SPATIAL AND TEMPORAL VARIABILITY OF SURFACE COVER IN AN ESTUARINE ECOSYSTEM FROM SATELLITE IMAGERY AND FIELD OBSERVATIONS

A dissertation submitted to Kent State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy

by

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## GLOSSARY OF TERMS

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<tr>
<td>DN</td>
<td>Digital Number</td>
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<tr>
<td>ESEM</td>
<td>Environmental Scanning Electron Microscopic</td>
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<tr>
<td>ETM+</td>
<td>Enhanced Thematic Mapper Plus</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>MIR</td>
<td>Mid Infrared</td>
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<tr>
<td>NDGI</td>
<td>Normalized Difference Ground Index</td>
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<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
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<td>NDWI</td>
<td>Normalized Difference Water Index</td>
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<tr>
<td>NERR</td>
<td>National Estuarine Research Reserve</td>
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<tr>
<td>NIR</td>
<td>Near Infrared</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>OWC</td>
<td>Old Woman Creek</td>
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<td>PCA</td>
<td>Principal Component Analysis</td>
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<td>Pseudo-Color Tables</td>
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<td>RMSE</td>
<td>Root Mean Square Error</td>
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<td>TM</td>
<td>Thematic Mapper</td>
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<td>TSP</td>
<td>Total Suspended Particulate</td>
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<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
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CHAPTER 1

1.1 Summary

This study determined the capability of moderate resolution satellite imagery of 30 meter pixel dimension to investigate the spatial and temporal changes of Old Woman Creek National Estuarine Research Reserve, which is a dynamic coastal wetland of Lake Erie. Water quality and land cover reflectance data is interpreted with respect to in-situ sample measurements collected every 16 days in coincidence with the Landsat-5 TM over passing days mainly in summer 2005 and 2006. The study involved a variety of qualitative and quantitative, physical and remote sensing measurements generated from surface water and its constituents, aquatic emergent and terrestrial macrophytes, exposed mudflats, and radiometrically corrected Landsat-5 TM imagery. The prevailing environmental and climatic conditions of the area regulated the spatial and temporal variability of those land cover types.

The study developed a suspended sediment concentration calibration method and two land cover variability mapping methods using Landsat-5 TM data. The two wetland mapping methods are based on principal component analysis (PCA) and scattergram segmentation of selected normalized difference remote sensing indices. In addition, the mineralogy and morphology of suspended particulates were investigated using an X-Ray diffraction (XRD) technique and environmental scanning electron microscopy (ESEM) which revealed the dominance of silica and calcite in surface water.
The surface water samples provided total suspended particulate concentration (TSP) measurements which reported 0.7 correlation against normalized difference water index (NDWI) of bands 1 and 5, establishing a model to quantify TSP concentration in surface water. The principal component analysis (PCA) extracted endmember land covers reporting 87% of total variance and their spatial and temporal distribution was mapped in order to identify the seasonal variability of macrophytes, open-water, and exposed ground. One dimensional spaces of normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and normalized difference ground index (NDGI) segmented their respective scattergrams to identify the land cover interfaces in order to re-map the same land cover variability for better evaluation of the two wetland mapping techniques.
CHAPTER 2

Introduction

2.1 Research objectives

The purpose of this dissertation is to develop a satellite remote sensing monitoring program to evaluate the surface reflectors of Old Woman Creek National Estuarine Research Reserve in Huron, Ohio. This study determines the capability of moderate resolution imagery with 30 meter pixel dimensions to investigate a small coastal wetland which has an area of 0.6 square kilometers that extends 2 kilometers south of the Lake Erie shore in north central Ohio. Terrigenous suspended sediments and algal communities are two main contaminants in surface water that are easily detectable by remote sensing. Their temporal and spatial variability depend on the prevailing environmental, climatic, and agricultural conditions of the area. The in-situ data were collected every 16 days in coincidence with Landsat-5 Thematic Mapper (TM) over passing days, during Summers 2005 and 2006. The study involved qualitative and quantitative, physical and remote sensing measurements generated from surface water, aquatic emergent macrophytes, exposed mudflats, and Landsat-5 TM data.

The dominant surface reflectors have been categorized as surface water, aquatic emergent and terrestrial macrophytes, and exposed mudflats. There are four main objectives of the study: (1) develop effective remote sensing algorithms for total
suspended particulate (TSP) concentration using Landsat-5 TM spectral data, (2) apply varimax-rotated principal component analysis (PCA) to identify the distribution patterns of dominant surface reflectors, (3) identify land cover endmembers based on scattergrams and normalized difference remote sensing indices, and (4) identify lithogenic particulates in surface water.

In chapter three, I focus on total suspended particulate (TSP) concentration in open surface water because it is easily detected by satellite remote sensing. The TSP includes; terrigenous suspended sediments, phytoplankton, zooplankton and all other dissolved organics matter in surface water column. The primary aim of chapter three is to statistically evaluate the correlation of spectral data from the Landsat-5 TM with laboratory measurements of the TSP concentration to develop an effective remote sensing algorithm. Chapter four describes an application of varimax-rotated principal component analysis (PCA) to identify the spatial and temporal distribution of dominant surface reflectors in the vicinity of OWC. Atmospherically corrected Landsat-5 TM reflectance data from visible, near infrared (NIR), and mid infrared (MIR) bands were used for the analysis. Chapter five approaches scattergrams and normalized difference remote sensing indices to overcome the limitations of spatial resolution of Landsat-5 TM imagery in applications over small spatial extent like Old Woman Creek. This phenomenon is common in highly dynamic environments such as wetlands where land cover shifts rapidly between aquatic and terrestrial. The lithogenic particulates in surface water, identified by X-ray diffraction (XRD) and environmental scanning electron microscopy
(ESEM), are addressed in chapter six. Finally, chapter seven summarizes the overall findings of this study and their significance for future investigations.

2.2 Environmental settings

Old Woman Creek is the only National Estuarine Research Reserve (NERR) in the Great Lakes biogeographic region. It is located at the south central shore of Lake Erie, North Central Ohio and drains approximately 27 square miles within Huron and Erie counties, where agriculture is the primary land use practice of the area (Figure 2.1). The research reserve encompasses a total of 2,310,755 square meters where the estuarine setting spreads over 607,128 square meters. The approximate elevation is 250 meters above sea level. According to the hydrogeomorphic classification for Great Lakes marshes, OWC is a riverine wetland system (Albert et. al., 2005). It is further classified as an open drowned river mouth which often separates the estuary from the Lake by a sand barrier. This separation is breached either occasionally or frequently when pressure from stream flow or an increase of Lake water level blows out the sand barrier (Albert et. al., 2005). The Glossary of Geology (Bates and Jackson, 1980) defines a fresh water estuary as: “In the Great Lakes and other large lakes, the lower reach of a tributary to the lake that has a drowned river mouth, shows a zone of transition from stream water to lake water and is influenced by changes in lake level as a result of seiches and wind tides” (Herdendorf, 1990). The two processes that break the barrier are: (a) storm flow from the watershed, and (b) Lake Erie storm surges that spill over the bar and enter into the estuary (Herdendorf, Klarer, and Herdendorf, 2004). Fluctuations of lake level influence the creek near Lake Erie. In most years, the mouth of the wetland is closed during
considerable periods of Summer and Fall because low stream discharges are insufficient
to maintain an opening in the beach (Krieger, 2003). In 2005, the barrier beach barred off
the estuary from June to August. The development of this sandy mouth bar is common
during summer creating a stagnant water body by isolating waters of Old Woman Creek
from Central Lake Erie.

As a transition zone between land and water, OWC estuary and its immediate
environment contain several distinct habitats, including woodlands, a prairie remnant,
creek valley, swamp forest, marshes, wooded cover, open waters of the estuary, an island,
barrier beach, and near shore Lake Erie (Figure 2.2). The OWC watershed overlies shale
and sandstone bedrock formations. The modern soils are mixed with till and glacial
lacustrine deposits (Krieger, 2003; Buchanan, 1982). The creek is a second order stream,
where the estuarine portion of OWC extends 2.1 km southward from the creek mouth.
The estuary is segmented into three sections: (1) lake lagoon, (2) main basin, and (3)
south basin. The lake lagoon is a small, elongated basin that lies between U.S. Route 6
and the barrier beach. The main and south estuarine regions are bisected by a local
Conrail line. A narrow channel runs the entire length of the estuary along its eastern
margin and carries discharge waters directly into Lake Erie. A secondary channel that
splits off the main channel at the southern end of the main basin follows a course to the
west. A small island with a star shape which is located at the center of the main basin
between these channels is a unique feature of this environment. The large surface area to
depth ratio in the main basin ensures that bottom sediments are easily re-suspended by
moderate winds and bioturbation (Klarer, et. al., 1992; Krieger et. al., 2003). The south
basin of the estuary is more riverine-like and is comprised of a narrow channel that extends south from the Conrail bridge to the vicinity of the Darrow road bridge. Depths range up to 3.5 meters in the inlet channel, but most of the estuary is less than 1 meter deep. The shallows are often overgrown by dense beds of *Nelumbo lutea* (American water lotus). Water retention time in the estuary is generally less than a day except at times when the mouth is barred across, which occurs over 40% of the time (Herdendorf, Klarer, and Herdendorf, 2004).
Figure 2.1. The location of Old Woman Creek watershed with respect to the central basin of Lake Erie. The study area is outlined in red which is detailed in Figure 2.2. (Source GIS data: http://www.dnr.state.oh.us)
Figure 2.2. The study area. © 2007 Nishanthi Wijekoon.
2.3 Literature review

2.3.1 Previous Studies at OWC

In 1980, Old Woman Creek was designated as the seventh National Estuarine Research Reserve (NERR) in the United States. As with many wetlands, OWC receives sediments, nutrients, and organic pollutants from its watershed through its tributaries and plays a beneficial role in reducing the loading of these materials entering Lake Erie. There is however wide variation in the monthly, seasonal, and annual sediment loads exported from OWC and many attempts have been reported during past decades to characterize the great variability of seasonal and annual loads (Krieger, 2003; Matisoff et al., 2003 & 2002; Baker, 1993 & 1998; Baker and Richards, 1993 & 1998; Heath, 1992; Buchanan, 1983). The magnitude of temporal dynamics of sedimentation rates are dependent on a number of variables including bed rock and soil types, local topographic relief, climate, land cover, biological activity, and a variety of human factors.

In addition to the sediment load investigations, various aspects of the site of the Old Woman Creek have been studied by previous researchers. The glacial history of Erie and Huron counties was described and the major morainal systems were mapped by Lois Campbell in her Ph. D. dissertation (Campbell, 1955). Specific study of the regional geology in the vicinity of the estuary began in 1963 with the work of C. E. Herdendorf in his Master’s Thesis entitled “Geology of the Vermillion Quadrangle, Ohio”, which contained the first detailed bedrock map for the area (Herdendorf, 1963 & 1966). In 1983, David Buchanan studied transport and deposition of sediment in OWC estuary in a detailed manner. His study found that the majority of sediment originates from erosion on
the till plain in the upper creek basin and only silts and clays are transported into and
deposited in the estuary. During the last 100 years, the combined effects of rising lake
levels and sediment deposition have decreased the water depth in the estuary to such a
degree that shallow-water aquatic vegetation has begun to colonize its surface. The
sediment depositional rate in the estuary over the last 8,000 years has averaged 0.03 inch
per year (Buchanan, 1983). Agricultural development of the watershed of Old Woman
Creek during last 100 years has greatly accelerated this rate to be around 0.4 inch per
year in 1983 (Buchanan, 1983).

The distribution of aquatic macrophytes in Old Woman Creek estuary was first
systematically recognized and inventoried in 1973 by Marshall (Marshall and Stuckey,
1974). Thereafter, aquatic macrophytes and algal floras were examined and possible
causes for their shift were discussed in detail by Klarer and Millie (1992). They
suggested that storm events were a major factor in regulating phytoplankton species
composition and dynamics in the vicinity. Their research discussed the primary
productivity in Old Woman Creek, which appears to be dominated by algal communities
rather than by macrophytes (Klarer and Millie, 1992).

2.3.2 Remote monitoring of wetlands

Knowledge of the distribution of fine sediment within surface water becomes an
important issue to consider in any water quality study of an estuary. Methods used to
measure suspended sediment in estuaries are often based on in-situ measurements and
subsequent laboratory analysis of samples collected from a small number of locations.
Those approaches, while accurate, are time consuming and do not easily provide the
researchers with an understanding of the spatial or temporal dimensions of variability of total suspended particulates (TSP) within the estuary (Nellis et al., 1998). In contrast, remote sensing techniques provide an efficient and reasonably accurate large scale method for investigation of changes in TSP concentrations in estuarine settings, but this approach requires careful validation by comparing with in situ data (Woodruff et al., 1999; Rainey et al. 2003; Nakamura et al., 2004). Accordingly, the application of remote sensing techniques to wetland assessment has increased since the 1980’s (Kite & Pietroniro, 2000).

Since the late 1970’s, remote sensing studies of suspended sediment have been made using data from airborne and space borne platforms. Remote sensing methods provide the ability to measure the optical characteristics of upwelling electromagnetic radiation influenced by the TSP in near surface water (Svehla et al., 1975; Wass et al., 1997; Woodruff et al., 1999; Ritchie et al., 2000; Schmugge et al., 2002; Froidefond et al., 2002; Bowers et al., 2004; Binding et al., 2005). Studies that have used satellite data from the Landsat-5 TM indicate the capability of space-borne platforms to assess the TSP variability in open surface water (Lira et al., 1997; Forget and Ouillon, 1998; Nellis et al., 1998; Li et al., 2001; Islam et al., 2001 & 2002; Wang et al., 2004; Warrick et al., 2004). The color of the water in an estuary, which is the basis of remote investigation of estuarine settings, depends upon the optical properties of water and the materials dissolved and suspended in the water column (Bowers et al., 2004).
2.3.3 Remote monitoring at Old Woman Creek

In the Summer of 2002, the National Oceanic and Atmospheric Administration (NOAA) Estuarine Reserves Division and Coastal Services Center conducted a remote sensing and geographic information system (GIS) needs assessment of each reserve system to identify the common issues, capacity needs, and data used in the system (Schuyler et al., 2002). The priority issues of remote monitoring reported during that survey for Old Woman Creek estuary were land use change, conservation practices in agriculture, and near shore and stream aquatic mapping. The report further indicated that the lack of high resolution imagery, staff time, and trained resource people were bottlenecks to using remote sensing in the vicinity (Schuyler et al., 2002).

In Summer of each year, one aerial photograph of the estuary is captured primarily to look at vegetation change or to facilitate zoning decisions within local government (Schuyler et al., 2002). In 1998, a spatio-temporal modeling approach to soil erosion and contaminated sediment transport in Old Woman Creek estuary was developed by monitoring terrain surfaces and shoreline changes using digital elevation models (DEM) generated from periodical aerial photographs of the area (Ali & Li, 2000). Those aerial photos were acquired by the National Geodetic Survey of NOAA in mid 1997 and the GPS ground control network surveyed by a GIS research team at the Ohio State University (Ali & Li, 2000).

Recently, Landsat-7 and MODIS satellite data have been used to measure water quality parameters in Old Woman Creek estuary (Zhang, 2005). This work developed three exponential regression models to correlate suspended sediment concentration and
turbidity measurements which were obtained from National Estuarine Research Reserve (NERR) Centralized Data Management Office, with the reflectance data of bands 2 and 4 from the Landsat-7 ETM+ imagery (Zhang, 2005).

2.4 Atmospheric correction

2.4.1 Landsat-5 TM data

In this study, Landsat-5 TM data are used for calibration of TSP concentration, principal component analysis, and scattergram analysis. This instrument is well suited to study environmental problems because the Earth’s surface reflects in the visible, near infrared, and mid infrared regions, and emits in the thermal infrared spectral region (Obenschain et al., 1997). The TM sensor collects earth surface reflectance data from visible, near and mid infrared regions of the electromagnetic (EM) spectrum (Table 2.1). The satellite revisits every 16 days around 12 noon in Eastern Time and that is an appropriate temporal resolution to investigate a dynamic wetland. Landsat-5 TM data are freely available through OhioView, a remote sensing consortium of Ohio’s public research universities. I used Path 19 Row 31 imagery clipped to 4,593,182 square meters focusing on the old Woman Creek estuary and it’s suburbs for all remote sensing analysis.
Table 2.1. Band definitions for Landsat-5 TM (Obenschain et al., 1997).

<table>
<thead>
<tr>
<th>Band</th>
<th>Type</th>
<th>Wavelength (μm)</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blue-Green</td>
<td>0.45-0.515</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>Green</td>
<td>0.52-0.605</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>Red</td>
<td>0.63-0.69</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>Near IR</td>
<td>0.77-0.90</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>SWIR</td>
<td>1.55-1.75</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>LWIR</td>
<td>10.4-12.5</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>SWIR</td>
<td>2.09-2.35</td>
<td>30</td>
</tr>
</tbody>
</table>
2.4.2 Dark object subtraction

In the satellite imagery, effects of atmospheric haze were reduced by applying simple dark object subtraction to each band. The additive term was identified by constructing histograms for each spectral band using the entire frame of data. The minimum digital number (DN) found in all of the pixels of the image was determined and one less than the minimum DN was taken to be the dark object for a given spectral band. This quantity was subtracted from the entire frame of data (Chavez, 1988).

2.4.3 Landsat-5 TM radiometric calibration

Radiometric calibration normalizes the dark object corrected DN in order to compare the spectral data between images acquired in different dates. This technique was also used for the comparison of data collected with different sensors such as TM and ETM+ in Landsat-5 and Landsat-7 respectively (Chander and Markham, 2003). Calibration procedures that have been developed to convert DN into spectral radiance, and then to planetary reflectance at top-of-atmosphere ($\rho$) or temperature was used. This is a two step procedure; (1) DN conversion to radiance, and (2) radiance conversion to $\rho$ for reflective bands and to temperature for emissive band. Formulation models for Landsat-5 TM gain are time-dependent equations of each band which were developed by Chander and Markham (2003). The lookup tables they generated from the lifetime gain model equations for all bands were used for radiometric calibration of Landsat-5 TM digital numbers (Chander and Markham, 2003). This approach is similar to the current calibration method of Landsat-7 ETM+ described in *Landsat-7 ETM+ Data Handbook.*
In step one, DN-to-radiance conversion for an L1 product was performed according to the following equation (Chander and Markham, 2003).

\[
L_\lambda = \left( \frac{L_{MAX_\lambda} - L_{MIN_\lambda}}{Q_{cal_{max}}} \right) Q_{cal} + L_{MIN_\lambda}
\]

Where,

- \( L_\lambda \) = spectral radiance at the sensor’s aperture in W/(m² sr μm);
- \( Q_{cal} \) = quantized calibrated pixel value in DNs;
- \( Q_{cal_{min}} \) = minimum quantized calibrated pixel value (DN=0) corresponding to \( L_{MIN_\lambda} \);
- \( Q_{cal_{max}} \) = maximum quantized calibrated pixel value (DN=255) corresponding to \( L_{MAX_\lambda} \);
- \( L_{MIN_\lambda} \) = spectral radiance that is scaled to \( Q_{cal_{min}} \) in W/(m² sr μm);
- \( L_{MAX_\lambda} \) = spectral radiance that is scaled to \( Q_{cal_{max}} \) in W/(m² sr μm).

The above equation can also be defined as

\[
L_\lambda = G_{rescale} \times Q_{cal} + B_{rescale}
\]

where

\[
G_{rescale} = \left( \frac{L_{MAX_\lambda} - L_{MIN_\lambda}}{Q_{cal_{max}}} \right)
\]

\[
B_{rescale} = L_{MIN_\lambda}.
\]

Table 2.2 provides band specific \( L_{MIN_\lambda} \) and \( L_{MAX_\lambda} \) parameters and the corresponding \( G_{rescale} \) and \( B_{rescale} \) values used at different times for the Landsat-5 TM calibration procedure.
Table 2.2. Landsat-5 TM postcalibration dynamic ranges for U. S. processed Landsat-5 TM data (Chander and Markham, 2003).

<table>
<thead>
<tr>
<th>Processing Date</th>
<th>Spectral Radiances, $LMIN_{\lambda}$ and $LMAX_{\lambda}$ in W/(m$^2$ sr $\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From March 1, 1984 To May 4, 2003</td>
</tr>
<tr>
<td>Band</td>
<td>$LMIN_{\lambda}$</td>
</tr>
<tr>
<td>1</td>
<td>-1.52</td>
</tr>
<tr>
<td>2</td>
<td>-2.84</td>
</tr>
<tr>
<td>3</td>
<td>-1.17</td>
</tr>
<tr>
<td>4</td>
<td>-1.51</td>
</tr>
<tr>
<td>5</td>
<td>-0.37</td>
</tr>
<tr>
<td>6</td>
<td>1.2378</td>
</tr>
<tr>
<td>7</td>
<td>-0.15</td>
</tr>
</tbody>
</table>
In step two, spectral radiance ($L_\lambda$) was converted to unitless planetary reflectance at the top of the atmosphere ($\rho$). There are two advantages of using reflectance instead of radiances. First, the cosine effect of different solar zenith angles due to the time difference between data acquisitions can be removed, and second, it compensates for different values of the exoatmospheric solar irradiances arising from spectral band differences (Chander and Markham, 2003). The combined surface and atmospheric reflectance of the earth is computed according to

$$\rho = \frac{\pi L_\lambda \ d^2}{ESUN_\lambda \ \cos\theta_s}$$

where

$\rho$ = unitless planetary reflectance;

$L_\lambda$ = spectral radiance at the sensor’s aperture;

d = earth-sun distance in astronomical units;

$ESUN_\lambda$ = mean solar exoatmospheric irradiances;

$\theta_s$ = solar zenith angle in degrees.

Table 2.3 gives solar exoatmospheric spectral irradiances for Landsat-5 TM data.
Table 2.3. The solar exoatmospheric spectral irradiances (Chander and Markham, 2003).

<table>
<thead>
<tr>
<th>Band</th>
<th>Landsat-5 TM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1957</td>
</tr>
<tr>
<td>2</td>
<td>1826</td>
</tr>
<tr>
<td>3</td>
<td>1554</td>
</tr>
<tr>
<td>4</td>
<td>1036</td>
</tr>
<tr>
<td>5</td>
<td>215.0</td>
</tr>
<tr>
<td>7</td>
<td>80.67</td>
</tr>
</tbody>
</table>

Units: ESUN = W/(m² sr µm)
The earth-sun distance can be calculated in astronomical units using following equation

\[ d = 1 + 0.0167 \sin\left[2\pi\left(D - 93.5\right)/365\right] \]

where \( D \) is the day number of the year (Van der Meer, 1996). Solar zenith angle is calculated using solar elevation angle which is available in Landsat-5 TM metadata based on the simple relationship of

\[ \text{solar zenith angle} = (90 - \text{solar elevation angle}) \].

Table 2.4 represents solar zenith angles and earth-sun distances that I applied to all satellite images using in the current study.

For the emissive band (band 6), the spectral radiance is converted to effective at-satellite temperature based on

\[ T = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} \]

where

- \( T \) = effective at-satellite temperature in kelvin;
- \( K_1 \) = calibration constant 1 in W/(m² sr μm);
- \( K_2 \) = calibration constant 2 in kelvin;
- \( L_\lambda \) = spectral radiance at the sensor’s aperture.

Calibration constants \( K_1 \) and \( K_2 \) for Landsat-5 TM is given as 607.76 W/(m² sr μm) and 1260.56 K respectively (Chander and Markham, 2003).
Table 2.4. Solar zenith angles and earth-sun distances for Landsat-5 TM imagery that were used for the study. The solar elevation angle and the day of the year were accessed from [http://edcns17.cr.gov/EarthExplorer](http://edcns17.cr.gov/EarthExplorer) for calculation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month and Day</th>
<th>Solar Zenith Angle in Degrees</th>
<th>Earth-Sun distance in astronomical units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>April-11</td>
<td>38.977</td>
<td>1.002150</td>
</tr>
<tr>
<td></td>
<td>May-13</td>
<td>29.774</td>
<td>1.010500</td>
</tr>
<tr>
<td></td>
<td>May-29</td>
<td>27.324</td>
<td>1.013636</td>
</tr>
<tr>
<td></td>
<td>June-14</td>
<td>26.492</td>
<td>1.015744</td>
</tr>
<tr>
<td></td>
<td>June-30</td>
<td>27.106</td>
<td>1.016665</td>
</tr>
<tr>
<td></td>
<td>August-01</td>
<td>31.564</td>
<td>1.014764</td>
</tr>
<tr>
<td></td>
<td>August-17</td>
<td>35.112</td>
<td>1.012085</td>
</tr>
<tr>
<td></td>
<td>September-02</td>
<td>39.421</td>
<td>1.008495</td>
</tr>
<tr>
<td></td>
<td>October-04</td>
<td>49.689</td>
<td>0.999713</td>
</tr>
<tr>
<td>2006</td>
<td>June-17</td>
<td>25.756</td>
<td>1.016011</td>
</tr>
<tr>
<td></td>
<td>July-19</td>
<td>28.500</td>
<td>1.016128</td>
</tr>
<tr>
<td></td>
<td>August-04</td>
<td>31.400</td>
<td>1.014314</td>
</tr>
<tr>
<td></td>
<td>September-05</td>
<td>39.645</td>
<td>1.007741</td>
</tr>
<tr>
<td></td>
<td>September-21</td>
<td>44.736</td>
<td>1.003425</td>
</tr>
<tr>
<td></td>
<td>October-07</td>
<td>50.159</td>
<td>0.998851</td>
</tr>
</tbody>
</table>

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CHAPTER 3

Quantitative remote mapping of total suspended particulate (TSP) concentration in a shallow water estuary

3.1 Abstract

Dynamic estuarine environments exhibit considerable spatial and temporal heterogeneity of water quality and thus require remote sensing approaches to rapidly gather quantitative synoptic data. Simultaneous acquisition of water samples were performed at 15 sampling stations in the Old Woman Creek (OWC) estuary with Landsat-5 TM during over passing days from June to October in 2005 and 2006. The study employs a novel definition for the normalized difference water index (NDWI) which evaluated the contrasting ratio between the visible and the infrared bands of Landsat-5 TM imagery to detect open surface water bodies and map their total suspended particulate (TSP) dynamics. The normalized difference algorithms between the visible and the middle infrared (MIR) bands which eliminates the vegetation moisture accounted by the traditional NDWI approaches identifies a significant contrast between land and water surfaces. In estuarine waters, the remote estimation of TSP concentration using optical algorithms mainly exploits the upwelling radiation in the visible region. The NDWI of the blue and the middle infrared (MIR) bands (NDWI$_{1&5}$) of Landsat-5 TM sensor was identified as the most effective algorithm for TSP estimation based on a linear correlation of 0.70. The analysis revealed the capability of moderate resolution satellite
imagery to quantify TSP concentration in a shallow coastal wetland.

3.2 Introduction

Estuaries contain significant quantities of terrigenous material which result in great optical complexity due to the presence of inorganic particulates and a great variety of particulate organic matter (Woodruff et al., 1999). The goal of this research is to calibrate the total suspended particulate (TSP) concentration at the Old Woman Creek estuary using moderate resolution (30 m × 30 m) satellite imagery. The purpose was to determine whether moderate resolution imagery is capable of investigating TSP dynamics in this coastal wetland with an area of 600,000 square meters that extends 2,100 meters south of the Lake Erie shore.

TSP is one of the visible indicators associated with water quality and it is governed by biological activities of surface water, human impact, and other environmental and climatic factors over the watershed. The remote sensing data acquired through the visible region of the electromagnetic spectrum from Landsat-5 TM sensor are important in detecting TSP distribution patterns. In this study, TSP refers to terrigenous suspended sediments, phytoplankton, zooplankton and all other organic particulates in the surface water column. I investigated nine normalized difference remote sensing indices derived using the visible and infrared Landsat-5 TM bands to identify their relationship to the TSP concentration in the surface water column at Old Woman Creek estuary. Because I focused on open water, each resulted remote sensing index was called the normalized difference water index with a subscript denoting the bands that were involved in the
algorithm \((\text{NDWI}_{x,y})\) where \(x\) is the visible band and \(y\) is the infrared (IR) band. The general equation used for the study was:

\[
\text{NDWI}_{\text{Visible} \& \text{Infrared}} = \frac{R_{\text{Visible Band}} - R_{\text{Infrared Band}}}{R_{\text{Visible Band}} + R_{\text{Infrared Band}}}
\]

where \(R\) is the percent reflectance. NDWI identifies water bearing pixels based on the ratio of the difference between the visible and the infrared bands over the sum of the same. Although different researchers define this index according to their ultimate perspectives, the basic aim of my study was to identify open surface water layer and quantify its spatial TSP dynamics.

### 3.3 Literature review

Traditional TSP monitoring methods depend on the in-situ measurements and the subsequent laboratory analysis (Pfannkuche and Schmidt, 2003). Although these methods provide accurate measurements, they are time consuming and economically less important. They also fail to perform the real-time spatial overview of TSP quantitatively which is a remarkable step in monitoring water quality (Nellis et al., 1998; Wang, et al., 2004). The current study addresses those drawbacks of the traditional approaches.

Since late 1970’s remote sensing studies of suspended sediments have been made using data from satellite platforms. One of the first studies done in the detection of suspended sediment by means of remote sensing is the quantitative estimation of suspended sediment in water bodies using a portable radiometer (Richie et al., 1976). Some of the later work was based on simple linear regressions of in-situ measurements and Landsat MSS data (Richie and Cooper, 1988). Air borne remote sensing had also
been used in calibration techniques of suspended sediment concentration to provide high resolution spatial information (Wass et al., 1997). There are several studies that reported the spatial and the temporal changes in sedimentation and their distribution patterns using Landsat-5 TM imagery and in-situ measurements (Lira et al., 1997; Nellis et al., 1998; Ritchie and Schiebe, 2000; Li. et al., 2001; Chen et al., 2004; Wang, et al., 2004).

Modeling of the concentration of suspended particles on reflectance measurements has been worked out quantitatively establishing a criterion based on the absolute determination of water quality (Topliss et al., 1990; Bhargava and Mariam, 1991; Lira et al., 1997; Forget and Ouillon, 1998; Ruhl et al., 2001; Schmugge et al., 2002; Liu et al., 2003; Mishra, 2004; Bowers et al, 2004; Miller and MsKee, 2004). Regression modeling had been carried out using single band visible reflectance to estimate the suspended sediment concentration in turbid waters (Islam et al., 2001; Binding et al, 2005).

Attempts to estimate suspended and dissolved matter concentrations in estuarine waters using reflectance band ratios have also been reported (Doxaran et al., 2002 and 2005; Menon et al., 2006).

Normalized difference band ratios are defined and applied by many remote sensing scientists in several different ways to fulfill the objective of their research (Table 3.1). The normalized difference band combination of blue and MIR bands (NDWI1&5) had been used to identify snow cover variations together with in-situ records (Delbart et al., 2005). The current study is the first application of the same algorithm (NDWI1&5) to quantify TSP concentration in estuarine surface water using Landsat-5 TM data.

Therefore, the objective of this study was to investigate the effectiveness of NDWIx&y
algorithms to quantify TSP concentration of open surface water in Old Woman Creek estuary and map the TSP distribution pattern quantitatively based on the most successful algorithm in spatial and temporal perspective.

Table 3.1. The previous applications of normalized difference band combinations from satellite imagery.

<table>
<thead>
<tr>
<th>Remote sensing index</th>
<th>Definition</th>
<th>Application</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Difference Water Index</td>
<td>( NDWI = \frac{R_{\text{band}4} - R_{\text{band}5}}{R_{\text{band}4} + R_{\text{band}5}} )</td>
<td>Investigation of the vegetation moisture</td>
<td>Gao, 1996; Zarco-Tejada et al., 2003; Jackson et al., 2004; Dennison, et al., 2005; Delbart et al., 2005; Chen et al, 2005</td>
</tr>
<tr>
<td>Normalized Difference Moisture Index</td>
<td>( NDMI = \frac{R_{\text{band}4} - R_{\text{band}5}}{R_{\text{band}4} + R_{\text{band}5}} )</td>
<td>Detection of the forest disturbances</td>
<td>Jin and Sader, 2005</td>
</tr>
<tr>
<td>Normalized Difference Water Index</td>
<td>( NDWI = \frac{R_{\text{band}2} - R_{\text{band}4}}{R_{\text{band}2} + R_{\text{band}4}} )</td>
<td>Identification of the pixels as been wet in classification studies of water layer in coastal marshes</td>
<td>Chen et al., 2004; Hurd et al., 2005</td>
</tr>
<tr>
<td>Normalized Difference Snow Index</td>
<td>( NDSI = \frac{R_{\text{band}2} - R_{\text{band}5}}{R_{\text{band}2} + R_{\text{band}5}} )</td>
<td>snow-cover mapping</td>
<td>Hall et al., 1998</td>
</tr>
<tr>
<td>Normalized Difference Snow Index</td>
<td>( NDSI = \frac{R_{\text{band}1} - R_{\text{band}5}}{R_{\text{band}1} + R_{\text{band}5}} )</td>
<td>snow-cover mapping</td>
<td>Delbart et al., 2005</td>
</tr>
</tbody>
</table>
3.4 Study area

The Old Woman Creek estuary is located at the drowned mouth of a small tributary along the south central shore of Lake Erie, north central Ohio. The three main segments of the estuary; lake lagoon, main basin and south basin comprise 4%, 82%, and 14% of the total estuarine area respectively. A detailed description of the environmental setting is included in section 2.2. Depths range from 1 meter to 3.7 meters in the inlet channel along the eastern margin of the main basin, but most of the remaining estuarine setting is less than 1 meter deep (Herdendorf, Klarer, and Herdendorf, 2004). When using remote sensing to measure any properties of surface waters, it is important to make certain that the spectral signature at the sensor represents the water constituents alone, and not the estuarine bottom (Tolk et al., 2000). Therefore, water sampling stations were selected along the eastern channel which has a greater depth in comparison to the rest of the open waters. The first and the fifteenth sampling stations were located within the Lake Lagoon and the south basin while the remaining thirteen locations were spaced along the eastern channel of the main basin (Figure 3.1).
Figure 3.1. Sampling stations were located along the eastern margin of the Old Woman Creek estuary where the main channel runs to Lake Erie. © 2007 Nishanthi Wijekoon.
3.5 Methods

3.5.1 Field techniques

The location of the sampling stations accessible by boat was determined in advance by investigating both Landsat-5 TM and ETM+ images available for the past few years. The temporal and the spatial resolution of the imagery are 16 days and 30 meters respectively. The selected 15 sampling stations were located and reoccupied by Universal Transverse Mercator (UTM) coordinates using a Global Positioning System (GPS) unit. The boat facility for sample collection was provided by the OWC estuarine research center. Since Old Woman Creek estuary is a small water body, maximum care was taken to be at the middle of the open surface water during sampling to eliminate the contamination of pixels by aquatic and terrestrial vegetation. The surface water samples were collected into 1 liter screw-capped Nalgene bottles to ground-truth images along the GPS referenced transects during days with Landsat-5 TM overpasses. The data acquired during Summer 2005 and 2006 from June to October were considered. In 2005, I collected samples directly from the top of the open water whereas in summer 2006, the samples were collected from about 6-12 inches below the surface as some references indicated the shallowest reliable turbidity readings typically occur slightly below the water surface (Binding et al., 2005; Wang et al., 2004; Woodruff et al., 1999).

3.5.2 Quantification of TSP concentration in surface water

The TSP concentration was measured directly using two methods; (1) filtering a known volume of estuarine water through pre-weighted filter types and (2) laser diffraction technique. Three filter types, (1) 0.7 μm GF/F glass microfiber filters, (2) 0.45
μm Durapore membrane filters made from polyvinylidifluoride (PVDF), and (3) 0.8 μm polycarbonate membrane filters were used for the study. One hundred milliliters of surface water was filtered to quantify the TSP concentration. The filters were oven-dried at 60 °C for 24 hours and then measured for dry mass to estimate TSP concentration in μg/L. The most effective filter type to quantify TSP concentration in the estuarine water was evaluated based on the correlation generated from regression between the two methods. In the laser diffraction method employed by the Malvern Mastersizer 2000, the concentration is detected by the scattering of the instrument’s laser beam due to suspended particulates as the light passes through the sample cell while the sample is continuously pumped thought the cell at a constant rate. I used 2500 rounds per minute as the pumping rate through out the study. The results were reported as percentage volume concentration. The instrument also measures the particle size spectrum of fine particles with grain sizes in a range of 0.02 μm to 2000 μm. This method is both accurate and efficient in comparison to traditional hydrometer or sieving methods of analyzing fine-grained sediment. The correlation of the resulting TSP concentrations as volume percentage and μg/L were evaluated. The in-situ data were used to calibrate the spatial and temporal distribution patterns of NDWIx&y measured by remote sensing.

3.5.3 Satellite data

The Landsat -5 TM scenes (Path 19/ Row31) were acquired from 2005 and 2006 for normalized difference band ratio analysis. The effect of atmospheric haze was reduced by a simple dark object subtraction method which is discussed in section 2.4.2
(Chavez, 1988). Then, the dark object subtracted digital numbers were radiometrically calibrated to convert them into reflectance based on the method described in section 2.4.3 (Chander and Markham, 2003). To focus only on the wetland region of Old Woman Creek, the Landsat-5 TM images were clipped to the analysis region that included the coastal marsh and the adjacent uplands. The square-shaped clips covered an area of 4,593,182 square meters including a part of the creek, the estuary and a portion of Lake Erie.

3.5.4 Remote sensing indices

Nine new 32 bit raster layers were added to the existing files to store the results of the calculated indices. Then, an EASI model was generated to calculate all possible normalized difference remote sensing indices between the visible and the infrared bands using Focus in PCI Geomatica 10.0 (Table 3.2). A special case among selected algorithms was that the values resulted from the algorithm between bands 3 and 4 is the inverse of Normalized Difference Vegetation Index (NDVI).
Table 3.2. The normalized difference algorithms between the visible and the infrared bands of Landsat-5 TM were used for NDWI calculations which were regressed against TSP concentration. The respective band is shown as a subscript of each R which is the reflectance.

<table>
<thead>
<tr>
<th>Remote sensing index</th>
<th>Algorithm</th>
<th>Abbreviation used in plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDWI$_{1&amp;4}$</td>
<td>$\frac{R_{\text{band}1} - R_{\text{band}4}}{R_{\text{band}1} + R_{\text{band}4}}$</td>
<td>1&amp;4</td>
</tr>
<tr>
<td>NDWI$_{1&amp;5}$</td>
<td>$\frac{R_{\text{band}1} - R_{\text{band}5}}{R_{\text{band}1} + R_{\text{band}5}}$</td>
<td>1&amp;5</td>
</tr>
<tr>
<td>NDWI$_{1&amp;7}$</td>
<td>$\frac{R_{\text{band}1} - R_{\text{band}7}}{R_{\text{band}1} + R_{\text{band}7}}$</td>
<td>1&amp;7</td>
</tr>
<tr>
<td>NDWI$_{2&amp;4}$</td>
<td>$\frac{R_{\text{band}2} - R_{\text{band}4}}{R_{\text{band}2} + R_{\text{band}4}}$</td>
<td>2&amp;4</td>
</tr>
<tr>
<td>NDWI$_{2&amp;5}$</td>
<td>$\frac{R_{\text{band}2} - R_{\text{band}5}}{R_{\text{band}2} + R_{\text{band}5}}$</td>
<td>2&amp;5</td>
</tr>
<tr>
<td>NDWI$_{2&amp;7}$</td>
<td>$\frac{R_{\text{band}2} - R_{\text{band}7}}{R_{\text{band}2} + R_{\text{band}7}}$</td>
<td>2&amp;7</td>
</tr>
<tr>
<td>NDWI$_{3&amp;4}$ (Inverse of NDVI)</td>
<td>$\frac{R_{\text{band}3} - R_{\text{band}4}}{R_{\text{band}3} + R_{\text{band}4}}$</td>
<td>3&amp;4</td>
</tr>
<tr>
<td>NDWI$_{3&amp;5}$</td>
<td>$\frac{R_{\text{band}3} - R_{\text{band}5}}{R_{\text{band}3} + R_{\text{band}5}}$</td>
<td>3&amp;5</td>
</tr>
<tr>
<td>NDWI$_{3&amp;7}$</td>
<td>$\frac{R_{\text{band}3} - R_{\text{band}7}}{R_{\text{band}3} + R_{\text{band}7}}$</td>
<td>3&amp;7</td>
</tr>
</tbody>
</table>
3.5.5 Land cover interfaces

It was important to identify the specific remote sensing index value that represents the interface or threshold between water and other land covers. The interface value was used as a break-point in pseudo-color tables (PCT) to select open water pixels with minimum interference of mixed spectral signature and mask out the land cover types other than open-water. I focused on five dominant land cover types of the vicinity; (1) Lake Erie water, (2) estuarine water, (3) terrestrial macrophytes, (4) aquatic macrophytes, and (5) urban structures such as roads to perform this analysis using eight clipped satellite images in 2005. First, a set of representative pixels which I assumed to be uncontaminated with mixed spectral signatures were selected for each land cover type from all imagery. This endmember pixel selection was performed based on real-time field observations and the spectral properties of the endmembers. Then, I extracted the percent reflectance values for each Landsat-5 TM reflectance band relevant for the selected pixels. For each acquisition day of the imagery, the percent reflectance values of the same land cover type were averaged to assign a percent reflectance value that represented the land cover endmembers. For algorithms in Table 3.2, I calculated representative NDWI values based on the representative percent reflectance. Finally, a break point which was applied to the pseudo-color table (PCT) to extract the open-water regions based on the significantly contrasting variation of the representative indices.
3.5.6 Spatial distribution patterns for open surface water

According to the NDWI_{x,y} of each pixel, the pseudo-color spatial and temporal distribution patterns of open surface water were interpreted. The land covers other than open water were masked based on the selected break point value. The resulting patterns were compared with the real-time field observations to evaluate the validity of the interface value. The most acceptable open water distribution patterns were considered to calibrate the TSP concentration which is described in section 3.5.2, I assumed that those patterns extracted the open water pixels with minimum mixed spectral properties.

3.5.7 Algorithm evaluation for TSP calibration

The sampling stations located within the masked regions tend to generate mixed spectral signatures. Hence, I selected only the sampling stations located within the most acceptable spatial distribution patterns of water for TSP calibration. The relationship between the laboratory measurements of TSP concentrations and the NDWI values of those selected algorithms was evaluated using regression analysis.
3.6 Results and Discussion

3.6.1 Effectiveness of filters

Strong linear correlations were reported for TSP concentration between the laser diffraction technique and the dry filter mass method measured in each sample. The linear correlations of $r^2 = 0.96$ for 0.45 $\mu$m PVDF membrane filters and $r^2 = 0.92$ for 0.7 $\mu$m GF/F glass microfiber filters were reported. The polycarbonate membrane filters of 0.8 $\mu$m recorded a linear correlation of 0.83. Since the maximum correlation among selected filters was recorded by the first two filter varieties, repetitive studies to quantify TSP concentration were performed using them. Unit conversion for the TSP concentration from volume % to mg/L was carried out using regression statistics generated from the filter measurements (Figure 3.2 and Figure 3.3). Following equations were used for the conversion; $y = 4656 \cdot 1.16 x + 7.48$ for the GF/F measurements and $y = 4839 \cdot 0.74 x - 5.09$ for the 0.45 $\mu$m Durapore membrane measurements where $x$ and $y$ are the TSP concentrations in units of volume percentage and mg/L respectively.

The laser diffraction measurements provide a non-intrusive, simple to implement method that is frequently employed to assess the size of particles in 0.02 to 2000 $\mu$m range. The particle size spectrum of each sample indicated that maximum and minimum particle sizes were within the range that is measurable by laser diffraction technique. The reported D90 values were far below the maximum and it confirmed the reliability of measurements in volume % to evaluate the TSP concentration.
Figure 3.2. TSP concentration (circles) in mg/L for 0.7 μm GF/F glass microfiber filters vs. % volume from laser diffraction and the regression line (solid line) based on measurements in June 17, 2006 (n=15).

Figure 3.3. TSP concentration (squares) in mg/L for 0.45 μm PVDF membrane filters vs. % volume from laser diffraction and the regression line (solid line) based on measurements in June 17, 2006 (n=15).
3.6.2 Variability of TSP concentration in 2005 and 2006

In both Summers of 2005 and 2006, sampling stations 1 and 15 which were located near the estuarine mouth and the southern basin recorded the TSP concentrations less than 50 mg/L. The low TSP concentration in the southern basin indicated less TSP input from the estuarine watershed between June and October. In summer 2005, the tidal energy generated by the moderate winds and the biological activities of fish population accounted for the irregular variability of TSP concentration levels up to 150 mg/L within the main basin (Figure 3.4). Moderate winds have the capacity to re-suspend the bottom sediments easily by eroding, transporting, and re-depositing due to the large surface area to depth ratio in the main basin (Klarer, et. al., 1992; Krieger et. al., 2003). In June, mating activities of an incredibly high fish population of carp accounted for the localized increase of TSP concentrations. During the period from July to September, dense beds of American Lotus (*Nelumbo lutea*) and water lily (*Nymphaea odorata*) grew in the shallow regions of the wetland and were particularly important conditions to the TSP variability in the main basin. The movements of their stems by the winds over the water body also increased the TSP concentrations in certain localities from the normal conditions. In October, the decay of the leaves of those aquatic macrophytes led to an increase of the organic particulate component within the TSP load in random locations. This phenomenon caused TSP concentrations greater than 50 mg/L in sampling stations in the north eastern part of the main basin where I observed the open water surface. During this mid to late Summer, extensive macrophyte beds invaded the estuary mainly around the central island, masking the TSP dynamics from the satellite sensor.
In Summer 2006, the maximum TSP concentration during the study period was recorded in June 17th 2006 at certain localities of the estuary. Unfortunately, I was unable to perform remote sensing analysis for the Landsat-5 TM imagery on that day because it was extremely hazy. Only four satellite images with free of clouds or haze were available during the period between July and September where very low TSP concentration values varied from 0 to 50 mg/L (Figure 3.5). There was no significant variability of TSP concentration among the fifteen sampling stations in each particular sampling day. That observation indicated the homogeneity of TSP conditions along the eastern margin of the estuary in a daily basis except June. I observed significantly high fish population in June because it was their mating season and therefore, the localized increase of the TSP concentrations were regulated by their activities. During that period, the closed estuarine mouth trapped them within the wetland. In July, storm events over the watershed opened the sandy barrier beach letting the fish communities to migrate into Lake Erie minimizing their disturbance to this shallow water body.
Figure 3.4. The variability of TSP concentration in summer 2005.

Figure 3.5. The variability of TSP concentration in summer 2006.
3.6.3 Land cover interfaces for remote sensing indices

The importance of the interface values between different land covers is remarkable due to its ability to edit pseudo-color tables (PCT), map land cover distribution patterns, and mask unnecessary land covers to extract the areas of interest. Since I focused on the surface water quality studies, the NDWIs that resulted in a significant contrast between water and other surface covers were considered. The basic assumption used in the process of interface evaluation was that the pixels considered for the representative NDWI calculation were minimally contaminated with other land cover types and they represented the endmember properties of the land cover of interest. Eight satellite images from 2005 were used in the study to extract representative percent reflectance in order to calculate the remote sensing indices that are defined in Table 3.2. When open waters of Old Woman Creek estuary were invaded by aquatic macrophytes during late Summer, fewer endmember pixels were averaged to assign a representative percent reflectance value for the estuarine open water pixels during that period. The spectral patterns generated from the representative percent reflectance of the dominant land cover endmembers based on Landsat-5 TM imagery in May 29th 2005 is shown in Figure 3.6. I evaluated all eight images but included only the resulting values of May 29th in this chapter because it was an excellent representative condition of this environment with healthy green vegetation and considerably exposed surface water.

The overall percent reflectance of water bodies is considerably lower than the land for all Landsat-5 TM reflective bands. Compared to the visible bands, the reflectance of the MIR bands are lower for the open surface water. The reflectance of the
Figure 3.6. The spectral patterns of endmember pixels of dominant land covers are demonstrated using 751 pseudo-color composite of Landsat-5 TM imagery in May 29th 2005.
visible bands varies depending on the components present in the surface water column. The reflectance of visible bands increases with the increase of TSP concentration in the surface water column but this phenomenon does not affect the variability of the MIR reflectance. Healthy green vegetation always has very high reflectance through the NIR region of the EM spectrum. When there are high levels of chlorophyll \( a \) present due to the phytoplankton in the open surface water, again the NIR region detects higher reflectance for open water in the vicinity. Dry bare ground and urban structures such as roads have higher reflectance in IR region compared to visible bands. When the percent reflectance of the visible bands are greater than the IR bands, then the resulting NDWI becomes a positive value. It is a negative value for the pixels reporting higher reflectance values for the IR regions than the visible.

In all cases, the NDWI values varied from -1.0 to +1.0. Only the NDWIs calculated from bands 1&5, 2&5, and 3&5 always recorded positive values for open surface water and negative values for other land covers (Figure 3.7). The variability of other NDWIs did not show such significant contrast for open-water regions and in resulted positive as well as negative values with seasonal changes through out the year. Therefore, I used 0.0 as the break point for PCT editing of the NDWI and all pixels less than that value, i.e. negative values, were assumed as other than open water and masked out in white color to extract only the surface water pixels. The significant positive and negative contrast of the selected NDWI values resulted from the water and the land also able to use as a remarkable boundary in land cover classification.
Figure 3.7. The representative NDWI values for endmembers of selected dominant land covers at Old Woman Creek estuarine settings in May 29th 2005.
3.6.4 Spatial distribution patterns of open surface water

The representative NDWIs of bands 1&5, 2&5, and 3&5 always reported significant contrasts between open water and other land covers. Therefore, I generated their spatial and temporal distribution patterns (Figure 3.8). The interface between water and land was considered as 0.0 and all values less than that were masked as other land covers. The comparison of the resulting imagery with real-time field observations revealed that the NDWI_{2&5} and the NDWI_{3&5} detected some pixels with initial emerging stages of the aquatic macrophyte as open-water pixels during May. During that period, the pixels with less coverage of aquatic macrophytes and more exposure of open water were detected as open-water by both NDWI_{2&5} and NDWI_{3&5} algorithms. These two algorithms eliminated those regions from the open-water category only after the macrophyte beds matured. As a consequence, the regions bearing mature leaves of the aquatic macrophytes show similar response for all three algorithms. Therefore, a similarity of the spatial distribution pattern of the three selected algorithms was observed for the period from June to early September. Again, the latter two algorithms detected more pixels as open water in October compared to the NDWI_{1&5} because they identified decaying American Lotus and water lily as open water endmember due to less coverage by the aquatic macrophytes and more exposure of open water. The NDWI_{2&5} and the NDWI_{3&5} failed to differentiate the minor signal of aquatic macrophytes in a water bearing pixel until they spread enough to cover a significant proportion of the pixel. Specifically, the north western part and the eastern margin along the creek illustrated this effect because those regions comprised of extensive beds of American Lotus (\textit{Nelumbo}...
*lutea* and water lily (*Nymphaea odorata*) in Summer. The entire creek path was covered by their broad leaves during mid-late Summer allowing few pixels at north eastern part of the main basin to be exposed. In some localities, especially along the eastern and the south eastern regions, they were densely grown, overlapping their leaves and creating an excellent leaf cover over the estuarine surface masking the open water from the space sensors. I experienced the difficulty of rowing the boat upstream through this leaf cover during the field cruises in August and September.

It was difficult to identify a stable break point value to edit PCT for other algorithms which were calculated from visible bands 2 and 3 with MIR bands because the endmember NDWIs did not interpret the constant contrast between land and water (Figure 3.8). Those indices varied randomly with the seasonal changes throughout the year in a range of positive to negative values between -1.0 and +1.0. Consequently, I failed to generate acceptable systematic spatial distribution patterns for open water based on those algorithms.
Figure 3.8. The spatial distribution patterns of open surface water generated from normalized difference band combinations of 1&5, 2&5, and 3&5. The break point 0.00 was used to edit pseudo-color tables (PCT) and the values less than that were masked in white color to eliminate other land covers and to extract only open water pixels.
3.6.5 Algorithm evaluation for TSP calibration

The most effective algorithm among all possible normalized difference indices was selected based on two criteria: (1) the highest correlation between the NDWI\textsubscript{visible\&IR} and the TSP concentration and (2) the spatial distribution pattern of the open surface water. I was able to locate thirty nine sampling stations within the open water by field observations and comparison of spatial patterns of NDWI\textsubscript{visible\&5} for the TSP calibration process. The record of positive values by all three algorithms for sampling stations assured their minimal contamination due to a mixed spectral signature. The highest correlation of 0.70 resulted using the NDWI\textsubscript{1\&5} (Figure 3.9). The NDWI\textsubscript{2\&5} and the NDWI\textsubscript{3\&5} reported correlations of 0.55 and 0.59 with the TSP concentrations respectively. According to these results, the normalized difference indices calculated from the visible bands with the band 5 has greater ability to detect lower levels of suspended particulates in open surface water than the visible bands with bands 4 and 7. The blue region of the electromagnetic spectrum (EMS) is more sensitive in detecting the TSP in surface water than the green and the red bands. For this study, the NIR reflectance was considerably low for estuarine water regions. This may be due to the very low density of chlorophyll \textit{a} in surface water or the insufficient spatial extent of open surface water in Old Woman Creek estuary which was not adequate to provide the spectral information for chlorophyll \textit{a} through the moderate resolution imagery. Usually, the presence of algal bloom in surface water significantly increases the reflectance value of the NIR band in satellite imagery due to the remarkable chlorophyll \textit{a} content in algae.
Figure 3.9. The arrow shows the maximum correlation reported between the TSP concentration and the remote sensing indices. The definitions for normalized difference band combinations are in Table 3.2.
3.6.6 The most effective algorithm

Based on the selected 39 measurements from June to October in 2005, I established a relationship for which NDWI1&5 varied from 0.0 to 0.5 for a given TSP concentration in a range of 40 to 120 mg/L. The linear correlation between TSP concentration and NDWI1&5 is shown in Figure 3.10. The estimates of TSP concentration can be obtained according to \[ TSP = (152.04 \times NDWI_{1&5}) + 43.05 \] for the given range of NDWI1&5 (Figure 3.10). This study did not reveal the relationship for the NDWI1&5 values greater than 0.5 where the TSP concentrations were greater than 120 mg/L.

I classified the TSP concentrations stepwise in open surface water regions based on the generated regression coefficients of slope 152.04 and intercept 43.05 using 20 mg/L as step size. Subsequently, the spatial and temporal distribution patterns of TSP dynamics were plotted (Figure 3.11). Among all 2005 imagery, April 11th reported the lowest TSP concentration pattern where I estimated the maximum TSP concentration of 86 mg/L in few localities whereas an average of 74 mg/L was anticipated in the northern, eastern, and south eastern parts of the main basin. As it was early Spring, the cultivation practices had not yet been initiated within the Old Woman Creek watershed which led to the observation of low TSP concentration. In May, I observed considerably high NDWI1&5 and 0.94 was recorded as the maximum of the year which was reported in May 29th whereas 0.76 was the maximum recorded in May 13th. Because those values were beyond the calibration range, I did not apply the regression coefficient to predict TSP dynamics for both days in May. Besides, it was obvious that May evidenced the TSP maxima based on the spatial and temporal distribution patterns where the majority of
$y = 152.04x + 43.05$

$R^2 = 0.70$

Figure 3.10. Scatter plot of measured TSP concentration vs. NDWI\textsubscript{1&5} values derived from percent reflectance of Landsat-5 TM imagery in 2005 ($r^2 = 0.70$) ($n = 39$).
Figure 3.11. Spatial and temporal distribution pattern of TSP concentration in open surface water at Old Woman Creek estuary in 2005. © 2007 Nishanthi Wijekoon.
the pixels were in maroon color which stands for NDWI$_{1.5}$ greater than 0.5000 (Figure 3.11). In May, three main factors were responsible for the high TSP levels; (1) initiation of agricultural practices in the Old Woman Creek watershed, (2) considerable storm events over the watershed, and (3) mating activities of significantly high fish population. About 80% of the entire watershed is primarily comprised of agricultural lands where most of them are directly connected to the uppermost tributaries of the creek. The lack of woodland buffer in many areas between tributaries and the cultivation plots enhanced soil erosion during May when the initial land tilling is affected by the Spring storms. As we observed in the field, the TSP dynamic in June 14th was mainly due to disturbances in bottom sediment and the water column by extensively high fish mating activities.

According to weather data from the National Estuarine Research Reserve centralized data management office (NERR CDMO), there was considerably high precipitation during 20th and 26th of April where the maximum of 35.8 mm reported in April 23rd. In addition, a few storm events less than 10 mm were reported on 23rd and 28th of May (Figure 3.12). Those storm events increased open-water area from April to end of May and the maximum open-water area recorded in May 29th satellite imagery (Figure 3.13).

A rapid decrease in open surface water area towards September was due to rapid spread of American Lotus (Nelumbo lutea) and water lily (Nymphaea odorata) over the surface water when the environmental and the climatic conditions for their growth excelled. Their growth retreated in late September and the broad leaves started to dry and decay which exposed the open-water once again to the atmosphere (Figure 3.13). The
decomposing particulates that were registered as an increase of NDWI1&5 in some pixels of the north eastern part of the main basin along the creek where they were spread by surface winds over the estuary. The slight back flow of Lake Erie water through the open barrier beach at the wetland mouth also tended to trap that surface particulate load around this region. The October 4th condition in Figure 3.11 apparently indicated this phenomenon.
Figure 3.12. The average precipitation over 15 minute periods at Old Woman Creek estuary in 2005 where the arrows indicate the Landsat-5 TM over passing days (source: http://cdmo.baruch.sc.edu).
Figure 3.13. The temporal variation of open surface water area estimated based on the NDWI_{1&5} by avoiding the pixels of mixed spectral properties.
3.6.7 Effect of sampling depth for calibration

The sampling methods, top of the water surface and about 6-12 inches below the water surface, were an important aspect which influenced the variability of ground measurements in two Summers. In water quality studies, the spectral signal of the space sensor is a measurement of entire TSP load in a water body including both surface floating matter and the suspended load in surface water column. In 2005, as I collected the samples directly from the top of the surface water, the floating particulates on the surface such as fine decomposing debris of aquatic macrophyte leaves and the upper most suspension load accounted in ground measurement. In 2006, the water samples were collected 6-12 inches below the surface water which eliminated some of the surface floating particulates and the results resembled an under estimation from the reality especially during late Summer and Fall because it was the period that the floating particulates are abundant in the estuary. The correlation between measured TSP concentration vs. NDWI$_{1,5}$ was 0.35 in Summer 2006 in comparison to 0.70 in Summer 2005. The root mean square error (RMSE) of 2005 measurements was 12.9 where as it was 11.9 in 2006 (Figure 3.14).

The comparison of the surface water reflectance properties with the same season of the previous year showed the seasonal similarity of the water quality in the main basin. Since there was only four good quality images available during late Summer 2006, I was able to compare few days in July, August, and September for both years.

The overlapping histogram patterns of NDWI$_{1,5}$ indicated the analogous surface water conditions for August 1$^{st}$, August 17$^{th}$, and September 2$^{nd}$ in 2005 with July 19$^{th}$,
Figure 3.14. Scatter plot of measured TSP concentration vs. NDWI$_{1&5}$ values derived from percent reflectance of Landsat-5 TM imagery in 2005 ($r^2 = 0.70$) ($n = 39$) (RMSE = 12.9) and 2006 ($r^2 = 0.35$) ($n = 42$) (RMSE = 11.9).
August 4th, and September 5th in 2006 respectively. The TSP concentration on September 21st in 2006 is closely related to that of early September conditions rather than October in 2005 (Figure 3.15). Consequently, the different correlations between TSP concentration and NDWI$_{1.5}$ for the two years occurred (0.7 for 2005 and 0.35 for 2006) not due to water quality variability, but by the effect from sampling depth as discussed in the section 3.6.7. Therefore, the ground measurements were under estimated compared to Landsat-5 TM data. Hence, it is important to sample the top most water layer during remote sensing calibration studies in shallow and small scale water bodies based on satellite sensors with moderate resolution.
Figure 3.15. Number of open water bearing pixels for each NDWI<sub>1&5</sub> shows the seasonal similarity of water quality in the main basin of Old Woman Creek estuary.
3.7 Conclusion

This study identified an effective normalized difference algorithm to retrieve total TSP concentration in Old Woman Creek estuary using the Landsat-5 TM sensor. It was obvious that moderate resolution (30 m × 30 m) satellite imagery has capability to detect TSP dynamics in a coastal wetland of 600,000 square meters in extent. The NDWIs between visible and middle infrared (MIR) bands played a better role in masking the land covers other than surface water by generating contrasting positive and negative values for water and land respectively. Hence, 0.0 represented the interface of land and water for NDWI1&5, NDWI2&5, and NDWI3&5. The latter two algorithms failed to differentiate the mixed spectral signature during initial stages of aquatic macrophyte growth in south western part of the estuary around April and May. Once the vegetation becomes mature, all three algorithms were able to demarcate land and water but the NDWI2&5 and the NDWI3&5 still detected few undesirable pixels as water. An empirical relationship of correlation 0.70 by linear regression has been established between the NDWI1&5 and the TSP concentration. The NDWI2&5 and the NDWI3&5 reported correlations of 0.55 and 0.59 with the TSP concentrations respectively. The established NDWI1&5 is capable of retrieving TSP concentrations in the range of 40-140 mg/L. In algorithm development for water quality studies over fairly small areas by means of remote sensing, the location of sampling station and the sampling depth are considerably important. The seasonal equivalence of NDWI1&5 values during the late Summers in 2005 and 2006 indicated the recurring water quality conditions within the main basin in both years. But the slope variability (152.04 in 2005 and 44.03 in 2006) in the scatter plots of
measured TSP concentration vs. NDWI1&5 appeared due to the different sampling depths in two seasons (Figure 3.14). Usually, relationship between field samples and satellite data depends on the optical depth of a particular region. In this case study, the optical depth was very shallow due to considerable amount of TSP in surface water so that a surface sample captured all the reflectance information through thematic mapper sensor. Therefore, in the calibration process, samples should be collected from the top of the surface water and the care should be taken to be at the center of the open water to minimize spectral signature effects from other land covers over the selected pixels. However, more ground-truth validation should be carried out to fine-tune the established algorithm.
CHAPTER 4

Wetland land cover classification using principal component analysis of Landsat TM data

4.1 Abstract

Land cover types present at the Old Woman Creek National Estuarine Research Reserve (NERR) were assessed and mapped using principal component analysis (PCA). The PCA extracted synthetic reflectance spectra of physically meaningful latent variables were correlated with spectrophotometric reflectance spectra measured from field samples for each of the dominant land cover classes. Reflectance data from eight Landsat-5 thematic mapper (TM) images were combined to determine the spatial and the temporal variability of dominant land cover types in 2005. The first four principal components accounted for 87% of the total variance in entire dataset. The notable variables extracted were: (1) exposed ground or submerged ground (32 % of variance, as component-1), and (2) photosynthetic macrophytes (18 % of variance, component-4). Component-1 also encompassed the reflectance signatures from non-photosynthetic macrophytes due to its spectral similarity ($r^2=0.75$) with exposed ground in satellite data of moderate spatial and spectral resolution. Component-2 and component-3 accounted 19 % and 18 % variance of the entire dataset, respectively. Integration of these two components and their spatial and temporal variability are discussed in detail. This study introduces an accurate and efficient novel land cover mapping technique for shallow coastal wetlands.
4.2 Introduction

Wetlands are dynamic environments where land cover shifts between terrestrial and aquatic settings in response to climatic and seasonal variations. The importance of frequent monitoring, identification and mapping of surface reflectors is a key element in the study of wetlands and their adjacent uplands (Nemani and Running, 1996; Ozemi and Bouer, 2002). Scientists are faced with the task of determining sampling strategies to assess the distribution patterns of the land cover types accurately (Shuman & Ambrose, 2003). Thus, remotely sensed images have been extensively used to characterize spatial and temporal changes of wetlands using multi-spectral reflectance (e.g., Jennings et al., 1992; Richardson and Harris, 1995; Ramsey and Jensen, 1996; Barrette et al., 2000; Shuman and Ambrose, 2003). This chapter describes how principal component analysis (PCA) of reflectance data from moderate spatial resolution satellite imagery can be used to classify and map land cover variability in a highly dynamic coastal wetland of Lake Erie.

PCA of remotely sensed image data have been used for various mapping and information extraction purposes over the last 30 years (Tyler, 1974; Fontanel et al., 1975). These traditional PCA approaches address the identification of land cover types using different color composites of Landsat data. One major application of PCA of correlated multi-dimensional data is dimensionality reduction, which reduces the number of images or variables that are needed for the analysis (e.g. Bryne et al., 1980). Another major application facilitates the visual interpretation of a mass of data having uniform a priori significance, by reducing redundancy, i.e. by invoking correlation between
channels (Bryne et al., 1980). In selective PCA, subsets of all available bands were used as inputs to enhance and map the spectral contrast between different spectral regions (Chavez and Kwartend, 1989). Another approach involved change detection of forest cover by examining comparisons of vegetation indices for different dates of imagery (Coppin and Bauer, 1994; Collins and Woodcock, 1996; Nordberg and Evertson, 2005; Kleinod et al., 2005). Change detection of submerged vegetation in an estuarine ecosystem performed by PCA using Landsat TM data revealed pros and cons of PCA in detecting submerged eelgrass beds (Macleod and Congalton, 1998). Classifications of the principal components of different images were found to yield generally higher classification accuracies than the other methods. In Geographic Information System (GIS), PCA is widely used in socioeconomic applications to reduce duplication of information among correlated variables extracted from census data (Wang, 2006). A PCA approach and GIS interpretation similar to the current study had been reported in a socioeconomic investigation which used U. S. census data in a comparison with normalized difference vegetation index (NDVI) from Landsat-5 TM imagery (Lo, 1997; Lo and Faber, 1997). Although those methods perform reasonably well in certain applications they do not address the spectral properties of resulting components relative to Landsat spectral bands. The study discussed in this chapter is the first one concerning land cover classification using PCA of Landsat TM data in a dynamic wetland. The method provides valuable information to assess seasonal variability of an estuary using satellite imagery.
The current study was based on both the ground and the remote sensing investigations of the Old Woman Creek National Estuarine Research Reserve (NERR) in 2005. During field visits, it was noted that macrophytes, mudflats as well as phytoplankton and suspended sediment in surface water were the dominant surface reflectors of the area. The aquatic macrophytes of Old Woman Creek estuary were first systematically inventoried in 1973 by recognizing five distinct vegetation sites in the estuary through ground observations (Marshal and Stuckey, 1974). During the 1980’s, aerial photographs were used to map the changing vegetation distribution patterns where rising water levels were expected to have a significant impact on the vegetation of Old Woman Creek estuary (Klarer & Millie, 1992). Algal species at Old Woman Creek have been identified by previous research (Lavrentyev et al., 2004).

In this study, I used visible, near infrared (NIR), and mid infrared (MIR) surface reflective spectral bands of Landsat-5 TM sensor as original input variables of PCA in order to identify the underlying components of surface reflectance. It has been shown that the thermal channel does not contribute much to the analysis of land cover (Foppa et al., 2002). The resulting factors represent linear combinations of the raw data that account for measurable percentages of the original variances. The maximum number of components that can be extracted is limited by the number of spectral bands used from the satellite imagery.

The objective of the present study was to extract, identify, and map the distribution patterns of the underlying variables of the Landsat-5 TM reflectance measurements at Old Woman Creek estuary in time and space for effective resource
management. These latent variables were responsible for the surface variability and I used % variance, factor loadings, and factor scores resulting from the PCA to achieve these objectives. Real time field observations and sampling of reflector types in coincidence with Landsat-5 TM overflights provided strong evidence to identify the spectral signatures derived from the PCA.

4.3 Wetland settings

The main basin of the Old Woman Creek estuary which is located at the south central shore of Lake Erie north central Ohio was chosen as the study area (Figure 4.1). The two main reasons to select the main basin for this analysis are; (1) its dynamic land cover variability with respect to seasonal changes, and (2) the larger spatial extent compared to the lake lagoon and the south basin. This investigation was conducted over an area of approximately 500,000 square meters in the main basin, which is a transition zone between land and water with a significant invasion of emergent aquatic macrophytes over the open water during mid-late Summer. The central island of the main basin is densely covered with terrestrial macrophytes in Summer whereas it becomes a barren land from late Fall to Spring when the tree canopies shed their leaves.
Figure 4.1. The study focused on the land cover variability in the main basin of the Old Woman Creek estuary. Each point represents one pixel which has a spatial resolution of 30 meter × 30 meter.

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4.4 Methods

4.4.1 Field techniques

The field survey to ground truth the satellite data was carried out from 14 June to 4 October 2005. The observed dominant surface reflectors were aquatic and terrestrial macrophytes, phytoplankton and suspended sediment in water, and exposed mudflats. The dominant aquatic emergent macrophytes within the estuary were common reed (*Phragmites australis*), cattail (*Typha spp.*), American lotus (*Nelumbo lutea*), and water lily (*Nymphaea spp.*). I collected samples of surface water, selected emergent aquatic and terrestrial macrophytes, and exposed mudflats every 16 days in coincidence with Landsat-5 TM over flights. The reference reflectance spectra of each sample were measured using LabSpecPro FR spectrophotometer which has a spectral range from 400 to 2500 nm. The mean reference reflectance spectra of in-situ samples were averaged over the wavelengths corresponding to the Landsat-5 TM spectral bands and compared with the synthetic image-based spectral patterns resulted from the factor loadings of PCA in order to identify the resulting components.

4.4.2 Satellite imagery analysis

The Landsat-5 Thematic Mapper (TM) images of Path 19 Row 31 were processed from images achieved free of charge by the OhioView remote sensing consortium (URL: http://www.ohioview.org). The observation dates were 11 April, 13 May, 29 May, 14 June, 1 August, 17 August, 2 September, and 4 October. Remote sensing analysis was performed using the commercially available PCI Geomatica 10.0 software package. Each scene was corrected for haze by applying the histogram minimum method (Chavez,
Then, the dark object subtracted digital numbers were radiometrically calibrated using coefficients derived by Chander and Markham to obtain reflectance (Chander and Markham, 2003). A sub-scene of 500,000 square meters containing the study area was extracted from each image. This region included 611 30 meter × 30 meter pixels.

### 4.4.3 Principal component analysis (PCA)

PCA is a mathematical transformation which uses an entire set of variables to transform an original data into a small set of orthogonally related latent variables. For the suite of 8 images, spectral reflectance for 6 Landsat-5 TM bands in the visible (VIS), near-infrared (NIR), and middle infra-red (MIR) were used as input variables to the PCA routing in the Statistical Package for the Social Sciences (SPSS) software package. Varimax-rotation was applied to maximize the variance between the resulting components in order to achieve a maximum differentiation (Kaiser, 1958). The analysis was assigned to extract five components based on a correlation matrix. The varimax rotation algorithm selected an orthogonal rotation of the original components, so that the variance of the squared principal components was maximized (Broersen et al., 2005). In PCA, the original data matrix of pixel reflectance vs. input variables was transformed into a component matrix of input variables vs. factor loadings. The factor loadings are scaled correlation coefficients between the original variables and the newly derived components. These values are derived based on the decomposition of the correlation matrix. Factor scores, which are the actual values of individual pixels for the resulting factors, were calculated as variables using a regression method (Kachigan, 1991). The
meaningful components were extracted based on three criteria; (1) percentage of variance, (2) eigenvalue, and (3) a scree plot.

4.4.4 Spatio-temporal distribution patterns

For each factor, a time series of maps was generated by spatial interpolation of factor scores using 2-D spline interpolation in the ArcGIS 9.2 GIS package. For each principal component, the dBase files of resulting factor scores were used as the source for point shape files which were transformed into Universal Transverse Mercator (UTM) zone 17 of North American Datum of 1983. Each data point represented the reflectance properties of one 30 meter × 30 meter Landsat-5 TM pixel. The evenly spaced point data of factor scores were interpolated into spline raster surfaces using spatial analyst in ArcMap to interpret the spatial distribution patterns of the resulting meaningful components.

4.5 Results and discussion

PCA produced a new set of images which represented latent physically meaningful components that are uncorrelated, independent, and orthogonal with each other (Lo and Faber, 1997). These components explained a high proportion of variance in the original set of input data. Components were ordered such that the maximum percentage of variance was explained by the first component, with a progressive decrease toward later extracted components. While PCA was applied to six spectral reflectance bands, the correlation matrix for these variables indicated high positive relationships between (1) bands 5 and 7 (r = 0.854), and (2) bands 5 and 4 (r = 0.738). The mid
infrared (MIR) bands, i.e. bands 5 and 7, had the highest correlation among the entire input data set. A high negative correlation was reported between bands 3 and 4 ($r = -0.677$), thus pixels of high percent reflectance for band 4 accounted a low percent reflectance for band 3 or vice versa (Table 4.1).

4.5.1 Principal components

While the analysis was assigned to extract five components, only four meaningful components corresponded to coherent surface reflector types. These represented 32%, 19%, 18%, and 18% percent variance respectively, and were extracted based on the rule that the minimum eigenvalue should not be less than one for the scaled rotational sums of squared loadings (Table 4.2). Therefore, the first four components explained about 87% of the total variance. The scree plot (Figure 4.2), which shows the eigenvalue of each successive component demonstrates the difference in significance between components 1-4 and component-5. In this plot, factors along the tail of the curve primarily represent the effect of random error variance. Factor loading values of the four meaningful components were plotted against the mid-point of the respective wavelength of the Landsat-5 TM reflective spectral band in order to generate synthetic spectral patterns for each of the newly derived components (Figure 4.3). Factor loading values vary from -1 to +1, and indicate the degree to which each of the Landsat-5 TM reflectance band correlates with specific components. Physically meaningful components were identified by comparing these spectral profiles with reference spectra measured by spectrophotometric analysis of real field samples of selected land cover types using a LabSpec Pro FR spectrophotometer (Figure 4.4).
Table 4.1. The correlation matrix of variables.

<table>
<thead>
<tr>
<th></th>
<th>Band-1</th>
<th>Band-2</th>
<th>Band-3</th>
<th>Band-4</th>
<th>Band-5</th>
<th>Band-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band-1</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band-2</td>
<td>0.335</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band-3</td>
<td>0.523</td>
<td>0.636</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band-4</td>
<td>-0.161</td>
<td>-0.517</td>
<td>-0.677</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band-5</td>
<td>0.094</td>
<td>-0.253</td>
<td>-0.220</td>
<td>0.738</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>Band-7</td>
<td>0.234</td>
<td>-0.012</td>
<td>0.207</td>
<td>0.344</td>
<td>0.854</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Table 4.2. The rotational sums of squared loadings.

<table>
<thead>
<tr>
<th>Rotational sums of squared loadings</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>1.900</td>
</tr>
<tr>
<td>% of variance</td>
<td>31.673</td>
</tr>
<tr>
<td>Cumulative % of variance</td>
<td>31.673</td>
</tr>
</tbody>
</table>
Figure 4.2. The scree plot indicates the fraction of rotated eigenvalue accounted for the five empirical orthogonal functions.
Figure 4.3. The synthetic image-based spectra of meaningful principal components from PCA.
Figure 4.4. The mean reference reflectance spectra of selected land cover endmembers (above) were averaged over the wavelengths corresponding to Landsat-5 TM band widths to obtain the average mean reflectance spectra (below) in order to compare with the synthetic component spectra resulted from the factor loading values of PCA.
4.5.2 Comparison of components with reference spectra

4.5.2.1 Component-1 and component-4

The reference reflectance spectra were averaged over wavelengths corresponding to the Landsat-5 TM spectral bands to obtain an appropriate pattern for comparison with the synthetic image spectra derived from PCA (Figure 4.4). These reference spectra were successfully applied to identify the synthetic spectral patterns of component-1 and component-4 using correlation plots. Component-1, which accounted 32% of the total variance, was positively correlated with the reference spectrum of exposed ground (R²=0.93) and with the reference spectrum for the dried vegetation which I defined as non-photosynthetic macrophytes (R²=0.62). A very high negative correlation of 0.97 was obtained between the spectral reflectance of component-1 and the estuarine open water reference spectrum (Figure 4.5). Component-1 also exhibited high positive factor loadings of 0.881 and 0.981 with Landsat-5 TM bands 5 and 7 which are in MIR region of the electromagnetic spectrum. Hence, the regions with high positive factor scores of component-1 were labeled as exposed ground and/or non-photosynthetic macrophytes whereas those with high negative factor scores were designated as submerged areas of open-water.

In April and October, a considerable amount of the estuary was covered by exposed ground, leafless tree trunks, and dried aquatic macrophytes, where latter two categories were designated in this study as non-photosynthetic macrophytes. In particular, two dried *Phragmites* regions were observed northeast and southeast of the island in the main basin in October. An application of herbicide called “Imazapyr” in mid August
Figure 4.5. The correlation plots between PCA derived synthetic image spectrum of component-1 with spectrophotometric measured reference spectra of exposed ground, non-photosynthetic macrophytes, and open-water.
2005 was responsible for this localized destruction of the vegetation. The commercial name of the Imazapyr is “Habitat” which is commonly used to inhibit the growth of *Phragmites australis* (common reed), an invasive species that has been invading many wetlands in North America.

Component-4 represented both the aquatic emergent and the terrestrial healthy green vegetation because its factor loading spectra displayed a remarkable correlation of 0.91 with the spectra of field samples (Figure 4.6). This factor accounted for 18% of the total variance in the entire data set. The only high positive factor loading values of this component was 0.822 with the near infrared band of Landsat-5 TM. This band represents the energy reflected from healthy green vegetation. Although the inundated areas of the wetland should be classified as submerged, some of those regions exhibited the spectral properties of component-4 due to vegetation floating on the surface water in mid-to-late summer. Thus, I labeled component-4 as photosynthetic macrophytes. Consequently, the submerged areas that were delineated by high negative factor scores of component-1 were the only regions that we identified as open-water, free of large floating vegetation.
Figure 4.6. The correlation plot between PCA derived synthetic image spectrum of component-4 with spectrophotometric measured reference spectrum of photosynthetic macrophytes.
**4.5.2.2 Component-2 and component-3**

Component-2 and component-3 are associated with surface water, vegetation moisture, or soil moisture. For both of these components, the infrared region of the thematic mapper sensor detected very low reflectance compared to the visible region. The reflectance variability in the visible region differentiated the two components. Component-2 is dominated by reflectance in band 2, while component-3 had maximum reflectance in band 1.

Component-2, which accounted for 19% of the total variance, showed high positive factor loading values of 0.944 with band 2 which is the green band of the Landsat-5 TM. In contrast, component-1 recorded its only negative loading of -0.6 with band 2. Thus, component-2 has high correlation with green spectral reflectance and therefore it could be chlorophyll $a$. The presence of algae, whether visible filamentous green algae or microscopic diatoms, imparts some of the characteristics of a vegetated surface, the most obvious feature being a trough in a red region caused by chlorophyll $a$ absorption (Thompson et al., 1998).

The only high positive factor loading value reported in component-3 (18% of total variance) was 0.967 with band 1, the blue region of the Landsat-5 TM sensor. Band 1 is frequently used to detect total particulates in surface water. The presence of a significant amount of total suspended particulates generally increases the reflectance recorded in band 1. Accordingly, when contaminants in surface water are dominated by a combination of suspended particulates, including terrigenous suspended sediments,
phytoplankton, zooplankton, and other organic matter, my analysis isolated it as component-3, which I labeled total suspended particulates.

4.5.3 Spatial and temporal distribution

Each newly derived variable which is a principal component of the study area was evaluated based on its spatial and temporal distribution patterns. The factor score values, which were the real weights of the resulted variables relevant for individual pixels, were separated into 12 classes using a step-size of 0.5. High positive factor scores indicate a high positive correlation between the spectral properties of those pixels and the synthetic spectral pattern of the respective meaningful component. The high absolute values of negative factor scores represented a high negative correlation in the same aspect. In this study, factor scores vary over a range of -4.0 and +4.0. The absolute values are important regardless the negative or positive sign. Factor scores between -0.5 and +0.5 were masked and considered not significant.

4.5.3.1 Component-1 and component-4

Land cover variability in Old Woman Creek estuary was largely due to two factors; (1) changes in vegetation distribution patterns, and (2) water level fluctuations. The factors are governed by favorable environmental and climatic conditions associated with the wetland setting. Usually, these conditions are driven by the seasonal variability. For the spatial distribution patterns of component-1, high positive factor scores were restricted to the region in and around Star-Island during April and gradually faded out as the Spring progressed (Figure 4.7). The two main reasons for this decrease in the area of
exposed ground were: (1) the leafing out of the canopies of terrestrial macrophytes on Star-Island, and (2) the growth of the new aerial parts of *Phragmites* and *Typha* beds overwhelming their dried counterparts from previous Summer. Thus, no exposed ground was detected by PCA during the period from June to October within Star Island.

The satellite imagery that was captured on October 4 symbolized the nature of the land cover just before the Fall color display. The distribution of component-1 revealed that the island was covered by tree canopies even on October 4. The decline of estuarine water level by about 1.5 feet during late August led to exposed shallow regions around the star island and the southeastern part of the main basin. The collapsed sandy barrier beach at the estuarine mouth regulated the water level decline. The broad leaves of American lotus and water lilies that covered the surface water in most of the shallow areas dried out and sank into the estuarine bottom during that period, leading to exposed ground and non-photosynthetic vegetation around the island. Another significant feature observed was dried *Phragmites* in two localized regions of the wetland due to the application of “Imazapyr”, a herbicide used to control the invasive giant grass species. These non-photosynthetic macrophytes were detected by the Landsat TM sensor on October 4 as high positive factor scores of component-1. The moderate spatial resolution of 30 meter × 30 meter pixel size was not sufficient to distinguish the difference between the exposed grounds and the dried-macrophytes due to their spectral similarity and their coexistence in this environment. The correlation between the spectra of these two land cover types was 0.75 (Figure 4.8). However, in the future, this PCA method could be applied to reflectance data from other satellites with finer spatial, spectral, and temporal
resolutions. This could provide more detailed information regarding differentiation of these two land cover types. In 2005, the spatial distribution patterns of high negative factor scores of component-1, corresponded to open-water regions which gradually decreased towards the end of Summer due to invasion of floating aquatic macrophytes. Areas with factor scores between -0.5 and +0.5 for component-1 were not significant and are masked out in white in Figure 4.7.

The spatial and temporal maps of high positive factor scores of component-4 characterized the seasonal variability of healthy green macrophytes. The first substantial occurrence of photosynthetic macrophytes occurs on the island as the terrestrial tree canopies initiated their leaf out at the end of May. Then component-2 gradually propagated around the island over shallow regions, mainly representing growth of common reed (*Phragmites australis*) and cattail (*Typha spp.*) in June. The open-water regions narrowed due to the invasion of the floating broad leaves of American lotus (*Nelumbo lutea*) and water lily (*Nymphaea spp.*) in July and August. At these times, the deeper part of the water column was masked by the dense leaf cover and the satellite sensor detected these areas as healthy green macrophytes. The peak greenness occurred in August and progressively decreased towards Fall due to decomposition of aquatic emergent macrophytes, exposure of shallow regions by drop of the water level, and the transformation of the greenness into Fall colors (Figure 4.7).
Figure 4.7. The spatial and temporal variability of component-1 and component-4 from April to October in 2005. The component-1 demonstrates a positive correlation with exposed ground and/or non-photosynthetic macrophytes and a negative correlation with submerged ground with open-water. The component-4 demonstrates a positive correlation with photosynthetic macrophytes.

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Figure 4.8. The correlation plot between spectrophotometric reflectance spectra of exposed ground and non-photosynthetic macrophytes.
4.5.3.2 Component-2 and component-3

Variations in the spatial patterns of component-2 and component-3 with time elucidated the dominance of each component for specific days (Figure 4.9). While these components have more complex physical interpretations than component-1 or component-4, they provide some information on seasonal variability. The spectral signatures of component-2 and component-3 most likely correspond to variations in water quality as the low factor loadings in the infrared region may represent moisture in the environment. The moisture could be in the form of vegetation or soil moisture or open water. I deduced these two components as chlorophyll $a$ (component-2) and total suspended particulates (component-3) based on their spectral properties in the visible region. The high positive factor scores of component-2 in May and October might be represented the Spring and Fall bloom within this inland water body, respectively. On May 13, coverage of the entire main basin with high positive factor scores for component-2 indicates the initial stages of the leafing out of trees and the Spring eutrophication of surface water. In the case of leafing out, chlorophyll $a$ coexisted with the vegetation moisture. This phenomenon displayed the presence of chlorophyll $a$ under moist conditions in both macrophyte and microphyte communities. Although I defined these two components as water quality parameters based on their spectral properties, this result is subject to some uncertainty due to the complex spatial patterns in some of those images.

Another possible explanation for the patterns of component-2 and component-3 is that they could represent combinations of several different land cover parameters that the
PCA failed to delineate. The dynamic nature of the environment and the moderate spatial scale result in many pixels being covered with several different land surface types. Hence, one pixel may represent a mixture of spectral properties of a variety of land covers. Although it was not assessed in this study, the impacts of fractional coverage of pixels in the study area are being explored based on spectral mixture analysis. This will be helpful for further identification of component-2 and component-3. Extended studies on this topic will also be helpful in addressing the complicated spatial and temporal distribution of these two components generated by overlapping signals from several different land covers or by the lack of spectral resolution in Landsat-5 TM data.
Figure 4.9. The spatial and temporal variability of component-2 and component-3 from April to October in 2005. The component-2 could be defined as chlorophyll \( a \) where as the component-3 is believed to be the presence of total suspended particulates. © 2007 Nishanthi Wijekoon.
4.6 Conclusion

PCA can be used to reduce the dimensionality of a data set and also to extract the underlying dynamic variables in order to map their spatial and temporal distribution in wetlands. The spatial interpolation of factor scores which were the actual loadings of resulted components on each pixel provided a reliable visual interpretation of land cover variability. Synthetic spectra derived using PCA were correlated with spectrophotometric spectra from field samples. The degree of correlation thus represented the spectral similarity between the meaningful PCA components and real world land covers, with higher degrees of correlation indicating more spectral similarity.

I identified component-1 as exposed ground or non-photosynthetic vegetation and component-4 as photosynthetic vegetation. Interpretation of component-2 and component-3 is more complex due to the mixed spectral properties of pixels resulting from the low spatial and spectral resolution of the satellite sensor. This leads to insufficient information for a detailed delineation of this small scale dynamic environment.

While the PCA of reflectance data was able to map the photosynthetic vegetation successfully as component-4 (18 % of variance), the spatial and spectral resolution of Landsat-5 TM was not sufficient to demarcate the difference between the various photosynthetic macrophyte species. Also, the differentiation of the exposed ground and the dried-macrophytes was convoluted due to spectral similarity of those two land cover types. Hence, PCA categorized both land cover types into high positive factor scores of component-1 (32 % of variance). The high negative factor scores illustrated submerged
areas with open water which is contrary to exposed ground. However, the study has revealed the capability of PCA to extract and map the variability of major land cover types in a dynamic wetland. In the future, it will possible to use satellite data with finer spatial, spectral, and temporal resolution to fine tune this type of PCA, resulting in more detailed land cover information in wetlands.
CHAPTER 5

Multispectral analysis of wetland reflectance for land cover mapping

5.1 Abstract

The objective of this chapter is to find the applicability of satellite image spectroscopy to map the spatial and temporal land cover variability of a small scale wetland using multispectral Landsat-5 TM imagery. The spectral classification was performed using scattergrams which were generated using the percent reflectance of two selected bands either from visible or infrared (IR) regions. The normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and a here in defined normalized difference ground index (NDGI) of the selected band combinations were calculated and the extending arms of the scattergrams were segmented using the one-dimensional space of the specific index values in order to define critical interface values of 0.5, 0.0, and 0.4 respectively. The interface values delineated the dominant land cover endmembers from the pixels with mixed spectral properties. The validity of the three extracted endmembers; photosynthetic vegetation, open-water, and exposed-ground, was evaluated based on their spectral patterns and spatio-temporal distribution from April to October in 2005. The scattergram-resulted image based reflectance spectra of endmembers were correlated with the spectrophotometric resulted reference reflectance spectra obtained from the field samples of major land cover types. A correlation of 0.98 was reported for both photosynthetic and non-photosynthetic image endmembers with
their respective field reference endmembers. A correlation of 0.75 was reported for exposed ground where as 0.81 correlation was reported for open-water. This mapping method is an effective approach to capture dynamic variability of wetlands for better management.

5.2 Introduction

Extensive loss of wetlands has occurred over many centuries throughout the world. As the value of wetlands to the society has become recognized, it is important to monitor frequently to conserve these valuable resources (Ozesmi and Bauer, 2002). Satellite remote sensing provides a synoptic view of the spatio-temporal dynamics of land cover in estuarine environments. In traditional remote sensing classifications, it was assumed that the spatial extent of land cover constituents must be larger than the pixel size and assigned only one land cover type to each pixel. In the real world, pixels containing mixed spectral information are commonly found in remotely sensed data due to the limitations of the spectral and spatial resolutions of the sensor. Landsat-5 TM imagery that I used in this study has 30 meter ×30 meter spatial resolution which is not sufficient to delineate the heterogeneity of the features on the ground in many localities of a small scale estuary such as Old Woman Creek National Estuarine Research Reserve, Ohio. It would therefore be advantageous to develop an endmember scenario based on scattergrams and the respective normalized difference remote sensing indices which could provide effective land cover mapping technique for dynamic wetlands.

The method discussed in this chapter does not require extensive training data to map the dominant land cover types in a cost effective and time-conserving way for
effective resource management. I explored the use of spectral information extracted from
the scattergrams to unravel the land cover endmembers and map their spatial and
temporal distribution using eight Landsat-5 TM images in 2005. An approach of three
scattergrams segmented by the normalized difference remote sensing indices of their
respective bands was used to delineate land cover types by visible-infrared reflectance.
The extracted endmembers were used to develop a time series of Landsat-5 TM imagery
covering a range of photosynthetic to non-photosynthetic land cover types in the wetland
vicinity.

5.3 Literature review

Satellite image classification as a wetland land cover information extraction tool
has been used for more than two decades (Lulla, 1983; Hardisky et al., 1986; FGDC,
1992; Ozesmi and Bauer, 2002). The ability to map wetland land cover through space
borne remote sensing has been demonstrated using Landsat data by many researchers.
The use of Landsat MSS satellite imagery had been discussed for surveying wetlands,
coastal ecosystems and aquatic environments (Lulla, 1983). Appropriate endmember
selection is the key to successful spectral mixture analysis and two important aspects are
identifying the number of endmembers and extracting their corresponding spectral
signatures which are the measurements of the spectral response of different features in
the bands of the remote sensor (Song, 2005; Elmore et al., 2000; Thompkin et al, 1997).
Usually, it is difficult to separate different wetland land cover types from one another
because of the overlap in their spectral signatures (Gluck et al, 1996).
Pixels with mixed pixel properties have been recognized as a problem affecting the effective use of remotely sensed data in land cover classification and change detection (Fisher, 1997; Cracknell, 1998; Lu and Weng, 2004). Mixed pixels lead to the problem of composite signatures as the pure spectral responses of specific features are confused with the pure responses of other features (Campbell, 2002).

The thematic mapper (TM) sensor on board of satellite Landsat-5 has only 7 multispectral bands with a spectral resolution on the order of 100 nm. In 2003, an approach of normalized difference build-up index was reported in mapping urban areas using Landsat TM imagery (Zha et al., 2003). The study discussed in this chapter is the first one concerning wetland land cover classification using three different selected scattergrams segmented by their one-dimensional spaces of normalized difference remote sensing index based on Landsat TM data. The method provides valuable information to evaluate the validity of the seasonal spatio-temporal dynamics mapped using the principal component analysis (PCA) technique in chapter four.

5.4 Study area

The study area is Old Woman Creek estuary, which is located on the south central shore of Lake Erie, north central Ohio. A detailed description of the study area is included in section 2.2. As the main basin of the estuary displayed a remarkable shift between land and water with seasonal variability compared to the other regions, I focused on the same reflectance data set used in the analysis in chapter four which was collected within the main basin including the Star Island (Figure 4.1).
The terrestrial macrophytes were dominant in the island during Summer. There were extensive *Phragmites* beds surrounding the island which is unique to this environment (Herdendorf et al., 2004). *Phragmites australis* is an invasive giant reed which has become an important issue for wetland managers throughout North America. The constant fluctuations of water level at Old Woman Creek are particularly susceptible to *Phragmites* invasion. *Phragmites* initially appeared in the mid 1980’s and in 2005, they comprised ~40% of the vegetation cover. In 2005 August, a herbicide called “Habitat” was sprayed over two localized regions at north east and south east to the Star Island as a management practice to eliminate this invasive species from Old Woman Creek estuary. The mapping method discussed in this chapter identifies the *Phragmites* beds affected by the application of “Habitat”.

### 5.5 Methodology

#### 5.5.1 Radiometric calibration

The Landsat-5 TM images of Path 19 Row 31 used in this study were acquired under clear sky conditions. The ground observation and surface reflector sample collection was performed around 12 noon each day coincidence with the satellite over flights. A data set of 611 pixels covering the main basin was extracted from each image for the analysis. The dark object-subtracted data were radiometrically converted to at-sensor reflectance using image based correction method which is described in section 2.4.2 and 2.4.3. Formulation models for Landsat-5 TM gain are time-dependent equations of each band which were developed by Chander and Markham in 2003. The lookup
tables they generated from the lifetime gain model equations for all bands were used for radiometric calibration of Landsat-5 TM digital numbers (Chander and Markham, 2003).

### 5.5.2 Endmember selection

The selection of appropriate endmembers is a vital role in successful land cover analysis. Endmembers must define a cohesive set of spectra that are representative of physical components on the surface, but they also must model the spectral variability inherent to the scene (Elmore et al, 2000). I used two main methods to decide endmembers; (1) the image endmember, and (2) the reference endmember. The image endmember method selects the percent reflectance of endmembers based on the percent reflectance of image pixels presumed to be pure. The endmembers were extracted by the segmentation of scattergrams of selected Landsat-5 TM band combinations based on the normalized difference remote sensing index of those two respective bands. The pixels with minimum mixed spectral properties were extracted using the critical interface values of each normalized difference remote sensing index which cross cuts the extending arm of the scattergram.

In contrast, the reference endmember method is based on the percent reflectance of endmembers that were derived using experimental observations in the field or generating spectrophotometric reflectance spectra using real samples (Shimazaki & Tateishi, 2001). I used a combination of both methods to evaluate the validity of the spectral properties of the selected endmembers.
5.5.3 Image endmembers

I generated image scattergrams, the diagrams that show comparisons between the reflectance values of two spectral bands, to examine their spectral relationship. Although I experimented on several different band pairs, only three most effective normalized difference remote sensing indices for classification in this environment are reported in this chapter. In addition to the normalized difference vegetation index (NDVI), which is universally recognized to identify healthy green vegetation, I present the results of normalized difference water index (NDWI), and normalized difference ground index (NDGI) in order to segregate the regions of open-water and exposed-ground respectively.

5.5.3.1 Normalized difference vegetation index

The scatter plot of Landsat-5 TM bands of red and NIR compared with the normalized difference vegetation index (NDVI) in order to identify the pixels with healthy green vegetation and their spectral properties. NDVI was extracted using the following formula for Landsat-5 TM data (Lo, 1997; Elmore et al., 2000):

\[
NDVI = \frac{R_4 - R_3}{R_4 + R_3}
\]

where \( R \) is the percent reflectance of the specific band which is denoted as a subscript. The value 3 is the red band (0.63-0.69 \( \mu \text{m} \)) and the value 4 is the near infrared band (0.76-0.90 \( \mu \text{m} \)). The index is a ratio transform which contrasts the energy reflectance from healthy green vegetation with that of other land covers such as urban, barren, non-photosynthetic, and/or water. The index value ranges from -1 to +1 as the greenness increases and we separated the regions having NDVI greater than 0.5 as green.
macrophytes. The sensitivity of NDVI to the presence of vegetation and its common use in extracting biophysical parameters was the basis for the band selection (Song, 2005).

5.5.3.2 Normalized difference water index

The NDWI of blue and middle infrared (MIR) bands (NDWI$_{1&5}$) which is comprehensively described in chapter three was used to identify the open-water regions. The following formula was used to calculate the NDWI:

$$NDWI_{1&5} = \frac{(R_1 - R_5)}{(R_1 + R_5)}$$

where $R$ is the percent reflectance of the specific band which is denoted as a subscript. The value 1 is the blue band (0.45 -0.52 $\mu$m) and the value 5 is the middle infrared band (1.55-1.75 $\mu$m). The index is a ratio transform which contrasts the energy reflectance from open-water with that of other land covers such as urban, barren, photosynthetic, and/or non-photosynthetic. The index value ranges from -1 to +1 and I isolated the regions having NDWI greater than 0.0 as open-water (see chapter 3).

5.5.3.3 Normalized difference ground index

Since NIR and MIR bands also represented significant reflectance contrast for non-photosynthetic vegetation or exposed-ground with respect to other land cover types, the percent reflectance of bands 4 and 7 was also used to generate scatter plots. The index is defined as

$$NDGI = \frac{(R_4 - R_7)}{(R_4 + R_7)}$$

where $R$ is the percent reflectance of the specific band which is denoted as a subscript. The value 4 is the near infrared band (0.77-0.90 $\mu$m) and the value 7 is the middle
infrared band (2.09-2.35 μm). The index is a ratio transform which contrasts the energy reflectance from exposed-ground and/or dried macrophytes which I designated as non-photosynthetic macrophytes with that of other land covers. Usually, the index value ranges from -1 to +1 and I isolated the regions having NDGI less than 0.4 as exposed-ground.

5.5.4 Reference endmembers

The generation of reference spectra for the dominant land cover endmembers is described in section 4.4.1 in chapter four. The same mean reflectance spectra of in-situ samples were averaged over the wavelengths correspond to Landsat-5 TM band widths and compared with the synthetic spectra resulted from the image endmember scattergrams described in sections 5.5.3.1, 5.5.3.2, and 5.5.3.3.

5.5.5 Spatio-temporal distribution patterns

The normalized difference remote sensing index values greater than the assigned interface value were interpolated into spline surfaces using ArcGIS 9.2 in order to interpret the spatial distribution patterns of minimally mixed pixels. The index values less than that were masked out in white to eliminate a combination of other land covers and mixed pixels. The final spatio-temporal variability maps were generated by importing spline surfaces of extracted land cover endmembers into ArcMap.

5.6 Results and discussion

The endmembers that I extracted are (1) photosynthetic vegetation (green vegetation), (2) open estuarine water, and (3) non-photosynthetic vegetation (dried
vegetation) or exposed-ground. The initial identification of endmembers was based on geographical coordinates recorded during field observations. Since the aquatic and the terrestrial green vegetation had similar spectral properties, I decided to categorize them as one endmember called photosynthetic vegetation. Their spectral similarity through moderate spatial and spectral resolution satellite imagery failed to differentiate the unique spectral signatures among different species of healthy green vegetation. Also, the spectral similarity between dried-vegetation and exposed-ground classified them into one land cover type.

5.6.1 Scattergrams

Scattergrams give an idea of the spectral data distribution by plotting the data of two different bands against each other. The axes were chosen to illustrate maximum variance in the data by experimenting on several different band combinations. The arms or the separate clusters outside the main data cloud represent endmembers. The scattergrams confirmed the presence of three dominant endmembers and their spectral signatures for eight different days (Figure 5.7) (Table 5.1). In addition, the scattergrams provided information on the spectral properties of submerged vegetation in June 14th which is not easily detected by other classification methods.

5.6.1.1 Scattergram of NDVI

In the NIR/Red space, the points of the scatter form a longitudinal envelop where the low percent reflectance values of band 4 exhibited a tendency to transform into a triangular envelop (Figure 5.1). According to the data set of this case study within the
two dimensional NIR/Red space, NDVI provides very good separation for only one endmember which spans a range of NDVI values between 1.0 and 0.5. The non-vegetation features distributed below the NDVI dimension of 0.5. Hence, 0.5 line of dimension can be identified as the critical interface for healthy green vegetation. The trendlines of NDVI displayed an exponential distribution of \( y = 0.98e^{2.46x} \) with a correlation of 0.98 with NDVI values ranging from -1 to +1 (Figure 5.2). For the entire data set which includes all types of land cover, NDVI varies from -0.2 to 0.8. The healthy green vegetation endmember was segmented from the rest of the data cloud, as long as the pixels have distinct spectral signature. Figure 5.1 illustrates the variability of endmember spectral signatures of healthy green vegetation and non-vegetation derived from eight Landsat-5 TM images over Old Woman Creek estuary. The entire data envelop is a combination of all land cover types in the vicinity. The dashed lines define the one dimensional space of Normalized Difference Vegetation Index in the two dimensional NIR/Red space where healthy green vegetation span an ellipse elongated along the Near-Infrared axis. At 30 meter × 30 meter spatial resolution NDVI can separate entire community of healthy green vegetation as one land cover class. The different plant species as well as aquatic, terrestrial, and submerged vegetation were failed to differentiate.
Table 5.1. Variability of endmembers for the images considered in 2005.

<table>
<thead>
<tr>
<th>Month &amp; day in 2005</th>
<th>pure endmembers</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open-water</td>
<td>Photosynthetic vegetation</td>
<td>Non-photosynthetic vegetation / exposed ground</td>
</tr>
<tr>
<td>April-11</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>May-13</td>
<td>√</td>
<td></td>
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</tr>
<tr>
<td>May-29</td>
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<tr>
<td>June-14</td>
<td>√</td>
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<tr>
<td>August-01</td>
<td>√</td>
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<tr>
<td>August-17</td>
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<tr>
<td>September-02</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>October-04</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
Figure 5.1. Spectral variation of photosynthetic vegetation and non-photosynthetic vegetation derived from Landsat-5 TM data collected from April to October 2005. The dashed lines are NDVI isolines with values marked at the end of the line.
Figure 5.2. The exponential relationship between the slope of NDVI isolines with NDVI values ranging from -1 to +1.
5.6.1.2 Scattergram of NDWI

In the Blue/ MIR (band 5) space, the points of the scatter form a longitudinal envelop (Figure 5.3). According to the data set of this case study within the two dimensional Blue/ MIR space, NDWI provides very good separation for only one endmember which spans a range of NDWI values between 0.0 and 0.7. The non-open water features distributed below the NDWI dimension of 0.0 which reported negative values. Hence, 0.0 line of dimension was identified as the critical interface for healthy green vegetation. The trendlines of NDWI displayed an exponential distribution of \( y = 1.01e^{-2.14x} \) with a correlation of 1.00 with NDWI values ranging from -1 to +1 (Figure 5.4). For the entire data set which includes all types of land cover, NDWI varies from -0.6 to 0.7. The open-water endmember was segmented from the rest of the data cloud as long as the pixels have distinct spectral signature. Figure 5.3 illustrates the variability of endmember spectral signatures of band 1 and band 5 for open-water derived from eight Landsat-5 TM images over Old Woman Creek estuary. The entire data envelop is a combination of all land cover types in the vicinity. The dashed lines define the one dimensional space of Normalized Difference Water Index in the two dimensional Blue/ MIR space where open-water span a circle around the very low percent reflectance of the MIR band.
Figure 5.3. Spectral variation of open surface water derived from Landsat-5 TM data collected from April to October 2005. The dashed lines are NDWI isolines with values marked at the end of the line.
Figure 5.4. The exponential relationship between the slope of NDWI isolines with NDWI values ranging from -1 to +1.
5.6.1.3 Scattergram of NDGI

In the NIR/MIR (band 7) space, the points of the scatter form a triangular envelop (Figure 5.5). According to the data set of this study within the two dimensional Near-Infrared/ Mid-Infrared space, NDGI provides very good separation for all three endmembers which span in a range of NDGI values between 0.1 and 0.8. The ends of the triangular diagram represent the three major endmembers and I used this index to map the regions of exposed ground and non-photosynthetic vegetation which reported values ranging from 0.1 to 0.4 of NDGI. Hence, 0.4 line of dimension can be identified as the critical interface for this land cover type. The trendlines of NDGI displayed an exponential distribution of $y = 0.77 e^{2.09 x}$ with a correlation of 0.98 with NDGI values ranging from -1 to +1 (Figure 5.6). The exposed-ground endmember was segmented from the rest of the data cloud, as long as the pixels have its distinct spectral signature. Figure 5.5 illustrates the variability of endmember spectral signatures of exposed ground derived from eight Landsat-5 TM images over Old Woman Creek estuary. The entire data envelop is a combination of all land cover types in the vicinity. The dashed lines define the one dimensional space of Normalized Difference Ground Index in the two dimensional NIR/MIR space where exposed ground span an elongated ellipse around the data cloud along the axis of band 7.
Figure 5.5. Spectral variation of exposed ground/ non-photosynthetic vegetation derived from Landsat-5 TM data collected from April to October 2005. The dashed lines are NDGI isolines with values marked at the end of the line. The red circle represents exposed-ground/non-photosynthetic endmember whereas green and blue circles illustrate the photosynthetic and open-water endmembers respectively.
Figure 5.6. The exponential relationship between the slope of NDGI isolines with NDGI values ranging from -1 to +1.

\[
y = 0.77e^{2.90x} \\
R^2 = 0.98
\]
5.6.2 Spectral and spatio-temporal patterns of image endmembers

Because NIR/ Red and NIR/MIR (band 7) scatterplots illustrated a triangular data envelop, I re-plotted the scattergrams for the same dimensional space using the data of each individual dates during the study period (Figure 5.7). The resulted scattergram panel represented the seasonal and spectral variability of band 3, band 4 and band 7 with respect to land cover endmembers; open-water, photosynthetic vegetation, and non-photosynthetic vegetation or exposed-ground. On April 11\textsuperscript{th}, only two endmembers, open-water and exposed-ground were able to identify. In early May, when the tree canopies initiated their blooming, majority of the land represented mixed spectral properties of both exposed-ground and photosynthetic vegetation. As a consequence, it was complicated to identify a pure endmember for either vegetation or exposed ground during this period. Water was the only endmember that was clearly demarcated in all individual scattergrams. The individual scattergram of October 4\textsuperscript{th} exhibited a triangular shape of data scatter indicating the presence of all three endmembers. It was the only image that reported the remarkable occurrence of all three endmembers in same environmental conditions. Otherwise, the land cover shifts between three endmembers in response to climatic and environmental changes coexisting only two dominant land cover types at the time of each imagery. The spatial and temporal interpolations also evidenced this two endmember phenomenon except the image on October 4.

The spread of macrophytes initiated in May within the Star-Island and stretched out along the surrounding shallow region gradually with time. The south western part of the wetland was almost covered by aquatic macrophytes and the eastern margin of the
main basin is the area that is minimally covered by them. However, most of the creek path was also masked by the macrophytes in late Summer and the white color areas within the main basin in Figure 5.8 was believed to be the regions having pixels with mixed spectral properties (Figure 5.8).

The effect from the application of “Imazapyr” over the north eastern and south eastern regions around the Star-Island was observed only in October 4th spatial pattern because the thematic mapper (TM) sensor extracted the dried *Phragmites australis* as non-photosynthetic vegetation once they changes their color from green to brown completely. In PCA technique described in chapter four, this phenomenon was able to recognize in advance than the scattergram method. The PCA was able to detect this variation once those *Phragmites australis* beds turned into wilting stage. In endmember scenario, we can overcome this problem by assigning a critical interface value for each normalized difference remote sensing index after a long-term investigation.
Figure 5.7. Spectral variability of dominant land cover types in selected individual Landsat-5 TM imagery with seasonal variability. The percent reflectance of NIR band and Red band is plotted along Y-axis and X-axis respectively.
Figure 5.8. Spatial and temporal variability of photosynthetic vegetation, open-water, and exposed-ground/ non-photosynthetic vegetation. © 2007 Nishanthi Wijekoon.
5.6.2.1 Water endmember

The spectral properties of the open-water endmember in 2005 resulted two prevailing spectral patterns which differ from the percent reflectance of green and red spectral regions of the electromagnetic spectrum (Figure 5.9) (Figure 5.10). The maximum reflectance in band 2 which is the green band was observed during five days of analysis where as two days reported as optimal reflectance in band 3 which is the red band. In addition, the satellite data collected on June 14th were an exceptional case compared to suspended particulate reflectance from open-water column because of the spectral signature of submerged vegetation was recorded as open-water endmember.

Among the days of high reflectance in band two, May and October displayed highest percent reflectance compared to August 1st and September 2nd. As the reflectance of band 2 increases with the occurrence of chlorophyll a which is an indicator of phytoplankton in surface water, I argue that the high reflectance values in May and October generated due to Spring and Fall blooms in this fresh water body. The Spring bloom of phytoplankton occurred in May when the wetland received nutrients from its watershed as contaminated surface runoff from agricultural plots. The eutrophication also induced by the closed mouth of the estuary and the warm climatic conditions in Summer. In October, the open estuarine mouth regulated the back flow of Lake Erie water with nutrients into the estuary where I noticed another higher density of chlorophyll a episode which was identified as the Fall bloom of this inland fresh water estuary. The laboratory measurements of surface water samples also confirmed this outbreak of chlorophyll a during October. The water endmember spectral patterns in April 11 and August 17
Figure 5.9. Spectra of open-water endmember for the dates which exhibited a maximum percent reflectance in Green region (band 2) of Landsat-5 TM wavelength.
Figure 5.10. Spectra of open-water endmember for the dates which exhibited a maximum percent reflectance in Red region (band 3) of Landsat-5 TM wavelength. The spectral pattern on June 14th illustrates the submerged aquatic vegetation, specially the emerging stages of American lotus and water lily.
dominated the percent reflectance in red region of EMS indicating that the prominence of the suspended sediment concentration over the chlorophyll a concentration in surface water. According to the Ohio Department of Natural Resources statistical information, more than 80% of the Old Woman Creek watershed is composed of agricultural lands. Therefore, when the farming activities are initiated in early Spring the density of suspended sediment overrides the density of chlorophyll a in April 11. The dominant red band reflectance in August 17 controlled by several factors: (1) the average precipitation of 10-20 mm over the watershed through out the previous week of Landsat TM overpass day, (2) the debris of decaying aquatic macrophytes, (3) The mass destruction of phytoplankton which was dominant in August 1 due to depletion of nutrients within this closed wetland system, and (4) the application of herbicide named Imazapyr over the selected regions of common reed (Phragmites australis) growths which also washed off into the water body by the storm events of the previous week. Another elucidation of the endmember spectral pattern in August 17 is the presence of pheopigments which is the product of dead phytoplankton in surface water. If the third factor, the mass destruction of phytoplankton, is the cause for this spectral pattern then the leading signature in red region transpire due to pheopigments or gelbstuff.

A deviated phenomena from the rest of the temporal pattern occurred in June 14. The water endmember displayed maximum reflectance in NIR region whereas the other scenes indicated higher reflectance in visible region. The emerging aquatic macrophytes which were still few inches below the water surface were predominated a submerged
state. Hence, the resulted spectral pattern was a combined signal of open-water and aquatic submerged macrophytes.

**5.6.2.2 Photosynthetic vegetation endmember**

Percent reflectance in the NIR region varied in a range of 35 % to 50 % with intensity of green vegetation which was governed by the seasonal variability (Figure 5.11). The initial stages of green vegetation indicated 40 % NIR reflectance during late May which progressively reached to a maximum of 50 % in August and then gradually decreased towards 35 % during fall due to decay of aquatic macrophytes and fall color display. The maximum percent NIR reflectance of 50 was reported in August when the photosynthetic vegetation displayed optimal healthy green color. In August, lush green canopies of terrestrial vegetation comprised the entire Star-Island. The surrounding mudflats were ideal habitats for the growth of common reed (*Phragmites australis*) and cattail (*Typha spp.*) which accounted about 40 % of the wetland land cover in August. During the late Summer months, the overlapping broad leaves of American lotus (*Nelumbo lutea*) and water lily (*Nymphaea spp.*) floating on the open-water surface also contributed to the photosynthetic vegetation endmember.
Figure 5.11. Spectra of photosynthetic vegetation endmember for the dates which exhibited a maximum percent reflectance in Near-Infrared region (band 4) of Landsat-5 TM wavelength.
5.6.2.3 Exposed ground/ non-photosynthetic vegetation

On April 11, lack of photosynthetic vegetation in the vicinity was remarkably illustrated in Figure 5.8. The spectral properties of spectrophotometric generated exposed mudflats significantly correlated with the image extracted spectral pattern which only represented the exposed-ground on April 11. In contrast, the corresponding endmember that I observed on October 4 occurred due to two phenomena: (1) natural, and (2) human-induced. Opening of the barrier beach at the estuarine mouth was the natural phenomenon which led to expand the areas of exposed-ground. The storm events over the watershed released the wetland water into Lake Erie by decreasing the water level which caused the exposure of shallow regions. The most significant human-induced phenomenon was the application of herbicide over the *Phragmites australis* on mid August which displayed the wilting and shrinking of those giant reeds on October. This event was remarkably detected by the thematic mapper sensor. Since there was no sufficient time frame to completely dried out those large grass plants, the pure endmember spectrum for this land cover class demonstrated a slightly higher percent reflectance in band 2 compared to the spectral properties of completely dried *Phragmites* and exposed-ground (Figure 5.12).
Figure 5.12. Spectra of exposed ground/ non-photosynthetic vegetation endmember which was identified in spring and end of fall 2005.
5.6.3 The reference endmembers

The identification of image endmember spectra assessed an approach of comparison with reference endmember spectra. The transformation of reference spectra into a form that is comparable with image spectra derived from Landsat-5 TM data are described in Figure 4.4 of chapter four.

5.6.4 The correlation plots

The proper identification of land cover types was based on the correlation plots between reference and image endmembers. A correlation of 0.98 between the averaged-reference spectrum of non-photosynthetic vegetation and NDGI extracted image endmember confirmed the accuracy of the usage of NDGI in identification of this land cover type (Figure 5.13). Dried aerial parts of *Phragmites australis*, *Typha spp.* and some terrestrial vegetation were used to generate the reference spectrum which was commonly observed in Spring and late Fall in the Old Woman Creek wetland. The same image endmember displayed a positive correlation of 0.75 with the reference spectrum of exposed-ground (Figure 5.14). The NDVI extracted endmember displayed a correlation of 0.98 with photosynthetic macrophytes while the NDWI extracted endmember correlated with open-water reference spectra by 0.81 (Figure 5.15) (Figure 5.16).
Figure 5.13. Correlation plot between NDGI derived synthetic image spectrum with spectrophotometric measured reference spectrum of non-photosynthetic macrophytes.
Figure 5.14. Correlation plot between NDGI derived synthetic image spectrum with spectrophotometric measured reference spectrum of exposed-ground.
Figure 5.15. Correlation plot between NDVI derived synthetic image spectrum with spectrophotometric measured reference spectrum of photosynthetic macrophytes.
Figure 5.16. Correlation plot between NDWI derived synthetic image spectrum with spectrophotometric measured reference spectrum of open-water.
5.7. Conclusion

It was the purpose of this study to determine if the segmentation of scattergrams by the respective normalized difference remote sensing indices approach can provide an accurate and reliable means to characterize and map the spatial and temporal patterns of land cover types in a dynamic wetland. The results presented here indicate that approach can successfully capture the basic land cover types, such as photosynthetic vegetation, exposed ground, and open-water that are relevant for wetland land cover characterization.

As scattergrams of NDVI and NDGI displayed a tendency to be triangular data envelops, the three selected endmembers were independent of each other by their spectral properties. The central data cloud represented the pixels with mixed spectral properties. Although it is possible to extract the three major land cover types of the Old Woman Creek environment using one remote sensing index, either NDVI or NDGI, I used three indices (NDVI, NDWI, and NDGI) for this study to improve the accuracy of spectral signature extraction because each index that I used was capable of enhancing the spectral characteristics identical to different land cover types. For the current study, the moderate spatial and spectral resolution of Landsat-5 TM data was a significant issue which limited the number of identifiable endmembers. The satellite imagery with a higher spatial and spectral resolution would be capable of extracting higher number of endmembers for the same environmental settings as they provide more information in order to differentiate minor spectral and spatial variations. The critical interface values for the normalized difference remote sensing indices for Old Woman Creek in 2005 were 0.5, 0.0, and 0.4 for NDVI, NDWI, and NDGI respectively. Due to the robust nature of this mapping
technique, it should be applicable to other wetland land cover classification in different areas. However, in such cases, the determination of critical interface values for each normalized difference remote sensing index should be reassigned for the new environment of interest based on the spectral characteristics of dominant land cover types identified by field and remote sensing investigations.
CHAPTER 6

Mineralogy of suspended particulates in Old Woman Creek Estuary

6.1 Abstract

Old Woman Creek surface waters frequently carry sediment load as well as dissolved load. This study was conducted to evaluate the potential of XRD/ESEM (X-ray diffraction/ Environmental Scanning Electron Microscopy) to obtain information on the morphology and mineralogy of suspended sediment samples from the main basin surface water. The results revealed the dominance of crystalline silica and calcite as suspended load whereas large amount of crystalline silica was evidenced as the main mineral component in bottom sediment samples. As fresh water Ostracods are common in Old Woman Creek waters, it is believed that the high concentration of calcite originated from their shells influence the abundance of calcite in surface suspended particulate composition. The silica signature generated from surface or bottom sediment samples produced a sharp peak with high intensity at 2 theta value of 26.57 which indicated the major quartz peak of crystalline silica. A peak at the same 2 theta value with a significant broad base indicates the presence of biogenic silica. Hence, it is believed that silica, the principal mineralogy in bottom sediment and a dominant component in suspended load did not originate from the diatomaceous algae, which are composed by amorphous silica. The X-ray diffraction patterns of suspended and bottom silica are more close to that of crystalline silica, which is believed to be detrital grains derived from the watershed.
6.2 Introduction

Characterizing the nature and origin of suspended particulate in surface water is an essential step in determining the role of these materials in the study of total suspended particulate (TSP). Particles that exist in suspension in estuarine water are ubiquitous, principally by virtue of their small size and collectively make up the material known as suspended sediment (Hiller, 2001). Generally, the grain size of the terrigenous component of suspended particulates carried by most streams is less than 63 μm, representing the size class silt and clay. In addition, there are phytoplankton, zooplankton, mineral crystals etc. Usually, it is believed that these terrigenous particles are derived from the catchment area due to weathering of rocks and soil or anthropogenic sources (Liaghati et al., 2005). Other potential sources include materials eroded from soil, rocks, and stream banks; the re-suspension of estuarine bed sediment; in-stream and estuarine biological products; atmospheric deposition; and all other types of run off from the watershed. All or some of these factors may be combined in almost any proportion (Hiller, 2001).

The sediment load of a stream consists of particulate matter derived from a number of sources. Sediment loads are typically subdivided into three modes: bedload (clasts that slide, roll, or saltate near the stream bed), suspended load (clasts that remain mixed throughout the water column due to turbulence), and dissolved load (chemicals in solution as ions or as molecules adsorbed to colloids) (Evans and Seamov, 1997). In the Old Woman Creek wetland, the current research focused mainly on the mineralogy of surface suspended particulate which is a combination of suspended and dissolved load. In
addition, the mineralogy of bottom sediments was also examined. Increased suspended sediment load leads to numerous problems including increased turbidity, reduction in light penetration into a stream, increased water temperature, abrasion damage to aquatic organisms, siltation of reservoirs, and change of substrate (Evans and Seamov, 1997).

The objective of the present study was to evaluate the use of ESEM/XRD analysis to obtain information on the morphology and composition of particles from sediment samples derived from two different estuarine strata; surface water and wetland bottom. Such an investigation is thus required to understand the total suspended particulates (TSP) composition in this estuarine system. Silica was identified as the main component in bottom sediments, where as both silica and calcite were the major mineralogy in suspended particulates. Because of the dominance of silica in different estuarine strata, I postulated the role of Old Woman Creek fresh water body in estuarine silica cycling under closed mouth condition in Summer 2006. During the period of this study, the estuarine water was isolated from the central Lake Erie waters by a sandy barrier beach at the mouth.

6.3 Literature review

During last few decades, there has been a growing interest in using suspended sediment characteristics to evaluate the contributions of various sources in a drainage basin. The characterization based on mineralogy and morphology reflected the dynamics of the sediment source and the processes taking place during transport and storage within the channel system (Boer and Crosby, 1995).
As many methods of suspended sediment analysis require a considerable amount of sediments, researchers frequently use continuous flow centrifuging methods to collect large volumes of sediment from surface water bodies. Such methods may create sampling artifacts, for example because of floc breakage, and is time consuming which increases the cost of field sampling and severely limits sampling frequency (Boer and Crosby, 1995; Lartiges et al., 2001). I used a simple filtering technique through membrane filters for suspended sediment collection from surface water (Pazos et al., 2000).

An alternative approach to suspended sediment characterization is to use microscopy techniques. This permits analysis of small samples which decreases field processing time and offers the potential of increasing sampling frequency. Electron microscopy has been used for the study of sediments for several decades. Early uses were limited to the description of particles in terms of shape, size, and reaction to certain chemicals. Advances in environmental scanning electron microscopy (ESEM) coupled with refined specimen preparation techniques, and the advent of X-ray diffraction technique (XRD) has enabled detailed characterization of particles. SEM and XRD have been applied successfully to the investigation of suspended matter in surface water of estuaries and seas (Bernard et al., 1986; Eisma, 1986). Fresh water estuaries have been identified as an important source of dissolved silica (Struyf et al., 2005). In Spring and Summer, eutrophication phenomenon eventually induce the dissolved silica uptake by diatoms and thus influencing the ratio of diatomaceous to non-diatom phytoplankton community (Smayda, 1997; Billen, 2001).
6.4 Study area

Old Woman Creek estuary is located at the south central shore of Lake Erie in north central Ohio and a detailed description of this vicinity is included in section 2.2. The bed rock geology consists of the Huron Shale Member and the Cleveland Shale Member of the Devonian Ohio Shale, the overlying Mississippian Bedford Shale and the overlying Mississippian Berea Sandstone (Herdendorf, 1963, 1966). The study reported in this chapter is a sediment particle characterization from five selected sampling stations in the Old Woman Creek estuary in July 19, 2006 (Figure 6.1). The sampling stations were located within the main basin along the eastern margin of the creek. Usually, the surface area to depth ratio is high in the main basin. Hence, re-suspension of bottom sediments is common in this vicinity due to wind circulation over open surface water. During mid-Summer months, the floating aquatic emergent vegetation, mainly American lotus and water lilies enhance the water mixing by wind circulation due to the movement of their long stems.

6.5 Methods

6.5.1 Field techniques

Suspended and bottom sediment samples were collected from Old Woman Creek estuary on July 19, 2007. Five sampling stations were located along the eastern margin of the main basin and the distance between 2 stations was about 200 meters. The water depth was less than 2 meters in all sampling stations.
Figure 6.1. Sampling stations of the Old Woman Creek estuary were located along the eastern margin of the main basin where the creek runs to Lake Erie. © 2007 Nishanthi Wijekoon.
6.5.2 Analytical techniques

6.5.2.1 Environmental scanning electron microscopy

Environmental scanning electron microscopy (ESEM) was used to examine filtered sediment from the surface water samples. An aliquot of the sampled surface water (100 ml) was filtered with 0.8 μm polycarbonate membrane filters as they are designed for SEM analysis of fragile biological samples. An advantage of the design of these filters is minimization of drying artifacts from surface tension forces. The filtration was conducted within several hours after the sampling to minimize aggregation of small particles (Buffle and Leppard, 1995a and 1995b). The filters were oven dried at 60 °C for 24 hours and examined through ESEM to identify the morphology of particulate types in surface water.

6.5.2.2 X-ray diffraction

As I did not have a facility to conduct continuous flow centrifuging during suspended sediment sample collection, aliquots of 2 liters of surface water was allowed to settle in Nalgene beakers. After 48 hours, the supernatant was decanted and further dried at 60 °C until a dry residue of suspended sediment remained.

The bottom sediment samples were filtered through a 63 μm wet sieve in order to remove particles greater than that size as there is a less tendency for them to exist in suspended load in a small wetland dominated with stagnant water in the day of sampling. The filtrate was allowed to settle and the residue was oven dried at 60 °C.

The dry solid samples of suspended sediments and bottom sediments were ground into a fine powder before they were mounted on a slot specially designed for X-ray
diffractometer. The interpretation of the X-ray diffractograms was based on the intensity of peaks with respect to angles in degrees 2 theta depending on the mineralogical composition. The X-ray powder diffraction was based on the Bragg equation (Figure 6.2):

\[ n\lambda = 2d \sin \theta_n \]

where \( d \) is the distance between crystallographic planes, \( \theta \) is the glancing angle at which the X-rays are reflected, \( n \) is an integer, and \( \lambda \) is the wavelength of X-rays (Moore and Reynolds, 1997).
Figure 6.2. Reflection of X-rays from 2 planes of a solid mineral.
6.6 Results and discussion

Suspended sediments in the Old Woman Creek wetland originated both from the watershed (allochthonous) and within the wetland (autochthonous). For the periods of less precipitation and closed-mouth conditions, part of organic matter which originated from the decay of plant debris and biological particulates are autochthonous as they were originated within this wetland. In late Summer, the contribution of organic matter due to decaying of plant material is a common phenomenon. The organic matter is also transported into the wetland along the creek during the storm events over the watershed.

The similarity in the mineralogic composition of the surface sediments in five sampling stations within the main basin indicate sufficient mixing within this small environmental settings for a specific day. As the estuarine mouth was barred off the wetland water from Lake Erie on the day of sampling, the water body was in a stagnant state and the sediment transport was minimal with flow currents. I conducted sampling two weeks after the end of fish mating season and hence, the re-suspension of bottom sediment originated only from surface wind currents over the estuary.

Based on the observations during ESEM analysis it was thought that there would be about four different types of particles in each of those unglycolated suspended sediment sample. The representative ESEM images of surface water samples shown in Figures 6.3, 6.6, 6.9, 6.12, and 6.15 display similar morphologies consisting of green algae, diatom, calcite, and halite crystals. According to the XRD patterns, the main mineralogy of the suspended sediments is calcite and quartz (Figure 6.4, 6.7, 6.10, 6.13, and 6.16). Minor intensities of halite and illite are also observed. Some of the
characteristic XRD peaks of those minerals present are denoted as: Q=quartz, Ca=calcite, I=illite, and H=halite. The bottom sediment samples are mainly composed by quartz (Figure 6.5, 6.8, 6.11, 6.14, and 6.17). Hence, the bulk of the surface particulate material seems to be calcite and quartz, the foremost composition of bottom sediment samples was quartz.

The comparison of XRD patterns for crystalline and amorphous quartz provides evidence that the SiO2 peak for both suspended and bottom particulates to be crystalline quartz. The XRD signal for amorphous quartz displays a broader base than that of crystalline silica. As a consequence, the silica present in this environment mainly had a lithogenic origin rather than biogenic origin on the specific day of sampling. During the closed conditions of sandy barrier beach at the mouth, the wetland act as a silica recycler, transforming the silica budget between dissolved, biogenic, and lithogenic silica within the estuarine ecosystem. The illustration in Figure 6.18 indicates the potential silica cycling within this environment particularly during Spring and Summer (Figure 6.18). As the wetland biology is extensively dynamic in Spring and Summer, dissolved silica in estuarine water is utilized by marsh macrophytes, sediments, and diatoms. The macrophytes deposit dissolved silica in the plant tissue as solid amorphous silica which is known as phytoliths (Kauffman et al. 1981). Although I haven’t performed any experiments on phytoliths during this study, a previous research in North American wetlands demonstrated the capability of Phragmites australis to contain silica in total dry weight in the form of phytoliths (Conley, 2002; Meyerson et al., 2000).
The dead plant matter has higher relative silica contents as they release organic carbon and nitrogen during decay. The remaining silica could be either buried in sediment or slowly dissolve in surface water. The property of resistance to decomposition of phytoliths has been used as an indicator to reconstruct past environments (Piperno, 1988). Particularly, in Spring and Summer, the content of dissolve silica in surface water decreases due to diatom growth. The diatoms are a major group of eukaryotic algae and one of the most common types of phytoplankton. They are unicellular or colonial and have a cell wall made of silicon dioxide (SiO₂). Two major groups of diatoms are generally recognized in Old Woman Creek’s surface water: the centric diatoms which exhibited radial symmetry (symmetry about a point) and the pennate diatoms which were bilaterally symmetrical (symmetry about a line). The shape and markings of the valve are the means by which species are identified.

The second foremost mineral in suspended sediments is Calcite. I believe the origin of calcite in suspended load is from fresh water Ostracoda which are dominant in this environment. Ostracoda is a class of the Crustacea, typically around one mm in size, but varying between 0.2 to 30 mm, laterally compressed and protected by a calcareous shell which is hinged by two valves. They live in marine as well as fresh water bodies as a part of zooplankton.
Figure 6.3. Scanning electron micrograph of total suspended particulates (TSP) collected from the sampling station-1 of Old Woman Creek estuary by the filtration method. The right image illustrates a higher resolution compared to the left image. The resolution is denoted on the micrograph in micrometers.
Figure 6.4. Examples of XRD patterns of the surface suspended sediment samples collected at sampling station-1. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.

Figure 6.5. Examples of XRD patterns of the bottom sediment samples collected at sampling station-1. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.
Figure 6.6. Scanning electron micrograph of total suspended particulates (TSP) collected from the sampling station-2 of Old Woman Creek estuary by the filtration method. The right image illustrates a higher resolution compared to the left image. The resolution is denoted on the micrograph in micrometers.
Figure 6.7. Examples of XRD patterns of the surface suspended sediment samples collected at sampling station-2. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.

Figure 6.8. Examples of XRD patterns of the bottom sediment samples collected at sampling station-2. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.
Figure 6.9. Scanning electron micrograph of total suspended particulates (TSP) collected from the sampling station-3 of Old Woman Creek estuary by the filtration method. The right image illustrates a higher resolution compared to the left image. The resolution is denoted on the micrograph in micrometers.
Figure 6.10. Examples of XRD patterns of the surface suspended sediment samples collected at sampling station-3. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.

Figure 6.11. Examples of XRD patterns of the bottom sediment samples collected at sampling station-3. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.
Figure 6.12. Scanning electron micrograph of total suspended particulates (TSP) collected from the sampling station-4 of Old Woman Creek estuary by the filtration method. The right image illustrates a higher resolution compared to the left image. The resolution is denoted on the micrograph in micrometers.
Figure 6.13. Examples of XRD patterns of the surface suspended sediment samples collected at sampling station-4. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.

Figure 6.14. Examples of XRD patterns of the bottom sediment samples collected at sampling station-4. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.
Figure 6.15. Scanning electron micrograph of total suspended particulates (TSP) collected from the sampling station-5 of Old Woman Creek estuary by the filtration method. The right image illustrates a higher resolution compared to the left image. The resolution is denoted on the micrograph in micrometers.
Figure 6.16. Examples of XRD patterns of the surface suspended sediment samples collected at sampling station-5. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.

Figure 6.17. Examples of XRD patterns of the bottom sediment samples collected at sampling station-5. Some of the characteristic XRD peaks of the various minerals present are identified and labeled.
Figure 6.18. Silica cycling at Old Woman Creek in Summer 2006 when the barrier beach is closed.
5.7 Conclusion

The suspended sediment in the main basin of the Old Woman Creek estuary is a complex mixture of mainly re-suspended estuarine bed sediment and in-stream and estuarine biological products. The similarity of the mineral composition in surface water particulates and bottom sediment confirmed that wind circulation over the estuarine water re-suspended the bottom sediments which were largely contributed to the TSP load in Old Woman Creek estuary on the specific day of sampling. These components include mainly silica and calcite. The significant abundance of crystalline silica in both suspended and bed load dominates the crystalline quartz peak in all X-ray diffractograms over a possible amorphous silica peak. Due to the low abundance of diatomaceous algae compared to the high proportions of crystalline silica particulates, a peak with minor X-ray intensity by amorphous silica could be hidden by the sharp and high intensity peak of crystalline silica. The potential source for crystalline silica in this environment is mechanical weathering products of lithogenic silicate minerals within the watershed and the back flush of central Lake Erie waters across the sandy barrier beach during high Lake water levels. On this particular day of sampling, the re-suspension of bottom sediments by wind currents brought the particulates of crystalline silica into the suspended load from the bed load.
CHAPTER 7

Overview

7.1 Overview of goals and strategy

The four goals of this dissertation were: 1) develop an effective remote sensing algorithm for total suspended particulate concentration, 2) apply varimax-rotated principal component analysis to identify the distribution patterns of dominant surface reflectors, 3) identify the land cover endmembers based on scattergrams and normalized difference remote sensing indices, and 4) identify lithogenic particulates in surface water. The first three goals exploited field data and Landsat-5 TM reflectance measurements, whereas the fourth goal was achieved utilizing field data only. The four consecutive chapters from three to six described the achievement of each goal in manuscript format. Chapter three explained a calibration method to examine total suspended particulates in surface water based on a novel definition to normalized difference water index (NDWI). Chapters four and five introduced two methods for land cover mapping in a wetland which provided a setting to compare pros and cons between these two techniques. The spatial and temporal land cover variability mapping using those two different techniques helped to evaluate the validity of PCA method over the scattergram segmentation method. The extensive spread of broad floating leaves of some aquatic macrophytes reduced the dimensions of open surface water during Summer 2005. Hence, the extraction of open surface water as a separate meaningful component by PCA was not
possible due to insufficient reflectance information which led to significantly low % of variance compared to the entire data set. However, the spatial and temporal extents of aquatic macrophytes and exposed-ground were able to be delineated clearly. One of the significant observations was that the negative factor score values of component-1 represented the submerged regions which overlap with the spatial distribution of open-water which was described in chapter five. The scattergram segmentation method delineated the spatial and temporal coverage of open-water based on normalized difference water index (NDWI) calculated using bands 1 and 5, which was also described in chapter three. The overlap of the spatial and temporal extents of PCA-derived and scattergram-derived maps evidenced the validity of those methods. Chapter six, which described an ESEM and XRD approach to identify mineralogy and morphology of suspended particulates in surface water revealed the dominance of calcite and silica. It also provided evidence of silica recycling in this environment which was a preliminary finding that could be developed into a separate research project during the wetland water is barred off from Lake Erie waters by a barrier beach at the mouth.

7.2 Calibrating total suspended particulate concentration

This study employed a novel definition for the NDWI by evaluating the contrasting reflectance ratio between the visible and the infrared bands of Landsat-5 TM imagery in order to delineate open surface water areas from other land covers and map the TSP dynamics in surface water quantitatively. Water samples collected from the top of the open water provided more reliable measurements which correlated with satellite data compared to the measurements driven from the samples collected at 6-12 inches
below the water surface. The correlation of all possible normalized difference indices between visible and infrared bands with TSP concentration measurements were investigated in detail. In 2005, NDWI_{1&5}, NDWI_{2&5}, and NDWI_{3&5} reported correlations of 0.70, 0.55, and 0.59 with TSP concentration measurements respectively. The results indicated the reliability of the contrasting ratio between the band 1 and the band 5 for better interpretation of TSP concentration in open surface water. The correlation of 0.7 indicated that the Landsat-5 TM reflectance remarkably correlates with the top-most water layer. The critical value for land-water interface based on NDWI_{1&5} for this wetland environment was 0.0 while NDWI varied in a range from -1.0 to +1.0. All positive values indicated the open-water. The NDWI_{1&5} maps demonstrated the distribution of open surface water during Summer 2005 in space and time. Although my calibration span in a range of 40-140 mg/L of TSP, this study is a preliminary investigation which could be extended for higher range of TSP calibration research program for other open water bodies.

7.3 Wetland land cover classification and mapping

The most important achievement throughout this study was the development of two land cover mapping techniques for Old Woman Creek estuary based on principal component analysis and scattergrams of selected normalized difference remote sensing indices using Landsat-5 TM data. The comparison of spectrophotometric spectra of field samples with the synthetic spectra generated from the meaningful principal components and the endmembers of the scattergrams helped to identify the dominant land covers. PCA reduced the dimensionality of the reflectance data collected through six regions of
electromagnetic spectrum. The first four principal components accounted for 87% of the total variance in entire data set. The component-1 which contributed a variance of 32% was identified as exposed or submerged ground depending on the spatial distribution of high positive and high negative factor scores respectively. The spatial and temporal coverage of photosynthetic macrophytes were displayed by the component-4 which contributed to a variance of 18%. However, it seemed that the component-2 and component-3 represented water quality parameters of chlorophyll $a$ and suspended particulates, although it was controversial to make that conclusion due to some limitations in interpreting a small shallow wetland using moderate resolution satellite imagery. These two components contributed 37% of the total variance of the entire data set. The constraints that lead to poor elucidation of those two components are: 1) moderate spatial resolution of 30 meter $\times$ 30 meter, 2) lower spectral resolution of Landsat-5 TM due to broad spectral reflectance bands, 3) relatively small spatial extent of this highly dynamic estuary, and 4) the mixed spectral properties generated due to all of the above factors.

In addition to the spectrophotometric spectra of field samples, the endmember land cover types were easily identified by plotting the spectra of the extended arms of the scattergrams. Three normalized difference remote sensing indices: normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and normalized difference ground index (NDGI), of selected band combinations used to generate the scatterplots. One-dimensional spaces of 0.5, 0.0, and 0.4 for NDVI, NDWI, and NDGI were identified as critical land cover interfaces and the values greater than that of NDVI
and NDWI, and the values less than that of NDGI were masked out during mapping to extract only the land cover of interest. The triangular shape of the scattergrams of NDVI and NDGI also evidenced the existence of three endmembers in this environment. Consequently, those two remote sensing indices also could provide spatial extents of the land cover types. Due to the difficulty of identification of the interface values for all land covers within one triangular scatterplot, I combined the extracted signatures from all three indices to construct the final spatial and temporal series for 2005. The photosynthetic and non-photosynthetic endmember spectral properties correlated with spectrophotometric spectra of their respective field samples by 0.98. Correlations of 0.75 and 0.81 reported for exposed ground and open water endmembers with their respective field samples.

Compared to PCA mapping method, scattergram segmentation is capable to map open surface water remarkably because an individual remote sensing index (NDWI) was applied to perform the extraction of the water signal. Hence, without concerning the proportion of the area, the NDWI is capable of extracting open surface water which is not detected by PCA as a separate meaningful component. But it was observed that the negative factor scores of component-1 were responsible for that land cover type indicating the submerged areas which are contradictory to the exposed ground. The special and temporal variability of submerged ground adequately overlaps the spatial coverage constructed using NDWI in scatterplot segmentation method. In addition, the PCA extracted the remarkable dispersal of photosynthetic to non-photosynthetic vegetation and exposed ground.
7.4 Mineralogy of suspended particulates

Analysis of suspended and bottom sediments helped to identify the main particulate mineralogy in this environment. SEM and XRD analysis revealed two major mineralogical components in surface sediments and one major mineralogical component in bottom sediment. In a mineralogical sense, the suspended sediments are mainly composed with calcite and crystalline silica where as the dominant phase of bottom sediments was crystalline silica. The morphological studies by ESEM indicated the presence of calcite and diatoms in surface water. Although the diatoms are composed of amorphous silica, the XRD patterns indicate a strong signal for crystalline silica. This important observation occurs due to the dominance of the crystalline phase over the amorphous phase of silica on that particular day within this environment. According to the environmental and climatic conditions, during the period of study, the only possible way to encounter crystalline silica particulate in surface suspended sediment composition is re-suspension of bottom sediments due to wind circulation over the water body.

7.5 Future studies

The calibration of a NDWI algorithm provides an important remote sensing approach for quantitative TSP mapping in open surface water. However, it requires more ground truthing of satellite data in a TSP concentration range greater than 40-140 mg/L in order to fine-tune the established algorithm.

Each of the mapping methods used in this dissertation performed reasonably for the Old Woman Creek estuary in order to achieve the purpose described. The spectra
generated from field samples, PCA, and scattergram segmentation is identical to this environment for the particular period of study. Hence, regeneration of all spectra is required in an application over different environmental settings. Despite the fact that the PCA resulted component-1 and component-4 provided a better visual interpretation of land cover variability, still it is controversial for component-2 and component-3 due to mixed spectral properties of pixels. One hypothesis is that the striping problem of Landsat-5 TM may generate this controversial result due to systematic and random noise. Hence, a similar research approach on large scale water bodies using Landsat-5 TM data is needed in order to clarify the complicated spatial distribution of component-2 component-3. The dark and light striping problem in Landsat-5 TM data due to aging of the satellite may cause this indistinct result.

The scattergram segmentation method could be further improved through a careful study on spectral properties of endmembers. Even though I used three normalized difference remote sensing indices for mapping, the investigation of the applicability of one selected normalized difference remote sensing index with a triangular scatterplot such as NDVI or NDGI is important.

Finally, as it was observed by XRD, the presence of crystalline silica in both suspended and bottom sediments as the dominant mineralogical phase, and the understanding of the presence of amorphous silica in suspended sediments through ESEM morphological studies indicates that a detailed research program could be implemented for silica recycling within Old Woman Creek estuary. When the mouth bar is closed mostly during the Summer, the isolated water body is ideal to execute a detailed
study of biogenic, crystalline, and dissolved silica recycling to provide new insight to suspended sediment studies at Old Woman Creek estuary.


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