A Review of Existing Wetland Evaluation and Assessment Methods:

Remote Sensing and GIS Methodologies for Modelling and Mapping Wetland Variables and Functions
and
Available Remotely-Sensed Imagery and Geo-Spatial Datasets

FINAL REPORT

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1.0 Introduction

Wetlands are environments where water is present at, or near the surface for all or part of the year (more detailed definitions are provided below in the discussion of wetland classifications and inventories, 2.2). The purpose of this document is to provide a comprehensive review of the scientific literature as it relates to: wetland inventory, evaluation and assessment to identify wetland attributes (functions, values, conditions) that have been quantitatively assessed in existing systems, models, programs and protocols (in Ontario and worldwide); the current remote sensing and GIS methodologies for modeling wetland variables and functions; and an assessment of remotely-sensed information and available GIS spatial datasets to determine if there are quantifiable attributes that are related to the wetland attributes described above. This document is organized in four main chapters:

1. Introduction
2. Wetland Evaluations and Assessments
3. Remote Sensing and GIS Methodologies for Modeling and Mapping Wetland Variables and Functions
4. Available Remotely-Sensed Imagery and GIS Spatial Datasets

The literature for this review has been assembled through the appraisal of academic databases, examination of local, provincial- and state-wide, regional and national wetland authorities (e.g. Delaware Department of Natural Resources and Environmental Control, the New Zealand Ministry of the Environment, etc.) and consideration of World Wide Web sources. This literature included six key reviews of wetland evaluation systems, three key web databases, seven texts, forty-two technical manuals, and over 150 journal articles. These are provided (in part) in the reference section as well as in an organized bibliography found at the end of this report. This report is not a review of every possible wetland reference, but rather an assessment of literature that is most relevant to the current OMNR (Ontario Ministry of Natural Resources) goal of refinement and re-design of aspects of its wetland evaluation strategy and protocol. The literature presented is representative of the contexts, approaches and methods used worldwide at a variety of scales for a large and diverse set of goals. It includes very recent technologies and methodologies as well as aspects of important historical wetland evaluation programs. The organization of each chapter follows similar structures found in the literature, in order to facilitate comparison, and to maintain consistency for future evaluations.

2.0 Wetland Classification, Inventory, Evaluation and Assessment

Wetlands provide many types of services but are under threat from modification for agricultural and land development, climate change, and invasive species among other stressors. They are often hard to delineate (map) and classify using a given set of attributes because of their spatially and temporally dynamic nature. Mitsch and Gosselink (2007) outline six aspects of wetlands that exhibit spatio-temporal dynamics, including function, flora and fauna, size and location, and changes due to anthropogenic influences (Mitsch and Gosselink, 2007). It is the variable composition of wetlands that make it difficult to map and statistically evaluate them in a consistent manner. Yet different government and management entities assign set definitions to satisfy many diverse mandates. Many governmental and non-governmental organizations have created systems or models to assess, evaluate, score and provide designation to wetlands that are located within their jurisdictions.

Wetlands can be considered in the elemental terms of their functions (attributes), values (product or services) and/or conditions (Vives, 1996; Bartoldus, 1999; Papas and Holmes, 2007). Functions are "the things that wetlands do" (Bartoldus, 1999) and include: flood water control; ground water recharge; ground water discharge; nutrient, sediment, and contaminant retention; food web support; shoreline stabilization; erosion control; storm protection; stabilization of local climatic conditions; water transport; wildlife habitat; land and aquatic vegetation; protected species presence and usage; proximity questions; wetland size (Lodge *et al.*, 1995; Hruby *et al.*, 1998; Thiesing, 2001; OWES, 2002; Carletti *et al*., 2004; Papas and Holmes, 2007; etc.). Values are the products and/or services provided by wetlands which can include recreational, cultural, heritage, educational, aboriginal use, aesthetic quality, wildlife resources, fisheries, forage resources, agricultural resources, water supply, and forest resources (Roth *et al.,* 1996; Bartoldus, 1999; OWES, 2002; Carletti *et al*., 2004; Papas and Holmes, 2007; etc.). These include services provided to humans and to other species. Condition is representative of overall wetland health, ecosystem functioning or ecological integrity, biological diversity (wetland type, diversity of surrounding areas, vegetation communities, etc.); habitat suitability (including patch suitability, species richness, etc.), and proper functioning condition (Pritchard *et al.*, 1996; Schroeder, 1996a; Bryan *et al.,* 1997; Karr and Chu, 1997; Papas and Holmes, 2007; etc.) among others. Components of wetland assessments are often made up of several functions, values and/or conditions and usually include: a hydrologic/aquatic component, a biological/ biodiversity component, (Thiesing, 2001; OWES, 2002; Carletti *et* al., 2004), an erosion component (Carletti *et al*., 2004), a direct anthropic use/social component (OWES, 2002; Carletti *et al.*, 2004), and a special features component (OWES, 2002).

This section of the report aims to provide an overview of the types of wetland evaluation and assessment systems that are currently in use in North America, Australia, and Europe. It describes five main categories of evaluation systems in general terms and then the reader is directed to a complete synoptic Excel database that accompanies this report. It summarizes the systems, information on their general categorization, the basic methods of evaluation, whether or not GIS or remote sensing is used, the jurisdiction (location/region) in which the system is applied, the scale of wetlands assessed, and the various functions, values and/or conditions that are assessed by each method.

2.1 Existing wetland evaluation systems, models, protocols and programs

There are many different systems, models, methods, programs and protocols around that world that are used to identify and evaluate wetlands. (For the purposes of this report, these shall be considered and referred to as wetland evaluation **methods)**. These are important for obtaining information about wetlands slated for destruction for anthropogenic development, for understanding the functioning of attributes in wetlands for future planning purposes, to use in conservation and restoration programs, and for understanding and management of species habitat, including species at risk (Thiesing, 2001). These range from simple classifications of wetland land cover to detailed evaluations of wetland functions and values. Scales of application vary from local to regional or national, but as area increases the number and detail of attributes assessed typically decreases. In general, the assessment methods can be categorized into five groups, including:

1. classification and inventories
2. rapid assessment protocols
3. primarily functional assessments
4. primarily bio-assessments
5. system-based evaluations

Many current assessment methods are field based with all input data being dependent upon field measurements. Some use remote sensing (especially thematic classification) to provide land cover assessment or mapping, but the most common application of remote sensing data or derived land cover maps has been to assist selection of field sites for further evaluation. Other methods use GIS to model functions and attributes using field data collected specifically for that purpose. Some methods use existing data sets available in geo-spatial databases. Many methods have been developed specifically for small jurisdictions (e.g. counties or states) while a few have been developed for landscape, regional or country-wide use. There have been several compilations of existing wetland assessment and evaluation methods in North America (World Wildlife Fund, 1992; Bartoldus, 1999; Carletti *et al.*,

2004) Europe, (Vives, 1996; Carletti *et al.*, 2004), Asia and Australia (Papas and Holmes, 2007), among others. For this appraisal of wetland evaluation methods, several key sources were found to provide the most up to date information on these systems and methods. These include: *Statewide Wetlands Strategies* (World Wildlife Fund, 1992); *A Comprehensive Review of Wetland Assessment Procedures* (Bartoldus, 1999); *Ecosystem Management and Restoration Information System (*US Army Corps of Engineers, 2001); *A critical review of representative wetland rapid assessment methods in North America* (Carletti *et al.*, 2004); *Review of Rapid Methods for Assessing Wetland Condition (*Fennessy *et al.*, 2004); *Index of Wetland Condition: A Review of Wetland Assessment Methods* (Papas and Holmes, 2007); *Ecological Assessment Methods Database,* (National Biological Information Structure, Center for Biological Informatics of the U.S. Geological Survey, 2008) among others. In addition, technical manuals and evaluation reports for each method were also assessed where they were accessible (including softcopy access online, or hardcopy ordering via telephone or internet).

The majority of the assessment methods have been developed in the United States for particular state-based usage with some methods that can be applied regionally or country-wide. In many cases, the evaluation systems are expanded versions of previously developed systems from other jurisdictions (indicated in the database). For the organization (and brevity) of this section, **Wetland Classification and Inventory (2.2)** methods are described in detail here. This is because this category does not lend itself to being easily listed in an Excel database with the other four categories; therefore this category (Wetland Classification and Inventory) is not listed in the Excel file, but fully explored in the text here. The remaining four categories are described briefly in the text in general. Then a complete listing of the 64 methods (by category) is provided for, and explained in the accompanying Excel database. These 64 methods are the most commonly presented in the literature and the most relevant to the authors' understanding of the OMNR's information needs regarding its current project to redefine and redesign the Ontario wetland evaluation system. The methods are listed based upon their general categorization in the above noted key sources, and the underlying elemental variables of each method are grouped by the components (e.g. biological, hydrologic, etc) derived either from the methods themselves, as assessed by the key sources above, or as assessed by the author. In some cases, some methods may have characteristics from several of the four categories, but are included in the one category (e.g. rapid assessment protocol, primarily functional, etc.) with which they are most commonly associated in the literature sources, or for which their underlying elemental variables are predominantly related. This database lists 64 evaluation methods and 198 functions, values and conditions assessed by these methods. The list does not include all possible methods used worldwide (as even after extensive review,

other methods continue to be located); however, it does provide a comprehensive representation of assessment methods currently available. In the Excel database the methods are listed in the rows, with the various attributes associated with each listed in the columns as: 1) overall category, 2) method, 3) reference/jurisdiction, 4) method of evaluation, 5) method classification scheme, 6) remote sensing/GIS components, 7) other related methods, 8) location/scale. Columns 9 through 216 list the various functions, values and conditions that are assessed. If a function, value or condition is assessed for the particular method then a check mark appears in the associated column. There are four tables (worksheets, Tables 5 – 8) provided in the Excel database that list: Table 5 – all 64 methods by method type; Table 6 – all 64 methods by variable type; Table 7 – all system-based methods by method type; and Table 8 – all system-based methods by variable type.

2.2 Wetland classification and inventory

Wetland classification and inventories, as described in this section, are examples of those used in countries that have taken an intensive approach to locating, mapping, characterizing, evaluating, and managing wetlands. Cowardin *et al*. (1979) states that the key goal of wetland classification should be to create boundaries on ecosystems of similar classes that can subsequently be used for "inventory, evaluation and management". Most classification systems still follow this discrete spatial representation of wetlands despite recent efforts to represent ecological entities such as wetlands as more integrated with their surroundings in terms of flows and functions. All classification systems have as their fundamental basis an explicit definition of wetlands. The Ramsar Convention Manual (2006) defines wetlands as "areas where water is the primary factor controlling the environment and the associated plant and animal life. They occur where the water table is at or near the surface of the land, or where the land is covered by shallow water." Wetlands are specifically defined as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres" and "may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands" (Ramsar Convention Manual, 2006). The definition assigned to wetlands by the Canadian government is "land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment" (National Wetlands Working Group, 1997). The Southern Ontario Wetland Evaluation system defines wetlands as "lands that are seasonally or permanently flooded by shallow water as well as lands where the water table is close to the surface; in either case, the presence of abundant water has

caused the formation of hydric soils and has favoured the dominance of either hydrophytic or water tolerant plants" (OWES, 2002). It can be seen that for three different jurisdictions, there are similar yet fundamentally different definitions for wetlands.

2.2.1 Wetland classification systems

The Ramsar Classification System for Wetland Type (Ramsar Convention Manual, 2006) classifies wetlands into three broad categories including: Marine/Coastal Wetlands, Inland Wetlands, and Human-made Wetlands. This system was adopted by Ramsar as a means to apply the criteria for the designation of Wetlands of International Importance. The general categories (marsh, fen, peatland, water) and methods to categorize them are given as guidelines for member countries to develop national interpretation or classification systems. Also, in many cases, guidelines are provided to identify specific individual wetland types (e.g. wet grasslands, mangroves, etc.). The following paragraphs summarize the Canadian Wetland Classification system as well as systems developed in other countries.

In Canada there are several different classification and inventory systems created for diverse purposes (Milton and Hélie, 2003). At the national scale, the Canadian Wetland Classification System (National Wetlands Working Group, 1997) categorizes wetlands in a hierarchical format. 'Class' is the top-most and broadest category, the mid-category is 'Form' and at the finest level, is 'Type'. Classes are comprised of: bogs, fens, swamps, marshes and shallow waters (usually 2m deep or less). Form is based in part upon surface form and hydrologic systems, such as the ombrogenous system and the minerogenous system. The minerogenous system is subdivided into several other groups, whereas the ombrogenous system only contains peatlands (bogs). This is because ombrogenous systems only receive input from precipitation and are hydrologically isolated. Wetland Type, the lowest level of the hierarchy, has eight groups defined by general characteristics of the plants present (see the *Canadian Wetland Classification System*, National Wetlands Working Group, 1997). The Canadian Wetland Classification System has been adopted by the federal government and many other provincial and local government and non-governmental organizations. However, a national inventory of wetlands in Canada has yet to be conducted.

Cowardin *et al.* (1979) created the Classification of Wetlands and Deepwater Habitats to replace a system that was used for a classification and was originally completed in the United States in 1954. The 1954 classification system was simple and lacked critical differences between specific wetlands. The Cowardin system is hierarchically structured with three key groups of systems and subsystems (e.g., marine, estuarine, riverine, lacustrine, palustrine) with classes, subclasses and dominance types as the second level of the hierarchy and modifiers of these creating the third level.

The Hydrogeomorphic (HGM) Classification for Wetlands (Brinson, 1993) was developed for the US Army Corps of Engineers. It is based on classification of hydrologic and geomorphic wetland function while ignoring biotic structure. A key benefit to this system is that the environment in which the wetland is situated is considered, including assessment of wetland complexes, uplands, and the watershed. There are other classification systems that also use hydrologic or geomorphic function, but HGM was the most commonly cited in the evaluation systems that were reviewed. This classification has three key components: geomorphic setting (the topographic location of the wetland in the landscape); water source and its transport (as inputs to the wetland); and hydrodynamics (the direction and strength of water movement in the wetland). Geomorphic setting is categorized in a hierarchical system with four major groups: Depressional Wetlands, Extensive Peatland, Riverine Wetlands (floodplain, not channel), and Fringe Wetlands. Water sources include precipitation, surface flow, and groundwater discharge, which are often ranked based upon the contribution to wetlands if data is not readily available. Using this information, wetlands may be subsequently categorized into six ecosystem types: prairie pothole marsh, ombrotropic peat bog, high-gradient riverine forest, low gradient riverine forest, tidal freshwater marsh and tidal saltmarsh. Hydrodynamics are classified as three key categories: vertical fluctuations, uni-directional flows, or bi-directional flows. For this classification system an observer would use a deductive approach in the field to assess indicators (e.g., high water, soil texture, flows, etc.) of these different functions and then assign a wetland category.

Wetland classification in Australia is based on water regime, salinity and vegetation with over 40 different wetland types in Australia, classified into three broad categories of marine and coastal zone wetlands, inland wetlands and human-made wetlands (Papas and Holmes, 2007). This system follows the Ramsar system in evaluation and identification of wetlands of significant importance. Three additions to the Ramsar system include non-tidal freshwater forested wetlands, rock pools and inland karst systems.

Recently, a hierarchical wetland classification system was developed in New Zealand (Clarkson *et al.*, 2003). It assesses wetlands at four levels, the first being the hydrosystem which assesses the hydrologic setting and salinity to classify a wetland as Estuarine or Palustrine. Below this, but in the same hierarchy level, are sub-hydrosystems discriminated by flow regime and including: Estuarine - intertidal, subtidal, non-tidal and inter-dunal; and Palustrine - permanent and ephemeral. The second hierarchy level is wetland class with a subsystem of wetland form; the third level is structural class and the final level is dominant vegetation cover type.

The classification systems described above, or some modified version of them, are used in the inventory and evaluation of wetlands as described in the following section. The design of the classification system is an important first step before conducting an inventory and commencing wetland evaluation.

2.2.2 Wetland inventories: Objectives, data types and general methodologies

The main objective of wetland inventories is to describe or provide a visual representation of the extent and/or type of wetlands that are present in a landscape (Thiesing, 2001). Dahl and Watmough (2007) define wetland inventories as a "count, measurement, catalogue, or estimate of the extent of the wetland resource for a defined geographic area". This section summarizes the national wetland inventories of Canada and the U.S. as well as the European CORINE program, followed by representative examples of inventory activities at provincial and regional scales.

Development of the Canadian Wetland Inventory (CWI) was initiated in 2002 in response to Canada's poor ability to track, monitor and report on the status of its wetland resources (Milton and Hélie, 2003) and its obligations for reporting under the Ramsar Convention (Ramsar Convention Manual, 2006). The CWI project is currently being administered by several entities such as the Canadian Wildlife Service of Environment Canada, the North American Wetland Conservation Council (Canada), and Ducks Unlimited Canada, among others. The first phase of the inventory was to develop methodology for wetland mapping and monitoring. The key was to be able to consistently map wetlands across Canada with a minimum mapping unit of 1 ha (Fournier *et al.*, 2007). In development of the inventory several existing inventories were assessed (e.g. the CORINE (Co-ordination of Information on the Environment) Land Cover Program (Europe); NWI (National Wetland Inventory (USA), etc.). Common aspects adapted from these inventories included:

1. The main data sources are, in general, satellite and aerial imagery, and data selection is dependent on the required minimum mapping unit (MMU). Secondary and tertiary data types include existing data or reference maps (e.g., hydrographic layer, (from the Canadian National Topographic Database (NTDB); provincial base maps with wetlands classified (e.g., Southern Ontario Land Resource Information System (SOLRIS); the Conservation Atlas of Wetlands, St. Lawrence Valley, Quebec, etc.)) and other datasets such as Digital Elevation Models (DEM), soil surface maps, and other soil and climate datasets.
2. The MMU has the greatest impact on the inventory (Fournier *et al.*, 2007) as it determines not only the smallest object size to be mapped but it influences the attribute

precision (the level of detail in a classification hierarchy), the intensity and cost of fieldwork, the type and cost of geo-spatial data (particularly remote sensing data, which increases significantly in cost with increasing resolution due to an associated decrease in coverage per image), the data processing infrastructure requirements (smaller MMUs and higher resolution produce larger data sets), and the required analytical techniques and expertise (see next point).

3. Although the estimation of wetland aerial extent improves with increasing spatial resolution, there is an associated increase in spatial variability and at higher resolutions expert interpretation is needed.
4. Conventional image classification techniques based on spectral reflectance or brightness in individual pixels and parametric data distributions (e.g., the maximum likelihood classifier) do not work well for all but the broadest wetland class types. Smaller MMUs and associated higher resolution require advanced image classification techniques and expertise. These may include object segmentation/classification, non-parametric classification (e.g., neural networks; expert/rule-based classification), and additional spatial or contextual analysis (Chapter 3 presents details related to these issues).

The MMU for the CWI was selected to be 1 ha based on three key issues: availability of satellite imagery; compatibility with other existing maps (e.g., Global Land Cover (created with Landsat images (Latifovic and Pouliot, 2005)); the Canadian Forest Service vegetation land cover map (Wood *et al.*, 2002; Wulder *et al.*, 2003); and resolution needs for regional and local assessment of wetlands. The intent was to map the five classes of the Canadian Wetland Classification System. Data used in the CWI are: Landsat 7 ETM+ (national mosaic); radar products (RADARSAT-1 images in C-band with HH polarization, see Grenier *et al*. (2007) in **3.2.1.5**); the hydrographic layer; the vegetation land cover map produced by the Canadian Forest Service; the agricultural land cover map produced by Agriculture and Agri-Food Canada, and ecoregional maps created by the Ecological Stratification Working Group (Fournier *et al.*, 2007). The methodology to be used to create these wetland maps is based on object-based segmentation/classification (see **3.2.1.5**). However, it appears that this project has become stalled, and although investigation and testing of the methodologies and data types have been initiated, there has not been progress towards implementation of the program.

The National Wetlands Inventory (NWI) conducted by the U.S. Fish and Wildlife Service provides digital wetland information throughout the United States (Dahl, 2006). The NWI provides

spatial extent and change information using the Cowardin *et al.* (1979) classification system described above with three broad classes of Salt Water Habitat, Freshwater Habitat and Uplands and a variety of subclasses (Dahl, 2006). The inventory system was developed to contribute to four long-term objectives for wetland classification and management: "(1) describe ecological units that have certain homogeneous natural attributes; (2) arrange these units in a system that will aid decisions about resource management; (3) furnish units for inventory and mapping; and (4) provide uniformity in concepts and terminology throughout the United States" (Cowardin *et al.*, 1979). The current inventory is updated, and a report describing the status on trends in wetlands in the U.S. is produced every five to eight years (Fournier *et al*., 2007). The target MMU is 0.4 ha with the actual smallest wetland unit being identified as 0.005 acres (not all units at this size are detected, however) (Dahl, 2006). The information provided by the NWI (available online, http://www.fws.gov/nwi/index.html) includes both wetland maps, and status and trend documentation. For the contiguous states, state boundaries and 35 other subdivisions are used to segment the data. Supplemental data from coastal fringes and 4371 field sample plots are used within these subdivisions. The imagery used is primarily high resolution (e.g. IKONOS) satellite imagery acquired during the leaf-off period to aid detection of the spatial extent of the wetlands (Dahl, 2006). To supplement these data, National Agriculture Imagery Program (NAIP) imagery (aerial or satellite with a spatial resolution of 1m or less) is also used. Secondary and tertiary data include topographic maps, soil data and coastal navigational charts.

The CORINE (Co-ordination of Information on the Environment) Land Cover Program in Europe was designed to provide consistent land cover information for all twelve member states of the European Community (European Environment Agency, 2008). The mapping scale is 1: 100,000 with an MMU of 25 ha. The classification contains a significant wetland class that is hierarchically structured from the broad class of Wetlands to Inland Wetlands containing the sub-categories of inland marshes and peat bogs, and Coastal Wetlands containing the sub-categories of salt marshes, saline and intertidal flats. The data used for this classification program are Landsat TM, Landsat MSS and SPOT (HRV XS) along with additional aerial photographic imagery (1: 50,000 and 1: 20,000) and field data ((European Environment Agency, 2008). Computer-aided photo-interpretation is used with transformed and/or classified imagery that includes vegetation indices, principal component analysis, and supervised classification.

The Natural Resources Values and Information System (NRVIS) layers provide coverage of the province of Ontario (NRVIS, 2002). Initially, in the past, this information was published as OMNR Ontario Base Maps (OBM) at 1:10,000 (southern Ontario) and 1:20,000 scales (northern Ontario).

These maps were developed from aerial photography obtained in the spring and include wetlands that were interpreted from the aerial photos. Newer layers include OWES evaluated wetlands that were taken from the OMNR's evaluated wetland files (OWES, 2002, e.g., NRVIS Wetland Unit). The OWES recognizes four main wetland types (bog, fen, swamp, marsh), and one sub-type: open water marsh. This framework is similar to the Canadian Wetland Classification System which is based on five classes (bog, fen, marsh, open water, swamp). These layers do not inventory all wetlands in Ontario.

The Southern Ontario Land Resource Information System (SOLRIS, 2003) land use/land cover classification follows the ecological land classification system for southern Ontario (Lee *et al.,* 1998; SOLRIS, 2008). Ecological land classifications include all components of earth systems (e.g. air, water, land, biota, etc.) and are based upon the hierarchical structure of ecosystems that are nested within other ecosystems (Environment Canada, 2005). One distinct aspect of SOLRIS is the development of methodology for wetland and ephemeral water mapping. This inventory used remote sensing and spatial modelling techniques to identify and classify wetland features at the community series level with one goal being to delineate wetlands not previously inventoried by NRVIS ("Unevaluated Wetlands"), and to additionally identify ephemeral wetlands. The SOLRIS classification is an adaptive wetland mapping process consisting of three key components including: a the high precision DEM component that uses Classification and Regression Trees (CART) to create a rule-based classification methodology to determine the thresholds for wetland separation (creating a swamp class constrained by woodland boundaries); a spectral data component (including both optical and radar imagery to assess swamps in areas with deciduous vegetation and level topography); and a medium precision DEM wet soils component to assess swamps in areas with coniferous vegetation and steep slopes (Hogg and Mostoway, 2007). Data used include Landsat, Radarsat, and Indian Remote Sensing (IRS) imagery (23 m, multispectral), OMNR Forest Resources Inventory photos, CIR aerial photos, high and medium precision DEMs, TSI (topographic soils index, derived from the OBM contours and quaternary geology layer designed to overlay depressions with soils), and the NRVIS layers for Wetlands, Open Water and Wooded Area, (SOLRIS, 2003). This adaptive method was applied to a reference site to compare with wetland evaluations obtained through fieldwork and Ontario Wetland Evaluation System maps derived from field work and the NRVIS Wetland layer. The overall correspondence for the wetland (swamp, marsh, shallow-open water classes) was approximately 94%. Using only the high precision DEM method, the accuracy was 82%.

The Conservation Atlas of Wetlands provides an inventory of wetlands in the St. Lawrence Valley (Environment Canada, 2006). This inventory uses the Canadian Wetland Classification System

with a fourteen class structure (peatland, marsh, agriculture floodplain, water body, fallow, hay field and pastureland, annual crop 1, annual crop 2, high-density coniferous, low-density coniferous, mixed forest, dry deciduous, mesic deciduous and urban area). In the field, over 1000 observations of wetlands were made in summer of 2000. Thirty-four RADARSAT 1 images (April to June, 1999) were used, from which texture measures (Mean and Contrast, etc. (see Haralick, 1979)) were derived. A DEM was developed from NTDB 1: 50,000 sheets (and used to orthorectify the radar imagery and to create a slope product and a waterway proximity index), and six Landsat-TM scenes (from 1993 and 1994) transformed using principal component analysis (PCA) A classification and regression tree (CART) method (see Chapter 3) was used with these data to map wetlands. The minimum mapping unit was 1 ha, so following classification all wetlands under 1 ha were eliminated. Peatland accuracy using the Landsat data alone was 80% and 98% using the full Landsat-Radarsat-Topography data set.

There are many inventories of wetlands completed at the national, regional, landscape and local scales. Many of the evaluation methods reviewed utilize existing inventory data and maps to delineate wetlands of interest for assessment. Sometimes the evaluation methods have an inventory component that must be completed prior to the assessment of the underlying functions, values and conditions.

2.3 Rapid assessment protocols

Rapid assessment protocols (RAPs) are strategies and techniques (but for consistency will be referred to as **methods** for this report) used to collect data and assess aspects of wetlands quickly and cheaply (Thiesing 2001; Fennessy *et al*., 2004). Examples of RAPs include assessment for restoration/renewal programs, wetland ranking in resource administration, evaluation of best management practices and assessment of water habitat usage (Fennessy *et al.,* 2004). When developing RAPs key priorities to consider are (Fennessy *et al.*, 2004):

1. The method must be able to measure wetland ecological condition.
2. The method must be fast (which is defined as two people taking less than ½ day in the field, and ½ day in the office to obtain results).
3. There must be an on-site evaluation of the wetland involved.
4. There cannot be scoring points assigned to a wetland simply based on its potential to perform given functions or provide a given service; it must be doing so currently.
5. The method and results must be verifiable.

In design and implementation of a RAP, three aspects must be addressed: which classification scheme to use; the scoring system for wetland elements; and which elements (functions, values, and conditions) can be recognized for the wetland of interest. RAPs are methods that evaluate individual

wetlands or small groups of wetlands, and must occur both quickly and for little cost. Although, Fennessy *et al.* (2004) suggest that the results of rapid assessment must be verifiable through empirical study, Thiesing (2001) suggests that data from such assessments can be evaluated through expert opinion and provide qualitative and subjective verification.

Fennessy *et al.* (2004) identified seven RAPs that met the criteria outlined above; these were also in part identified by Bartoldus (1999). Four representative examples are: the Montana Wetland Assessment Method (MT Form, Burglund, 1999); Minnesota Routine Assessment Method (MNRAM) (Bartoldus, 1999; EMRRP, 2003; Fennessy *et al.*, 2004); Florida's Wetland Rapid Assessment Procedure (WRAP) (Miller and Gunsalus, 1999); and the Wisconsin Rapid Assessment Methodology (WI RAM) (Wisconsin Dept. of Natural Resources, 1992). Thiesing (2001) describes several RAPs that are also depicted by Bartoldus (1999) including the Habitat Evaluation Procedure (HEP) (US Fish and Wildlife Service, 1980). These and other RAPs are outlined in the Excel database accompanying this report.

2.4 Wetland assessment based primarily on function

Functional assessments evaluate the functions that wetlands provide such as flood water attenuation, nutrient/pollutant maintenance, etc. Often, RAPs can be considered as functional assessments, but the key difference is the time and cost it takes to assess one wetland (Bartoldus, 1999; Fennessy *et al.*, 2004). Functional assessments are often model-based and allow for a high degree of reproducibility (Thiesing, 2001) and predictable outcomes. The HGM (Hydrogeomorphic) method (Smith *et al.*, 1995) is a primary example of a functional assessment. It was derived from the HGM Classification system (Brinson, 1993; Smith *et al.*, 1995) as described in Section **2.2.1** and designed to provide quantifiable and consistent measurements and data across large regions. HGM-assessed wetlands are compared on a functional basis to one another and to reference standards (Smith *et al.*, 1995). The methods and models applied can be based solely on current/recent field data, on existing archived data, or on a combination of both. Other components which may not necessarily be considered as wetland functions can also be included, but the majority of elements assessed are functional. The general expertise needed to perform these evaluations ranges from trained lay persons to specialists in geology, hydrology and/or ecology (wetland scientists), as well as familiarity with the area of interest (Smith *et al.*, 1995; Bartoldus, 1999). These methods can assess individual wetlands up to wetland-complexes across regions. Some examples of methods in this category are: Maryland Department of the Environment Method (Bartoldus, 1999); New Hampshire Method (Ammann and

Lindley Stone, 1991); Oregon Freshwater Wetland Assessment Methodology (OFWAM) (Roth *et al.*, 1996); the Florida Water Quality Index (WQI) (Lodge *et al.*, 1995), the Wetland Evaluation Technique (WET) (Adamus *et al.*, 1987). These and other primarily functional assessments are outlined in the Excel database accompanying this report.

2.5 Wetland assessment based primarily on biological components

Bio-assessments are based on the premise that the biotic community found in a wetland reflects the overall health or condition of the wetland (Papas and Holmes, 2007). As wetlands are altered, the diversity of the biotic component typically declines and the species composition changes. Often, terms such as "biotic integrity", "ecological integrity", "biological condition" (Adamus, 1995) are associated with bio-assessments. For example, the Index of Biological Integrity (IBI) (Karr and Chu, 1997) assesses wetlands based on metrics (e.g., richness, number of members present, etc.) for specific species of interest that are combined to form an index score. Often the scores developed for these types of indices are related back to reference wetlands in terms of how the test wetland functions in comparison to the reference wetland (e.g. if it is the same or more or less functioning). These types of methods may also contain some evaluated functional variables, but are often most commonly based on metrics that characterize the abundance, diversity and distribution of plants and animals. Bio-assessments can be applied at scales ranging from single wetlands to regional areas and can be based on field data and/or previously derived geographical-data (e.g., habitat area maps, etc.). They generally require specialists in the species of interest (e.g., botanists, ornithologists, etc.) to conduct the inventory, which can require many days in the field along with continued follow-up visits. Examples of assessments in this category include the Avian Richness Evaluation Method (Adamus, 1993a, 1995) and the Index of Marsh Bird Community Integrity (DeLuca *et al.,* 2004). These and others are outlined in the Excel database that accompanies this report.

2.6 Wetland assessment based primarily on existing GIS data

Many of the above-noted methods use GIS layers or thematic maps that were derived from remote sensing products (or from other sources) as input into the models used for wetland evaluation, and most have very significant field components to acquire the necessary data. However, there are several assessment systems that have been developed to use only GIS and remote sensing data without field assessment. To create the databases, GIS expertise is required, but subsequent use by other non-GIS experts is possible. The data commonly used in these methods include: DEMs, streams, water flow path, water quality classifications, watersheds, land use / land cover data derived from computer

classification or visual interpretation of remotely sensed imagery, roads (transportation maps), soils (hydric soil data), endangered species occurrences, wetland boundaries, types primary productivity data, (Kang *et al*., 1994; Sutter *et al.,* 1999; Tiner, 2002; Wockner, 2006; Zampella *et al.*, 2008) among others. Time to conduct such assessments depends on whether the system has been fully developed, on the availability of, and access to the data, and on the ability of the GIS analysts to manipulate the data and create a user-friendly interface with easily interpretable outcomes for managers. These assessment methods use both open source (e.g., GRASS for WIMS) and/or proprietary software (e.g. ESRI GIS products for SWAMP, SCREAM (see Excel database for further details on these methods). The resulting outputs are similar to those for the other assessment methods that require field data acquisition and include overall measures of condition or comparative index values. Many of these methods are transferable to other areas of interest depending upon the expertise of the developers and users. Some methods outlined in this section are tracking systems that provide access to existing wetland evaluations and data. Examples of all of these types of methods are also outlined in the accompanying Excel database.

2.7 Recommendations on the existing evaluation methods

A primary goal of the current OMNR project to re-define and refine its wetland evaluation system is to develop a quantitative and mostly objective means of evaluating wetlands based on a scoring system where scores are generated from existing digital geo-spatial data wherever possible. The desired outcome is to move from a heavily weighted field-based methodology to one that is more computer-based.

There are several systems-based methods that are currently in use and are outlined in the Excel database (Tables 7 and 8). These methods incorporate readily available GIS technology and existing digital data to rank wetlands based upon predominantly functional aspects of wetlands (e.g. hydrology, sediment processes, biogeochemistry, habitat features, etc.). Many of these functions are assessed in the field for the OWES and thus there is already a similarity between these system-based methods and the existing OWES. These GIS-based methods include SWAMP (Sutter, 2002), SCREAM (Stein *et al.*, 2004), methods which use ESRI's GIS products and WIMS (Kang *et al.*, 1994) which uses both GRASS and ESRI's GIS products. W-PAWF (Tiner, 2002) also uses a GIS to derive the functions and functional indices for assessment of wetlands at the watershed scale. WIMS also evaluates two values (aesthetic quality and recreation) that the current Ontario evaluation system also assesses. These system-based methods evaluate wetlands in southern California, South Carolina, Delaware, and Michigan. These look particularly at individual tidal and riverine wetlands (SWAMP), multiple habitats

in a hierarchical structure from stream to watershed (SCREAM); and watershed scale wetlands (W-PAWF). SCREAM is especially intriguing because of the ability to assess wetlands at multiple scales (e.g. stream to watershed). The key to these GIS-based systems is that once they are developed, there isn't the need for GIS expertise to be a user, and much of the subjectivity of the evaluation process is removed. Additionally, possibly the values that are important and currently assessed in the OWES (e.g. species at risk, etc.) could be incorporated if the digital information was available. Modelling a new digital-based OWES on one (or combinations of) these system-based methods may be a good option for this project.

In addition to these system-based methods, many of the methods described in the accompanying Excel spreadsheet are also field-based methods, like the current OWES. These methods are shown to work well for the areas of investigation, and to provide information for the maintenance and modification of wetlands in the given jurisdictions. They all vary from one another in terms of the underlying functions, values and conditions that are assessed. Previous attempts (Stow *et al.*, 2004; Findlay, 2005) have been made to correlate the current field-measured variables in the OWES to GIS derived metrics without good results. It may prove advantageous to also review and select some of these other elemental variables from these other field-based systems and determine if better relationships can be derived or to add to the re-design the evaluation system to include other attributes that are more amenable to geo-spatial data.

Further to developing a GIS-based system for the new OWES, there should be consideration to making available a web-based summary database that allows access across the web to the evaluation information. This would enable access to many stakeholders, possibly within a participatory framework.

3.0 Remote Sensing and GIS Methodologies for Modeling and Mapping Wetland Variables and Functions

This chapter describes current remote sensing and GIS methodologies for modeling and mapping wetland variables and functions.

3.1 Remote sensing

Remote sensing can provide spatial and temporal data at different scales that can be used to analyze wetlands over time. There are many reasons why employing aerial and satellite remote sensing is useful for assessing wetlands (Ozesmi and Bauer, 2002). For satellite imagery, these include the repeatability of coverage, the availability of regional coverage including adjacent upland areas, and the digital nature of satellite remote sensing products (Ozesmi and Bauer, 2002). Aerial photography advantages include the ability to incorporate greater wetland attribute precision (e.g., assess more classes of wetlands) and to capture linear or small wetlands (Ozesmi and Bauer, 2002). Using remote sensing for monitoring of wetlands can be cost effective as current and historical information often exist and wetlands can be assessed at different scales by employing a multitude of sensors (Roller, 1977) or by employing a hierarchical methodology. Limitations of remotely sensed data include the restricted environmental information (Lee and Lunetta, 1995) as images only represent surface reflectance that, depending on the information requirements, may or may not be related to surface land cover types or landscape processes. Additionally, the temporal dynamics of wetlands (both seasonally and annually) make it difficult to represent all possible wetland characteristics with only one date of imagery per year or with individual dates of imagery over several years. The phenology and hydrology varies from year to year due to environmental conditions, therefore even images obtained on anniversary dates can be affected by differences in snowpack and weather occurring before they were acquired. Other issues with using remote sensing include the spatial variation in brightness within images of moderate to large view angles (represented by the bidirectional reflectance distribution function (BDRF)), radiometric effects such as atmospheric characteristics that are often different for each date of image acquisition, sensor calibration, which can require additional processing and may vary over time, and geometric correction and ortho-rectification processing requirements. Many algorithms exist to aid in correction or reduction of each of these effects, some which have more accumulated empirical evidence of working better than others. The degree to which such corrections are needed depends on the application. Coarse level attributes and modelling can be done with imagery that has not been highly processed to reduce these effects; more precise attribute mapping requires more precision in the imagery and greater processing. Essentially, costs increases with increased accuracy and precision requirements.

Overall, it is well accepted that the advantages of using remote sensing for wetland analysis outweigh the limitations (Lee and Lunetta, 1995; Ozesmi and Bauer, 2002; Davidson and Finlayson, 2007). With the diversity of available imagery (satellite and aerial), multi-scale spatial and temporal coverage can be obtained and combined with historical imagery to develop a useful temporal sequence of baseline data. These capabilities allow for ongoing management and conservation of wetlands under the mandates of the various conventions and policies (Davidson and Finlayson, 2007).

Remote sensing for wetland analysis has used many different techniques for a diverse set of applications, and many of these are summarized in general categories in Table 1. Delineation can be manual or automatic, with the former being more common and the latter being not well developed due to the variability of wetland edges in imagery. Classification can be of delineated wetland areas/features, or of pixels first with delineation then occurring after classification, based upon the output class map.

Table 1. Broad categorization of applications of remote sensing for wetland analysis.

General Category	**Sub-category of interest**	**Study**
Delineation	Features in wetlands (e.g. beaver dams)	Hudon *et al.* (2005); Stevens *et al.* (2007)
	Areal extent	Murphy *et al.* (2007)
	Surrounding land cover delineation	O'Hara *et al.* (2003)
Classification	Wetland land cover classification	Berberoglu *et al*. (2004); Li and Chen (2005); Durieux *et al.* (2007); Grenier *et al.*(2007); Wright and Gallant (2007); Laba *et al.* (2008)
	Wetland vegetation classification	Belluco *et al.* (2006); Filippi and Jensen (2006); Dillabaugh and King (2008); Laba *et al.*(2008)
	Surrounding land cover classification	Chiu and Couloigner, 2006; Durieux *et al.,* 2007; Wright and Gallant, 2007
	Transition zone mapping	Chiu and Couloigner (2006)
	Habitat Mapping	Harvey and Hill (2003)
Biophysical modelling	Estimating wetland biomass	Tan *et al.* (2003); Li *et al.* (2007); Dillabaugh and King (2008)
	Assessing spatial statistics to examine condition-landscape pattern relationships	Mita *et al.* (2007)
	Modelling Gross Primary Production (GPP), Gross and Net Ecosystem Exchange (GEE, NEE)	Yan *et al.*(2008)
	Spatial distribution of soil and floc (soil aggregates, e.g. floccules), total phosphorus	Rivero *et al.* (2007)
	Hydrologic assessments	Quinton *et al*. (2003); Pietroniro and

		Leconte (2005); Harris *et al*. (2006); Alsdorf *et al*. (2007); McHugh *et al* (2007); Temini *et al.*(2007); Lang and Kasischke (2008); Pavelsky and Smith (2008); Sass and Creed (2008)
	Estimating carbon emissions	Poulter *et al*. (2007)
Temporal Analysis	Seasonal change	Pope *et al.* (1997); Kent and Nystrom Mast (2005); Alcaraz *et al.* (2006); Beeri and Phillips (2007); Lu and Kwoun (2008)
	Annual change	Munyati (2000); Kent and Nystrom Mast (2005); Alcaraz *et al.* (2006); Melesse *et al.* (2006); Baker *et al.* (2007); Beeri and Phillips (2007); Sass and Creed (2008)

3.2 Sensors used for wetlands analysis

Table 2 (modified after Pietroniro and Leconte, 2000, 2005) summarizes the different satellites/sensors, and potential uses for mapping and analysing the underlying components. It is a synopsis of the sensor types commonly cited in the literature (i.e. not every sensor currently in use is listed) for wetlands analysis and mapping. All of these different sources of data can be assessed in wetland analysis and mapping using a variety of methods. More detail is given in the following paragraphs.

Table 2 – Common sensors used for remote sensing of wetlands and wetland variables (modified from Pietroniro and Leconte, 2000, 2005).

	Satellite / Sensor	**Dates of Service (Temporal Resolution)**	**Spectral Range (µm)**	**Approximate Spatial Resolution (pixel size)**	**Approx. Swath (km)**
Coarse Optical Imaging Sensors	AVHRR	October 1978-present	5 bands (0.58 – 12.50)	1 km	2400
	OrbView-2/SeaWIFS		8 bands (0.40 – 0.88)	1 km, 4.5km	2800, 1500
	Terra/MODIS	December 1999 - present	36 bands (.405 – 14.385)	250m, 500m, 1km	2330
	Envisat / MERIS	June 2002 - present	15 bands (.390 to 1.040)	300 m	1150
	SPOT / VGT 1 VGT 2	1998 – present 2002 - present	4 bands (0.48 – 1.75)	1km	120, 2250
Medium Optical Imaging Sensors	Landsat / TM, ETM+	1972 - present	7 bands (0.45 – 2.35 plus thermal (10.4-12.5)) plus	30m, 80m, 120 m	180

			PAN		
	EO-1/ Hyperion	November 2000 - present	242 bands (0.36 to 2.6)	30 m	7.5
	IRS	1988- present	4 bands (0.52 – 1.70) plus PAN	6 m, 24 m	23, 70
	Terra/ASTER	December 1999 - present	14 bands (0.52 – 2.430 plus thermal (8.125 – 11.65))	15 m, 30 m 90 m	60
	SPOT / HRG	February 1986 - present	4 bands (0.48 – 1.75) plus PAN	2.5m – 20m	60 x 60 60 x 80
Fine Optical Imaging Sensors	IKONOS	Sept 1999 – present	4 bands (0.45 – 0.9) plus PAN	1m (PAN), 4m	11
	GEOEYE -1	Sept 2008 – present	4 bands (0.45 – 0.9) plus PAN	0.5m (PAN), 1.65m	15.2
	EROS-A	May 2000 - present	Panchromatic only	1.9 m	14
	OrbView-3	June 2003 - present	0.45 – 0.9	1m, 4m	8
	Quickbird/ BGIS 2000	October 2001 - present	4 bands (0.45 – 0.9) plus PAN	0.61m, 2.4m	16.5
	Worldview I	Sept 2007 - present	Panchromatic only	0.50 m	17.6
	Worldview II	Launch 2008/2009 (mid)	8 bands (0.45 – 1.04) plus PAN	0.50 m, 1.84m	17.6
	Historical and recent aerial imagery	Early 1900s to present	Panchromatic only, colour and colour IR		
Airborne				Total Field of View	Samples per line
	MIVIS		20 bands (0.43–0.833) 8 bands (1.15–1.6); 64 bands (2.0–2.5); 10 bands(8.2–12.7)	71°	
	CASI 1500		288 bands (0.40 – 1.5)	40.5°	1490
	SASI 600		100 bands (0.95 – 2.45	40.0°	640
	AVIRIS		224 bands (0.4 – 2.5)	34°	677
	HYDICE		210 (0.4-2.5)	9°	320
	ROSIS		115 bands (.42 – .88)	8°	512
RADAR	Envisat/ESA	March 2002 - present	C-band, single, dual polarization	30m – 1 km	58 – 405 depending

					on resolution
	Shuttle Radar Topography Mission (SRTM)	February 2000 (single pass onboard the shuttle)	C-band, X-band	~30 m – 90m	Whole earth coverage
	ERS – 1/SAR	July 1991 – March 2000	C-band, VV polarization	30 m	100
	ERS-2 / SAR	March 2002 - present	C band, VV polarization	30 m	100
	JERS -1 /	February 1992 – October 1998	3 visible and near infrared bands L-band (HH polarization)	18 m x 24m	75
	ALOS/PALSAR	January 2006 - present	L-band, single, dual, or quad polarization;	10m - 100 m	20 – 350
	TerraSAR-X	2007 - present	X-band, dual/ single/quad polarization	1 m – 16 m	10 – 100
	Radarsat 1	November 1995 - present	C-band; HH polarization	8 – 500m	45 – 500 depending on resolution
	Radarsat 2	December 2007 - present	C-band Dual/single/quad polarization,	3-100m	3 – 500 depending on resolution
LIDAR	Airborne Light detection and ranging	1990s to present	Laser wavelengths, usually about 1.0	0.1 – 2m depending on sensor and altitude	1-10

Typically the sensors used for wetland analyses can be categorized by the scale at which imagery is obtained. At very coarse scales, regional optical satellite sensors can map continental areas. The minimum image pixel size at these scales ranges from about 250 m to over a kilometres and swaths can greater than 2000 km. These types of images generally encompass broad ecozones and information or attribute precision obtained is very coarse. Variables that have been modelled indirectly include precipitation, evapotranspiration, water surface fraction (Temini *et al.*, 2007) while broad land cover/land use can be classified directly from the imagery.

At moderate resolutions, minimum pixel sizes are typically in the tens of metres and swaths can cover up to approximately 200 km. These types of images would generally (at the larger end)

encompass whole wetland complexes (landscape level) and could cover regional areas (e.g. eastern or southern Ontario) with several images. Minimum wetland sizes for mapping are greater than 1 ha at these scales. This results in the mapping of wetlands and wetland variables at a landscape scale including those applications noted above for coarser scales and more regional studies (e.g., Prairie Potholes Regions (Mita *et al.,* 2007); estimation of carbon emissions from a peat fire (Poulter *et al*., 2007); and further examples listed in section **3.3** below).

High resolution imagery can be obtained from some satellite sensors and from airborne sensors. Minimum pixel sizes range from a few centimetres to approximately 5 m with swaths covering up to 20 km. These images can cover individual wetlands (e.g. a marsh within a wetland complex) or small wetland complexes, and can provide information about spatial characteristics within wetlands (e.g., classify specific salt-marsh vegetation (Belluco *et al.*, 2006); relate remotely sensed derived metrics to biomass (Dillabaugh and King, 2008); examine the distribution of beaver dams (Stevens *et al.,* 2007); identify dredged spoil disposal sites, and sites colonized by the common reed (Hudon *et al.*, 2005), among others). High resolution aerial imagery (both recent and historical) can be used with manual interpretation methods to accurately delineate wetland cover types (Harvey and Hill, 2001).

In all cases, the spectral bands and the spectral resolution (the bandwidth of each spectral band) are critical determinants of the type and precision/accuracy of information that can be derived for wetlands. Healthy vegetation reflects strongly in the near infrared (NIR, ~ 0.7 to 1.1 μm) portion of the spectrum and differentiations can be made between live plants and dead plants based upon this information (Lyon, 2001). Additionally, distinctions can be made between submerged plants (as water absorbs NIR) in comparison to floating or emergent vegetation. Soil and soil moisture, while displaying reflectance variation in the visible, are better assessed using the mid infrared (MIR, 1.1 to 2.4 μm) portion of the spectrum, which is absorbed strongly by water. This portion of the spectrum has specifically been shown to be useful in identification of hydric soils (Lyon, 2001). The edges of water bodies can be identified well using NIR (e.g., the boundary of water/soil/vegetation) due to the significant contrast between water with almost no NIR reflectance and adjacent land with reflectance of about 30-60% for soil, rock, or vegetation. In the visible portion of the spectrum, sediment loaded water reflects more in the green and red and clear water. Shallow water may also reflect more in the visible than deep water if radiation can penetrate to the bottom of the water body and reflect back to the sensor. Vegetation and water indices (usually some calculation / combination of several of the available spectral bands) can help delineate water and vegetation and model their condition more readily than individual bands alone.

Radar imagery has been shown to be useful for mapping wetlands at landscape to regional scales (Hess *et al.*, 2003; Racine *et al.,* 2005; Durieux *et al.,* 2007; Grenier *et al*., 2007; Henderson and Lewis, 2008). It works well in detecting seasonal changes, including in flooding, in wetlands (Pope *et al.,* 1997; Lu and Kwoun, 2008). Strong positive and linear correlations have been found between radar backscatter and wetland vegetation biomass (Li *et al.*, 2007). Radar imagery has also proven useful for assessing wetland classes and specific wetland vegetation, including invasive species (Li and Chen, 2005; Racine *et al.*, 2005; Grenier *et al.,* 2007). Wavelengths that work well for the detection of wetlands include both L-band (about 20cm wavelength) and C-band (about 5.5 cm wavelength) at landscape to regional scales. One X-band satellite system (shorter wavelength than C-band) and other X-band airborne systems exist, while P-band (longer wavelength than L-band) is very restricted in use. Longer wavelengths penetrate deeper into vegetation canopies than shorter wavelengths and are better suited to modelling and mapping of forested wetlands and swamps with standing dead trees. C-band has been to shown to detect herbaceous wetlands well (Henderson and Lewis, 2008). Both bands (C and L) detect open water well due to specular reflectance of its smooth surface creating a black object in the imagery. Depending on the spatial resolution, incidence angle and canopy openness, radar signals in either L or C-band may 'double bounce' or corner reflect off trunks, particularly standing snags in open swamps, producing bright point signals. Use of more than one wavelength generally improves mapping accuracy. Radar can also be polarized in both the emitted and received signals. Henderson and Lewis (2008) found that HH polarization was generally used more than VV but cross-polarization (HV or VH) also proved to be useful. The swath of satellite-based radar images can range from 20 km to 500 km and can cover similar areas as high to moderate resolution optical imagery. Radarsat II is a C-band sensor with advanced polarimetric capabilities and multiple possible resolutions and image swaths that should prove advantageous in wetland mapping. ALOS/PALSAR is a recently launched L-band sensor that also should be useful for wetland mapping and analysis. TerraSAR-X is an X-band sensor launched in 2007, which may also prove to be useful for wetland analysis. Additional information on radar methods and applications is given in where appropriate in sections 3.3.1 – 3.3.3, which summarize the general types of methods used in remote sensing of wetlands.

A final senor type is LIDAR (light detection and ranging) which scans beneath an aircraft with pulses of laser light and produces an elevation/terrain model and a return intensity image (Lillesand *et al.*, 2008; Poulter *et al.*, 2007). It can be used to create stream cross sections, overland flow paths for wetland hydrologic modelling and map vegetation canopy height or vertical structure if canopy penetration is significant and multiple returns can be processed, canopy, (LIDAR, 2008).

3.3 Remote sensing methods for wetlands analysis

Analyses performed with remotely sensed imagery can be broken down into three broad categories. These types of analyses are derived from the sources described above and include: mapping, biophysical modeling and temporal analysis. Table 3 provides a synopsis of the types of studies that have been completed for each of the categories including the scale of the study, the method used, and the applicability to the area of interest. There is some overlap between categories as certain types of classifiers or analysis techniques can be applied in more than one category (1st column of Table 3). Following the table are detailed descriptions of these different methods and the representative studies provided. Additionally, Table 3 provides a synopsis of the types of GIS analyses of wetlands that are outlined in detail in section 3.4. The accuracies of the varying classifications range from low (e.g. near 30%) to very high (e.g. near 100%); for relations, R^2 values were moderate (0.5-0.7) to high (near 0.9) depending on the sensor, resolution, attribute precision, environmental conditions, etc.

Table 3. A synopsis of the types of Remote Sensing and GIS analyses of wetlands.

Overall Category	Type of Technique	Scale	Example Applications and Potential Contributions	Representative Studies
Mapping	Classification – Parametric techniques (supervised and unsupervised)	Local (e.g. by plant species) to regional (e.g. wetland class, wetland complexes, etc.)	Not necessarily applicable to (or needed for) the current OMNR project to refine the OWES as several classifications have already been undertaken for Ontario area that could be used. These have fairly broad classes (e.g. SOLRIS; fen, bog, swamp, open marsh,); if there was an interest in mapping more locally (e.g. plant species, especially for determination if some rare species are present) some of the reviewed methodologies may prove to be useful.	Harvey and Hill (2003); O'hara *et al*. (2003); Belluco *et al.* (2006); Laba *et al*. (2008)
	Classification – Non-parametric techniques (fuzzy classification, subpixel unmixing classification, Artificial Neural Networks (ANN), object-based segmentation and classification)	Local (e.g. by plant species) to regional (e.g. wetland class, wetland complexes, etc.)	As above, and for some classifiers such as neural networks, multiple sources of data can be used; (e.g. DEMs, multi-sources of imagery; other data (e.g. quaternary geological layers). Most of these methods are proving to be more accurate than traditional (e.g. Maximum Likelihood) methods.	Berberoglu *et al*. (2004); Rogers and Kearney (2004); Schmid *et al.* (2005); Chiu and Couloigner (2006); Filippi and Jensen (2006); Durieux *et al*. (2007); Grenier *et al*. (2007)
	Classification – Nonmetric (decision/classification trees)	Landscape to regional (although theoretically should be able to classify at the local level)	As above. Most studies show accuracy improvements with the addition of ancillary data.	Li and Chen (2005); Wright and Gallant (2007)
Biophysical Modelling	Hydrologic	Local to landscape to regional	Relations between runoff and percent cover or runoff and cover type; changes assessed in surface/near surface soil; image-based indices as indicators of soil moisture conditions and vegetation stress; radar backscatter and flood mapping; water surface elevation correlated with inundated area (generated from NIR band). These studies clearly show the value of vegetation and moisture indices and the ability to assess hydrologic features/functions (e.g. surface water, flooding	Quinton *et al.* (2003); Harris *et al*. (2005); Lang and Kasischke (2008)

			inundation, etc.) that are key in many existing evaluation systems.	
	Biogeochemical	Local to landscape	High potential to assess soil properties that may be useful in predicting some wetland functions (e.g. substrate/soil composition; organic material composition, ecological integrity of the wetland, etc). E.g., one study showed strong relationships between indices derived from imagery, distance measures and total soil phosphorus.	Rivero *et al.*(2007)
	Biological	Local to landscape	Predictions of above-ground biomass and net aerial primary productivity are possible using image-based indices; relationships between tide height and vegetation indices (negative correlations). Studies have shown the ability to produce other spatial distribution maps that may be used to aid in the assessment of wetlands (e.g. functions such as ecological integrity; dominant land use; amount of impervious surface; overall wetland condition; overall biological condition, etc.).	Hardisky *et al.* (1984) Tan *et al.* (2003); Li *et al*. (2007); Dillabaugh and King (2008); Yan *et al*. (2008)
Change detection of wetlands	Seasonal change	Landscape	Assess flooding extent and water level changes within a season and link to key hydrologic functions.	Pope *et al.* (1997); Lu and Kwoun (2008)
	Annual change	Local, landscape and regional	Presence/absence of vegetation or changes in percent cover; annual changes in evapotranspiration (ET) and spatial distribution of ET; soil moisture related to percent cover (e.g. unsaturated, saturated, inundated); hydrologic dynamics of wetlands. These studies aid assessment of the overall "health" of wetlands and trends in wetland dynamics.	Munyati (2000); Melesse *et al*. (2006); Baker *et al.* (2007); Sass and Creed (2008)
	Combined seasonal and annual change	Local, landscape and regional	Change in total wetland area and rates of wetland loss; correlations between functional traits and principal components of image data; defined ecosystem functioning types; annual and seasonal NDVI trends; mapping recharge and discharge per season and determine surface water trends over multiple years; These types of methods can provide important seasonal hydrologic information that may be missing from many evaluation systems because of singular field site visits.	Kent and Nystrom Mast (2005); Alcaraz *et al*. (2006); Beeri and Phillips (2007)

			They provide additional information on functions (e.g. rates of change, trends, etc.).	
GIS analyses of wetlands	Mapping	Local, landscape, regional	Interpolation of soil pH distribution in combination with thematic maps to assess species distribution of mangroves; using GIS and a combination of data, beaver pond occurrence and their correlation with stream order, elevation, deciduous cover and amphibians can be statistically assessed; mapping wetland area using a Bayesian probability model as a post-classifier to improve the quality of a thematic map; Strong potential for use of multiple data sources including non-remotely sensed data (e.g. soil data) to map wetland characteristics. Also the ability to improve upon products derived from remotely sensed data.	Vaiphasa *et al*. (2006); Hogg and Todd (2007); Murphy *et al.*(2007); Stevens *et al*. (2007)
	Change analyses	Local, landscape, regional	Decadal change in total soil phosphorous (P); extent of increase in total soil P; change in land cover types in wetlands; changes in wetland plant communities; changes in water levels; These studies have shown that hydrologic dynamics of wetlands and soil properties can be monitored effectively using GIS.	DeBusk *et al*. (2001); Papastergiadou *et al*. (2008); Wilcox *et al*. (2008)
	Biophysical modeling	Local, landscape and regional	Predicting patterns of plant species; assessing habitat quality and diversity; impacts of human activity by characterization of activities and water chemistry. These studies have shown to accurately assess biophysical properties of wetlands.	Van horssen *et al.* (1999); Berberoglu *et al*. (2004); Morrice *et al*. (2008)
	Population analyses and habitat conservation	Local, and landscape	Calculation of population and habitat requirement statistics; habitat suitability assessment; connectivity of core areas assessment; assessment of breeding bird wetland habitat. These studies have shown to be able to assess fauna population statistics and information for which remote sensing is not readily or directly able in most cases.	Beazley *et al.* (2005); Connor and Gabor (2006)

3.3.1 Mapping

Processing of imagery into land cover categories for thematic mapping generally requires the evaluation of the reflectance or brightness of pixels or objects (Lee and Lunetta, 1995). There are several key land cover classification techniques that can be employed including algorithms that are based on parametric, non-parametric and/or non-metric statistics (Jensen, 2005); which comprise most existing classification algorithms (Ozesmi and Bauer, 2002). Parametric classifiers assume the underlying remote sensing data are normally distributed (particularly the data for each land cover class to be mapped). Common algorithms include the maximum likelihood classifier, usually used in conjunction with training data in supervised classification, and the Iterative Self-Organizing Data Analysis Technique (ISODATA) clustering technique, used in unsupervised classification where no input sample data for given land cover types or features is used. Non-parametric techniques can be used if the underlying remote sensing data are not normally distributed, if the data are non-ratio (e.g., categorical attribute data), or if the composition and form of the wetland is unknown (Jensen, 2005). These techniques include nearest-neighbour, fuzzy, neural network, and object-based classifications. The non-metric techniques include rule-based decision trees that use real data (e.g. spectral reflectance values) and/or categorical attributes (e.g. set classes like forest, agriculture, etc.). In addition to these technology-dependent methods, manual interpretation of imagery has also been used to delineate wetlands, and wetland cover types (Harvey and Hill, 2001). The main interpretation cues used to manually digitise classes include tone and texture. Interpretation is highly dependent upon the skill of the remote sensing interpreter, and their expertise in wetlands on the whole (Harvey and Hill, 2001). There have been many attempts to automatically map wetland classes or delineate wetland boundaries using remotely sensed imagery and technology-based methodologies.

3.3.1.1 Parametric methods: supervised classification

In supervised classification, for selected classes such as bog, fen, swamp, marsh, etc., training pixels known to be representative of the spectral and/or spatial characteristics of a given class are delineated in the image. The separability of the training data in the feature space (the input variables such as spectral bands) can be analyzed using multivariate variance-weighted measures of distance between class means, such as the Bhattacharyya Distance, Transformed

Divergence or Jeffries-Matsusita (JM) distance (Jensen, 2005). Such analyses are used to provide an indication of which thematic classes have potential to be accurately classified and which pairs of classes may be confused with each in the classification. An additional use is in testing of which input variables (spectral bands, texture measures, etc.) provide the greatest potential for accurate classification or discrimination of selected classes. Most separability algorithms scale the resulting distance measure into a small range that is easier to analyze. For example, in some cases, the algorithm can scale the resultant distance into a range between 0 and 2, where `0' indicates complete overlap of two classes and `2' indicates a complete separation between the two classes. If there are classes that are overlapping and the separability is inadequate (e.g. less than 1.7), a decision concerning re-training or merging of classes should be made. Following training, in the classification stage, each image pixel is assigned to the class it most resembles based on a given rule(s) applied to the training data probability distribution functions. The maximum likelihood classifier (MLC) is the most widely used algorithm for supervised classification. From the training data distributions, the statistical probability (the Bayesian likelihood) can be calculated that an unknown pixel belongs to each land cover type; the pixel is then assigned to the class in which it has the greatest likelihood of belonging. The MLC technique is often used in comparative studies as a reference against which other classification techniques are evaluated (Jensen, 2005; Lillesand *et al.*, 2008).

As an example, Laba *et al*. (2008) used four 2004 Quickbird images to create thematic maps of four marshes along the Hudson River in New York State. They used training data interpreted from 2002 aerial photos and assessed in the field followed by MLC to created 20-class maps of these four marshes. The twenty classes included: railroad causeway, open water/tidal channel, unvegetated mud/sand flat, vegetated lower intertidal, salt panne, *Typha angustifolia*, *Scripus* sp., *Lythrum salicaria*, *Scirpus pungens*, *P. australis*, salt meadow, wooded swamp, scrub/shrub, *Trapa natans*, submerged aquatic vegetation, *Acorus calamus*, *Polygonum* sp., *Spartina alternifolia*, wrack line and upland (non-tidal). Two methods were used to assess the classification accuracy. The first was a conventional error matrix including user's and producer's accuracies for each class, (UA and PA, respectively; PA = 100% - % errors of omission; UA = 100% - % errors of commission (Lillesand *et al*., 2008), overall accuracy and the kappa metric (accuracy – random class assignment accuracy) (Jensen, 2005)). Individual classes had PA and UA values ranging from 33 to 100%. Overall accuracies for the four

marshes were 64.9%, 67.5%, 68.4% and 73.6%. The second method was fuzzy accuracy assessment, which allows class mixes in each pixel and degrees of acceptable mis-classification. Fuzzy assessment sets were obtained in the field to fully understand the composition, frequency, magnitude and source of errors in the maps. Overall class accuracies using the fuzzy method ranged from 75 to 83%.

3.3.1.2 Parametric methods: unsupervised classification

Unsupervised classification is used when there is no prior knowledge of land cover, or for data flow automation, or to aid analysis of inherent spectral class discrimination in an image. An algorithm, such as the Iterative Self-Organizing Data Analysis Technique (ISODATA) clusters pixels into natural groupings based upon their spectral properties. After these clusters are developed, the groups are then assigned to specific classes either through ground based investigation or examination of the clusters' spectral properties (Jensen, 2005).

The ISODATA technique is a developed set of rules that is based upon a *K*-means clustering algorithm (Jensen, 2005). The user assigns several values to parameters such as maximum number of clusters, maximum number of iterations and maximum percentage of pixels allowed to remain unchanged between iterations (Jensen, 2005). In the first iteration, arbitrary cluster means are determined and each pixel is assigned to the closest cluster based on its Euclidean distance to all cluster means. The cluster means are then re-calculated and pixels are re-assigned to the closest cluster in subsequent iterations. Within the iterative process, clusters may be merged, split or eliminated based on certain inputs regarding the minimum allowable size of clusters and the minimum allowable distance between any two cluster means (Lira *et al*., 1999). The process stops when the cluster means do not change more than a specified threshold or after the specified number of iterations has been reached.

O'hara *et al*. (2003) assessed land use/land cover change of the Mississippi Gulf Coast area over the period of 1991 to 2000 using Landsat images. They assessed the spatial characteristics/spectral profiles of desired classes (including: water, wetland, urban/built-up, forested vegetation, non-forested vegetation, and barren). Using the ISODATA technique they generated 30 clusters per test area, and manually merged these to the six desired classes of interest. From this, class signatures (training data) were developed and used to classify the remaining parts of the imagery using a MLC. This was completed for both leaf-on and leaf-off imagery, and seasonal change detection was performed between these image dates as well as

over the entire nine year period. Accuracy was assessed using a random set of 81 field-visited sites. Overall accuracy for the six classes was 90%. The most significant class confusion was during dry years when grasslands and pastures were classified as barren lands. Over the nine years they found an increase of more than 36% in urban built up land corresponding to 26,000 acres.

Harvey and Hill (2003) used ISODATA clustering to assess 1999 Landsat TM and SPOT XS/PAN data for mapping cover types suitable for saltwater crocodile nesting habitat, and mapping saltwater crocodiles nesting areas that were within a suitable distance to water in the Melacca Swamp near Darwin, Australia. For the mapping of cover types, ISODATA clusters were produced and assigned to the classes: open water, mangrove forest, open swamp, swamp with tree canopy, exposed shore and open sedge/grassland. These were subsequently re-classified to two classes of suitable and unsuitable cover. Cover type mapping was assessed by comparing the ISODATA classification of Landsat TM data with a similar classification of SPOT XS, SPOT PAN data, and with manual interpretation of true colour aerial imagery. From the air photos, 14 detailed species level classes were mapped (e.g. trees: *Melaleuca, Acacia, Eucalyptus*, and sedges: *Typha*, *P. karka*, etc.); and suitable/unsuitable cover was assessed from that. For mapping nesting areas that were within a suitable distance to water a water delineation index (MIR/Green * 100) was used with the Landsat TM imagery to delineate permanent water bodies from non-water areas. As the crocodiles nested within 100 m of permanent water bodies, 200 m buffers were created around the permanent water bodies to include all potential habitats and then the buffered water bodies were overlaid with the cover type map. Best or most suitable habitat was assessed when grid cells including both suitable cover and distance to water bodies were present. Helicopter-sampling collected validation data used to assess the developed habitat maps. Overall accuracy for the detailed air photo interpreted land cover classes was 89% with individual accuracies for classes representing crocodile habitats ranging from 93% to 100%. For the lower detailed classes from the satellite imagery, the Landsat TM derived maps were the most accurate at 86%, followed by SPOT XS (82%) and SPOT PAN (71%). Overall they found that mapping of suitable habitat with satellite imagery was not appropriate for crocodile nesting habitat, but that the satellite imagery could assess general land-cover classes adequately.

As was seen with the O'hara *et al.* (2003) study, often methods are used together to produce the best possible thematic map, or delineated entity. Belluco *et al.* (2006) used multiple

aerial image types (1m pixels), including the hyperspectral sensors (CASI, MIVIS, and ROSIS (see Table 2) and high resolution satellite images (IKONOS, Quickbird) to assess how well three different parametric methods classified the Lagoon of Venice in Italy (in particular the San Felice salt marsh), containing four key halophytic species *Spartina maritima, Limonium narbonense, Scarcocornia fruticosa,* and *Juncus* spp. They compared three classifiers: unsupervised *K*-means, supervised Spectral Angle Mapper (SAM), another non-parametric classifier (Lillesand *et al.*, 2008), and MLC. Analyses of combinations of the spectral bands included: all original bands; reduced number of bands using feature selection based on Bhattacharrya distance and Maximum Noise Fraction (MNF) transform; and spectral averaging using a reduced number of broad bands. Ground data were obtained at the same time as the aerial missions and included assessments of cover. The best results the four species of interest plus soil and water were obtained using the MLC method and were ranked by sensor as follows: 99.2% (ROSIS), 97.2% (IKONOS), 96.6% (Quickbird), 92.6% (CASI), and 88.3% (MIVIS). The best MLC accuracies were obtained by reducing the number of bands using the MNF transform (MLC is known to decline in performance when more than about six input bands are used (Swain and Davis, 1978)). This was not necessary for the SAM method which had the second highest overall accuracies, and the SAM classification performance was assessed as declining when such reductions were applied. The lowest accuracies in all tests were for *K*-means clustering, which, as the basis for the ISODATA algorithm described above, simply uses the distance between an unknown pixel and cluster means with no accounting for cluster variance as in MLC. The overall results were that salt-water tidal marshes species specific vegetation maps could be obtained using 1 m pixel imagery and the methods described.

3.3.1.3 Non-parametric methods: fuzzy classification

Classifications can be hard or soft. Hard classification assigns a pixel or defined object specifically to one class of *n*-available classes. Soft (e.g., fuzzy) classification assigns a membership value that represents the degree of similarity of the unknown pixel to the training data representing each class. Membership can be assigned based upon a variety of distance relations (e.g., nearest neighbour) or using a membership function (linear or non-linear) that describes the transition in the data values from one class to another. The membership values can be ranked between zero, representing a complete uncertainty of membership and one representing complete certainty of membership for each class (Flanders *et al.*, 2003). Fuzzy

classifications can be converted to hard classifications, usually by simply mapping the class with the highest membership and leaving the remaining membership values for review.

Chiu and Couloigner (2006) used a Fuzzy C-Means (FCM) algorithm to extract potential wetlands from Landsat ETM+ imagery over Prince Albert National Park, Saskatchewan. The FCM algorithm was modified by adding spatial information (e.g., consideration of eight neighbouring pixels) along with the spectral information. The purpose was to obtain the degree of class mixing in transition zones based upon the membership values. The Landsat image was first decomposed using a Tasseled Cap transformation, which translates data into components such as brightness, greenness and wetness (Lillesand *et al.,* 2008) in an analogous manner to principal components analysis. Additionally, pure water bodies were masked out using a normalized differenced water index (NDWI) (Rogers and Kearney, 2004). Seven classes were mapped, including: water body, deciduous forest, wetland, transitions of deciduous forest-wetland, mixed stand, transitions of deciduous forest-mixed stand, transitions of wetland-mixed stand and transitions of deciduous forest-wetland-mixed stand. Overall accuracy of the standard FCM classification was 71.3%, and the overall accuracy of the modified FCM classification was 85.8%.

3.3.1.4 Non-parametric methods: subpixel classifications

Individual pixels are often comprised of more than one class type (e.g., 25% water, 30% soil, 45% vegetation) and it is useful to be able to determine the proportion of the classes that are within individual pixels. While fuzzy membership scores may indicate the proportion of each land cover type in each pixel, linear spectral unmixing or spectral mixture analysis is a process directly linked to reflectance theory based on linear mixing of radiance from multiple classes within a pixel area (Jensen, 2005). From the location of endmembers (pixels of one class only – i.e., pure samples of each class) within an n-dimensional space (where the number of endmembers does not exceed the number of spectral bands used in the linear mixing model), a linear mixing model (Rogers and Kearney, 2004; Jensen, 2005) is used to determine the proportion of each end member in each pixel.

Schmid *et al.* (2005) used spectral unmixing of hyperspectral aerial imagery, Landsat data and ASTER data to detect changes in wetlands in the wetland area of La Mancha Alta in central Spain. Five endmembers were derived from the higher resolution hyperspectral imagery including: hygrophytic vegetation, wetland soils A (dried, exposed soil surface with seasonal

flooding) and B (cultivation practices bare soil: fallow or sowed with crops), wet salt crust and upland soil. The endmembers were transferred to the coarser multispectral satellite data (Landsat and ASTER) which showed that the spectral characteristics of the endmembers remained relatively stable from hyperspectral to multispectral data. This subsequently allowed for the temporal comparison and assessment of change using the multi-date medium resolution multispectral imagery.

3.3.1.5 Non-parametric methods: Artificial Neural Network (ANN) classification

An artificial neural network (ANN) mimics the human brain, although in a very limited capacity, acting as a system of neurons working in conjunction to learn the structure of the data in question (Jensen, 2005). Unlike a logic program or simple algorithm, a neural network does not reach the conclusions following step-by-step methods, but follows a non-linear, non-structured pattern depending on how connections or paths of the neurons in the network are adjusted and weighted (Jensen, 2005). The most common neural network is the backpropagation ANN (Kavzoglu and Mather, 2003; Jensen, 2005). A generalized delta net program code creates an overall structure for the neural network including an input layer, hidden layers with underlying nodes and paths, and an output layer. The network then learns the underlying image data structure based upon the data in the input layer neurons or nodes (spectral bands or other geo-spatial variables). The data are passed through a given set of nodes in the interior (hidden) layers) and modified by a set of weights before being passed on to the next layer (another hidden layer or the output layer, depending on the network structure). The difference between the network generated output and the actual output (the class label numbers) defines the error, which is propagated back through the network to adjust the weights at each node. Then the data are passed through the network again and this error adjustment procedure is repeated for many (often up to 100,000) iterations, each time reducing the error between the network output classes and actual classes. Once the error is minimized below a user defined threshold, the network training is complete and it can be used to classify any unknown pixel (Pao, 1989). Figure 1 provides a simple diagram of the components of a backpropagating ANN in feed-forward mode: the input layer, hidden layers and output layer (Kavzoglu and

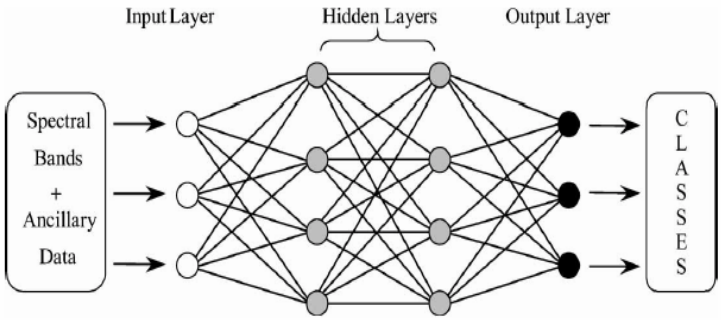

Figure 1 - Four-layer forward pass neural network.
(Kavzoglu and Mather, 2003, Figure 1)

Mather, 2003, Figure 1). Neural networks are often considered to be "black-boxes" where, although the input parameters and data are known, what actually goes on inside is not definitively known. Much user testing of network structure, input learning rates, number of iterations, etc. is often required, and the training process can be very slow for datasets the size of a Landsat scene. ANNs can be trained well to classify the data in the region close to the training sites, but it is often difficult to extend the trained network to pixels further away from training sites.

Berberoglu *et al*. (2004) used Landsat TM data to classify coastal wetland habitat along the eastern Mediterranean coast of Turkey using MLC and a back-propagating ANN. The ANN included six input layers (the six non-thermal Landsat TM bands), 24 hidden layers and 14 output layers (subsequently amalgamated to 8). The 8 classes of interest were beach, fore-dune, dune slack, dune scrub, agriculture, temp water, salt marsh, lagoon and bulrush (sic). The overall accuracy obtained for the ANN was 90.2% and 76.0% for the MLC. UAs and PAs ranged from 64% to 100.0% for the ANN and 48% to 99% for the MLC. These outputs were subsequently used with field-based vegetation analysis and bird survey information in a GIS to assess the quality of habitats (see 3.4 below).

Filippi and Jensen (2006) compared a fuzzy learning vector quantization (FLVQ) ANN to traditional multi-layer perceptron (trained with back-propagation) ANN for classifying coastal vegetation habitat at the JFK Space Centre in Florida, USA. FLVQ ANNs incorporate both the benefits of ANNs and fuzzy logic, complementing each other as ANNs focus on learning while fuzzy logic focuses on approximate reasoning and imprecision. The 12 classes of interest were sand cordgrass, slash pine, live oak hammock, grape vine, unid shrub, willow community, mixed graminoid marsh, cabbage palm hammock, oak/saw palmetto scrub, citrus grove 1 and 2, and dry/burned vegetation. Airborne hyperspectral AVIRIS data (20m pixels; 224 spectral bands in the 0.38 – 2.50 μm spectral range) were classified with an overall accuracy of 82.82% (FLVQ ANN) and 84.66% (traditional ANN), this difference being non-significant. However, the FLVQ network only required 3.6% of the computational time required by the traditional ANN.

3.3.1.6 Non-parametric methods: Object-based segmentation and classification

The various methods described above can classify both pixels and/or objects. The main intent behind object-based classification is to create (segment) and classify objects that represent

real world land cover entities (e.g. bogs, upland forest, streams) that are relevant to ecological analysis and land management.

Image segmentation

The technical objective in segmentation is to define objects that have minimized within-object variability, and maximized between-object variability. The creation of objects from individual pixels is based upon the spectral and spatial properties of neighbouring pixels and subsequently created objects (Burnett and Blaschke, 2003). Segmentation algorithms fall into two main categories: edge-based and area-based (Jensen, 2005). Edges occur where there are sharp changes in brightness values. In edge-based segmentation, the growth of objects is based upon these edges and subsequent linked edges that may signify borders between objects. Problems can occur if edges are not present where a real border exists, or if edges are present where no real border exists. Area-based (also known as region-based or region growing) segmentation compares pixels or groups of pixels (the 'seed') and merges comparable areas as long as they are homogenous within a defined tolerance. Large heterogeneous areas can also be split into smaller homogenous units. Some segmentation algorithms use a combination of splitting and merging.

The following discussion focuses on aspects of Definiens Developer 7 EII Earth which is the most widely available and commonly used object-based software available worldwide. Two common algorithms for object segmentation are multi-resolution and spectral difference segmentation. The key parameter in multi-resolution segmentation is a unitless variable of scale that is correlated to the image's pixel size and is related to the parameters of colour and shape (Laliberte *et al*., 2004). Objects are defined and delineated based upon spectral similarity of pixels, contrast of an object with neighbouring objects and object shape characteristics. The larger the value of the scale parameter the larger the image objects will be (Benz *et al*., 2004). As the segmentation proceeds, the pixels are first grouped to minimize within-object heterogeneity. Objects are subsequently grouped based upon spectral similarity, contrast with

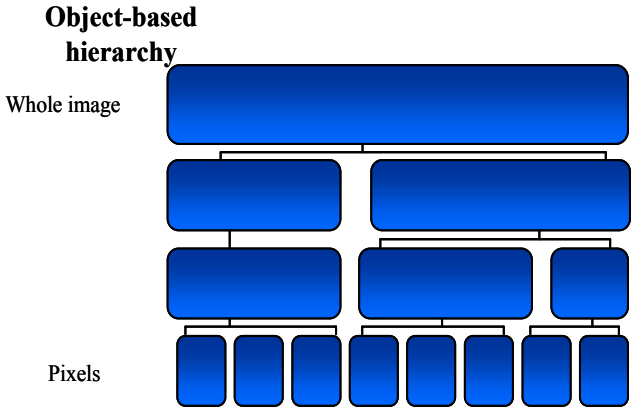

Figure 2: Object-based hierarchy with the lowest level representing pixels and the top level representing the whole scene. Mid-levels represent segmented object levels.

neighbouring objects and shape characteristics (Yan *et al.*, 2006). Objects are grown evenly and simultaneously across the entire scene. Colour (spectral information) and shape (smoothness and compactness) can be weighted by the user (Laliberte *et al*., 2004). As objects are created they are merged together following the scale, shape, colour, smoothness and compactness parameters. The process ends once the growth surpasses the values defined (Laliberte *et al*., 2004). This creates one object level in a hierarchy (Figure 2). The multi-resolution segmentation process can be applied again with a different scale parameter to the first object level to obtain a second level of objects at a higher or lower level in the hierarchy.

For the spectral difference segmentation, there must be a level of objects previously segmented (i.e., cannot use the spectral difference segmentation on pixels directly) which are then grown into larger objects. This algorithm merges neighbouring objects based upon a mean layer brightness value. The objects are merged if the difference in this value is below a specified maximum. This method can be useful in distinguishing classes of interest if a distinct difference is noted in one particular band between classes of interest. This algorithm can be weighted to only consider the difference(s) for that particular band.

Object-based decision classification

Objects can be classified at any level within the developed hierarchy. A set of decision rules is developed for each class that are applied to each object to assign it a membership value(s) to particular classes. Possible classification rules can relate to the object's features including shape and texture. The position of an object in the segmentation hierarchy and its relationships to other classes in its level, within the hierarchy, and to the overall scene, can also be used as classification rules. Additionally, all of the rules can be applied to all classes or to individual classes. At the individual level, classification features can be set with ranges of outcomes (e.g., all rectangular fit values between 0.75 and 0.85 classified as one class), with one set value, or with a specified minimum and maximum.

Grenier *et al*. (2007) used Landsat ETM+ and Radarsat-1 imagery to map wetlands in two sites for the Canadian Wildlife Service Canadian Wetland Inventory (CWI) with the five classes of bog, fen, marsh, swamp and shallow water. Objects were found at each of three segmentation levels and were subsequently merged back into the five classes of interest. Accuracy was assessed both thematically and spatially based on interpretation of Landsat colour composites and use of photos taken from a helicopter. For thematic accuracy, all wetlands were

combined into one wetlands class versus 'other' (open water was not validated as confusion was thought to be very low), resulting in 82% and 90% accuracy for the two study sites. In addition, accuracy was assessed between the five wetland classes, resulting in 76% and 68%, respectively. Significant confusion between most of the classes reduced the utility of these thematic maps. For the spatial accuracy assessment, an expert rated each wetland object on a scale of 1 to 5 where 5 meant more than 85% of the wetland was included in the object, 1 meant 40% or less of the object was wetland and 2 through 4 fell in between these two bounds. A score of 0 was given for completely wrong object classifications. At one site, more than 50% of the wetlands were well delineated while at the other site 50% (fen) to 84% (shallow water) of the known wetlands were over 85% within the given segmented object.

Durieux *et al*. (2007) used 300 m Medium Resolution Imaging Spectrometer Instrument (MERIS) data, 100 m JERS-1 radar data, and SRTM (Shuttle Radar Topography Mission) to classify wetland complexes in western Siberia. They were interested in seven classes including river, riparian vegetation, lichen and mosses, lakes, dark taiga, broadleaf forest, bogs and anthropic area/bare soil. A Landsat TM derived pixel-based thematic map with an accuracy of 89% was used for validation. The object-based technique used was the fractal net evolution approach (FNEA) which segments images simultaneously at two levels and then subsequently builds semantics between the levels and the corresponding level units (patches). The first object level was created using multi-resolution segmentation solely based upon the radar backscatter and the second object level was created using the spectral difference algorithm for three MERIS bands (555-565 nm, green; 677.5-685nm, red; and 855-875nm, NIR). A classification rule set was defined using the three levels of segmentation (e.g. objects that overlapped SRTM water bodies and areas with low backscatter on the radar image were considered lakes). The overall accuracy for this classification was 72.5%.

3.3.1.7 Nonmetric methods: Decision/classification trees

Classification trees can be used with remotely sensed data and ancillary data to develop land cover maps. A classification tree generally leads to categorical decisions about the pixel and/or object of interest. Decision trees are composed of branches that represent the attributes whereas the leaves are the decisions (Figure 3). Classification trees are thought to be more 'transparent' than artificial neural networks as all decisions are readily apparent in the resulting tree. Classification trees also easily incorporate data from multiple measurement scales (e.g. nominal, ordinal, interval and ratio) (Wright and Gallant, 2007).

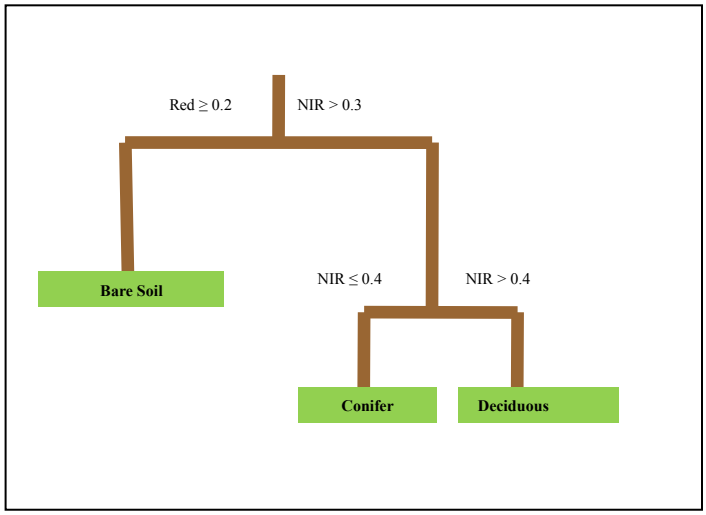

Figure 3. A simple classification tree.

Li and Chen (2005) used a rule-based classification, a decision tree classifier and combined analyses with Radarsat-1 data, Landsat ETM+ data and a DEM to classify three wetlands in eastern Canada (Mer Bleue Bog, Ontario, Lac St. Pierre, Quebec and Goose Bay/Happy Valley, NFLD and Labrador). For the decision tree classifier, the expert decision rules repeatedly divided the data into same-natured sites. The decision-tree classification was applied to the Landsat ETM+ data alone, and to the ETM+ and SAR data combined. For the rule-based classification four keys steps were followed. A slope gradient (percentage) image was derived from the DEM. The Landsat ETM+ was supplemented with different vegetation and water indices (NDVI and NDWI), principal components and band ratios, which were used as input into a general supervised classification with land cover classes of water, marsh, open fen, treed fen, open bog, treed bog, forest, grass/shrub and other. Thirdly, the SAR image speckle was reduced using a Lee filter and then segmented into objects which were classified into four classes designated as lowest, low, medium and high backscatter. Finally, a wetland map was derived using knowledge-based decision rules within a GIS framework. In the Mer Bleue Bog, the general land cover distribution was open bog, treed bog and marsh; for Lac St. Pierre, the general distribution was marsh and swamp; and for Goose Bay/Happy Valley, the general

distribution was open bog, treed bog and open fen. Overall, Li and Chen (2005) found that higher accuracies were obtained using the rule-based classification at each site.

Wright and Gallant (2007) assessed palustrine wetlands in Yellowstone National Park. The classes of interest included two levels, one between palustrine wetlands and non-wetlands (uplands) and one between five classes of palustrine wetlands including: aquatic bed, emergent, forested, scrub/shrub and unconsolidated shore. The data were Landsat 5 TM from 1988, 1997 and 2003 and Landsat 7 ETM+ from two dates per year for 1999 to 2002. All Landsat data were converted using the Tasseled Cap transformation to brightness, greenness and wetness. For the Landsat ETM+ 7 data where two dates per year were available, per pixel differences were assessed for the 6 bands and the 3 Tasseled Cap indices to capture any phenological differences between uplands and wetlands, and between the different wetland types. Canonical discriminant analysis was used to reduce redundancy by minimizing the dimensionality of the original data. Image textures were also assessed and a 5x5 window was found to be optimal for distinguishing between wetlands and non-wetlands while a 3x3 window best discriminated amongst the palustrine wetlands. A 30-m DEM was used to derive the hydrologic variables slope and wetness index {log (upstream contributing area/tan slope)}. Additional data included vegetation layers (habitat and cover type) and landforms (based on type/degree of stream drainage, type of surficial materials, slope gradient distribution, slope curvature, relief and shape of bedrock exposure at a scale of 1 – 100 ha). A bedrock geology classification, the Yellowstone soil classification, available climate data, and the Yellowstone National Wetland Inventory (NWI) data were also included. They created classification trees for each of the seven years of data for four different combinations of data including: (1) TM canonical discriminant scores in wetland/upland areas only, (2) TM imagery plus image texture, (3) TM imagery plus texture and DEM terrain information, (4) all the above predictors and all ancillary GIS information. Error was assessed using 100,000 pixels sampled from locations not used for training or decision tree pruning. Overall, they found that in relation to use of spectral data alone, addition of the non-spectral data (GIS, terrain, and image texture) halved the overall error rate in detection of palustrine wetlands for the coarser wetlands/no wetlands model. Additionally, the classification tree technique improved the discrimination between emergent wetlands and other classes. Their results were three times more accurate than the 1992 NLCD model covering the entire Rocky

Mountain region. The availability of the second Landsat ETM+ image in each year did not improve detection or classification.

3.3.1.8 Summary

Classification of wetlands is a critical first step in wetland mapping, monitoring and analysis. At the very least, it is important to be able to delineate wetlands of interest from surrounding land covers. There are many ways to create classification maps of wetlands. In general, the most commonly used methods and those that have been shown to perform best include any or all of the following: 1. multiple types of data (e.g. multiple remotely sensed data types such as radar, optical imagery, LIDAR) or GIS data layers (e.g., DEMs and variables derived from DEMs, soil surveys, quaternary geological layers, etc.); 2. transformations of multiple data variables (e.g. Tasseled Cap transformation, principal components or canonical discriminant analysis), vegetation indices and water indices, or spatial variables such as image texture; 3. classification methods that are non parametric (many data types deviate from normality), and are able to include categorical and continuous variables. At the coarsest resolution level, (e.g. AVHRR, MERIS, etc.) wetland complexes can be delineated and very general broad classes (wetlands, forests, etc.) can be discriminated. The classes that can be readily distinguished with medium resolution imagery include broad wetland classes (e.g. bog, fen, swamp, marsh, open water), and corresponding adjacent land cover classes. With spectral unmixing, proportions of land cover types (e.g. bare soil, water, vegetation, etc.) can also be distinguished. With higher resolution imagery some specific vegetation species can be distinguished and certain vegetation structure characteristics can be mapped. Further detailed information on the composition and structure of wetlands can also be assessed through biophysical modelling as described below.

3.3.2 Biophysical modelling

Biophysical variables of wetlands can be estimated directly or indirectly using remote sensing (Jensen, 2005). Direct quantifications include measurements such as the apparent temperature of rocks (using thermal bands) (Jensen, 2005)). The assessment of variables derived from imagery (Jensen, 2005) is one of the indirect ways in which wetland functions can be assessed. Components that can be derived directly from imagery (e.g. indices, principal components, sub-pixel fractions, etc.) are used alone and/or in combination to

determine/detect/model some physical attribute (e.g., moisture, LAI, temperature used to model vegetation stress (Jensen, 2005)). Using common statistical techniques such as multiple regression, empirical measurements of *in situ* field- variables can be modelled against metrics derived from remotely sensed imagery (e.g., field measured biomass related to texture measures, vegetation indices and principal components (Dillabaugh and King, 2008), or moisture–indices and standing water indices related to field measured near-surface volumetric moisture content and water-table position (Harris *et al.*, 2006)). Biophysical modelling can be broken down into three key categories where research is more related to hydrologic, biogeochemical, and biological functions or attributes.

3.3.2.1 Hydrologic modelling

All of the three wetland components have an impact on one another; however, the hydrologic component is thought to be the greatest contributor to the overall functioning of wetlands (National Wetlands Working Group, 1997; Cronk and Fennessy, 2001; Mitsch and Gosselink, 2007). Not surprisingly, there are many studies using remote sensing to assess some element of the hydrologic system within wetlands. Hydrologic systems have three key components including atmospheric water, surface water, and ground water and generally, the hydrology of wetlands is concerned with all three (Winter and Llamas, 1993). Relationships between wetland types and some of these components (e.g., surface water), and between remotely sensed derived metrics and these components, have been assessed in many studies, examples of which are given below.

Quinton *et al.* (2003) determined the relationships between fen and bog cover types and runoff discharged from the Liard river drainage basin in the North West Territories, Canada. Land cover was classified using IKONOS and Landsat images. Additional data layers included topographic data to compute drainage area, density and average slope. Stream discharge was monitored at gauging stations. Using both land cover classifications, the overall area covered by fens and bogs was estimated, as well as the connectivity of wetland pixels in the drainage basin system. These measures were subsequently correlated to the amount of annual runoff and a small degree of correlation was found between annual runoff and percent cover (fens and bogs). Individually (e.g., fens versus bogs), these relations were (not surprisingly) correlated in opposite directions due to the unique hydrologic functioning of each wetland type.

Harris *et al*. (2005) related changes in surface and near-surface soil moisture to spectral characteristics of *Sphagnum* moss (*S. magellanicum*, *S. pulchrum*) in a Welsh bog, (Cors Fochno, Britain). The samples were saturated and kept in environmental cabinets and were allowed to dry over 15 days. They were gradually re-hydrated using rainfall simulators for 6 days until reaching full saturation. A handheld spectroradiometer was used with wavebands between 0.35 to 2.50 µm. They found that decreasing soil moisture increased VIS, NIR and MIR reflectance and there were strong correlations between soil moisture and water and vegetation indices. Water indices (WBI, bands in the NIR), and Moisture Stress Index (MSI)) were sensitive to reductions in soil moisture but not as sensitive to re-wetting for one of the species. MSI gave a good indication of soil moisture conditions although that was dependent on the target species. Both of vegetation indices tested showed some indication of plant-water stress associated with drying.

Lang and Kasischke (2008) assessed the relationships between radar backscatter and soil moisture and inundation. In particular, the study assessed Envisat C-band SAR with HH and VV polarization (30 m pixels) to detect extents of flooding and levels of soil moisture during leaf-off and leaf-on periods at the Patuxent Wildlife Research Centre, Maryland. At twenty-four field sites of deciduous forest located in wetland, upland and transitional hydrology they collected aerial inundation, averaged volumetric water content (soil moisture), basal area, percent canopy cover, climate data, and stream discharge data. Correlation analyses found strong relationships between inundation extent and stream discharge, precipitation, and air temperature. There was a positive linear relationship between flooding and backscatter coefficients for both the C-HH and C-VV data. Stepwise multiple regression using all field variables (area inundated, canopy closure, basal area, and canopy height) to predict backscatter found that canopy closure explained the most variation for both polarizations followed by flooding and then tree height. Soil moisture was found to be significantly related to both C-HH and C-VV backscatter although C-HH was better correlated to inundation over the whole year. In general, they found that C-HH SAR data could detect both inundation and soil moisture during leaf-off and leaf-on seasons, while C-VV SAR data could detect the pattern during the leaf-off season.

Pavelsky and Smith (2008) assessed the relationship between floodplain inundation and river level fluctuations using MODIS time series data in the Peace-Athabasca River Delta (PAD), a Ramsar Convention wetland. Water surface elevation at four locations in the PAD was

highly correlated with MODIS inundated area (generated from the NIR band) for 2007 (when water levels, inundation and connectivity were high) as compared 2006 when water levels were lower.

The majority of hydrologic studies reviewed focus on assessing inundation within an individual wetland or in a wetland complex (including the upland portions of the landscape), and varied from high to coarse spatial resolution. Soil moisture studies were more focused on individual wetlands and were localized at a fine spatial scale.

3.3.2.2 Biogeochemical

The physical/chemical component (biogeochemical cycling) of wetlands is concerned with the chemical conversions and chemical movement within wetlands. These can be movement within the soil profile, or through conversion to gases (e.g. denitrification) and release into the atmosphere. This area of remote sensing is limited in its scope, and there are few associated studies. In most cases, including the study listed below, GIS data types and analysis are more prevalent than purely remotely sensed image analysis. Several biogeochemical studies using predominantly GIS data and methods are described in the **3.4** below.

Rivero *et al*. (2007) used Landsat ETM+ and ASTER data (transformed to NDVI, $NDVI_{green}$, and NDWI), measured field data (soil and floc (soil agglomerations) total phosphorus, TP) and ancillary environmental data to determine the spatial distribution of soil TP and floc TP in the Florida Everglades. They used univariate spatial methods (e.g. kriging for interpolation between sample points), multiple regression, and hybrid/multivariate geostatistical methods. Three spectral indices were derived from the Landsat ETM+ and ASTER data. The linear multiple stepwise regression model had the highest R^2 value (0.75) using $NDVI_{green}$ from Landsat ETM+, distance to water control structures (e.g. levees), and the y-coordinates (providing flow patterns), with the latter two contributing very little to the overall prediction. In general, ETM+ NDVI showed a stronger relation to soil TP than did the ASTER NDVI (which could be explained by the seasonality of the images (e.g. Landsat obtained in the spring, ASTER acquired at the end of the wet season).

3.3.2.3 Biological

Both the hydrologic and biogeochemistry components of wetlands have an influence on the species that are present, including both plants and animals; however remote sensing is

generally more able to directly assess vegetation and some of the functions and attributes associated with vegetation.

Hardisky *et al.* (1984) used a hand-held spectroradiometer to mimic three of the Landsat TM4 bands (red, NIR, MIR) and regressed spectral indices (NDVI, and an infrared index where MIR was substituted for RED in the traditional NDVI equation) against biomass (specifically, *Spartina alterniflora*) found in salt-marshes. They then used the models to predict above-ground biomass (from clipped samples of live and dead vegetation) and net aerial primary production (NAPP). The infrared index provided a better biomass model for sampling done from May through July while NDVI was better for biomass sampled between August to October. Both indices underestimated NAPP.

Tan *et al.* (2003) used Landsat ETM+ data to estimate wetland vegetation biomass in the Poyang wetland, China. Linear regression of vegetation indices (NDVI, Difference Vegetation Index (DVI), GVI, and the brightness of the NIR band) with field measured biomass produced a best model of DVI versus biomass ($R^2 = 0.85$) that was used to map total biomass for the entire Poyang wetland.

Li *et al*. (2007) had found in the literature that there were strong positive and linear correlations between biomass and backscatter of SAR. They compared Radarsat I backscatter and Landsat TM NDVI in regression modelling of mangrove biomass in the Pearl River Delta region of China. Overall, Radarsat provided a more accurate model, and, as in the literature, backscatter was well correlated with increasing biomass.

Dillabaugh and King (2008) used IKONOS imagery to model field sampled biomass in three riparian marshes, in eastern Ontario. They extracted GLCM image textures (e.g. Homogeneity, Contrast, Dissimilarity, etc.) using two window sizes (3x3 and 5x5) and several vegetation indices from the imagery. Using stepwise regression they obtained a highly significant model that was subsequently used to map continuous biomass distribution in the three wetlands. However, due to an RMSE of about 40% (relative to the mean field measured biomass), they aggregated the data into three classes of biomass (high, medium, low) to produce a map that corresponded well to the known spatial distribution of biomass in the wetlands.

Yan *et al*. (2008) modelled Gross Primary Production (GPP) and Net Ecosystem Exchange (NEE) in a large wetland at the mouth of the Yangtze River using MODIS vegetation and water indices. Daily GPP values in the field were assessed using eddy covariance analysis

and 8-day average GPP and NEE were calculated to match the temporal resolution of the MODIS imagery. Of the three MODIS indices used to estimate GPP (NDVI; enhanced vegetation index, EVI; land surface water index, LSWI), EVI was the best predictor of GPP, but GPP was underestimated using these indices. They also assessed the relationship between tide height (one parameter of the covariance analysis) and the vegetation indices, and found a negative correlation that would amplify the bias in the EVI measurement. They showed clear decreases of EVI and NDVI in the summer at the study site closest to the sea, which traditionally has higher tides at that point.

3.3.2.4 Summary

Biophysical modelling is an emergent area of wetlands analysis. Almost all studies conducted to date have been empirical, developing statistical models relating image and/or geo-spatial data to field measured biophysical characteristics. In this approach, strong field sample design and data collection are required to properly develop and validate models, but if permanent sample plots are established for non-destructive sampling, efficiency can be increased when modelling and monitoring over time is implemented. Little has been done using theoretical approaches such as radiative transfer modelling, which is often applied in agriculture and sometimes in forests, probably because of the typically complex and dynamic spatial distributions of vegetation, soils and water found in wetlands. Overall, biophysical modelling has the potential to contribute to the development of wetland evaluation systems for conservation, maintenance and management of these ecosystems.

3.3.3 Change detection and analysis in wetlands

Singh (1989) describes change detection as a method of differentiating variations in a particular entity, surface area or in a process over time. Generally, change detection techniques are algorithms that can be applied to images or thematic maps. Some are simple methods where single band images or derived indices from two or three dates are overlaid.

Change detection techniques can be classified into three broad groups (Lu *et al.*, 2004). Algebraic techniques include: image differencing, image regression, image ratioing, change vector analysis, and background subtraction. Transformations include Principal Component Analysis (PCA), Tasseled Cap, Gramm-Schmidt, and chi-square transformations. Classification is the third major class of change detection techniques and includes: post-classification

comparison, spectral-temporal combined analysis, expectation-maximization (EM) detection, the mapping of change classes using a given classifier (e.g. ANNs), and hybrid methods including a combination of the above.

The selection of a change detection technique is difficult and often requires comparative study to determine the most appropriate method for the particular study area. Often multiple methods are compared (e.g., Fung (1990) compared three methods; Mas (1999) compared six methods; Lu *et al.* (2004) compared seven major detection categories (e.g. algebraic, transformation, classification, etc.) with thirty-one different methods; Lu *et al.(*2005) compared eight methods). In these studies, the most commonly compared methods include: image differencing, and post-classification comparison (PCC). These methods were consistently specified as the most preferred change detection methods for accuracy, simplicity, and ease of implementation.

In image differencing, an image (a spectral band or transformation such as a vegetation index) from one date is subtracted from the same image of a second date. Large differences identified by a user-defined threshold are considered to be pixels that have changed. Thresholds can be defined as a given number of standard deviations (e.g., 1.5, 2, 3) from the mean (provided the change histogram is normally distributed), as the mean should be close to zero if most of the image has not changed. Field observations and other higher resolution data can aid in determining appropriate thresholds or more than one threshold can be tested and used to produce change maps. Image-based methods such as image differencing are very useful direct means to map reflectance changes, particularly when implemented using a vegetation index such as NDVI. However, for single images such as a given spectral band, they do not indicate the direction of change or the nature of the before and after land cover classes. It should also be noted that the two images should be radiometrically matched (relatively or absolutely calibrated) to ensure that atmospheric or sensor differences between dates are not detected as surface reflectance changes.

Post-classification comparison (PCC) analysis uses maps such as land cover classifications that have been developed from imagery (Lunetta and Elvidge, 1998, and as described in O'Hara *et al.*, 2003). This approach provides the direction of the change (from/to change) for example, from wetland to urban. The maps from each date can also be compared on a pixel-by-pixel basis using a change detection matrix (Jensen, 2005). In this matrix, the pixels along the diagonal reflect the no-change areas; the pixels in the rows and columns represent the

differences between the two maps, with the columns generally representing the later date and the rows representing the earlier date. Errors contained within either of the classification maps will be amplified by any subsequent PCC (Coppin *et al*., 2004). It is imperative to choose the most accurate classification technique available. These techniques include classification methods described above, but all have limitations affecting accuracy. Often these studies overlap with classification studies because of the importance of the input data. For wetlands, change is often assessed either over a season or over many years, or some combination of the two. Studies on seasonal differences are not as readily abundant as those that assess change in wetlands over years.

3.3.3.1 Seasonal change assessment

Pope *et al.* (1997) used shuttle imaging radar (SIR-C) images that were acquired in April (dry season) and October (wet season) in 1994 over the Yucatan Peninsula to assess seasonal differences of the marshes located there. They made field observations at eleven marsh sites, taking detailed biophysical measurements including vegetation cover and height, live biomass amounts, and water depth. Vegetation cover, height and biomass change could not be detected between the field inspections in April and October. They were, however, able to assess increased flooding in the marshes by measuring increases in backscatter in taller, densely covered marshes, decreases in backscatter in sparsely covered marshes and an increase in phase difference between the wet and dry seasons in all marshes.

Lu and Kwoun (2008) used ERS (C-band VV) (1 & 2) and Radarsat-1 data (C-band HH) to assess water-level changes in coastal wetlands in Louisiana using 47 interferograms from which interferometric coherence was calculated. Interferometry is the processing of radar images taken at two angles (simultaneously or sequentially) to derive the phase difference at each pixel, which is strongly related to the elevation of the surface. The correlation (coherence) between the two signals is also related to the type of surface backscatterer, which in turn can indicate land cover type (e.g., correlation is lower for forests than for bare soils). They initially found that the total radar backscatter over wetlands was a sum of canopy surface backscatter, canopy volume backscatter and double-bounce trunk-water backscatter and that the contributions of each of these to the total backscatter was dependent upon the vegetation type (structure), leaf on/off condition, canopy closure and other conditions. They also found that the Radarsat HH data can map water-level changes over the coastal area, but that vegetation must be present in

order for the double-bounce trunk-water backscattering to occur (e.g. over open water this method is useless). Combining C-band and L-band images improved the water level sampling. Additionally, Radarsat C-band HH data demonstrated the seasonal water difference more than the ERS C-band VV data.

Slatton *et al.* (2008) used airborne SAR (NASA's AIRSAR, C-, L- and P-band) data and LIDAR data to assess seasonal difference in plant responses to water inundation (both climatic and tidal) in coastal marshes in the Galveston Bay area, Texas. They found that the AIRSARs L-band was most suited to mapping the phenological changes in plants in these marshes, and that additional information including tide levels and topography are needed to assess the seasonal changes.

3.3.3.2 Annual change assessment

Munyati (2000) used four Landsat images from 1984, 1988, 1991 and 1994 to assess change in wetlands of the Kafue flats in Zambia. Seasonal differences were minimized by choosing near anniversary images. Each image (after radiometric corrections had been applied) was subsequently classified using the supervised MLC algorithm with six classes derived from one reference image for which ground observations were obtained. The six classes were subsequently merged to dense green vegetation and *other* for each of the four years. These four maps were subsequently overlaid with 1984 on the bottom and 1994 on top to produce a map that showed the presence of dark green vegetation in each year.

Melesse *et al*. (2006) assessed the spatial and temporal changes of evapotranspiration (ET) over a prairie wetland restoration project in northern Minnesota (divided into five sub-basins) during the period of 2000 to 2004. The data used were 12 Landsat TM and ETM+ images from 2000 to 2003 (for the months of June, July and August), a DEM and climate data. The DEM was used to delineate sub-basins based upon the surface drainage. These data were input to the Surface Energy Balance Algorithms for Land (SEBAL) model which uses the band information from Landsat images, along with climate data to solve the surface energy balance equation including the components of: net radiation at the surface, soil heat flux (based upon NDVI) and surface temperature (based on the thermal band), sensible heat flux and finally, latent heat flux (which can be converted to ET by dividing by the latent heat of vaporization; this methodology has apparently been well tested throughout the world with reliable results). Spatial

maps of ET were generated for each scene showing how it increased by almost 50% over the study time period, which closely corresponded to the evolution of the restoration project.

Baker *et al.* (2007) used the algebraic technique of change vector analysis (CVA) to map changes in wetlands in Montana using Landsat ETM+ (2001) and Landsat TM (1988) imagery. CVA can determine the direction and the magnitude of change. It identifies thresholds of change magnitude that will separate actual change in the wetlands from variability in land cover classes, and false change that may be associated with radiometric issues including instrumental and atmospheric discrepancies. For this study, CVA was performed on the first three Tasseled Cap components of brightness, greenness and wetness. Overall, the accuracy of this method was assessed to be 75.2%, with high UAs and PAs for the unchanged wetland class (97.2%, and 88.3%, respectively) but lower UAs and PAs for the unchanged non-wetland class (50.0% and 76.0%, respectively).

Sass and Creed (2008) used ERS (1 & 2) SAR data to assess the change in surface hydrologic patterns that occurred along the Utikuma River drainage basin in the Boreal plain ecozone. They first assessed the relationship using regression models between the SAR backscatter coefficient and ground-based volumetric soil moisture at eighteen sites during four sampling periods and found that the models explained 31 to 67% of the variance. When these were combined to one dataset, the model captured 45% of the variance. They subsequently used the regression model equation to predict volumetric soil moisture for all pixels and then classified the results (using fuzzy classification) into three key classes: unsaturated, saturated and inundated. They next obtained nine historical ERS (1&2) images from 1992 to 2004. By combining the saturated and inundated classes into one 'Wetlands' class they were able to classify each of the nine images into percent cover of wetlands over the time period. Then, using these thematic maps, landscape metrics were identified including total number of wetland patches and percent cover of wetlands that were connected to lakes. Over time, they determined that the drainage basin showed hydrologic dynamics that switched between two states, low connectivity of wetlands and high connectivity of wetlands. Analysing the patterns of change over time showed that during dryer periods the wetlands were distinctly disconnected, and even with some change to wetter conditions wetlands still remained mostly disconnected from each other (although they did become more numerous and larger). It was only during a very wet period that connectivity between wetlands and to corresponding lakes increased.

3.3.3.3 Seasonal and annual change assessment

Kent and Nystrom Mast (2005) assessed the losses in wetland area for the San Dieguito Lagoon, California for the period 1928 to 1994 using aerial photographs. Each of four images was classified into wetland and non-wetland using supervised and unsupervised algorithms. The change in total wetland area was assessed using a post-classification comparison. The rate of loss was assessed between years, and an annualized rate of loss was also derived. It was shown that the greatest rate of loss of 3% per year occurred between 1928 and 1945, with a lower annualized rate of loss occurring between 1975 and 1994 for 0.3% per year. Unless accuracy is very high for each contributory map, these types of results must be interpreted with caution. Accuracy was only assessed for the 1994 data (96%).

Alcaraz *et al*. (2006) combined wetland ecosystems into ecosystem functional types (EFTs) to understand large area change of wetlands on the Iberian Peninsula. They used NDVI derived from AVHRR ten-day composites from 1982 to 1999 and took three attributes from the NDVI annual curve (annual integral (a proxy of primary production), inter-seasonal variability, date of maximum NDVI) to define twelve functional traits. To understand the contribution of each of the three attributes a principal component analysis (PCA) was carried out and correlations between the functional attributes and the PCs were assessed. EFTs were developed based on the dynamics of the NDVI derived metrics over time and the images were classified based on the EFT classes. They defined 49 EFTs and showed that the annual integral NDVI declined south-eastwards across the Iberian Peninsula. They were also able to spatially define the areas and times of maximum NDVI along the peninsula in each season.

Beeri and Phillips (2007) assessed the seasonal and annual variability of open water in wetlands in the Missouri Coteau ecoregion (an area of approximately 2,500 km^2), part of the Prairie Pothole Region in northern US (North Dakota) and Southern Canada. They first developed a spectral library for water and wetland cover using field based spectroradiometer measurements and collected water samples at several sites. Next, they modelled the ground based measurements using satellite data acquired during the spring, mid-summer and late summer for thirty-one Landsat images acquired from 1997 to 2005. Finally, they calculated the area of water for individual basins to determine seasonal, basin-level advance and retreat of water at the eco-region scale. They were able to accurately map possible recharge (spring located water) and discharge (summer located water) over individual seasons. Additionally, they

found that over the nine year time period there was a 50% reduction in surface water overall, which could be related to the reduced snowfall, or anthropogenic activities.

3.3.3.4 Summary

The change detection analyses reviewed here show the importance of the time period of assessment of the particular function or variable of interest. Mapping wetlands at one time period or even at one time period over several years does not distinctly capture the actual dynamics of the wetlands. It is very likely that important characteristics are over or under-estimated because of static, one-date, (or same date through several years) assessments. The best assessment should include a multi-temporal component of at least the seasonal differences, which could subsequently be used as baseline data for future seasonal studies of the same wetland.

All three general methods of mapping, biophysical modelling and change analyses described in 3.1 to 3.3 above have potential to provide the information needed to understand these dynamic land covers at local, landscape and regional scales. The most commonly used remotely sensed derived metrics to assess wetland variables are vegetation and other water/moisture indices derived from specific spectral bands. The next most commonly used metric is texture (many possible texture measures), along with radar backscatter coefficients. Although the review provided above has attempted to categorize methods that have been tested, they often overlap or are implemented in hybrid or combined ways. The products of these methods are generally used in conjunction with other data in Geographical Information Systems (GIS). The following section describes studies that are based within a GIS framework, where analysis of remotely sensed data alone was not the focus.

3.4 GIS analyses of wetlands

Geographic Information Systems (GIS) are useful because of their capability to integrate a number of data types, including remotely sensed data (e.g. thematic maps, change statistics, biophysically modelled variables, etc.) and other geo-spatial data types such as soils, topographic, and census data. Rather than deriving metrics directly from imagery (e.g. using band brightness/reflectance or radar backscatter), information is derived from products previously created such as thematic maps, DEMs, etc., many which may have been derived from remotely sensed imagery. In the previous section, many studies (Harvey and Hill, 2003; Quinton

et al., 2003; Berberoglu *et al*., 2004; Rivero *et al*., 2007; Wright and Gallant, 2007 (among others)) had GIS components, however their remote sensing components were critical factors in the research and warranted their inclusion in that section. To maintain consistency with the analysis of remotely sensed methodologies, GIS methodologies have also been sub-divided into three broad groups: mapping, biophysical modelling, and change analysis. An additional group, Population analyses and habitat conservation, includes species population studies that are well-suited to GIS. This section includes one study that is not specifically related to wetlands although wetlands may be a habitat of interest for the species of interest.

3.4.1 Mapping wetlands

As has been previously noted, in most organizations, delineation of wetland boundaries is a primary activity in evaluation programs (despite the often non-discreet and dynamic nature of such boundaries). Additionally, most evaluation programs reviewed include assessment of wetland vegetation species and composition. There have been many GIS-based studies that have used both remotely sensed data and other geo-spatial data to map wetlands and wetland boundaries. Topography is a key component for mapping and evaluating wetlands. Topography acts as a major control on wetland distribution (Murphy *et al.*, 2007) and influences many of the processes that occur within wetlands, specifically the hydrologic functioning, distribution of soil carbon stocks, decomposition, net primary production, among others (Ferone and Devito, 2004; Ju and Chen, 2005; Murphy *et al.,* 2007; Murphy *et al.*, 2009). DEMs, as representations of topography, are often used to derive wetland variables. Topographic indices, such as the soil wetness index (SWI) and depth-to-water (DTW) index (Murphy *et al.*, 2009) are often derived from DEMs that are, in turn, generally created with remotely sensed imagery (e.g. LIDAR, optical imagery, interferometric radar, etc.). The use of DEMs in some GIS wetlands research is reviewed in several of the following studies.

Vaiphasa *et al*. (2006) attempted to map seven species of Mangrove for the Talumpuk Cape in Thailand by integrating soil pH data (specific pH ranges are known for each species) with thematic maps derived from remote sensing. Maps of soil pH generated from interpolation (ordinary kriging) between field measurement points were combined with an MLC thematic map of the seven species derived from ASTER imagery (overall accuracy = 76.0%) using a Bayesian

post-classifier. The overall accuracy of the vegetation map increased to 88.2% and included significant improvements in the UAs and PAs for the individual classes.

Hogg and Todd (2007) used three methods to delineate the boundaries of 463 wetlands near Bolton, Ontario. They used a DEM to derive wetland terrain variables (topographic index, contributing area and slope, standard deviation of slope, planform curvature, profile curvature, minimum sink depth, positive hydraulic slope, mass balance hydraulic slope, and positive mass balance hydraulic slope). Field collected wetland data from the OWES and from the Duck's Unlimited Canada Mallard Ecology Study (MES, www.ducks.ca) were used for calibration and validation. The terrain variables were assessed using logistic regression to determine which should be retained for subsequent mapping. The first predictive model used to map wetland area was the visual derivative threshold method (where topographic index and positive mass balance hydraulic slope (two uncorrelated variables) were used in a density slicing approach (thresholds are developed for each variable based upon the relationship with wetland calibration polygons (OWES and MES data)). The second predictive model was a logistic regression model and the third model used a classification and regression tree (CART) statistical analysis which splits data based upon prediction rules (thresholds for six uncorrelated DEM terrain variables) until the data become uniform or meets some set minimum number of observations. Using the visual derivative threshold method, the overall accuracy of wetland mapping was 99% however 37% of upland was also mapped as wetland, resulting in a large commission error. With reduction of the threshold values, the wetland mapping accuracy decreased significantly. For the CART method, the overall validation accuracy was 84%, providing the best result for mapping the boundaries of wetlands in the study area.

Stevens *et al*. (2007) used beaver pond mapping for conservation of amphibians in the foothills of Alberta. They first conducted field sampling and verified that there were more frogs and toads in areas with higher densities of beaver ponds while very few were captured or observed near unobstructed streams. For the beaver pond GIS analysis, they used a DEM and landscape metrics digitized from vegetation inventory data and anthropogenic layers to derive values to relate to beaver occupied ponds versus unoccupied ponds (including disturbance (distance to roads, and/or cutblocks), forest structure and composition (mean forest height, per cent deciduous, percent *Populus* spp. (beaver food)), stream hydrology (stream order and slope), and mean elevation). They found that stream order, elevation and percent deciduous cover were

highly correlated with beaver pond occurrence, while non-significant relations were obtained for stream slope, mean forest height, per cent *Populus* and distance to nearest cutblock.

3.4.2 Biophysical modelling

Biophysical variables of wetlands are estimated more indirectly using GIS through the assessment of a multitude of variables either derived from remotely sensed imagery or from some other source.

Van horssen *et al.* (1999) used kriging to produce spatial patterns of wetland plants for use as input in a GIS-based model to predict the overall patterns of species in a wetland area in the Netherlands. These predictions were subsequently validated with field data. To predict the spatial patterns of the wetland plants, multiple stepwise logistic regression was used and included the variables: absence or presence of 78 wetland plant species, soil type, land use type, hydrologic conditions and thirteen groundwater geochemical variables (e.g., pH, Cl^-, etc). Each regression equation resulted in a response value that could be attributed to relative frequency of plant species presence. The results showed that 13% of the predictions were 80% or more correct, 20% of the predictions were 60 to 80% correct, over 56% of the predictions were 40 to 60% correct and 10% of the predictions were 40% or less correct. This response was spatially distributed with the most correct predictions being distributed to the south-southwest.

As described in section **3.3.1.4**, Berberoglu *et al*. (2004) classified a Landsat image for 8 classes using an ANN with an accuracy of 90.2%. This thematic map was next compared to data from vegetation surveys made in the field, and to data from available bird surveys. They assessed vegetation layers, relative coverage, plant abundance and species composition, with additional information such as land use type, geological structure, soil formation, slope, aspect and elevation also being recorded. With these data, they were able to assess habitat quality and diversity, by plant species and bird species, for each of the four land cover types mapped by the ANN. This comparison showed that salt marshes contained almost two times as many plant and bird species as the other land cover types per unit area and “hot spots” of bird and plant biodiversity were located directly within the wetlands for future conservation consideration.

Morrice *et al*. (2008) assessed the impacts of human activity on the Great Lakes coastline, by characterizing the relationships between the activities (agriculture, population and development, point source pollution, and atmospheric deposition) and water chemistry. They

tested 98 wetlands along the US shore of the Great Lakes (encompassing three wetland classes: riverine, protected, and open coastal) which was subsequently divided into 762 segment-sheds (containing shoreline and boundaries at the mid-points of streams of second order or higher). For each segment-shed, 207 variables were taken from publicly available web databases to represent human activities. Using multivariate analyses, the segment-sheds were grouped into clusters of similar stressor regimes. In the field, water samples were taken from each wetland (proportional to the wetland size) and analyzed in the lab for total nitrogen, total phosphorus, ammonium nitrogen, nitrate nitrogen, chlorophyll, chloride, total suspended solids and dissolved organic carbon. The stressor clusters were assessed using principal component analysis to determine the type of stress they represented (e.g., agriculture, etc.) and wetlands were assigned a stress class based on the underlying segment-shed clusters. Multiple regression was subsequently used to determine the relationships between the water variables and the stressor. There was strong and significant correlation between presence of total nitrogen, total phosphorus, chlorophyll, chloride, total suspended solids and the Agriculture PC1, with both Agriculture PC1 and point source pollution PC1 explaining a significant portion of the variance in most of the water quality parameters (excluding dissolved organic carbon). Human population PC1 and atmospheric deposition PC1 also explained significant variance of several water quality measures.

Much of the biophysical modelling approaches reviewed in the literature uses some form of regression modelling (Ballester *et al*., 2003; Wei and Chow-Fraser, 2008 and others as noted above). The overall benefits to using GIS are the capability for spatial modelling and incorporation of other data types. These other data included: water variables, soil variables, vegetation variables, DEMs (and derived products), anthropogenic data, species specific data (including risk factors, breeding habitat, etc.) and basically any data that are, or can be spatially represented.

3.4.3 Change analysis

There have been several GIS studies that have used both remotely sensed data and other geo-spatial data to map wetland change over time. Like remote sensing studies, these often focus on either seasonal changes, annual changes or some combination of both.

DeBusk *et al*. (2001) were interested in understanding the distribution and change in spatial extent and pattern of total soil phosphorus (P) concentration between 1990 and 1998 in the Florida Everglades Water Conservation Areas (WCAs). They sampled the surface and underlying soil at 62 sites in 1998, taking soil cores to a depth of 10 cm to match similar data collected during a soil study completed in 1990. Ordinary kriging of the point data was used to create an interpolated map of soil total P. They also used indicator kriging, which incorporates calculation of the probability of soil P that is in excess of specified thresholds. This enables an indication of occurrence or non-occurrence, providing a representation of the probability of the spatial distribution of soil P. They found that the soil P concentrations varied from site to site with strong relationships between higher soil P concentrations and the surface inflow structures entering the WCAs. Direct comparison of sites between years was not conducted due to the inability to confirm that the sites were actually the same, but the interpolated soil P maps were used to facilitate a temporal comparison. An increase over time in low levels or background levels of soil P concentration was found, which may indicate a release of soil P in saturated soils. Through this mapping process they were able to estimate that approximately 48% of the area would have been considered soil P enriched in 1990 as compared to 73% of the area in 1998.

Papastergiadou *et al*. (2008) used GIS analyses and aerial imagery to determine the change in land cover of a wetland on Lake Cheimaditida, northern Greece. Using black and white aerial photos from 1945, 1969, 1982 and 1996, manual delineation of the borders of land cover types (urban areas/villages, rocks, arable land, open water areas/lakes, peat lands/fen, wet meadows/marshes, reed beds, pastures, scrubs and trees and forests) was conducted for each year. They subsequently developed spatial histories of each cover type in the region, showing that there had been significant reductions in open water (converting to reed beds) and peat lands/fen, as well as an increase in arable land.

Wilcox *et al*. (2008) used GIS analyses and interpretation of air photos (1950s to 2001) to assess the relationship between changes in wetland plant communities (especially *Typha* and graminoid meadow marsh) and lake water levels at sixteen sites along the US shoreline of Lake Ontario. They first visually interpreted vegetation boundaries for four different kinds of wetlands (drowned river mouth, barrier beach, open embayment, and protected embayment) using a modified version of the Ecological Land Classification (ELC) system for southern Ontario. This was supported with collected field data and subsequently digitized. Additionally,

wetland basin boundaries were delineated using mean monthly high water levels and a DEM. The photo interpreted polygons were subsequently clipped to match the overall largest possible wetland extent of each time period. Wetland vegetation classes were subsequently limited to four key classes: floating-leaf vegetation, meadow marsh (sedges and grasses), mixed-emergent vegetation, and *Typha*, and the area and percent cover were calculated for each. Over the entire time period it was found that *Typha* had expanded both landward (and up-slope) into the meadow marshes as well as into the open water, with meadow marshes decreasing over time. Through the decades, it was found that in the 1950s lake levels remained relatively high and meadow marsh coverage remained relatively constant. With a drop in lake levels in the 1960s there wasn't a corresponding drop in *Typha* levels, and meadow marsh continued to maintain similar coverage to the 1950s. With an increase in lake water levels in the 1970s there was a substantial increase of *Typha* coverage and a reduction in meadow marsh coverage. *Typha* continued to increase at more sites with increased and sustained lakes levels during the 1980s to 2001.

The latter two studies above have strong remote sensing components through the photo-interpretation of land cover. However, because these classifications were manually conducted with expert knowledge, and not by using a classification algorithm or transformation methodology, and because the outputs were subsequently used with other data sets or through polygon analysis they were included in this GIS section. Change assessment using GIS is very similar to that using remote sensing but the addition of ancillary data can provide more detailed change information. Additionally, the use of long-term geo-spatial data sets not dependent upon imagery is an important advantage of GIS-based change detection.

3.4.4 Population analysis and habitat conservation

Two types of data that are amenable to integration into GIS databases and analyses are faunal population and habitat information. These types of information can be combined with other data (e.g., maps, biophysical information, and change information) to add to the overall evaluation of wetlands. The first study below is not an implicitly wetland study, however, wetlands were considered as special elements for the conservation of habitat for the species of interest.

Beazley *et al.* (2005) used a three track approach to develop a biodiversity conservation system in Nova Scotia using GIS and simple models. The three tracks of representation, special elements, and focal species were assessed separately and then combined to identify priority areas for conservation. In each section they used existing data sets to create the information of interest. For the representation portion they created four classifications, including land cover, area of contiguous natural area, road density and forest cover maturity and from these developed three features: contiguous natural terrestrial ecosystems, roadless areas, and uneven-aged forest stands. Areas where the three overlapped were considered as priorities for representation of "natural" landscapes. In the special elements category, they assessed four groups including: critical areas for species at risk, rarity-weighted richness (an index calculated from the occurrence records for rare species), significant ecological sites, and old and unique forests to determine critical areas for species at risk including hotspots of rarity. For the focal species they investigated five key factors including those that were "of disproportional functional importance in an ecosystem", need large areas, need unique habitats or are indicators of habitat quality, are vulnerable, and/or are appealing to the society to aid in conservation. The focal species they selected were the American moose, the American marten, and the Northern Goshawk, and they created population distributions for each of the three species. From these they calculated population and habitat requirement statistics and developed habitat suitability coverages. To develop core (conservation) areas they overlapped all priority areas from each of the three tracks and manually selected those of high overlap and concentration as the core areas. They also assessed the connectivity of the core areas through cost-distance analysis for each of the three species. They were unable to attain a 12% representation in 14 natural land covers (an initial study goal), but delineated 59 new core areas that were overlaps of the priority areas in each of the three tracks.

To assess breeding water bird wetland habitat near Saint John, New Brunswick, Connor and Gabor (2006) used historical water level data and GIS wetlands inventory to estimate the duration of the seasonal flood and the extent of the breeding habitat. They assessed five seasonally flooded wetlands and five impoundments (where water levels are maintained throughout a season) representing the wetland types within the Saint John area. The availability of breeding habitat was assessed by linking long term river data to sampled water depth. Water depths of 15, 30 and 60 cm were chosen to determine what period the wetlands provided the

suitable habitat. Within the different types of wetlands the proportion of brood-rearing habitat ranged from 11 to 69%. For the waterfowl brood, surveys of their use of the wetlands and impoundments were conducted via helicopter to determine broods (including, age, species, and number of ducklings). They observed ten species of waterfowl broods. For relative abundance of wetland obligate birds, call-response surveys were conducted. They obtained responses from four species of wetland obligate birds and found that mean species richness was higher at the impoundments than in the seasonally flooded wetlands.

3.4.5 Summary

Mapping with GIS is useful and allows the combination of some previously derived remotely sensed thematic maps with ancillary data (e.g., DEMs (and variables derived from DEMs, such as drainage, slope, etc.); maps interpolated from point source data, etc.). For biophysical modelling, data are often assessed through regression modelling (Ballester *et al*., 2003; Wei and Chow-Fraser, 2008, etc.). Change assessment using GIS also allows for the addition of ancillary data that can provide more detailed information about the change. GIS also allows for an assessment of fauna species related data and then relating those data to other wetland information. The overall benefits to using GIS are the capability for spatial modelling and incorporation of other data types. These other data include: water variables, soil variables, vegetation variables, DEMs (and derived products), anthropogenic data, species specific data (including risk factors, breeding habitat, etc.) and basically any data that are, or can be spatially represented. Many of these data types may be readily available in the Land Information Ontario (LIO) database as well from other sources.

3.5 Recommendations on current remote sensing and GIS methodologies

There are many methods that are available for the analysis of wetlands within both remote sensing and GIS contexts. For the current OMNR effort to re-define and refine the OWES, the literature provides abundant empirical evidence and insight regarding the potential to utilize relationships between remote sensing derived metrics and current functions, values and conditions evaluated by the OWES. There is strong accumulated support for the use of certain data types and processing techniques for many information requirements associated with wetlands (e.g., if the function of interest is inundation, then the NIR spectral band or radar imagery should be used, the latter providing weather independent imagery). Alternatively, in

efforts to develop new methodology for wetland assessment (e.g. systems-based using, where possible, available geo-spatial data), the first step would be to review the current available data in the Land Information Ontario (LIO) system (see Chapter 4.0 below) and determine what is available and where the gaps are. Then, critical missing data could be acquired or derived using the methodologies described in Chapter 3. These remote sensing and GIS data types and methods are the most up-to-date and commonly used for wetlands analysis. The key issues would be determining if they are transferable to Ontario, and if required they could be acquired or implemented in a cost-effective manner. The following chapter describes existing LIO data that have potential for integration into wetland evaluation.

4.0 Available Remotely-Sensed Imagery and GIS Spatial Datasets

Current wetland evaluation methods, and existing GIS and remote sensing methodologies use a variety of digital data. For the area of interest for this project, Ontario in general and southern Ontario in particular, there are many sources of digital data that are available from Land Information Ontario (LIO). The LIO database can be accessed in two ways: through the Ontario Geospatial Data Exchange (OGDE) through a University and directly from the MNR itself. The data in the LIO warehouse can be categorized into three key groups: 1) the fundamental dataset which is available through the OGDE; 2) publically accessible data which are available from the Ontario Ministry of Natural Resources (OMNR) LIO website, and 3) other restricted data. The restricted data may also be available through the OGDE, but requires manual requests and downloading by the official academic contact (generally in the institution's library). The LIO data listed in this review includes the fundamental dataset and data that were readily accessible through the OMNR LIO website. Restricted data that appear to be useful are mentioned but not explicitly described.

Other data are available (although licensing aspects/shared data requirements for research would need full investigation) and these include data from: the Canadian Forest Service (CFS), Canadian Centre for Remote Sensing (CCRS), the Atlas of Canada, Quaternary Geology of Ontario, and Statistics Canada among others. The following table is a listing of the data available for the southern Ontario region. It is not an exhaustive list, but is representative of the types of data that are available for the region. In the columns, the list gives a general data category related to similar data categories found in the evaluation methods Excel spreadsheet, a data name, location of the data, a brief description of the data, and an indication of whether or not it has been used in a particular study before or if the authors feel it may be useful for the development of a new wetlands evaluation system. Similar data types are currently used in other existing evaluation systems, and could be considered representative of many of the functions and values currently assessed.

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Table 4. A comprehensive listing of digital data sources for wetland analyses in southern Ontario

General Category	Data Name	Fundamental Dataset (y/n)	Location of the data	Description of the data	Used or Potential Use?
Imagery and thematic data	Aerial Photos (Ayr 2003; Breslau 2003; Elmira 2003; New Hamburg 2003; Wellesley 2003 and others)	N	LIO	-restricted; colour infrared and black and white	-could be useful if current or as historical data
	IKONOS (Multispectral and PAN)	N	LIO	-restricted	-depends upon dates etc.
	Landsat 7 – ETM + data	N	LIO	-restricted (however, as of April 2009 Landsat imagery (current ETM+ and archived imagery) will be free from the USGS)	-depends upon dates etc; however current imagery could be obtained from the USGS
	Atlas of Canada Base Maps	N	Atlas of Canada	-base map data (including boundaries, transportation networks, hydrography, ice cover; (1:2000000 – 1:30000000)	-may prove to be useful with other land cover products;
	Crown Land Use Policy Atlas (2002)	N	LIO	-thematic map of approximately 10 classes (Modifying land use area, primary land use areas and other land use areas) derived from several individual layers of data from the LIO	-may prove to be useful with other land cover products; combining a social aspect in with land cover delineation
	Haliburton Country Enhanced Wetland Mapping/ Muskoka District Enhanced Wetland Mapping	N	LIO	-restricted	-may prove to be useful with other land cover products; especially if the particular areas are selected as a test sites
	Land Cover Map of Canada (1995)	N	CCRS	-land cover map derived from AVHRR data (31 classes; resolution of 1 km)	-may prove to be useful with other land cover products;

	Provincial Land Cover (2000)	Y	LIO	-thematic map of Ontario from 2000; 27 classes, including 9 wetland classes; not validated; based on Landsat ETM+ data; MMU is 0.5ha	-as it hasn't been validated the accuracy is questionable; but may prove to be useful with other land cover products
	Statistics Canada	N	Stats Can.	-thematic maps (e.g. agriculture maps, environment maps); statistical information on land use	-potential to develop layers for social functions and values
	EcoRegion/ EcoDistrict/ EcoZone	N	LIO	-EcoRegion - area of land where the vegetation response to the features or landform follows a consistent pattern -EcoDistrict - subdivision of an EcoRegion based upon a characteristic pattern of physiographic features -EcoZone – gives ecological context for Ontario; based on surficial geology and climate. scale is 1:1,000,000;	-assessments that could be used instead of typical inventories (land use/cover class based)
	Forest products for Eastern Ontario	N	Eastern Ontario Model Forest	-GIS products such as wooded area by watershed, forest area by type and age, road density by watershed, wooded patch size and shape by watershed, protected areas	-may prove to be useful with other land cover products; plus the additional information may focus area for test sites
	Vegetation Area / Edge /Line	N	LIO	-restricted	
	Wetland Unit	Y	LIO	-delineates wetlands in Ontario (five key classes: bog, fen, marsh, swamp, open water); lists scores for those wetlands already assessed under the field based OWES	-can be used to confirm locations; or limit areas of interest.
	Evaluated Wetland	N	LIO	-restricted	-can be used to confirm locations; or limit areas of interest.

	Wooded Area	Y	LIO	-areas covered by trees	-can be used to confirm locations; or limit areas of interest;
Biological	Aquaculture Area of Impact	N	LIO	-areas of impact around 15 fish culture operations (Fish Culture Stations layer) in Ontario; two spatial areas are defined (areas of sensitivity and areas of concern);	-some evaluation systems use similar buffers (CRAM, ORAM, etc.) around wetlands; these may be good test areas
	Moose Aquatic Feeding Area (MAFA)	N	LIO	-identifies and ranks areas of Moose feeding; generally providing 2.5 metre buffers on either sides of streams; plus provides a ranking for habitat (ranging from nil potential to very high potential); also potentially provides information about aquatic vegetation types	-some evaluation systems (CRAM, ORAM, etc.) use similar buffers around wetlands; these may be good test areas; especially if information regarding aquatic vegetation types is available
	Aquatic Resource Area	N	LIO	-restricted	
	Beaver Dam	N	LIO	-locations of beaver dams on streams -could also be considered under hydrologic components	-similar data (Stevens *et al.,* 2007) used to delineate areas of beaver ponds/wetlands for designation of amphibian habitat; also could be used for habitat assessment (for beavers)
	Breeding Area	N	LIO	-provides sites where certain species habitually breed (e.g. deer, caribou, grouse, marten, moose);	-could be used for habitat delineation (as in existing habitat related assessments e.g. HEP, MnRAM, ORAM, CT Method, EPW, OWES, WIMS, W-PAWF, NC-Crews, SWAMP)
	Breeding Bird Atlas (10 km square, 100 km block, random sample point, region)	N	LIO	-sampling areas (10 km, 100 km) and administrative regions to collect breeding bird information for all birds in Ontario	-could be used to determine locations of sampling; (methods using breeding bird data: WET, AREM, HAT, W-PAWF)

	Calving Fawning Sites	N	LIO	-samples sites where certain species (e.g. deer, elk, moose) habitually fawn/calve	-could be used for habitat delineation (as in existing habitat related assessments e.g. HEP, MnRAM, ORAM, CT Method, EPW, OWES, WIMS, W-PAWF, NC-Crews, SWAMP)
	Den Site	N	LIO	-sites where species birth and nurse their young (including Arctic Fox, Black Bear, Eastern Wolf, Grey Wolf, Marten, Red Fox, Wolverine)	- as above
	Feeding Area/Fish; Feeding Area/Wildlife	N	LIO	-areas where fish habitually feed (includes 40 different fish species) -areas where wildlife habitually feed (including Bald Eagle, Beaver!, Golden Eagle, Karner Blue Butterfly, Osprey,	- as above
	Fire Disturbance Area	N	LIO	-perimeters of forest fires; no indication of severity of fire or impacts on forest cover	-for disturbance information (biological features – Eastern Ontario Wetland Evaluation System, Monitoring Wetland Conditions – New Zealand)
	Habitat Planning Range	N	LIO	-areas where habitat criteria, climate data, and species data combine to make exemplary habitat for certain species (over 55 flora and fauna species)	-could be used for habitat delineation (as in existing habitat related assessments e.g. HEP, MnRAM, ORAM, CT Method, EPW, OWES, WIMS, W-PAWF, NC-Crews, SWAMP); creating habitat suitability (habitat scores)
	Invasive Species Occurrence Data Management Model	N	LIO	-geographic extents where invasive species are present	-used in CRAM, ORAM, New Zealand Method, WQI

	Nesting Sites	N	LIO	-point features of locations of nest of particular bird species (over 45 bird species)	-could be used for habitat delineation (as in existing habitat related assessments e.g. HEP, MnRAM, ORAM, CT Method, EPW, OWES, WIMS, W-PAWF, NC-Crews, SWAMP); creating habitat suitability (habitat scores)
	Travel Corridor (Fish and Wildlife)	N	LIO	-designates areas/routes that are used by wildlife species for migration (caribou, deer, elk, moose and waterfowl; and 13 fish species)	- as above; also could be used for connectivity functions
	Wintering Area	N	LIO	-areas where species winter (for caribou, deer area/deer yard; elk, Moose early/late/ combined, snake)	- as above re. habitat delineation
	Wild Rice Stands	N	LIO	-areas where wild rice grows	-could be used for habitat delineation
Hydrologic/ Geomorphological **Most evaluation systems (excluding some of the biological assessments) use hydrologic characteristics; these various data layers would prove very useful (e.g. see SWAMP,	Bedrock Geology of Ontario (@ 1 million and 250,000) (includes the layers: Fault, dikes,	Y	LIO	-geological map of Ontario including: bedrock area, dikes, faults, granulite facies, iron formations and kimberlite	-similar datasets used in other current evaluations (soils in particular, e.g. ORAM, PAM HEP, ESI, WHAP, SWAMP, WIMS); could be used in a similar manner
	Contours	Y	LIO	-continuous lines (from vertices) at constant elevations from mean sea level	-yes; to create DEMs (although these are already available in the LIO)
	Constructed Drain	N	LIO	-constructed ditches and natural watercourses that have been modified in Ontario (from 1990 onward); accuracy of data is variable	-useful for hydrologic functioning

SCREAM, HGM, etc)	Dam	N	LIO	-restricted	-could be useful for the hydrologic functioning of wetlands (similar to that for beaver dams)
	Drainage Line / Drainage Point	Y	LIO	-presence of falls or rapids on a river having a width greater than 40 metres at 1:20000 scale and 20 metres at 1:10000 scale (known as a double line river). -as above for widths less than 40 metres (known as a single line river), or rocks which occur in waterbodies collected from interpreted aerial photography.	-important for the hydrologic functioning of wetlands
	Tile Drainage Area	N	LIO	-locations of fields with tile drainage	- as above
	Hydrography and Hypsography (Area, Edge, Line, and Site at 250K)	N	LIO	-restricted	- critical for hydrologic functioning/function assessment
	Mineral Deposit	N	LIO	-an overview of mineral deposits; deposit name(s), location, size of the deposit (e.g., occurrence, prospect, producer or past producer), minerals and commodities.	-potential for geomorphologic functioning
	Mineral Licks	N	LIO	-areas of mud pools or puddles; fed by slow seeping springs; used by wildlife	-could be used to exclude areas that may be classified as wetlands or assessed as wetlands in error/confusion
	OBM DTM Coverage / DEM – V2.0	Y	LIO	-Digital terrain models derived from Ontario Base maps; DEMs	-used in many evaluations; specifically in almost all systems-based methods
	Quaternary Geology of Ontario	N	OGDE	-detailed geology of Ontario (including drainage layers, lakes, provincial boundaries and township boundaries)	-critical for hydrologic functioning/function assessment
	Soils Ontario	Y	LIO	-provides soil coverage	-as above

	Surficial Geology of Southern Ontario	N	LIO	-	-as above
	Water Body Segment	Y	LIO	- polygon or line feature that identifies a segment of a body of water such as a lake, pond, river, stream, or reservoir. A Waterbody Segment may be the Waterbody in its entirety or a component of the Waterbody. (includes water area permanent, water area, seasonally inundated), water line intermittent (linear waterbody), water line permanent, water line seasonally inundated, wetland area permanent, wetland area seasonally inundated, wetland line permanent, wetland line, seasonally inundated	-as above
	Water Edge	Y	LIO	-provides outlines/ edges of water bodies (all) in Ontario	-important for the hydrologic functioning of wetlands
	Water Lot	N	LIO	-piece of land that underlies a water body (commercial and private)	-as above
	Water Structure	Y	LIO	-man-made structure inside waterbodies (Dams, lock-gates, sea lamprey barriers)	-as above
	Water Supply	N	LIO	-point feature identifying sources of water (springs, water intake)	-as above
	Water Well	N	LIO	-point features that includes holes made in the ground to locate or to obtain ground water or to test or to obtain information regarding ground water or an aquifer.	-as above
	Watersheds (Primary, Secondary, Tertiary, Quaternary)	N	LIO	- hierarchical structuring of watersheds	-as above

Social/Special	ANSI, (Areas of Natural and Scientific Interest)	N	LIO	-provides information on land and water areas that have been designated as important for heritage, educational purposes, scientific study, and/or for protection; decomposed into two groups: ANSI, Earth Science which contain sensitive or significant geological features; and ANSI, Life Science which are for natural ecosystems; communities and species	-similar data is used in some evaluation systems already
	Bear Management Area	N	LIO	-polygons of potential bear habitat to provide hunting for non-residents by bear tour operators	-could be used for a social component (e.g. recreation); or for habitat component assessment
	Cottage Residential Areas/ Cottage Residential Sites	N	LIO	-area of dwellings having an official designation and often represented by a cottage and/or residential association. The occupancy may be seasonal or year-round. -site of human occupancy and type of occupancy (seasonal or year-round)	-for special features/or social context (and for adjacent land use)
	Conservation Area/Authority/Reserve Regulations	Y	LIO	-areas of public land that are set aside under the Public Lands Act; prohibited activities include mining; commercial logging; hydro-electric development; extraction of aggregates, peats and soils	-potential for special features (special areas/ uniqueness)
	Crown Game Preserve	Y	LIO	-perimeters around the crown game preserves are located	-potential for social features (recreation; education, etc) and for adjacent land use
	Crown Leased Land	Y	LIO	-areas of crown land that are leased to the public	-as above

	Environmentally Sensitive Areas	N	LIO	-an area with values which are identified to be of local interest and designated and managed by a municipality. It may represent the habitat of vulnerable, threatened or endangered species.	-critical for the special features component (used in MDT, Descriptive Approach, current OWES, WQI, WHAP, W-PAWF, WIMS)
	Significant Ecological Area	N	LIO	-a polygon feature that identifies an area of interest to the Ministry that is ecologically significant, and warrants special consideration, excluding ANSI's, wetlands, parks, reserves or ESA's (classes include: designated old growth forest, no-cut area, old growth forest, significant ecological community, significant valley, significant woodland, wetland unevaluated).	-as above
	Forest Management Unit	Y	LIO	-provides boundaries of forest management administrative areas; (areas are used for forest resource planning and management)	-could be used for adjacent/land use information
	Land Ownership	Y	LIO	-areas of ownership and general land use	--could be useful for social features including aesthetics, recreation, etc. (already assessed in OWES)
	Land Use Plan Area	N	LIO	-land use planning initiatives are established or approved for a geographic area. Examples for OMNR include the Ontario's Living Legacy (OLL) Land Use Strategy, Temagami Land Use Plan Area, Madawaska Highlands Area, District Land Use Guidelines Area (DLUG), OLL Signature; Sites (that have land use policy), etc.	-could be useful for social features including aesthetics, recreation, etc.
	Mine Site	Y	LIO		

	Municipal Parks	Y	LIO	-areas where there are parks in major municipalities (e.g. Toronto, Ottawa)	-potential for social features (recreation/education/ aesthetics)
	National Parks	Y	LIO	-national park locations in Ontario	-as above
	National Wildlife Areas	Y	LIO		
	Natural Heritage Value Areas	N	LIO	-areas not currently protected but in the planning stage of protection (may have interim protection)	-as above
	NGO Nature Reserves	Y	LIO		
	Peat Production Area	N	LIO	-areas that are designated as suitable for peat extraction;	-could be used to exclude areas that may be classified as wetlands or assessed as wetlands in error/confusion (e.g. if designated for peat extraction obviously not provincially significant?)
	Provincial Park	Y	LIO	-provincial park locations in Ontario	-potential for social features (recreation/education/ aesthetics)
	Railway Segment	Y	LIO	-portion of a line of steel track providing a runway for trains and other wheeled vehicles. Railways are shown as linear features along their centre lines.	-several methods (EOWES, AMNEW, NJ Method) use road files; train files may also prove useful
	Road Segment	Y	LIO	-a line feature that identifies a length of road having similar features and rankings.	-several methods (EOWES, AMNEW, NJ Method) use road files
	Trail Segment	Y	LIO		-as above: trail files may also prove useful
	Transport Line/Point	N	LIO	-restricted	

	Airport	Y	LIO	-shows tracts of land that are used for airports (runways, outbuildings etc);	-could be useful as an indicator of nearby land use; several methods (EOWES, AMNEW, NJ Method) use road files; airport files may also prove useful
	Tourism Establishment Area	N	LIO	- polygon feature that identifies an area containing facilities and services for tourists; (includes classes of commercial campground, commercial parking lot, golf courses, inns, horse riding stables, main base lodge (remote and not remote); marina/dock, museum, outpost (remote and not remote); playgrounds, ski hill (remote and not remote) shooting range, store, sugar shack, tree tapping)	-use for social features: e.g. aesthetic, education, scientific, heritage, recreation
	Traditional Land Use Area / Site	N	LIO	-polygons identifying areas used (past and present) that are deemed special (bear baiting stations, berry picking areas, bird watching sites, lookout (potential lookouts); semi-permanent structures; traditional fishing areas; traditional hunting grounds; viewpoints and viewscapes)	-as above
	Tree Improvement Area	N	LIO	-areas designated for study and improvement for tree species (includes archive areas, breeding halls, breeding orchards, clonal seed orchard, clonal test; family test, farm field test, progeny test, provenance test, seedling seed orchard, short term test)	-could be used for designation of special areas/uniqueness or for social features; land use

	Utility Line / site	Y	LIO	- line feature that identifies a conduit for providing services such as power, water, communications, or heating fuel (communication lines, hydro line, natural gas pipeline, submerged communication/hydro/gas/water, unknown lines; water pipelines	-could be used for proximity questions/or disturbance questions (fixing lines)
	Waste Disposal Sites	N	LIO	-areas that are designated for waste disposal (includes compost, hazardous waste, household waste, industrial waste, septic drying bed, septic field, sewage disposal, tile bed, transfer stations)	-could be used for proximity questions (e.g. to pollution sources (SWAMP))
	Wilderness Areas	N	LIO	-areas regulated under the Wilderness Area Act. They can be embedded in other protected areas and have values such as historical or natural heritage but they have no formal class system or management planning.	-could be used for special features (special areas/ uniqueness)
	Wood use area	N	LIO	-areas that are used for harvesting wood for construction or fuel (building material areas, and fuelwood areas)	-useful for social features (land use)

There are many sources of data available for developing system-based wetland evaluation systems as listed above in Table 4. The next step would be to select system-based evaluation methods to test and assess whether or not all necessary data are available or if other data must be derived/developed. Further assessment of some of the restricted sources (e.g. satellite and aerial imagery) is also warranted. These would be important for evaluation of remote sensing methods to derive other wetland functions and values that may be of interest, or for use in a new evaluation system.

5.0 Overall Conclusions

This document has provided an in-depth investigation into the currently existing wetland evaluation methods; the current state of research of wetlands using remote sensing and GIS and a comprehensive review of available digital data for wetland analysis in southern Ontario. It is based on a comprehensive review of the scientific literature as it relates to: wetland evaluation methods; current remote sensors; analysis/classification methodologies using remotely sensed data or GIS modelling wetland variables and functions; and an assessment of available remotely-sensed information and GIS spatial datasets. A main goal of the current OMNR project to re-define and refine its wetland evaluation system is to develop a quantitative and mostly objective means of evaluating wetlands based on a scoring system where scores are generated from existing digital geo-spatial data wherever possible. The desired outcome is to move from a heavily weighted field-based methodology to one that is more computer-based. This review has shown that many of the evaluation methods are systems-based and are in use currently or have been tested in a research context. They incorporate readily available GIS technology and existing digital data to rank wetlands based upon predominantly functional aspects of wetlands (e.g. hydrology, sediment processes, biogeochemistry, habitat features, etc.). Many of these elements are currently being assessed in the field for the OWES. These GIS-based methods include SWAMP (Sutter, 2002), SCREAM (Stein *et al.*, 2004), W-PAWF (Tiner, 2002) and WIMS (Kang *et al.*, 1994). As has been mentioned, SCREAM is especially intriguing because of the ability to assess wetlands at multi-scales (e.g., stream to watershed).

In addition to these system-based methods, many of the methods described in the accompanying Excel spreadsheet are also field-based methods, like the current OWES. These methods are shown to work well for the areas of investigation, and to provide information for the maintenance and modification of wetlands in the given jurisdictions. They all vary from one another in terms of the underlying functions, values and conditions that are assessed. Previous attempts have been made to correlate the current field-measured variables in the OWES to GIS derived metrics without good results. It may prove advantageous to also review and select some of these other elemental variables from these other field-based systems and determine if better relationships can be derived or to add to the re-design of the evaluation system to include other attributes that are more amenable to geo-spatial data.

Many techniques for the analysis of wetlands from both remote sensing and GIS have been reviewed in this paper. To meet the main goal of developing a system that is derived from digital geo-spatial data, the techniques (either remote sensing or GIS) best suited to derive missing data variables can be implemented. Additionally if other elemental variables of wetlands that are assessed in other

field-based methods are determined to be potentially useful to the development of the new system, then relationships between remote sensing derived metrics and these other functions, values and conditions can also be assessed to determine if these too can be used in a system-based wetland evaluation. Through this review, it has been determined that is it feasible to develop a systems-based wetland evaluation methodology for the southern Ontario region, by basing this new system on the existing systems based methods and by utilizing expertly devised remote sensing and GIS techniques.

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