs, etc) in Alberta Canada to create wetland maps using a bottom-up approach in eCognition. Here he first broke the Landsat data down into 40 categories by species. Then he merged species groups up into 6 final wetland types; marsh, fen, bog, swamp, thicket and upland. This method is very time consuming and required a great deal of field truth since there were no base maps to work from, but it resulted in 77% overall accuracy compared to field truth. He had difficulty with some of the classes such as bog which had only 16.7% user's accuracy and 25% producer's accuracy. However, he had good results with swamp classification (77.3 % user's and 85% producer's accuracy). Smith is currently looking to merge Radarsat with Landsat for improved wetland mapping. When base maps do not exist, this intense bottom-up procedure may be favored over air photo interpretation for large areas, since it is less time-consuming than air-photo interpretation.

Merging SAR with Landsat takes advantage of the unique characteristics of an optical and microwave sensor. The best method for data fusion that we found, using traditional GIS software, was to create separate categorical maps from the SAR and optical sensors and then merge the categories post-classification. This resulted in 65-94% overall accuracy when compared to existing maps. When compared to field truth over a complex of wetland ecosystems, our classification had 89% accuracy. When using SAR, the wetland extent is subject to the extent of inundation at the time of the SAR overpass collections. Thus care must be taken when mapping seasonally flooded wetlands in particular, and tidally influenced coastal wetlands. With the launch of additional SAR satellites (Radarsat-II, Envisat, ALOS PALSAR), obtaining data from critical time periods will be more feasible. Since cloud-cover is not a problem with SAR imagery all collections are usable.

The ability of SAR to detect the changing extent of flooding can also be an asset when monitoring changes in inundation across a landscape. The capability of SAR for monitoring flooding beneath a forest canopy is unique to the microwave sensors. We reviewed two methods to derive inundation extent of forested wetlands; a thresholding technique on an individual date image to eliminate all non-flooded areas (section 5.2 Figure 9); and a multi-temporal technique that utilizes information from several dates of imagery (section 6.0 Figures 13-16) to produce a seasonal inundation map.

8.2 Cost-Benefits of Different Mapping Techniques

Instead of comparing methods by comparing costs, which can vary by facility, we decided to compare the time required to process imagery and create wetland products on a per scene basis (80-100 km). Note that our test sites were defined by the radar scenes and thus Landsat imagery were ordered to match this and clipped accordingly. It is assumed that ERDAS Imagine on a UNIX Sun Microsystem workstation is available for image processing and ArcInfo or ArcGIS are available for polygon coverage processing and analysis. For the bottom-up approach, it is assumed that eCognition software is available. Data costs and georeferencing time are not included. The data costs are described later in this section.

From Table 23 it is apparent that the methods developed from this project are much less time consuming than traditional air photo interpretation or the bottom-up approach with Landsat taken by Smith (2004). Note that all of these times are rough estimates. Since baseline detailed maps already exist for the Great Lakes, the methods developed under this project provide a feasible means for monitoring changes in the coastal wetlands, in adjacent uplands and in monitoring changes in extent of inundation. Once these methods have been applied, those smaller areas of change which are of concern may be focused on more closely with field truth and high resolution imagery or air photo interpretation. These labor-intensive detailed methods would be otherwise prohibitively expensive and unmanageable for monitoring the entire Great Lakes region.

Table 23. Comparison of land classification and change detection methodologies and the estimated time required to create each product defined as an 80-100 km x 80-100 km scene.

Product	Method	Data Sources	Status	Time Required per 80-100 km scene	Resolution
Land Cover/Use Change	Hybrid change using existing categorical maps	Landsat MSS and ETM, NWI, MIRIS, or equivalent	Semi-automatic	26 hours	25-50 m
Landsat-SAR fusion Classification Map	Maximum Likelihood Classifications and Recombination	JERS, ERS, Radarsat, Landsat	Manual	13 hours	30 m
SAR Forested Wetland Inundation Extent Map	Maximum Likelihood Classification and merging with NWI or equivalent	JERS and NWI	Semi-automatic	8.5 hours	30 m
Air Photo Classification Map	Air Photo Interpretation	Air Photos	Manual	1000+ hours	0.5 m
Landsat Classification Map (no base map)	Bottom-up Landsat classification	Landsat and helicopter based field training and testing sites	Manual, no existing base-map, requires eCognition software	120+ hours	30 m

A break-down of the rough time estimates required for each step of the three methods developed under this project are given below.

A Landsat-SAR fused Classification Methods 13 hours per area

a. Get the data organized and into Imagine (including image data and reference) and filter SAR imagery: 3 hours
b. Landsat Classification (our sites it has been around 12-15 classes): 2 hours
c. Radar Classification (approximately 9 classes): 2 hours
d. Combined the classified products: 30 minutes
e. Identifying the final classes in combined results: 2 hours
f. Clean-up the results (clump, sieve, etc) : 1 hour
g. Validation analysis to reference data (random points, accuracy): 2.5 hours

B Hybrid Change Methods 26 hours

B.1 Post-categorical change 4 hrs

a. Convert older categorical map (NWI or MIRIS) coverage to raster format
b. Mosaic counties together and subset to study area
c. Recode new categorical map to older map categories
d. Combine old and new categorical maps to create categorical change map

B.2 Create Radiometric Change 8 hrs

e. Register early Landsat image date image to later date image, change pixel spacings to match if necessary.
f. Radiometrically balance first date to second date.
g. Create radiometric change magnitude file.
h. Determine threshold in magnitude file that best separates changes of interest from low magnitude noise.
i. Recode magnitude channel into a binary mask.

B.3 Hybrid Change and Create Change coverage 14 hrs

j. Multiply categorical change map with change magnitude mask.
k. Review areas flagged as change in the hybrid change map in both the early date image and later date image to verify validity.
l. Copy and paste polygons from older coverage to change coverage or draw new change polygons over later date image.
m. Enter From/To change attributes
n. Clean up stray polygons and for NWI- rejoin new cover with existing cover

C SAR-Derived Forest Inundation Extent Map 8.5 hrs

a. Speckle filter JERS imagery with Lee-Sigma (3x3, 5x5) and convert JERS floating point data to 16-bit 2 hours
b. Run Maximum likelihood classifier with 100 classes then group classes based on comparison to original composite imagery and IFMAP, NWI 3-4 hours
c. Clean-up the results (clump, sieve, etc) : 1 hour
d. Convert raster to polygon coverage and overlay with NWI grabbing only areas that intersect 1.5 hours

8.3 Data Costs

It should be noted that the trend is toward more affordable data, and NASA, the Canadian Space Agency (CSA), and the European Space Agency (ESA) are all working to reduce the cost of satellite imagery. As an example, NASA has worked to reduce the cost of a Landsat scene from over $4000 for Landsat TM to around $700 for Landsat ETM. Archive data are also much less expensive, with the NALC triplicate costing merely $45 per set and the JERS imagery costing around $25 per scene. The Envisat and ERS data were purchased under a data grant for production costs (around $150 per scene). The Radarsat data used for this project were obtained for free under a data grant from NASA. Some Radarsat imagery can be obtained from the Radarsat web page for free, but typical costs for a new scene of imagery are on the order of $1000 per scene.

9.0 First Views of Envisat Imagery over Great Lakes Wetlands

Envisat imagery were received near the end of the project from the spring of 2004 collections. The Envisat satellite has full-polarization capabilities with a choice of two polarizations in delivered products. Figure 22 presents a two band VV HH composite with red-VV and cyan-HH and Figure 23 is a zoom in of the area indicated. As past research (Hess *et al*. 1995, Bourgeau-Chavez *et al*. 1997) has noted, the HH polarization is much better for delineating wetlands than the VV polarization. This difference in polarization allows us to delineate emergent wetlands. The color composite shows the potential emergent wetlands very clearly in cyan. Other areas that may be highlighted with enhanced backscatter at C-HH are some wet farm fields, row structure of cropland, sparse leaf-off forested wetlands and shrublands, and urban areas. This first view of the Envisat satellite imagery shows great potential for utility in Great Lakes coastal wetland monitoring. A seasonal dataset combined with L-band radar and Landsat would provide a great deal of information on extent of inundation and wetland types in both the emergent and forested wetlands.

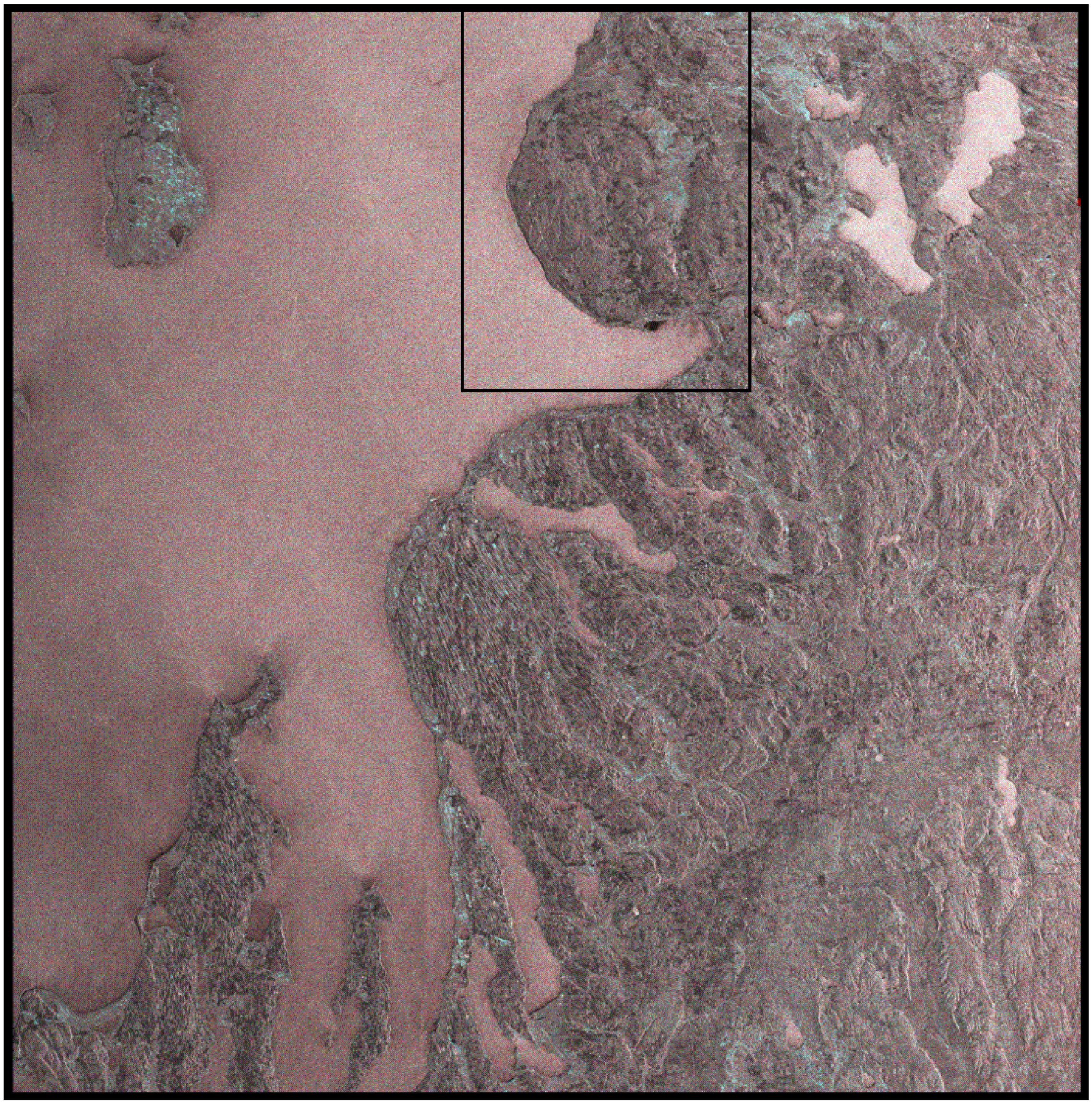


Figure 22. Envisat scene of the Mackinac-Leelenau study area collected on 4 May 2004. The red channel is C-VV and the green and blue channels areC-HH (cyan).

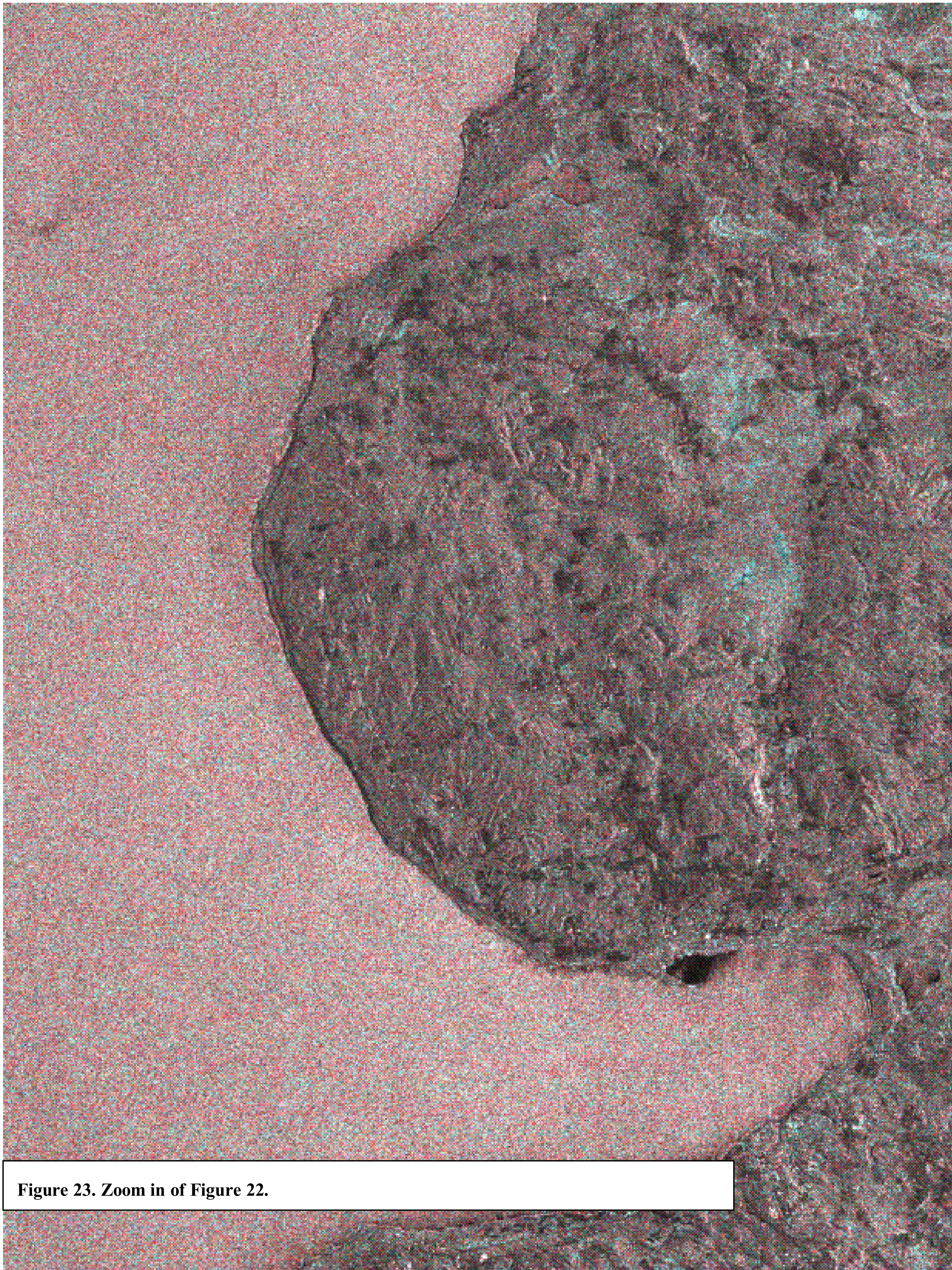


Figure 23. Zoom in of Figure 22.

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