Improving Wetland Characterization with Multi-Sensor, Multi-Temporal SAR and Optical/Infrared Data Fusion

Laura L. Bourgeau-Chavez, Kevin Riordan*, Richard B. Powell, Nicole Miller** and Mitch Nowels***
Michigan Technological University, Michigan Tech Research Institute, 3600 Green Ct., Ste. 100, Ann Arbor, MI, USA
** Independent Researcher, 85B East Jefferson Rd. Pittsford, NY, USA*
*** Radiance Technologies, Inc. Bldg 1103, Suite 210 Stennis Space Center MS, USA*
**** 8700 SW 174th Street, Miami, FL, USA*

1. Introduction

Wetlands provide habitat and food sources for wildlife, protect waterways, act as natural filtration systems, and serve major ecological roles in the overall health of our local, regional and global ecosystems. While wetlands serve such vital ecological functions, due to their limited capacity for adaptation wetland ecosystems are highly vulnerable to change, from both climatic (IPCC 2008) and anthropogenic sources. In the past, wetlands have been drained and converted to uplands at an alarming rate and the remaining wetlands are subject to a number of threats including eutrophication, climate change, invasive plant species, and the interaction between these stressors. Due to these vulnerabilities, there exists a need for policy and resource managers to have an operational strategy for monitoring the extent, composition, and vigor of wetlands at a synoptic scale. For regional areas, such as the coastal Great Lakes, Boreal Canada, or vast wetland complexes such as the Pantanal, Mesopotamian marshlands, or the Greater Everglades, cost-effective implementable methods are necessary. For fine scale studies, cost is generally less of an issue and the highest resolution data with the highest cost may be justified. In this chapter, we focus on methods for regional scale mapping and monitoring where the minimum mapping unit of interest is 5 acres, and thus use moderate resolution satellite imagery (20-30 m). The focus is on multi-sensor data fusion between SAR single channel and/or multi-channel data and Optical/IR sensor data. Case studies in the Great Lakes and Boreal peatlands demonstrate the advantages and widespread utilty of a hybrid SAR-Optical/IR approach.

While many definitions of wetlands exist, both scientific and legal, in essence wetlands are defined by: (1) the presence of water at, above, or near the ground surface; (2) hydric soils; and (3) vegetation species adapted to or tolerant of wet soil conditions. Remote sensing can be used to map and monitor two of the defining wetland features; vegetation type and surface water/wet soils.

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.

Traditionally, optical data have been used to map wetlands along with other land cover and land use. However, due to the complexity of wetland ecosystems it would be beneficial to include a fusion of sensors, operating in different frequencies (thermal, optical, lidar, radar, infrared) that measure various aspects of wetlands for improved mapping accuracy. Optical and infrared data are well suited to mapping vegetation ecosystem types and condition. Complementary to Optical/IR, Synthetic Aperture Radar (SAR) data are capable of detecting flooding beneath a vegetation canopy, monitoring water levels and soil moisture, and also for distinguishing other biophysical vegetation characteristics such as level of biomass.

2. Optical/IR Wetland Mapping Background

Multispectral data that includes near infrared and shortwave infrared bands allow improved wetland detection and mapping over visible sensors alone. The near-infrared portion of the electromagnetic spectrum has been used to identify plant and hydrologic wetland conditions using both color infrared (CIR) aerial photography and satellite remote sensing systems (Ozesmi and Bauer, 2002). The most broadly used wetlands map in the United States, the National Wetlands Inventory (NWI), uses aerial CIR photography and photo interpretation techniques to provide fine scale maps of wetland distribution (Peters, 1994). However, this labor-intensive methodology requires a 10-year repeat interval for new map production (Wilen and Frayer, 1990).

To effectively monitor changes to wetlands, data collection must be timely (1-5 year minimum) and cost effective. The National Oceanic and Atmospheric Administration's Coastal Change and Analysis Program (C-CAP) uses the Landsat Thematic Mapper (TM) sensor to provide a more timely and cost effective national system of coastal wetland maps (Klemas *et al.*, 1993) on a 5 year repeat interval. However, both NWI and NOAA C-CAP maps offer only broad classes of wetland, such as estuarine emergent or palustrine forested. Finer classes of actual species or ecosystem types are not mapped.

Since various targets reflect and absorb solar radiation differently, they can often be distinguished by their spectral reflectance signatures (Jensen, 2007). Spectral reflectance studies have been useful for determining regions of the electromagnetic spectrum which provide greatest discrimination between two or more wetland species (Schmidt & Skidmore 2003, Becker *et al* 2005). However, many studies have concluded that it is difficult to accurately classify wetland species types based solely on Optical/IR spectral characteristics (Ozesmi and Bauer, 2002).

3. Satellite SAR Wetland Mapping

SAR data have unique capabilities because the long microwave wavelengths penetrate vegetation cover and are sensitive to wet soil and flooded conditions that may exist beneath a canopy. An enhanced signature is often received from a canopy underlain by water due to a double-bounce effect of the incoming radiation from the smooth water surface and vertical stems of the canopy. The microwave scattering received by a SAR sensor from a wetland is dependent upon the wavelength, polarization, and incidence angle at which the energy was transmitted, the surface roughness, vegetative biomass, dielectric properties of the vegetation and soils (moisture in the plant canopy and on the ground), and the presence or absence of a flooded surface. Therefore, the SAR wavelength, polarization and incidence angle need to be carefully chosen to maximize the scattering to distinguish wetlands from uplands and to distinguish between wetland ecosystem types. A combination of wavelengths, polarizations, and/or incidence angles provides the most information about the various wetlands and thus the greatest capability to effectively map wetland ecosystem types with SAR.

Current and recently orbiting SAR satellites available commercially are of three different wavelengths; L-band (~23 cm wavelength); C-band (~5.7 cm wavelength), and X-band (~3.5 cm wavelength). Of these SAR satellites, many are of a fixed incidence angle, but some have varying incidence angles. To detect flooding beneath a vegetation canopy, steep incidence angles (<35 degrees) are generally best (Hess *et al*. 1990). For temperate, sub-tropical and boreal regions, longer wavelengths such as L-band are more useful for mapping forested and high biomass herbaceous wetlands than C-band or X-band. C-band or X-band data have limited ability to map flooding beneath forest canopies. C-band data are most useful in forests during leaf-off condition and for sparse canopies, and have been used to map extent of inundation in floodplain swamps of Roanoke (Townsend 2001, 2002, Lang *et al*. 2008).

In Figure 1, theoretical scattering of a C-band sensor from forested versus herbaceous landscapes in various dry to flooded conditions is shown. Here it is demonstrated how the degree of inundation affects the scattering from the herbaceous canopy. In the case of wet soils and low inundation in an herbaceous canopy, enhanced backscatter is often observed at C-band, with some double-bounce effects. However, as the water levels increase the backscatter can first get stronger and then lessen until it reaches a low specular reflection case (where scattering is away from the sensor) from the water surface in the highly inundated situation (Kasischke and Bourgeau-Chavez 1997, Kasischke *et al*. 2003, Bourgeau-Chavez *et al*. 2005). Figure 1 also shows the typical scattering from a closed versus open canopy forest at C-band. With most scattering from the branches and leaves at C-band in the closed canopy case, and little to no penetration to the ground surface. However, the longer wavelength L-band generally penetrates a closed canopy forest and has been found to be best for discriminating flooded from non-flooded forests (Hess *et al*. 1990, Ramsey 1998, Bourgeau-Chavez *et al*. 2001). C-band is best for discriminating emergent wetlands from agriculture and herbaceous uplands (Bourgeau-Chavez *et al*. 2001).

SAR polarization is also important, and horizontal send and receive (HH) polarization has been found to be most useful for detecting wetlands. While, the cross-polarizations (Horizontal send and Vertical receive HV) are necessary for discrimination of woody versus herbaceous vegetation types due to their sensitivity to biomass (Ramsey 1998). VV polarization is also sensitive to soil moisture and flood condition (Bourgeau-Chavez *et al*. 2001).

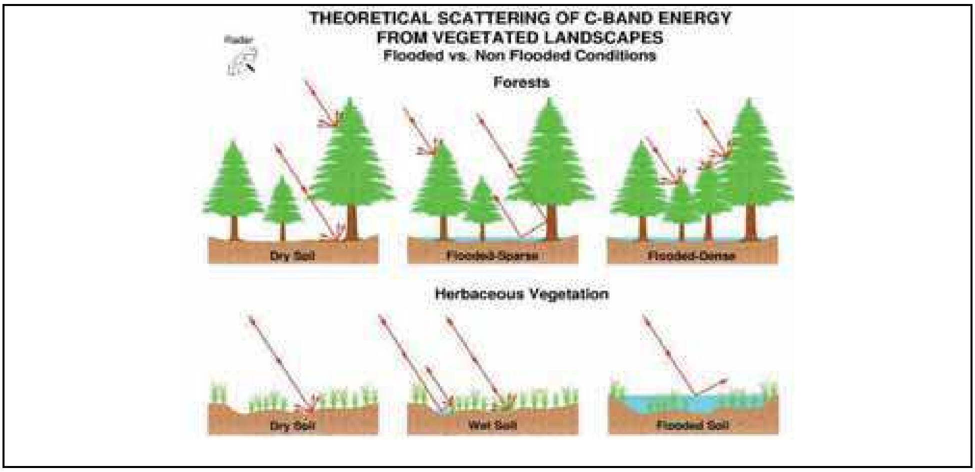

Fig. 1. Diagram showing theoretical scattering of C-band energy from forested and herbaceous ecosystems in dry, wet and flooded conditions, with open and closed forest canopies.

One primary advantage of using SAR over visible data is the detection of forested wetlands and the ability for SAR data to be collected irrespective of cloud cover or solar illumination because it is an active sensor. It is very difficult to detect flooding beneath a forested canopy with Optical/IR, unless there are large gaps in the canopy. Many researchers have found significant improvement in distinguishing swamp from other wetland classes and uplands with SAR (Lang *et al*. 2008, Grenier *et al*. 2007, Baghdadi *et al*. 2001, Hess *et al*. 1990, Bourgeau-Chavez *et al*. 2004).

Several researchers have evaluated the utility of SAR for wetland mapping using single and multi-date single channel SAR data (Costa *et al*. 1998, Whitcomb *et al*. 2009, Arzandeh and Wang 2002, Rao *et al*. 1999) and others have evaluated polarimetric SAR (Hess *et al*. 1990, 1995, Bourgeau-Chavez *et al*. 2001, Pope *et al*. 1994, 1997, Crawford *et al*. 1999, Wang and Davis 1997, Touzi *et al*. 2007). See Henderson and Lewis (2008) and Ramsey (1998) for a more thorough review of past research on wetland ecosystem analysis with SAR. Many early studies conducted to determine the utility of multi-polarization/multi-frequency data, focused on NASA's Shuttle Imaging Radar - C (SIR-C) which was fully polarimetric at L- and C-bands (L-HH, L-HV, L-VH, L-VV, C-HH, C-HV, C-VH, C-VV and X-VV) and fully polarimetric AirSAR (P-band (72 cm), L-band, C-band) for wetland classification in tropical and temperate landscapes (Hess *et al*. 1995, Pope *et al*. 1994, 1997, Bourgeau-Chavez *et al*. 2001). These studies demonstrated the utility of multi-band data and early polarimetric analyses (e.g. HH-VV phase difference) for mapping forested and herbaceous wetlands (Pope *et al*. 1997).

While several researchers have evaluated the use of SAR alone for mapping wetlands, until more recently, few have evaluated SAR and Optical/IR fusion for wetland mapping (Lozano-Garcia and Hoffer 1993, Augustein and Warrender, 1998, Toyra *et al*. 2001, Rio and Lozano-Garcia 2000, Bourgeau-Chavez *et al*. 2004, 2008, 2009, Li and Chen 2005, Grenier *et al*. 2007). Since the SAR and Optical/IR data measure different features of wetlands, it is logical that a synergistic approach between the two sensor types would increase wetland mapping accuracy. Further since the presence of standing water causes the SAR energy to interact differently depending on the dominant vegetation type, it would be advantageous to combine SAR with optical and infrared data for mapping purposes.

4. SAR and Optical Data Fusion

Of the few broad-scale SAR wetland mapping efforts that have been undertaken, , Canada is incorporating Radarsat-1 and Radarsat-2 data with Landsat mosaics (100m resolution) and SPOT data in the development of the Canadian Wetland Inventory (Grenier *et al*. 2007, Fournier *et al*. 2005, *pers. comm*. *Grenier 2009*) which will cover the entire country. There is also an effort underway to use the JERS mosaics (100 m resolution summer and winter products) of Boreal North America alone to map wetlands across Canada, as has already been done for Alaska (Whitcomb *et al*. 2009).

In this chapter, we review case study of multi-sensor, multi-date, SAR-optical/IR fusion methods and results for mapping wetlands in two main study areas, the Great Lakes and a Boreal peatland region in Alberta, Canada. The techniques are developed with broad scale mapping in mind, but are demonstrated on local to regional wetland areas. In all but one of these case studies, satellite SAR data are used in conjunction with Landsat TM, and in most cases SAR data from multiple sensors are fused. The exception, is the case studies on mapping the invasive plant species *Phragmites australis* on Lake St. Clair, where PALSAR data are used alone and compared to hyperspectral AVIRIS.

4.1 Case Study: Lakes Ontario and St. Clair Coastal Wetland Mapping

The Great Lakes Coastal Wetlands Consortium (GLCWC) was mandated to develop a monitoring plan for assessing the health of the coastal wetlands which are vital to the overall health and maintenance of the Great Lakes ecosystem (Bourgeau-Chavez *et al*. 2004, 8). The only way to monitor an ecosystem the scale of the Great Lakes basin is through integrated remote sensing and field observations in a GIS. Landscape indicators in need of monitoring through remote sensing include wetland type and extent, adjacent land cover, adjacent land use, intensity of land use, and invasive plant species. The GLCWC sought implementable, cost-effective yet robust methods with a minimum mapping unit of 5 acres. To meet these needs a few pilot studies were conducted to demonstrate various monitoring methods. A hybrid SAR Optical/IR methodology that used satellite sensor data of 30 m resolution and would allow for detection of areas as small as 1 hectare was found to be the most promising. This methodology would be cost-effective and data management for the entire Great Lakes Basin would be reasonable compared to higher resolution, smaller footprint imagery. And the use of two complementary data types in the mapping was expected to reduce omission and comission errors.

Two study sites were selected for demonstration of this hybrid SAR-optical data fusion, coastal areas of Lakes St. Clair and Ontario (Figure 2). Coastal Lake St. Clair was chosen because it has a diversity of land cover and land use 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 area was chosen because it is mainly rural, with many agricultural fields, has isolated patches of herbaceous wetlands, and a relatively large amount of potentially forested wetlands. These two areas provide different sets of land cover and land use classes and thus an opportunity to test the hybrid-sensor methodology in diverse settings.

4.1.1 Remote Sensing Data

The data used in this case study were archival SAR and Landsat data from multiple dates, and multiple sensors (Table 1). For the Landsat images, each containing 7 bands, the blue and thermal IR bands for each date were removed from the analysis. The blue channel is generally quite noisy and the thermal band is of coarser resolution than 30 m. The JERS (L-band) sensor used for this project had horizontal send and receive polarization (L-HH) and was operational from 1992-8. This sensor has a resolution of 30 m, incidence angle of 35^{o}, and a footprint of 80 km x 80 km. To complement these data, we also acquired C-band (5.7 cm wavelength) SAR data from the European ERS-1 and Canadian Radarsat-1 (R-1) satellites. The ERS-1 sensor has vertical send and receive polarization (C-VV) and is collected at a central incidence angle of 23^{o}. The Radarsat sensor has horizontal send and receive polarizations (C-HH). It also has pointing capabilities and can be collected in various modes and incidence angles. The R-1 data used were of standard beam 7 mode, which has an incidence angle of 47^{o}. Both C-band sensors have 30 m resolution and 100 km x 100 km footprints.

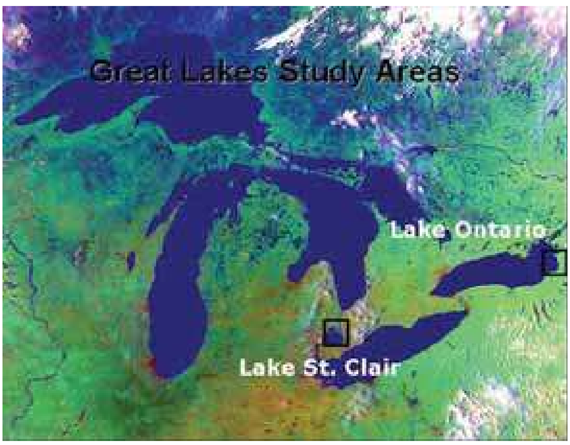

Fig. 2. Great Lakes pilot study areas for hybrid SAR-Optical/IR mapping for the Great Lakes Coastal Wetlands Consortium project.

Site	Sensor	Spring	Summer	Fall
Lake St. Clair	Landsat TM	23 March 2001	30 August 2001	30 October 2000
Lake St. Clair	JERS	28 March 1995	10 August 1998	
Lake St. Clair	Radarsat-1			3 & 27 October 1998
Lake Ontario	Landsat TM	24 June 1993	12 August 2002	18 December 2002
Lake Ontario	JERS	11 April 1993	8 July 1993	17 October 1993
Lake Ontario	ERS-1	17 April 1993	7 June 1993	25 October 1993

Table 1. Data used in the Great Lakes Hybrid SAR-Optical/IR wetland and landscape indicator mapping.

Since this was a demonstration project with minimal funding, data sets chosen were not optimal but were chosen based on cost and ease of availability (Table 1). At both sites three dates of Landsat data were used. There were a total of four radar scenes for Lake St. Clair and 6 radar scenes for Lake Ontario. There are as many as 6 years between the JERS and Landsat collections for Lake St. Clair and 10 years between data collections for Lake Ontario, but analysis of the imagery indicated that few major changes in land use have occurred in these areas during that time period. Also, it was not as much of an issue due to the methodology; a site would first be checked for vegetation cover in the more recent Landsat and then checked for flooding in the older SAR. However, it is realized that using data with such a wide time span will introduce errors. The optimal data set would be from the same year, with SAR and TM from the same months. However, the datasets met the needs of this investigation, which was simply to demonstrate a methodology.

4.1.2 Image Interpretation

For the Lake St. Clair site, the imagery and products were evaluated by comparison to the NWI, land cover/land use maps, field checks (October 2003) and expert field knowledge (Field ecologist/botanist Dennis Albert of Michigan Natural Features Inventory).

Although the ancillary maps and field work showed many forested wetlands within our study area, the dates of JERS imagery show all of the forests the same, very bright in the spring (March 1995) and all are gray in the summer scene (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 herbaceous vegetation are apparent on these two dates, as well as in the October Radarsat scenes.

Figure 3 shows a red-green-blue false color composite of the 3 October 1998 R-1 scene, 10 August 1998 JERS scene, and 28 March 1995 JERS scene, respectively. In this composite, the orange areas were dominated by cattail (*Typha spp.*), and the green by Phragmites (*Phragmites australis*). 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 light blue forest area 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 channel), but not enhanced backscatter. This combination of R-1 and JERS allows for a good interpretation of this scene, discerning tall dense herbaceous vegetation from short sparse herbaceous vegetation, and different hydrological and biophysical properties.

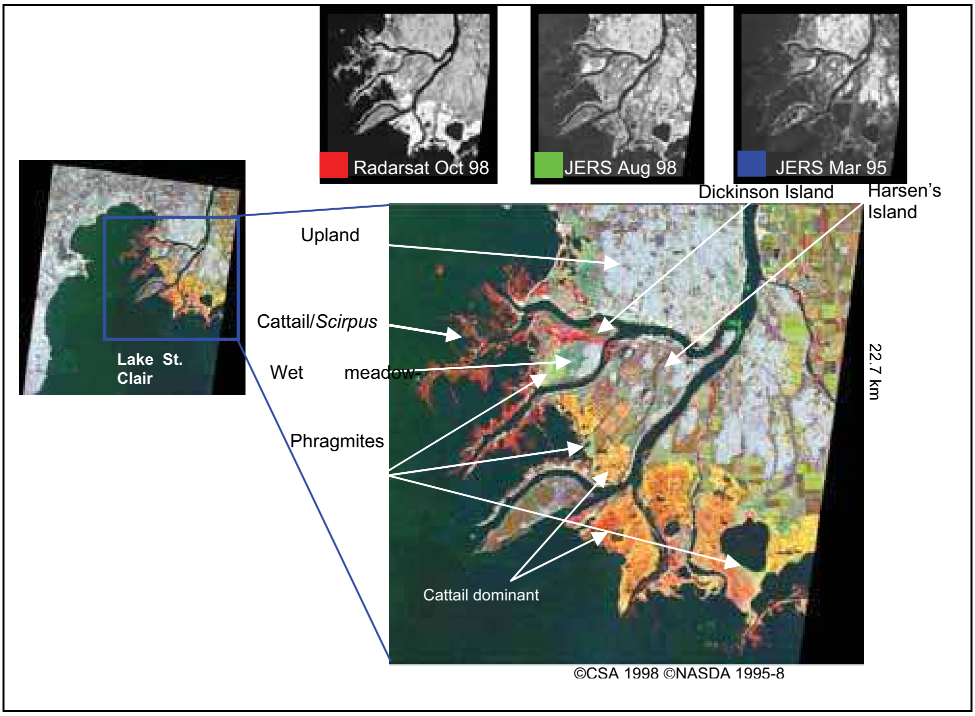

Fig. 3. Three dates, two sensor false color composites from Radarsat-1 and JERS satellites over the Lake St. Clair Delta. This Figure clearly defines Typha (cattail), and the invasive species *Phragmites australis* from other upland and wetland ecosystems.

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 4 presents false color composites of the two sensor 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 (Table 2). In November of 2003, we conducted a field check to determine any vegetation difference between the red and green areas. The red areas visited were dominated by mixed grasses. It is likely that in the spring imagery the vegetation is fallen over or decomposed, 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, the green areas visited in the field contained a mixture of grasses, cattail and shrubs (mainly *Cornus stolonifera*). These sites were 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 grass 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 grass 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.

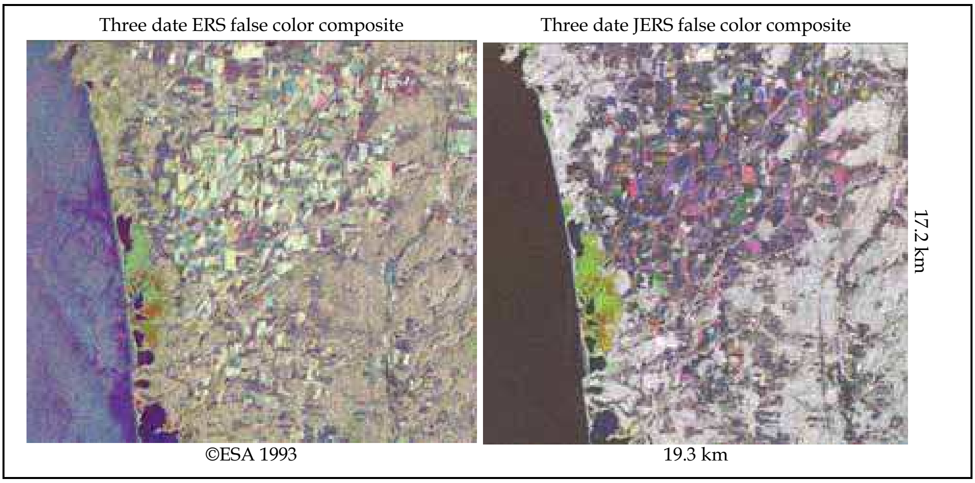

Fig. 4. Three date ERS false color composite of 25 October, 7 June and 17 April 1993 ERS imagery over eastern Lake Ontario compared to a 17 October, 8 July and 11 April 1993 JERS composite.

Site	Sensor	Spring Brightness	Summer Brightness	Fall Brightness
Grass	ERS-1 C-VV	dark	dark	gray
Shrub/herbaceous	ERS-1 C-VV	gray	bright	gray
Grass	JERS L-HH	dark	dark	gray
Shrub/herbaceous	JERS L-HH	dark	bright	gray

Table 2. Appearance of “grass” versus “shrub/herbaceous” sites in coastal Lake Ontario in spring, summer and fall of 1993. Grasses are red areas in JERS composite of Figure 3 and Shrub/herbaceous are green areas.

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 (note that coastal wetlands are hydrologically connected to the Great Lakes), 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 5). The white areas of Figure 5 show the SAR-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 5) and in other cases it is less.

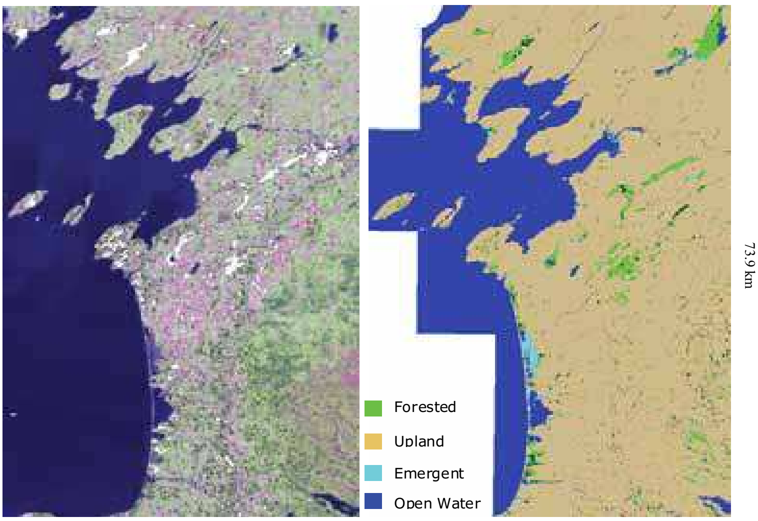

Fig. 5. Landsat 5, 4, 3 composite with SAR-derived potentially flooded forests (white areas) overlaid 9 (left). The NWI is presented for comparison (right) with forested wetlands colored green. Note that the NWI is not the exact area of the Landsat scene.

One technique that has been used somewhat operationally for detecting forested wetlands, is to map forest cover with Optical/IR and then create either a single-date thresholded image, as is presented here, or a multi-date SAR image to determine inundation and thus, forested wetland. Using remote sensing to detect flooding beneath a canopy is limited by the timing of the data acquisitions. Therefore, only the forests that were inundated on the date of image acquisition will be mapped as forested wetland. The multi-season data helps reduce this limitation, but relying on species type and other ancillary data such as hydric soils, as well as enhanced SAR backscatter to determine wetland status would be more reliable, hence hybrid approaches are recommended. One useful parameter the SAR can be used for is to monitor changes in extent of inundation from one date to the next (Bourgeau-Chavez *et al*. 2005, Lang *et al*. 2008, Townsend 2001, Wang *et al*. 2004).

4.1.3 Mapping Methodology

Several techniques were considered and evaluated for merging the multi-sensor, multi-date Great Lakes datasets and producing a land cover land use map, but the best method appeared to be the simplest, which involved creating separate SAR and Landsat land cover/land use products and then fusing the products in a GIS. This method preserved the unique characteristics of each sensor, while taking advantage of their complementary nature.

4.1.3.1 Lake St. Clair Study Site

The two-step methodology was first applied to the Lake St. Clair study site where the 15-band Landsat layer 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 field data and existing maps. The 12 classes created were: Water, High Density Urban, Low Density Urban, Forest, Emergent Wetland, Wetland Shrub, Wetland-permanent, Forage Crops, Cropland 1, Cropland 2, Cropland 3, Cropland 4. The second step of the process involved the classification of the 4-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 were: Forest/Urban, Phragmites, Scirpus/ open submergent and emergent, Cattails, Wet Meadow, Forage Crops, Cropland1, Cropland2, and Cropland3

The individual classification results were then fused 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 3 and the final map is in Figure 6.

Due to limited funding and the archival nature of the dataset, an accuracy assessment was conducted based on existing maps. The NWI, which is the basemap for the GLCWC, was first used as a reference. Then IFMAP (Integrated Forest Monitoring, Assessment and Prescription), which relies on NWI to some extent, was used because it includes upland classes that NWI does not. IFMAP was 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 and accuracy could therefore only be assessed on the U.S. side of the map. NWI and IFMAP have only broad wetland categories (e.g. palustrine emergent, scrub-shrub, etc).

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
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)

Table 3. Combined Landsat and radar landcover results for the Lake St. Clair study site.

Using over 3000 randomly selected validation points, comparison to the NWI as reference, resulted in 94% overall accuracy of our wetlands map. Comparison to IFMAP resulted in 72% overall accuracy when areas of wetland that IFMAP called "open water"were eliminated. Analysis of the imagery revealed that the timing of data collections and the lake levels can have a large effect on the boundaries mapped for emergents along the water's edge. A SAR comparison of 2 image dates with a change of 19 cm in lake level showed a huge change in visibility of wetlands on the fingers of the St. Clair river delta (Figure 7). In this figure, lake water level is 19 cm higher on the first date, causing specular reflection (low return-dark). A decrease in inundation on the second date reveals the vegetation causing double bounce scattering (bright return-red). This exemplifies the need for multi-date data to "see" the wetlands that may be nearly completely inundated by water on a particular date in both SAR and optical/IR.

In comparison to IFMAP, the hybrid SAR-Optical classification did well with low density urban, Typha, Phragmites, low herbaceous, Scirpus and cropland (all above 60% user's accuracy, Typha above 86%). There were some issues with wet meadow (42.25% user's accuracy) where there is confusion in IFMAP with tree species, row crop and herbaceous upland. Further investigation of this type is needed. The classes were quite different for IFMAP, but for lowland deciduous, the SAR-Optical map had 81% producer's accuracy, 65% and 77% producer's accuracy for emergent and non-forested wetland and 78% producer's accuracy for low density urban.

A visual comparison was also made between our classification of the Canadian side of the study area using 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 two classification maps with eight categories including forest, urban, 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.

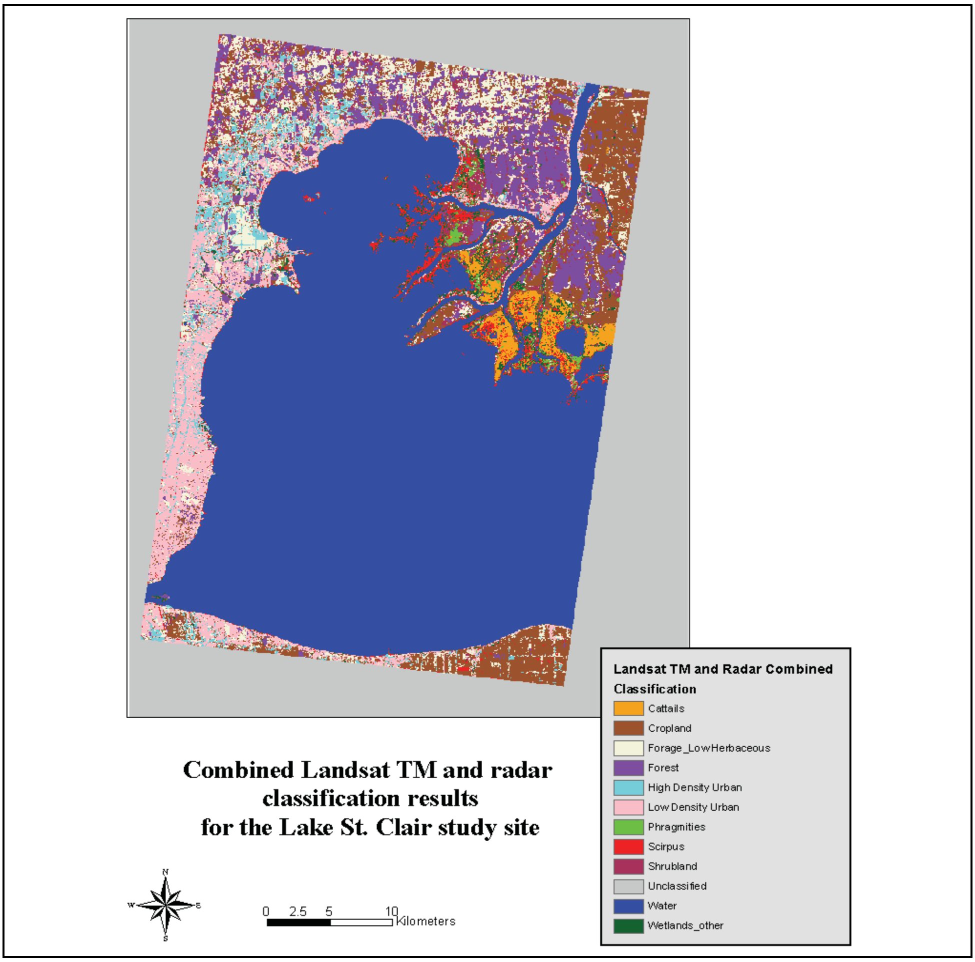

Figure 6. Landsat and SAR fused land cover classification results for the Lake St. Clair study area.

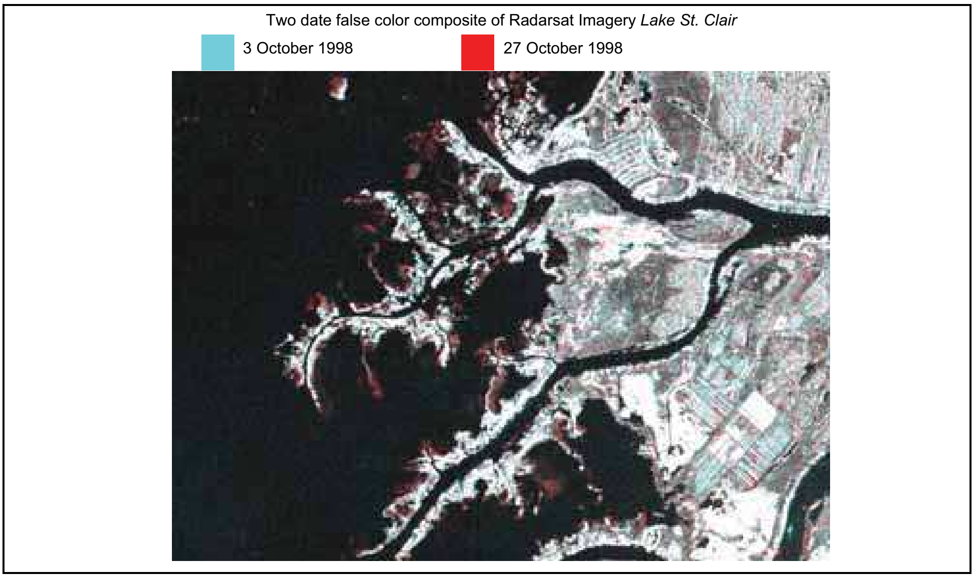

Fig. 7. Two date false color composite of Radarsat imagery. Cyan is the 3 October 1998 image and red is the 27 October 1998 image. Water level dropped by 19 cm between the first and second date.

4.1.3.2 Lake Ontario Study Site

The same techniques used for Lake St. Clair were applied to the datasets for Lake Ontario, however the classes were slightly different. First, Landsat imagery was classified into 13 different landcover classes; Water, High Density Urban, Low Density Urban, Deciduous Forest,Coniferous Forest, Mixed Forest, Row Crops, Low Herbaceous, Bare Soil, Emergent Wetlands, Shrubland, Fields-Hay, Wetlands-other. The radar imagery was classified into 9 classes; Water, Urban/Flooded Forest, Flooded Shrubland/ Wet Meadow, Emergent Wetland, Forest1, Forest2, Row Crop 1, Row Crop 2, and Herbaceous Field. These individual Landsat and SAR classes were then fused into a single product, just as they were for Lake St. Clair. The 12 final combined classes are described in Table 4. The final map is presented in Figure 8.

A comparison was made between the SAR-Optical map and the NWI with 5000 random points Note that the NWI has more generalized classes so the comparison is not straight forward, and there are over 2 decades between the NWI creation and the SAR-Optical/IR map, so some differences may be due to changes in the wetland, either succession or loss. The results in comparison to the NWI showed 94% overall accuracy, with all classes greater than 89% user's accuracy, except shrubby wetland for which we only had 13 points, none of which were correctly classed. 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% agreement for emergent wetlands is quite good considering the likely turnover of some areas to agriculture and the likely succession 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 from a biocomplexity study conducted by Cornell University (Mark Bain).

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
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.

Table 4. Classes for the combined Landsat and radar classification at the Lake Ontario study site.

The state of New York did not have a land cover/land use map comparable to IFMAP, and many errors were found in the National Land Cover Dataset (NLCD). However, field data collected in the largest coastal wetland complex in the image were available with GPS locations. The Biocomplexity study of Cornell University allowed for comparison of the SAR-Optical/IR hybrid map to 55 study points which represented cattail dominated, shrub, forested, and mixed emergent wetlands. The overall accuracy of this comparison was 89%, with 91% user's accuracy for wetland shrub, 89% user's for emergent wetland, and 67% for forested wetland. This assessment is quite good considering the likelihood of error in the geolocation of the study points due to the small plot size in reference to the 30 m pixels. Some of the points did fall on boundaries of open water/wetland or upland/wetland causing errors. The producer's accuracy ranged from 25 to 75% in the reference categories of specific species types that we did not map. The cattail field points corresponded to the wetland shrub (dark pink) areas in the Landsat-SAR fused classification. Therefore, the pink areas of our Landsat-SAR map should be labelled as shrub/high biomass herbaceous wetlands.

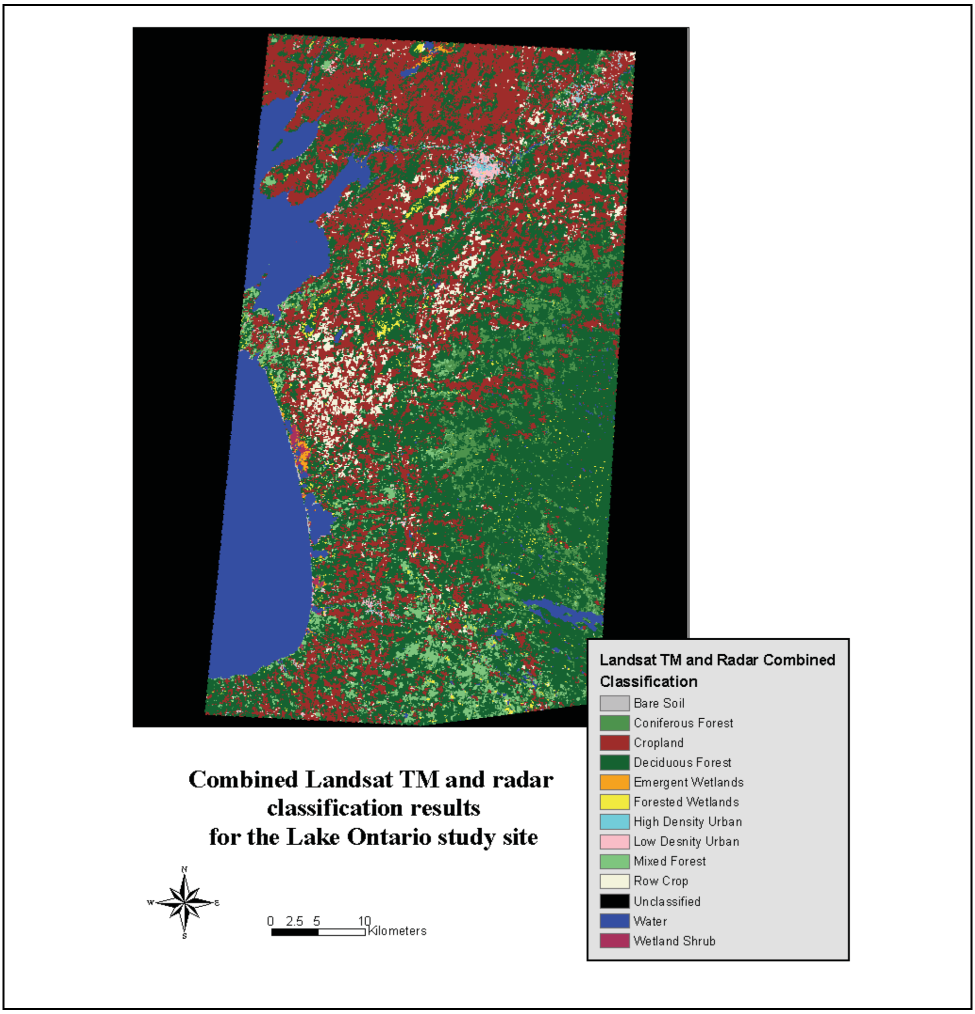

Fig. 8. Landsat and SAR fused land cover classification of the Lake Ontario study area.

4.1.4 Summary

These two study areas demonstrated the utility of a fusion of SAR and Optical/IR data for mapping landscape indicators of wetland health (wetland extent, adjacent land use intensity, etc.) in a region surrounded by high intensity urban versus a more rural area. In one case mapping of forested wetlands was possible and in the other, timing of data collections did not allow evaluation of forested wetland mapping. However, a simple approach to the mapping provided desirable results with the archival data, showing the complementary nature of the two types of sensors. Although the reference data and remote sensing data were not optimal [there are discrepancies in years of data collection (Landsat versus SAR (1990s-2001) and years of validation maps (1970s, 2000) and levels of vegetation classes between the SAR-Optical map and validation maps (fine scale species versus broad emergent classes)], these case studies demonstrated the added benefits of fusing Optical/IR data with another complementary sensor such as radar and resulted in a recommendation by the Great Lakes Coastal Wetlands Consortium for monitoring landscape indicators (Bourgeau-Chavez *et al*. 2008). In the next case study, current data are used and ongoing validation is being conducted for the specific species class levels. This case study is a continuing investigation and only preliminary results are shown here, however it provides a better validation of the results through field methods, further exemplifying the utility of SAR in wetland mapping.

4.2 Case Study: Invasive *Phragmites australis* Species Mapping on Lake St. Clair

One of the main wetland stressors in the Great Lakes is invasion by the problematic species Phragmites (*Phragmites australis*). This species invades native habitat creating dense thickets and deep detritus that virtually eliminates ecological function. A predicted drop in Great Lakes water levels due to global climate change is anticipated to increase the spread of the invasive Phragmites in the Great Lakes coastal zone, and a method to map this species and its spread would be of great assistance to land managers for control.

Several studies have focused on detecting and mapping invasive species in small catchments of the Great Lakes with high resolution hyperspectral and/or lidar (e.g. Lopez *et al*. 2006, Wilcox *et al*. 2003). However, such high-resolution mapping of the entire Great Lakes coastline or comprehensive field studies would be very costly. Others have found 30 m satellite imagery including Landsat, SPOT and Hyperion to be useful for mapping invasives (Arzandeh and Wang 2003, Pengra *et al*. 2007), however Landsat has spectral limitations and Hyperion is no longer operational.

Using a variation of the satellite SAR techniques described in the last section, which included a delineation of this invasive species using archival multi-date JERS and Radarsat-I, we are currently evaluating dual polarization PALSAR data, and have plans to incorporate Radarsat-2 data once it becomes available to distinguish a wider range of species.

4.2.1 Remote Sensing Data

ALOS PALSAR is the follow-on to JERS which showed the greatest potential in previous studies for mapping Phragmites (Bourgeau-Chavez *et al*. 2004, 2008). PALSAR was launched in 2006, and is available in three modes with various imaging parameters. Here we evaluate the dual-polarization product which has 20 m resolution, two channels (L-HH, L-HV), 70 x 70 km footprint, and is collected at an incidence angle of 34°. Up until recently, most satellite SAR systems were of a single channel, however with the recent launch of ALOS PALSAR and Radarsat-2, the utility of multi-channel SAR and polarimetric data are beginning to be more broadly evaluated for a variety of applications, demonstrating further mapping capabilities beyond that of single and multi-channel data.